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DURABILITY OF CONCRETE EXPOSED TO MAGNESIUM  
CHLORIDE ANTI-ICING CHEMICALS

By

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B.Eng., Ryerson University, 2003

A thesis

presented to Ryerson University

in partial fulfillment of the  
of the requirements for the degree of

Master of Applied Science

In the Program of

Civil Engineering

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## ABSTRACT

### DURABILITY OF CONCRETE EXPOSED TO MAGNESIUM CHLORIDE ANTI-ICING CHEMICALS

By

Sherry Sutherland  
Master of Applied Science, 2006

Civil Engineering  
Ryerson University

The objective of this study was to determine if/how magnesium chloride ( $\text{MgCl}_2$ ) influences the durability of typical sidewalk concrete being used in Ontario. The effects of  $\text{MgCl}_2$  on deicer salt scaling were reviewed with the hypothesis that  $\text{MgCl}_2$  at higher concentrations will cause more scaling. When the early results were inconclusive, the focus of this research was then moved to determining if initial exposure to  $\text{NaCl}$  was a contributing factor, and if the mechanism causing deterioration was due to exposure at high temperatures rather than low temperatures. Mortar specimens were examined for the influence of  $\text{MgCl}_2$  on expansion and compressive strength. It was found that  $\text{MgCl}_2$  had little effect on deicer salt scaling, but caused an increase in expansion and a decrease in compressive strength with increased  $\text{MgCl}_2$  concentrations.

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**DEDICATION**



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## Chapter 1

### INTRODUCTION

#### 1.1 General

Chemical degradation of concrete due to sulphate attack, corrosion of reinforcing steel, alkali-silica reaction, and carbonation has been a major concern for engineers for years, despite the relative chemical stability of concrete compared to steel.

Over the past few years, there has been growing concern for the state of exterior concrete flatwork throughout Ontario. Many concrete surfaces, such as sidewalks, curbs, patios, driveways, and highway barriers are being subjected to scaling at a very early age, resulting in the concrete deteriorating well before the end of its design life. This increase in scaling coincides with the introduction of a variety of new anti-icing chemicals being used by municipalities in an effort to optimize winter road maintenance practices so as to not jeopardize road safety, while minimizing the potential harm to the environment (Environment Canada, 2003). There is considerable interest in magnesium chloride because of its anti-icing properties and effectiveness at lower temperatures. Some even believe that these new anti-icers are better for the environment, although this is debated in numerous studies (Fischel, 2001; Environment Canada 2001; Environment Canada, 2003; Ministry of Transportation Ontario, 2003; Environment Canada, 2004; Elwell and MacDonald, 2005; and Insurance Corporation of British Columbia, 2006).

In addition to the chemical degradation of concrete, a number of potential human health effects (irritation of skin, eyes, respiratory tract, and digestive tract; as well as a small

increase in the cancer rate due to the trace metals found in deicers) and environmental impacts (chloride based deicers increase the salinity of rivers, streams, and lakes) have been noted (Anderson and Rock, 2001). Some of the deicers also have high levels of nitrates which can interfere with the oxygen intake from the blood in infants. Also sodium, calcium and magnesium chlorides may contribute to the mobilization of trace metals from the soil to the surface and groundwater (Lewis, 2001).

Over 5 million tonnes of “road salts” are used in Canada annually to help in snow and ice removal on public and private roads, parking lots and sidewalks (Transportation Association of Canada, 2003). Since the 1930’s, sand and sodium chloride have been used for snow and ice control, enabling many roads to remain open during the winter months. In the 1950’s, the harmful effects of deicing salts had become widely known. Since the 1960’s, numerous studies have been conducted on the environmental and human health effects and corrosion from the use of deicers (Government of Canada, 2004). In 2000, Environment Canada proposed that salts be considered toxic under the Canadian Environmental Protection Act of 1999. However, Environment Canada also stated that human safety must never be compromised.

According to Environment Canada, anti-icing is a proactive approach to winter road maintenance. It is the application of chemicals or brine to prevent the formation of the road/ice bond. Studies have shown that pre-treating the road with brine uses less chemicals than applying dry deicers to eat through accumulated snow and ice (Environment Canada, 2003).

## 1.2 Research Objectives

The objective of this research was to investigate if/how magnesium chloride influences the durability of typical sidewalk concrete being used in Ontario. The early phases of this research focused on the resistance of samples to scaling with a hypothesis that  $\text{MgCl}_2$  at higher concentrations will cause more severe scaling. The early phases demonstrated results that did not support this hypothesis. Accordingly, the objective of this research was modified to investigating if another mechanism may be causing the deterioration that is being seen in the field, namely, magnesium sulphate attack at normal (above freezing) temperature.

## 1.3 Scope of Research

This research project was divided into three phases. The purpose of Phase 1 (P1) was to determine the most aggressive concentration of magnesium chloride ( $\text{MgCl}_2$ ), with respect to scaling. The purpose of Phase 2 (P2) was to determine if samples first treated with 3% sodium chloride ( $\text{NaCl}$ ) and then  $\text{MgCl}_2$  (at same concentrations used in P1) would prove the hypothesis. The objective of Phase 3 (P3) then became to determine if another mechanism is responsible for causing the deterioration that is being seen in the field. Phase 3 focused on mortar specimens to see if expansion and loss of strength were occurring and if the concentration of  $\text{MgCl}_2$  has an effect..

## 1.4 Thesis Layout

Chapter 2 is a literature review which summarizes historical and current practices and technologies associated with this research. This chapter discusses the mechanism and methods of measurement for freeze/thaw and salt scaling deterioration, the role of supplementary cementing materials (SCMs), the effect of various deicers and anti-icers, and field data outlining evidence of the problem.

Chapter 3 details the experimental program for this research project. This chapter outlines the procedures, materials and equipment used throughout the study as well as outlines the fresh/hardened testing that was performed.

Chapter 4 pertains to the analysis of results. This chapter attempts to investigate thoroughly the results to derive or explain relationships among various parameters involved in this research.

Chapter 5 concludes this thesis with a summary of all relevant findings, as well as possible recommendations which may be utilized for continued research in this area.

## Chapter 2

### LITERATURE REVIEW

This chapter will provide an extensive background into topics which are relevant to this research including various aspects on mechanism of freeze/thaw deterioration, mechanism of salt scaling deterioration, chloride binding and the transport mechanism, effect of supplementary cementing materials on concrete durability and effect of various chemical deicers and anti-icers on concrete durability.

#### 2.1 General

Sand and sodium chloride have been used for snow and ice control since the 1930's. By the 1950's some of the harmful effects of deicing salts had become widely known. However, the benefits of using deicers and sand for increasing safety of winter driving remained a major factor in the continuing use of these deicers. Since the 1960's numerous studies have been conducted on the environmental, human health effects and corrosion from the use of deicers. A report prepared by Environment Canada (2000) proposed that road salts be considered toxic under the Canadian Environmental Protection Act of 1999. However, the report also stated that the use of deicing agents was an important component of the strategies to keep roads open and safe during the winter and minimize traffic accidents. It further concluded that human safety must never be compromised (Pigeon et al, 1995).



## 2.2 Mechanism of Freeze/Thaw Deterioration

Water expands approximately 9% upon freezing. Concrete that is saturated when the temperature drops below freezing point is therefore subjected to expansive forces, leading to cracks developing parallel to the surface. The opened crack then allows water to fill in once there is an increase in temperature, and becomes available to generate additional forces upon the next cycle of freezing, opening the crack further eventually leading to failure of the surface. There are a number of theories to explain the physical aspects of the freeze-thaw mechanism, which are discussed in the following sections.

### 2.2.1 Hydraulic Pressure Theory (ACI Committee 201, 1992)

Water expands on freezing, with ice having a volume 9 percent greater than that of water. The freezing will occur first in the larger pores and voids. It then progresses into smaller pores as the temperature is lowered. As the transition from water to ice proceeds, when the pores are critically saturated, the water is expelled from the capillaries resulting in hydrostatic pressure. The drainage of water along pore walls will induce hydraulic pressure, the magnitude of which depends on the rate of freezing, degree of saturation, pore structure, and the length of flow path to the nearest void for the water to escape. Failure will occur when the pressure exceeds the tensile strength of concrete (ACI Committee 201, 1992).

### 2.2.2 Litvan's Model (Litvan, 1976)

The difference in vapour pressure between surface ice and super-cooled pore water results in dehydration of concrete by the movement of water towards the surface. If this movement is significantly restricted failure may occur.

### 2.2.3 Solar Effects (Moukwa and Adkins, 1988)

This theory addresses the effect of the sun's energy on freezing and thawing of the surface of concrete. It is based on the theory that the sun's rays heat up the surface of the concrete very rapidly above ambient temperature. Once the sun's energy is no longer available, freezing occurs in two directions, from the top downwards and from frozen concrete upwards towards the surface. Two-dimensional freezing results in convergence of the two freezing fronts somewhere below the surface in an ice lens. This formation of ice lenses creates a weak layer, resulting in scaling.

#### 2.2.4 Osmotic Pressure Theory [Powers, 1955]

Osmotic pressure develops due to the concentration gradient between capillary water and gel water. Gel water migrates to the capillaries to relieve the imposed gradient, thus fuelling ice formation in the capillaries. The osmotic pressure develops in the direction toward the capillary pores. Therefore, the total pressure required to force the capillary water out of the pores will be a combination of the hydraulic pressure and osmotic pressure, and this combined pressure would contribute to stressing the concrete.

#### 2.2.5 Supercooling [Radjy et al, 1972]

Water in cement pastes will often freeze below melting temperature. The extent of the supercooling of pore water is a function of the capillary size and the concentration of solute. The extent of supercooling will affect the rate of ice front propagation and thus the development of hydraulic pressure. It has been found that excessive supercooling followed by freezing results in mechanical failure.

## 2.3 Mechanism of Salt Scaling Deterioration

The increase in deterioration when deicers are used is due to five factors which are discussed in the following sections (Mehta, 1986).

### 2.3.1 Degree of Saturation

One of the known effects of the application of deicing salts is that it tends to increase the degree of saturation of concrete at a given relative humidity. This effect originates from the fact that salt solutions have a lower vapour pressure than water (Marchand et al, 1994).

A previous study (MacInnis and Whiting, 1979) explains that under 88% relative humidity condition and an equilibrium, the average degree of saturation of various concrete specimens initially saturated with water was 73% while the average degree of saturation for companion specimens initially saturated with a 10% NaCl solution (in mass) was 92%. Such a phenomenon is of particular importance in connection with the deicer salt scaling deterioration of concrete structures in practice. The application of deicing salts is more likely to maintain them above the critical degree of saturation. The hygroscopical effect of deicing salts is, however, less critical when concrete is tested in the laboratory since most test procedures, specimens, after a certain drying period, are re-saturated prior to testing (MacInnis and Whiting, 1979).

### 2.3.2 Disruption in Concrete Pores

Water in the largest pores freezes first, and water in small pores cannot freeze or would freeze at very low temperature due to the high surface forces in small pores. These surface forces result in a high chemical potential of water, and thus hinder ice crystal formation. The unfrozen water tends to reduce its potential and migrates to locations where it is able to freeze, such as the larger pores. As a result, drying shrinkage occurs in the gel structure while ice accumulates in large pores or cracks, leading to the formation of new cracks or extension of old ones. At a lower freezing rate the diffusion of gel water is the dominant feature causing drying shrinkage in the gel structure, whereas at a first freezing rate diffusion of gel water does not have time to evolve and hydraulic pressure governs the freezing deterioration and induces cracks in the matrix (Pentala, 1998).

### 2.3.3 Salt Concentration Gradients

Pore water in the surface layer, which contains the highest concentration of salts, would freeze at low temperature because salt reduces the freezing point of water. A deep layer, where salt concentration is lower may freeze at the same time. The combined effects of temperature gradient and salt concentration gradient along the depth will probably keep the intermediate layer between the surface and the deep layer in liquid state, and it would freeze upon intensive cooling. The resulting pressure from delayed freezing may cause the scaling of the surface because it cannot be relieved through the frozen layers (Yamato et al, 1987).

#### 2.3.4 Temperature Shock

The solubility of all chemicals varies with temperature: the lower the temperature, the less the solubility. But the decrease in solubility has a limit, a point where no more of the chemical can dissolve and depress the freezing point. This is known as the eutectic point (the lowest possible freezing point of a solution). The temperature at which the brine will freeze continues to decrease as more salt is added and the concentration is raised. Each freeze point depressant has its own eutectic point (Environment Canada, 2004). I believe adding deicers to snow and ice covered concrete is more detrimental to concrete than leaving the ice for the duration of the winter. Once concrete is frozen, it is better to leave it frozen. When deicers are used, this increases the number of freeze/thaw cycles that the concrete will go through in its lifetime. The more cycles of freeze/thaw the concrete is likely to undergo will increase its chances of deterioration.

#### 2.3.5 Crystal Growth in Pores

The water in concrete pores contains dissolved ions and salts, which causes an initial super-cooling. As temperature drops to its freezing point, ice crystals will form in the larger capillaries, thus increasing the alkali concentration of the unfrozen solution at the freezing sites, which raises the osmotic potential of the unfrozen solution causing water to be taken away from surrounding smaller pores into the freezing sites. This suction dilutes the solution allowing further growth of ice. When the pores are filled with the solution, any further crystallization will induce a buildup of pressure (Cody et al, 1996)

## 2.4 Chloride Binding and Transport Mechanism

Numerous mechanisms of deterioration can occur in concrete structures. It appears that chloride ingress and carbonation are the dominating mechanisms of deterioration (Gaal, 2004). The interaction of externally-derived chloride with concrete has two main elements, the transport and the reaction of the chloride ions with the concrete.

### 2.4.1 Transport Mechanism

There are two basic transport mechanisms for the penetration of chlorides, diffusion of chloride ions and the transport of chloride ions combined with water transport (Bucea et al, 2005). It is important to understand how the chloride ions are transported in concrete prior to dealing with the mechanism of deterioration.

Diffusion is the process by which matter is transported from one part of a system to another because of random molecular motions. Quantitative measurements of the rate at which a diffusion process occurs are usually expressed in terms of a diffusion coefficient. The diffusion coefficient, however, is not a true physical property but the proportionality constant in Fick's Law (Drioli et al, 2006). Chloride ingress into concrete is usually modeled as a diffusion process; however, other transport mechanisms like convection and absorption may contribute to the ingress of chloride ions. Fick's first and second law of diffusion describes the process of diffusion in a mathematical way (Drioli et al, 2006).

The mathematical formulation assumes a constant load of chlorides, which leads to a uniaxial permeation into a homogenous semi-infinite medium.

Chlorides may also penetrate by absorption (capillary forces) and convection. While the larger part of a concrete structure retains capillary moisture, even in arid environments, the partially saturated surface zone is prone to accelerated chloride ingress due to capillary forces. However, the harsh winter season, where de-icing agents are used, is preceded by the fall where structures are exposed to moisture without chlorides. Even in relatively dry concrete, exposure to moisture results in rapid filling of the accessible pore space, after which bulk moisture movement virtually ceases because of the loss of driving potential (capillary attraction). Therefore, the primary mode of transport of chloride ions is diffusion (Cady, 1983). Chloride ions are carried by moisture through pores in the cement hydrates. However, concrete is far from homogeneous as it mainly contains impervious aggregates, and porous cement hydrates. If the water to binder ratio of the concrete mixture is reduced, the pores are reduced in size and number, subsequently the diffusion coefficient is reduced (Bamforth 1994).

Cracks do accelerate ingress of chlorides into concrete. The question is, whether or not, the diffusion hypothesis is still valid in a structure that shows cracks. Chloride ingress into cracked concrete is not well understood; for now the crack width is suggested as a criterion for the durability of concrete. It is assumed that the additional chloride ingress, because of the cracks, is negligible in case of small crack widths.



Laboratory studies, outlined in Table 2.1, show that the chloride ingress rate associated with water absorption into cracks with a width of 0.05 mm to 0.50 mm, could be considered to be similar to the ingress rate in sound concrete (Gaal, 2004).

**Table 2.1 – Limiting Crack Widths for Regular Diffusion (Gaal, 2004)**

Author	Crack Width (mm)
Paulsson Tralla 2002	0.05
Li 2002	0.10
Rehm 1964	0.15
Mangat 1987a/ 1987b	0.20
Boulfiza 2003	0.20
Schiebel 1986	0.25
Francois 1999	0.50

The crack width criterion, however, disregards the depth and the number of cracks. Since the chlorides penetrate into the concrete through the concrete crack surface area, a better understanding of the vulnerability of concrete to accelerated chloride ingress could be obtained by using the specific crack surface area (Gaal, 2004).

At high concrete temperatures the ingress of chlorides is faster than at low temperatures. Usually, the increased movement of ions is considered with an increased diffusion coefficient. Many studies have been carried out; however, the results differ considerably, from a 100% increase at 50°C temperature difference [Andrade 2003] to a 20% increase at a 60°C temperature difference [Jooss 2002]. In these studies, the specimens were heated up to a temperature of 80°C, whereas most structures never experience such temperatures (Gaal, 2004)

The presence of a pore solution is indispensable to facilitate the diffusion of chlorides to greater depths. It is clear that the moisture content in the pores determines to what extent diffusion will occur. Even though the concrete is not saturated, as in laboratory tests, it is clear that sufficient moisture is present in the concrete to facilitate diffusion of chloride towards the reinforcement [Nilsson 2000]. However, the degree of saturation will influence the chloride ingress rate and this relationship between the moisture content and the diffusion coefficient cannot accurately be defined. The somewhat reduced rate of ingress of chlorides is overcome by adopting an effective diffusion coefficient (Gaal, 2004).

Most concrete bridges are, in contrast to laboratory specimens, only exposed to chlorides during several months each year. However, the cumulative duration of salt application to the highway bridges is unknown. Therefore, it is assumed that highway bridges are exposed to chlorides all year long (Gaal, 2004).

#### 2.4.2 Chloride Binding

Numerous studies have reported the chloride binding ability of cements and its dependence on various parameters such as the associated cation type ( $\text{Ca}^{2+}$ ,  $\text{Na}^{+}$ ), cement type and content, mineral admixtures, water-cement ratio, curing period and sulphate additions (Hanson et al, 1984; Byfors et al, 1986; Arya et al, 1989; Rasheeduzzafar et al, 1991; Hussain et al, 1993; and Suryavanshi et al, 1996).

A few researchers during the 1980's showed the process of chloride binding at room temperature in the form of a chloro-complex called Friedel's salt,  $3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{CaCl}_2\cdot 10\text{H}_2\text{O}$ , in cement rich in  $\text{C}_3\text{A}$  by applying techniques such as differential thermal analysis (DTA) and X-ray diffraction (XRD) (Page et al, 1981). Friedel's salt is important when understanding chloride binding in concrete for a number of reasons. First, it is more stable than the hydroxyl aluminate  $\text{AF}_m$ . Second,  $\text{AF}_m$  phases exhibit anion exchange: their composition is sensitive to their local chemical environment. Thus when chloride diffuses into cement, diffusion profiles may be affected by ion exchange and binding into  $\text{AF}_m$  phases (Birnin-Yauri and Glasser, 1998).

Chemical binding in Friedel's salts is only a limited portion of the total binding. There is also physical binding occurring at pore surfaces in electrical double-layers. Nilsson (1996) showed that various mechanisms give a non-linear binding not being proportional to the concentration of chloride but more significant at lower concentrations than at higher. Alkali hydroxide and chloride compete for the same binding sites, which is why the leaching of alkalis is an important process that changes chloride binding over time.

The chloride ions that are present in the hardened cement paste can be subdivided in free and bound chlorides. The binding of chlorides is either physical or chemical. In a previous study, it was found that the proportion of bound chloride remained approximately constant regardless of the water-cement ratio (Gaal, 2004).

### Chemical Binding of Chlorides

One of the dominating parameters of chemical chloride binding is the tricalcium aluminate ( $C_3A$ ) content of the cement. The chlorides are partially bound by  $C_3A$  and form Friedel's salt. Depending on the  $C_3A$  content, 50 to 80% of chloride ions, which are added to the mix, may be bound by aluminate phases (Justnes, 1983; Polder et al, 2002). The bound chlorides are released if the concrete is carbonated or if the concrete is exposed to sulphates. It is found that if the pH value drops below 11.0, due to carbonation, most of the bound chlorides are released (Hussain et al, 1994).

### Physical Binding of Chlorides

Physical binding takes place when the amorphous calcium silicate hydrate (CSH) gel adsorbs the chlorides. The CSH gel is formed during the cement hydration. The physically bound chlorides will move towards lower concentrations on the gel surface at a much slower rate than the free chlorides in the pore water. This indicates that the free chlorides will dominate the diffusion (Justnes, 1983).

**Table 2.2 – Binding of Chlorides as a Function of Cement Type with Chlorides Added to Paste (Arya et al, 1990)**

Cement Type	Replacement	Total Cl <sup>-</sup> added (% by mass of binder)	Bound Cl <sup>-</sup> (% by mass of binder)	Bound/Total (%)
T10/GU	-	1.0	0.385	39
T10/GU	15%PFA	1.0	0.532	53
T10/GU	35%PFA	1.0	0.605	61
T10/GU	70%GGBFS	1.0	0.711	71
T10/GU	15%CSF	1.0	0.322	32

Note: PFA (Pulverized Fuel Ash), GGBFS (Slag), CSF (Condensed Silica Fume).

If concrete is exposed to permeation of chlorides from the environment, the binding is hardly influenced by the binder type, as can be seen in Table 2.3 (Arya et al, 1990).

**Table 2.3 – Binding of Chlorides as a Function of Cement Type with Samples Submerged in Chloride Solution (Arya et al, 1990)**

Cement Type	Replacement	Total Cl <sup>-</sup> added (% by mass of binder)	Free Cl <sup>-</sup> (% by mass of binder)	Bound Cl <sup>-</sup> (% by mass of binder)	Bound/Total (%)
T10/GU	-	1.635	0.831	0.804	50
T10/GU	30%PFA	1.887	0.818	1.069	57
T10/GU	70%GGBFS	1.750	0.830	0.920	53
T10/GU	10%CSF	1.265	0.684	0.581	46

Note: PFA (Pulverized Fuel Ash), GGBFS (Slag), CSF (Condensed Silica Fume).

It is suggested that not only tricalcium aluminate chemically binds chlorides but that all aluminate phases bind chlorides (Mohammed and Hamada, 2003).

## 2.5 Effect of Supplementary Cementing Materials

Supplementary cementing materials (SCMs) contribute to the properties of hardened concrete through hydraulic or Pozzolan activity. SCM's react chemically with calcium hydroxide released from the hydration of Portland cement to form cement compounds. SCM's make concrete mixtures more economical, reduce permeability, increase strength, or influence other concrete properties. Typically used SCM's in Ontario are ground granulated blast furnace slag (GGBFS), fly ash (FA) and silica fume (SF).

The use of SCM's will affect the properties of concrete by slowing hydration reaction, influencing the reaction rate temperature, changing chemical composition of solubles in the aqueous phase during/after mixing and changing the pore structure as well as the permeability (Boyd, 1995).

A greater influence of temperature on the reaction rate and having a slower hydration rate will increase the risk of early frost damage. Different chemical composition of the solubles in the aqueous phase will affect the stability of air entrained bubbles, and a change of pore structure may affect the spacing factors. Permeability will be longer in young concretes due to the slower hydration, in comparison to Portland cement concretes (Virtanen, 1983).

The durability of concrete in the presence of de-icing can be divided in two parts, the durability of the concrete itself, and the durability of the top portion of the concrete. The durability of the top layer is not only dependent on the material properties, but also on the mixing, placing, and finishing procedures. There is a considerable amount of literature on the effects of de-icing salts on the durability of concrete; however, there is a limited amount on the effects of de-icing chemicals with respect to concretes containing SCM's. There are conflicting results among the literature relating to SCM's, overwhelming agreement exists stating that slag and fly ash increase scaling as compared to their Portland cement counterparts (Fagerlund, 1987). There were significant improvements in scaling found with introduction of slag (Fagerlund, 1982), which was attributed to the reduced diffusivity of chloride ions. It has also been found that slag reduces chloride ion ingress, but did not improve performance. Research findings also consistently show that mixes containing slag and/or fly ash with excessive scaling have had good freeze/thaw resistance (Boyd, 1995). This difference suggests that slag and fly ash only affect the surface quality of the paste rather than the bulk matrix. This also suggests that the concrete may have been inadequately finished and cured as the time of set with SCM's increases. If the concrete finishers trap the bleed water below the surface or insufficiently cure this would make the surface layer of the concrete more susceptible to scaling. It has also been suggested that because of slower hydration and greater influence of temperature on reaction rate, concretes with SCM's may be inadequately cured resulting in less mature pastes more susceptible to scaling.

Although there are studies on the type of curing used showing conflicting results as well. A number of studies show that some curing compounds perform better than extensive moist curing (Klieger and Gebler, 1987; Marchand et al, 1994). There are also studies that have found that an increase in moist curing results in more scaling (Bilodeau et al, 1991).

The diffusion resistance of concrete to chloride ions is normally expressed in terms of chloride diffusion coefficient. Diffusion is mainly influenced by the pore size distribution. The diffusion coefficient has been found to decrease with the increase in strength and also with the addition of SCMs such as slag, fly ash and silica fume. Figure 2.1 shows that an increase in strength leads to an improvement in the diffusion resistance and reduction in the diffusion coefficient. Also, it can be seen that an addition of 65% slag, or 30% fly ash or 7% silica fume to general use Portland cement improves diffusion characteristics (Bucea et al, 2005).

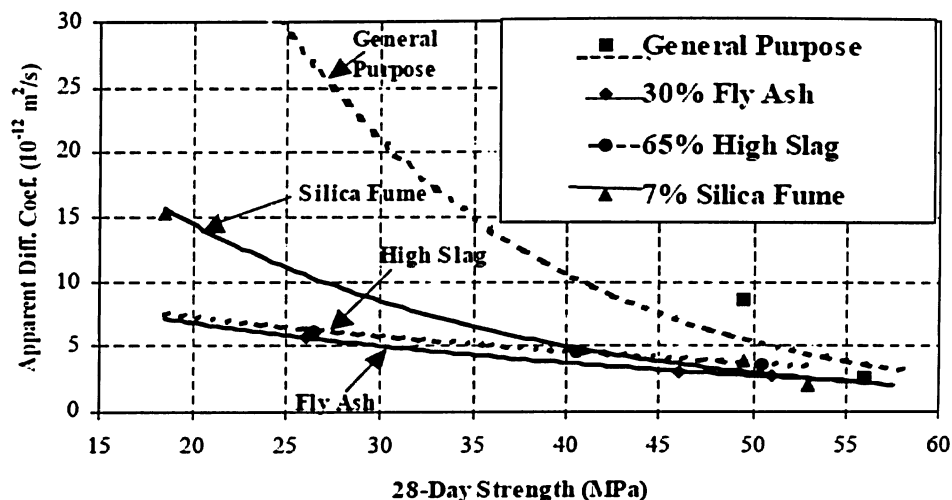


Figure 2.1 – Effect of Binder on Strength and Diffusion Coefficient (Bucea et al, 2005)



### 2.5.1 Effect of Ground Granulated Blast Furnace Slag on Durability of Concrete

Durability, as defined by the Cement Association of Canada, refers to the ability of concrete to resist deterioration from the environment or from the service in which it is placed.

It is believed that increased durability of concretes incorporating ground granulated blast furnace slag (GGBFS) results from a finer pore structure and reduced contents of easily leached calcium hydroxide in the hardened cement paste. Subsequently, the volume previously occupied by the calcium hydroxide is also filled in with hydration products resulting in a less permeable material. Permeability controls the physical and chemical processes of degradation caused by the action of migrating water; therefore, permeability to water determines the rate of deterioration (Malhotra, 1987).

Chemical compounds similar to CSH form during the pozzolanic reaction of slag causing pore refinement. It has been found that slag is more efficient in blocking the pores since it reacts not only with  $\text{Ca(OH)}_2$  but also with water to form CSH and calcium aluminates, whereas fly ash only reacts with  $\text{Ca(OH)}_2$ . Chloride ions may be trapped or bound by some of the components of concrete. Thus, the additional formation of CSH gel results in the absorption of more chloride ions and blocking of diffusing paths. A higher content of  $\text{C}_3\text{A}$  in slag can also absorb more chlorides to form Friedel's salt (Mendoza, 2003).

The results of investigations of the de-icing salt scaling of GGBFS concretes appear to be conflicting. In many cases slag concrete appears to have reduced scaling durability (Bilodeau et al, 1991; Fagerlund, 1989; and Gunter et al, 1987). The average capillary pore size appears to increase with carbonation in slag concrete, leading to reduction in scaling resistance. On the other hand, the results of the field study of a seven-year old slag concrete have shown that there was less carbonation on the concrete sections, and scaling tests done on cores from this concrete and field observations indicated that slag concretes had better scaling resistance (Boyd, 1995).

#### 2.5.2 Effect of Fly Ash on the Durability of Concrete

Fly ash is part of the composite that forms the concrete mass, fly ash acts in part as fine aggregate and in part as a cementitious component. Fly ash influences the rheological properties of fresh concrete, the strength, finish, porosity, and durability of the hardened concrete. There have been many investigations carried out on the scaling resistance of fly ash concretes. However, the available results are often contradictory.

There are laboratory studies which show that the use of fly ash in a properly air entrained concrete can lead to significant scaling (Gebler and Klieger, 1986; Klieger and Gebler, 1987; Whiting, 1989; and Bilodeau and Malhotra, 1992). On the other hand, there are investigations showing good scaling resistance of concretes incorporating fly ash up to 30% replacement of cement (Bilodeau et al, 1991). One of the reasons for the contradictions is the varying nature of fly ash from batch to batch. Also, the slow rate of

hydration of fly ash concretes and the brittleness of the cement paste, caused by the reduced amount of calcium hydroxide in the hardened paste, add to the scaling durability problems. However, the addition of some fly ashes could also refine the pore structure of the matrix, resulting in lower surface permeability and reduced freezable water content.

Permeability is fundamental in determining the rates of mass transport relative to destructive chemical action. A number of investigations have been made on the influence of fly ash on the relative permeability of concrete pipes containing fly ash substituted for cement in amounts of 30-50% examined the permeability of concrete pipes exposed to de-icing chemicals and containing between 30-50% fly ash (Davis, 1954).

It was found that the concrete permeability was directly related to the quantity of hydrated cementitious material at any given time. After 28 days of curing, the fly ash concrete were more permeable than the control concretes. At 6 months, this was reversed. Davis (1954) assumed this was due to the Pozzolanic reaction of fly ash (Malhotra and Ramezaniapour, 1994).

(Kanitakis, 1982) used an initial surface absorption test to examine concrete with and without a low-calcium fly ash. Kanitakis (1982) concluded that at early ages, fly ash concrete behaves as a lean mixture concrete which is permeable. At later ages, permeability is reduced as the pozzolanic action proceeds.

### 2.5.3 Effect of Silica Fume on the Durability of Concrete

There are some conflicting reports regarding the de-icing salt resistance of silica fume concrete. Some studies suggest that normal strength, air-entrained silica fume concrete is more susceptible to de-icer salt scaling than a comparable Portland cement concrete (Pigeon et al, 1987; Plante and Bilodeau, 1989). Other investigations have shown that silica fume can improve the scaling resistance of concrete (Virtanen, 1983; and Pigeon et al, 1986). Excellent scaling resistance of air-entrained silica fume concrete in field conditions has been reported by researchers, when silica fume concrete was under 10% (Virtanen, 1983; and Pigeon et al, 1986). Also, non-air entrained normal strength silica fume concretes have been found to have better scaling resistance than similarly non-air entrained Portland cement concretes. Further studies show that in silica fume concrete, when the water-to-cementitious material ratio is less than or equal to 0.30, air entrainment is generally not required for scaling resistance. The advantage that silica fume can bring to the concretes is the refined pore structure of the matrix, reduced capillary pore size, and the resulting lower surface permeability.

## 2.6 Effect of Various Chemical De-Icers & Anti-Icers

In this section, five of the most commonly used de-icers and anti-icers are outlined in further detail. Table 2.4 summarizes some of the properties of these deicers and anti-icers. It should be noted that the eutectic temperature refers to the point at which a substance freezes or melts.

**Table 2.4 – Properties of Various De-Icers and Anti-Icers**

Chemical	Practical Working Temp. (°C)	Eutectic Temp. (°C)	Eutectic Conc. (%)
Calcium Chloride (CaCl <sub>2</sub> )	-31.6	-51	29.8
Sodium Chloride (NaCl)	-9.4	-21	23.3
Magnesium Chloride (MgCl <sub>2</sub> )	-15	-33	21.6
Calcium Magnesium Acetate (CMA)	-6	-27.5	32.5
Potassium Acetate	-26	-60	49

### i. Sodium Chloride (NaCl)

Sodium chloride has been around for a long time, and naturally occurring product. NaCl could be anywhere from hundreds of millions years old to being grown only a year ago in a solar salt pond. Highway agencies have used NaCl for about 60 years, and NaCl is the most studied and understood of all the de-icers. NaCl is quick reliable and inexpensive. NaCl is being incorporated into these new anti-icing technologies (along with calcium or magnesium chloride) in a pre-wetting application. This tends to keep the cost down compared to using the new technologies alone.

## ii. Calcium Chloride ( $\text{CaCl}_2$ )

Calcium chloride is described as, versatile and exothermic.  $\text{CaCl}_2$  is effective at much lower temperatures than most de-icers with a eutectic temperature of  $-51^\circ\text{C}$ . It absorbs moisture from the atmosphere and gives off heat when turned into liquid.  $\text{CaCl}_2$  is a good compliment to  $\text{NaCl}$  as it would prevent pavement freezing problems and provide the moisture that salt needs to go into solution.

## iii. Magnesium Chloride ( $\text{MgCl}_2$ )

Magnesium chloride is described as, anti-freeze for the road.  $\text{MgCl}_2$  is also effective at lower temperatures than, with a eutectic temperature of  $-33.6^\circ\text{C}$ .  $\text{MgCl}_2$  is hygroscopic, which mean that it takes up and retains moisture. It gets this moisture from the air, pavement, snow and ice, etc.  $\text{MgCl}_2$  is usually applied as a liquid right onto the bare pavement before a storm arrives. This prevents snow from sticking to the roads and prevents frost or black ice to form by lowering the freezing temperature of water.  $\text{MgCl}_2$  can be used not only as an anti-icing agent, but also as a pre-wetting agent for sand which causes the abrasive sand to stick to the snow pack better.

## iv. Calcium Magnesium Acetate (CMA)

Calcium Magnesium Acetate is a patented chemical formulation of dolomitic limestone and acetic acid, and has been used for over 25 years. CMA can be used in liquid form or combined with salt or sand. CMA doesn't melt ice and snow, but it turns ice and snow into an oatmeal texture allowing for easy plow removal. CMA has to be applied at the onset of a storm to be effective and is more effective as an anti-icer than a deicer.

#### v. Potassium Acetate

Potassium Acetate is a reaction of acetic acid with potassium carbonate, and is used primarily as a runway deicer. Other uses are to keep rail switches open, free manhole covers, and even as antifreeze in toilet water. Potassium Acetate is most useful as a pre-wetting agent for CMA, road salt or other de-icers and sand.

Traditionally sodium chloride de-icer salts have been used in Ontario for use on bridge decks, sidewalks, and parking lots. Recently there are many new deicer salts being used in Ontario (Calcium Chloride ( $\text{CaCl}_2$ ), Magnesium Chloride ( $\text{MgCl}_2$ ), and other organic compounds), for a number of reasons (Hooton and Julio-Betancourt, 2005]:

- NaCl is considered hazardous to the environment and the Canadian government implemented a “Code of Practice” for the environmental management of road salts on April 3, 2004
- Pre-wetted salts start melting ice and snow earlier
- Brines and pre-wetted de-icers stick to pavement and require lower doses
- Anti-icing can be applied before storms
- $\text{MgCl}_2$  and  $\text{CaCl}_2$  are effective at lower temperatures

Magnesium Chloride ( $\text{MgCl}_2$ ) and Calcium Chloride ( $\text{CaCl}_2$ ) are also being used instead of Rock Salt for deicing for severe applications. Compared to NaCl,  $\text{CaCl}_2$  and  $\text{MgCl}_2$  are more effective. They work at lower temperatures. However, they may corrode cars faster, they attack concrete faster and  $\text{CaCl}_2$  and  $\text{MgCl}_2$  stick to surfaces much longer (hygroscopic).

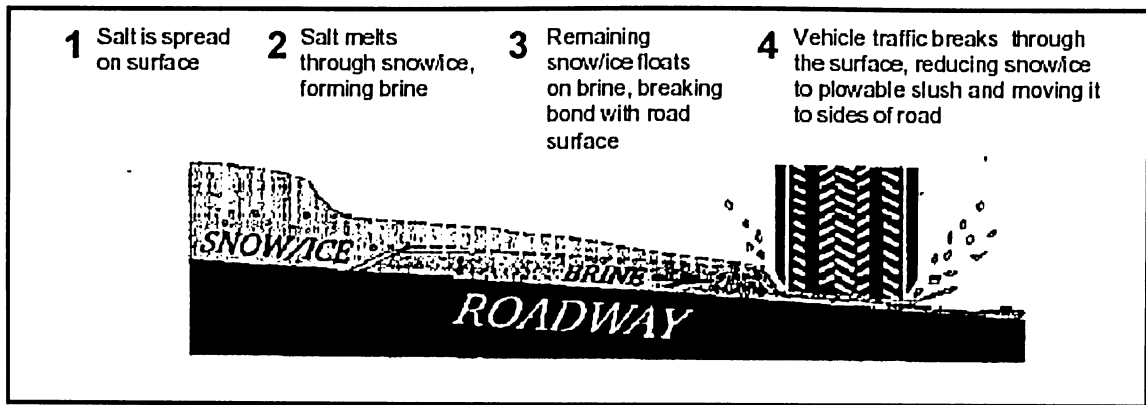
The next two sub-sections will explain the differences between de-icing and anti-icing technologies in more detail.

### 2.6.1 Mechanism of De-Icer Action

Deicing chemicals are incapable of melting snow and ice in their dry (solid) state. They first must attract or come into contact with moisture to form a brine (chemical/water solution). The brine then penetrates down through the ice and snow until it reaches the concrete surface.

As snow accumulates on the road and is packed down by traffic it bonds to the pavement, making it difficult to remove by mechanical means. The only way to break the ice-pavement bond is with de-icing. During normal de-icing operations, road salt is applied on top of the snow pack. If there is enough moisture and heat, usually as the result of a combination of sunshine, traffic, and warmer daytime temperatures, the road salt dissolves and forms a brine. The shrinking road salt particles, now coated in brine, will then auger down through the snow pack to the surface of the road, melting all the way. In snow pack conditions larger and heavier crystals of road salt with the staying power are needed to be able to melt down to the road surface. Due to its density, brine moves downward through the snow pack to the road surface.





**Figure 2.2 – The Role of Salt in Ice Removal**

Figure 2.2 outlines the steps that are taken in ice removal when de-icers are being used. First, road salt is spread on the surface. The surface could be snow pack, ice, or freshly fallen snow that hasn't yet been packed down by traffic. Then the road salt draws moisture from the snow or ice and begins to form brine. The salt crystals are now coated with a layer of brine, enabling them to begin auguring down to the surface. When the brine reaches the interface between the snow/ice and pavement, it flows down the cross fall. Due to the brine action, the bond begins to weaken as the ice melts. Eventually the bond is broken and the remaining snow/ice floats on the brine layer rather than on the pavement. Vehicular traffic breaks through the surface and reduces the remaining snow/ice to slush. Continuing traffic moves the slush to the sides of the road. After an appropriate time period, to ensure that all of the salt crystals have melted and become diluted, it's time to bring out the plows and clear the remainder of the slush away. Once the road dries, and assuming that no further precipitation falls, bare pavement should be achieved within a reasonable period after the plows have passed by (TAC, 2004).

One of the most effective ways to reduce the amount of time needed for solid salt to become brine is to apply salt brine along with the solid salt, a technique known as pre-wetting. Pre-wetting is the process of adding a liquid to sand and/or salt before it is applied to the road surface. Pre-wetting begins the dissolving process and increases salt adherence when it is applied, resulting in faster melting action and better retention rates on the road surface. Users estimate that pre-wetting can result in a 20-25% reduction in salt usage (Environment Canada, 2001).

This is an approach that is also effective in keeping the salt on the road. When a liquid is applied to a rock salt particle it absorbs a minor amount of the liquid. This increases its density and also begins the dissolving process as the liquid softens and encapsulates the particle. When the wetted salt particle hits the road surface, it has less of a tendency to bounce and slide; and because of the moisture around its perimeter, traffic action will not tend to blow it off as easily as a dry particle. This increased efficiency means pre-wetting may reduce the quantity of salt required. The pre-wetting technique involves the use of salt brine or liquid calcium chloride to wet the salt as it is spread on the road. Spraying stockpiles and truck loads has been tried, but was not practical as the granules were not uniformly coated and the liquid tended to drain out of the solid material.

## 2.6.2 Mechanism of Anti-Icer Action

Anti-icing is the application of a de-icer before or early in a storm to dissolve with the precipitation and to prevent ice from bonding with the road surface. With anti-icing, a smaller amount of chemical is required to prevent the bond from forming than if the chemicals were applied to an existing compacted layer of snow and ice. Timing of application is critical factor in anti-icing, and therefore this technique relies on accurate and up-to-date weather information.

The use of liquid-only applications for some storm situations is becoming more popular. This involves the application of straight brine in advance of the storm to prevent the formation of the ice-pavement bond. The timing of the applications, rather than the chemical that is used, is what defines the anti-icing strategy.

Liquid brine applications are particularly efficient at accurately wetting the pavement to get a head start on maintaining surface friction. The melt reaction time is quicker without temperature, moisture, and time requirement to dissolve solid salt. Subsequent applications are often required, and may be either liquid or solid depending on the precipitation type, intensity, and duration.

Experience suggests that anti-icing is an extremely effective technique for providing high levels of service during winter storms and for providing that level of service with reduced costs and reduced quantities of chemicals as compared with more traditional methods.

### 2.6.3 Factors Effecting De-Icing and Anti-Icing Effectiveness

According to the Transportation Association of Canada (TAC), there are three main factors that will effect the effectiveness of the de-icer or anti-icer being used (Temperature, Moisture and Time):

Temperature is the critical factor in breaking the bond and turning de-icers to brine. Heat is required to break this bond, causing the separate ions to go into solution. When there isn't enough heat present in the atmosphere, the de-icer will draw it from the nearest available source, which is the pavement, as it dissolves into brine. Under certain conditions, it may be advisable to apply a heat-producing catalyst such as liquid calcium chloride, which may be especially beneficial at lower temperatures.

A solid salt particle will dissolve in the first moisture it encounters, provided the temperature is adequate to provide the necessary heat. Dry salt will remain dry unless moisture is introduced from precipitation, humidity, or directly by means of pre-wetting. Once the salt starts to go into brine solution, it will continue to melt snow and ice, producing more moisture, which in turn dissolves more of the particles. The early brine solution is considered saturated and no more salt can dissolve into the moisture. If there is enough precipitation and moisture, the dissolving reaction will continue until all of the salt particles have dissolved into brine. Any moisture added beyond that point would dilute the brine, reducing its effectiveness.

When a deicer is applied early in the storm, the first precipitation provides the moisture required to break the electrolytic salt bonds and create the brine, reducing the possibility of snow and ice sticking or packing on the pavement surface. It also prevents a later build-up and allows the plow to remove the snow easier and earlier.

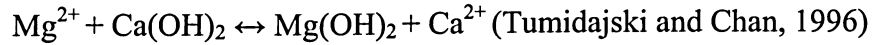
The amount of time required for the salt to go into solution and for melting to occur is determined by temperature and moisture, since the resulting brine volume must be dispersed down the road surface cross fall or by traffic tracking. The pavement temperature trend will speed or slow the chemical reaction. The characteristics of the salt being used will also affect the time to react.

#### 2.6.4 Effect of $\text{MgCl}_2$ deicers on Concrete

The principal phases of the hydrated cement paste for all concretes are calcium-silicate-hydrate (CSH), calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ), which are the result of calcium silicates reacting with water. When  $\text{MgCl}_2$  deicers are used for deicing concrete surfaces, there are a number of mechanisms that lead to compromising the expected service life of the structure; calcium dissolution by magnesium, replacement of CSH by MSH, and the alteration of ettringite to chloroaluminate.

### Calcium Dissolution by Magnesium

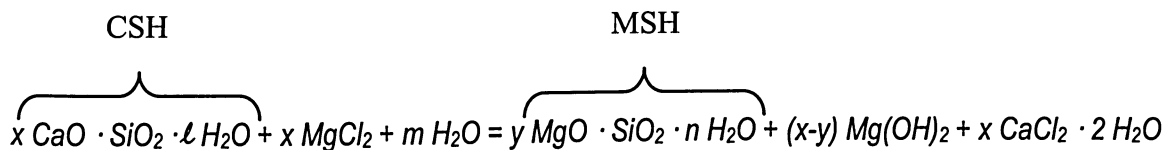
Mg<sup>2+</sup> ions react with calcium hydroxide to form magnesium hydroxide and Ca<sup>2+</sup> ions:



The Mg(OH)<sub>2</sub> is almost insoluble and shifts the equilibrium to the right with depletes the Ca(OH)<sub>2</sub> in the hydrated cement phase. Additionally, there are tensile stresses associated with the formation of Mg(OH)<sub>2</sub> because the molar volume of Mg(OH)<sub>2</sub> exceeds that of Ca(OH)<sub>2</sub>. The concrete will crack when the tensile strength of the hydrated cement paste is exceeded (Tumidajski and Chan, 1996).

### Replacement of CSH by MSH

Also, magnesium will substitute for calcium in the calcium silicate hydrate (CSH) eventually forming magnesium silicate hydrate (MSH). This non-cementitious MSH occupies space which would normally be occupied by the strong and binding CSH. The hydrated cement paste gradually loses its calcium ions which are replaced by magnesium ions. Using a modification of Bonen's equation, the general reaction of the formation of MSH from CSH in MgCl<sub>2</sub> solution can be written as follows:



Note:  $\ell + m = n + 3x - y$  (Lee et al, 1998)

In a previous study (Lee et al, 1998), it was found that chloride solutions commonly promoted decalcification of paste and altered ettringite to chloroaluminate. Also, magnesium-bearing deicer solutions caused severe paste deterioration by forming brucite and non-cementitious magnesium silicate hydrate. Sodium chloride was found to be less destructive in wetting/drying experiments, and slightly more destructive in freeze/thaw experiments. Magnesium chloride was found to have rapid deterioration in wetting/drying experiments, but freeze/thaw cycling was less deleterious due to the precipitation of a protective coat of new mineral matter on the concrete surface. Magnesium produced significant deterioration because of the wide spread replacement of CSH by non-cementitious MSH resulting from reactions between  $Mg^{2+}$  and the CSH cement phase. In another study (Lee et al, 2000), it was found that the magnesium component of deicer salts proved to be the most deleterious. Magnesium promoted the replacement of CSH by non-cementitious MSH with resulting paste shrinkage and cracking. The growth of abundant, potentially expansive brucite especially in the paste-fine aggregate interface furthered debonding of fine aggregate.

#### Alteration of Ettringite to Chloroaluminate

The reaction of sulfate and chloride in many brines used for anti-icing, with the hydrated aluminate or  $Ca(OH)_2$  phases have been reported by Tumidajski and Chan (1996) to form calcium-sulfo-aluminate ( $3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$ ) and Friedel's Salt ( $3CaO \cdot CaCl_2 \cdot 10H_2O$ ). It was found that both of these eventually converted to expansive ettringite ( $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ ) (Tumidajski and Chan, 1996).

## 2.7 Field Cases – Evidence of Problem

Over the past few years, there has been an increase in the number of scaling incidences in concrete flatwork across Ontario. This section outlines examples of case studies collected by the author.

### 2.7.1 Sidewalk in Commercial Parking Lot

The sidewalk shown in Figure 2.3 was constructed in Bancroft, Ontario, in September 2004, and experienced severe scaling in the spring of 2006. In this case, the sidewalk was not exposed to deicing chemicals in the first winter, as the building was still under construction. In the winter of 2005, commercially available deicing pellets were used to keep the sidewalk free of snow and ice. These pellets contained a combination of calcium and magnesium chloride.

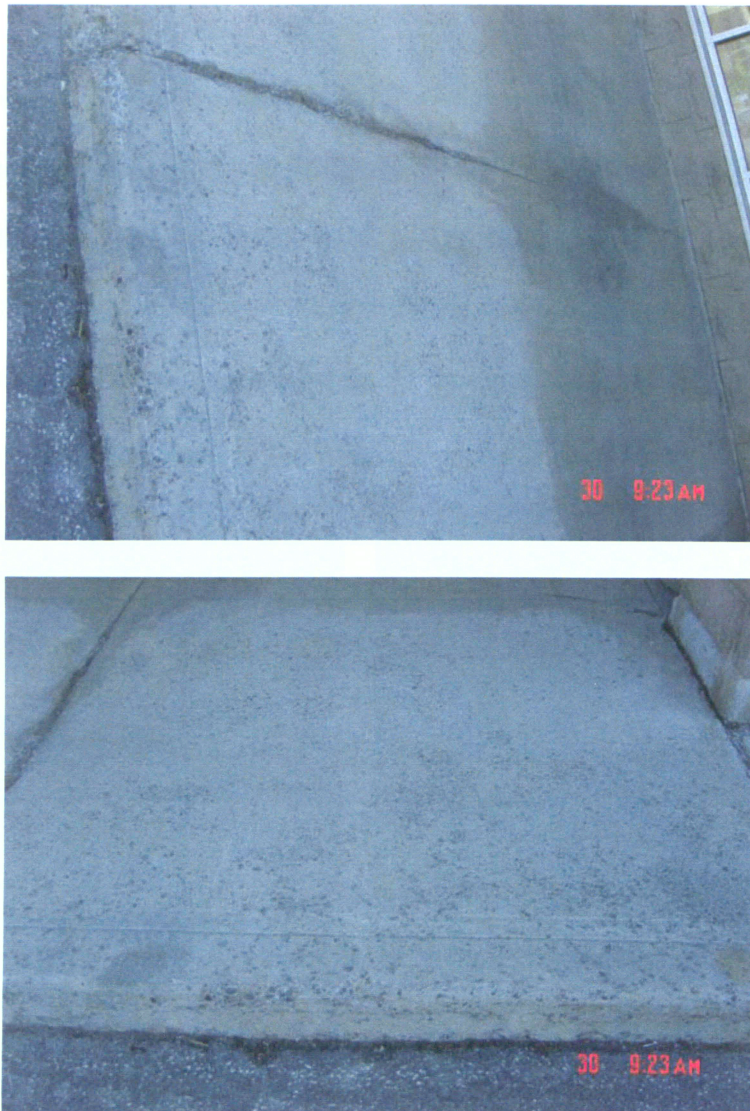


**Figure 2.3 – Sidewalk in Commercial Parking Lot exposed to  $\text{MgCl}_2$  deicing pellets**



### 2.7.2 Shopping Plaza Sidewalk

This sidewalk shown in Figure 2.4 was constructed in Brampton, Ontario, in August 2004, and experienced severe scaling in the spring of 2005, and again in 2006. In this case, only the section of the sidewalk not protected by the awning experienced scaling. This sidewalk was also subjected to the commercially available deicing pellets containing calcium and magnesium chloride.



**Figure 2.4 – Shopping Plaza Sidewalk exposed to deicers containing  $\text{CaCl}_2$  &  $\text{MgCl}_2$**

### 2.7.3 Residential Sidewalk

This sidewalk shown in Figure 2.5 was constructed in Markham, Ontario, in July 2005, and experienced severe scaling in the spring of 2006. The homeowner used as a commercially available anti-icer throughout winter 2005. The product details state that the product is environmentally friendly, less corrosive on metal, less toxic than even baking soda or common table salt, safer to use around vegetation/ plants/pets/ people, less irritating to the skin than other ice melters and does not leave an oily film or dry powder residue.

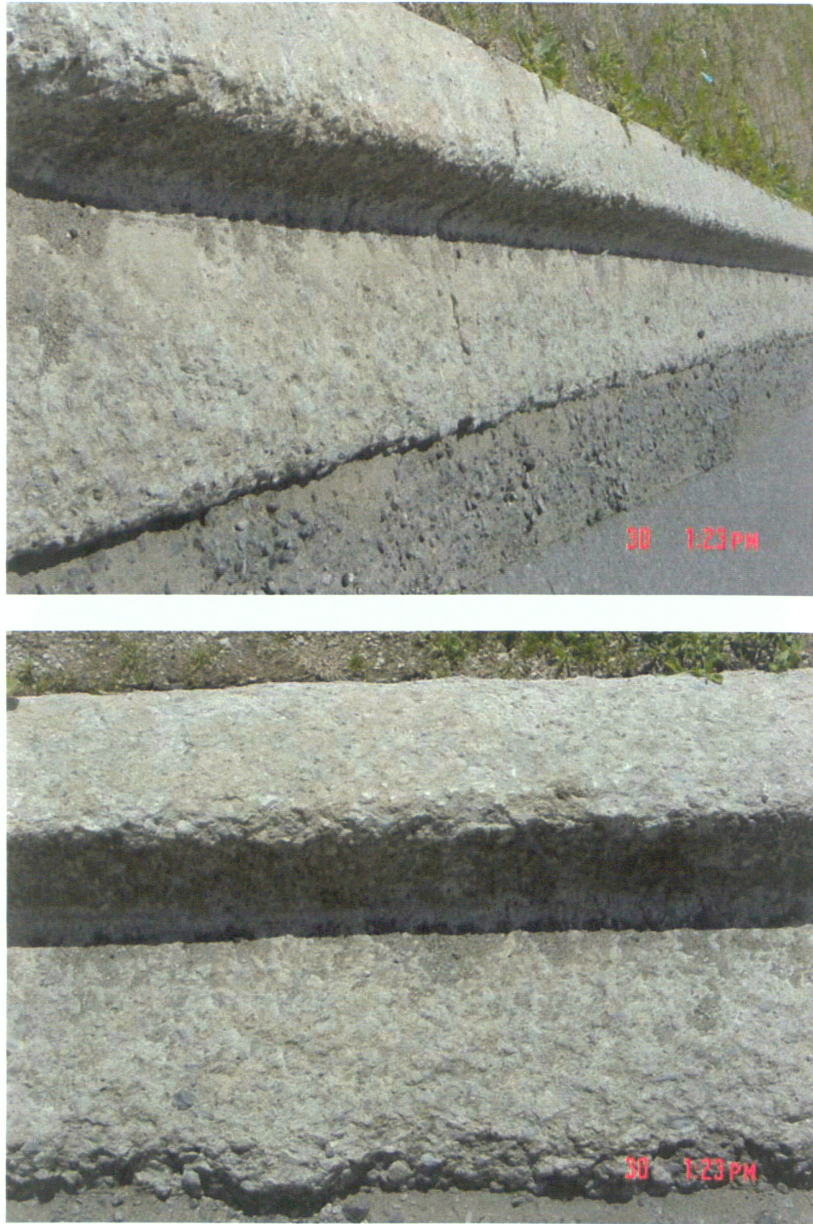


**Figure 2.5 – Residential Sidewalk exposed to  $\text{MgCl}_2$  anti-icer**



#### 2.7.4 Subdivision Curbs

These curbs shown in Figure 2.6 were constructed in Toronto, Ontario, in November 2003, and experienced severe scaling in the spring of 2006. The municipality has used a number of different deicing and anti-icing technologies during its service life.



**Figure 2.6 – Subdivision Curbs exposed to multiple chemical deicers**

## 2.8 Importance of Current Research

Based on the information presented in this literature review, it is apparent that there is a problem with concrete being exposed to current deicing and anti-icing products. There are many theories presented by various researchers to explain the interaction of “road salt” with concrete causing deterioration. However, there are a limited number of studies conducted to study deterioration mechanisms of currently used new anti-icing technologies (that contain high concentrations of magnesium chloride). So, it is important to study the deterioration mechanisms of these new anti-icers in order to finding a solution to the increased deterioration that has been seen in various concrete constructions during the past few years in Ontario.



## Chapter 3

### EXPERIMENTAL PROGRAM

#### 3.1 Introduction

A detailed experimental program was planned to study the influence of magnesium chloride anti-icers, at various concentrations on the durability of concrete and mortar specimens. The experimental program in this research project was divided into three phases.

##### 3.1.1 Phase 1 (P1)

The purpose of Phase 1 was to determine the most aggressive concentration of magnesium chloride ( $\text{MgCl}_2$ ), with respect to deicer salt scaling, using the modified MTO LS412 specification (MLS412 – explained later in this chapter). This phase was designed with the hypothesis that  $\text{MgCl}_2$  at higher concentrations will cause more severe scaling. Four concentrations of magnesium chloride (3%, 5%, 10% and 30%) were tested, along side a control sample of 3% sodium chloride ( $\text{NaCl}$ ). The control sample was used to correlate mass loss results to the standard, as 3%  $\text{NaCl}$  is what is commonly used in the MTO LS412 test method. A commercial-grade magnesium chloride anti-icer (Caliber M1000) was also tested. Two slabs (300 x 300 x 75 mm) were cast per exposure, which gave a total of 14 slabs for Phase 1. Table 3.1 outlines the concentration and solution that each slab was exposed to in Phase 1.

**Table 3.1 – Phase 1 Slab Exposures**

<b>Designation</b>	<b>Slab #</b>	<b>Conc. (%)</b>	<b>Chemical</b>
3N(50)P1(1)	1	3%	NaCl
3N(50)P1(2)	2	3%	NaCl
M1000(50)P1(3)	3	n/a	M1000
M1000(50)P1(4)	4	n/a	M1000
3M(50)P1(5)	5	3%	MgCl <sub>2</sub>
3M(50)P1(6)	6	3%	MgCl <sub>2</sub>
5M(50)P1(7)	7	5%	MgCl <sub>2</sub>
5M(50)P1(8)	8	5%	MgCl <sub>2</sub>
10M(50)P1(9)	9	10%	MgCl <sub>2</sub>
10M(50)P1(10)	10	10%	MgCl <sub>2</sub>
30M(50)P1(11)	11	30%	MgCl <sub>2</sub>
30M(50)P1(12)	12	30%	MgCl <sub>2</sub>

*Designation = (Concentration in % / Chemical (N=NaCl; M=MgCl<sub>2</sub>) / # of freeze thaw cycles / Phase / Slab #)*

The concentrations of 3%, 5%, 10%, and 30% MgCl<sub>2</sub> were used in a previous study that also looked at the scaling resistance of concrete exposed to MgCl<sub>2</sub> (Hooton and Julio-Betancourt, 2005), which allowed for comparison of results between studies. Caliber M1000 is a blend of “Caliber” deicer, derived from corn, with 30% MgCl<sub>2</sub>. M1000 is a commercial grade product that is being adopted by many municipalities for anti-icing, and pre-treating roads prior to storms. After 2 cycles of freezing and thawing it was decided to leave M1000 samples fully saturated in ambient conditions until Phase 2 (the M1000 solution did not freeze at -50°C). All other samples were subjected to 50 cycles of freezing (-50°C) and thawing (+23°C). A detailed explanation of the cycling is explained later in this chapter.

### 3.1.2 Phase 2 (P2)

The purpose of Phase 2 was to determine if samples first treated with 3% NaCl (some samples were exposed to NaCl for 25 cycles and others for 50) and then MgCl<sub>2</sub> at the same concentrations as in Phase 1 (for an additional 25 and 50 cycles) would cause scaling as was expected in the hypothesis. The process for freezing and thawing in Phase 2 is a little more complex than Phase 1. To allow for exposure to 3%NaCl for 50 cycles as well as 3% and 30% MgCl<sub>2</sub> for an additional 50 cycles; samples from Phase 1 were used. Slab 1 exposed to 3%NaCl in P1 was used in P2 and subjected to 3% MgCl<sub>2</sub> for an additional 50 cycles. Slab 2 exposed to 3%NaCl in P1 was used in P2 and subjected to 30% MgCl<sub>2</sub> for an additional 50 cycles. Slab 1 was then compared to Slabs 15 and 16, which were subjected to 3% NaCl for 25 cycles and then 3% MgCl<sub>2</sub> for an additional 25 cycles. Slab 2 was then compared to Slabs 21 and 22, which were subjected to 3% NaCl for 25 cycles and then 30% MgCl<sub>2</sub> for an additional 25 cycles. Slabs 17 and 18 were exposed to 3%NaCl for 25 cycles followed by 5% MgCl<sub>2</sub> for an additional 25 cycles. Slabs 19 and 20 were exposed to 3%NaCl for 25 cycles followed by 10% MgCl<sub>2</sub> for an additional 25 cycles. Slab 3 and 4 exposed to 2 cycles of freezing and thawing followed by complete saturation in ambient conditions for 40 days in P1, were then exposed to 50 complete cycles of freezing and thawing in P2. Slab 5 (P1) and Slab 23 (P2) were exposed to 3% MgCl<sub>2</sub>, and Slab 11 (P1) with Slab 24 (P2) were exposed to 30% MgCl<sub>2</sub>; all four slabs were left fully saturated in the 38°C room for 90 days. Table 3.2 outlines the concentration, solution and length of exposure that each slab was exposed to in Phase 2. Note that slabs # 13 through 24 were prepared for phase 2 while slabs #1 through 12 were used first in phase 1 (for 50 cycles) then continued to be tested in Phase 2.



**Table 3.2 – Phase 2 Slab Exposures**

<b>Designation</b>	<b>Slab #</b>	<b>Notes (Conc./Chemical/Exposure)</b>
3N(50)3M(50)P2(1)	1	Slab exposed to 3% NaCl for 50 cycles in P1, then 3% MgCl <sub>2</sub> for 50 additional cycles in P2
3N(50)30M(50)P2(2)	2	Slab exposed to 3% NaCl for 50 cycles in P1, then 30%MgCl <sub>2</sub> for 50 additional cycles in P2
M1000(2+40d+50)P2(3)	3	Slab exposed to M1000 for 2 cycles in P1, left fully saturated (in ambient conditions) for 40days, then M1000 for 50 cycles in P2
M1000(2+40d+50)P2(4)	4	Slab exposed to M1000 for 2 cycles in P1, left fully saturated (in ambient conditions) for 40days, then M1000 for 50 cycles in P2
3N(50)P2(13)	13	Slab exposed to 3% NaCl for 50 cycles in P2 (P2 Control Sample, can be compared to 3%NaCl(50)P1(1,2))
3N(50)P2(14)	14	Slab exposed to 3% NaCl for 50 cycles in P2 (P2 Control Sample, can be compared to 3%NaCl(50)P1(1,2))
3N(25)3M(25)P2(15)	15	Slab exposed to 3% NaCl for 25 cycles in P2, then 3% MgCl <sub>2</sub> for 25 additional cycles in P2 (Can be compared to 3%NaCl(50)3%MgCl <sub>2</sub> (50)P2(1))
3N(25)3M(25)P2(16)	16	Slab exposed to 3% NaCl for 25 cycles in P2, then 3% MgCl <sub>2</sub> for 25 additional cycles in P2 (Can be compared to 3%NaCl(50)3%MgCl <sub>2</sub> (50)P2(1))
3N(25)5M(25)P2(17)	17	Slab exposed to 3% NaCl for 25 cycles in P2, then 5% MgCl <sub>2</sub> for 25 additional cycles in P2
3N(25)5M(25)P2(18)	18	Slab exposed to 3% NaCl for 25 cycles in P2, then 5% MgCl <sub>2</sub> for 25 additional cycles in P2
3N(25)10M(25)P2(19)	19	Slab exposed to 3% NaCl for 25 cycles in P2, then 3% MgCl <sub>2</sub> for 25 additional cycles in P2
3N(25)10M(25)P2(20)	20	Slab exposed to 3% NaCl for 25 cycles in P2, then 3% MgCl <sub>2</sub> for 25 additional cycles in P2
3N(25)30M(25)P2(21)	21	Slab exposed to 3% NaCl for 25 cycles in P2, then 3% MgCl <sub>2</sub> for 25 additional cycles in P2 (Can be compared to 3%NaCl(50)30%MgCl <sub>2</sub> (50)P2(2))
3N(25)30M(25)P2(22)	22	Slab exposed to 3% NaCl for 25 cycles in P2, then 3% MgCl <sub>2</sub> for 25 additional cycles in P2 (Can be compared to 3%NaCl(50)30%MgCl <sub>2</sub> (50)P2(2))
3M(50)3M(90d)P2(5)	5	Slabs exposed to 3% MgCl <sub>2</sub> for 50 cycles in P1, then left in 38°C room for 90 days fully saturated in P2
3M(90d)P2(23)	23	Slabs left in 38°C room for 90 days fully saturated in P2
30M(50)30M(90d)P2(11)	11	Slabs exposed to 30% MgCl <sub>2</sub> for 50 cycles in P1, then left in 38°C room for 90 days fully saturated in P2
30M(90d)P2(24)	24	Slabs left in 38°C room for 90 days fully saturated in P2

*Designation = (Concentration in % / Chemical (N=NaCl; M=MgCl<sub>2</sub>) / # of freeze thaw cycles / Phase / Slab #)*

### 3.1.3 Phase 3 (P3)

Phase 3 focused on mortar specimens and their interaction with the same four concentrations of magnesium chloride (3%, 5%, 10% and 30%) and 3% sodium chloride solutions as in P1 and P2. Control specimens were subjected to a lime water control solution for comparison purposes.

Mortar cubes (50 x 50 x 50 mm) were cast in accordance to ASTM C109 specification, and prisms (285 x 25 x 25 mm) were cast in accordance with ASTM C157 specification. The water content of the mix was determined through flow measurements in accordance with ASTM C109 specification. The mortar was placed in the flow mould at the center of the flow table in two equal layers and each layer was tamped 20 times. The mortar was then cut to a plane surface flush to the mould and the mould was then removed 1 min after completing the mixing operation. The table began dropping immediately for 25 times in 15s. Then the flow was determined by measuring the diameters of the mortar along the lines scribed in the top of the table. The total of the four readings equals the percent increase of the original diameter of the mortar. Results of flow determination can be found in Chapter 4.

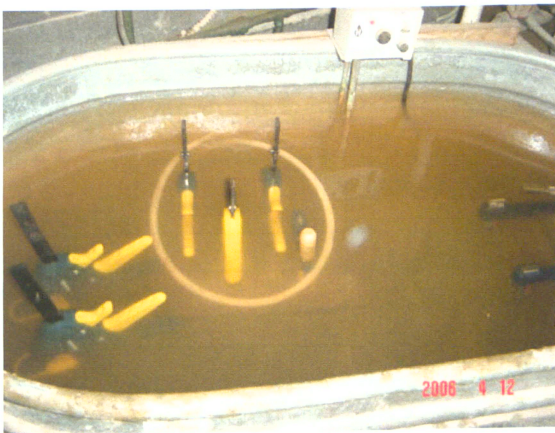
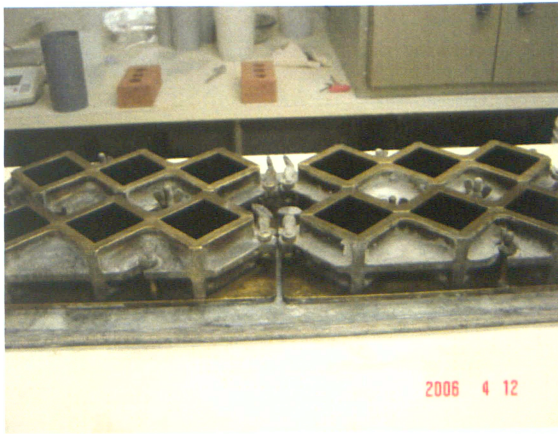
After mortar specimens were cast, they were placed into a  $35 \pm 3$  °C curing tank for  $23 \frac{1}{2}$  hours  $\pm$  30 minutes (as per ASTM C1012). Three cubes were tested at 1 day which met the 20 MPa requirement stated in ASTM C1012.

Once the strength was verified, three prisms and six cubes were put into each solution (Limewater, 3% NaCl, and 3%, 5%, 10%, 30% MgCl<sub>2</sub>). Three cubes were tested for compressive strength at both 28 and 56 days. Each prism was measured for expansion, every day for 7 days and then twice a week up to 77 days. Results can be found in Chapter 4.

Table 3.3 outlines the mix proportions used to make the mortar specimens; Figure 3.1 shows the apparatus that was used to cast the mortar cubes, and bars. The cement to sand ratio, as per ASTM C1012, was 0.36.

**Table 3.3 – Phase 3 Mix Proportions (9 cube mix = 72in<sup>3</sup>)**

<b>Materials</b>	<b>Design Weight (kg/m<sup>3</sup>)</b>	<b>Batch Weight (g/72in<sup>3</sup>)</b>
St. Marys Type GU/10 Cement	470	555
St. Marys Slag	157	185
Sand	1725	2035
Water (ml)	254	300



**Figure 3.1 – Mortar Cube Moulds, Mortar bar Moulds, and Curing Tank**

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### 3.2 Materials

The concrete used in this research project corresponded to a typical sidewalk concrete used in Ontario (25% GGBFS Type S, 32 MPa compressive strength at 28 days, C-2 exposure class, air content category 1). The concrete met both CAN/CSA A23.1-04, “Concrete Materials and Methods of Concrete Construction” and OPSS 1350-95, Material Specification for Concrete – Materials and Production” specifications.

The following describes the properties and characteristics of various ingredients used in making concrete and mortar for this research project.

#### **Portland Cement**

The cement used in this research project was Type GU/10 Normal Portland Cement manufactured and supplied by St. Marys Cement. A summary of chemical and physical properties of cement are presented in Table 3.4 and the mill certificate, supplied by St. Marys Cement, can be found in Appendix B.

## Supplementary Cementing Materials

The supplementary cementing material used throughout this research project was Ground Granulated Blast Furnace Slag supplied by St. Marys Cement. A summary of chemical and physical testing can be found in Table 3.4, and the mill certificate, supplied by St. Marys Cement, can be found in Appendix B.

**Table 3.4 – Physical and Chemical Properties of Cement and Slag**

	<b>Cement (Type GU/10)</b>	<b>Slag (Type S)</b>
<b>PHYSICAL PROPERTIES</b>		
Specific Gravity	3.15	2.92
<b>Fineness</b>		
Retained 325 (%)	6.4	0.0
Specific Surface, Blaine, m <sup>2</sup> /kg	410	555
<b>Compressive Strength</b>		
7-day (MPa)	32.5	26.7
28-day (MPa)	40.5	44.7
<b>Setting Time</b>		
Initial Setting Time (min)	91	-
Final Setting Time (min)	198	-
Air Content of Mortar (Volume %)	8.6	-
Autoclave Expansion (%)	0.333	0.164
<b>CHEMICAL ANALYSIS (%)</b>		
Silicon Dioxide (SiO <sub>2</sub> )	19.86	-
Aluminum Oxide (Al <sub>2</sub> O <sub>3</sub> )	4.45	7.25
Ferric Oxide (Fe <sub>2</sub> O <sub>3</sub> )	2.64	0.60
Calcium Oxide (CaO)	62.13	39.86
Magnesium Oxide (MgO)	3.27	10.64
Sodium Oxide (Na <sub>2</sub> O)	0.29	0.25
Potassium Oxide (K <sub>2</sub> O)	0.47	0.41
Phosphorous Oxide (P <sub>2</sub> O <sub>5</sub> )	0.17	-
Titanium Oxide (TiO <sub>2</sub> )	0.27	-
Sulfur Trioxide (SO <sub>3</sub> )	3.88	0.76
Sulfide	-	0.95
Total Alkali as Na <sub>2</sub> O	0.60	-
Loss On Ignition	2.0	-

## Coarse Aggregate

The coarse aggregate was crushed limestone supplied by CBM Aggregates Aberfoyle Pit, Aberfoyle, ON, with a maximum size of 19 mm. The relative density of the coarse aggregate was 2.73, and the absorption was 1.15%, these results were determined in accordance with CSA A23.2-12A. A summary of grading and physical testing can be found in Table 3.5.

**Table 3.5 – Coarse Aggregate Grading and Physical Testing**

Sieve Size	Total% Passing	Specification
26.5mm	100	100
22.4mm	100	-
19.0mm	91.3	85-100
16.0mm	75.7	65-90
13.2mm	57.0	-
9.5mm	28.2	20-55
6.7mm	9.0	-
4.75mm	2.3	0-10
Pan	0	-
Material Passing 75um Sieve	0.46	2.0% Max
Absorption	1.15	2.0% Max
Bulk Relative Density (SSD)	2.72 kg/m <sup>3</sup>	

## Fine Aggregate

The fine aggregate used was concrete sand supplied by CBM Aggregates Sunderland Pit, Sunderland, ON. The fineness modulus was 2.65; the absorption was 1.08%, and a relative density of 2.66, these results were determined in accordance with CSA A23.2-6A. A summary of grading and physical testing can be found in Table 3.6.

**Table 3.6 – Fine Aggregate Grading and Physical Testing**

Sieve Size	Total% Passing	Specification	
9.5mm	100.0	100	
4.75mm	97.9	95-100	
2.36mm	85.5	80-100	
1.18mm	69.3	50-85	
600µm	51.6	25-60	
300µm	24.6	10-30	
150µm	6.5	0-10	
75µm	1.5	0-3	
Pan	-	-	
Material Passing 75µm Sieve		1.3	3.0% Max
Fineness Modulus		2.65	2.3-3.1
Absorption		1.08	2.0% Max
Bulk Relative Density (SSD)		2.66 kg/m <sup>3</sup>	



## **Admixtures**

The admixtures were supplied by Grace Construction Products. The air entraining admixture used was Darex® AEA ED and the water reducer used was WRDA® 20. Information of the density and total solid content of each product can be found in Table 3.7. Product data sheets of these two admixtures can be found in Appendix B.

**Table 3.7 – Density and Total Solid Content of Admixtures**

	Specific Gravity	Total Solid Content	pH
Darex® AEA ED	1.008	-	11
WRDA® 20	1.200	47%	-

## **Water**

Potable water from the City of Toronto drinking water supply was used throughout this study.

### 3.3 Concrete Mix Design and Procedures

#### 3.3.1 Mix Design

The concrete used in this study conformed to CAN CSA A23.1-04, “*Concrete Materials and Methods of Concrete Construction*”. The class of exposure was C-2, “*Non-structurally reinforced (plain) concrete exposed to chlorides and freezing and thawing*”, which requires a maximum water-to-cementing materials ratio of 0.45, and a minimum 28-day compressive strength of 32MPa, and an air content category 1 (5-8% for 14-20 mm aggregate). Table 3.8 outlines the mix proportions that were used throughout this study.

**Table 3.8 – Mix Design**

<b>Materials</b>	<b>Design Weight (kg/m<sup>3</sup>)</b>	<b>Batch Weight (kg/0.08m<sup>3</sup>)</b>
St. Marys Type GU/10 Cement	225	18.0
St. Marys CemPlus Slag	75	6.0
20mm Stone	1130	90.4 kg + moisture
Sand	737	59.0 kg + moisture
Water	135	10.8
Slump	<i>Target = 100+/-25mm</i>	
Air	<i>Target = 6-8%</i>	
WR Grace WRDA 20	220 ml/100kg of cement	52.8 ml
WR Grace Darex AEA ED (6-8%)	50 ml/100kg of cement	12 ml

### 3.3.2 Batching

All materials used in this research project were brought to a stable temperature ( $23 \pm 2$  °C) prior to batching. Moisture contents of both fine and coarse aggregates were taken prior to weighing materials, and the masses were adjusted to incorporate the moisture content. The materials were then weighed into moisture-proof containers incorporating the moisture contents for each. Prior to the first batch, the mixer was lubricated with a batter to prevent mix water being absorbed by the mixer. This batter was similar to the actual design mix for this research project to allow for minimal change in the paste to aggregate ratio in the subsequent mixes. Once this batter was sufficiently mixed, using a sponge, the batter was spread over the entire surface of the pan including the mixing paddles. The remainder of the batter was removed from the mixer.

Three trial batches were conducted prior to the mixes used for the research project. These trial batches were used to obtain the desired slump and air requirements, admixture dosages were determined during these trial batches.

### 3.3.3 Mixing Procedure

For all the batch mixes used in both phase 1 and 2 (P1: *06-13-A and 06-13-B*; P2: *06-13-C and 06-13-D*), the same batching sequence was used. First half of the aggregate was added to the pan, then all of the cementitious material, followed by the remaining aggregate. Adding the aggregate in two layers minimized the amount of cement dust in the air and helped to thoroughly mix the cementitious material throughout with less clinging to the paddles and side of the pan. The air entraining admixture was added to the fine aggregate prior to being put into the pan. Once all of the dry materials were added to the pan, the mixer was turned on and all of the water was added. The water-reducer was added to the mix 30 seconds after water addition. Alternating periods of mixing and resting were used to allow thorough mixing of the concrete (mix 3 minutes, rest 3 minutes, mix 2 minutes, rest 3 minutes, mix 5 minutes). The total mixing time was 10 minutes. Figure 3.2 shows pictures of the water and chemical additions.



**Figure 3.2 – Addition of Water and Admixtures**

### 3.4 Testing Performed on Concrete

#### 3.4.1 Fresh Concrete Tests

There were two batches for Phase 1 (06-13-A & 06-13-B) and two for Phase 2 (06-13-C & 06-13-D). Two batches were required to make enough concrete for performing all the required tests. The temperature of the freshly mixed concrete was determined in accordance with ASTM C1064 specification. The slump of each batch was measured immediately after mixing in accordance with CSA A23.2-5C. The air content was determined in accordance with CSA A23.2-4C. The density and yield of each batch was determined in accordance with CSA A23.2-6C. Pictures from batching can be found in Appendix A.

#### 3.4.2 Hardened Concrete Tests

##### **Compressive Strength**

The strength test specimens were moulded and cured in accordance with CSA A23.2-3C. The moulds used were 100 x 200 mm plastic cylindrical moulds meeting the requirements of CSA A23.2-1D. The concrete was placed in three equal layers; each layer was rodded 20 times, with light tapping between layers to close voids. After consolidation the top surface was finished by striking off with the strike off bar. Then, to prevent evaporation, the specimens were covered immediately after finishing with a plastic lid.

The compressive strength for Batch 1 in Phase 1 (06-13-A) was tested at 1, 3, 7, 28, 56, and 90 days. Two cylinders were cast and tested per age. For the second batch in Phase 1 (06-13-B), one cylinder was cast per age, with the exception to 28 days where two were cast. These cylinders were cast to show that both mixes for Phase 1 were identical. The two batches for Phase 2 (06-13-C and 06-13-D) had two cylinders cast and broken per age at 3, 7, 28, and 56 days. A summary of the compressive strength results can be found in Chapter 4.

### **Hardened Air Void Analysis**

One cylinder per batch was cast for conducting the hardened air void analysis of the concrete. These cylinders were cured the same way as the cylinders being tested for compressive strength. At the age of 28 days, the cylinder samples were saw cut length wise into two equal halves, and one cut face from each cylinder was then polished. The prepared specimens were tested for air-void parameters in accordance with the ASTM C457 test method “Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete”, using the modified point count method. This procedure consists of the determination of the volumetric composition of the concrete by observation of the frequency with which areas of a given component coincide with a regular grid system of points at which stops are made to enable the determinations of composition. Based on the data collected, the air content and various parameters of the air void system are calculated. A summary of the hardened air void results can be found in Chapter 4.

## **Rapid Chloride Permeability**

One cylinder per batch was cast for conducting the rapid chloride permeability of the concrete. These cylinders were cured the same as the cylinders being tested for compressive strength. At the age of 28 days, using a water-cooled diamond saw a  $51 \pm 3$  mm slice was cut from the top of the cylinder. The specimens were then tested for rapid chloride permeability in accordance with the ASTM C1202 test method “Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration”. This test method consists of monitoring the amount of electrical current passed through concrete samples sliced at 51mm thick with a diameter of 102mm during a 6 hour period. A potential difference of 60 V dc is maintained across the ends of the specimen, one of which is immersed in a sodium chloride solution, the other in a sodium hydroxide solution. The total charge passed, in coulombs, has been found to be related to the resistance of the specimen to chloride ion penetration. A summary of the rapid chloride permeability results can be found in Chapter 4.

## **Scaling Resistance of Concrete (Modified MTO LS 412)**

Due to solutions containing above 5%  $\text{MgCl}_2$  not completely freezing in previous studies, A modified MTO LS412 specification (MLS412) was used. Trials were conducted with the highest concentration (30%  $\text{MgCl}_2$ ) to determine which lower temperature limit was required to completely freeze the solution, this was found to be  $-50^\circ\text{C}$ .

The MTO LS412 specification was then modified to allow for specimens to be subject to a temperature range of +23°C to -50°C. The rate of freezing and thawing was 0.3°C/minute. Using the built-in software of the environmental chamber, a program was designed to subject samples to a ramping period (+23°C to -50°C) over a 4 hour period, and then remained soaking at -50°C for 13 hours. Then, at the end of the soaking period of 13 hours, the program ramped (-50°C to +23°C) over a 4 hour period, and remained soaking at +23°C for 3 hours. This whole program takes 24 hours per cycle. After each 5 cycles, the solution was removed together with all of the scaled material and put into a water tight container, which was then placed in an oven at 105°C to dry out to a constant mass condition. This residue was cumulatively weighed after each 5 cycles, and defined as the mass loss expressed in kilograms per square meter of exposed slab area (as per MTO LS 412)

### 3.5 Equipment

#### 3.5.1 General

All of the moulds, consolidation equipment, and small tools used in this research project are in accordance with CSA A23.2-3C.



### 3.5.2 Environmental Chamber

For the deicer salt scaling portion of this thesis, an environmental chamber was used to ensure that the proper temperature ranges and ramp times were kept consistent throughout this study. The chamber was programmed to stop every 5 cycles so that mass loss measurements could be made. Figure 3.3 shows photos of the chamber used in this research study, the set-up of how samples were placed in the chamber can be seen in Figure 3.4. Each slab was rested on wood supports to allow free movement of air around the specimen. The wood supports were also placed on slatted shelves that allowed for a free flow of air between shelves and throughout the entire chamber.



**Figure 3.3 –Environmental Chamber**



**Figure 3.4 – Slab set-up in the Chamber**

### 3.6 Finishing Procedure adopted for Concrete Slab Specimens

Finishing greatly influences the durability of concrete. In this research project finishing of slab specimens was completed as per MTO Test Method LS412, which follows the guidelines outlined below. Immediately after the slabs were finished they were covered with plastic sheets and taken to a moist curing room.

The slabs in this research project were cast in the “best case scenario”, as all of the placing, finishing, and curing methods were done as per specification. This is not always the case in the field. Curing is the most commonly overlooked part of the finishing process.

According to the RMCAO's (Ready Mixed Concrete Association of Ontario) guide to durable concrete flatwork, concrete should not be finished while bleed water is still present. This causes excess water to be worked back into the concrete paste on surface, dramatically increasing the water/cementitious ratio and decreasing the concrete's strength and durability. This also seals the surface of the concrete causing all of the remaining bleed water to be trapped below the surface.

Concrete should not be overworked. If finishing operations are repeated more than required, additional paste is brought to the surface. Trapping bleed water, working it back into the surface, and overworking all create a weak surface which may lead to scaling and mortar flaking.

The best finishing procedure for all exposed concrete is to:

1. Strike-off the surface,
2. Bull-float before bleed water appears, and
3. Apply a broom texture to the surface once the bleed water has dissipated and the concrete has gained sufficient stiffness.

Proper curing must follow these finishing operations for the concrete to meet the durability requirements. One will not work without the other.

## Chapter 4

### RESULTS AND DISCUSSION

#### 4.1 General

Throughout this chapter the results from each phase of the experimental program will be presented. Tabular and graphical results portray only the final results or averages. Detailed data for each investigation can be found in the appropriate appendix which is clearly stated in each sub-section.

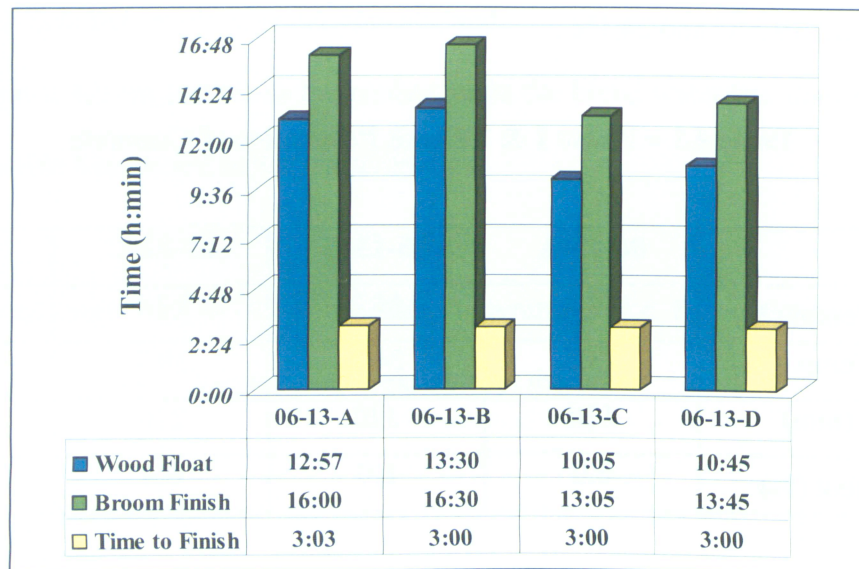
##### 4.1.1. Phases 1 and 2: Fresh Properties of Concrete

Table 4.1 presents the temperature, slump, and air content of freshly mixed concrete from different batches used for the casting of concrete specimens. The concrete temperature ranges between 19.3°C and 24.1°C.

**Table 4.1 – Phase 1 & 2 Fresh Properties of Concrete**

	<b>06-13-A</b>	<b>06-13-B</b>	<b>06-13-C</b>	<b>06-13-D</b>
Ambient Temp. (°C)	14.8	15.2	14.4	14.4
Concrete Temp. (°C)	23.3	24.1	19.7	19.3
Slump (mm)	120	120	210	210
Air Content (%)	6.0	6.0	6.4	6.4

In this research project, finishing of concrete slab specimens was completed as per MTO Test Method LS412. Immediately after the slabs were finished they were covered with plastic sheets and taken to the moist curing room. A summary of the finishing times for each batch (Phase 1: 06-13-A and 06-13-B; Phase 2: 06-13-C and 06-13-D) can be found in Figure 4.1. It can be seen that the finishing times between batches in each phase were identical, and slightly different between phases. This means that the slabs cast in each phase can be directly compared as the finishing should not interfere with the other variables being tested. The terms wood float and broom finish refer to the times at which each operation was completed. Once the moulds had been filled as per MTO test method LS412, the moulds were tapped around the perimeter to close any remaining voids and immediately screeded with a wood strike-off board, followed by two passes with a wood float. When the sheen of water had disappeared, the top surface of the specimens was then gently brushed with a paint brush to remove any laitance and to leave a slightly textured surface.



**Figure 4.1 – Phase 1 & 2 Finishing Times**

#### 4.1.2. Phase 1 and 2: Hardened Properties of Concrete

The hardened properties of concrete such as compressive strength, hardened air void, and rapid chloride permeability are presented in the following sub-sections.

##### Compressive Strength

Table 4.2 presents the results of compressive strength for P1 and P2, and Table 4.3 outlines the unit weight of each cylinder tested. The lower compressive strength in P2 samples is likely due to the higher slump, and entrained air content. The compressive strength values for P2 are however; more consistent with what would be seen in the field.

**Table 4.2 – Phase 1 and 2 Hardened Properties of Concrete**

Sample ID	Compressive Strength (MPa)					
	1-day	3-day	7-day	28-day	56-day	90-day
<b>Phase 1 06-13-A</b>	8.6	17.3	25.3	40.1	45.3	45.0
	8.8	17.5	26.6	40.5	44.7	45.5
<i>Average</i>	<i>8.7</i>	<i>17.4</i>	<i>26.0</i>	<i>40.3</i>	<i>45.0</i>	<i>45.3</i>
<b>Phase 1 06-13-B</b>	8.8	17.5	26.7	41.2	46.4	47.1
	-	-	-	41.0	-	-
<i>Average</i>	<i>8.8</i>	<i>17.5</i>	<i>26.7</i>	<i>41.1</i>	<i>46.4</i>	<i>47.1</i>
<b>Phase 2 06-13-C</b>	-	12.0	17.5	34.4	38.6	-
	-	11.5	19.2	33.4	37.9	-
<i>Average</i>	<i>-</i>	<i>11.8</i>	<i>18.4</i>	<i>33.9</i>	<i>38.3</i>	<i>-</i>
<b>Phase 2 06-13-D</b>	-	12.2	19.7	33.7	38.2	-
	-	12.1	19.0	33.7	39.9	-
<i>Average</i>	<i>-</i>	<i>12.2</i>	<i>19.4</i>	<i>33.7</i>	<i>39.1</i>	<i>-</i>

**Table 4.3 – Phase 1 and 2 Cylinder Unit Weights**

<b>Sample ID</b>	<b>Cylinder Unit Weights (kg/m<sup>3</sup>)</b>					
	<b>1-day</b>	<b>3-day</b>	<b>7-day</b>	<b>28-day</b>	<b>56-day</b>	<b>90-day</b>
<b>06-13-A</b>	2378	2384	2384	2378	2378	2384
	2384	2390	2384	2353	2378	2390
<b>06-13-B</b>	2378	2378	2378	2365	2378	2365
	-	-	-	2365	-	-
<b>06-13-C</b>	-	2341	2365	2341	2353	-
	-	2329	2353	2365	2353	-
<b>06-13-D</b>	-	2365	2353	2341	2341	-
	-	2341	2353	2365	2341	-

**Hardened Air Void Analysis**

Table 4.4 presents the results of hardened air void analysis for P1 and P2. The hardened air void results between all batches ranges between 4.7% and 5.2%. Entrained air greatly improves concrete's resistance to surface scaling caused by chemical deicers (Kosmatka et al, 2002). CSA A23.1 recommends an entrained air content between 5-8% for all concrete exposed to freeze-thaw and deicing chemicals.

**Table 4.4 – Phase 1 and 2 Hardened Air Void Analysis**

<b>Sample ID</b>	<b>Density</b>	<b>Total Air</b>	<b>Specific</b>	<b>Spacing Factor</b>
<b>06-13-A</b>	2384	4.7	35.85	0.128
<b>06-13-B</b>	2390	5.2	37.60	0.124
<b>06-13-C</b>	2365	5.0	36.73	0.126
<b>06-13-D</b>	2365	5.2	37.60	0.124



## Rapid Chloride Permeability

Table 4.5 presents the results of rapid chloride permeability for P1 and P2. The rapid chloride ion permeability between all batches ranges between 1822 and 2148 coulombs.

**Table 4.5 – Phase 1 & 2 Rapid Chloride Permeability Results at 56 days**

	<b>06-13-A</b>	<b>06-13-B</b>	<b>06-13-C</b>	<b>06-13-D</b>
Voltage	60	60	60	60
Current (mA)	111.3	90.5	105.2	95.5
Temperature (°C)	34	33	35	32
Time (hours)	6	6	6	6
<i>Coulombs</i>	<i>2148</i>	<i>1822</i>	<i>2108</i>	<i>1953</i>
Permeability Class	Moderate	Low	Moderate	Low

The permeability class stated in Table 4.5 is based on the information presented in ASTM 1202, Table 1. A sample will have a permeability class of low if the charge passed through the specimen is between 1000 – 2000 coulombs and moderate if between 2000 – 4000 coulombs. The samples in this research fall in the high end of low or the low end of moderate.



### Phase 3: Flow Results of Mortar

Table 4.6 presents the results of flow measurements for mortar used in P3. According to ASTM C109, the amount of mixing water shall be such as to produce a flow of  $110 \pm 5$  expressed as weight percent of cement. The quantity of water used in this study was 300mL, which gives a water to cementitious material ratio of 0.405. Figure 4.2 shows the measurement of flow.

**Table 4.6 – Phase 3 Flow Measurements**

Trial	Water (mL)	w/cm	Flow Measurements				Avg. Flow
			1	2	3	4	
1	250	0.338	5.32	5.05	4.93	4.56	24.3%
2	310	0.419	8.69	8.69	9.03	8.92	121.3%
3	300	0.405	8.54	8.23	8.52	8.66	112.7%



**Figure 4.2 – Picture of Flow Measurement**

## 4.2 Phase 1: Influence of Concentration of Chemical Solutions on Concrete Durability

The slabs being used for scaling resistance testing in Phase 1 were all cast with the same concrete, 32MPa C-2, as explained in Chapter 3. All of the placing, finishing, and curing methods were done as per specification prior to placement in the environmental chamber. The only variable between samples in Phase 1 was the type of ponding material being used (3%NaCl; 3%, 5%, 10%, and 30%  $\text{MgCl}_2$ ; and M1000). Table 4.7 outlines the cumulative mass loss of concrete slab specimens after each 5 cycles. Figures 4.3 to 4.5 give graphical representations.

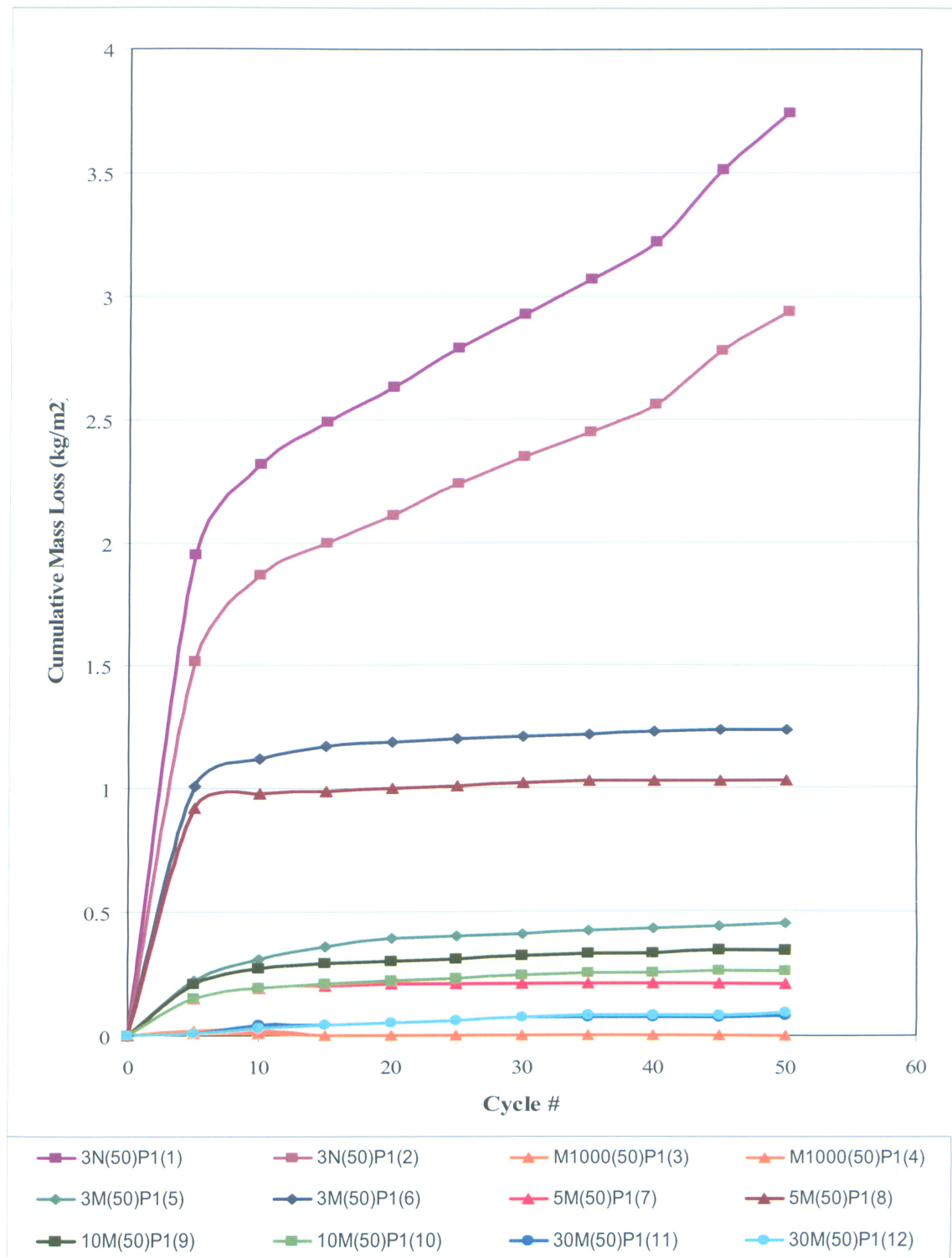
The most mass loss was found with 3% NaCl and the second most was found with 3%  $\text{MgCl}_2$ . These results are comparable to a previous study conducted by (Hooton and Julio-Betancourt, 2005), where it was found that the samples exposed to 3%  $\text{MgCl}_2$  were the worst case under the conditions tested. Hooton and Julio-Betancourt (2005) qualified these results as the concentrations of  $\text{MgCl}_2$  above 5% resulted in only partial freezing at the standard MTO LS412 freezing temperature of  $-18^\circ\text{C}$ . They believed that it is possible for the worst case concentration to be higher if the testing was repeated at a lower temperature such that all of the solutions froze. In this study, the MTO LS412 specification was modified with a lower limit of  $-50^\circ\text{C}$ . The solutions were all frozen, but the expected increase in mass loss of higher concentrations was not seen.

**Table 4.7 – Phase 1 Mass Loss Results**

# Cycles	Cumulative Mass Loss (kg/m <sup>2</sup> )					
	3N(50)P1(1,2)		M1000(50)P1(3,4)		3M(50)P1(5,6)	
Slab #	1	2	3	4	5	6
5	1.95	1.52	0.02	0.01	0.22	1.01
10	2.32	1.87	0.02	0.01	0.31	1.12
15	2.49	2.00	-	-	0.36	1.17
20	2.63	2.11	-	-	0.39	1.19
25	2.79	2.24	-	-	0.40	1.20
30	2.93	2.35	-	-	0.41	1.21
35	3.07	2.45	-	-	0.42	1.22
40	3.22	2.56	-	-	0.43	1.23
45	3.51	2.78	-	-	0.44	1.24
50	3.74	2.94	-	-	0.45	1.24
AVG	3.34		0.02		0.85	

# Cycles	Cumulative Mass Loss (kg/m <sup>2</sup> )					
	5M(50)P1(7,8)		10M(50)P1(9,10)		30M(50)P1(11,12)	
Slab #	7	8	9	10	11	12
5	0.15	0.92	0.21	0.15	0.01	0.01
10	0.19	0.98	0.27	0.19	0.04	0.03
15	0.20	0.99	0.29	0.21	0.04	0.04
20	0.21	1.00	0.30	0.22	0.05	0.05
25	0.21	1.01	0.31	0.23	0.06	0.06
30	0.21	1.02	0.32	0.24	0.07	0.07
35	0.21	1.03	0.33	0.25	0.07	0.08
40	0.21	1.03	0.33	0.25	0.07	0.08
45	0.21	1.03	0.34	0.26	0.07	0.08
50	0.21	1.03	0.34	0.26	0.08	0.09
AVG	0.62		0.30		0.09	

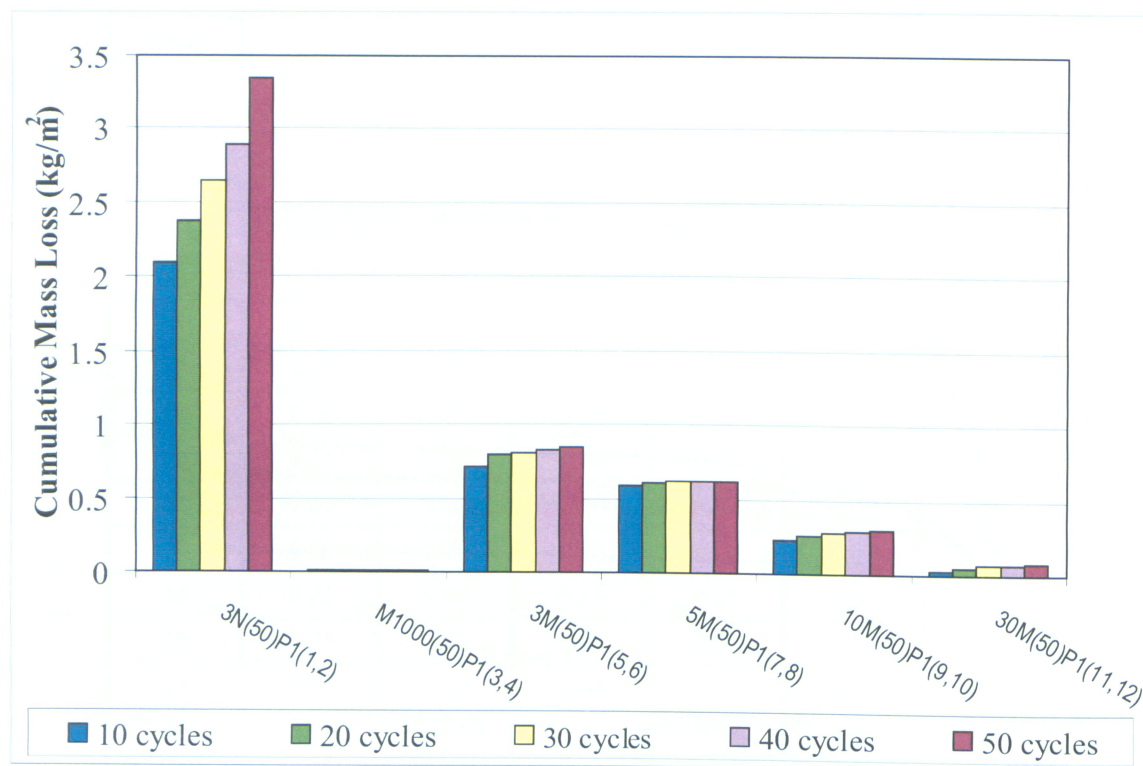
*Designation = (Concentration in % / Chemical (N=NaCl; M=MgCl<sub>2</sub>) / # of freeze thaw cycles / Phase / Slab #)*



Designation = (Concentration in % / Chemical (N=NaCl; M=MgCl<sub>2</sub>) / # of freeze thaw cycles / Phase / Slab #)

**Figure 4.3 – Phase 1 Cumulative Mass Loss Results**

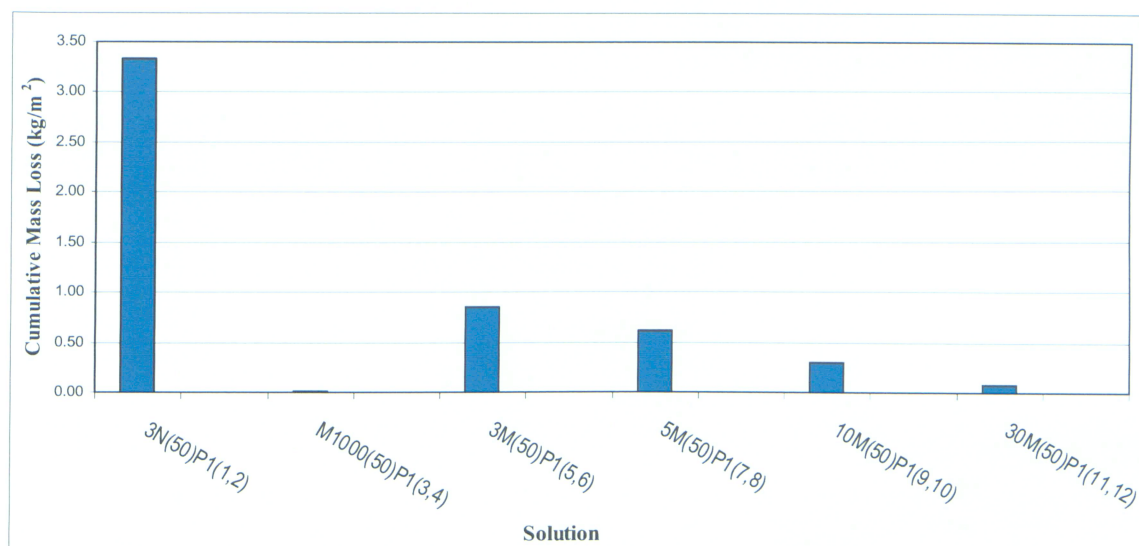
As can be seen in Figures 4.3 and 4.4, the 3% NaCl solution produced dramatically more mass loss when compared to the samples exposed to  $\text{MgCl}_2$  solutions. The  $\text{MgCl}_2$  concentration does not appear to affect the amount of scaling. These results are similar to results seen in a number of studies (Lee et al, 2000; Hooton and Julio-Betancourt, 2005). Lee et al (2000) found that compared to  $\text{MgCl}_2$  and  $\text{CaCl}_2$  exposures, NaCl was more deleterious in freeze-thaw experiments. Hooton and Julio-Betancourt (2005) also found higher loss in samples exposed to NaCl, but attributed this to only partial freezing of  $\text{MgCl}_2$  solutions above 5%  $\text{MgCl}_2$ .



*Designation = (Concentration in % / Chemical (N=NaCl; M=MgCl<sub>2</sub>) / # of freeze thaw cycles / Phase / Slab #)*

**Figure 4.4 – Phase 1 Cumulative Mass Loss Results**

Figure 4.5 shows the cumulative mass loss after 50 cycles. According to these Phase 1 results, there is a downward trend of mass loss with an increase in  $\text{MgCl}_2$  concentration. However,  $\text{MgCl}_2$  appears to have little or no effect on deicer salt scaling at concentrations higher than 5%.

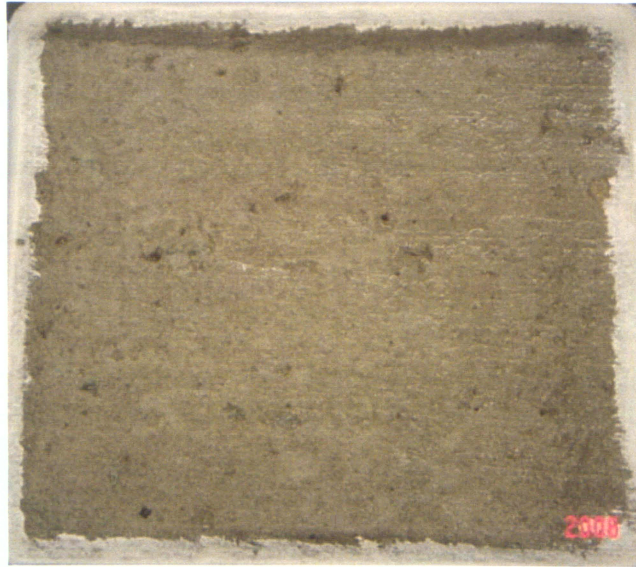


*Designation = (Concentration in % / Chemical (N=NaCl; M=MgCl<sub>2</sub>) / # of freeze thaw cycles / Phase / Slab #)*

**Figure 4.5 – Summary of Phase 1 Mass Loss Results at 50 cycles**



Figures 4.6 and 4.7 show the surface discoloration that was noticed on both Phase 1 and Phase 2 slabs after 50 cycles. This discoloration was more noticeable prior to removing the solution every 5 cycles.



**Figure 4.6 – Phase 1 Slab Exposed to 30% $\text{MgCl}_2$  at 50 cycles**



**Figure 4.7 – Phase 2 Slab Exposed to 30% $\text{MgCl}_2$  at 50 cycles**

Figure 4.8 shows the discoloration of the surface of Slab 11 that was exposed to 30% $\text{MgCl}_2$  in Phase 1. This was difficult to see in the air dried sample.



**Figure 4.8 – Phase 1 Slab Exposed to 30% $\text{MgCl}_2$  at 45 cycles with Solution**

Lee et al (2000) found that samples exposed to  $\text{MgCl}_2$  and freezing and thawing precipitated a protective coat of new material matter on the concrete surfaces. When this coat was removed, the concrete was found to have a brown-colored discoloration. This phenomenon and further investigation is explained in more detail later in this chapter.



#### 4.3 Phase 2: Influence of Multiple Chemical Exposures on Concrete Durability

The slabs cast for scaling resistance testing in Phase 2 were all cast with the same concrete as in Phase 1. All of the placing, finishing, and curing methods were done the same as in Phase 1. The only variable between samples in Phase 2 was the type of ponding material being used (3%NaCl; 3%, 5%, 10%, and 30% MgCl<sub>2</sub>; and M1000), and the length of exposure (25 and 50 cycles).

Table 4.8 outlines the cumulative mass loss of concrete slab specimens after each 5 cycles. Similar to P1, there is some variation noticed between comparison samples exposed to the same chemical. What is clear, however, is that MgCl<sub>2</sub>, even considering multiple chemical exposures, does not seem to influence the mass loss due to deicer salt scaling. Figures 4.9 to 4.11 give graphical representations.

**Table 4.8 – Phase 2 Mass Loss Results**

# Cycles	Cumulative Mass Loss (kg/m <sup>2</sup> )					
	3N(50)3M(50) P2(1)	3N(50)30M(50) P2(2)	3N(50)P2(13,14)		3N(25)3M(25)P2(15,16)	
<i>Slab #</i>	<i>1</i>	<i>2</i>	<i>13</i>	<i>14</i>	<i>15</i>	<i>16</i>
<b>5</b>	3.80	2.95	1.30	1.51	1.96	1.59
<b>10</b>	3.82	3.04	1.53	1.79	2.28	1.90
<b>15</b>	3.82	3.05	1.63	1.90	2.39	2.01
<b>20</b>	3.83	3.05	1.73	2.01	2.49	2.11
<b>25</b>	3.84	3.06	1.83	2.11	2.60	2.21
<b>30</b>	3.85	3.07	1.94	2.21	2.70	2.23
<b>35</b>	3.86	3.08	2.05	2.33	2.71	2.24
<b>40</b>	3.87	3.09	2.18	2.44	2.72	2.25
<b>45</b>	3.88	3.10	2.40	2.64	2.73	2.26
<b>50</b>	3.89	3.11	2.61	2.84	2.74	2.27
<b>AVG</b>	<b>3.89</b>	<b>3.11</b>	<b>2.72</b>		<b>2.51</b>	

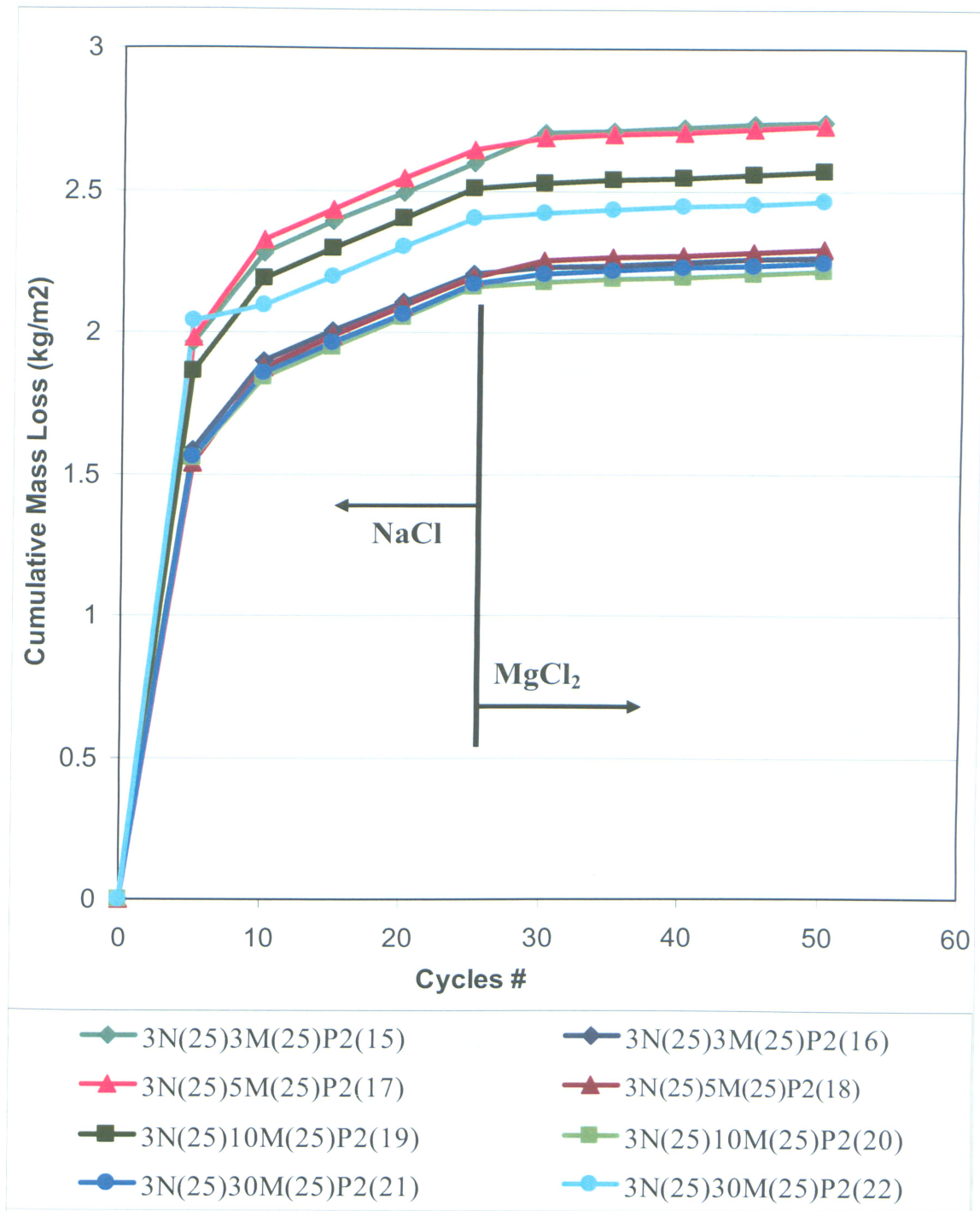
# Cycles	Cumulative Mass Loss (kg/m <sup>2</sup> )					
	3N(25)5M(25)P2(17,18)		3N(25)10M(25)P2(19,20)		3N(25)30M(25)P2(21,22)	
<i>Slab #</i>	<i>17</i>	<i>18</i>	<i>19</i>	<i>20</i>	<i>21</i>	<i>22</i>
<b>5</b>	1.99	1.54	1.86	1.55	1.56	2.04
<b>10</b>	2.33	1.88	2.19	1.84	1.86	2.09
<b>15</b>	2.43	1.99	2.30	1.95	1.96	2.20
<b>20</b>	2.54	2.09	2.40	2.05	2.07	2.30
<b>25</b>	2.65	2.20	2.51	2.16	2.17	2.40
<b>30</b>	2.69	2.26	2.53	2.18	2.21	2.42
<b>35</b>	2.70	2.27	2.54	2.19	2.22	2.43
<b>40</b>	2.71	2.28	2.55	2.20	2.23	2.44
<b>45</b>	2.72	2.29	2.56	2.21	2.24	2.45
<b>50</b>	2.73	2.30	2.57	2.22	2.25	2.46
<b>AVG</b>	<b>2.51</b>		<b>2.39</b>		<b>2.36</b>	

*Designation = (Concentration in % / Chemical (N=NaCl; M=MgCl<sub>2</sub>) / # of freeze thaw cycles / Phase / Slab #)*

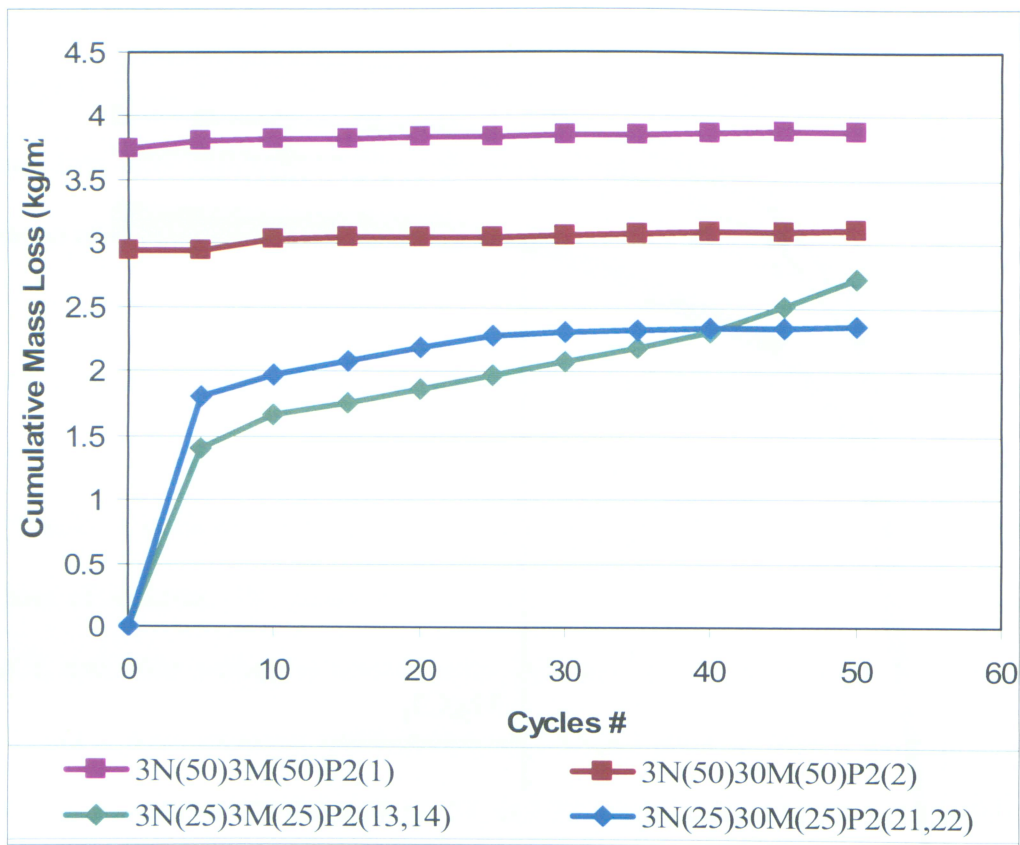
Figure 4.9 shows the cumulative mass loss that was seen when samples were exposed to 25 cycles of 3%NaCl followed by an additional 25 cycles exposed to (3%, 5%, 10%, and 30%) MgCl<sub>2</sub>. It can be seen that the majority of mass loss is seen in the first 5 cycles, and the mass loss after exposure to MgCl<sub>2</sub> does not vary with concentration. MgCl<sub>2</sub> appears to have no effect on deicer salt scaling.

Figure 4.10 examines the effect of length of exposure, by comparing samples exposed to 50 cycles and 25 cycles of 3%NaCl prior to exposure to 50 and 25 cycles of (3% and 30%) MgCl<sub>2</sub>. It is clear in this comparison that the length of exposure greatly affects the mass loss of samples. The majority of scaling is seen when the samples are exposed to 3%NaCl, and little scaling is noticed after exposure to MgCl<sub>2</sub>. It should be noted that slabs 1 and 2 were exposed to 50 cycles of 3%NaCl prior to MgCl<sub>2</sub> exposure for and additional 50 cycles, while slabs 13,14, 21, and 22 were exposed to 25 cycles of 3%NaCl prior to MgCl<sub>2</sub> exposure for and additional 25 cycles.

Figure 4.11 compares the cumulative mass loss over 50 cycles, confirming that MgCl<sub>2</sub> is having little effect on deicer salt scaling. The results found in P1 and P2 led to believe that the mechanism causing deterioration of concretes exposed to MgCl<sub>2</sub> may be due to exposure to higher temperatures rather than low.



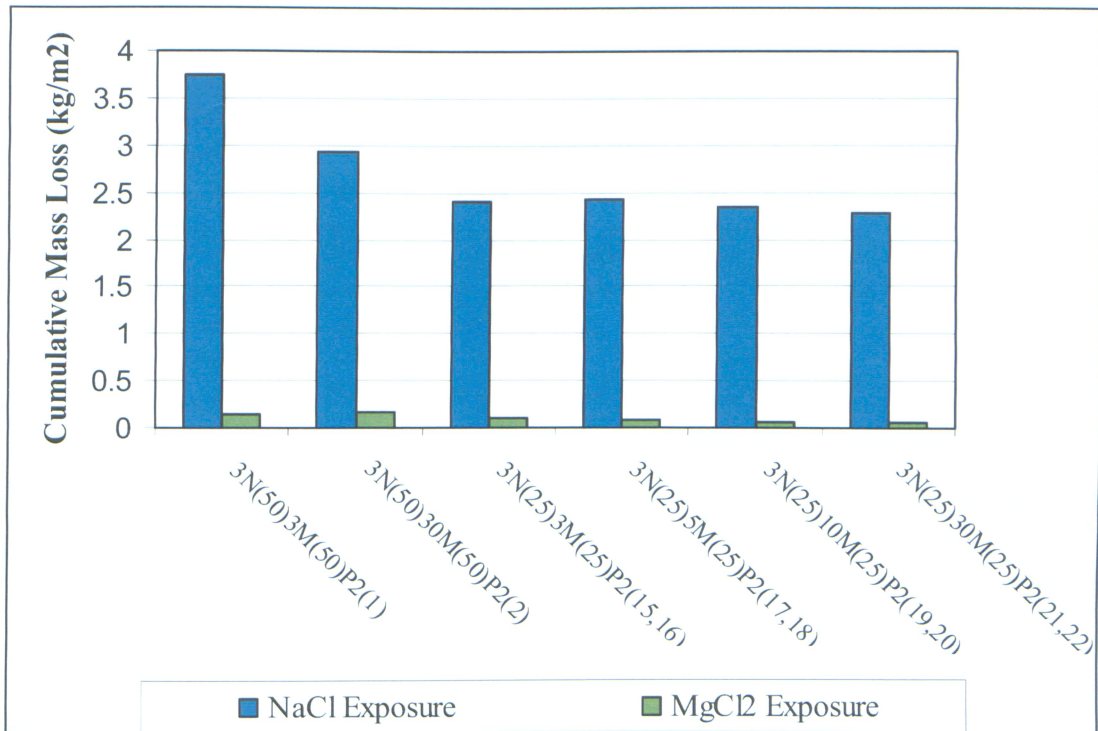
**Figure 4.9 – Phase 2 Cumulative Mass Loss**  
*(25 cycles of 3%NaCl) followed by (25 cycles of (3%, 5%, 10%, and 30%) MgCl<sub>2</sub> exposure)*



Designation = (Concentration in % / Chemical (N=NaCl; M=MgCl<sub>2</sub>) / # of freeze thaw cycles / Phase / Slab #)

**Figure 4.10 – Phase 2: Effect of Length of Exposure**

*Comparison of (50 cycles exposure to 3%NaCl followed by 50 cycles (3%, 30%) MgCl<sub>2</sub> exposure) to (25 cycles exposure to 3%NaCl followed by 25 cycles (3%, 30%) MgCl<sub>2</sub> exposure)*



Designation = (Concentration in % / Chemical (N=NaCl; M=MgCl<sub>2</sub>) / # of freeze thaw cycles / Phase / Slab #)

**Figure 4.11 – Relationship between Length of Exposure and Concrete Mass Loss**

#### 4.4 Phase 3: Influence of Magnesium Chloride on Compressive Strength of Mortar

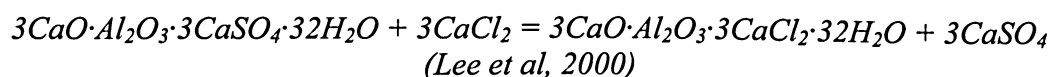
The compressive strength of the mortar specimens was tested as per the ASTM C109 specification. Three cubes (06-13-E7) were broken at 1 day to ensure that the specimens were at least 20 MPa prior to being put into solution (as per the ASTM C1012 specification). Table 4.9 summarizes the 1 day strength results.

**Table 4.9 – Phase 3, 1 day Compressive Strength Results**

Lab Code	24-hour			AVG
	A	B	C	
06-13-E7	24	25	25	25

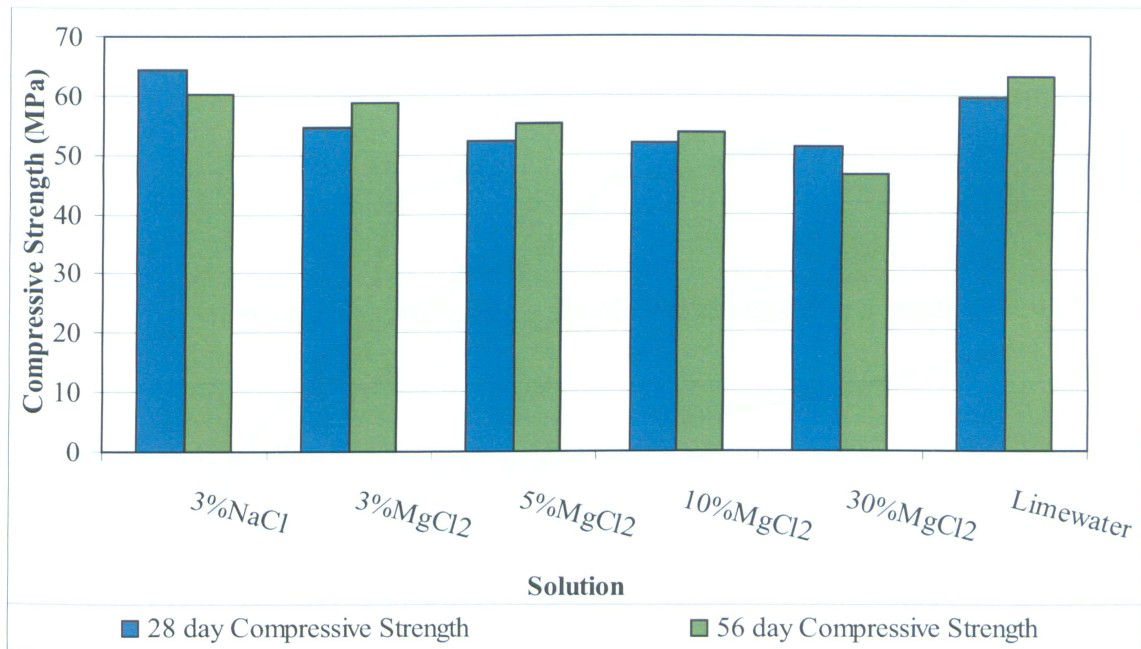
Results of compressive strength of mortar exposed to various chemical solutions are presented in Table 4.10, and Figure 4.12. The compressive strength at both 28 days and 56 days decreases with an increase in  $MgCl_2$  concentration. The lowest compressive strength was found with the sample that was exposed to the highest concentration of  $MgCl_2$  (30%). The samples exposed to 3%NaCl show an initial increase in strength at 28 days, followed by a slight decrease, when compared to the limewater control sample. This decrease has been reported in numerous studies (Ben-Yair, 1967; Ben-Yair, 1974; Ftikos and Parissakis, 1985; Lee et al, 2000), where it was found that the chlorides promoted formation of chloroaluminates and porous CSH.

In a previous study (Lee et al, 2000) the form and occurrence of chloroaluminate in the air voids suggested that it was actually trichloroaluminate ( $3CaO \cdot Al_2O_3 \cdot 3CaCl_2 \cdot 32H_2O$ ) which resulted from the replacement of pre-existing ettringite in which  $Cl^-$  ions substituted for  $SO_4^{2-}$  ions in the ettringite structure:



**Table 4.10 – Phase 3, 28 & 56 day Compressive Strength Results**

Lab Code	28-day strength (MPa)			AVG (MPa)	56-day strength (MPa)			AVG (MPa)
	A	B	C		D	E	F	
<b>06-13-E1 (3%NaCl)</b>	65	62	65	<b>64</b>	60	59	61	<b>60</b>
<b>06-13-E2 (3%MgCl<sub>2</sub>)</b>	51	57	55	<b>55</b>	60	58	58	<b>59</b>
<b>06-13-E3 (5%MgCl<sub>2</sub>)</b>	47	55	55	<b>52</b>	56	54	56	<b>55</b>
<b>06-13-E4 (10%MgCl<sub>2</sub>)</b>	49	54	53	<b>52</b>	60	52	50	<b>54</b>
<b>06-13-E5 (30%MgCl<sub>2</sub>)</b>	56	51	47	<b>51</b>	47	50	43	<b>47</b>
<b>06-13-E6 (Limewater)</b>	60	60	58	<b>60</b>	63	68	60	<b>63</b>



**Figure 4.12 – Mortar Cube Compressive Strength at Various Solution Exposures**



These results, similar to the findings in a previous study (Lee et al, 1998), show that the magnesium component of the deicer solutions proved to be the most deleterious. It is believed that magnesium promoted replacement of CSH by non-cohesive MSH. The penetration of magnesium into the hydrated concrete is attributed to chlorides promoting the leaching of calcium from CSH increasing the porosity of the concrete (Ftikos and Parissakis, 1985).

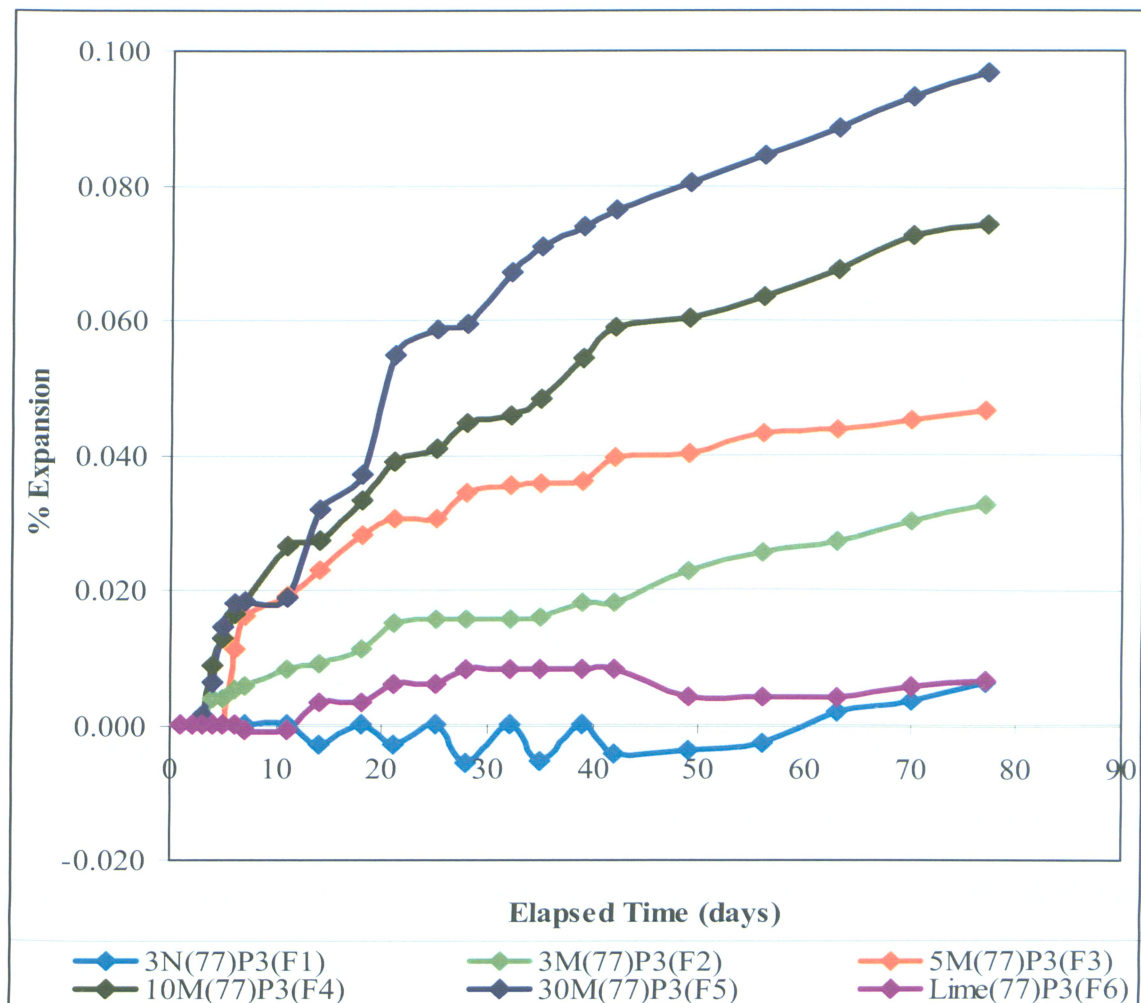
The reaction of dissolved magnesium with calcium silicate hydrates produces non-cohesive magnesium silicate hydrate (MSH). Replacement of calcium by magnesium creates mobile calcium which precipitates as calcite ( $\text{CaO}_3$ ) and/or portlandite ( $\text{Ca}(\text{OH})_2$ ) in the cement paste and aggregate pores. These newly formed materials may exert crystal growth pressures and initiate micro-fracturing (Cody et al, 1996).

#### 4.5 Phase 3: Influence of Magnesium Chloride on Mortar Bar Expansion

A summary of the results found for expansion of mortar bars exposed each solution can be found in Table 4.11. The mortar bars that were exposed to 3%NaCl initially showed increasing shrinkage until 56 days, and then minor expansion over the next 21 days. The mortar bars exposed to 3%MgCl<sub>2</sub> and 5%MgCl<sub>2</sub> showed minor expansion. The mortar bars exposed to 30% MgCl<sub>2</sub> had the highest expansion results.

**Table 4.11 – Summary of all Expansion Results**

Lab Code	Solution	% Expansion (after 77 days)
06-13-F1	3%NaCl	0.0063
06-13-F2	3%MgCl <sub>2</sub>	0.0325
06-13-F3	5%MgCl <sub>2</sub>	0.0463
06-13-F4	10%MgCl <sub>2</sub>	0.0745
06-13-F5	30%MgCl <sub>2</sub>	0.0969
06-13-F6	Limewater	0.0066



**Figure 4.13 – Mortar Cube Compressive Strength at Various Solution Exposures**

Figure 4.13 summarizes results of expansion of mortar prisms exposed to the same chemical concentrations as concrete specimens in phases 1 and 2. The expansion of mortar bars exposed to a 3% NaCl after 77 days was 0.0063. These samples exposed to 3% NaCl initially showed shrinkage up until 60 days. This was then followed by negligible expansion (less than the limewater control). Mortar bars exposed to the 3%  $\text{MgCl}_2$  solution had an expansion of 0.033 after 77 days. These samples exposed to 3%  $\text{MgCl}_2$  leveled out between 20-35 days and then began to show steady increase at a rate of 0.00038%/day.

Mortar bars exposed to a 5%  $\text{MgCl}_2$  solution had an expansion of 0.046 after 77 days. These samples exposed to 5%  $\text{MgCl}_2$  had an initial climb of 0.00381%/day in the first 10 days and then began to show steady increase at a rate of 0.00037%/day. Mortar bars exposed to a 10%  $\text{MgCl}_2$  solution had an expansion of 0.0745 after 77 days. These samples exposed to 10%  $\text{MgCl}_2$  show steady increase at a rate of 0.00097%/day. Mortar bars exposed to a 30%  $\text{MgCl}_2$  solution had an expansion of 0.0969 after 77 days. These samples exposed to 30%  $\text{MgCl}_2$  had an initial climb of 0.00313%/day between 3-20 days and then began to show steady increase at a rate of 0.00075%/day.

Brucite ( $\text{Mg}(\text{OH})_2$ ) crystallization in the alkaline concrete environment may contribute to damage by exerting crystal growth pressures on the surrounding concrete. This expansion seen in the 30%  $\text{MgCl}_2$  solution suggests that there definitely some type of crystals being formed. Mortar bars exposed to a limewater solution had an expansion of 0.0066 after 77 days.

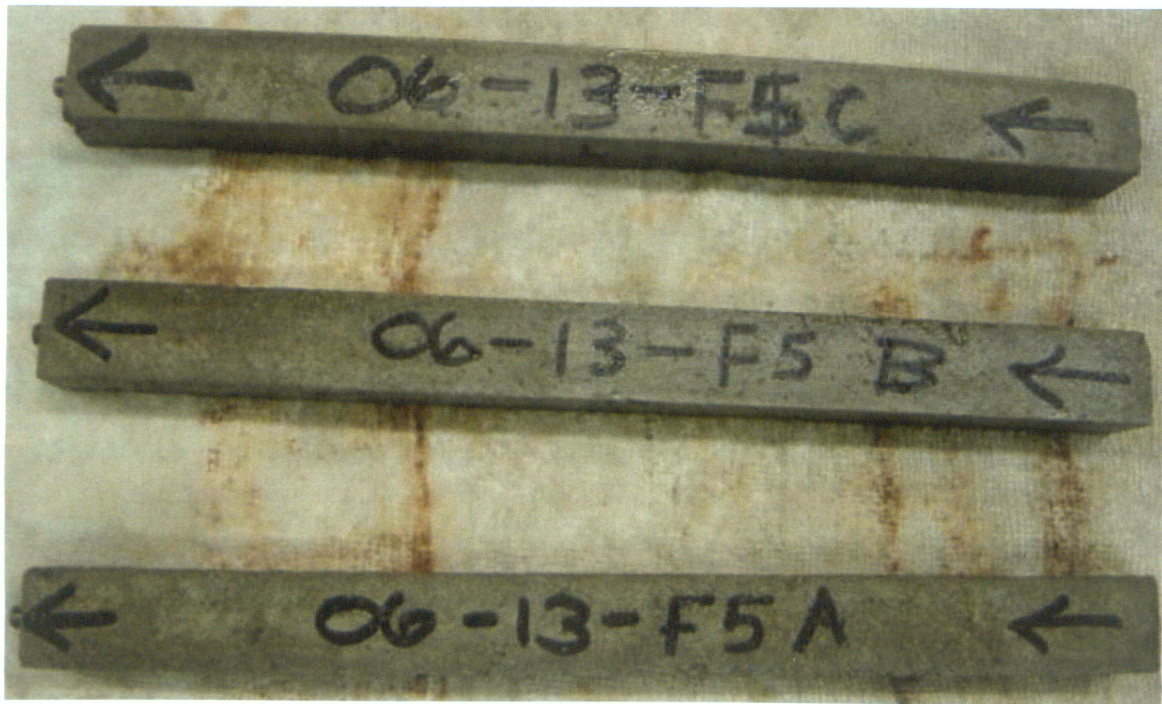
#### 4.6 Reaction Products formed During Mortar Testing

There are research studies that have shown the formation of a mucous film on the paste surface, and they have been associated with a mechanism of chloride corrosion of the cement paste. (Taylor, 1997) pointed out the possibility of magnesium silicate hydrate, which was proved in the works of other researchers. In a previous study (Kurdowski, 2004) a film was formed on durable mortars immersed in a strong chloride solution. It was composed of brucite and basic magnesium chloride. The protective role of this film, as foreseen by Kurdowski (2004), was temporary, and sooner or later, the film was destroyed. Kurdowski (2004) summarized in his paper that, CSH is relatively quickly decalcified in strong chloride solutions containing  $\text{MgCl}_2$ , and new phases are principally brucite and basic magnesium chloride, but MSH was also formed.

The mechanism of the film formation consists in the over saturation of the pore solution with magnesium compounds, due to the rapid diffusion of chloride ions into the interior of the paste, which must be counterbalanced by the diffusion of  $\text{OH}^-$  ions in the opposite direction. Thus, two fronts of high concentration of ions of  $\text{Cl}^-$  and  $\text{OH}^-$  meet, and the quick precipitation of magnesium compounds occurs. This precipitation can catch all the ions of magnesium, chloride and  $\text{OH}^-$ , thus hindering the transport of magnesium and chloride ions into the cement paste. Without doubt, this film plays the role of a protective layer in this period of chloride corrosion of the cement paste. However, the question is how long the role of this film can be maintained (Kurdowski, 2004).

Kurdowski (2004) believes that the positive role of film hindering the corrosion process would be transitory and, sooner or later, this film would become less impermeable, and, furthermore, quick destructive processes of concrete would start.

Figures 4.14 through 4.16 show the progression of film formation that was seen in Phase 3 of this research project.

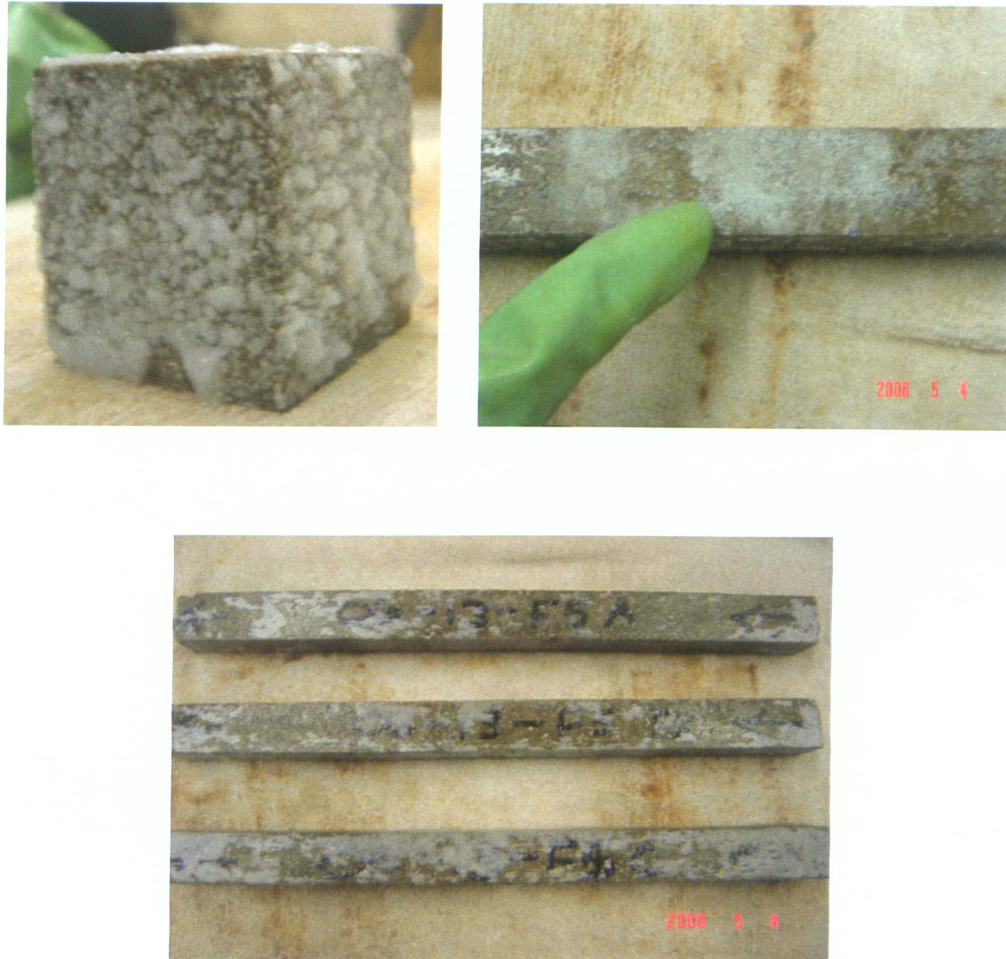


**Figure 4.14 – Formation of Film Seen on 30%  $\text{MgCl}_2$  Mortar Bars at 8 days**

Figure 4.14 shows mortar bars exposed to 30%  $\text{MgCl}_2$ , at 8 days there was a light film with a mucus consistency noticed. There didn't seem to be any visual deterioration at this point.

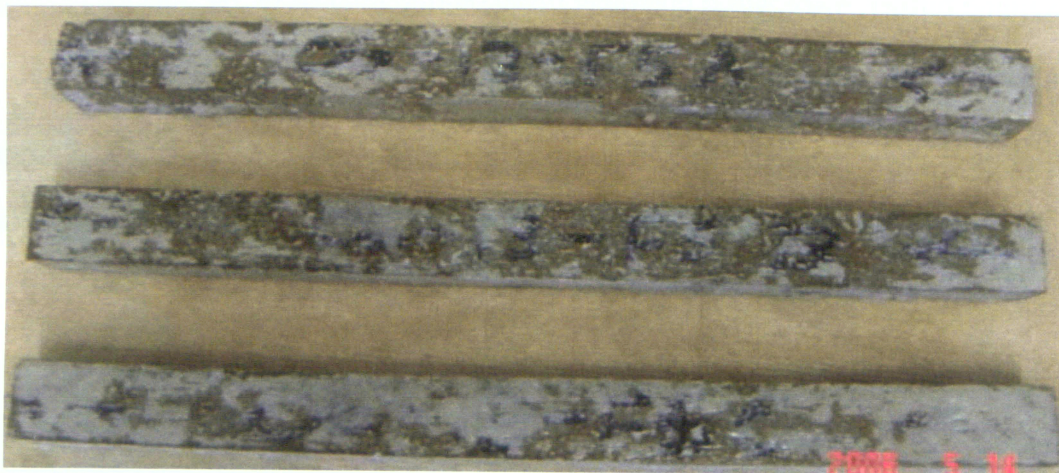


Figure 4.15 shows mortar bars exposed to 30%  $\text{MgCl}_2$ , at 22 days there was an obvious film noticed on the surface of both the prisms and the cubes. When the film was removed to examine further, there was a brownish discoloration noticed on the surface of both the prisms and cubes.

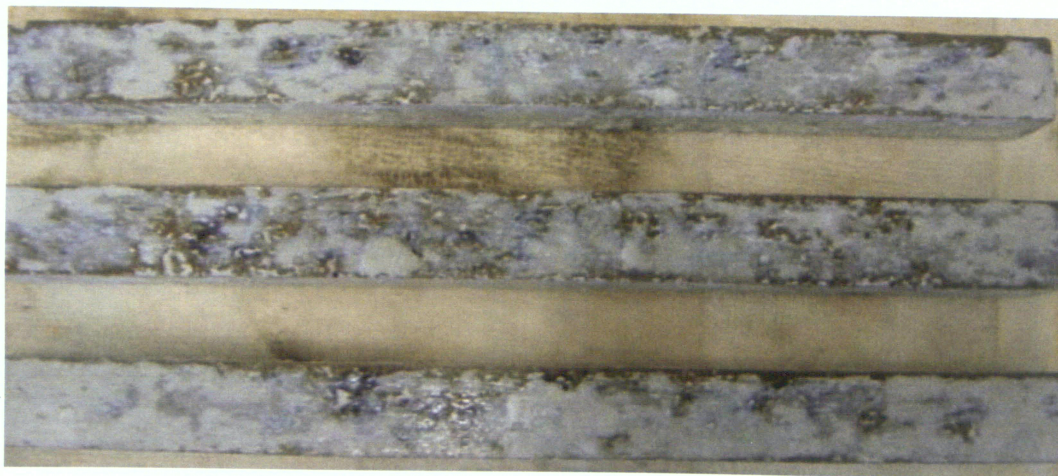


**Figure 4.15 – Formation of Film Seen on 30%  $\text{MgCl}_2$  Mortar Bars at 22 days**

Figure 4.16 shows mortar bars exposed to 30%  $\text{MgCl}_2$ , at 31 days the film was roughly the same consistency as it was at 22 days.



**Figure 4.16 – Formation of Film Seen on 30%  $\text{MgCl}_2$  Mortar Bars at 31 days**



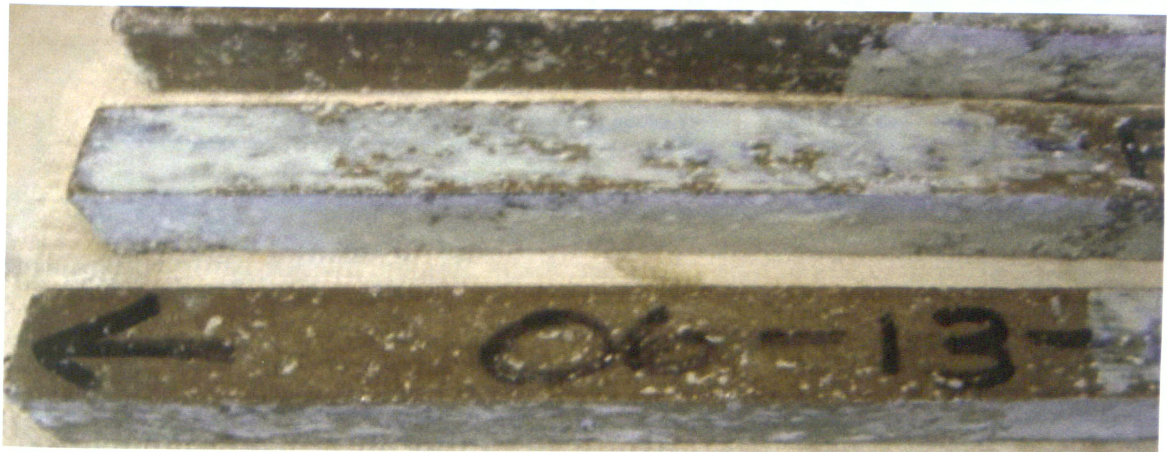
**Figure 4.17 – Formation of Film Seen on 30%  $\text{MgCl}_2$  Mortar Bars at 77 days**

Figure 4.17 shows mortar bars exposed to 30%  $\text{MgCl}_2$ , at 77 days there was a significant increase in the amount of film that was on the surface of the prisms. The brownish discoloration was also significantly darker. Figure 4.18 shows the bars with a portion of the film removed to show this change more clearly. Figure 4.19 compares the 30%  $\text{MgCl}_2$  bars to the Limewater bars at 77 days.

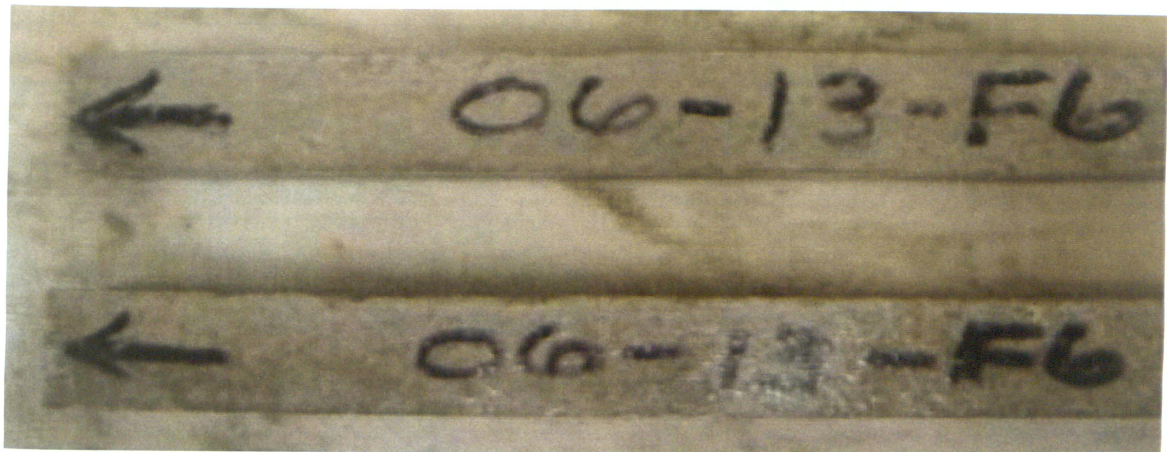




Figure 4.18 – 30%  $\text{MgCl}_2$  Mortar Bars at 77 days with a Portion of Film Removed



30% $\text{MgCl}_2$  @ 77 days



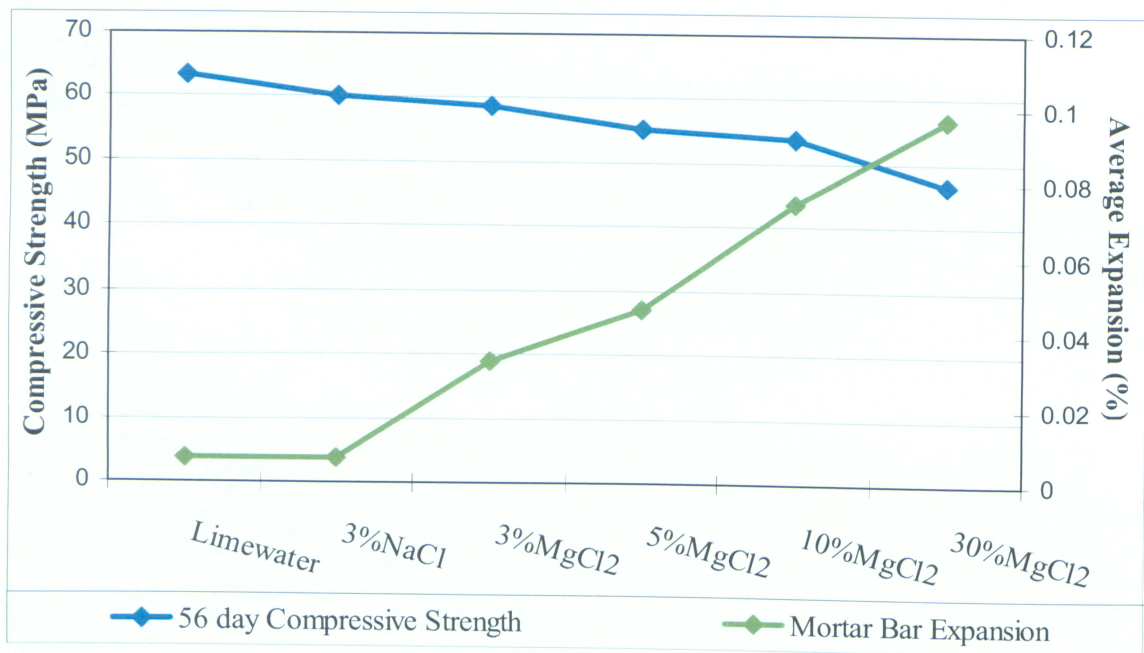
Limewater @ 77 days

Figure 4.19 – Phase 3 Comparison of Discoloration, Limewater to 30%  $\text{MgCl}_2$



#### 4.7 Correlation between Compressive Strength and Expansion in Mortar Specimens

As can be seen in Figure 4.20, there is a noticeable increase in mortar bar expansion with a decrease in compressive strength as the percent of  $\text{MgCl}_2$  is increased. In other words, it indicates that mortar bar expansion increases and cube compressive strength decreases with the increase of  $\text{MgCl}_2$  concentration. These results are in agreement with the fact that magnesium ions from the anti-icers react with hydroxide ions from the cement and form brucite,  $\text{Mg}(\text{OH})_2$ . Crystal growth pressures caused from this reaction lead to expansion of the concrete with rapid deterioration.



**Figure 4.20 – Correlation between Compressive Strength (56 day) and Expansion (77 day)**

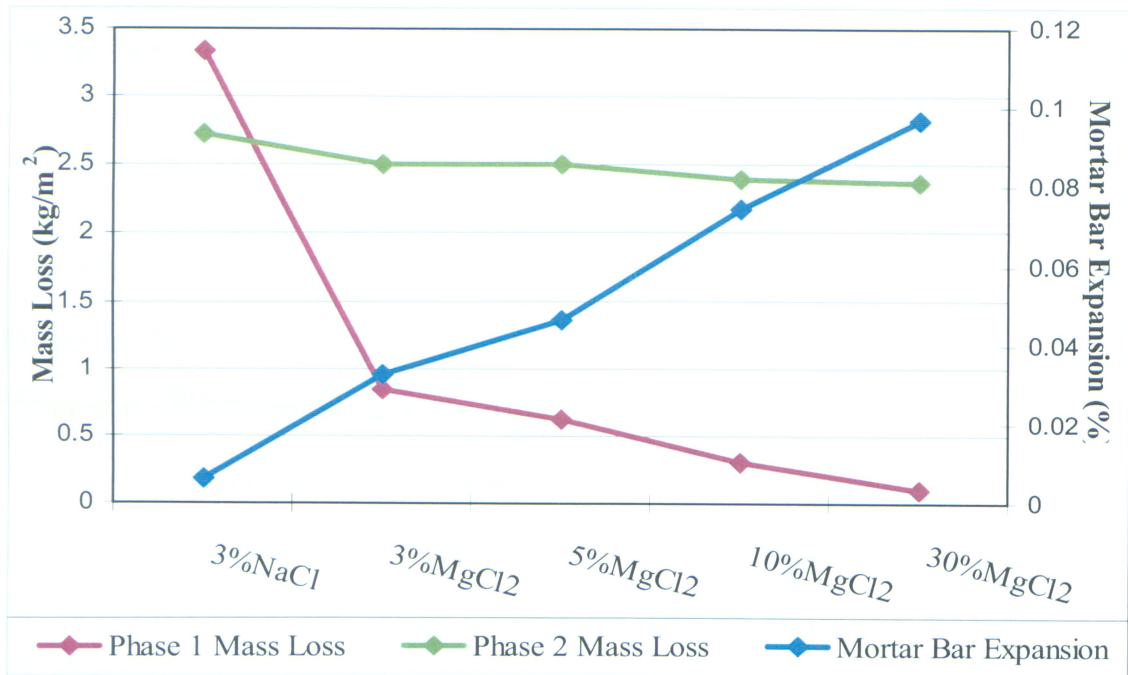
This mechanism (increase in expansion, decrease in strength, formation of protective film, and discoloration) can be mainly attributed to the formation of non-cohesive magnesium silicate hydrate (MSH), and expansive brucite.

MSH is produced by the reaction of dissolved magnesium with calcium silicate hydrates (CSH) in the cement. Replacement of calcium by magnesium creates mobile calcium which is precipitated as calcite ( $\text{CaCO}_3$ ) and/or portlandite ( $\text{Ca(OH)}_2$ ) in the cement paste and aggregate pores (Cody et al, 1996).

The magnesium in anti-icers contributes to the formation of expansive brucite and non-cementitious MSH, and the chloride in these new anti-icers promotes the decalcification of paste and alters ettringite to chloroaluminate (Taylor, 1997). According to Lee et al. (2000), this hydrated magnesium silicate has no binding power, in contrast to silica gel, and its formation therefore represents a final stage in the deterioration of concrete attacked by magnesium sulfate solutions. There seems to be similarities between the mechanisms of magnesium chloride attack and magnesium sulfate attack. In magnesium sulfate attack volume change is associated with the formation of calcium sulfoaluminate, which will more than double the solid volume. The relationship between the formations of chloroaluminate when concrete is exposed to magnesium chloride anti-icers and calcium sulfoaluminate when concrete is exposed to magnesium sulfate should be explored further.

#### 4.8 Correlation between Mortar Bar Expansion and Concrete Mass Loss

From Figure 4.21, there does not seem to be any correlation between the mortar bar expansion and mass loss of concrete specimens after exposed to various chemical solutions.



**Figure 4.21 – Correlation between Mortar bar Expansion and Concrete Mass Loss**

The absence of relationship between the mortar results and concrete results in this study can be attributed to a number of reasons. The mortar samples were completely immersed in solution while the concrete slabs were only exposed at the surface. Also, the mortar samples are much smaller than the concrete slabs. In the field, concrete is more likely to have cracks on the surface due to restricted shrinkage and expansion. In the laboratory study, the slabs were free to move and no cracks existed. Also, the mortar bars were tested at room temperature while the concrete was mainly tested at temperature below zero (except during thawing).

## Chapter 5

### CONCLUSIONS AND RECOMMENDATIONS

#### 5.1 Summary

The influence of magnesium chloride ( $\text{MgCl}_2$ ) on various properties (scaling resistance, compressive strength, expansion) of concrete and mortar samples was investigated in this research. This research project was divided into three phases. The purpose of Phase 1 (P1) was to determine the most aggressive concentration of magnesium chloride ( $\text{MgCl}_2$ ), with respect to deicer salt scaling, using the modified MTO LS412 specification (MLS412). Phase 2 (P2) studied the deterioration of concrete specimens first exposed to 3% sodium chloride ( $\text{NaCl}$ ) and then  $\text{MgCl}_2$  at various concentrations. Phase 3 (P3) focused on the performance of mortar specimens subjected to the same solutions as P1 and P2, to see if expansion was occurring and if  $\text{MgCl}_2$  influenced this expansion.

## 5.2 Conclusions

The following conclusions were drawn based on the results and observations of this research project:

1. An increase in  $\text{MgCl}_2$  concentration results in a decrease in compressive strength. Mortar samples exposed to the highest concentration of  $\text{MgCl}_2$  (30%) showed the lowest compressive strength at 56 days (47 MPa) when compared to lime water cured control samples (63 MPa). Results show a linear decrease in compressive strength with an increase in  $\text{MgCl}_2$  concentration.
2. An increase in  $\text{MgCl}_2$  concentration results in an increase in expansion of mortar samples. Mortar prisms exposed to 30% $\text{MgCl}_2$  showed the highest expansion at 77 days (0.069%) when compared to lime water cured control samples (0.007%). Results show a linear increase in expansion with an increase in  $\text{MgCl}_2$  concentration.
3. Concrete slabs exposed to 3% $\text{NaCl}$  for 50 cycles of freezing and thawing, as per the modified MTO LS412 specification, showed the highest amount of deterioration due to scaling ( $3.34 \text{ kg/m}^2$  of mass loss). The second most deterioration was found in samples exposed to 3% $\text{MgCl}_2$  with a mass loss of  $0.85 \text{ kg/m}^2$ .

4.  $\text{MgCl}_2$  does not appear to increase deterioration due to scaling at any percentage, even with an initial exposure to 3%NaCl.
5. Mortar prisms exposed to 30% $\text{MgCl}_2$  showed the formation of a white mucous film on the surface of the specimens. This film gradually got thicker between 22 and 77 days. This film was also noticed on the surface of slabs exposed to 30%  $\text{MgCl}_2$  in both P1 and P2. This is believed to be a protective film, hindering the transport of magnesium and chloride ions into the cement paste. It is also believed that the positive role of this film in hindering the deterioration process of the cement paste would be transitory, and will sooner or later become permeable and a quick destructive process of the concrete would begin.
6. All solutions (including 30%  $\text{MgCl}_2$ ) completely froze at  $-50^\circ\text{C}$ . However, the concentration of solution affected the time taken by the solution to physically freeze (higher concentrations took longer to freeze/thaw).

### 5.3 Recommendations

The following is a list of recommendations for future research:

1. The current test method, MTO LS412, used to measure the mass loss of specimens subjected to de-icer solutions, should be reviewed to better represent the field condition:
  - a. Different solutions have different freezing points which should be taken into consideration.
  - b. The time for solution to freeze and thaw should be taken into consideration when samples are being exposed to various concentrations of  $\text{MgCl}_2$
  - c. The temperature ranges currently used may not represent the field exposure (high and low). For instance, concrete exposed to direct sun radiation will experience higher temperatures at the surface.
  - d. Concrete surface temperature along with solution freezing points should be reviewed.
2. The film formation observed on samples should be examined further to confirm the formation of brucite with higher concentrations of  $\text{MgCl}_2$ .

3. The period of time before the protective film breaks down should be determined.
4. Freeze/thaw and de-icer salt scaling tests should be completed following the breakdown of the protective film.
5. It should be determined if thickness and length of protection of the protective film will vary between samples exposed to various finishing/curing techniques and various concentrations of  $\text{MgCl}_2$ .
6. The effect of supplementary cementing materials on the formation of brucite should be examined further. There is an abundance of conflicting arguments regarding supplementary cementing materials and their effect on scaling.





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## **APPENDIX A**

## Appendix A - Mix Design

Materials	Design Weight (kg/m <sup>3</sup> )	Batch Weight (kg/0.08m <sup>3</sup> )
St. Marys Type GU/10 Cement	225	18.0
St. Marys CemPlus Slag	75	6.0
20mm Stone	1130	90.4 kg + moisture
Sand	737	59.0 kg + moisture
Water	135	10.8
Slump	<i>Target = 100+/-25mm</i>	
Air	<i>Target = 6-8%</i>	
WR Grace WRDA 20	220 ml/100kg of cement	52.8 ml
WR Grace Darex AEA ED (6-8%)	50 ml/100kg of cement	12 ml

Material	Moisture (%)	Absorption (%)
20mm Stone	1.67	1.2
Concrete Sand	4.14	0.62

## Appendix A – Mix Procedure

- Added ½ the amount of aggregate to the mixer, added all cementitious, then rest of aggregate.
- Turned on mixer and added all water.
- Added Darex AEA ED to sand prior to addition.
- Added WRDA 20 to mix 30sec after water addition.
- Mix for 3 minutes
- Stop for 3 minutes
- Mix for 2 minutes
- Stop for 3 minutes
- Mix for 5 minutes

	<b>06-13-A</b>	<b>06-13-B</b>	<b>06-13-C</b>	<b>06-13-D</b>
Date Cast	1/13/06	1/13/06	3/3/06	3/3/06
Wood Float	12:57	1:30	10:05	10:45
Broom Finish	4:00	4:30	1:05	1:45
Moist cured in mould until : on next day	1:00	1:30	2:30	3:10



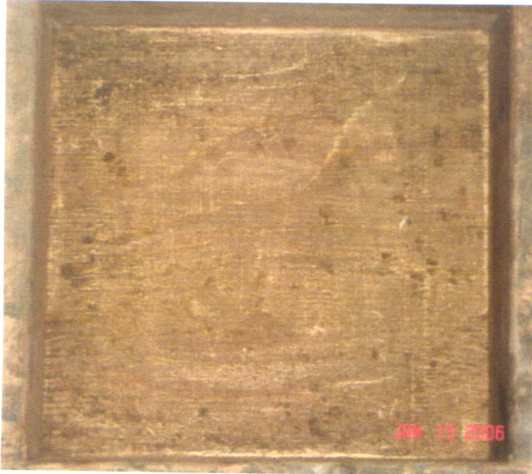
*Water Addition*



*Admixture Addition*



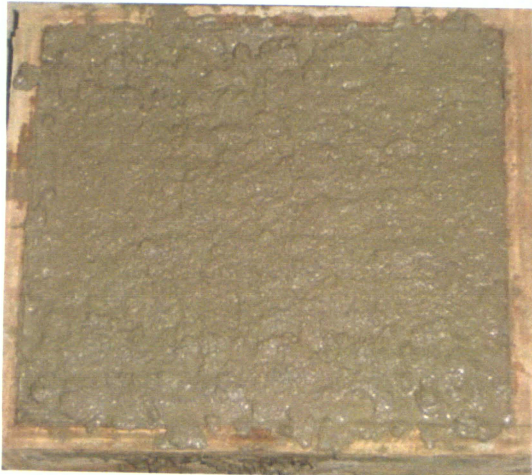
Appendix A – Finishing Slabs



*Wood Form*



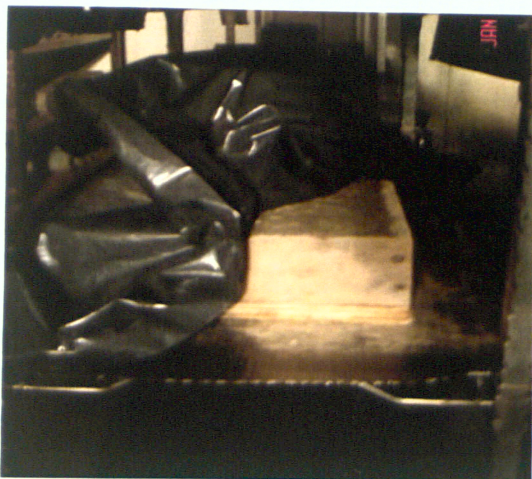
*Oiling Moulds*



*post-Float & pre-Broom Finish*



*post-Broom Finish*



*Curing, first 24-hours*



*Curing, 14days in moist curing room*



## Appendix A – Fresh Concrete Results

	06-13-A	06-13-B	06-13-C	06-13-D
Ambient Temp. (°C)	14.8	15.2	14.4	14.4
Concrete Temp. (°C)	23.3	24.1	19.7	19.3
Slump (mm)	120	120	210	210
Air (%)	6.0	6.0	6.4	6.4



*Slump Result*



*Air Result*



# Appendix A – Concrete Compressive Strength Data

Sample ID	Compressive Strength (MPa)					
	1-day	3-day	7-day	28-day	56-day	90-day
Phase 1 06-13-A	8.6	17.3	25.3	40.1	45.3	45.0
	8.8	17.5	26.6	40.5	44.7	45.5
<i>Average</i>	8.7	17.4	26.0	40.3	45.0	45.3
Phase 1 06-13-B	8.8	17.5	26.7	41.2	46.4	47.1
	-	-	-	41.0	-	-
<i>Average</i>	8.8	17.5	26.7	41.1	46.4	47.1
Phase 2 06-13-C	-	12.0	17.5	34.4	38.6	-
	-	11.5	19.2	33.4	37.9	-
<i>Average</i>	-	11.8	18.4	33.9	38.3	-
Phase 2 06-13-D	-	12.2	19.7	33.7	38.2	-
	-	12.1	19.0	33.7	39.9	-
<i>Average</i>	-	12.2	19.4	33.7	39.1	-

Sample ID	Cylinder Unit Weights (kg/m <sup>3</sup> )					
	1-day	3-day	7-day	28-day	56-day	90-day
06-13-A	2378	2384	2384	2378	2378	2384
	2384	2390	2384	2353	2378	2390
06-13-B	2378	2378	2378	2365	2378	2365
	-	-	-	2365	-	-
06-13-C	-	2341	2365	2341	2353	-
	-	2329	2353	2365	2353	-
06-13-D	-	2365	2353	2341	2341	-
	-	2341	2353	2365	2341	-

Figure 1 shows 24 cylindrical specimens of 2024-T3 aluminum alloy, arranged in two rows of 12. Each specimen is labeled with its identification number and the date of testing. The specimens are organized into two groups of six, each corresponding to a different test condition: 'A' (Control) and 'B' (Heat-treated). The labels include '06-13-A', '06-13-B', and '06-13-C'.

A-6



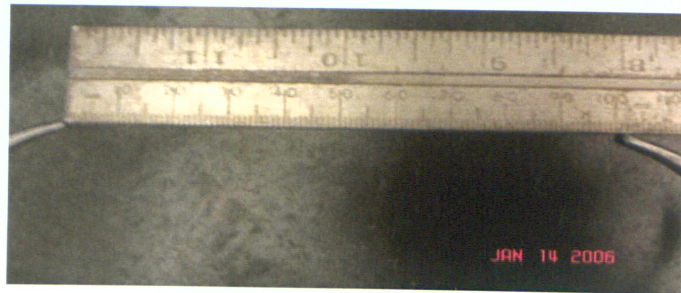
## Appendix A – Concrete Compressive Strength Data



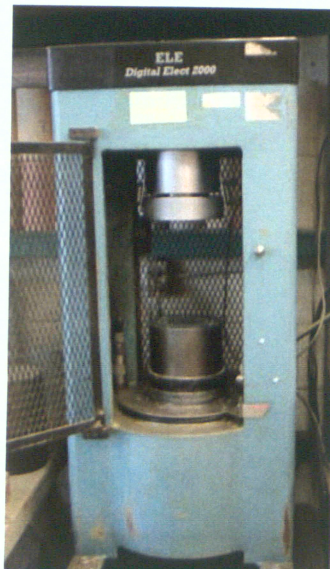
*Capping Cylinders Measuring*



*Cylinder Diameter*



*Cylinder Diameter*



*Compression Machine*

## Appendix A – Hardened Air Void Analysis

<b>Sample ID</b>	<b>Density (kg/m<sup>3</sup>)</b>	<b>Total Air Content (%)</b>	<b>Specific Surface (mm<sup>-1</sup>)</b>	<b>Spacing Factor (mm)</b>
<b>06-13-A</b>	2384	4.7	35.85	0.128
<b>06-13-B</b>	2390	5.2	37.60	0.124
<b>06-13-C</b>	2365	5.0	36.73	0.126
<b>06-13-D</b>	2365	5.2	37.60	0.124

### Interpretation of Results:

<b>CSA Class of Exposure</b>	<b>Total Air Content (%)</b>	<b>Specific Surface (mm<sup>-1</sup>)</b>	<b>Spacing Factor (mm)</b>
C, A, F, and S	3.0 Minimum	No Limit	0.230 Max. Mean 0.260 Max. Individual
w/cm <0.36	3.0 Minimum	No Limit	0.250 Max. Mean 0.300 Max. Individual
<b>MTO Class of Concrete</b>	<b>Total Air Content (%)</b>	<b>Specific Surface (mm<sup>-1</sup>)</b>	<b>Spacing Factor (mm)</b>
Silica Fume Concrete	3.0 Minimum	No Limit	0.250 Max. Mean 0.300 Max. Individual
Normal Concrete	3.0 Minimum	25.0 Minimum	0.200 Maximum

# Appendix A – Rapid Chloride Permeability (RCP) Data

Time	06-13-A		06-13-B		06-13-C		06-13-D	
	<i>mA</i>	<i>Temp.</i>	<i>mA</i>	<i>Temp.</i>	<i>mA</i>	<i>Temp.</i>	<i>mA</i>	<i>Temp.</i>
0:05	90.6	25	85.7	24	90.9	24	86.5	23
0:10	90.4	25	84.5	24	90.5	24	87.0	23
0:15	89.3	25	83.3	24	90.4	24	86.7	23
0:20	88.5	25	82.0	24	90.2	24	86.7	23
0:25	88.4	25	80.6	24	90.2	25	86.9	23
0:30	88.2	25	79.1	25	90.2	25	87.1	23
0:35	88.0	25	77.7	25	90.3	25	87.2	24
0:40	87.9	26	77.1	25	90.4	25	87.4	24
0:45	88.2	26	76.7	25	90.4	26	87.5	24
0:50	88.8	26	76.3	25	90.5	26	87.6	24
0:55	89.3	26	76.7	26	90.5	26	87.6	25
1:00	89.9	26	77.1	26	90.5	27	87.7	25
1:05	90.3	27	77.5	26	90.5	27	87.6	25
1:10	90.7	27	77.8	26	90.5	27	87.5	25
1:15	91.1	27	78.2	26	90.4	27	87.3	25
1:20	91.5	27	78.5	26	90.3	28	87.1	26
1:25	91.9	27	78.8	27	90.5	28	87.7	26
1:30	92.3	28	79.2	27	91.4	28	86.4	26
1:35	92.7	28	79.6	27	91.9	28	86.3	26
1:40	93.1	28	79.8	27	92.2	28	86.5	26
1:45	93.5	28	80.1	27	92.9	29	86.7	27
1:50	93.9	28	80.5	27	93.1	29	86.8	27
1:55	94.3	28	80.9	28	93.5	29	86.7	27
2:00	94.7	29	81.3	28	93.9	29	86.9	27
2:05	95.1	29	81.5	28	94.4	29	87.2	27
2:10	95.6	29	81.8	28	94.8	30	87.4	27
2:15	96.0	29	82.1	28	95.2	30	87.7	27
2:20	96.4	29	82.3	28	95.6	30	87.9	28
2:25	96.7	29	82.6	28	95.8	30	88.2	28
2:30	97.0	30	82.8	28	96.1	30	88.6	28
2:35	97.4	30	83.1	29	95.4	30	88.9	28
2:40	97.8	30	83.3	29	96.7	31	89.2	28
2:45	98.3	30	83.4	29	96.7	31	89.5	28
2:50	98.7	30	83.7	29	97.6	31	89.7	28
2:55	99.0	30	84.0	29	97.9	31	89.8	29
3:00	99.6	30	84.4	29	98.0	31	90.0	29
3:05	99.9	31	84.6	29	98.4	31	90.5	29
3:10	100.4	31	84.7	29	98.8	31	90.7	29
3:15	100.6	31	85.1	30	99.0	32	90.9	29
3:20	100.9	31	85.3	30	99.1	32	91.3	29
3:25	101.4	31	85.3	30	98.9	32	91.4	29
3:30	101.8	31	85.5	30	99.3	32	91.5	29
3:35	102.0	31	85.8	30	99.5	32	91.6	29
3:40	102.3	31	86.0	30	99.9	32	91.7	29

Time	06-13-A		06-13-B		06-13-C		06-13-D	
	<i>mA</i>	<i>Temp.</i>	<i>mA</i>	<i>Temp.</i>	<i>mA</i>	<i>Temp.</i>	<i>mA</i>	<i>Temp.</i>
3:45	102.7	32	86.0	30	100.3	32	92.0	30
3:50	103.1	32	86.5	30	100.6	33	92.1	30
3:55	103.4	32	86.4	30	100.7	33	91.8	30
4:00	103.8	32	86.6	30	100.8	33	91.9	30
4:05	104.0	32	86.6	31	101.0	33	92.8	30
4:10	104.5	32	86.8	31	101.0	33	93.1	30
4:15	104.9	32	87.1	31	100.8	33	92.7	30
4:20	105.1	32	87.7	31	101.4	33	92.4	30
4:25	105.4	33	87.7	31	102.0	33	92.4	30
4:30	105.9	33	88.1	31	102.2	34	92.6	30
4:35	106.2	33	88.3	31	102.3	34	92.8	30
4:40	106.4	33	88.6	31	103.1	34	93.4	31
4:45	106.8	33	88.8	31	103.4	34	93.0	31
4:50	107.1	33	89.1	31	103.6	34	93.0	31
4:55	107.4	33	88.9	32	103.7	34	93.3	31
5:00	107.8	33	89.1	32	103.6	34	93.7	31
5:05	108.0	33	89.0	32	103.7	34	93.7	31
5:10	108.2	33	89.6	32	103.7	34	93.6	31
5:15	108.6	34	89.6	32	104.0	34	93.9	31
5:20	108.9	34	89.5	32	104.0	35	94.3	31
5:25	109.3	34	89.5	32	104.2	35	94.1	31
5:30	109.7	34	89.8	32	104.4	35	94.5	31
5:35	110.0	34	90.2	32	104.5	35	94.3	31
5:40	110.2	34	90.2	32	104.3	35	94.5	31
5:45	110.6	34	90.3	32	104.4	35	94.4	31
5:50	110.6	34	90.5	32	104.5	35	94.7	31
5:55	111.0	34	90.4	32	104.9	35	95.0	32
6:00	111.3	34	90.6	33	105.1	35	95.1	32

#### RCP Results Summary

	06-13-A	06-13-B	06-13-C	06-13-D
Voltage	60	60	60	60
Current (mA)	111.3	90.5	105.2	95.5
Temperature (degC)	34	33	35	32
Time (hours)	6	6	6	6
<b><i>Coulombs</i></b>	<b><i>2148</i></b>	<b><i>1822</i></b>	<b><i>2108</i></b>	<b><i>1953</i></b>
Permeability Class	Low	Low	Low	Low



Appendix A – Rapid Chloride Permeability (RCP) Pictures



*RCP Moulds*



*Sample Preparation*



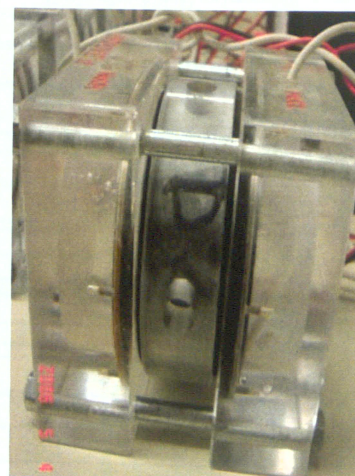
*Pressure Reading*



*Filter*



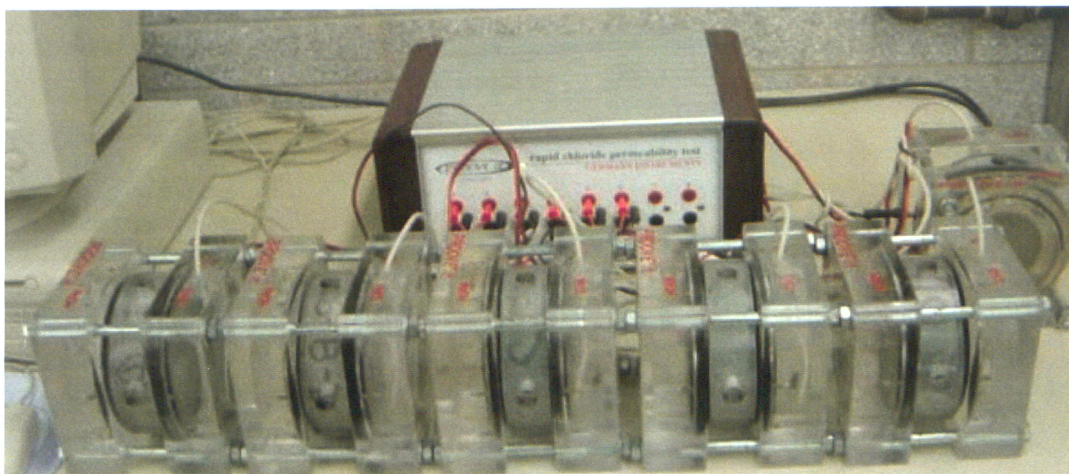
*Sample Preparation*







*RCP Machine*



*RCP Test in Progress*



*RCP Computer Monitoring Program*



## APPENDIX B

## Appendix B – Chemical Analysis of Cementitious Material (Type 10 Portland cement)

### Mill Test Report - CSA A3001-03 Type GU (10)

GSS-10(2-28)

Tuesday, February 28, 2006

Chemical		Physical		
Loss on Ignition	2.0 %	Fineness: Blaine SA	410	m <sup>2</sup> /kg
SiO <sub>2</sub>	19.86 %	Retained 325	6.4	%
Fe <sub>2</sub> O <sub>3</sub>	2.64 %	Retained 200		%
Al <sub>2</sub> O <sub>3</sub>	4.45 %	Normal Consistency	25.7	%
CaO	62.13 %	Autoclave Expansion	0.333	%
Free CaO	1.26 %	Vicat - Initial	91	minutes
MgO	3.27 %	- Final	198	minutes
SO <sub>3</sub>	3.88 %	Paste False Set		%
K <sub>2</sub> O	0.47 %	Entrained Air	8.6	%
Na <sub>2</sub> O	0.29 %	Sulphate Expansion	0.005	%
TiO <sub>2</sub>	0.27 %	Gilmore - Initial		minutes
P <sub>2</sub> O <sub>5</sub>	0.17 %	- Final		minutes
Mn <sub>2</sub> O <sub>3</sub>	0.14 %	Sulphate Resistance		%
Insoluble Residue	0.24 %	Heat of Hydration (7-D)		kJ/kg
Total Alkali as Na <sub>2</sub> O	0.60 %	(28-D)		kJ/kg
Colour Index	31.9			
Calculated Compounds		Compressive Strengths		
C <sub>3</sub> S	57 %	Age	MPa	PSI
C <sub>2</sub> S	14 %	1-Day	15.3	2221
C <sub>3</sub> A – ASTM	7 %	3-Day	25.9	3756
– CSA	7.3 %	7-Day	32.5	4721
C <sub>4</sub> AF	8 %	28-Day	40.5	5879

Appendix B – Chemical Analysis of Cementitious Material (GGBFS Slag)

**Mill Test Report - CSA A3001-03 Type S (Slag)**

February 28, 2006

**Chemical**

SO<sub>3</sub> 0%  
Sulphide 0.95%  
Blaine 555

**Physical**

Fineness: Retained 325 0.0%  
Autoclave Expansion 0.164%

**Compressive Strengths (MPa)**

Age	Slag	Reference Cement	% of Reference
7 Day	26.7	28.7	93
28 Day	44.7	35.1	127

Appendix B – Aggregate Testing Data (Coarse Aggregate)

**MTO LS 601 (Wash Pass 75um) & MTO LS 602 (Sieve Analysis)**

Sieve Size	Weight Retained		% Retained		Total% Passing	Specification
	Cumulative	Individual	Cumulative	Individual		
26.5mm	0	0	0	0	100	100
22.4mm	0	0	0	0	100	-
19.0mm	545.6	545.6	8.7	8.7	91.3	85-100
16.0mm	1526.7	981.1	24.3	15.6	75.7	65-90
13.2mm	2704.0	1177.3	43.0	18.7	57.0	-
9.5mm	4508.6	1804.6	71.8	28.7	28.2	20-55
6.7mm	5715.9	1207.3	91.0	19.2	9.0	-
4.75mm	6135.8	419.9	97.7	6.7	2.3	0-10
Pan	6266.7	130.9	99.7	2.1	0	-
<b>Material Passing 75um Sieve</b>					0.46	2.0% Max

# Appendix B – Aggregate Testing Data (Coarse Aggregate)

## MTO LS 604 (Relative Density & Absorption of Coarse Aggregate)

A	
Mass of oven-dry sample in air	
Test 1	
A =	3142
B =	3179.5
C =	2010
BULK RELATIVE DENSITY = 2.6866	
BULK RELATIVE DENSITY (SSD) = 2.7187	
APPARENT RELATIVE DENSITY = 2.7756	
ABSORPTION = 1.19	

B	
Mass of SSD sample in air	
Test 2	
A =	3087.1
B =	3121.3
C =	1980
BULK RELATIVE DENSITY = 2.7049	
BULK RELATIVE DENSITY (SSD) = 2.7349	
APPARENT RELATIVE DENSITY = 2.7885	
ABSORPTION = 1.11	

C	
Mass of sample in water	
Test 3	
A =	3058.9
B =	3094.1
C =	1960
BULK RELATIVE DENSITY = 2.6972	
BULK RELATIVE DENSITY (SSD) = 2.7282	
APPARENT RELATIVE DENSITY = 2.7836	
ABSORPTION = 1.15	

***Bulk Relative Density = 2.6962***

***Bulk Relative Density (SSD) = 2.7273***

***Apparent Relative Density = 2.7826***

***Absorption = 1.15 (2.0% Max.)***

Appendix B – Aggregate Testing Data (Fine Aggregate)

**MTO LS 601 (Wash Pass 75um) & MTO LS 602 (Sieve Analysis)**

<b>Sieve Size</b>	<b>Weight Retained</b>		<b>% Retained</b>		<b>Total% Passing</b>	<b>Specification</b>
	<b>Cumulative</b>	<b>Individual</b>	<b>Cumulative</b>	<b>Individual</b>		
<b>9.5mm</b>	0.0	0.0	0.0	0.0	100.0	100
<b>4.75mm</b>	6.1	6.1	2.1	2.1	97.9	95-100
<b>2.36mm</b>	42.0	35.9	14.5	12.4	85.5	80-100
<b>1.18mm</b>	88.8	46.8	30.7	16.2	69.3	50-85
<b>600um</b>	140.0	51.2	48.4	17.7	51.6	25-60
<b>300um</b>	217.9	77.9	75.4	27.0	24.6	10-30
<b>150um</b>	270.1	52.2	93.5	18.1	6.5	0-10
<b>75um</b>	284.8	14.7	98.5	5.1	1.5	0-3
<b>Pan</b>	286.1	1.3	99.0	0.4	-	-
<b>Material Passing 75um Sieve</b>					1.3	3.0% Max
<b>Fineness Modulus</b>					2.65	2.3-3.1

Appendix B – Aggregate Testing Data (Fine Aggregate)

**MTO LS 605 (Relative Density & Absorption of Fine Aggregate)**

A	
Mass of oven-dry sample in air	
Test 1	
A =	494.6
B =	684.4
C =	996.7
MF =	500.0
BULK RELATIVE DENSITY = 2.6351	
BULK RELATIVE DENSITY (SSD) = 2.6638	
APPARENT RELATIVE DENSITY = 2.7131	
ABSORPTION = 1.09	

B	
Mass of pycnometer filled with water	
Test 2	
A =	494.6
B =	684.4
C =	996.9
MF =	500.0
BULK RELATIVE DENSITY = 2.6379	
BULK RELATIVE DENSITY (SSD) = 2.6667	
APPARENT RELATIVE DENSITY = 2.7161	
ABSORPTION = 1.09	

C	
Mass of sample, pycnometer, and water	
Test 3	
A =	494.7
B =	684.4
C =	996.7
MF =	500.0
BULK RELATIVE DENSITY = 2.6356	
BULK RELATIVE DENSITY (SSD) = 2.6638	
APPARENT RELATIVE DENSITY = 2.7122	
ABSORPTION = 1.07	

***Bulk Relative Density = 2.6362***

***Bulk Relative Density (SSD) = 2.6648***

***Apparent Relative Density = 2.7138***

***Absorption = 1.08 (2.0% Max.)***

## Concrete

### PRODUCT INFORMATION

# WRDA® 20

Water-Reducing Admixture ASTM C 494, Type A

#### Description

WRDA® 20 is an aqueous solution of modified glucose polymer containing a catalyst which promotes more complete hydration of the portland cement. WRDA 20 is manufactured under rigid control to ensure uniform predictable performance. It is supplied as a dark brown, low viscosity liquid and is ready to use as received. WRDA 20 weighs approximately 1.20 kg/L (10.0 lbs/gal).

#### Uses

WRDA 20 is a general purpose water-reducing concrete admixture that is recommended for use in a wide variety of applications where concrete with normal setting characteristics is required. It is used in ready mix, job site, and concrete paver plants; for normal and lightweight concrete; in block, precast and prestress work ... wherever concrete is produced.

#### Advantages

WRDA 20 produces a mix with lower water content (typically 5% to 10% reduction) and higher compressive and flexural strengths at all ages than untreated concrete. WRDA 20 produces plastic concrete that is easier to place and finish, and yields a stronger, less permeable and more durable concrete.

#### Finishability

Finishers have stated that the cement paste or mortar in WRDA 20 admixed concrete has improved trowelability. Floating or troweling by hand or machine imparts a smooth, close tolerance surface.

#### Chemical Action

As a dispersing agent, WRDA 20 lessens the natural interparticle reaction between cement grains in water. The admixture is adsorbed onto the cement particles, where it reduces their tendency to clump together and thereby reduces the amount of water needed to produce a workable mix.

As a cement catalyst, WRDA 20 initiates a more complete hydration of the cement, beginning immediately after the cement and water come together. WRDA 20 also adds to the water retention and internal cohesiveness of the mix, reducing bleeding and segregation as it increases workability and placeability.

#### Addition Rates

WRDA 20 meets the requirements of ASTM C 494 as a Type A, Water-Reducing Admixture. Excellent results are obtained using an addition rate of 160 mL/100 kg (2.5 fl oz/100 lbs) of cementitious materials. In some cases it may be necessary to modify the addition rate due to variations in cement, aggregate and other jobsite conditions.

#### Compatibility with Other Admixtures

WRDA 20 is compatible with all other W.R. Grace admixtures. When used in combination with other admixtures, each admixture should be added separately into the mix.

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## Appendix B – Chemical Admixture Data (Water-Reducing Admixture)

### Dispensing Equipment

A complete line of accurate, automatic dispensing equipment is available. WRDA 20 may be added to the concrete mix on the sand or with the mix water.

### Packaging

WRDA 20 is available in bulk, delivered by metered tank trucks and 210 L (55 gallon) drums.

### Architects' Specifications

Concrete shall be designed in accordance with Standard Recommended Practice for Selecting Proportions for Concrete, ACI 211.

The water-reducing admixture shall be WRDA 20 as manufactured by Grace Construction Products, or its equivalent. It shall meet all the requirements of Specification for Chemical Admixtures for Concrete ASTM Designation C 494, as a Type A admixture. Certification of compliance shall be made available on request.

The admixture shall be delivered as a ready-to-use, liquid product and shall require no mixing at the batching plant or jobsite. The admixture shall not contain calcium chloride. It shall be used in strict accordance with manufacturer's recommendations.



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## Concrete

### PRODUCT INFORMATION

# Darex® AEA ED

Air-Entraining Admixture ASTM C 260

#### Description

Darex® AEA ED is an air-entraining admixture which generates a highly stable air void system for increased protection against damage from freezing and thawing, severe weathering, or deicer chemicals. Darex AEA ED is a complex mixture of organic acid salts in an aqueous solution specifically formulated for use as an air-entraining admixture for concrete and is manufactured under rigid control which provides uniform, predictable performance. It is supplied ready to use and does not require pre-mixing with water. One Liter of Darex AEA ED weighs 1.00 kg (8.34 lbs/gal). Darex AEA ED complies to ASTM C 260 Standard Specifications for Air-Entraining Admixtures for Concrete.

#### Uses

Darex AEA ED is used in ready-mix, block, and concrete products plants to improve air entrainment stability. Darex AEA ED performs well in conventional concrete and is effective in plasticizing mixes with slag, lightweight, or manufactured aggregates which tend to produce harsh concrete.



Darex AEA ED entrains air effectively with microsilica concrete and with fly ash concrete.

#### Air-entraining Action

Air is incorporated into the concrete by the mechanics of mixing and stabilized into millions of discrete semi-microscopic bubbles in the presence of a specifically designed air-entraining admixture such as Darex AEA ED. These air bubbles act much like flexible ball bearings increasing the mobility, or plasticity and workability of the concrete. This can permit a

reduction in mixing water with no loss of slump. Placeability is improved. Bleeding, plastic shrinkage and segregation are minimized.

Through the purposeful entrainment of air, Darex AEA ED markedly increases the durability of concrete to severe exposures particularly to freezing and thawing. It has also demonstrated a remarkable ability to impart resistance to the action of frost and deicing salts as well as sulfate, sea and alkaline waters.

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## Appendix B – Chemical Admixture Data (Air-Entraining Admixture)

### Compatibility with Other Admixtures

Darex AEA ED air-entraining admixture is fully effective and compatible in concrete with other admixtures. EACH ADMIXTURE, HOWEVER, SHOULD BE ADDED TO THE CONCRETE SEPARATELY.

### Addition Rates

There is no standard addition rate for Darex AEA ED air-entraining admixture. The amount to be used will depend upon the amount of air required for job conditions, usually in the range of 4 to 8%. Typical factors which might influence the amount of air-entraining admixture required are, temperature, cement, sand gradation, and the use of extra fine materials such as fly ash and microsilica. Typical Darex AEA ED addition rates generally range from 30 to 320 mL/100 kg (½ to 5 fl oz/100 lbs) of cement.

The air-entraining efficiency of Darex AEA ED becomes even greater when used with water-reducing and set-retarding agents. This may allow a reduction of up to ⅔ in the amount of Darex AEA ED required for the specified air content.

### Mix Adjustment

Entrained air results in increased yields with a consequent decrease in the cement content of the placed concrete. This condition calls for a mix adjustment, usually accomplished by reducing the fine aggregate content. This is in addition to the reduction in water content brought about by the increase in plasticity. Pretesting of the concrete should be performed to determine dosage and addition times of all admixtures.

### Dispensing Equipment

A complete line of accurate dispensing equipment is available. These dispensers can be located to discharge into the water line, the mixer, or on the sand.

### Packaging

Darex AEA ED is available in bulk, delivered by metered tank trucks and in 210 L (55 gal) drums. DAREX AEA ED WILL FREEZE AT ABOUT -1°C (30°F), BUT ITS AIR-ENTRAINING PROPERTIES ARE COMPLETELY RESTORED BY THAWING AND THOROUGH MECHANICAL AGITATION.

### Architects' Specification for Concrete Air-entraining Admixture

Concrete shall be air entrained concrete, containing 4 to 8% entrained air. The air contents in the concrete shall be determined by the pressure method (ASTM Designation C 231), gravimetric method (ASTM Designation C 138) or volume metric method (ASTM Designation C 173). The air-entraining admixture shall be Darex AEA ED as manufactured by Grace Construction Products, or equal. The air-entraining admixture shall be added at the concrete mixer or batching plant at approximately 30 to 320 mL/100 kg (½ to 5 fl oz/100 lbs) of cement, or in such quantities as to give the specified air contents.



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## **APPENDIX C**

# Appendix C - Phase 1 Scaling Resistance Data (as per modified\* MTO LS412)

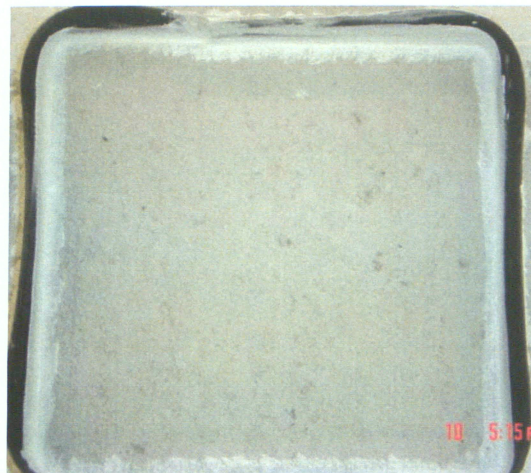
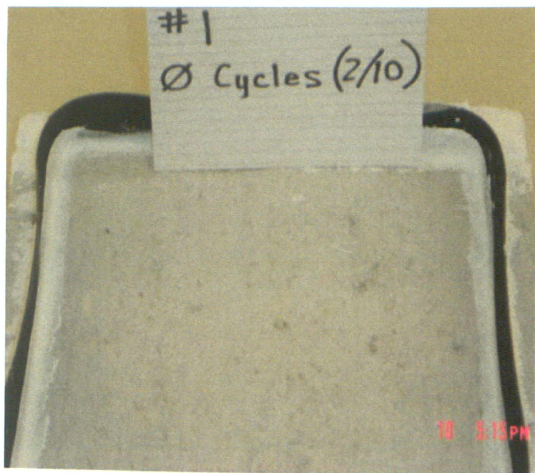
\*The lower temperature limit was lowered from -18degC to -50degC to ensure magnesium chloride solutions would freeze.

# Cycles	Cumulative Mass Loss (kg/m <sup>2</sup> )																
	3N(50)P1(1,2)			M1000(50)P1(3,4)			3M(50)P1(5,6)			5M(50)P1(7,8)			10M(50)P1(9,10)			30M(50)P1(11,12)	
	1	2	3	4	5	6	7	8	9	10	11	12					
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
5	1.95	1.52	0.02	0.01	0.22	1.01	0.15	0.92	0.21	0.15	0.01	0.01	0.01	0.01			
10	2.32	1.87	0.02	0.01	0.31	1.12	0.19	0.98	0.27	0.19	0.04	0.03	0.03	0.03			
15	2.49	2.00	-	-	0.36	1.17	0.20	0.99	0.29	0.21	0.04	0.04	0.04	0.04			
20	2.63	2.11	-	-	0.39	1.19	0.21	1.00	0.30	0.22	0.05	0.05	0.05	0.05			
25	2.79	2.24	-	-	0.40	1.20	0.21	1.01	0.31	0.23	0.06	0.06	0.06	0.06			
30	2.93	2.35	-	-	0.41	1.21	0.21	1.02	0.32	0.24	0.07	0.07	0.07	0.07			
35	3.07	2.45	-	-	0.42	1.22	0.21	1.03	0.33	0.25	0.07	0.08	0.08	0.08			
40	3.22	2.56	-	-	0.43	1.23	0.21	1.03	0.33	0.25	0.07	0.08	0.08	0.08			
45	3.51	2.78	-	-	0.44	1.24	0.21	1.03	0.34	0.26	0.07	0.08	0.08	0.08			
50	3.74	2.94	-	-	0.45	1.24	0.21	1.03	0.34	0.26	0.08	0.09	0.09	0.09			
AVG	3.34			0.02			0.85			0.62			0.30			0.09	



Appendix C – Phase 1 Freeze/Thaw Slabs

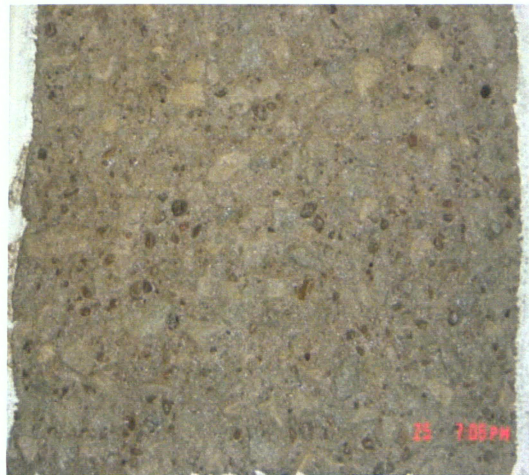
3%NaCl – Slab 1



*0 cycles*



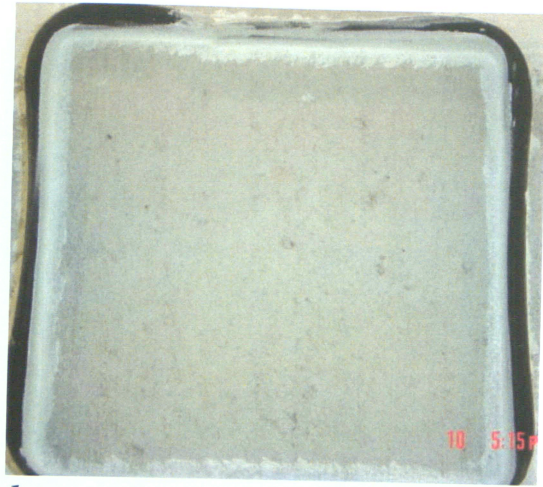
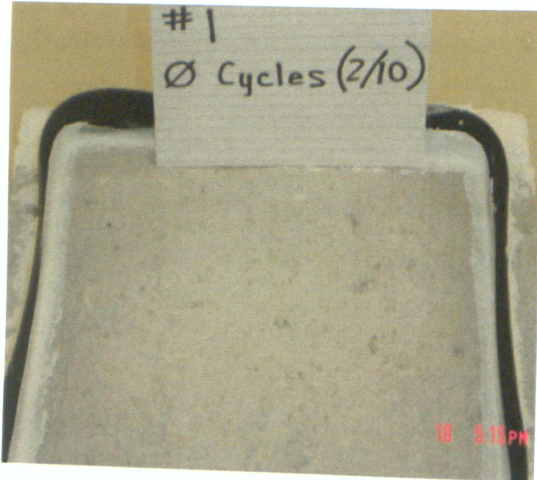
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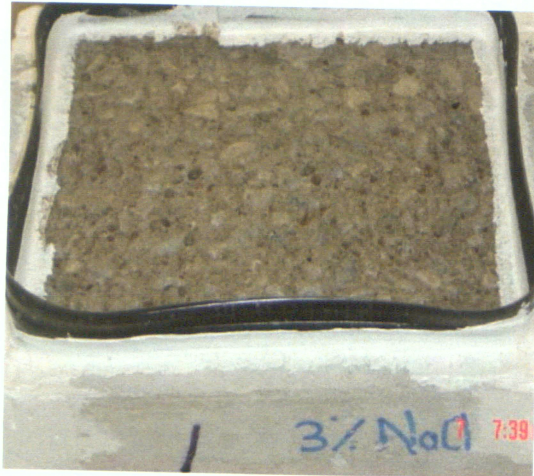
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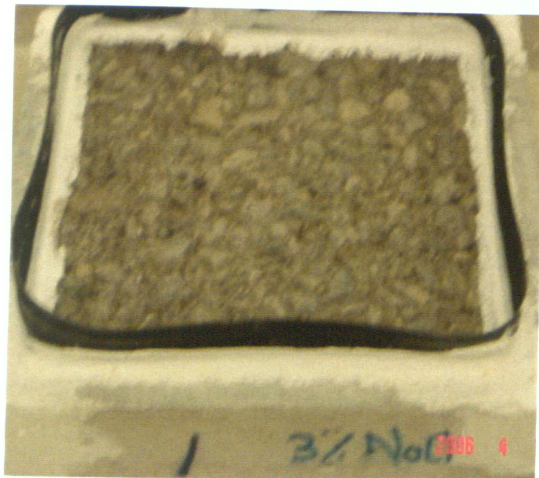
3%NaCl – Slab 1



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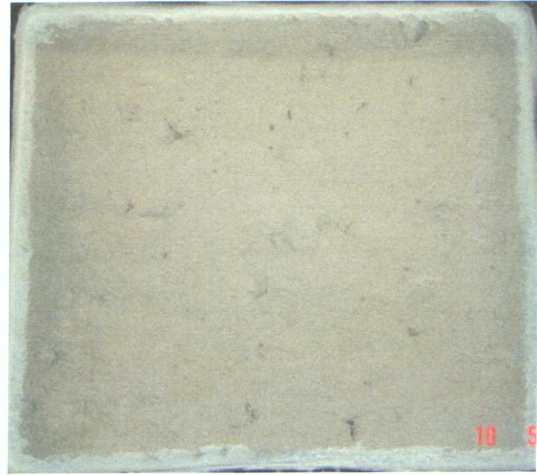
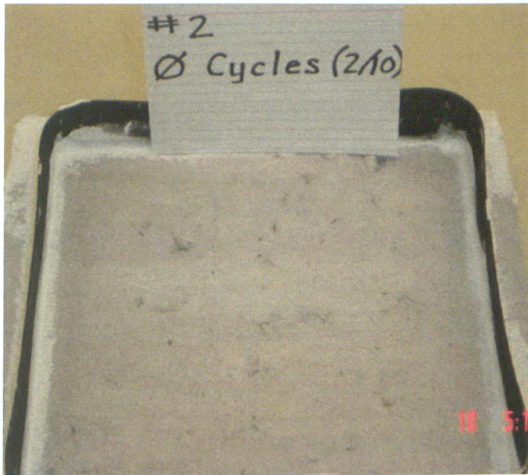
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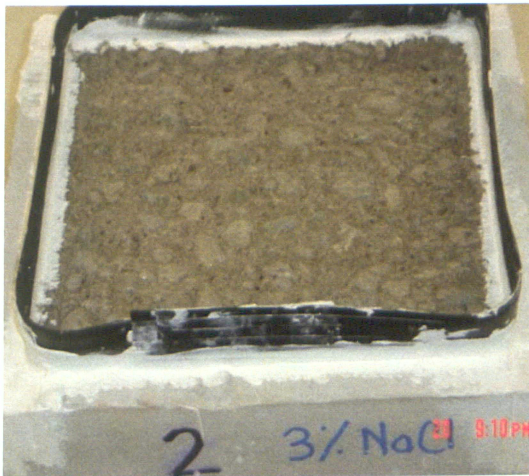
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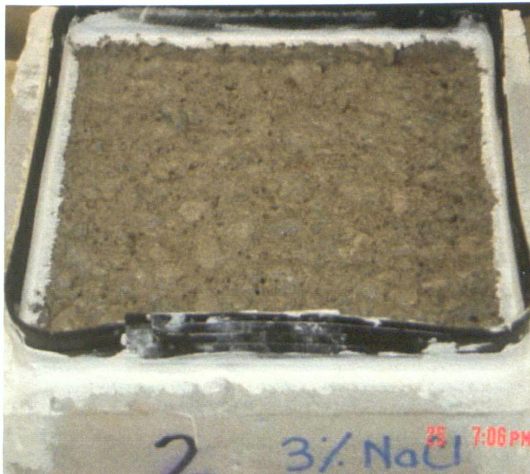
3%NaCl – Slab 2



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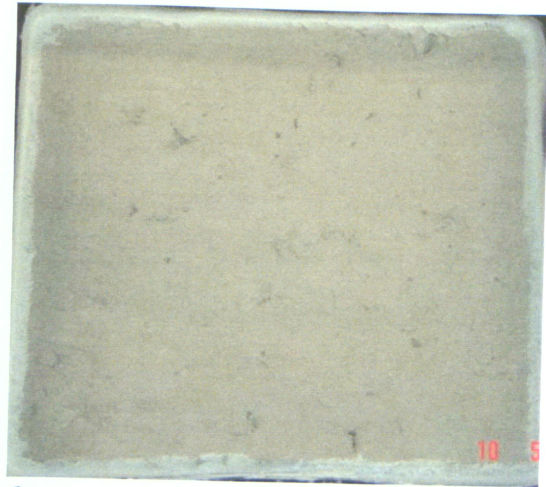
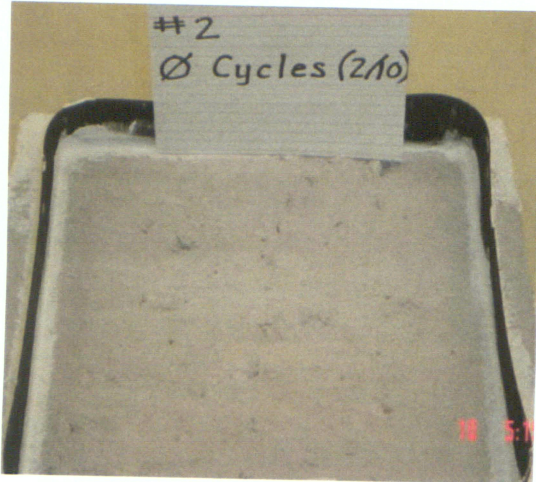
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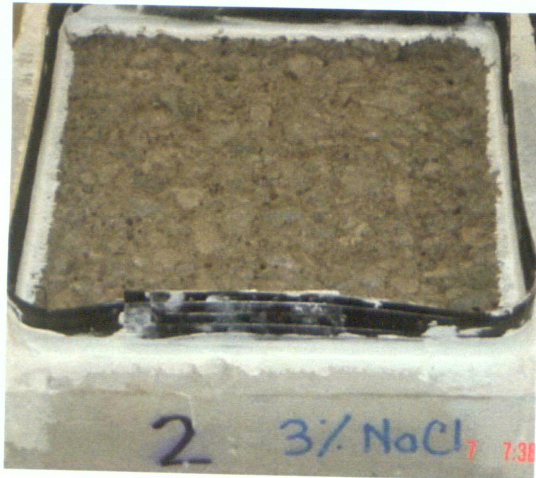
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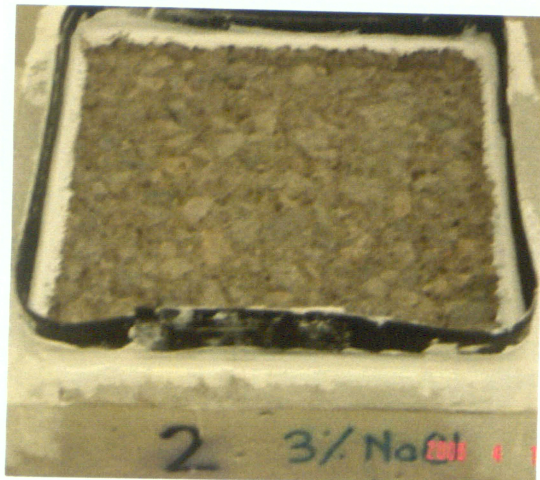
3%NaCl – Slab 2



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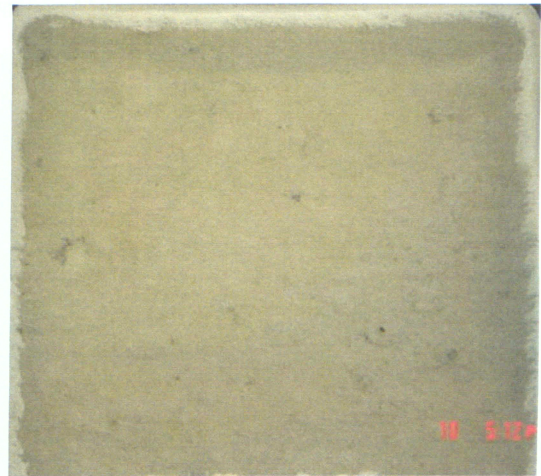
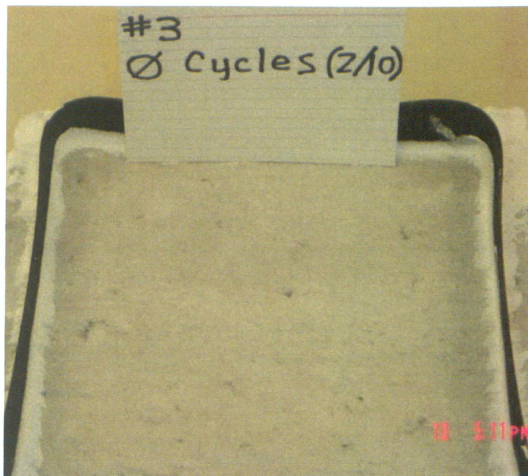
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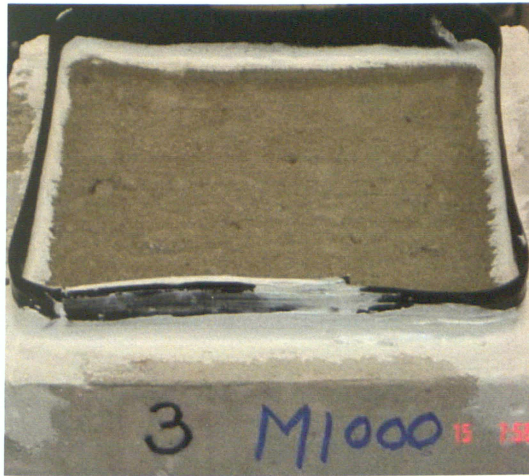
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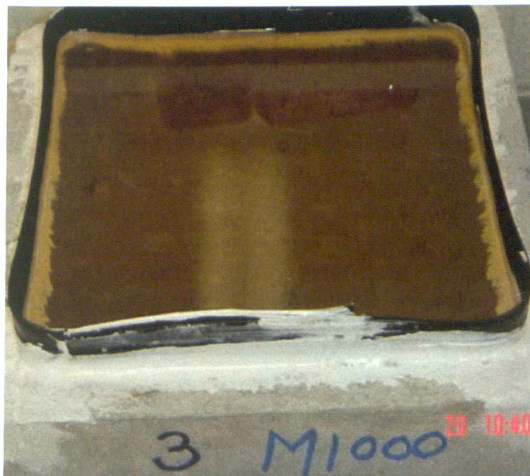
M1000 – Slab 3



*0 cycles*



*5 cycles*



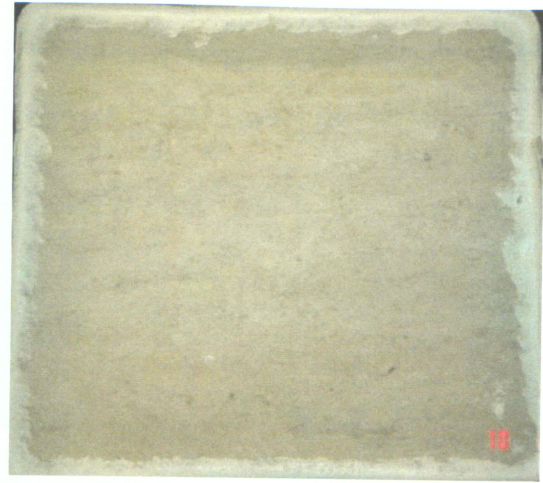
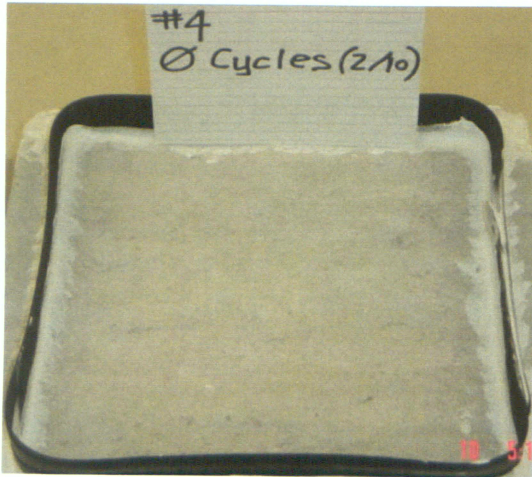
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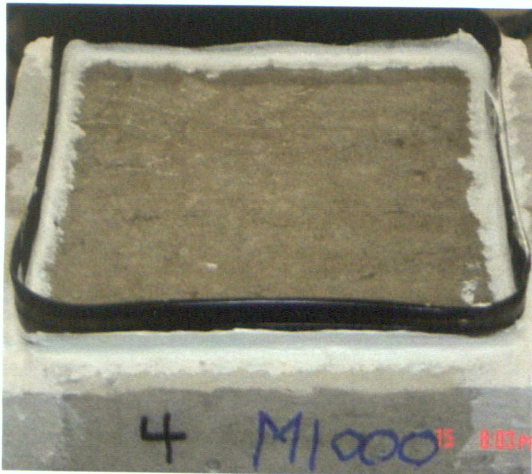
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M1000 – Slab 4



*0 cycles*



*5 cycles*



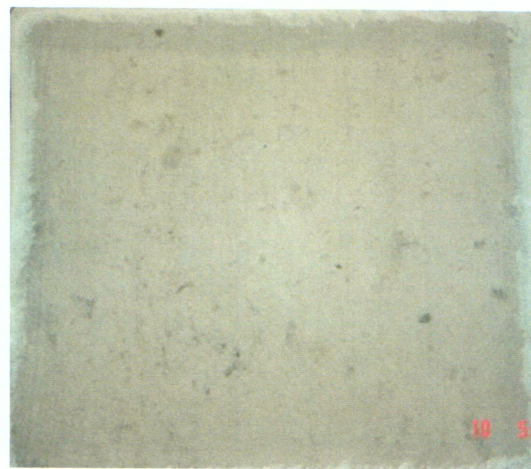
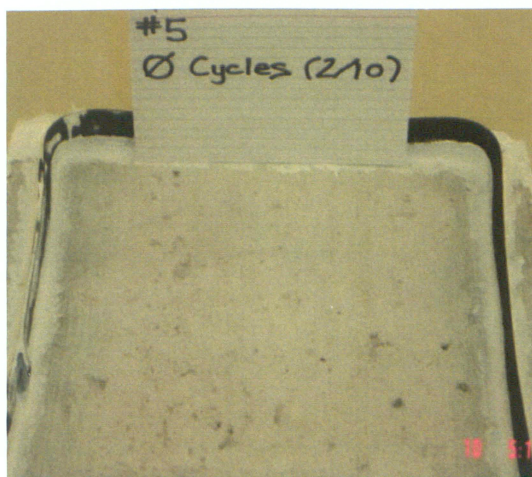
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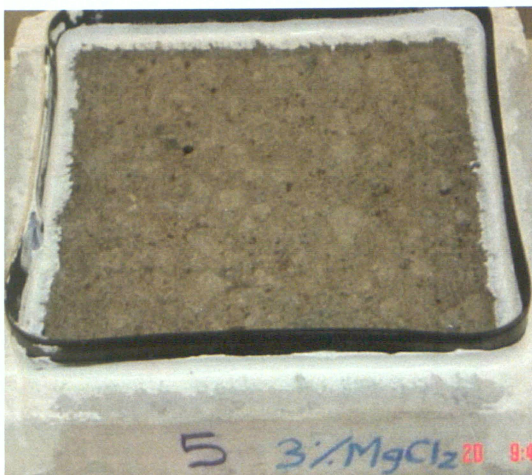
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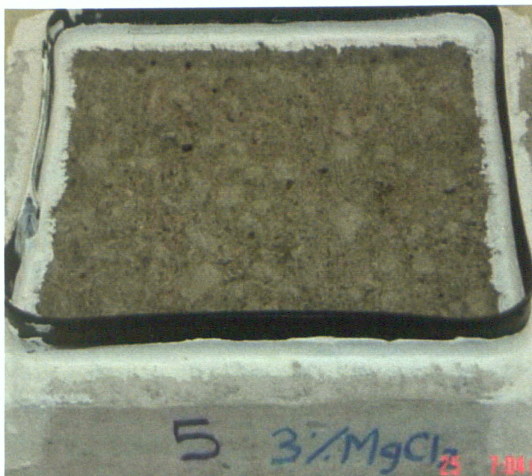
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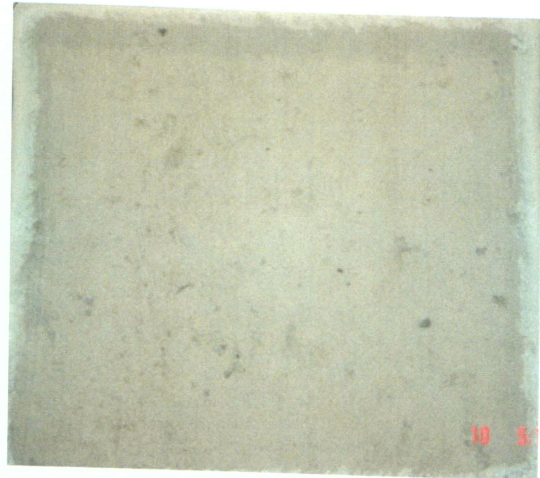
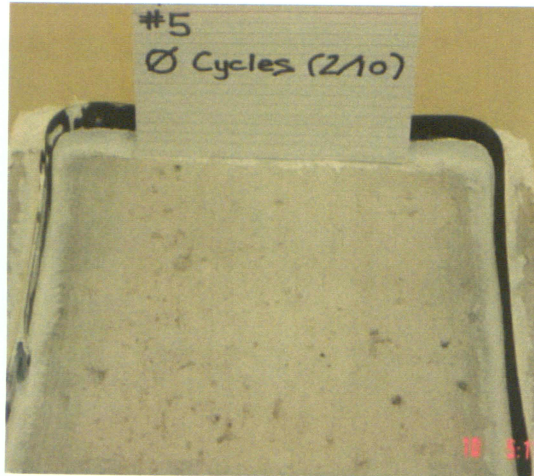
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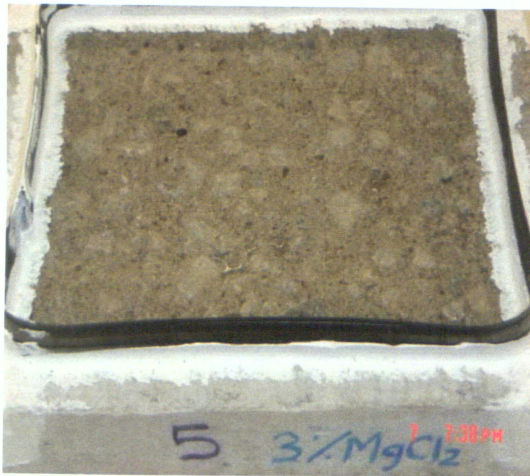
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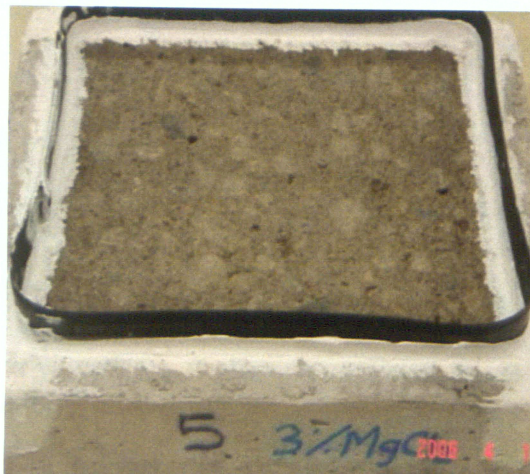
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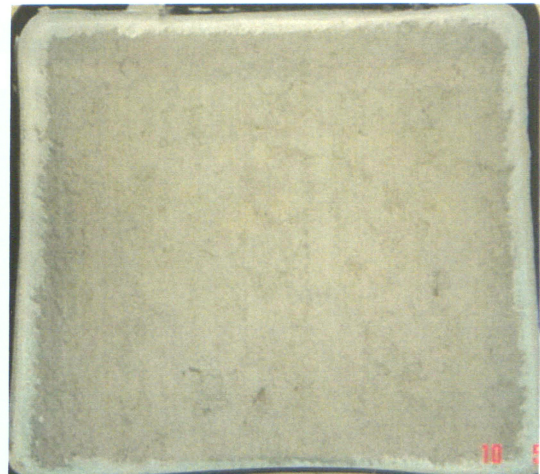
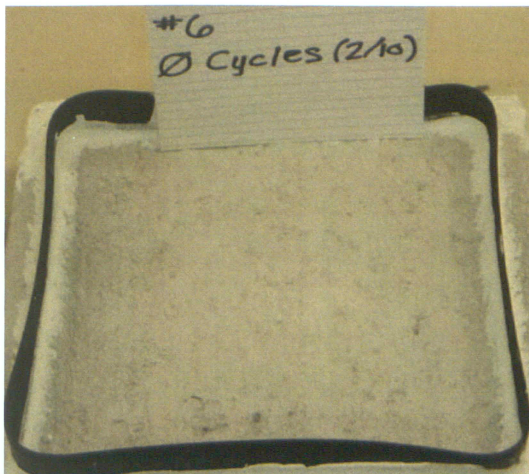
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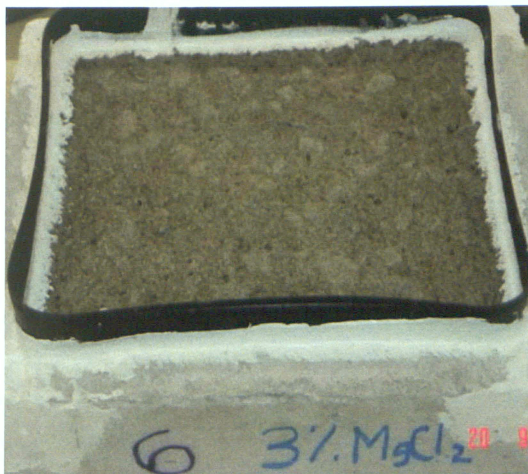
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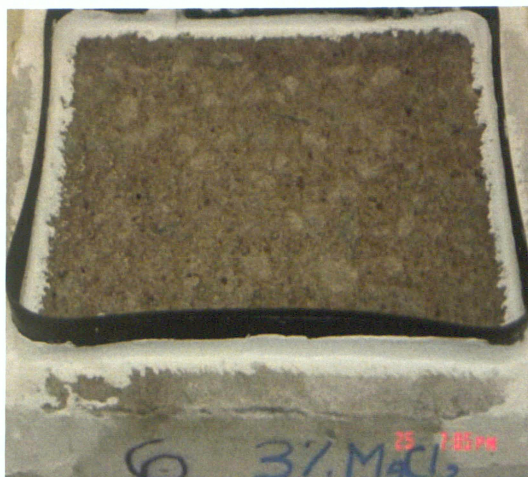
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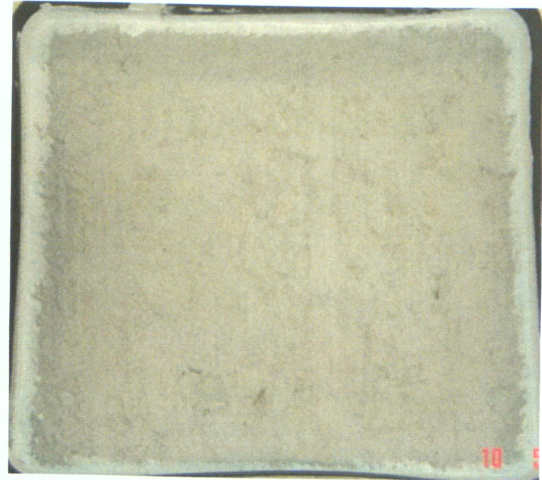
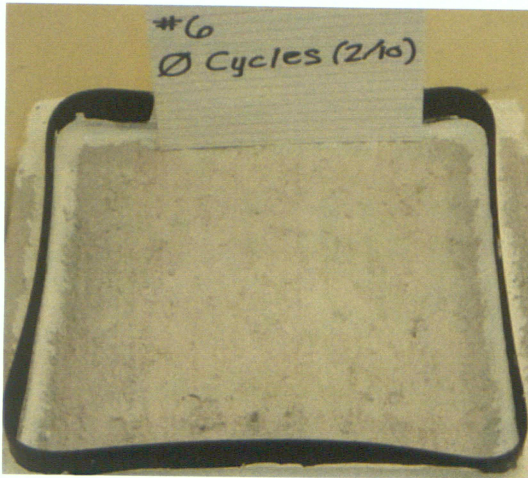
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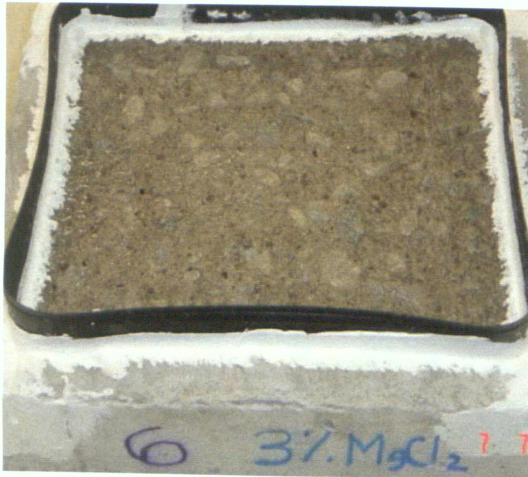
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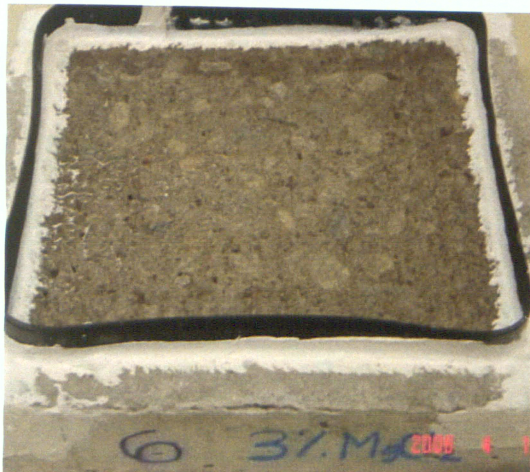
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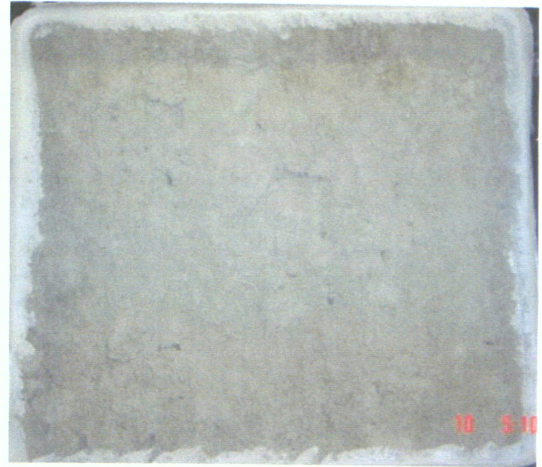
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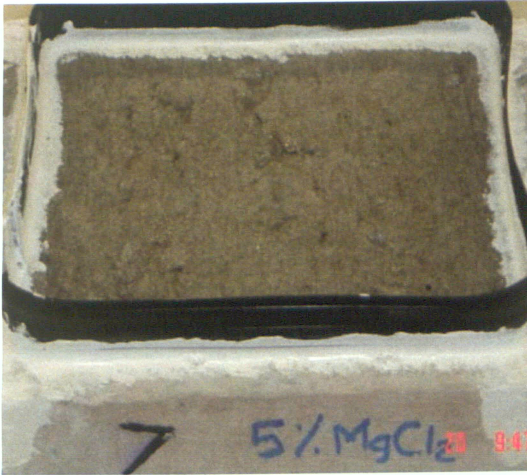
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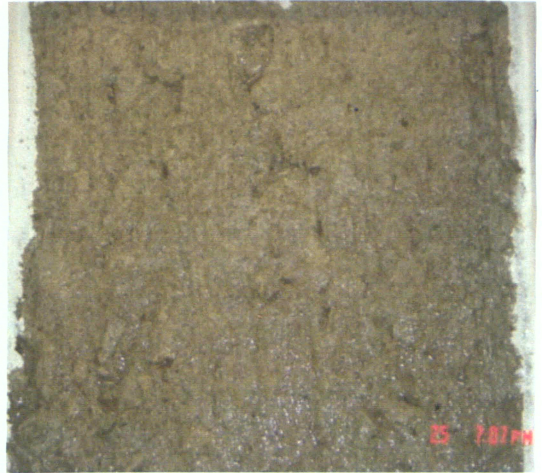
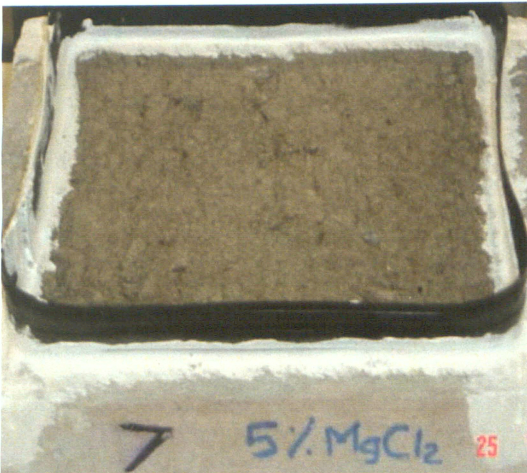
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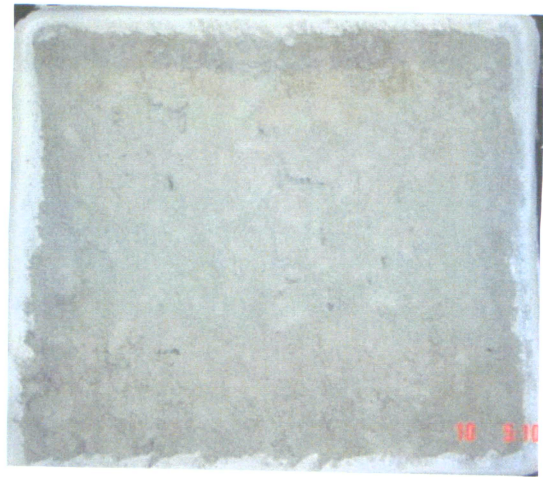
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*15 cycles*



5% MgCl<sub>2</sub> – Slab 7



*0 cycles*



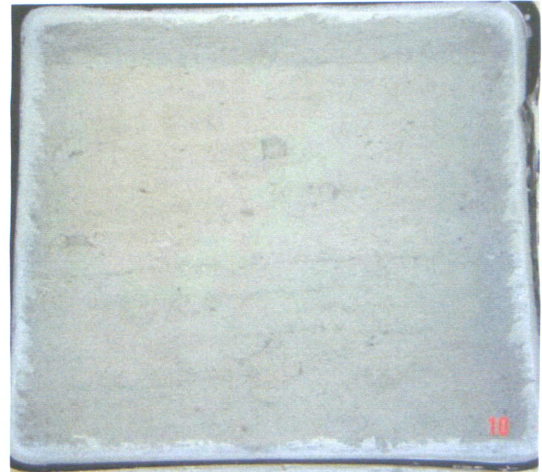
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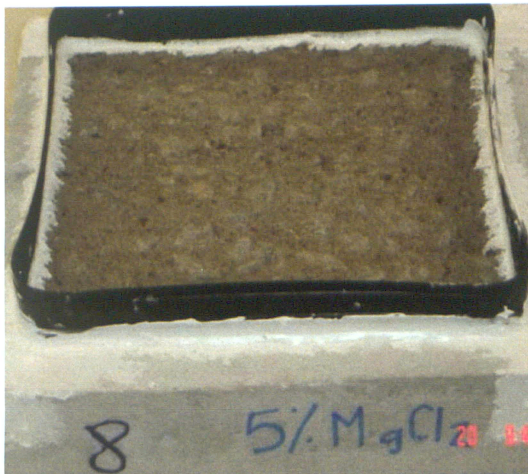
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5%MgCl<sub>2</sub> – Slab 8



*0 cycles*



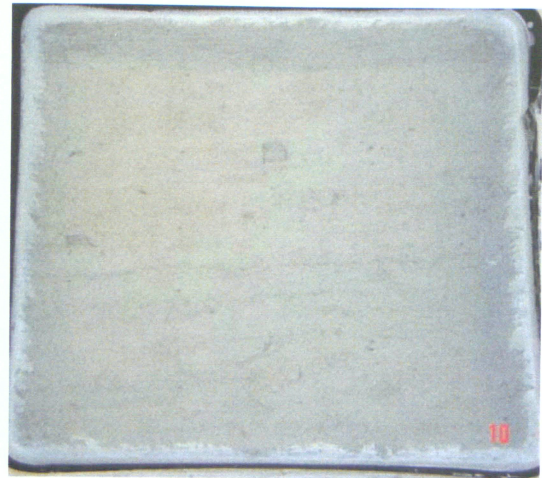
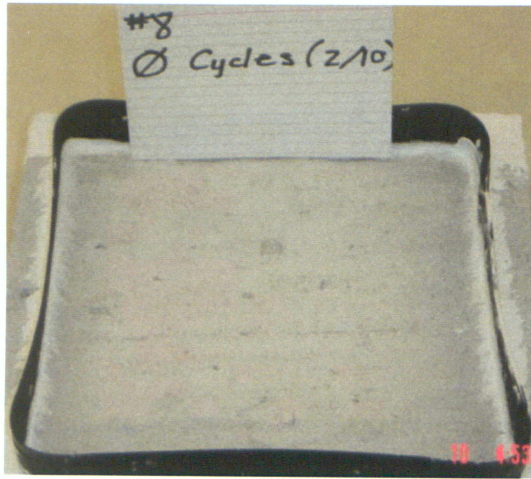
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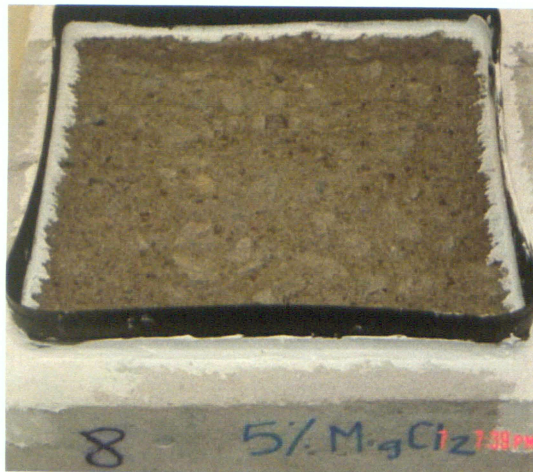
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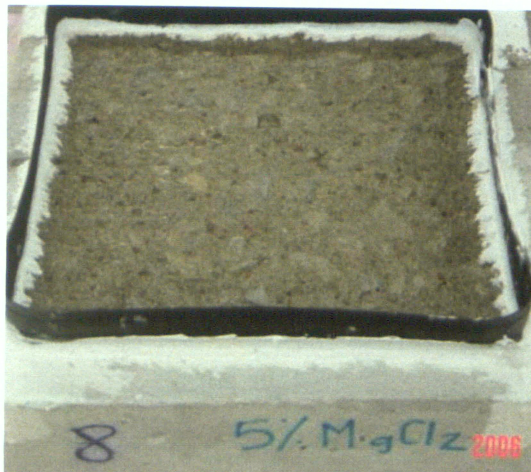
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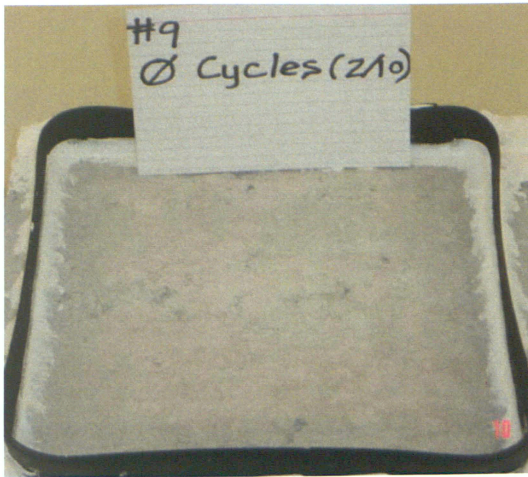
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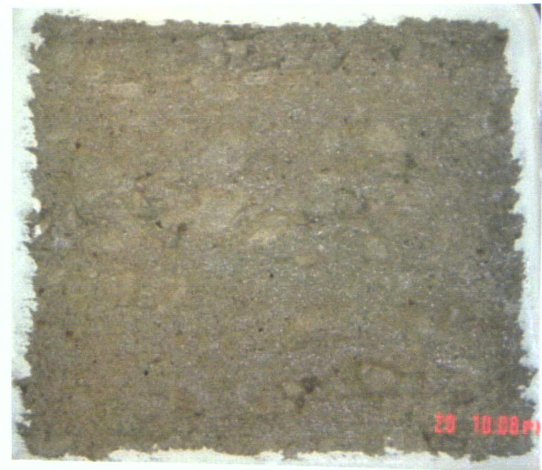
*50 cycles*



10% MgCl<sub>2</sub> – Slab 9



*0 cycles*



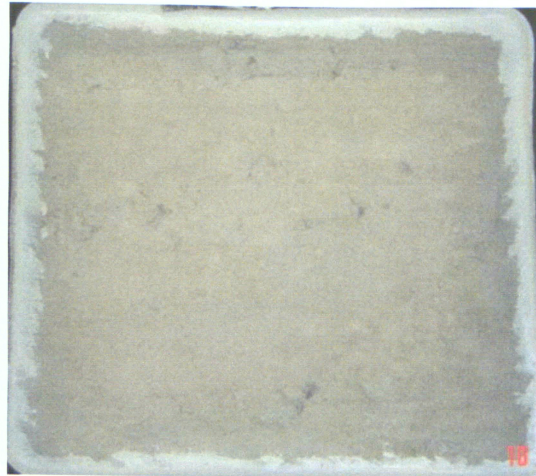
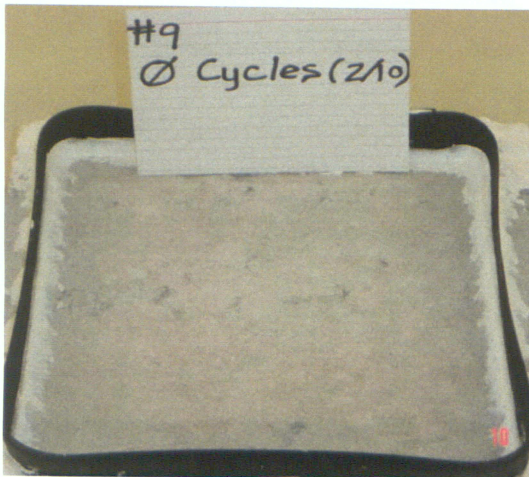
*10 cycles*



*15 cycles*



10%MgCl<sub>2</sub> – Slab 9



*0 cycles*



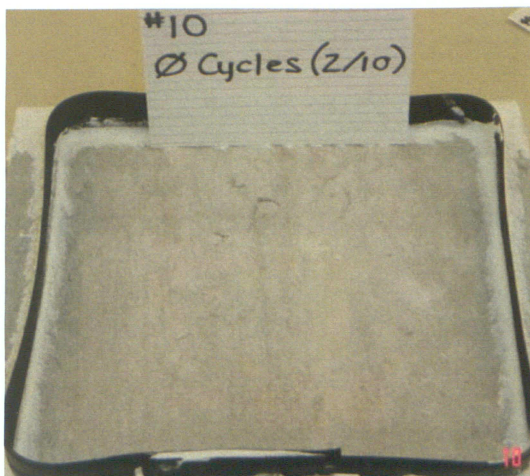
*25 cycles*



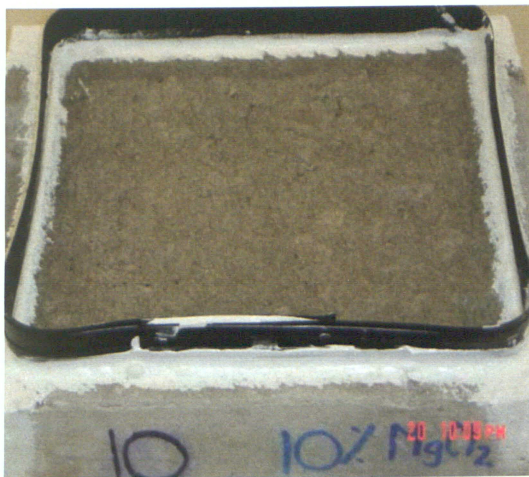
*50 cycles*



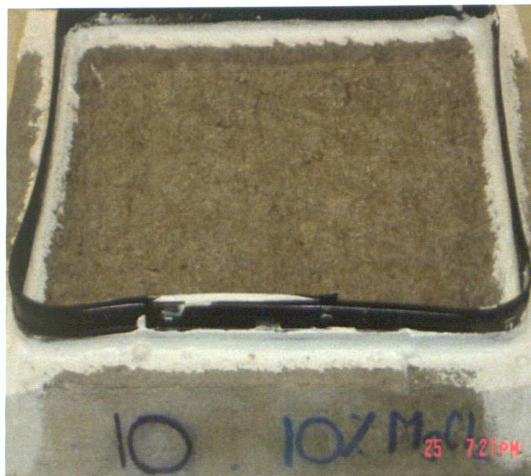
10%MgCl<sub>2</sub> – Slab 10



*0 cycles*



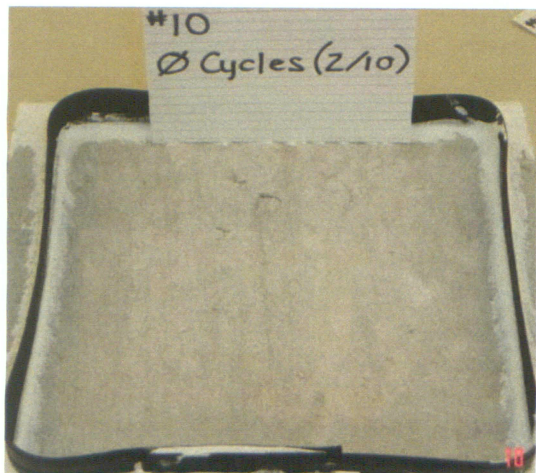
*10 cycles*



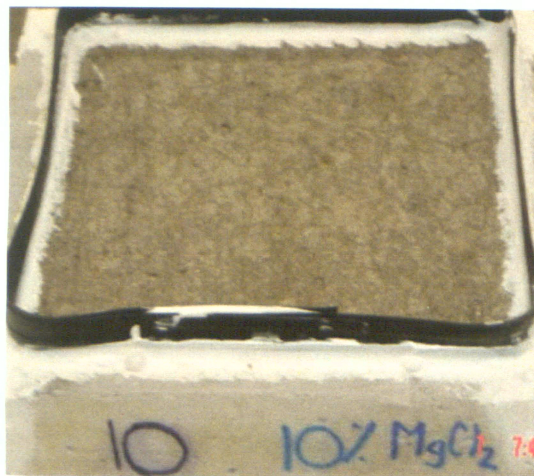
*15 cycles*



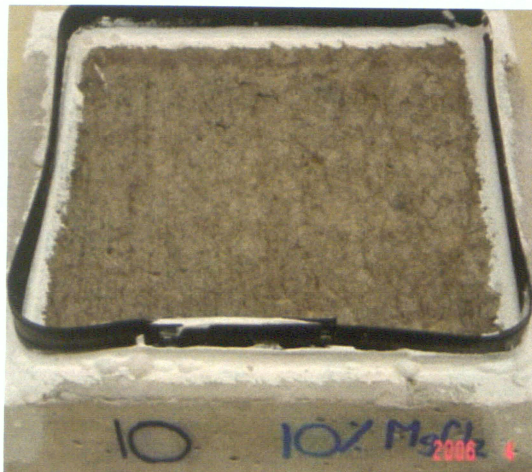
10%MgCl<sub>2</sub> – Slab 10



*0 cycles*



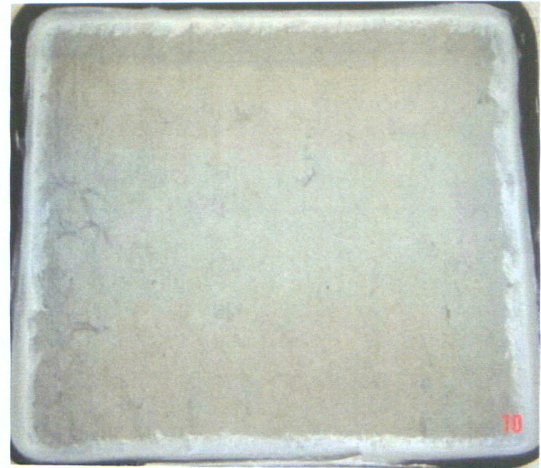
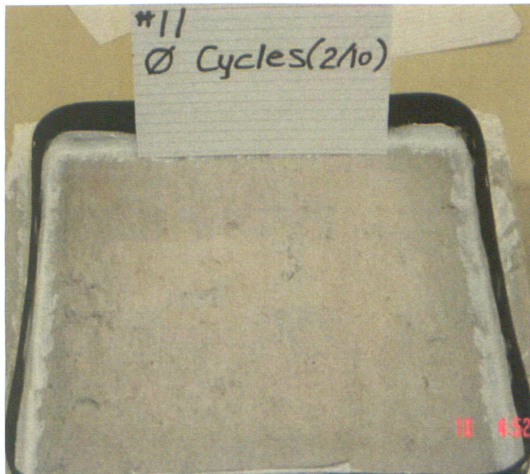
*25 cycles*



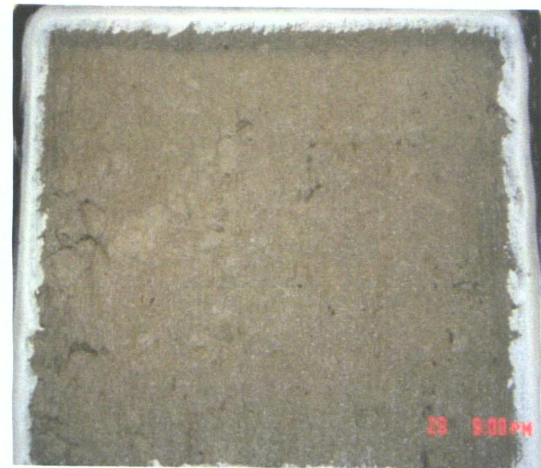
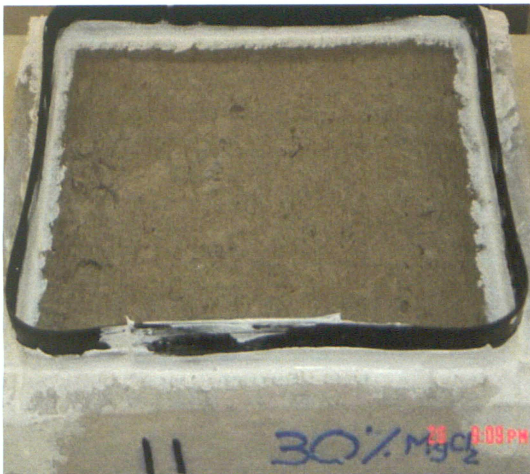
*50 cycles*



30%MgCl<sub>2</sub> – Slab 11



*0 cycles*



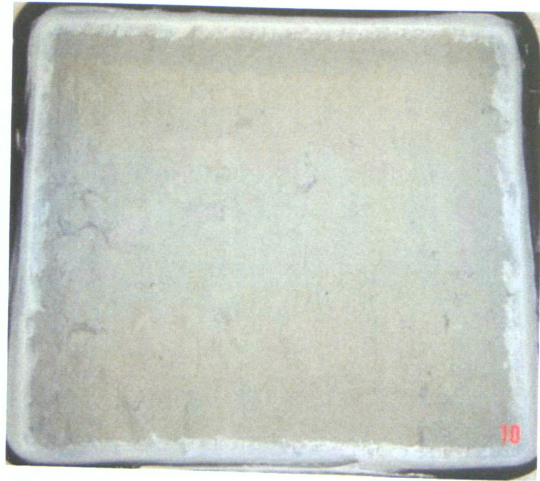
*10 cycles*



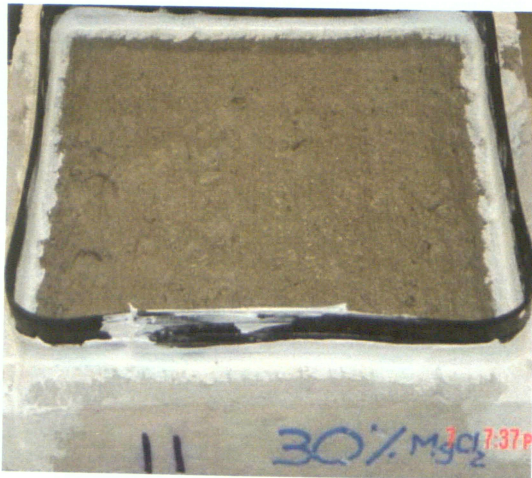
*15 cycles*



30% MgCl<sub>2</sub> – Slab 11



*0 cycles*



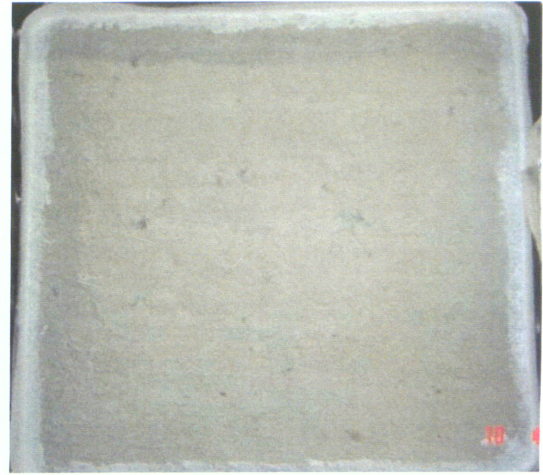
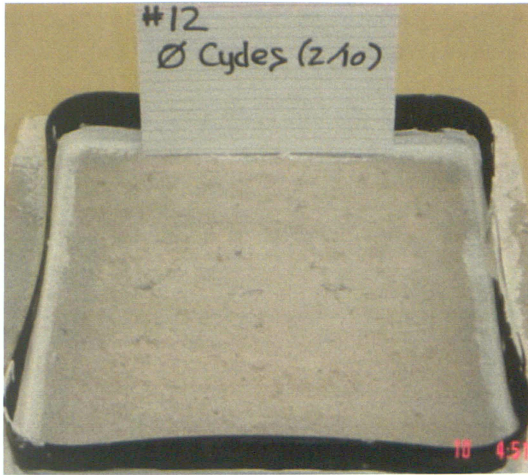
*25 cycles*



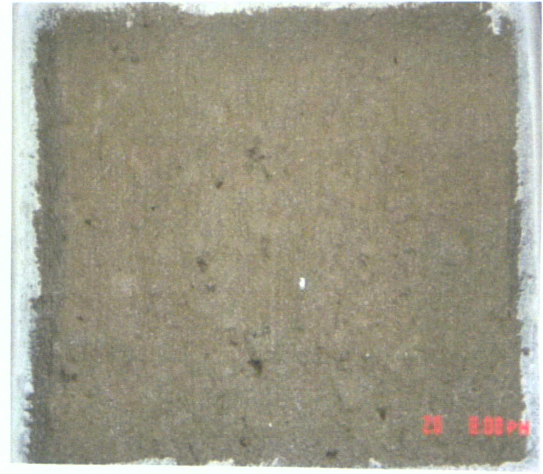
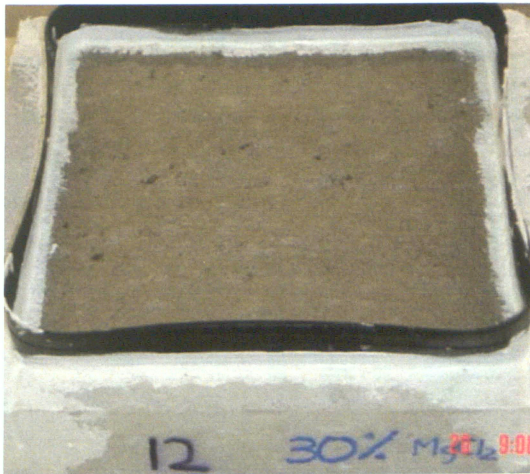
*50 cycles*



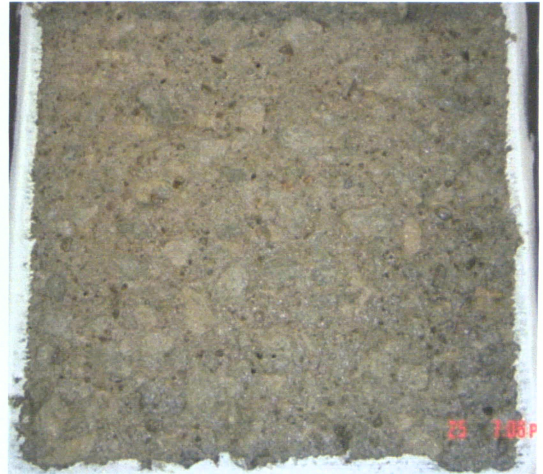
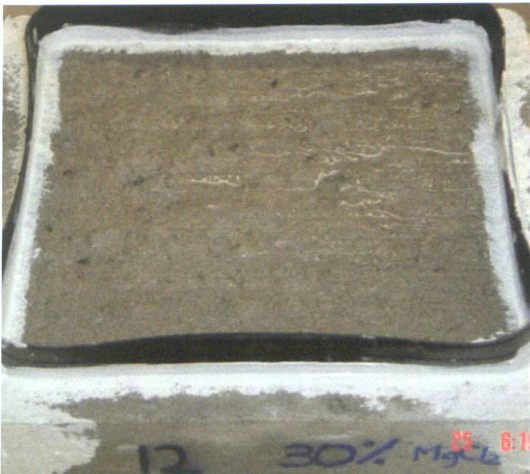
30%MgCl<sub>2</sub> – Slab 12



*0 cycles*



*10 cycles*



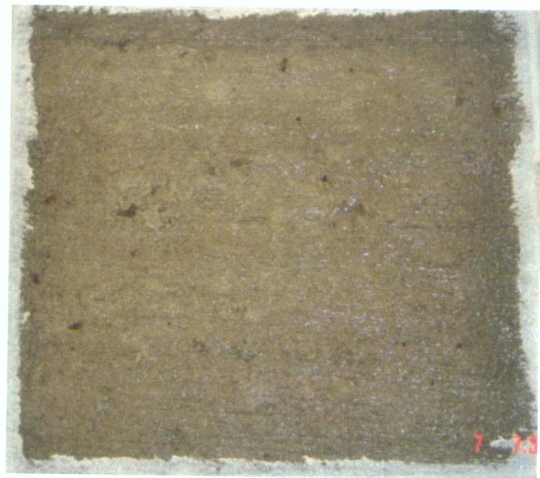
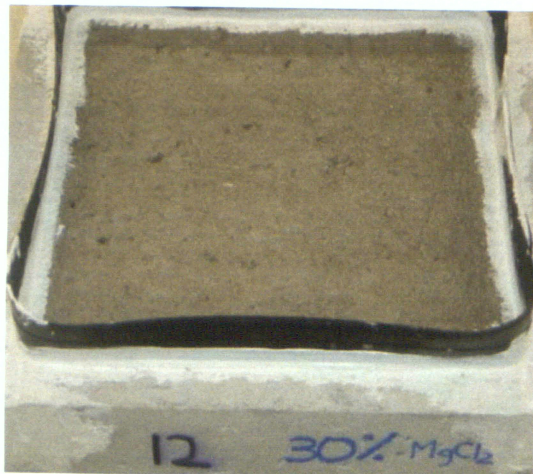
*15 cycles*



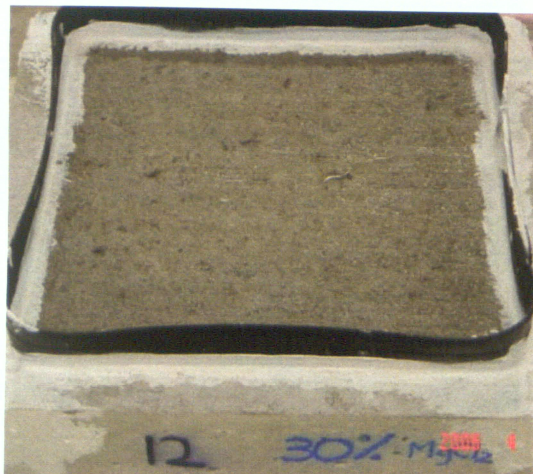
30%MgCl<sub>2</sub> – Slab 12



*0 cycles*



*25 cycles*



*50 cycles*



## APPENDIX D

# Appendix D - Phase 2 Sealing Resistance Data (as per modified\* MTO LS412)

\*The lower temperature limit was lowered from -18degC to -50degC to ensure magnesium chloride solutions would freeze.

# Cycles	Cumulative Mass Loss (kg/m <sup>2</sup> )														
	3N(50)3M(50) P2(I)	3N(50)30M(50)P2 (2)	3N(50)P2(13,14)			3N(25)3M(25)P2(15,16)			3N(25)5M(25)P2(17,18)			3N(25)10M(25)P2(19,20)			3N(25)30M(25)P2(21,22)
Slab #	1	2	13	14	15	16	17	18	19	20	21	22	23	24	25
5	3.80	2.95	1.30	1.51	1.96	1.59	1.99	1.54	1.86	1.55	1.56	2.04			
10	3.82	3.04	1.53	1.79	2.28	1.90	2.33	1.88	2.19	1.84	1.86	2.09			
15	3.82	3.05	1.63	1.90	2.39	2.01	2.43	1.99	2.30	1.95	1.96	2.20			
20	3.83	3.05	1.73	2.01	2.49	2.11	2.54	2.09	2.40	2.05	2.07	2.30			
25	3.84	3.06	1.83	2.11	2.60	2.21	2.65	2.20	2.51	2.16	2.17	2.40			
30	3.85	3.07	1.94	2.21	2.70	2.23	2.69	2.26	2.53	2.18	2.21	2.42			
35	3.86	3.08	2.05	2.33	2.71	2.24	2.70	2.27	2.54	2.19	2.22	2.43			
40	3.87	3.09	2.18	2.44	2.72	2.25	2.71	2.28	2.55	2.20	2.23	2.44			
45	3.88	3.10	2.40	2.64	2.73	2.26	2.72	2.29	2.56	2.21	2.24	2.45			
50	3.89	3.11	2.61	2.84	2.74	2.27	2.73	2.30	2.57	2.22	2.25	2.46			
AVG	3.89	3.11	2.72			2.51			2.51			2.39			2.36
AVG	0.15	0.17	-	-	0.14	0.06	0.08	0.10	0.06	0.06	0.08	0.06	0.07	0.08	0.06

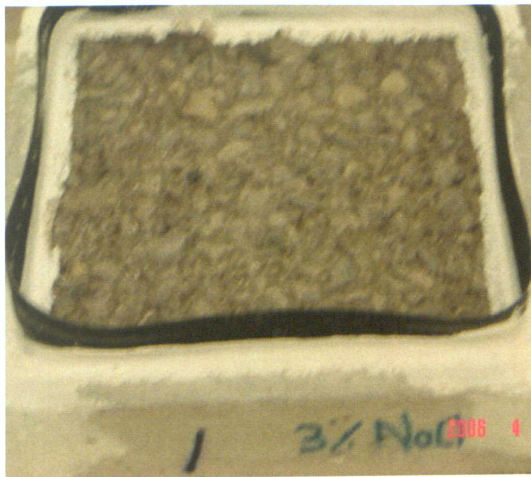
\*Results are cumulative including Phase 1 mass loss

\*\*For A1&A2 - Phase 2 mass loss only; For C15, C16, C17, C18, D19, D20, D21 & D22 - Final 25 cycles mass loss

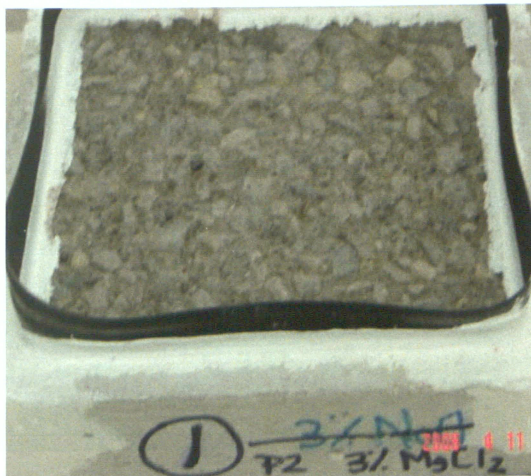


Appendix D – Phase 2 Freeze/Thaw Slabs

3%NaCl (50 cycles, Phase 1) & 3%MgCl<sub>2</sub> (50 cycles, Phase 2) – Slab 1



*0 cycles*



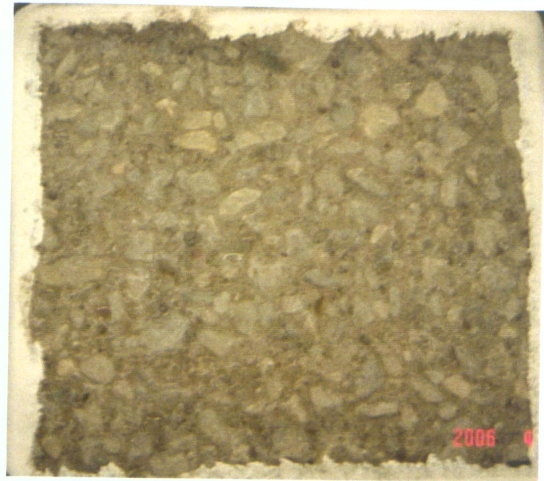
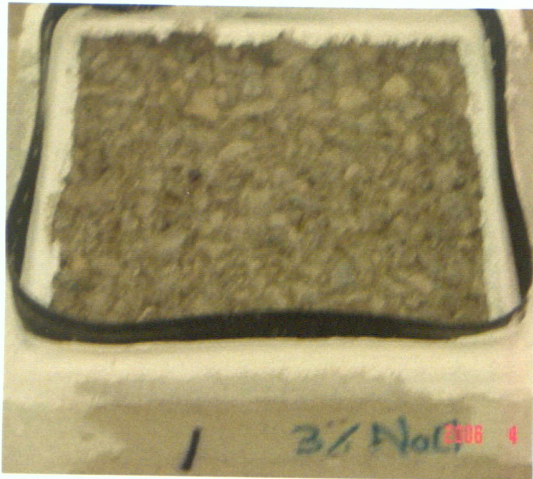
*10 cycles*



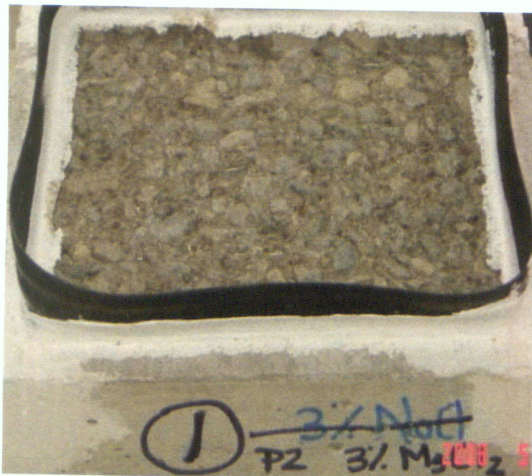
*15 cycles*



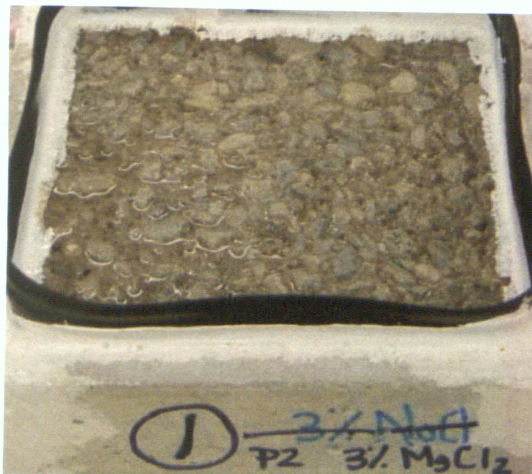
3%NaCl (50 cycles, Phase 1) & 3%MgCl<sub>2</sub> (50 cycles, Phase 2) – Slab 1



0 cycles



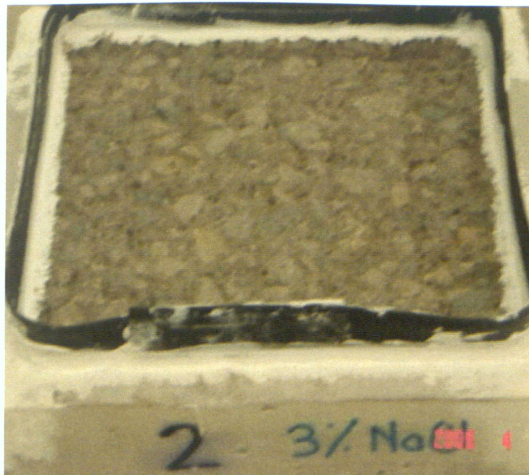
25 cycles



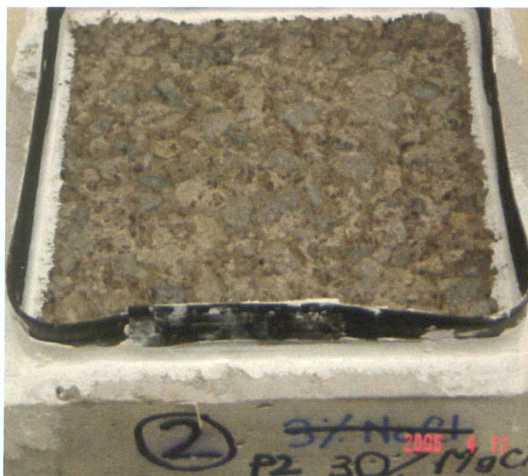
50 cycles



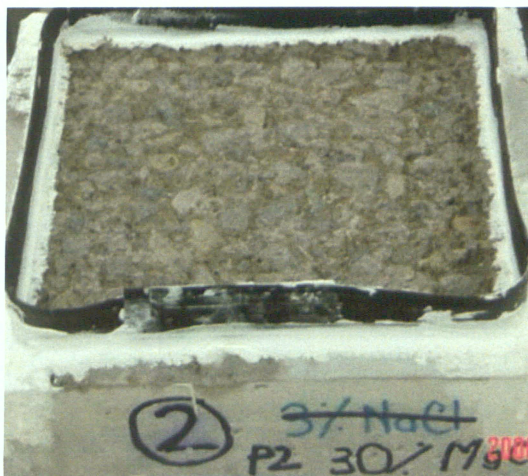
3%NaCl (50 cycles, Phase 1) & 30%MgCl<sub>2</sub> (50 cycles, Phase 2) – Slab 2



*0 cycles*



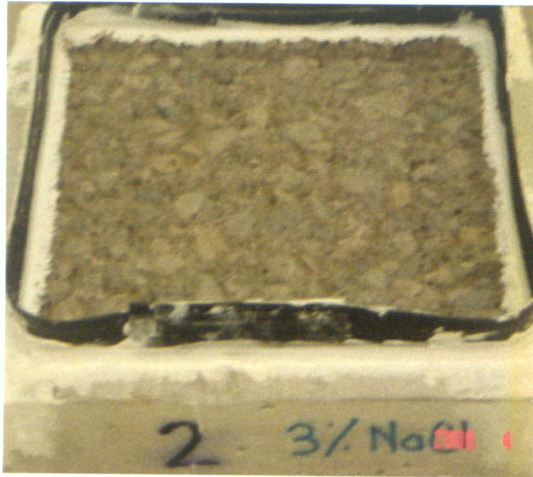
*10 cycles*



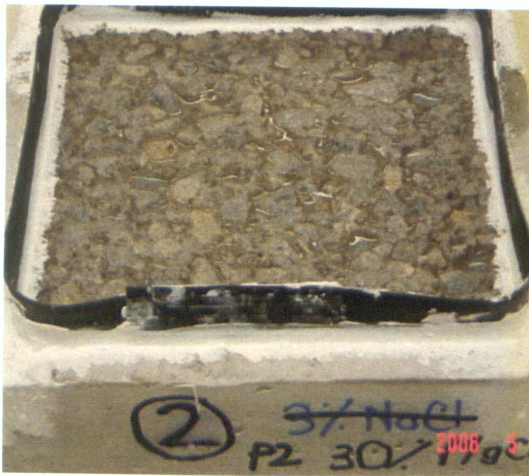
*15 cycles*



3%NaCl (50 cycles, Phase 1) & 30%MgCl<sub>2</sub> (50 cycles, Phase 2) – Slab 2



*0 cycles*



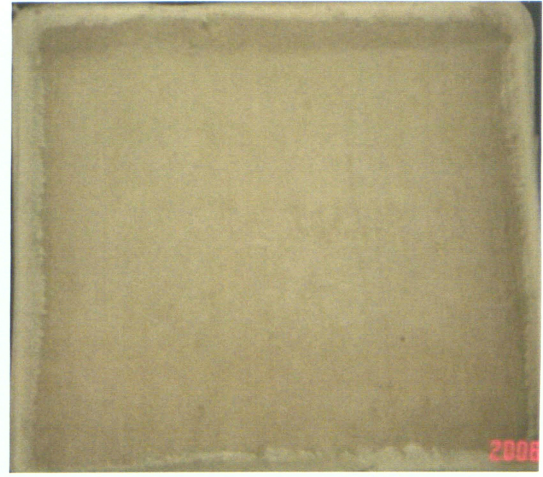
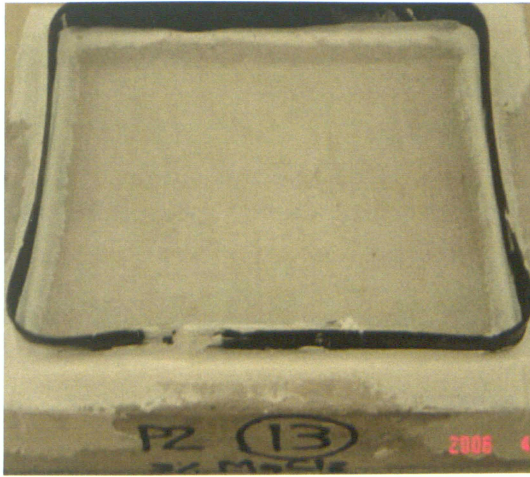
*25 cycles*



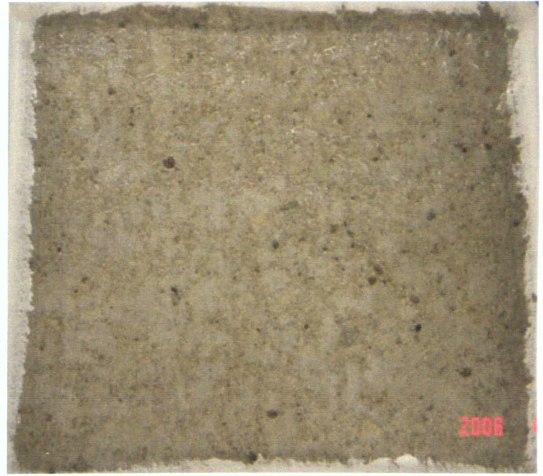
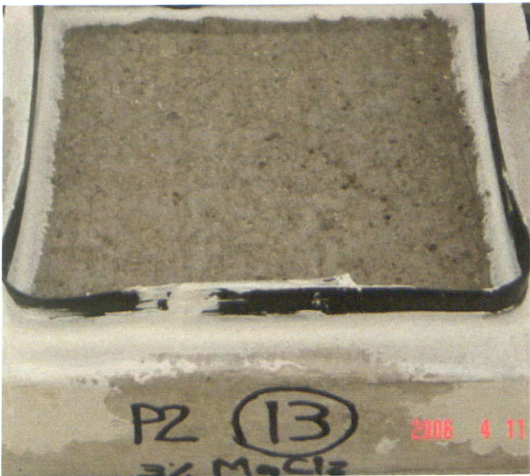
*50 cycles*



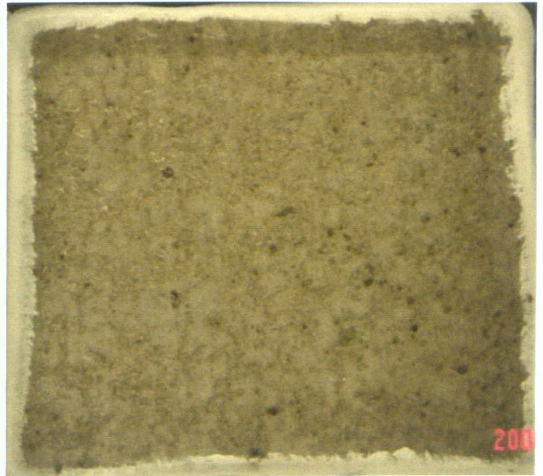
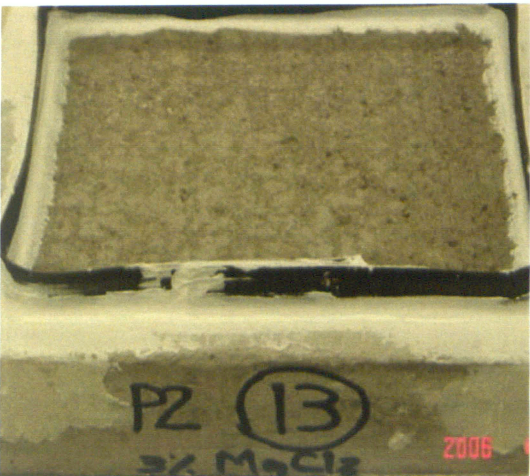
3%NaCl (25 cycles) & 3%MgCl<sub>2</sub> (25 cycles) – Slab 13



*0 cycles*



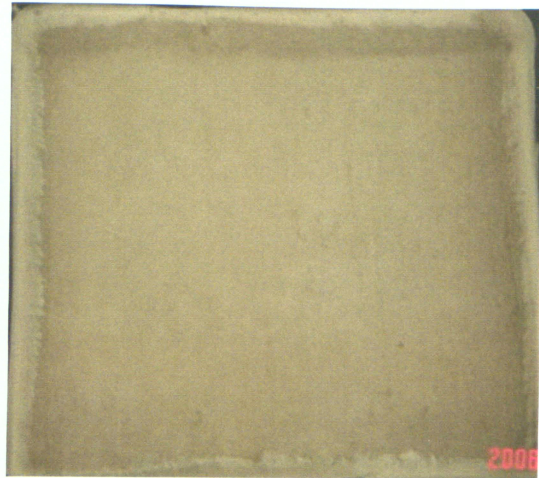
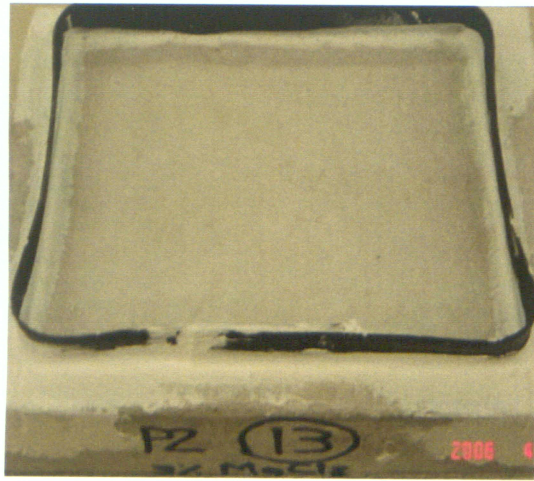
*10 cycles*



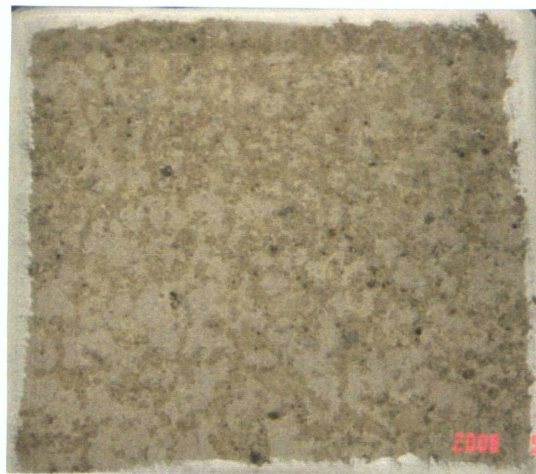
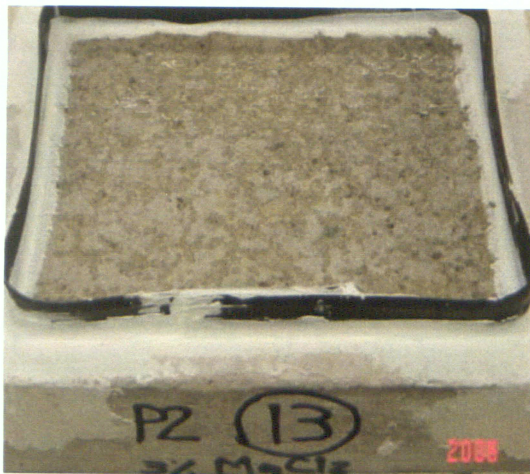
*15 cycles*



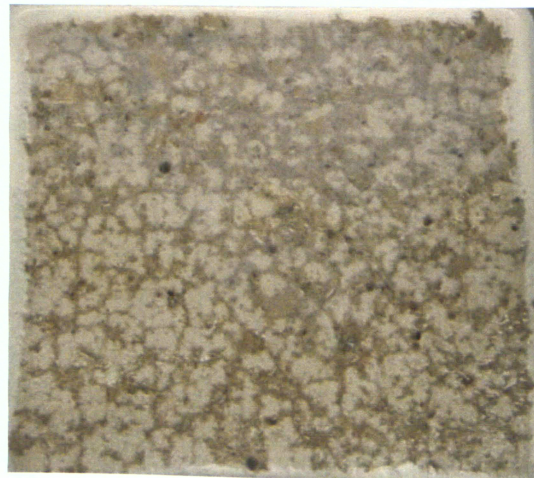
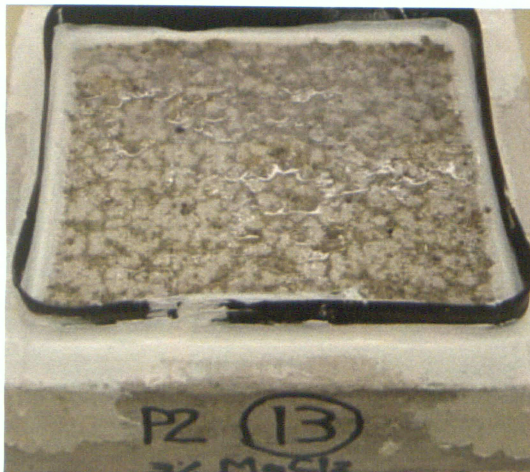
3%NaCl (25 cycles) & 3%MgCl<sub>2</sub> (25 cycles) – Slab 13



*0 cycles*



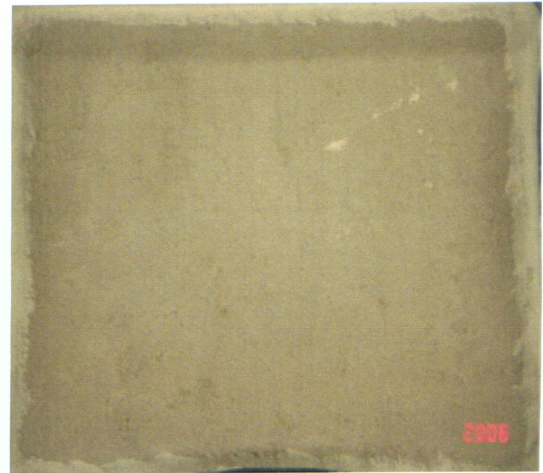
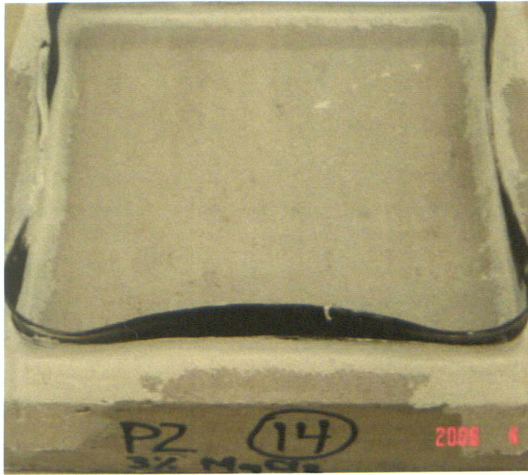
*25 cycles*



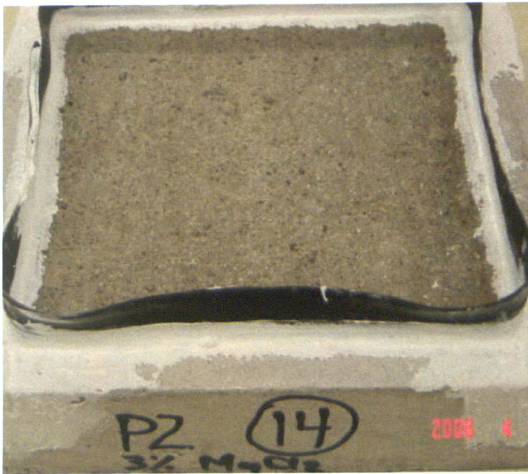
*50 cycles*



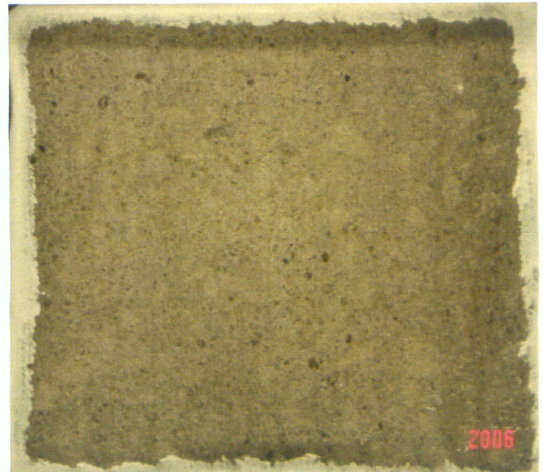
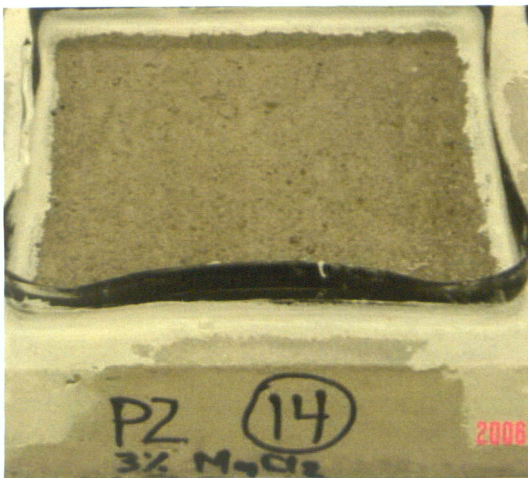
3%NaCl (25 cycles) & 3%MgCl<sub>2</sub> (25 cycles) – Slab 14



*0 cycles*



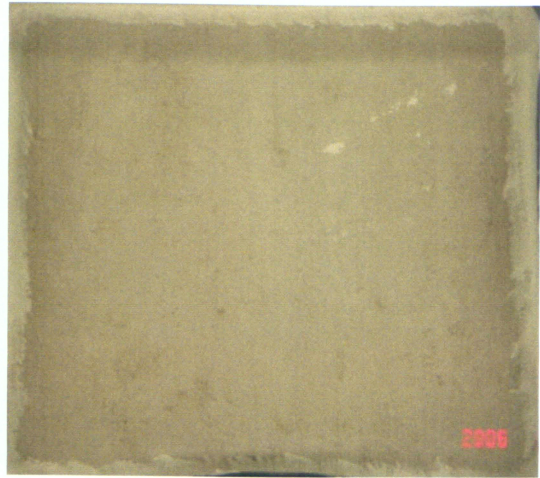
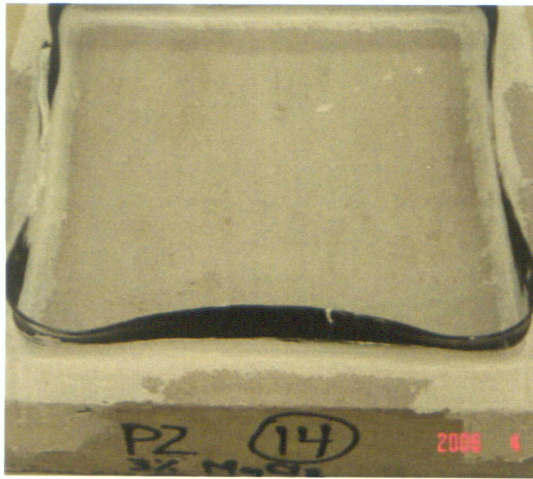
*10 cycles*



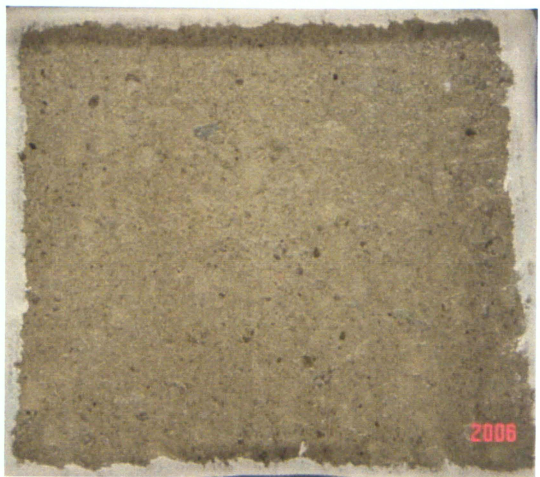
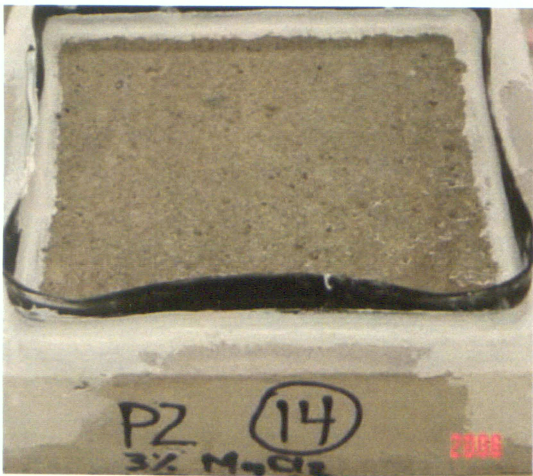
*15 cycles*



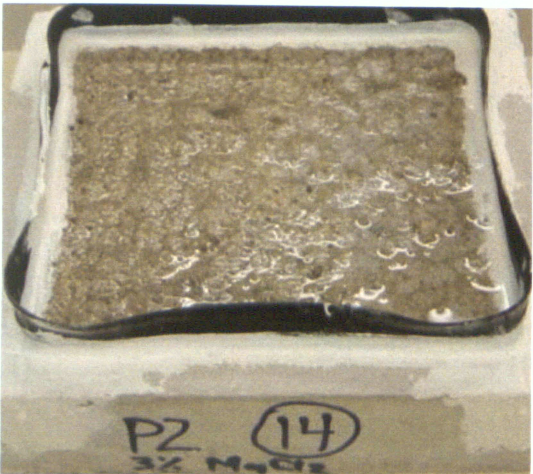
3%NaCl (25 cycles) & 3%MgCl<sub>2</sub> (25 cycles) – Slab 14



*0 cycles*



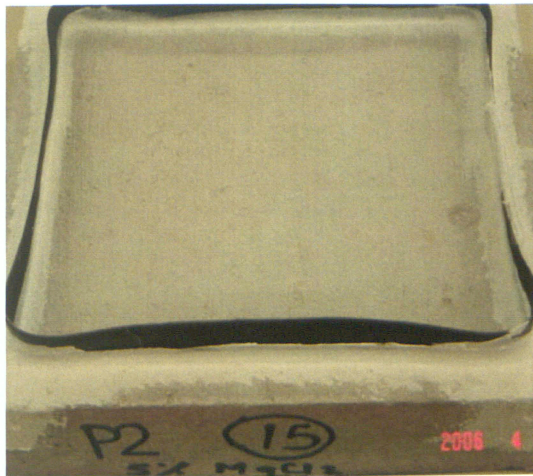
*25 cycles*



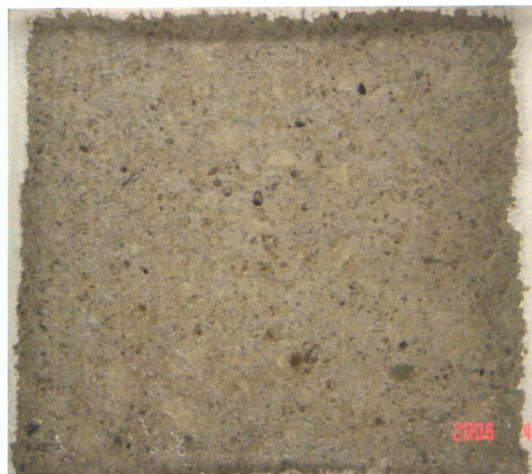
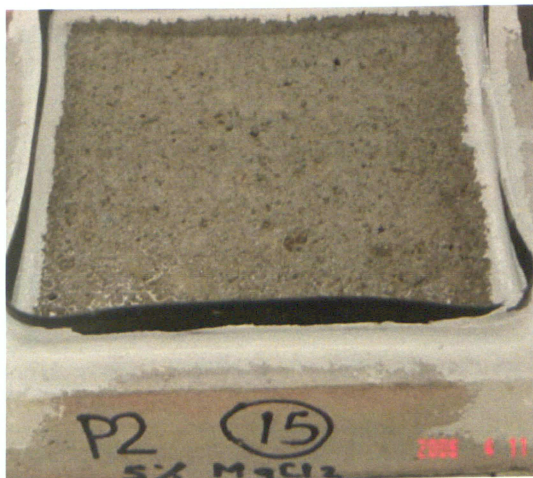
*50 cycles*



3%NaCl (25 cycles) & 5%MgCl<sub>2</sub> (25 cycles) – Slab 15



*0 cycles*



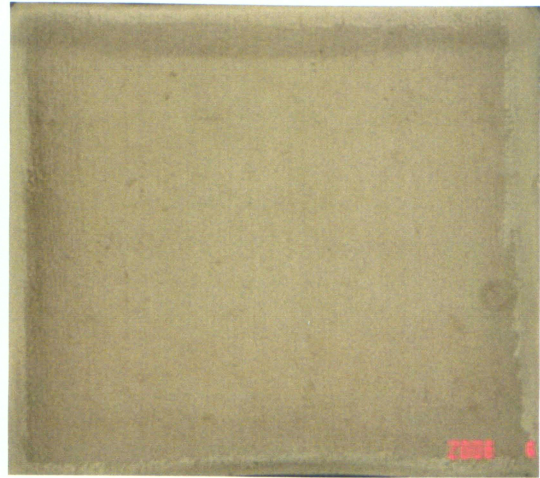
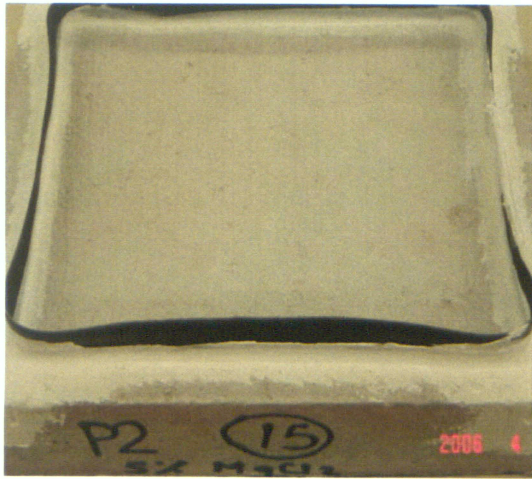
*10 cycles*



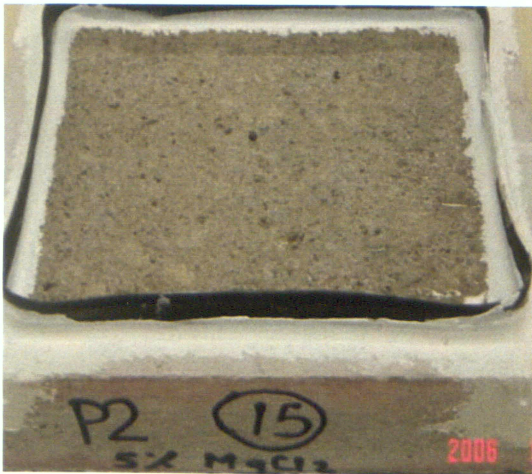
*15 cycles*



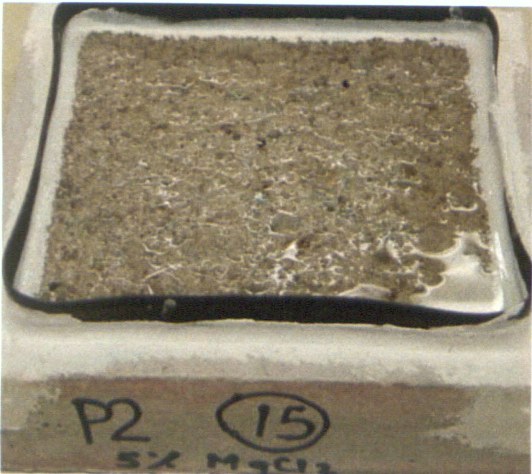
3%NaCl (25 cycles) & 5%MgCl<sub>2</sub> (25 cycles) – Slab 15



*0 cycles*



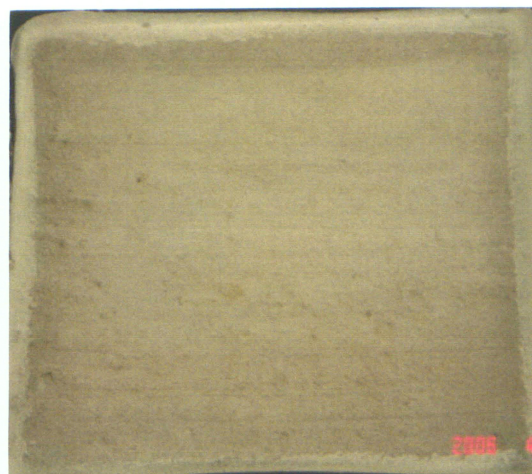
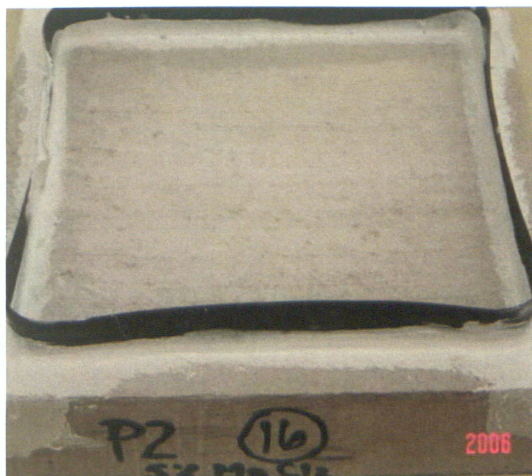
*25 cycles*



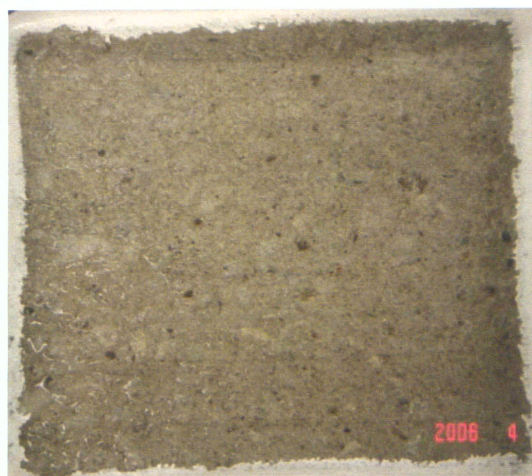
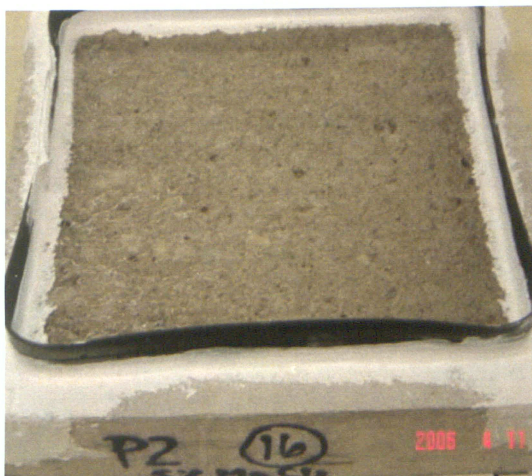
*50 cycles*



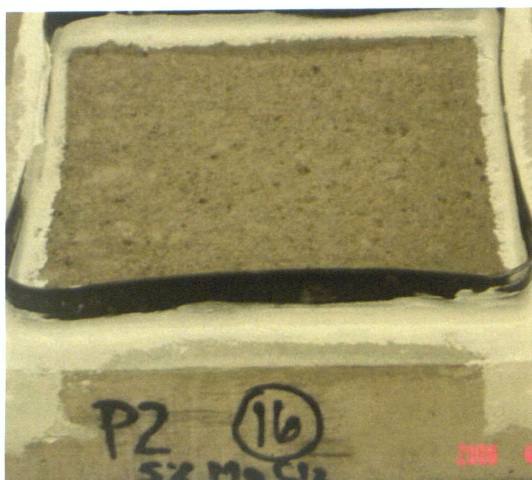
3%NaCl (25 cycles) & 5%MgCl<sub>2</sub> (25 cycles) – Slab 16



*0 cycles*



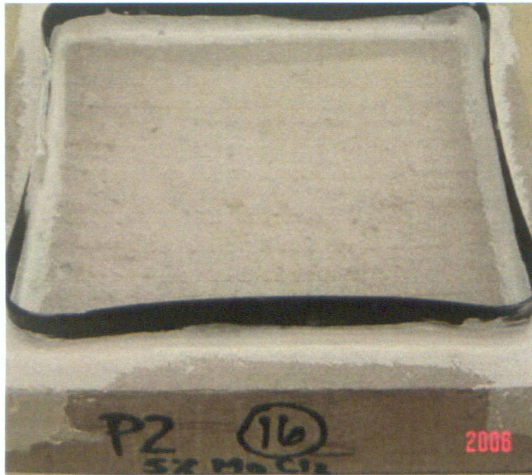
*10 cycles*



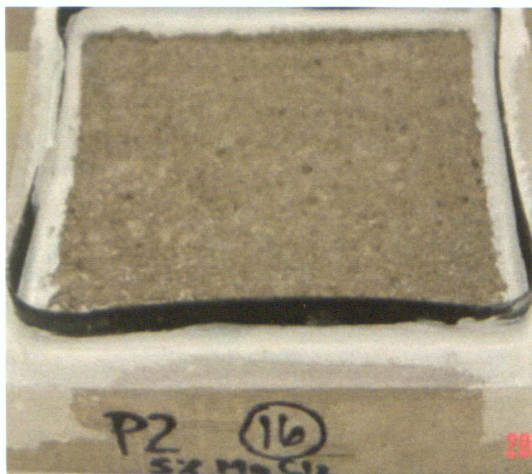
*15 cycles*



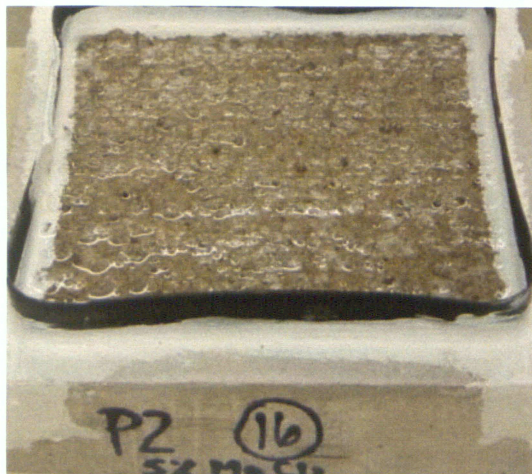
3%NaCl (25 cycles) & 5%MgCl<sub>2</sub> (25 cycles) – Slab 16



*0 cycles*



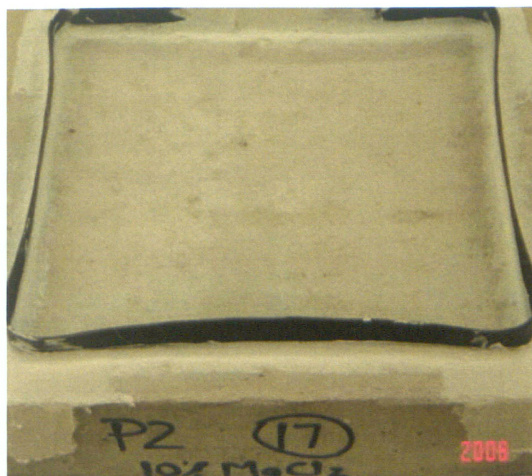
*25 cycles*



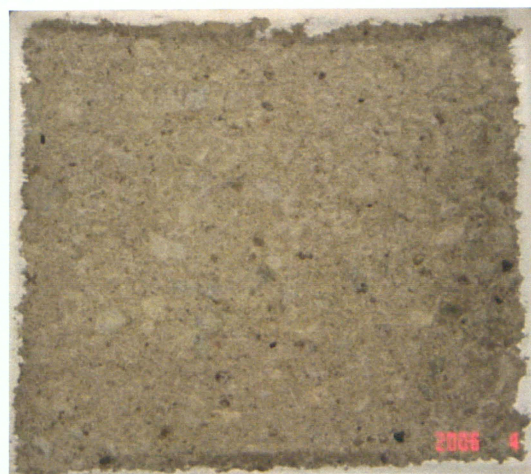
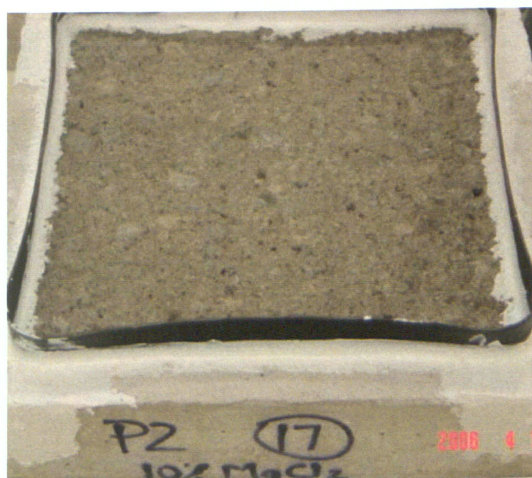
*50 cycles*



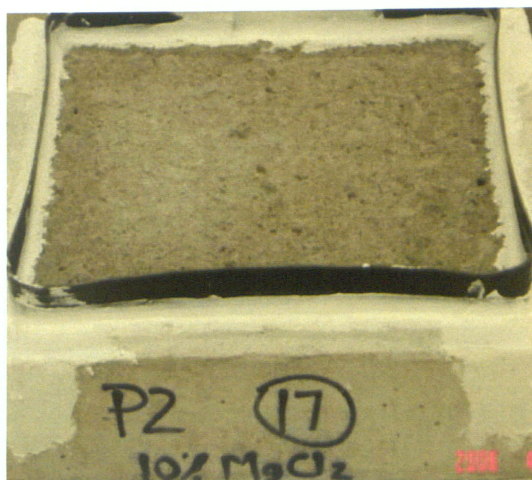
3%NaCl (25 cycles) & 10%MgCl<sub>2</sub> (25 cycles) – Slab 17



*0 cycles*



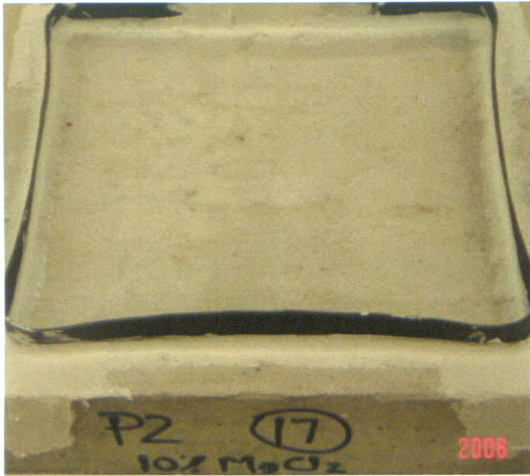
*10 cycles*



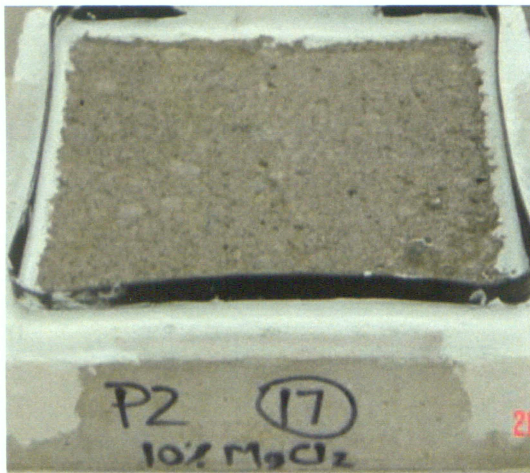
*15 cycles*



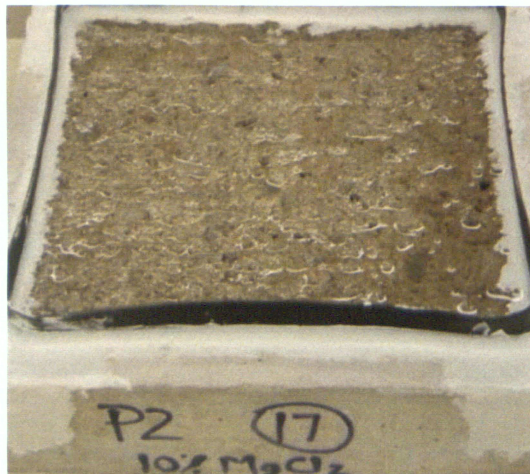
3%NaCl (25 cycles) & 10%MgCl<sub>2</sub> (25 cycles) – Slab 17



*0 cycles*



*25 cycles*



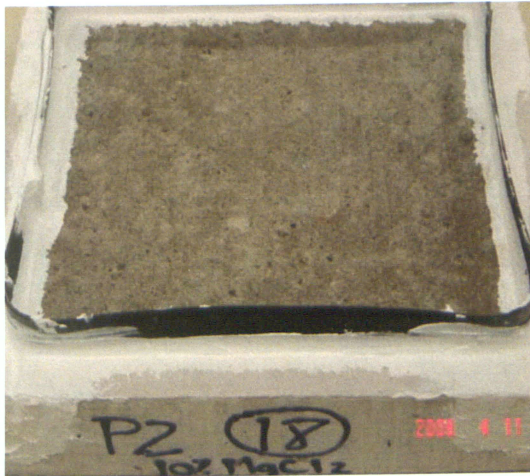
*50 cycles*



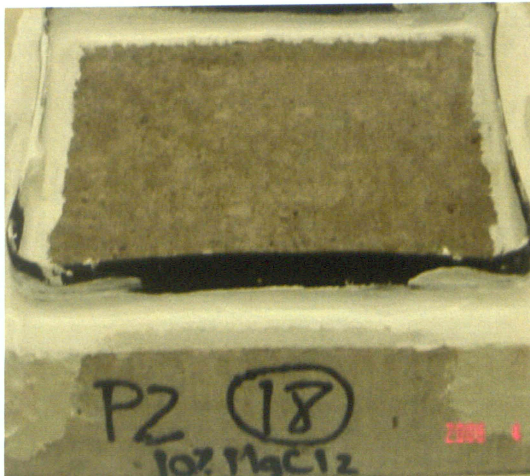
3%NaCl (25 cycles) & 10%MgCl<sub>2</sub> (25 cycles) – Slab 18



*0 cycles*



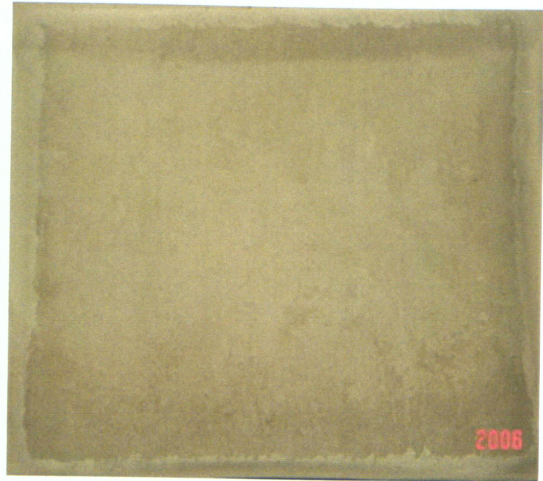
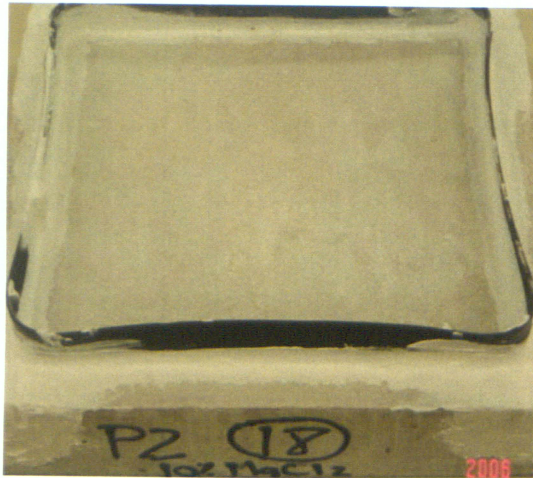
*10 cycles*



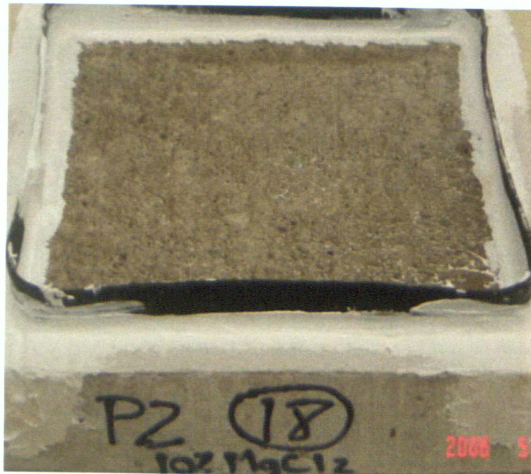
*15 cycles*



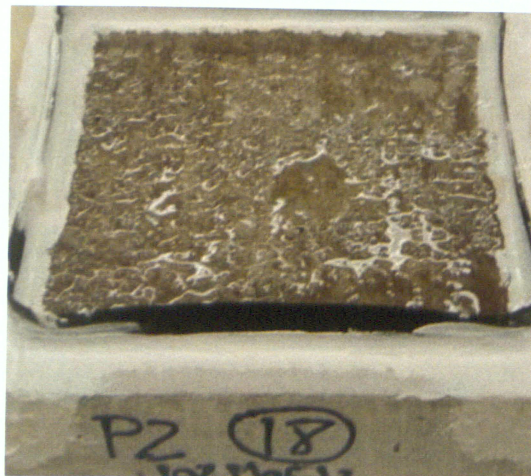
3%NaCl (25 cycles) & 10%MgCl<sub>2</sub> (25 cycles) – Slab 18



*0 cycles*



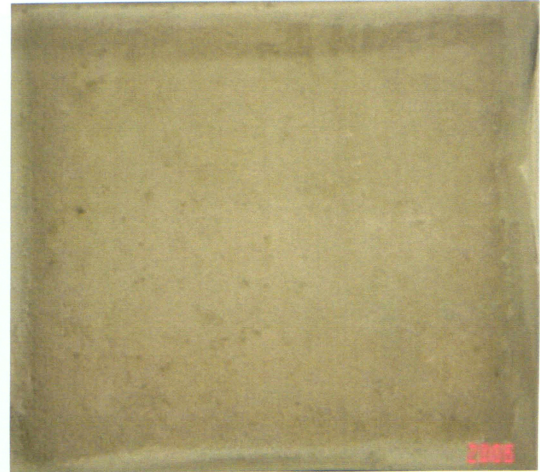
*25 cycles*



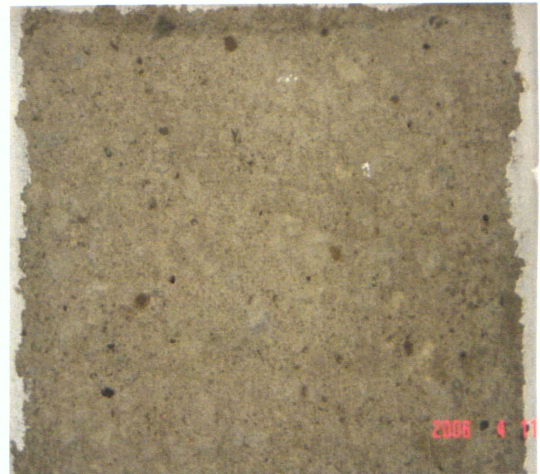
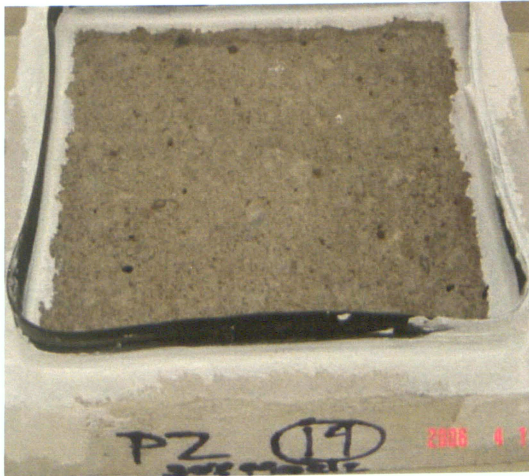
*50 cycles*



3%NaCl (25 cycles) & 30%MgCl<sub>2</sub> (25 cycles) – Slab 19



*0 cycles*



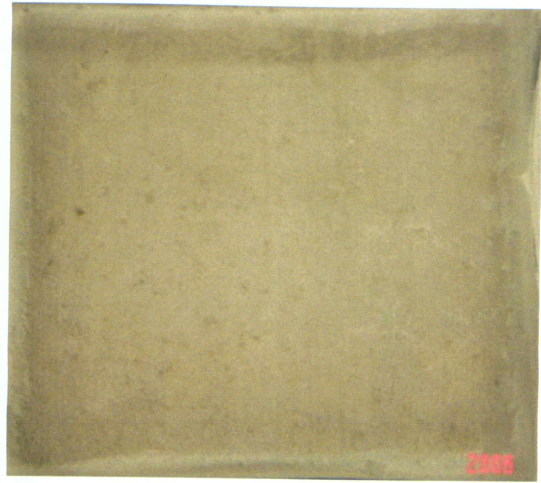
*10 cycles*



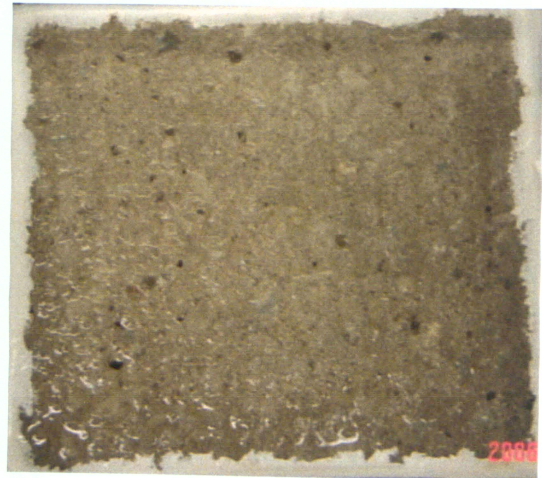
*15 cycles*



3%NaCl (25 cycles) & 30%MgCl<sub>2</sub> (25 cycles) – Slab 19



*0 cycles*



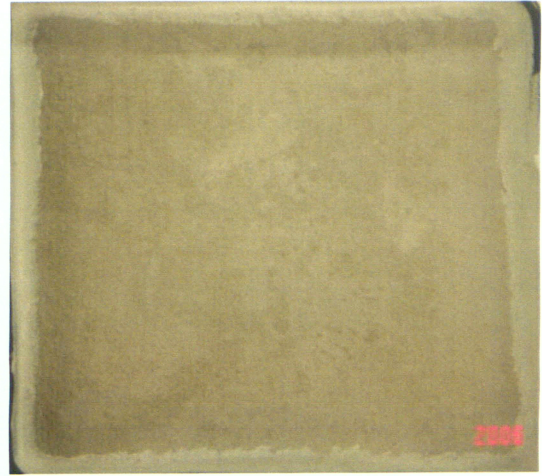
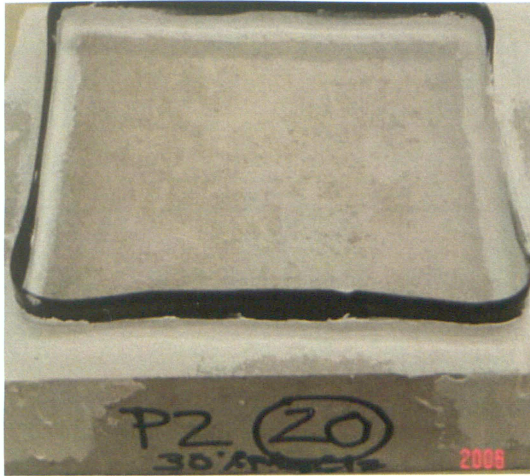
*25 cycles*



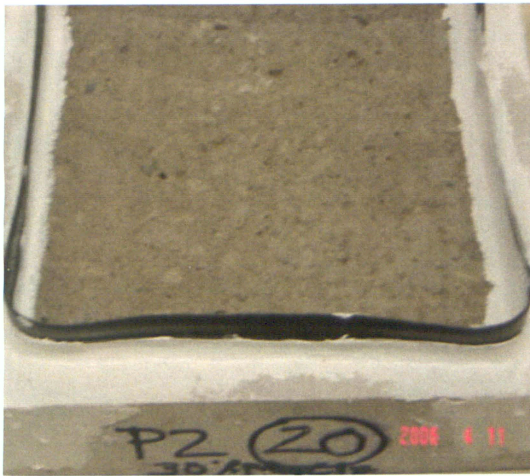
*50 cycles*



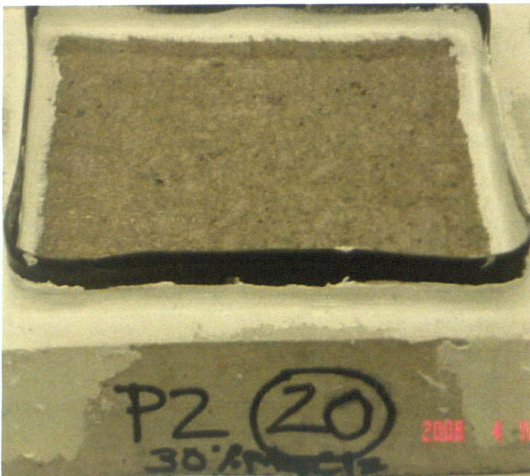
3%NaCl (25 cycles) & 30%MgCl<sub>2</sub> (25 cycles) – Slab 20



*0 cycles*



*10 cycles*



*15 cycles*



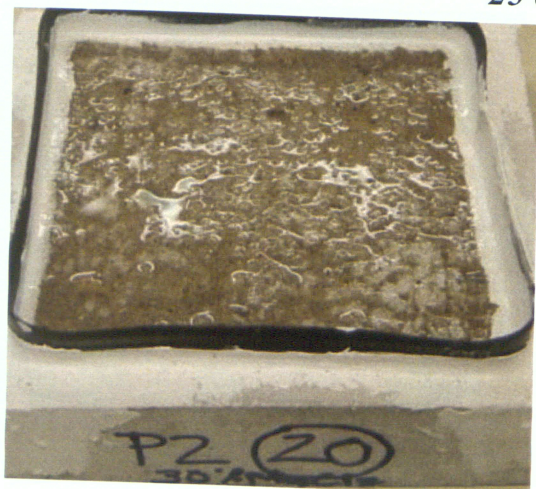
3%NaCl (25 cycles) & 30%MgCl<sub>2</sub> (25 cycles) – Slab 20



*0 cycles*



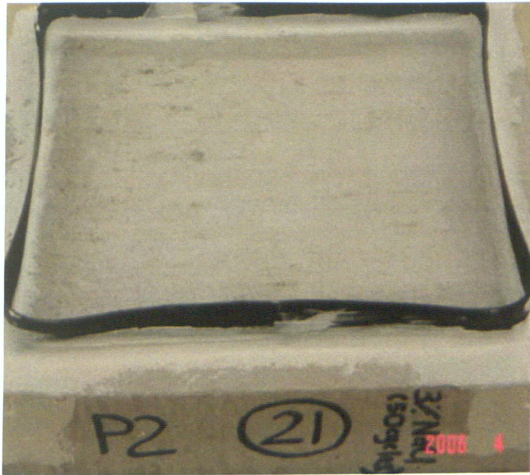
*25 cycles*



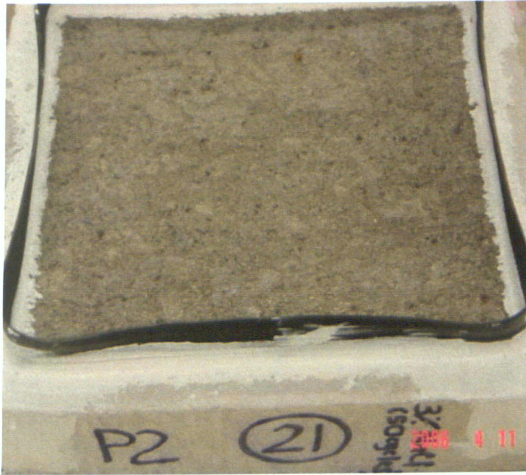
*50 cycles*



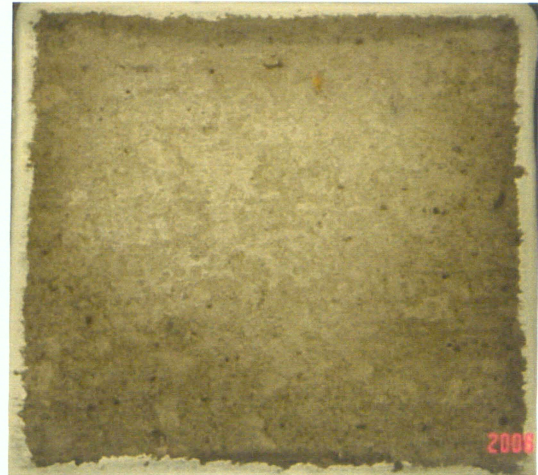
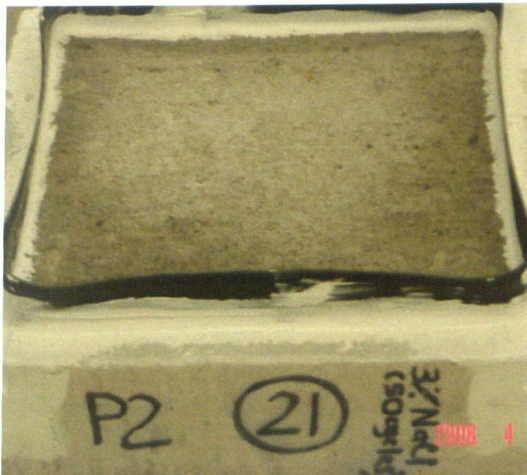
3%NaCl (50 cycles) – Slab 21



*0 cycles*



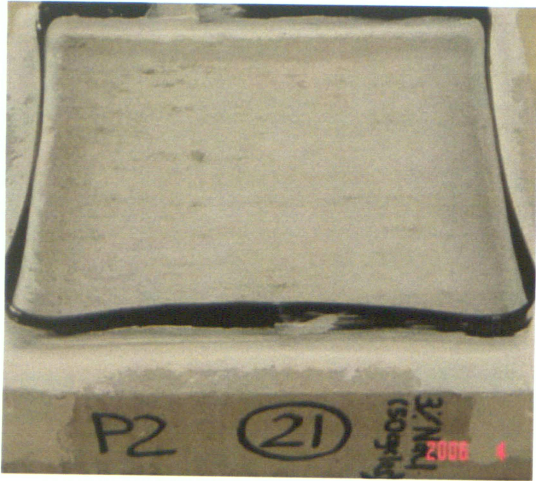
*10 cycles*



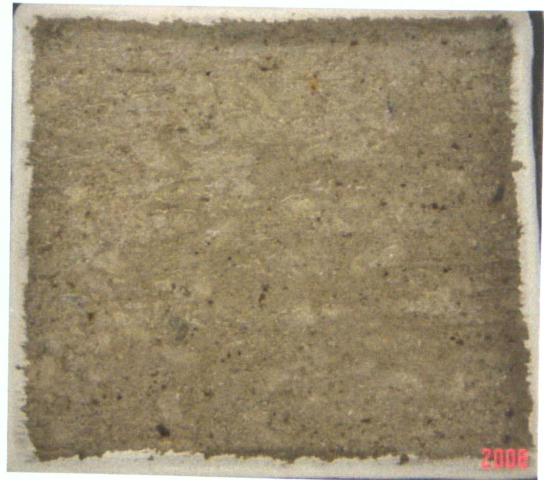
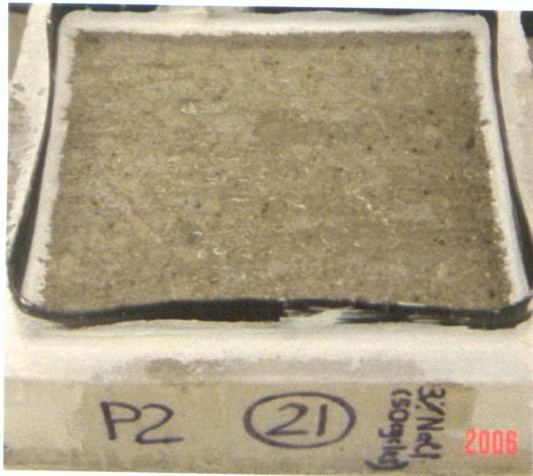
*15 cycles*



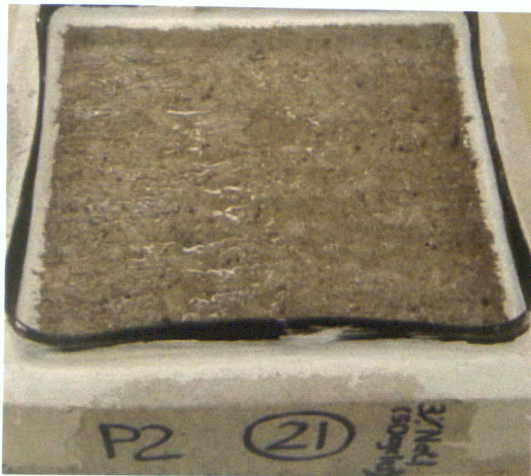
3%NaCl (50 cycles) – Slab 21



*0 cycles*



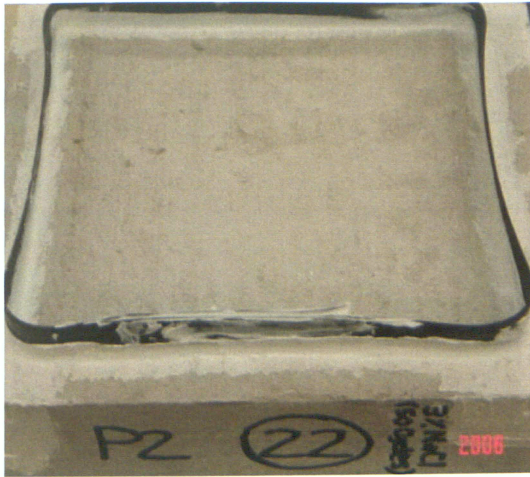
*25 cycles*



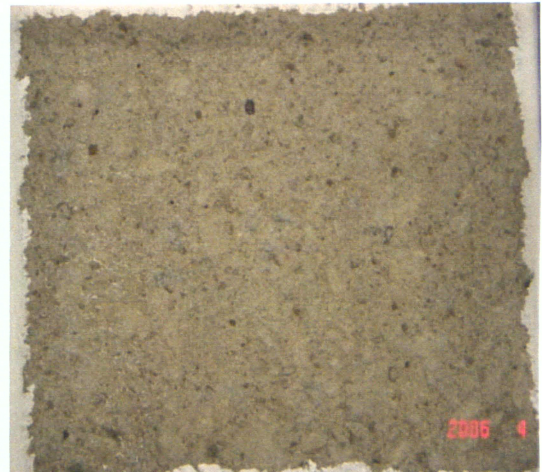
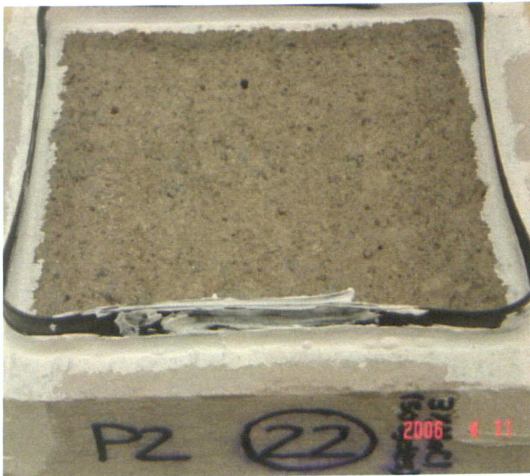
*50 cycles*



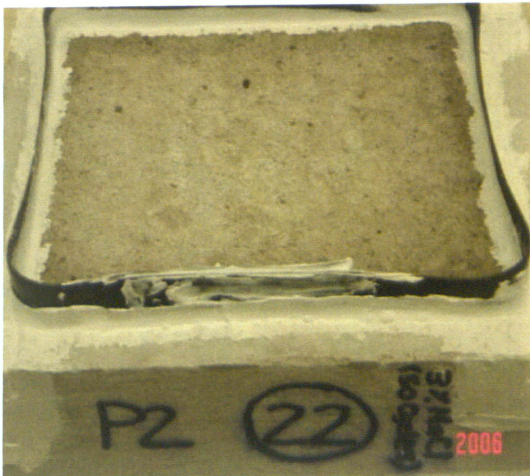
3%NaCl (50 cycles) – Slab 22



*0 cycles*



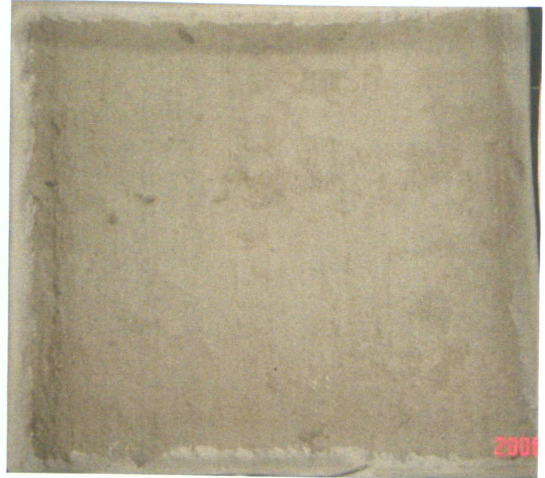
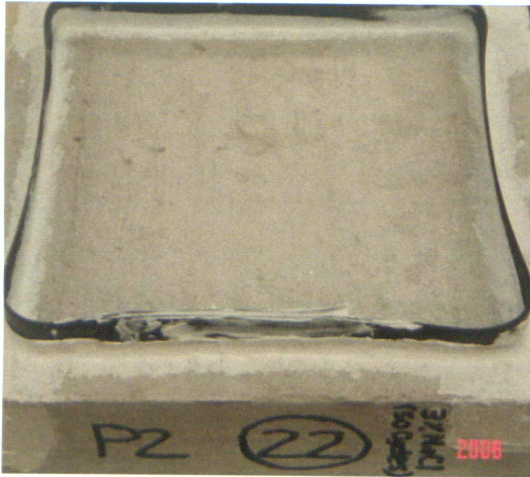
*10 cycles*



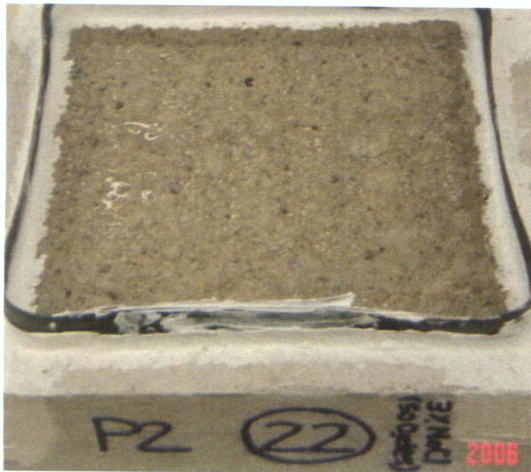
*15 cycles*



3%NaCl (50 cycles) – Slab 22



*0 cycles*



*25 cycles*



*50 cycles*

## **APPENDIX E**

**Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution  
ASTM C1012**

Lab # 06-13-F1 (3%NaCl)

Bar Length = 295.25 mm

Cement: St. Marys Type 10/GU - Leaside Lab Control

Stud Length = 20.627 mm

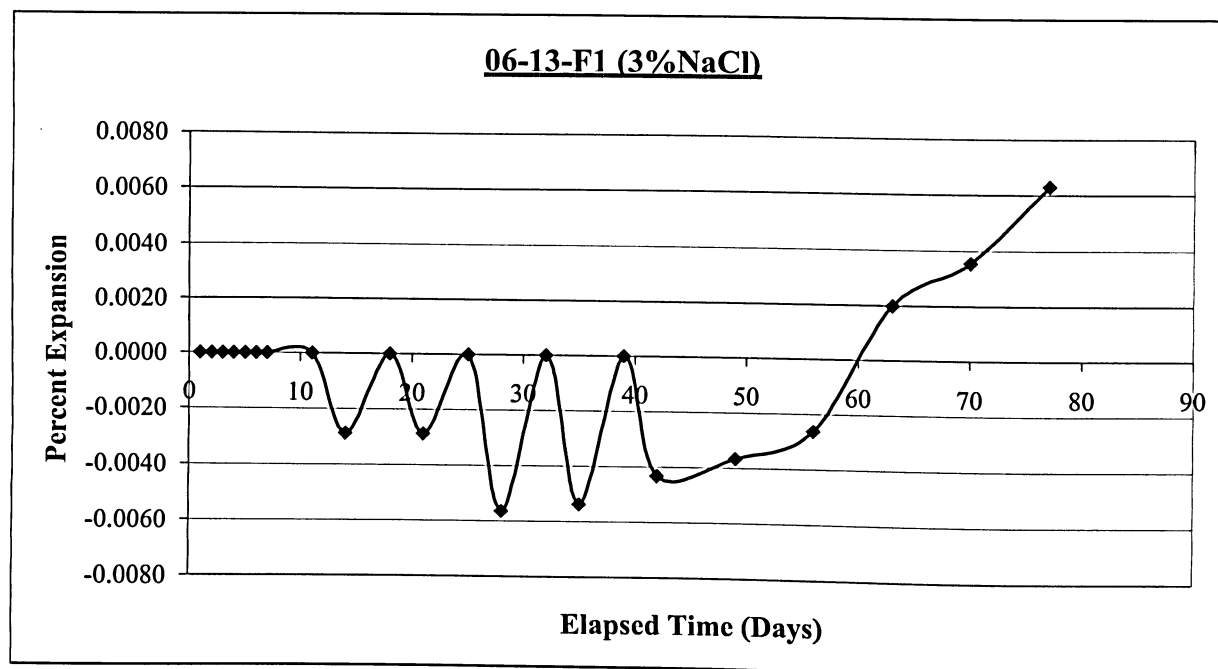
Slag: St. Marys - Leaside Lab Control (25%)

Aggregate: Concrete Sand - Leaside Lab Control

Gauge Length = 253.996 mm

Date & Time Cast		Gauge reading			Length Change			% Expansion			Avg. Expansion	
	12-Apr-06	A	B	C	A	B	C	A	B	C		
D&T Initial Reading		13-Apr-06	-0.058	0.414	3.984	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	1 Day Reading	14-Apr-06	-0.058	0.414	3.984	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	2 Day Reading	15-Apr-06	-0.058	0.414	3.984	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	3 Day Reading	16-Apr-06	-0.058	0.414	3.984	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	4 Day Reading	17-Apr-06	-0.058	0.414	3.984	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	5 Day Reading	18-Apr-06	-0.058	0.414	3.984	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	6 Day Reading	19-Apr-06	-0.058	0.414	3.984	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	7 Day Reading	20-Apr-06	-0.058	0.414	3.986	0.000	0.000	0.002	0.000	0.000	0.001	0.0000
D&T	11 Day Reading	24-Apr-06	-0.058	0.414	3.986	0.000	0.000	0.002	0.000	0.000	0.001	0.0000
D&T	14 Day Reading	27-Apr-06	-0.058	0.402	3.974	0.000	-0.012	-0.010	0.000	-0.005	-0.004	-0.0029
D&T	18 Day Reading	01-May-06	-0.058	0.402	3.974	0.000	-0.012	-0.010	0.000	-0.005	-0.004	0.0000
D&T	21 Day Reading	04-May-06	-0.058	0.402	3.974	0.000	-0.012	-0.010	0.000	-0.005	-0.004	-0.0029
D&T	25 Day Reading	08-May-06	-0.058	0.402	3.960	0.000	-0.012	-0.024	0.000	-0.005	-0.009	0.0000
D&T	28 Day Reading	11-May-06	-0.052	0.389	3.960	0.006	-0.025	-0.024	0.002	-0.010	-0.009	-0.0056
D&T	32 Day Reading	15-May-06	-0.052	0.389	3.960	0.006	-0.025	-0.024	0.002	-0.010	-0.009	0.0000
D&T	35 Day Reading	18-May-06	-0.050	0.389	3.960	0.008	-0.025	-0.024	0.003	-0.010	-0.009	-0.0054
D&T	39 Day Reading	22-May-06	-0.048	0.389	3.960	0.010	-0.025	-0.024	0.004	-0.010	-0.009	0.0000
D&T	42 Day Reading	25-May-06	-0.042	0.389	3.960	0.016	-0.025	-0.024	0.006	-0.010	-0.009	-0.0043
D&T	49 Day Reading	01-Jun-06	-0.040	0.388	3.964	0.018	-0.026	-0.020	0.007	-0.010	-0.008	-0.0037
D&T	56 Day Reading	08-Jun-06	-0.035	0.389	3.966	0.023	-0.025	-0.018	0.009	-0.010	-0.007	-0.0026
D&T	63 Day Reading	15-Jun-06	-0.026	0.403	3.978	0.032	-0.011	-0.006	0.013	-0.004	-0.002	0.0020
D&T	70 Day Reading	22-Jun-06	-0.022	0.411	3.978	0.036	-0.003	-0.006	0.014	-0.001	-0.002	0.0035
D&T	77 Day Reading	29-Jun-06	-0.020	0.426	3.982	0.038	0.012	-0.002	0.015	0.005	-0.001	0.0063

Total % Expansion: 0.0063



**Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution  
ASTM C1012**

Lab # 06-13-F2 (3%MgCl<sub>2</sub>)

Bar Length = 295.25 mm

Cement: St. Marys Type 10/GU - Leaside Lab Control

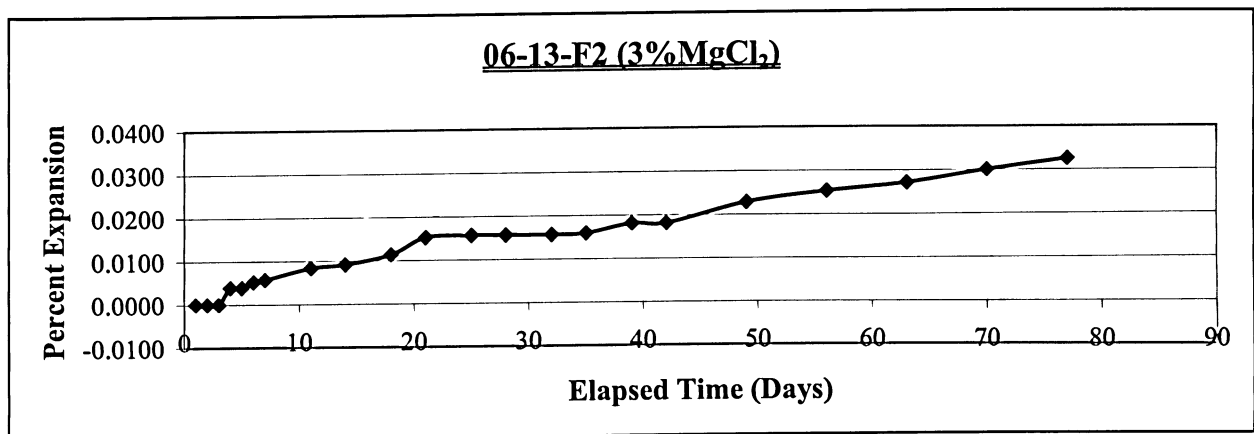
Stud Length = 20.627 mm

Slag: St. Marys - Leaside Lab Control (25%)

Aggregate: Concrete Sand - Leaside Lab Control

Gauge Length = 253.996 mm

Date & Time Cast		Gauge reading			Length Change			% Expansion			Avg. Expansion
	12-Apr-06	A	B	C	A	B	C	A	B	C	
D&T Initial Reading	13-Apr-06	3.818	-0.078	0.154	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 1 Day Reading	14-Apr-06	3.818	-0.078	0.154	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 2 Day Reading	15-Apr-06	3.818	-0.078	0.154	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 3 Day Reading	16-Apr-06	3.818	-0.078	0.154	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 4 Day Reading	17-Apr-06	3.818	-0.052	0.158	0.000	0.026	0.004	0.000	0.010	0.002	0.0039
D&T 5 Day Reading	18-Apr-06	3.818	-0.052	0.158	0.000	0.026	0.004	0.000	0.010	0.002	0.0039
D&T 6 Day Reading	19-Apr-06	3.818	-0.052	0.168	0.000	0.026	0.014	0.000	0.010	0.006	0.0052
D&T 7 Day Reading	20-Apr-06	3.822	-0.052	0.168	0.004	0.026	0.014	0.002	0.010	0.006	0.0058
D&T 11 Day Reading	24-Apr-06	3.822	-0.046	0.182	0.004	0.032	0.028	0.002	0.013	0.011	0.0084
D&T 14 Day Reading	27-Apr-06	3.828	-0.046	0.182	0.010	0.032	0.028	0.004	0.013	0.011	0.0092
D&T 18 Day Reading	01-May-06	3.830	-0.046	0.197	0.012	0.032	0.043	0.005	0.013	0.017	0.0114
D&T 21 Day Reading	04-May-06	3.848	-0.046	0.208	0.030	0.032	0.054	0.012	0.013	0.021	0.0152
D&T 25 Day Reading	08-May-06	3.848	-0.043	0.208	0.030	0.035	0.054	0.012	0.014	0.021	0.0156
D&T 28 Day Reading	11-May-06	3.848	-0.043	0.208	0.030	0.035	0.054	0.012	0.014	0.021	0.0156
D&T 32 Day Reading	15-May-06	3.848	-0.043	0.208	0.030	0.035	0.054	0.012	0.014	0.021	0.0156
D&T 35 Day Reading	18-May-06	3.850	-0.043	0.208	0.032	0.035	0.054	0.013	0.014	0.021	0.0159
D&T 39 Day Reading	22-May-06	3.862	-0.038	0.208	0.044	0.040	0.054	0.017	0.016	0.021	0.0181
D&T 42 Day Reading	25-May-06	3.862	-0.038	0.208	0.044	0.040	0.054	0.017	0.016	0.021	0.0181
D&T 49 Day Reading	01-Jun-06	3.882	-0.026	0.212	0.064	0.052	0.058	0.025	0.020	0.023	0.0228
D&T 56 Day Reading	08-Jun-06	3.894	-0.019	0.212	0.076	0.059	0.058	0.030	0.023	0.023	0.0253
D&T 63 Day Reading	15-Jun-06	3.899	-0.012	0.214	0.081	0.066	0.060	0.032	0.026	0.024	0.0272
D&T 70 Day Reading	22-Jun-06	3.910	-0.008	0.221	0.092	0.070	0.067	0.036	0.028	0.026	0.0301
D&T 77 Day Reading	29-Jun-06	3.918	-0.004	0.228	0.100	0.074	0.074	0.039	0.029	0.029	0.0325

Total % Expansion: **0.0325**



**Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution**  
**ASTM C1012**

Lab # 06-13-F3 (5%MgCl<sub>2</sub>)

Bar Length = 295.25 mm

Cement: St. Marys Type 10/GU - Leaside Lab Control

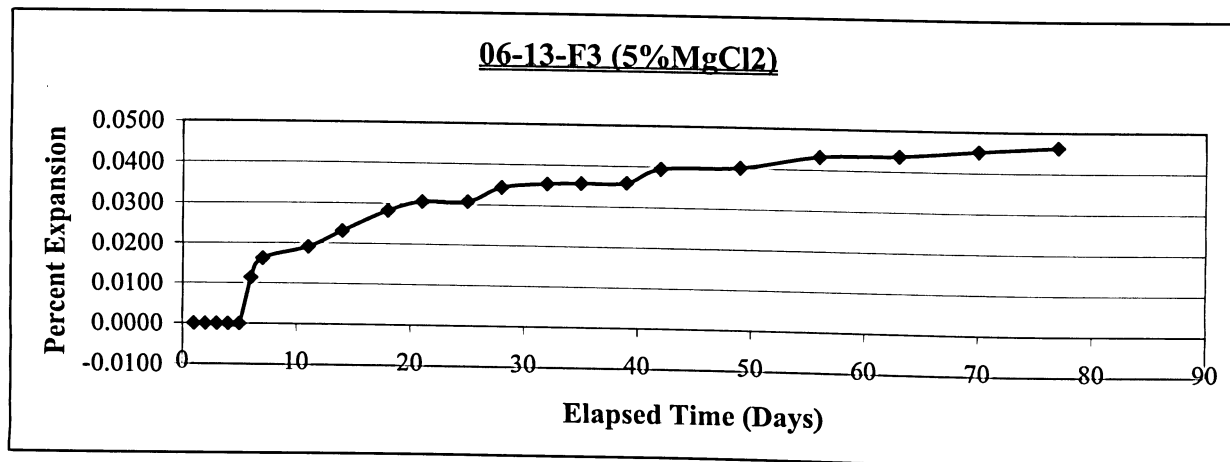
Stud Length = 20.627 mm

Slag: St. Marys - Leaside Lab Control (25%)

Aggregate: Concrete Sand - Leaside Lab Control

Gauge Length = 253.996 mm

Date & Time Cast		Gauge reading			Length Change			% Expansion			Avg. Expansion	
		12-Apr-06	A	B	C	A	B	C	A	B		C
D&T Initial Reading		13-Apr-06	0.020	0.276	-0.309	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	1 Day Reading	14-Apr-06	0.020	0.276	-0.309	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	2 Day Reading	15-Apr-06	0.020	0.276	-0.309	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	3 Day Reading	16-Apr-06	0.020	0.276	-0.309	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	4 Day Reading	17-Apr-06	0.020	0.276	-0.309	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	5 Day Reading	18-Apr-06	0.020	0.276	-0.309	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T	6 Day Reading	19-Apr-06	0.020	0.276	-0.222	0.000	0.000	0.087	0.000	0.000	0.034	0.0114
D&T	7 Day Reading	20-Apr-06	0.028	0.286	-0.204	0.008	0.010	0.106	0.003	0.004	0.042	0.0162
D&T	11 Day Reading	24-Apr-06	0.028	0.286	-0.182	0.008	0.010	0.127	0.003	0.004	0.050	0.0191
D&T	14 Day Reading	27-Apr-06	0.059	0.286	-0.182	0.039	0.010	0.127	0.015	0.004	0.050	0.0231
D&T	18 Day Reading	01-May-06	0.059	0.319	-0.176	0.039	0.043	0.133	0.015	0.017	0.052	0.0282
D&T	21 Day Reading	04-May-06	0.059	0.319	-0.158	0.039	0.043	0.151	0.015	0.017	0.059	0.0306
D&T	25 Day Reading	08-May-06	0.059	0.319	-0.157	0.039	0.043	0.152	0.015	0.017	0.060	0.0307
D&T	28 Day Reading	11-May-06	0.068	0.326	-0.145	0.048	0.050	0.164	0.019	0.020	0.065	0.0344
D&T	32 Day Reading	15-May-06	0.068	0.326	-0.137	0.048	0.050	0.172	0.019	0.020	0.068	0.0354
D&T	35 Day Reading	18-May-06	0.068	0.326	-0.135	0.048	0.050	0.174	0.019	0.020	0.069	0.0357
D&T	39 Day Reading	22-May-06	0.068	0.326	-0.133	0.048	0.050	0.176	0.019	0.020	0.069	0.0360
D&T	42 Day Reading	25-May-06	0.073	0.342	-0.127	0.053	0.066	0.182	0.021	0.026	0.072	0.0395
D&T	49 Day Reading	01-Jun-06	0.078	0.342	-0.127	0.058	0.066	0.182	0.023	0.026	0.072	0.0402
D&T	56 Day Reading	08-Jun-06	0.085	0.358	-0.127	0.065	0.082	0.182	0.026	0.032	0.072	0.0432
D&T	63 Day Reading	15-Jun-06	0.085	0.358	-0.123	0.065	0.082	0.186	0.026	0.032	0.073	0.0437
D&T	70 Day Reading	22-Jun-06	0.091	0.360	-0.120	0.071	0.084	0.189	0.028	0.033	0.074	0.0451
D&T	77 Day Reading	29-Jun-06	0.098	0.362	-0.120	0.078	0.086	0.189	0.031	0.034	0.074	0.0463

Total % Expansion: **0.0463**

**Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution  
ASTM C1012**

Lab # 06-13-F4 (10%MgCl<sub>2</sub>)

Bar Length = 295.25 mm

Cement: St. Marys Type 10/GU - Leaside Lab Control

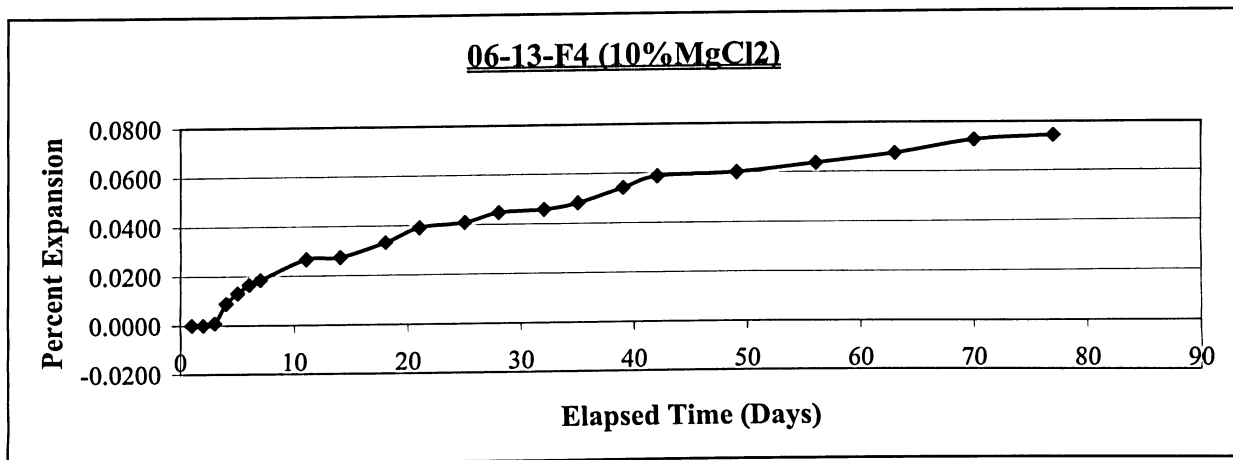
Stud Length = 20.627 mm

Slag: St. Marys - Leaside Lab Control (25%)

Gauge Length = 253.996 mm

Aggregate: Concrete Sand - Leaside Lab Control

Date & Time Cast		Gauge reading			Length Change			% Expansion			Avg. Expansion	
		12-Apr-06	A	B	C	A	B	C	A	B		C
D&T Initial Reading		13-Apr-06	-0.198	0.088	-0.158	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 1 Day Reading		14-Apr-06	-0.198	0.088	-0.158	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 2 Day Reading		15-Apr-06	-0.198	0.088	-0.158	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 3 Day Reading		16-Apr-06	-0.191	0.088	-0.158	0.007	0.000	0.000	0.003	0.000	0.000	0.0009
D&T 4 Day Reading		17-Apr-06	-0.185	0.088	-0.104	0.013	0.000	0.055	0.005	0.000	0.021	0.0089
D&T 5 Day Reading		18-Apr-06	-0.159	0.088	-0.098	0.040	0.000	0.060	0.016	0.000	0.024	0.0131
D&T 6 Day Reading		19-Apr-06	-0.149	0.088	-0.082	0.050	0.000	0.076	0.019	0.000	0.030	0.0165
D&T 7 Day Reading		20-Apr-06	-0.149	0.100	-0.079	0.050	0.012	0.079	0.019	0.005	0.031	0.0184
D&T 11 Day Reading		24-Apr-06	-0.119	0.133	-0.079	0.079	0.045	0.079	0.031	0.018	0.031	0.0266
D&T 14 Day Reading		27-Apr-06	-0.116	0.133	-0.077	0.082	0.045	0.081	0.032	0.018	0.032	0.0273
D&T 18 Day Reading		01-May-06	-0.099	0.133	-0.049	0.099	0.045	0.109	0.039	0.018	0.043	0.0332
D&T 21 Day Reading		04-May-06	-0.099	0.177	-0.048	0.099	0.089	0.110	0.039	0.035	0.043	0.0391
D&T 25 Day Reading		08-May-06	-0.099	0.177	-0.034	0.099	0.089	0.124	0.039	0.035	0.049	0.0409
D&T 28 Day Reading		11-May-06	-0.082	0.177	-0.022	0.116	0.089	0.136	0.046	0.035	0.054	0.0448
D&T 32 Day Reading		15-May-06	-0.082	0.177	-0.014	0.116	0.089	0.144	0.046	0.035	0.057	0.0458
D&T 35 Day Reading		18-May-06	-0.072	0.177	-0.005	0.126	0.089	0.153	0.050	0.035	0.060	0.0483
D&T 39 Day Reading		22-May-06	-0.063	0.210	-0.001	0.135	0.122	0.157	0.053	0.048	0.062	0.0543
D&T 42 Day Reading		25-May-06	-0.049	0.222	0.008	0.149	0.134	0.166	0.059	0.053	0.065	0.0588
D&T 49 Day Reading		01-Jun-06	-0.049	0.232	0.008	0.149	0.144	0.166	0.059	0.057	0.065	0.0602
D&T 56 Day Reading		08-Jun-06	-0.035	0.235	0.017	0.163	0.147	0.175	0.064	0.058	0.069	0.0636
D&T 63 Day Reading		15-Jun-06	-0.025	0.249	0.022	0.174	0.161	0.180	0.068	0.063	0.071	0.0675
D&T 70 Day Reading		22-Jun-06	-0.008	0.266	0.029	0.190	0.178	0.187	0.075	0.070	0.074	0.0728
D&T 77 Day Reading		29-Jun-06	0.000	0.266	0.034	0.198	0.178	0.192	0.078	0.070	0.076	0.0745

Total % Expansion: **0.0745**

**Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution  
ASTM C1012**

Lab # 06-13-F5 (30%MgCl<sub>2</sub>)

Bar Length = 295.25 mm

Cement: St. Marys Type 10/GU - Leaside Lab Control

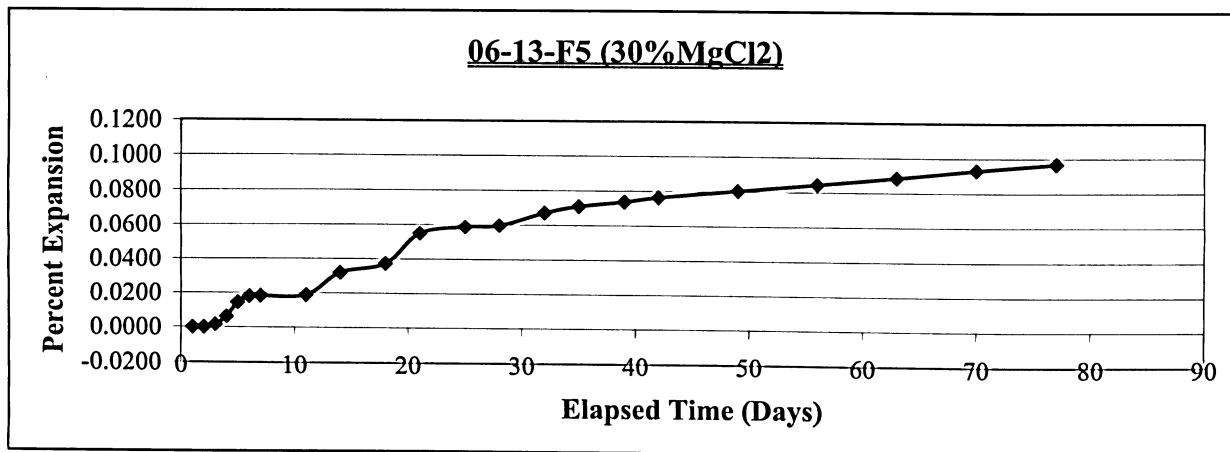
Stud Length = 20.627 mm

Slag: St. Marys - Leaside Lab Control (25%)

Aggregate: Concrete Sand - Leaside Lab Control

Gauge Length = 253.996 mm

Date & Time Cast		Gauge reading			Length Change			% Expansion			Avg. Expansion
	12-Apr-06	A	B	C	A	B	C	A	B	C	
D&T Initial Reading	13-Apr-06	3.834	1.966	4.056	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 1 Day Reading	14-Apr-06	3.834	1.966	4.056	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 2 Day Reading	15-Apr-06	3.834	1.966	4.056	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
D&T 3 Day Reading	16-Apr-06	3.834	1.978	4.056	0.000	0.012	0.000	0.000	0.005	0.000	0.0016
D&T 4 Day Reading	17-Apr-06	3.834	1.994	4.076	0.000	0.028	0.020	0.000	0.011	0.008	0.0063
D&T 5 Day Reading	18-Apr-06	3.838	2.028	4.101	0.004	0.062	0.045	0.002	0.024	0.018	0.0146
D&T 6 Day Reading	19-Apr-06	3.838	2.048	4.108	0.004	0.082	0.052	0.002	0.032	0.020	0.0181
D&T 7 Day Reading	20-Apr-06	3.838	2.048	4.110	0.004	0.082	0.054	0.002	0.032	0.021	0.0184
D&T 11 Day Reading	24-Apr-06	3.838	2.048	4.114	0.004	0.082	0.058	0.002	0.032	0.023	0.0189
D&T 14 Day Reading	27-Apr-06	3.848	2.104	4.147	0.014	0.138	0.091	0.006	0.054	0.036	0.0319
D&T 18 Day Reading	01-May-06	3.854	2.106	4.180	0.020	0.140	0.124	0.008	0.055	0.049	0.0373
D&T 21 Day Reading	04-May-06	3.955	2.138	4.180	0.121	0.172	0.124	0.048	0.068	0.049	0.0547
D&T 25 Day Reading	08-May-06	3.979	2.142	4.182	0.145	0.176	0.126	0.057	0.069	0.050	0.0587
D&T 28 Day Reading	11-May-06	3.980	2.142	4.188	0.146	0.176	0.132	0.057	0.069	0.052	0.0596
D&T 32 Day Reading	15-May-06	3.987	2.151	4.230	0.153	0.185	0.174	0.060	0.073	0.069	0.0672
D&T 35 Day Reading	18-May-06	4.008	2.151	4.238	0.174	0.185	0.182	0.069	0.073	0.072	0.0710
D&T 39 Day Reading	22-May-06	4.012	2.168	4.238	0.178	0.202	0.182	0.070	0.080	0.072	0.0738
D&T 42 Day Reading	25-May-06	4.020	2.176	4.242	0.186	0.210	0.186	0.073	0.083	0.073	0.0764
D&T 49 Day Reading	01-Jun-06	4.045	2.176	4.248	0.211	0.210	0.192	0.083	0.083	0.076	0.0804
D&T 56 Day Reading	08-Jun-06	4.050	2.195	4.254	0.216	0.229	0.198	0.085	0.090	0.078	0.0844
D&T 63 Day Reading	15-Jun-06	4.051	2.198	4.282	0.217	0.232	0.226	0.085	0.091	0.089	0.0886
D&T 70 Day Reading	22-Jun-06	4.066	2.202	4.298	0.232	0.236	0.242	0.091	0.093	0.095	0.0932
D&T 77 Day Reading	29-Jun-06	4.076	2.214	4.304	0.242	0.248	0.248	0.095	0.098	0.098	0.0969

Total % Expansion: **0.0969**

**Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution**  
**ASTM C1012**

Lab # Limewater

Bar Length = 295.25 mm

Cement: St. Marys Type 10/GU - Leaside Lab Control

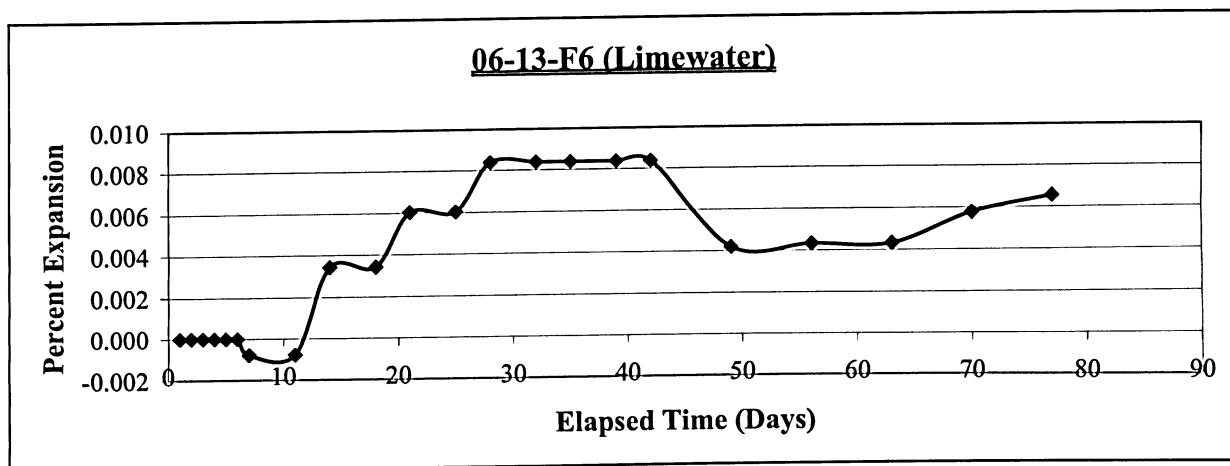
Stud Length = 20.627 mm

Slag: St. Marys - Leaside Lab Control (25%)

Gauge Length = 253.996 mm

Aggregate: Concrete Sand - Leaside Lab Control

Date & Time Cast		Gauge reading			Length Change			% Expansion			Avg. Expansion
	12-Apr-06	A	B	C	A	B	C	A	B	C	
D&T Initial Reading		13-Apr-06	4.266	1.160	-0.314	0.000	0.000	0.000	0.000	0.000	0.000
D&T 1 Day Reading		14-Apr-06	4.266	1.160	-0.314	0.000	0.000	0.000	0.000	0.000	0.000
D&T 2 Day Reading		15-Apr-06	4.266	1.160	-0.314	0.000	0.000	0.000	0.000	0.000	0.000
D&T 3 Day Reading		16-Apr-06	4.266	1.160	-0.314	0.000	0.000	0.000	0.000	0.000	0.000
D&T 4 Day Reading		17-Apr-06	4.266	1.160	-0.314	0.000	0.000	0.000	0.000	0.000	0.000
D&T 5 Day Reading		18-Apr-06	4.266	1.160	-0.314	0.000	0.000	0.000	0.000	0.000	0.000
D&T 6 Day Reading		19-Apr-06	4.266	1.160	-0.314	0.000	0.000	0.000	0.000	0.000	0.000
D&T 7 Day Reading		20-Apr-06	4.262	1.158	-0.314	-0.004	-0.002	0.000	-0.002	-0.001	0.000
D&T 11 Day Reading		24-Apr-06	4.262	1.158	-0.314	-0.004	-0.002	0.000	-0.002	-0.001	0.000
D&T 14 Day Reading		27-Apr-06	4.274	1.168	-0.304	0.008	0.008	0.010	0.003	0.003	0.004
D&T 18 Day Reading		01-May-06	4.274	1.168	-0.304	0.008	0.008	0.010	0.003	0.003	0.004
D&T 21 Day Reading		04-May-06	4.278	1.176	-0.296	0.012	0.016	0.018	0.005	0.006	0.007
D&T 25 Day Reading		08-May-06	4.278	1.176	-0.296	0.012	0.016	0.018	0.005	0.006	0.007
D&T 28 Day Reading		11-May-06	4.284	1.180	-0.288	0.018	0.020	0.026	0.007	0.008	0.010
D&T 32 Day Reading		15-May-06	4.284	1.180	-0.288	0.018	0.020	0.026	0.007	0.008	0.010
D&T 35 Day Reading		18-May-06	4.284	1.180	-0.288	0.018	0.020	0.026	0.007	0.008	0.010
D&T 39 Day Reading		22-May-06	4.284	1.180	-0.288	0.018	0.020	0.026	0.007	0.008	0.010
D&T 42 Day Reading		25-May-06	4.284	1.180	-0.288	0.018	0.020	0.026	0.007	0.008	0.010
D&T 49 Day Reading		01-Jun-06	4.272	1.184	-0.312	0.006	0.024	0.002	0.002	0.009	0.001
D&T 56 Day Reading		08-Jun-06	4.272	1.187	-0.314	0.006	0.027	0.000	0.002	0.011	0.000
D&T 63 Day Reading		15-Jun-06	4.272	1.187	-0.314	0.006	0.027	0.000	0.002	0.011	0.000
D&T 70 Day Reading		22-Jun-06	4.272	1.202	-0.318	0.006	0.042	-0.004	0.002	0.017	-0.002
D&T 77 Day Reading		29-Jun-06	4.272	1.208	-0.318	0.006	0.048	-0.004	0.002	0.019	-0.002

Total % Expansion: **0.0066**



## Appendix E - Prism and Cube Raw Data

### Mixing Procedure (as per ASTM C305-99 or CSA A456.2-C1):

1. Place all of the water in the bowl.
2. Add the cement to the water, then start the mixer and mix at slow speed for 30s.
3. Add the entire quantity of sand slowly over a 30s period, while mixing at the slow speed.
4. Stop mixer, change to medium speed and mix for 30s.
5. Stop the mixer and let the mortar stand for 1min30s. During the first 15s of this interval, quickly scrape down into the batch any mortar that may have collected on the side of the bowl. Then for the remainder of this interval, cover the bowl with the lid.
6. Finish by mixing for 1min at medium speed.

### Determination of Flow (as per ASTM C109):

Trial	Water (mL)	w/cm	Flow Measurements				Avg. Flow
			1	2	3	4	
1	250	0.338	5.3150	5.0455	4.9250	4.5555	24.3%
2	310	0.419	8.6940	8.6940	9.0270	8.9180	121.3%
3	300	0.405	8.5425	8.2345	8.5215	8.6565	112.7%

### Gauge Readings (as per ASTM C1012):

*\*See following 6 pages for raw data.*

### Compressive Strength of Cubes (MPa):

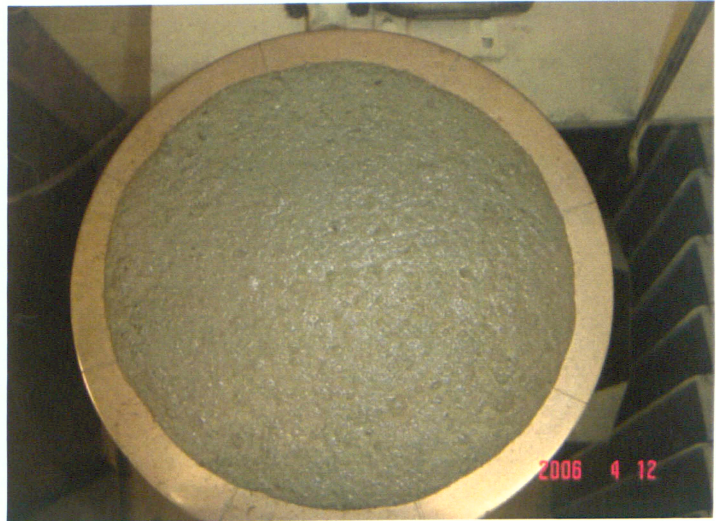
	24-hour			AVG
	A	B	C	
06-13-E7	24.10	24.60	25.00	24.57

	28-day			AVG	56-day			AVG
	A	B	C		D	E	F	
06-13-E1	65.33	62.48	65.08	64.30	60.20	59.40	60.90	60.17
06-13-E2	50.79	57.43	55.35	54.52	60.00	58.02	58.40	58.81
06-13-E3	46.96	54.73	55.06	52.25	56.40	53.70	55.80	55.30
06-13-E4	49.27	54.34	52.77	52.13	59.80	51.60	49.80	53.73
06-13-E5	55.96	50.98	47.44	51.46	47.40	49.70	42.50	46.53
06-13-E6	60.40	60.39	57.97	59.59	62.60	67.60	59.60	63.27

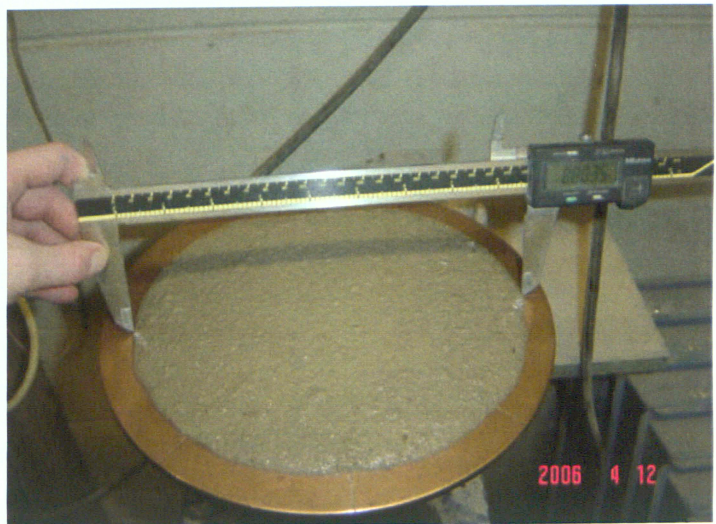
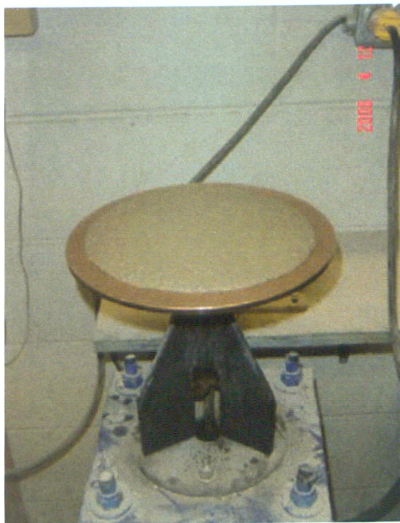
Appendix E – Pictures, Flow Determination



*Mortar Mixer*



*Flow Determination*



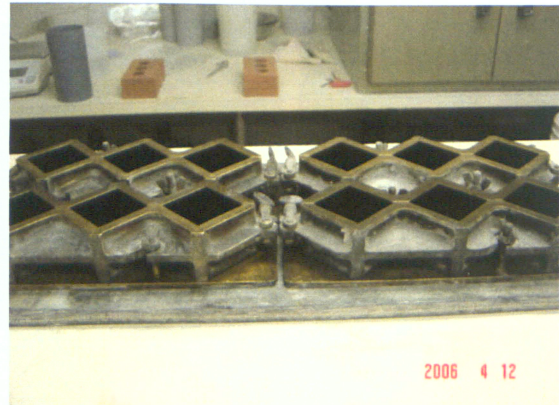
*Flow Determination*



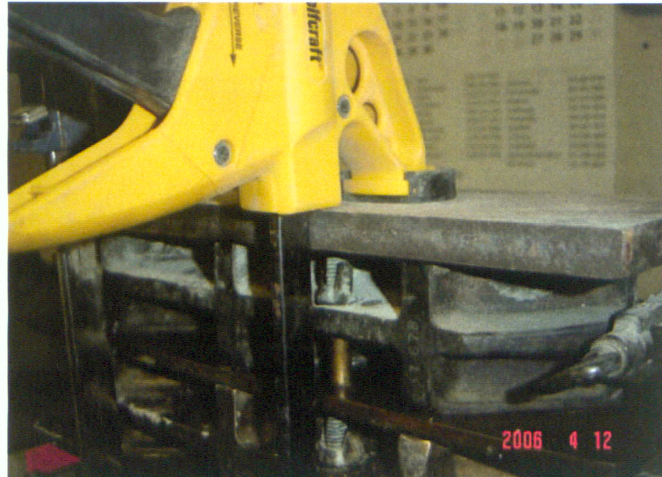
Appendix E – Pictures, Molding/Curing Prisms & Cubes



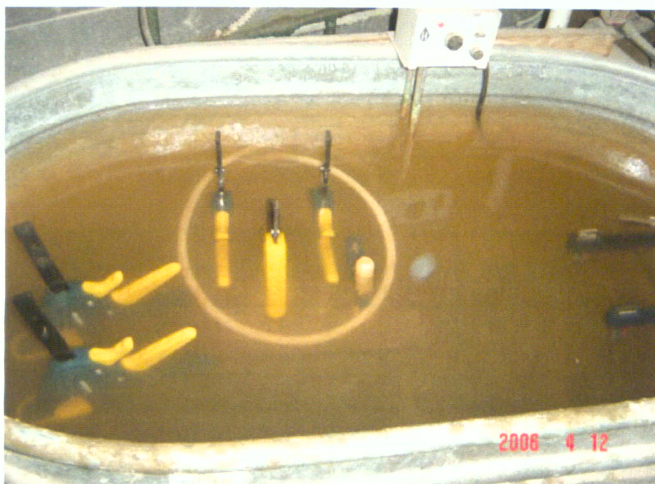
*Brass Prism Molds*



*Brass Cube Molds*



*Preparation for Hot Water Bath*



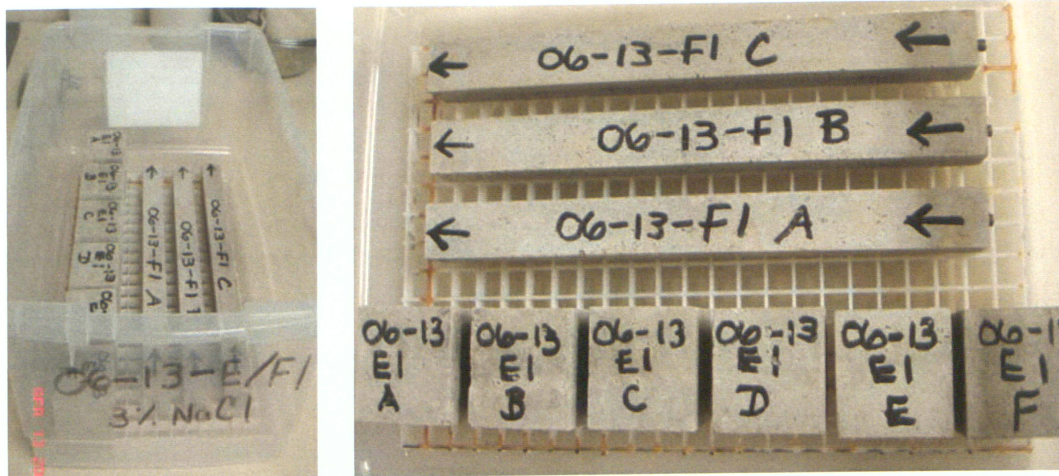
*Hot Water Bath*



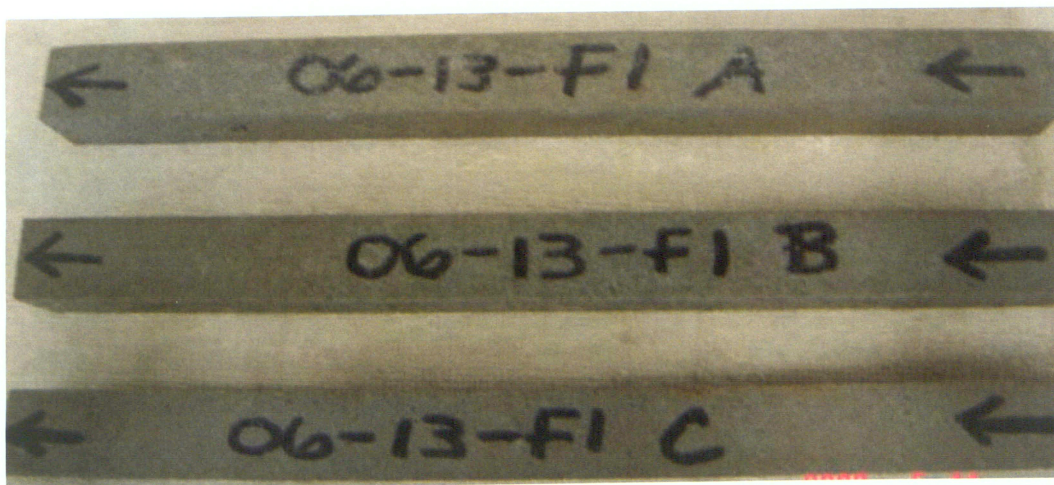
*Temperature of Bath*



Appendix E – Pictures, 06-13-E1/F1 (3% NaCl)



*Initial Picture (April 13, 2006)*



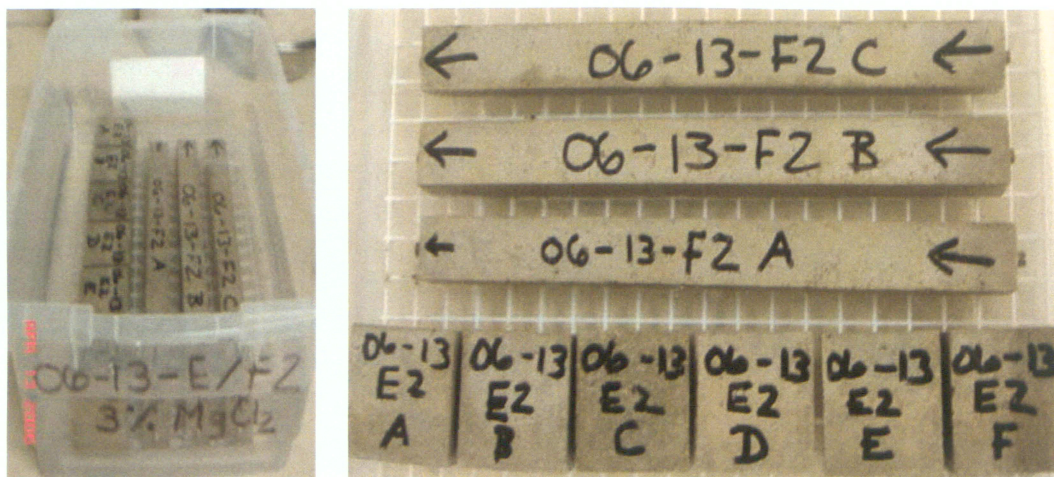
*31 day Picture (May 14, 2006)*



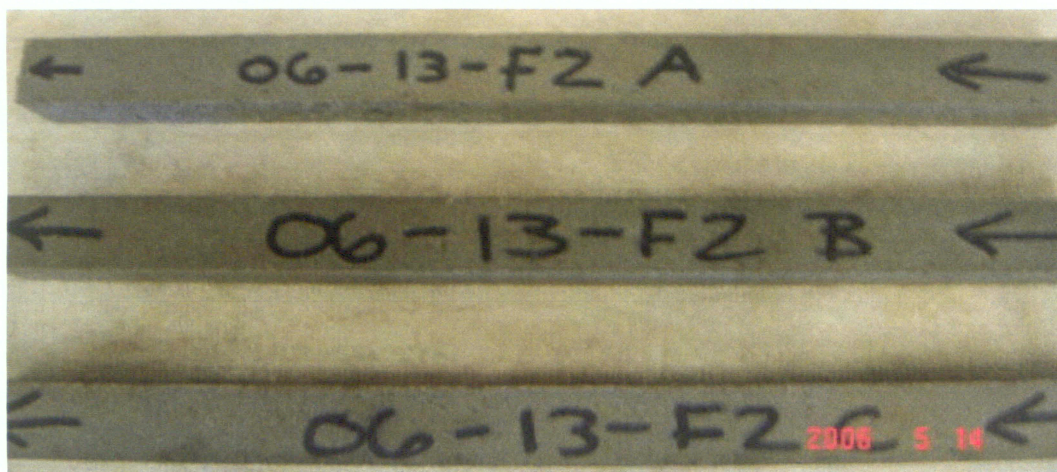
*77 day Picture (June 29, 2006)*



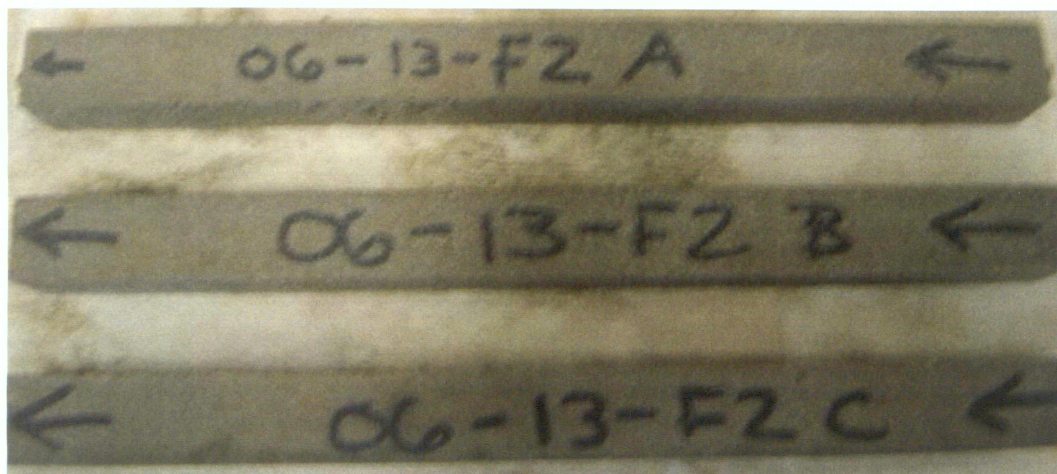
Appendix E – Pictures, 06-13-E2/F2 (3% MgCl<sub>2</sub>)



*Initial Picture (April 13, 2006)*



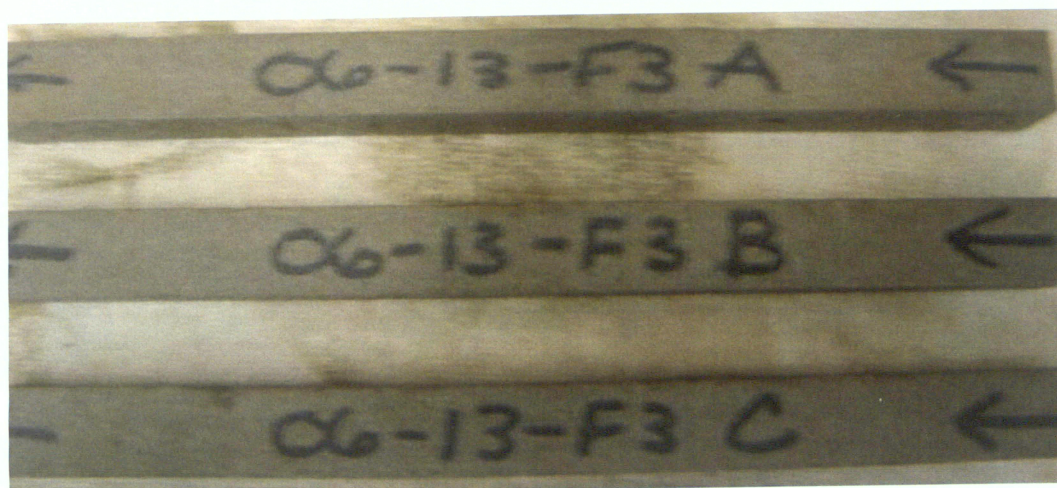
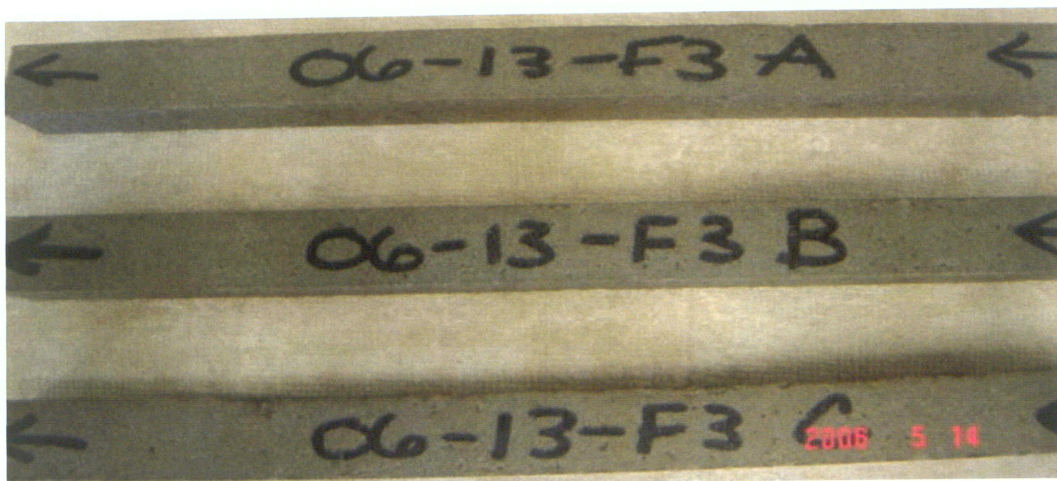
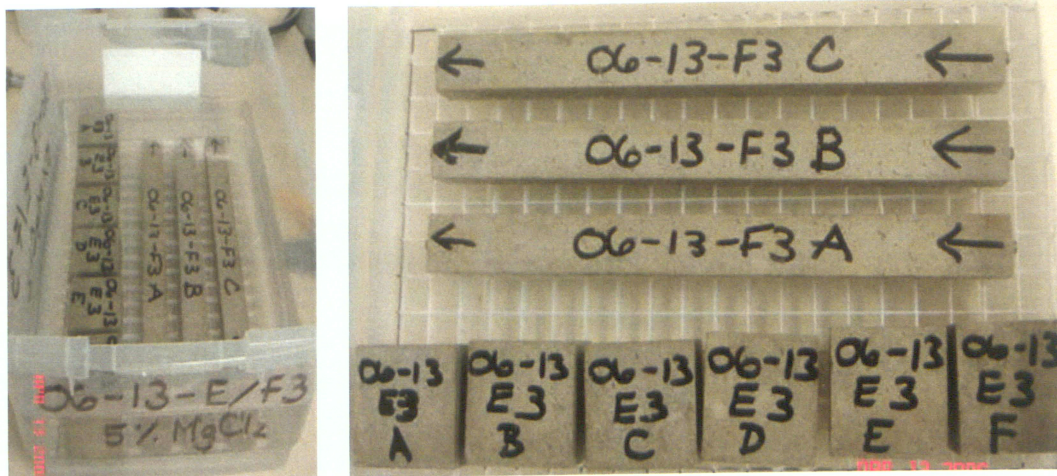
*31 day Picture (May 14, 2006)*



*77 day Picture (June 29, 2006)*

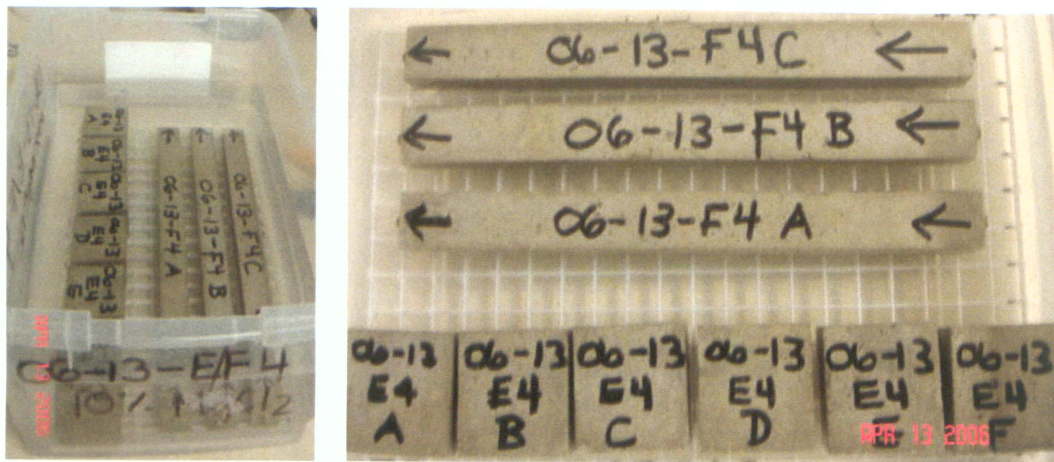


Appendix E – Pictures, 06-13-E3/F3 (5% MgCl<sub>2</sub>)





Appendix E – Pictures, 06-13-E4/F4 (10% MgCl<sub>2</sub>)



*Initial Picture (April 13, 2006)*



*31 day Picture (May 14, 2006)*

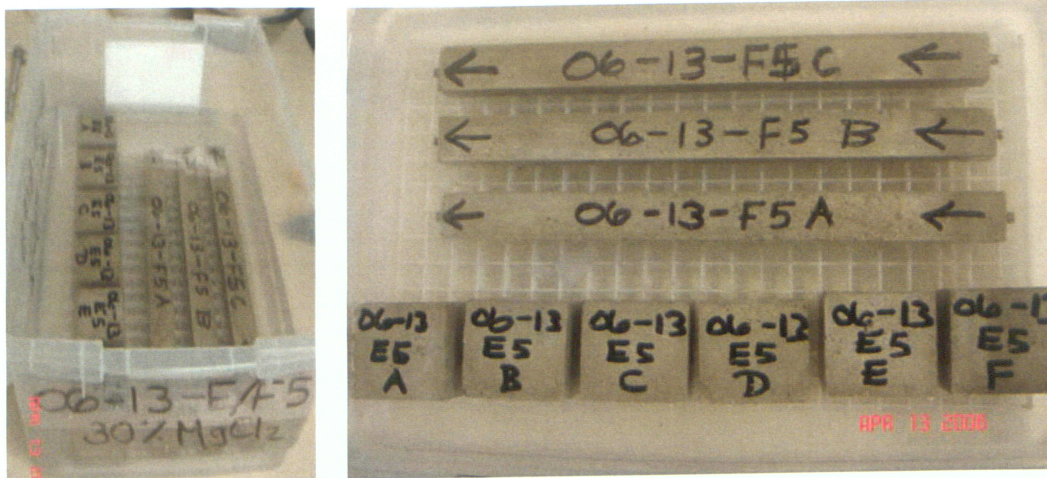


*77 day Picture (June 29, 2006)*

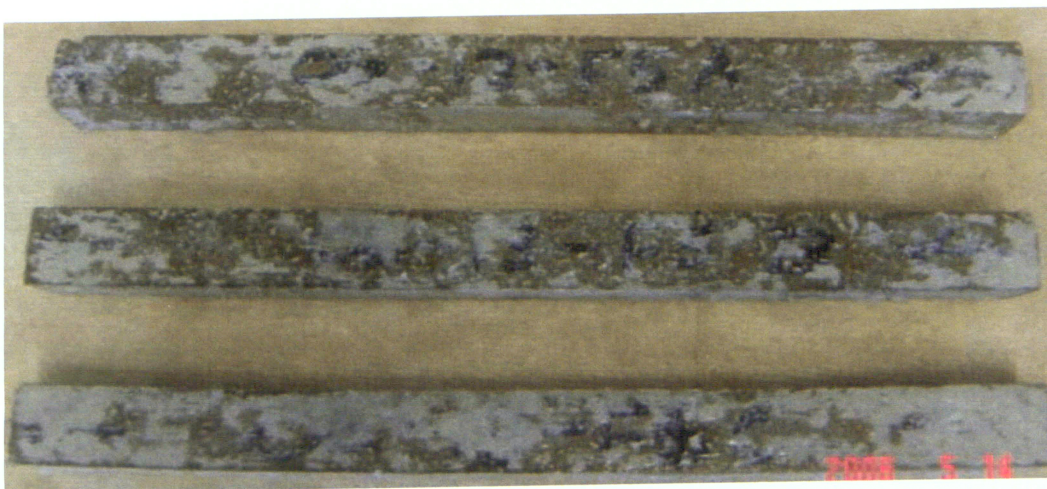




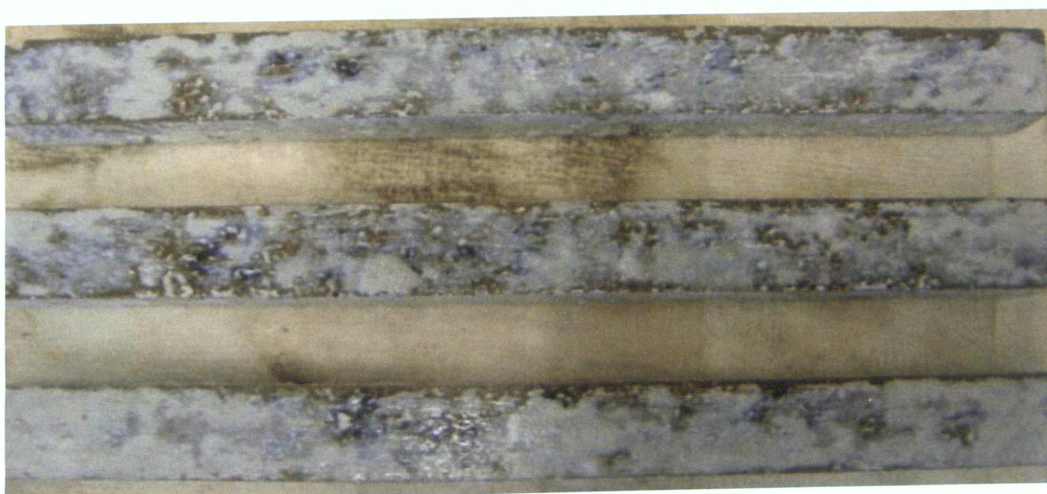
Appendix E – Pictures, 06-13-E5/F5 (30%  $\text{MgCl}_2$ )



*Initial Picture (April 13, 2006)*



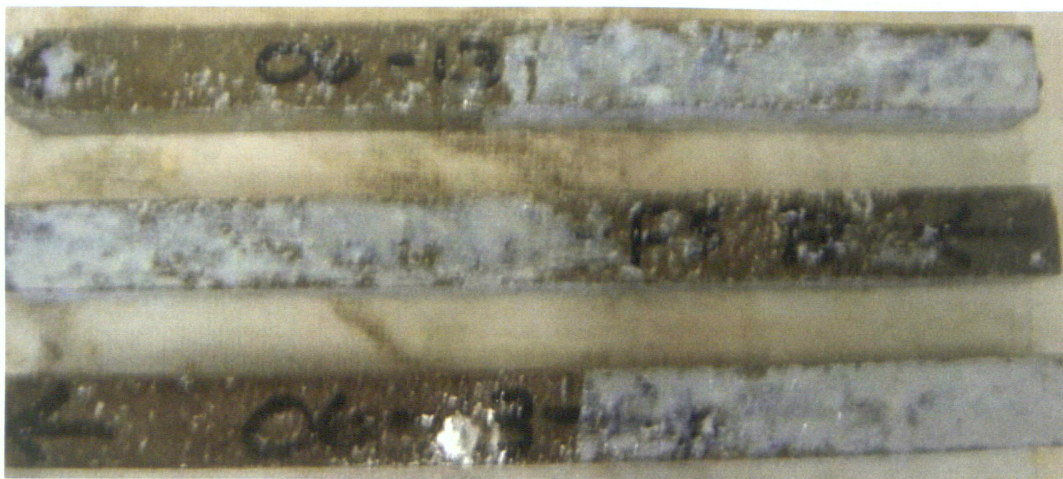
*31 day Picture (May 14, 2006)*



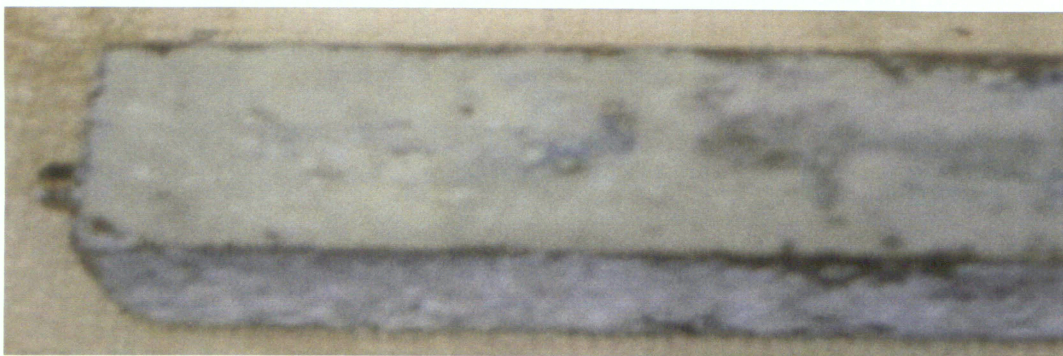
*77 day Picture (June 29, 2006)*



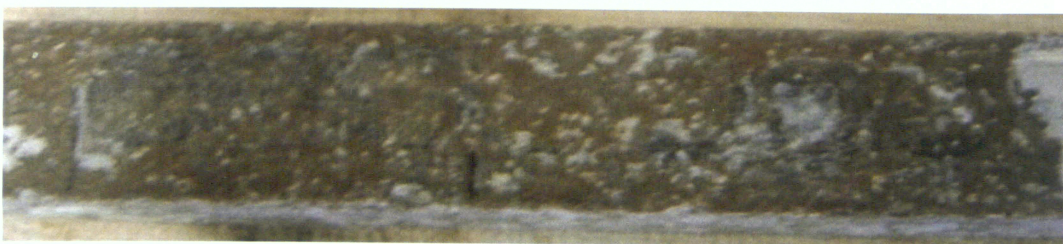
Appendix E – Pictures, 06-13-E5/F5 (30%  $\text{MgCl}_2$ )



*77 day Picture (June 29, 2006)*



*77 day Picture (June 29, 2006)*



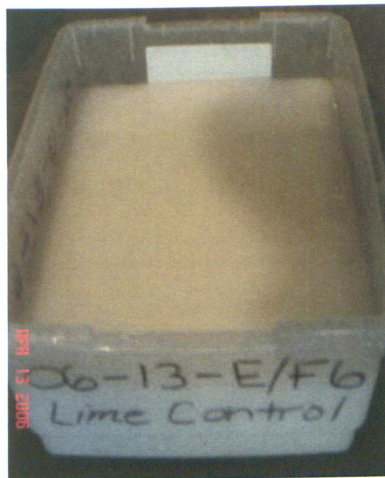
*77 day Picture (June 29, 2006)*



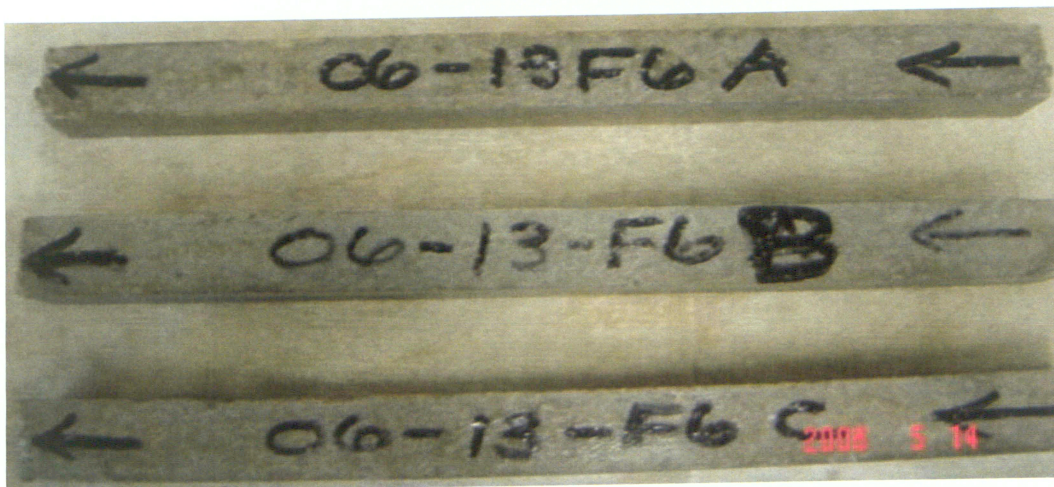
*77 day Picture (June 29, 2006)*



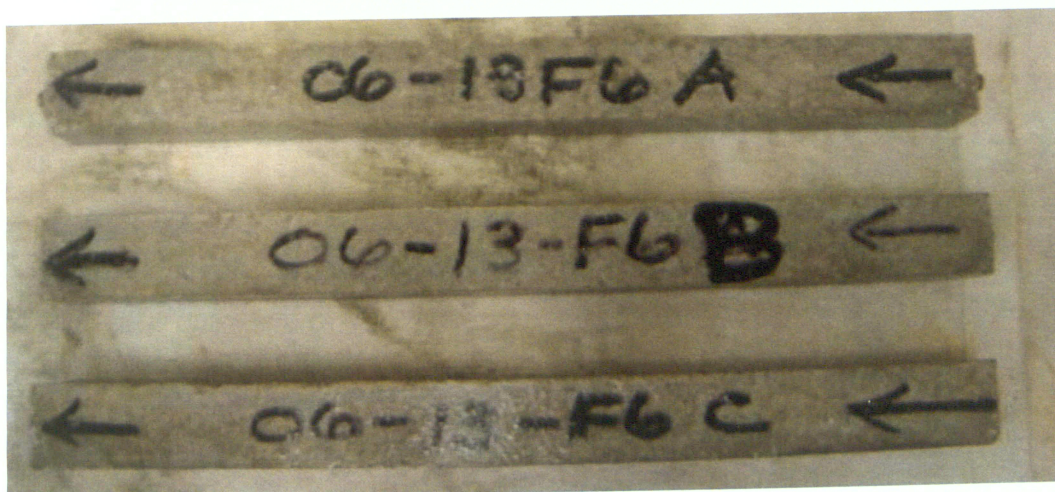
Appendix E – Pictures, 06-13-E6/F6 (Lime Control)



*Initial Picture (April 13, 2006)*



*31 day Picture (May 14, 2006)*



*77 day Picture (June 29, 2006)*