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A study of alkali-aggregate reactions in concrete measurement and prevention.

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A STUDY OF ALKALI-AGGREGATE REACTIONS IN CONCRETE: MEASUREMENT AND PREVENTION

by

Joseph Aduamoah-Larbi

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ABSTRACT

A study of alkali-aggregate reaction in concrete was carried out on six reactive aggregates from Ontario. The objectives of the study were to develop an accelerated test for screening potentially reactive aggregates and to evaluate the performance of concrete containing reactive aggregates subjected to various treatment processes.

A statistical analysis of the results of the accelerated tests and standard tests indicated that high and significant correlations exist between the accelerated tests and the standard tests. From the relationships between the accelerated tests and the standard tests, critical limits of expansion were established for the former. Expansions of 0.171% after 12 days and 0.330% after 24 days are considered excessive for reactive silica rocks tested in 1N NaOH solution. For reactive carbonate rocks tested in 1N NaOH solution the critical limit is 0.162% in 24 days. When tested in saturated NaCl solution, the critical limits are expansions of 0.041% in 12 days and 0.061% in 24 days for the reactive silica rocks and 0.071% in 24 days for the reactive carbonate rocks. The new accelerated tests are simpler to perform, faster, and consequently less expensive than the standard tests; the accelerated tests enable suspect aggregates (both alkali-silica/silicate and alkali-carbonate reactive rocks) to be screened within two months.

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On the basis of the results of the treatment tests performed on the reactive aggregates, a method of preventing alkali-aggregate reaction in concrete is proposed. Treatment of potentially reactive aggregates for 15 seconds and 1 minute respectively in 10% (by weight) solution of "STP" before use in concrete is considered effective in rendering the reactive aggregate inert in the concrete. Performance of such treated aggregate in concrete is comparable to that of a non-reactive aggregate. The "STP" is also effective in preventing deleterious expansions in concrete containing reactive aggregates; the treatment procedures being the same as that of the aggregates. The "STP", an acidic inorganic salt of moderate to high solubility at room temperature has been successfully used to protect concrete and carbonate rocks from frost damage. The "IP", an intermediate compound in the production of the "STP" is effective in controlling only alkali-silica reactions in concrete.

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CHAPTER 1

1.0 INTRODUCTION

1.1 Background and problem

Alkali-aggregate reaction in concrete is the name given to a group of chemical reactions between some minerals in the aggregates and the alkaline pore solution of the cement paste. The alkalies in the pore solutions are derived from the cement, but may be augmented by soluble alkalies in some aggregates for example, andesite, or by alkaline salts from the environment (Grattan-Bellew, 1981). The reaction occurs in the presence of moisture and is generally slow. It may not be recognized for many years (Swenson and Gillot, 1960).

One significant consequence of alkali-aggregate reaction is expansion. This expansion causes cracking of the concrete, especially if it is restrained. Cracking of concrete is undesirable for a number of reasons. The cracks serve as channels for movement of water and other solutions, particularly de-icing salts, resulting in rapid dissolution and leaching of the cement paste. The increased water ingress results in a higher degree of saturation and reduction in freeze-thaw durability. With reinforced concrete, there is an increased tendency for corrosion of reinforcements. The strength of the concrete is ultimately reduced, resulting in increased maintenance costs and reduced service life. In the United States of America, Great Britain, West Germany, Sweden, Denmark, Japan, and South Africa, there are at least sixteen major dams and seven hundred and sixty-five structures affected (Hobbs, 1986; Stark and DePuy, 1987). The structures include a number of bridges, foundation blocks at some electricity sub-stations, car parks, several sewerage treatment works, reservoirs, jetties, hospitals, a multi-storey building, a racecourse stand and a ventilating shaft, most of which are in Great Britain. In Ontario, Canada, alone, over one hundred and thirty highway structures are currently suffering from these expansive reactions (Rogers, 1985).

The alkali-aggregate reaction was first recognized in the early forties in southern California by Stanton (1940). Until then, all aggregates were considered inert. Ever since its recognition, numerous studies have been conducted to enable easy identification of potentially reactive aggregates. Other studies are still in progress. The objective of most of the studies is to establish a criterion for the use of the reactive aggregates in portland cement concrete. This marked upsurge in research is related to the increased number of cases of alkali-aggregate reaction reported worldwide and to the rapid depletion of good and durable aggregates, especially, near urban areas.

When reactive aggregates cause damage in concrete structures, the cost of renovation of such structures often exceeds the original cost of construction. Where major structures such as dams or bridges are involved, the loss may run into millions of dollars.

In Ontario, following the recognition of the concrete durability problems due to alkali-aggregate reactions, an extensive testing program was carried out in the early sixties and seventies. The quarries containing reactive aggregates were identified and criteria were developed for the use of these reactive aggregates in portland cement concrete (Rogers, 1986). In some cases, severe restrictions were placed on the use of the reactive rocks. However, in spite of all the investigations conducted and the construction measures developed for the use of these aggregates, there are still numerous concrete durability problems with these aggregates in concrete. As chemically inert concrete aggregates rapidly become depleted, there is the need to develop more reliable testing schemes and treatment procedures to enable use of the reactive aggregates in concrete.

1.2 Purpose of the study

Alkali-aggregate reactivity is complex in nature. Although research studies have been going on for the past four decades, the actual causes and mechanisms of the expansion are not fully understood at present.

Most of these reactive rock aggregates perform very well in asphalt or bituminous mixes. They are perfectly durable when used as building stone (Rogers, 1985). They have low porosity, are tough, dense, and resistant to abrasion and surface wear. Normal petrographic examination as performed in many laboratories sometimes does not fully identify potentially reactive aggregates. Recent work by the Ontario Ministry of Transport and Communications (Rogers, 1983, 1985, 1986) has shown that some rocks in Ontario, for example, previously thought to be unreactive are in fact reactive.

It is most important that reliable screening techniques and rapid testing methods be performed to identify and thoroughly investigate potentially reactive aggregates before use in expensive engineering works. Unfortunately, however, the current test methods are slow, expensive, time-consuming - requiring frequent monitoring for up to one year or more, and in most cases cannot be used for quality assurance testing.

In view of the slow rate of testing, high costs, and the unreliability of the current standard testing methods, the primary objectives of this study are to:

a. (i) develop a rapid, simple, inexpensive, and reliable new method(s) for screening potentially alkali-reactive concrete aggregates;

(ii) correlate the newly developed test methods with existing standard ASTM and CSA test methods; and

b. use the new test methods to evaluate the performance of concrete containing reactive aggregates subjected to various treatment processes.

Six reactive and two non-reactive rock aggregates from various active quarries in Ontario, Canada, were used for the study. Three of the reactive aggregates are carbonate-reactive, two are silica-reactive, and one silicate-reactive rock.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Concrete as a composite material

Concrete is a composite material consisting of a binder, which is portland cement and water, and a filler material, called aggregate. The aggregates - fine and coarse, are normally composed of sand and gravel or sand and crushed rock and comprise about three-quarters of the volume of the concrete; the cement paste together with the air voids occupy the rest (Mindess and Young, 1981). Sometimes concretes are made with small amounts of admixtures and these confer certain benefits to the concrete. The active constituent in the concrete is the cement paste and the performance of the concrete in service is largely determined by the properties of the cement paste (Neville, 1981).

Concrete is said to be durable if both the cement paste and the aggregates are durable and sound, respectively. Since the bulk of the concrete is composed of aggregates, any unsoundness in the aggregate leading to an increase in volume definitely affects volume stability, durability, structural integrity, and ultimate performance of the concrete (Dolar-Mantuani, 1985).

Reactive aggregates when used in concrete produce volume expansion; the expansion increases with increase in concentration of alkalies in the cement or from the environment. A portland cement containing less than or equal to 0.6% alkalies expressed as Na_2O equivalent ($\%Na_2O + 0.658\%K_2O$) by weight of cement is considered a low-alkali cement; a cement with high alkali increases the potential for alkali-aggregate reaction. Other factors which influence alkali-aggregate reactivity are temperature, moisture, and permeability of the cement paste. The latter is governed by the water/cement ratio and the degree of hydration of the cement constituents.

There are at present three known types of alkali-aggregate reactions. These are alkali-carbonate reaction, alkali-silica reaction, and alkali-silicate reaction. In Canada, and Ontario in particular, all three types have been identified and well documented (Gillot, 1975; Grattan-Bellew and Gillot, 1987).

2.2 Alkali-carbonate reaction and expansion

2.2.1 Mechanism of reaction and expansion

The reaction between certain fine-grained dolomitic limestone aggregates in concrete and the alkalies in the cement paste is known as alkali-carbonate reaction. This type of chemical reaction which was first detected in Canada by Swenson (1957) is believed to occur when the alkalies released from the cement during hydration attack the dolomite crystals in the reactive rocks (Hadley, 1961). The reaction can be written as:

$$\begin{array}{ccccccccc} CaMg(CO_3) & + & 2MOH & = & Mg(OH)_2 & + & CaCO_3 & + & M_2CO_3 \\ \text{Dolomite} & & \text{Alkali} & & \text{Brucite} & & \text{Calcite} & & \text{Alkali carbonate} \end{array} \qquad (1)$$

where,

M = K, Li, and Na.

This type of reaction in concrete is normally referred to as dedolomitization reaction (Swenson and Gillot, 1967). In concrete, the alkali carbonate produced in Reaction (1) is soluble and will react with calcium hydroxide occurring as a hydration product of the portland cement; for example,

Na_2CO_3	+	$Ca(OH)_2$	=	$2NaOH$	+	$CaCO_3$	(2)
Sodium carbonate		Calcium hydroxide		Sodium hydroxide		Calcium carbonate	

The calcium carbonate ($CaCO_3$) is insoluble, hence, it precipitates out of the solution. As Reaction (2) regenerates the alkali hydroxide, the dedolomitization reaction continues until the dolomite is completely reacted, or until the alkali hydroxide concentration is sufficiently reduced by secondary reactions (Hadley, 1961).

Many hypotheses have been proposed to explain the nature of the expansion encountered with reactive carbonate rocks. These include chemical (Walker, 1978), mechanical (Hadley, 1961; Newlon and Sherwood, 1964; Swenson and Gillot, 1964), and osmotic (Hadley, 1964; Swenson and Gillot, 1964) processes. One thing these hypotheses have in common and perhaps agree upon is that a chemical reaction called dedolomitization occurs. Out of these hypotheses, however, the osmotic pressure mechanisms, particularly those proposed by Hadley (1964) and Swenson and Gillot (1964), have so far provided the best correlation between hypothesis and observation.

According to the hypothesis proposed by Hadley (1964), there is migration of alkalies from the pore solution of the cement paste to dolomite crystals in the rock. The alkalies react with the dolomite to cause dedolomitization reaction as in Reaction (1). The products formed around the dolomite particles are: alkali carbonate, M_2CO_3, calcium carbonate, $CaCO_3$, and magnesium hydroxide (brucite), $Mg(OH)_2$ (Figure 2.1).

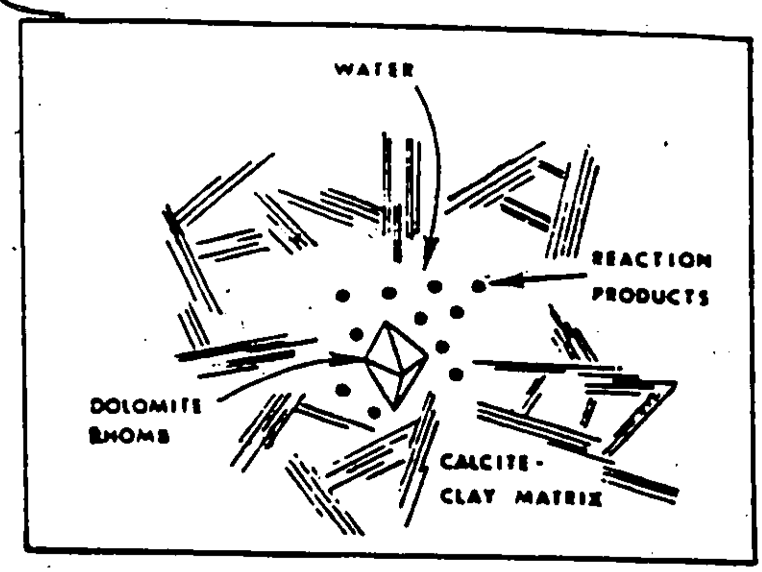


Figure 2.1: Possible expansion mechanism as proposed by Hadley (1964) showing dedolomitization products "trapped" around dolomite rhomb and the flow of water toward the high concentration of ions.
Source: Pagano and Cady (1982a).

Brucite $Mg(OH)_3$, is only slightly soluble but the alkali carbonate M_2CO_3 is more soluble and enters solution as in

Reaction (2). A high concentration of alkali carbonate in solution will then exist around the dolomite rhombs.

The interstitial clay around each rhomb acts as a semi-permeable membrane which "locks" the highly concentrated solution around the dolomite, but allows water to pass in the other direction. This sets up an osmotic pressure around the dolomite rhombs in the matrix of the rock, causing expansion. Thus, in the presence of higher dolomite content in the rock and higher alkaline solution, expansion increases.

Swenson and Gillot (1964) performed tests with dolomitic limestone aggregates from a quarry near Kingston, Ontario, Canada. This rock type is described in Section 2.2.2. In their hypothesis, there is initial dedolomitization reaction as in Reaction (1). However, according to them, the dolomite crystals in this reactive rock were formed under conditions of great pressure and zoned with inclusions of cloudy clay material consisting essentially of illite. The included clay is initially free of water but easily swells and exerts expansive forces when the unwetted surface, which is in an "active" state, is exposed to water. Thus, the large pressures developed by the swelling of the clay cause expansion, and cracks are formed. The cracks and channels open up the dolomite rhomb, permitting more water to reach the clay mineral. Thus, in the presence of water, the expanding clay lattice produces excess swelling pressures which physically break down the rock and concrete.

2.2.2 Nature of reactive carbonate rocks

The majority of the rocks that cause expansive alkali-carbonate reactions are dolomitic, argillaceous, and extremely fine-grained limestones with rhombs of dolomite dispersed in the matrix of the clay and finely disseminated calcite (Swenson, 1957; Gillot, 1963). The small rhombs of dolomite which occur in the microstructure of the alkali-expansive carbonate rocks are generally under 25um in diameter. Hand specimens are noted for their fine grain, conchoidal fracture and are frequently dark in color. The matrices appear darker in standard-thickness (30um) petrographic sections (Walker, 1974).

A particular kind of such reactive rocks found near Kingston, Ontario, is of Middle Ordovician age (Dolar-Mantuani, 1975; Swenson, 1957), has low porosity, and good physical properties (Swenson and Gillot, 1967). Hadley (1961) reported similar aggregates in Iowa, Illinois, and Indiana. Newlon and Sherwood (1964), also found expansive alkali-reactive carbonate rocks of the same type in Virginia. Despite their widespread geographic occurrence, one remarkable aspect of these reactive carbonate rocks is that they have the same texture, that is, rhombs of dolomite "floating" in a silty and clayey micrite-sized calcite matrix, with high amounts of acid-insoluble residue and approximately equal amounts of calcite and dolomite (Walker, 1974). The dedolomitization rate is found to be highest when the calcite to dolomite ratio in the reactive rock is nearly or equal to one (Hansen, 1964).

2.3 Alkali-silica reaction and expansion

2.3.1 Mechanism of reaction and expansion

Alkali-silica reaction is a chemical reaction between the hydroxyl ions (OH) in the pore solution of the cement paste and certain forms of silica which occasionally occur as part of the concrete aggregate (Hobbs, 1978). The reaction product is a gel, containing silica, sodium, potassium, calcium, and water (Gutteridge and Hobbs, 1980). The gel which is colourless but white when dry, imbibes water and occasionally induces internal stresses of such magnitude that extensive cracking occurs (Hobbs, 1978).

There is a controversy over the actual mechanism of the alkali-aggregate reaction. One group of researchers, for example Hansen (1944) and Dent Glasser and Kataoko (1981) consider that the expansion is associated with osmotic pressures generated by alkali-silica reaction products confined within an effective membrane of the cement paste. Other investigators, for example, Vivian (1950) and Hobbs (1981) argue that the expansion is mainly caused by a mechanical pressure exerted by the growing volume concentration of the reaction products. In each of these schools of thought, there is a common aggreement on the steps proposed by Hansen (1944), which lead to distress in the concrete. The four distinct steps are as follows:

(i) initial alkaline depolymerization and dissolution of reactive silica;

(ii) formation of a hydrous alkali-silica gel;

(iii) attraction of water by the gel;

(iv) formation of a fluid sol (a dilute suspension of colloidal particles);

The first step depends on the alkalinity of the pore solution. Alkaline hydrolysis opens up the structure of the aggregate and allows the pore fluid to further hydrolyze the reactive silica (Chaiken and Halstead, 1960).

In the second and third steps, the gel, as it takes up water, expands and fills the voids present in the concrete. This reduces the permeability to some extent but creates expansive stresses in the concrete (Stark, 1980). The fourth step takes place when expansion has occurred and further absorption of water by the gel turns the solid gel into a fluid sol which in some cases escape into surrounding cracks and voids as exudations (Tuthill, 1982).

2.3.2 Nature of reactive silica rocks

The rocks and minerals involved in the deleterious alkali-silica expansive reaction include the vitreous, poorly crystalline, and strained forms of silica which occur in sedimentary, igneous, and metamorphic rocks in the form of opal, chert, chalcedony, cristobalite, and tridymite (Mielenz, 1958; Buck, 1983; Hobbs, 1986; Grattan-Bellew and Gillot, 1987).

Others are cryptocrystalline rhyolites, dacites, latites, opaline concretions, fractured, strained, and inclusion-filled quartz and quartzites, as well as andesites (Mielenz, 1954).

Table 2.1 lists rocks, minerals, and synthetic substances known to be potentially deleterious concrete aggregates. In concrete structures where serious expansion and cracking have occurred as a result of alkali-silica reaction, the aggregate is frequently found to contain opaline silica. For this reason, opal is considered to be the most alkali-silica reactive mineral (Mielenz, 1958a). Opaline silica is a common constituent of cherts, volcanic rocks and tuffs, some shales, sandstones, limestones, coating materials on aggregates, and weathered rocks.

Table 2.2 is a summary of results of reactivity of various forms of silica at room temperature by Gaskin et al., (1955).

2.4 Alkali-silicate reaction and expansion

2.4.1 Mechanisms of reaction and expansion

A kind of reaction between some metamorphosed sedimentary rocks and alkalies in the pore solution of the paste of concrete is termed alkali-silicate reaction. The reaction is extremely slow but expansive. Alkali-silicate reaction was first recognized in Nova Scotia, Canada (Duncan et al., 1973), but currently, there are reported cases of such reactions in Sudbury, Northern Ontario (Grattan-Bellew, 1978), Ellesmere Island, Northwest Territories (Gillot and Swenson, 1973), South Africa, and New Zealand.

TABLE 2.1

Rocks, Minerals and Synthetic Substances Potentially Deleterious as Concrete Aggregates

Reactive Substance	Chemical Composition	Physical Character
Opal	$SiO_2.nH_2O$	Amorphous
Chalcedony	SiO_2	Microcrystalline to cryptocrstalline; commonly fibrous
Certain phases of quartz	SiO_2	Microcrystalline to cryptocrystalline; Crystalline but intensely fractured, strained, and/or inclusion-filled
Cristobalite	SiO_2	Crystalline
Tridymite	SiO_2	Crystalline
Rhyolitic, dacitic, latic, or andesitic glass or cryptocrystalline devitrification products	Siliceous, with lesser proportion of Al_2O_3, Fe_2O_3, alkali earths, and alkalies	Glass or cryptocrystalline material as the matrix of volcanic rocks or fragments in tuffs
Synthetic siliceous glasses	Siliceous, with lesser proportions of alkalies.	Glass

Source: Mielenz (1958a)

TABLE 2.2

Summary of Reactivity of Various Forms of Silica obtained at room temperature

Form of Silica	Reactivity
Macrocrystalline quartz	No sign of reactivity
Microcrystalline quartz	Slightly reactive
Cryptocrystalline quartz	Slightly reactive
Chalcedonic silica	Reactive and causes expansion when present in sufficient quantity (5-20%).
Opal	Strongly reactive and causes expansion
Christobalite	Reactive and causes expansion
Tridymite	Behaviour similar to cristobalite but less reactive

Source: Gaskin, Jones and Vivian (1955).

The mechanism of reaction is similar to that of alkali-silica reaction except that it is much slower. The attack of the reactive constituents in the aggregate by the cement alkalies results in the formation of a colourless silica gel. This gel imbibes water and expands. The expansion leads to cracking and ultimate deterioration of the concrete (Gillot, 1975).

One distinguishing feature of the alkali-silicate reaction from the alkali-silica reaction is that, the expansion of the individual rocks suggests adsorption of water on the previously "dry" alumino-silicate surfaces in the microcrystalline portion of the rock (Rogers, 1985). In addition, the results of some of the diagnostic tests used for detecting the alkali-silica reaction are misleading when used for suspected alkali-silicate rock aggregates. Both the quick chemical test (ASTM C 289) and the mortar bar test (ASTM C 227), if not well controlled and properly monitored give unreliable results (Grattan-Bellew, 1981).

2.4.2 Nature of reactive rocks

The rocks in this category are essentially argillites, phyllites, greywackes, schists, quartzites, and some glassy cryptocrystalline volcanic rocks (Gillot, 1986). The greywackes are composed of quartz and feldspar with accessory rock fragments (Grattan-Bellew and Gillot, 1987). According to Gillot (1986), some of the greywackes contain significant amount of clayey material which gives them a dark appearance.

The other types of rocks are generally sheared and the crystals are found to be commonly strained; the mica-type minerals and argillaceous constituents occur in the matrices. The phyllites and argillites usually contain minerals showing varying degrees of crystallization, shear, and preferred orientation (Duncan *et al.*, 1973).

2.5 Factors affecting alkali-aggregate reactions

2.5.1 Introduction

All alkali-aggregate reactions are affected by a number of common factors. The most important of them are: the type and concentration of alkalies, moisture or relative humidity of the environment, temperature, and admixtures (Gillot, 1975).

2.5.2 The alkalies in cement and their concentration in pore solutions of cement paste

The term "alkali", as used in connection with alkali-aggregate reactions, is sometimes a subject of controversy. Chemically speaking, the alkalies are those elements occupying the first column of the periodic table, for example, lithium, sodium, potassium, rubidium, and the rest. Of these, only sodium and potassium are common in cements (Lea, 1970). The others occur as insignificant amounts and are usually ignored.

Sodium and potassium are effective in causing distress in concrete (Davis, 1958; Swenson and Gillot, 1960), however, lithium tends to inhibit distress (McCoy and Cadwell, 1951). Results of studies of the comparative effects of high sodium versus high potassium contents, carried out by Davis (1958) suggested that the expansion is better correlated with the total alkali content expressed as equivalent percent Na_2O than to individual contents of sodium or potassium.

Despite its name, however, the fundamental reaction is not between alkali ions and the reactive aggregates, but between hydroxide ions (OH^-) and aggregate (Diamond, 1975). Vivian (1951) showed that attack on opal (and presumably on other reactive aggregates) depends on a high concentration of hydroxide ions in the solution and does not require a high concentration of alkali metal cations themselves.

It is widely believed that pore fluids in cement pastes of concrete are saturated with calcium hydroxide, $Ca(OH)_2$, formed as a hydration product of the calcium silicates in the cement. This opinion leads one group of investigators to believe that removal of lime, $Ca(OH)_2$, from the pore solution will prevent alkali aggregate reactivity (Chatterji, 1979; Chatterji <u>et</u> <u>al</u>., 1986). This concept is, however, misleading in that the concentration of the calcium hydroxide in the pore solution is far less than that required for promotion of the reaction. In fact, pure saturated calcium hydroxide solutions at room temperature have hydroxide concentrations of 0.04 moles/litre which is not enough to initiate the chemical reaction (Diamond, 1975). Research studies by Greenberg and Mehra (1963), Lawrence (1966), and Roberts (1968) on fresh and hardened cement pastes indicated that the hydroxide concentration ranged between 0.04 to 0.15 moles/litre for low-alkali cement and 0.08 ~~to~~ 0.70 moles/litre for high-alkali cements after the 28-day-old testing. It is therefore obvious that the alkalies NaOH and KOH in concrete pore solutions are principally responsible for the attack upon alkali-expansive rocks and minerals. A high amount of these alkalies in the cement will therefore increase the hydroxide concentration in the pore solution causing greater reactivity and consequent expansion in the concrete.

2.5.3 Effect of moisture

Moisture has been shown to be a requirement for expansion in all varieties of alkali-aggregate reaction. Tests have shown that concrete and mortar specimens containing potentially highly reactive aggregates, stored at low relative humidity, showed little or no expansion (Gillot, 1986). Field observations shows that concrete distress is most common in locations where there is availability of moisture, such as footings, bridge decks, dams and sidewalks (Gillot, 1975).

Inflow of water into concrete is dependent primarily on the permeability of the cement paste, and the factor which controls the permeability is the water/cement ratio (Neville, 1981). A high water/cement ratio increases water ingress into the concrete. Expansion of concrete and mortars can therefore be reduced by decreasing the water/cement ratio. However, this is not always the case. Grattan-Bellew (1983), reported an increase in expansion of mortar bars containing reactive aggregate with decreased water/cement ratio. He attributed this to an increase in concentration of alkali hydroxide ions in the pore solution.

Figure 2.2 shows the influence of water/cement ratio on expansion of alkali-silica reactive aggregates. Expansion in this case was found to be maximum at a water/cement ratio of about 0.42.

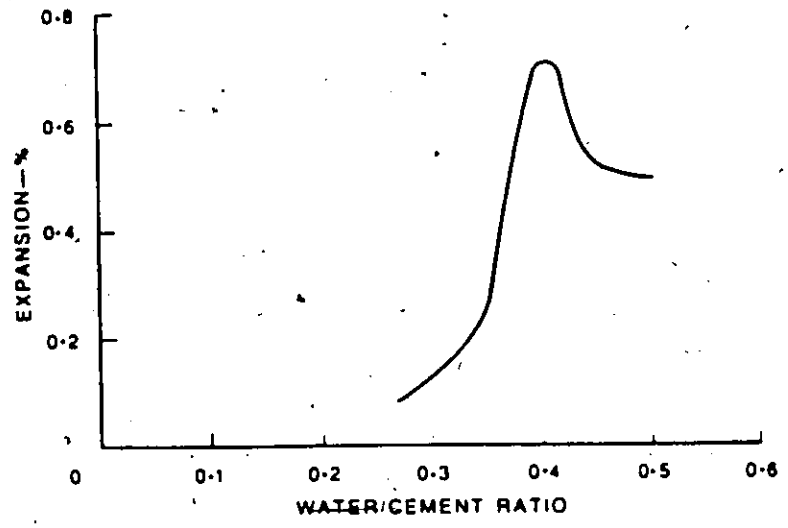


Figure 2.2: Influence of water/cement ratio upon expansion..

Source: Hobbs (1980).

2.5.4 Effect of temperature

Increases in temperature accelerate alkali-aggregate reactions as it does in all chemical reactions (Gillot, 1975). Initial expansion increases with increasing temperature, however, there have been reports of decrease in expansion with increasing temperature (Lerch, 1946; Swenson and Gillot, 1950).

In the alkali-silica reaction, the greatest expansion was at first reported to occur at 38°C, minimum expansion occurred at 10°C, and no significant expansion occurred at 60°C (Gudmundsson, 1973 in Gillot, 1975). However, recent work by Oberholster and Davies (1986) shows that highest expansion occurs in the neighbourhood of 80°C with reactive silica aggregates. Higher temperature conditioning has therefore been used as a means of accelerating expansion in test procedures (Chatterji, 1979; Ming-shu _et al_., 1983; Gogte, 1973; Oberholster and Davies, 1986).

2.5.5 Effect of admixtures

Some mineral admixtures which include natural pozzolans, flyash, pulverised blast furnace slag, and silica fume have been found to reduce expansion due to _alkali-silica_ and _alkali-silicate_ reactions (Stanton, 1949). A pozzolan is a "siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" (ASTM, 1986). Fly ash is a finely divided residue that results from the combustion of ground or powdered coal (ASTM, 1986). Condensed silica fume is a by-product of ferro-silicon industry. It is very finely divided with a high specific surface - about three times that of ordinary portland cement.

The pozzolans are generally used to replace part of the cement - about 25-65% by weight of the portland cement (Gillot, 1975). Experimental evidence (Gaze and Nixon, 1983) shows that reduction in expansion is not simply due to reduction in alkali content of the concrete which may result from cement replacement. In fact, the alkali content of some pozzolans far exceeds that of the cement replaced (Grattan-Bellew, 1983). The action of the pozzolans is that of a reaction between calcium hydroxide in the paste at ordinary temperatures to form compounds possessing cementitious properties, thereby reducing the hydroxide concentration and the permeability of the cement paste (Urhan, 1986). The effectiveness of this method of control, however, varies greatly with the type of pozzolans and with the type of chemical reaction. Mineral admixtures have not as yet proved effectiveness with alkali-carbonate reactions.

Some organic admixtures as well as calcium chloride ($CaCl_2$) and common salt (NaCl) have also been reported to affect expansion due to alkali-aggregate reaction. Alkali-aggregate reaction is found to increase with increased chloride content (Chatterji, 1978; Gillot, 1986).

2.6 Field evidence of alkali-aggregate reaction

Concrete which has been affected by alkali-aggregate reaction commonly develops a distinctive form of cracking often referred to as "pattern cracking" or "map cracking" (Figures 2.3 and 2.4) (Swenson, 1957; Hadley, 1964). Its appearance is the same all over the world and similar regardless of the type of alkali-aggregate reaction. Sometimes the developed cracks are visible only when the surface is moistened with water (Gillot, 1975).

Figure 2.3: Portion of the Beahurnois Dam, Quebec, constructed with reactive alkali-silica aggregate (Potsdam sandstone) showing pattern and map cracking. (Photo by Dr. Peter Hudec, 1986).

Figure 2.4: Pattern and map cracks in a sidewalk in Cornwall, Ontario, constructed with reactive alkali-carbonate rock aggregates from Cornwall, Ontario. (Photo by Dr. Peter Hudec, 1986).

There may also be evidence of expansion such as increase in dimensions of concrete elements; closing of joints and squeezing out of joint-filler materials; buckling of adjacent members and the crushing of weaker concretes (Walker, 1974). A colourless gel is a product of alkali-silica and alkali-silicate reactions, and when dry, this appears as white deposits on external surfaces and may be seen on internal surfaces filling-in cracks and void spaces (Hobbs, 1978).

During the initial stages of expansion, larger aggregate particles, particularly carbonate reactive ones, tend to show dark rims, which, when split open, show growth towards the interior of the particle. The rims sometimes serve as primary indications of reactions between the alkalies of the cement paste and the aggregate. Presence of the rims alone does not necessarily provide indication of alkali-aggregate reaction. This is because rims could also surround the gravel particle in the field prior to their use as aggregate. Rims also form in concrete owing to non-deleterious reactions between aggregates and concrete pore solutions during hydration of the cement (Gillot, 1986). Absence of the rims, however, does not imply absence of reaction.

In less resistant concretes, pop-outs and cracked aggregate particles serve as further indications of alkali-aggregate reaction.

2.7 Standard test methods for alkali-aggregate reactions

2.7.1 Introduction

The standard test methods for potential alkali-aggregate reactivity include: The Petrographic Examination, ASTM C 295; The Mortar Bar Method, ASTM C 227; The Concrete Prism Expansion Method, CSA A23.2 - 14A; The Chemical Method, ASTM C 289; and The Rock Cylinder Expansion Method, ASTM C 586.

The test for potential reactivity of aggregates (Chemical Method, ASTM C 289) is specifically designed to detect the amount of silica from the reactive rock which reacts with cement alkalies, and for this reason, it is not a suitable test for carbonate reactive rocks. The rock cylinder expansion test method is used to measure the change in length of small right circular cylinders by soaking them in 1M NaOH solution for 28 days. The method is not suitable, especially, for late or slow expansive rocks which require long periods of immersion. For this reason, this test method as well as the chemical method, ASTM C 289, were not employed in this study and will not be discussed further.

2.7.2 Petrographic Examination - ASTM C 289

This test method is designed to determine the physical and chemical characteristics of the aggregates that may be observed by petrographic methods. It is used to determine the relative amounts of the reactive constituents in the sample, and, if possible, to predict the performance of the reactive aggregates.

This is done by comparison with test data or service record of a known sample. The test is essentially a preliminary or screening test.

The basic procedure in this test method involves taking a representative sample of the suspect rock aggregate. With a stereoscopic microscope the particles are noted for features such as coatings or encrustations. The rock particles are then separated into groups depending on the rock type and quality. This is done with the aid of a hand lens, a pen knife, and a bottle of weak acid usually after washing the particles.

The relevant features normally noted include: particle shape, particle surface, texture, grain size, internal structure, packing and cementation of grains, colour, mineral composition, significant heterogeneities, general physical conditions of the rock types in the sample such as hardness, whether fractured or strained, and presence of constituents known to cause deleterious chemical reactions. Sometimes particle counts and quantification, if possible, of the various types of rock in the sample are also done.

2.7.3 The Mortar Bar Test - ASTM C 227

This is the standard test method used to determine the susceptibility of cement aggregate combinations to expansive reactions involving hydroxyl ions. The change in length of mortar bars containing the reactive aggregate is the variable measured for.

The apparatus, sample selection and preparation, grading requirements of the suspect aggregate, and details of the test procedure have been fully described in the Annual Book of ASTM Standards, Section 4 C 227. In this test, 25mm x 25mm x 300mm mortar bars containing the suspect aggregate are made. The maximum size of the aggregate is usually 4.0mm. The alkali content of the cement is usually raised to about 1.25% Na_2O equivalent. After casting, the bars are kept in the moulds at 38°C for 24 hours. The bars are then brought to room temperature (about 23°C) and the initial length measured. Following the initial length measurement, the bars are transferred into sealed containers or a moist chamber at a temperature of about 38°C. Length changes of the mortar bars are monitored with a suitable comparator for a period up to one year or more. Expansion greater than 0.05% at three months or 0.10% at six months is considered excessive. The mortar bar test is found to be too slow for alkali-carbonate reaction; the expansion produced after a period of one year is found to be insufficient for suspect carbonate rock aggregates to be classed as reactive (Swenson, 1957). For this reason, the test method is confined to alkali-silica reaction. When used for alkali-silicate reactive rocks, the temperature is usually elevated.

2.7.4 Concrete Prism Expansion Test - CSA 23.2 14A

The concrete prism expansion test method is suited to alkali-carbonate reactive aggregates. When used for siliceous and silicate aggregates, the expansion is best manifested at a temperature of about 38°C instead of the usual testing temperature of 23°C.

In this test, concrete prisms 120mm x 120mm x 450mm are made with suspect aggregate and normal portland cement. The prisms, after demoulding, are stored in a moist cabinet or a room for a period of at least one year and the associated expansions are measured with a suitable comparator periodically. The alkali content of the cement is usually increased to about 1.25% Na_2O equivalent (%Na_2O + 0.658%K_2O). Sometimes the prisms are exposed to de-icing salts. Details of sample selection, preparation, gradation, and storage conditions have been described in the Canadian Annual Book of Standards, CSA A23.2 1977. Expansion of the prisms greater than 0.025% at one year is considered excessive.

2.8 Methods of preventing alkali-aggregate reactions

2.8.1 Introduction

Once an aggregate has been identified as potentially expansive, there are various precautions that can be taken to arrest or suppress its reactivity in the concrete. The traditionally employed methods of preventing, or at least minimizing expansion due to alkali-aggregate reactions, include:

(i) use of an alternative source of aggregate (Smith, 1964);

(ii) dilution of aggregate with a non-reactive rock (Newlon and Sherwood, 1964; Walker, 1978);

(iii) beneficiation of aggregate (Swenson, 1972);

(iv) use of low-alkali cement (Swenson, 1972);

(v) protection of concrete from mortar and design considerations (Walker, 1978);

(vi) use of a proven pozzolan or other mineral admixtures (Mather, 1974);

(vii) and use of chemical additives (Newlon et al, 1971).

2.8.2 Use of alternative source of aggregate

The most obvious solution to potential durability problems due to alkali-aggregate reaction is the use of an alternative source of aggregate. Owing to the high cost of transportation, however, this option is not always feasible unless the alternative source is close to the concrete plant (Gillot, 1986). The method is also suitable in instances such as bridge construction, where the cost of the aggregate is only a small fraction of the total cost (Grattan-Bellew, 1983).

2.8.3 Dilution of aggregate with non-reactive rock

Dilution of potentially reactive aggregate with a non-reactive rock is sometimes employed if it is not economically feasible to avoid the use of the potentially reactive material. The dilution is usually up to about 80% of the coarse aggregate (Walker, 1974). The dilution method is seldom practised owing to cost of transportation of the non-reactive rock and cost of blending. In addition, tests need to be performed to determine the optimum blend for reducing deleterious expansion. The dilution method has, however, been applied to carbonate aggregates in the United States where dilution of 50% or more was used to reduce the expansion to acceptable levels (Newlon and Sherwood, 1964).

2.8.4 Beneficiation of reactive aggregates

Beneficiation of reactive aggregates is a process whereby the potentially reactive rock is removed, rendered inert by use of a protective coating, or prevented from contaminating durable aggregates in a stockpile or a quarry. There are various methods employed which include crushing techniques, coating of reactive aggregates with water-proof agents, or satisfying internal charges of aggregates (Hudec, Personal Communication). However, the two most commonly employed methods are selective quarrying and density separation (Grattan-Bellew, 1983).

Selective quarrying is the most common method used in all beneficiation techniques, but it is restricted essentially to horizontally layered beds of limestone and to igneous deposits with reactive dykes, where reactive dykes cut across durable aggregates.

Density separation can be used only when there is a significant difference between the reactive component and the good aggregate. This method was employed to remove opaline gravel by heavy media separation for the construction of the

Saskatchewan River Dam (Price, 1961). The main drawbacks in this method are the cost involved and the need for a marked difference in density between the reactive and non-reactive aggregates.

2.8.5 Use of low-alkali cement

This is the most commonly applied method of preventing deleterious expansions due to alkali-aggregate reactions. Unfortunately, the method is not always successful (Woolf, 1952; Stark, 1978). The reasons include difficulties in ensuring that low-alkali cement is actually in the concrete delivered at the construction site (Rogers, 1985). Another reason is that highly reactive rocks, such as those at Kingston and Cornwall, Ontario, may cause expansion even with low-alkali cement, especially at high temperatures (Swenson and Gillot, 1964). Furthermore, even if low-alkali cement is used, addition of alkaline earth salts ($NaCl$ and Na_2SO_4) to the concrete from groundwater or through the use of de-icing salts can still cause expansion. The sodium ions (Na^+) from the $NaCl$ and Na_2SO_4 for example, pick the hydroxyl ions (OH^-) from $Ca(OH)_2$ in the pore solution to form $NaOH$, which increases the alkali hydroxide concentration and initiates the reaction (Ming-shu et al., 1983; Chatterji, 1978).

2.8.6 Protection from moisture and design considerations

Laboratory studies conducted by Ludwig (1981) shows that the critical humidity above which expansion occurs in mortar is 85% R.H. The alkali-carbonate reaction has also been shown to produce expansive forces only when water is available (Swenson;

1957). If concrete is therefore kept dry, no damage will occur even though reactive aggregates may be used with high-alkali cements.

The degree of saturation and rate of flow of water into concrete or mortar is governed by the physical properties of the concrete, namely, the permeability and porosity of the paste, and the properties of the aggregate (Verbeck and Landgren, 1960; Powers, 1956). The permeability of the paste is controlled by the water/cement ratio of the concrete. All things being equal, a low water/cement ratio will produce a low permeability cement paste (Neville, 1981). Because expansion takes place only in the presence of moisture, the potentially reactive rock used with a moderately low-alkali cement will produce no appreciable deleterious expansions if a suitably low water/cement ratio is used (Walker, 1978).

In addition, if a known potentially reactive aggregate is to be used, the concrete structure or pavement could be designed to accommodate small amounts of expansion by providing expansion joints.

2.8.7 Use of a pozzolan

The effect of pozzolans on alkali-silica and alkali-silicate reaction has already been outlined in Section 2.5.5. The preventive effect of natural aggregates for example, tuff, as well as cementitious materials such as fly ash, pulverized blast furnace slag, and recently, silica fume has been investigated by many researchers (Stanton, 1949; Chatterji and Clausson-Kaas, 1974; Dunstan, 1981; Gaze and Nixon, 1983; Ming-shu et al, 1983; Hobbs, 1986; Davies and Oberholster, 1987; Diamond, 1981; Perry and Gillot, 1985; Collins and Bareham, 1987).

The mechanism of suppression of the expansive reaction involves reaction of the active component of the pozzolans with $Ca(OH)_2$ in the concrete to produce a C-S-H gel similar to that formed by hydration of the cement paste (Mindess and Young, 1981). This reaction reduces the akalinity which consequently inhibits further alkali-aggregate reaction. The C-S-H gel produced also fills some of the voids in the paste, which reduces the permeability of the paste, hence ingress of water. Pozzolans are usually used in amounts of up to 25-65%. The extra gel produced by the pozzolan reaction, coupled with the removal of porous $Ca(OH)_2$ has been found to reduce both the porosity and permeabilty in the cement paste (Bakker, 1981).

2.8.8 Use of chemical additives

Other preventive measures by use of chemical additives have been proposed. Many of these have been tested for their effectiveness (McCoy and Cadwell, 1951). Salts of lithium were found to be the most effective. The addition of 0.72% Li_2CO_3 caused a marked reduction in the expansion of test bars but, because of the high cost, it has not been used in practice. Recently, the addition of $FeCl_3$ has been proposed as a method of reducing expansion due to alkali-carbonate reactivity (Pagano and Cady, 1982a). Reduced expansions were observed but, in the case of the most expansive aggregate, 11% $FeCl_3$ had to be added to reduce expansions to safe level (Pagano and Cady, 1982b). This quantity, if used, can affect the setting of the concrete and possibly cause corrosion of reinforcing steel.

2.9 Use of the chemicals "IP" and "STP"

Research findings and results of work performed with the "STP" and "IP" are currently in the reviewing process for patenting. For this reason the chemical name and other properties of the "STP" and "IP" will not be disclosed. It is hoped however that the patent will be granted soon and when that is done the identity of these two chemicals will be disclosed.

The "STP" is an inorganic salt of moderate to high solubility at room temperature. It is acidic. Concentration of about 10% (by weight) solution of the "STP" has a pH of about 2.8-3.2. In the presence of a hydroxide ion (OH) as for example in a solution of sodium hydroxide (NaOH), there is precipitation of an insoluble inorganic material - the chemistry of which is still under study.

The "IP" is the intermediate product in the production of the "STP". In the raw form it occurs as granules. It is insoluble in water but in the presence of a hydroxide, it reacts to form a precipitate (Schincariol, 1986). Both the "STP" and the "IP" have been successfully used to prevent damage to carbonate rocks and concrete by frost (Schincariol, 1986).

The mechanism of suppresion of damage to rocks and concrete with "STP" is viewed to be more a physical than a chemical reaction. When a porous material, for example, rock or concrete containing some adsorped/absorped hydroxide, ions is brought into contact with a solution of the "STP", an insoluble precipitate is formed in the surface layer within the permeable pores of the material. The accessible outer pores become blocked or clogged, and since the pores are blocked, ingress of water into the material (the primary cause of most physical damage to porous materials) is prevented. Based on this principle, the "STP" could be applied to either the potentially reactive rock aggregate before its use in concrete or to the concrete containing reactive aggregates. In the latter case, application should be done immediately after the concrete is emplaced.

CHAPTER 3

3.0 SAMPLING AND GEOLOGY

3.1 Sampling

Three of the reactive rock samples (SUD, STT, KIN) for the study were supplied from the Materials Division of the Ministry of Transport and Communications in Toronto through Dr. Peter Hudec of the Department of Geology, University of Windsor. Dr. Hudec also provided three of the reactive aggregates. These were the alkali-carbonate reactive rocks from the McLeod Quarry in Cornwall and the alkali-silica reactive chert from the New Bigging Pit near Putnam, Ontario. The two non-reactive aggregates used as controls were obtained from the Civil Engineering Laboratory of the University of Windsor.

The sand used in casting the mortar bars, concrete prisms and blocks was supplied by George White and Sons from the Leamington Sand and Gravel Pit in Essex County, Ontario.

All the aggregate samples used in this study were collected from quarries with known service records and their descriptions have been given in Appendix A. Their locations are shown in Figure 3.

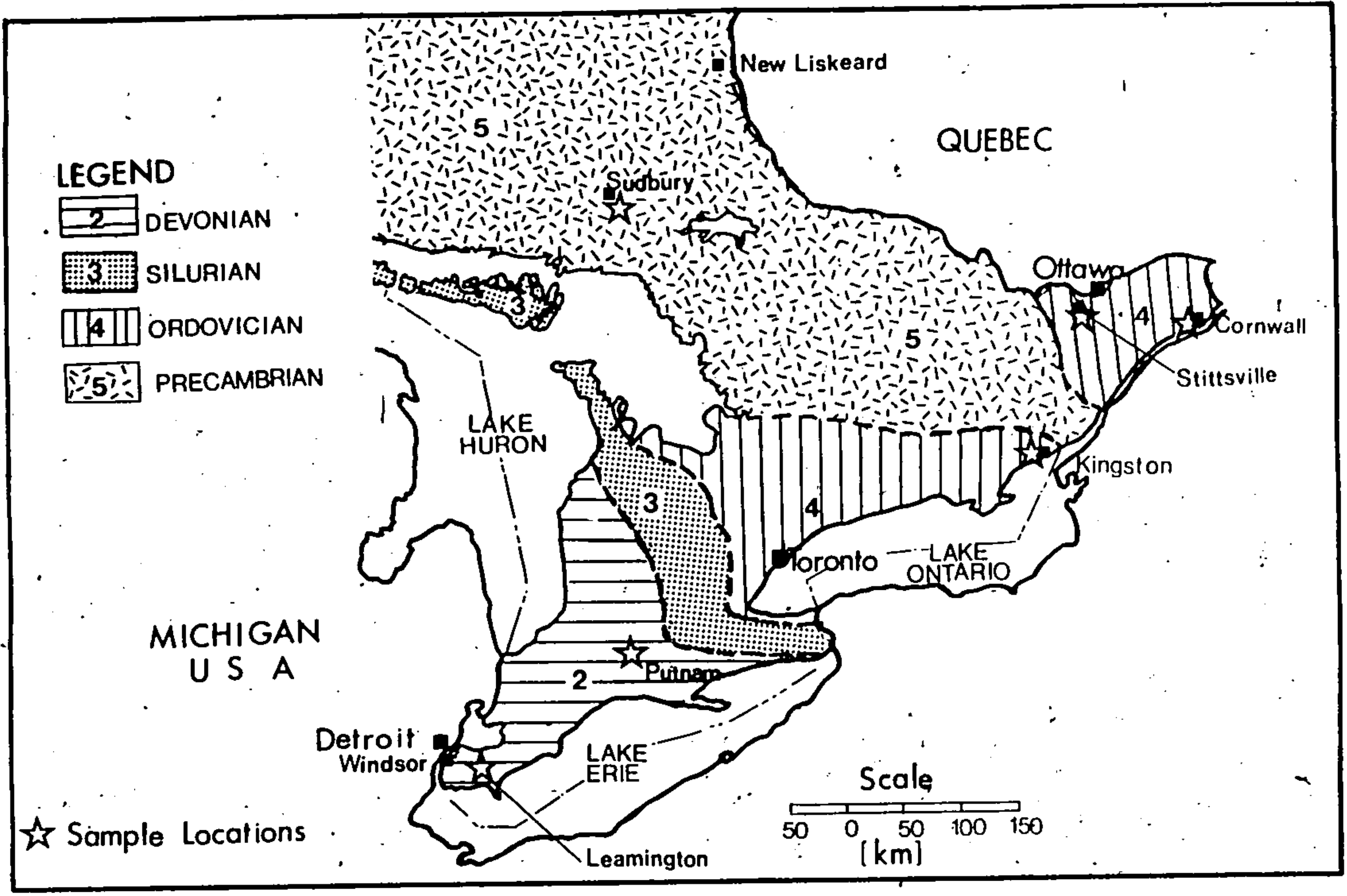


Figure 3: Generalized geology and sample location map.
Source: Rogers (1983)

3.2 Geology

There are four groups of reactive rocks used in this study. The first group of reactive rocks is alkali-silicate reactive. They consist of argillites, greywackes and quartz arenites (or quarzitic sandstones) of the Huronian Supergroup which is of Middle Precambrian Age (Magni *et al*., 1986). These rocks are found in northern Ontario from Blind River through Sudbury to New Liskeard (Figure 3). The percentage of reactive rock types in the gravels of the Sudbury area is between 65 and 90 percent.

The second group of alkali-reactive rocks are argillaceous dolomitic limestones. These rocks are alkali-carbonate reactive and belong to the Gull River Formation and the Ottawa Limestone which are Ordovician in age. Only certain beds are reactive. They are beds of fine-grained dolomitic limestone with significant clay mineral content (Dolar-Mantuani, 1969; Grattan-Bellew, 1981).

Near Stittsville, certain siliceous limestone of the Bobycaygeon Formation which is part of the Simcoe Group and Ordovician in age have been identified to be alkali-silica reactive. The reactive beds of the formation are medium-to fine-grained limestone. The colour is medium dark grey. The rocks are medium bedded with intercalations of slightly shaley and cherty limestone. The minerals involved with the alkali-silica reaction are vitreous, poorly crystalline, and strained forms of silica such as opal, chalcedony, and tridymite.

In southwestern Ontario near Putnam, cherts of Middle to Lower Devonian age have been identified to be <u>alkali-silica</u> reactive (Gillot and Swenson, 1973; Douglas, 1968). The colour of the cherts are dark blue, light blue and white. They are nodular and cryptocrystalline in texture. The reactive minerals are chert, opal, cristobalite, and chalcedony.

CHAPTER 4

4.0 EXPERIMENTAL PROCEDURES

4.1 Outline

In all, six different series of tests were performed during the one year study period. These tests could broadly be classed into two types of tests: screening tests and treatment tests.

The screening tests were designed to discriminate between potentially reactive and non-reactive aggregates. They included:

(A) Standard Tests:

- (i) ASTM C 227: Mortar Bar Test
- (ii) CSA A23.2 - 14A: The Concrete Prism Expansion Test

(B) Accelerated Tests:

- (i) Elevated Temperature (80°C ± 5°C) Test
- (ii) Ambient Temperature (23°C ± 2°C) Test

The principal accelerating condition was fortification of the concrete alkali with sodium hydroxide (1N NaOH) solution. Saturated salt (NaCl) solution was also used as a comparative reagent with sodium hydroxide solution.

The treatment tests were designed to evaluate the performance of concrete containing reactive aggregates subjected to various treatment processes.

They included:

(A) Partial replacement of sand used in casting concrete with "IP" (5% by weight of sand);

(B) Treatment of concrete containing reactive aggregates with 10% by weight solution of "STP";

(C) Treatment of reactive aggregates with 10% by weight solution of "STP" prior to use in casting concrete.

The details of the treatment processes are outlined in Section 4.2.5.

A single bag of cement was used throughout the entire study and after chemical analysis, its alkali content was found to be 0.781% Na_2O equivalent. The sand used in casting all the concrete and mortar was analyzed for its particle size distribution by dry sieving on the coarser fractions down to the portion retained on 75um sieve size.

Petrographic analysis, was carried out on all the rock samples. The standard ASTM and CSA tests employed in this study were, Petrographic Examination (ASTM C 295/MTC), Mortar Bar Test ASTM C 227, and Concrete Prism Expansion Test CSA A23.2 - 14A.

4.2 Description of procedures

4.2.1 Characterization of concrete components

4.2.1.1 Petrographic analysis of coarse aggregates (MTC)

About 600g of each aggregate were examined using a hand lens. The particle size of the aggregates ranged from 19.0mm (3/4") to 6.3mm (1/4"). A pen knife and a small bottle of weak hydrochloric acid were used to aid in separating the rock particles into groups depending on the rock type and quality. Four quality categories were recognized:

(i) Good aggregate, (Factor of 1);
(ii) Fair aggregate, (Factor of 3);
(ii) Poor aggregate, (Factor of 6);
(iv) Deleterious aggregate, (Factor of 10);

The manner in which the quality categories and factors were derived has been explained by Hudec (1982).

A petrographic number (P.N.) was calculated for each of the rock aggregates by multiplying the percentages of each group by the appropriate factor. The higher the petrographic number, the poorer the quality of the rock aggregate. The results have been presented in Appendix B. For concrete paving, the limiting petrographic number for aggregates is 125 or less and for structural concrete, the maximum allowable petrographic number is 140.

4.2.1.2 Particle size distribution of sand

About 800g of the sand were dried overnight in an oven maintained at 105°C. The sand was allowed to cool, then run through a series of well-cleaned sieves (4.75mm, 2.36mm, 1.18mm, 0.60mm, 0.30mm, 0.15mm, and 0.075mm), by sieving in a mechanical shaker according to the procedure outlined by Lambe (1951).

For the purpose of this study, the finer clay-sized fraction passing 0.075mm sieve and retained in the pan was not further analyzed. The particle size distribution and the parameters of the sand are shown in Figure B1 of Appendix B.

4.2.2 ASTM / CSA standard test methods

4.2.2.1 Sample preparation (ASTM/CSA)

All the rock samples described in Section 3.1, with the exception of the sand were initially crushed, washed, and oven-dried at a temperature of about 105°C for 24 hours in accordance with ASTM 14 C 227-81. After cooling, each sample was passed through a stack of sieves ranging from 19.5mm (3/4") to 0.60mm (0.024"), and sieved in a manner described in Section 4.2.1.2. The various sizes obtained from the sieve analysis were separately put into plastic bags and labelled.

4.2.2.2 Concrete Prism Expansion Test

In this test concrete prisms were made with the reactive carbonate aggregates previously mentioned in Section 3.1 and portland cement. The sizes of the prisms were modified slightly to suit the available laboratory facilities. The dimensions of all the prisms were the same and were approximately 150mm x 50mm x 50mm. Stainless steel studs of 5mm in diameter and 30mm in length were cast in the test prisms at the centre of each end (Figure 4.1).

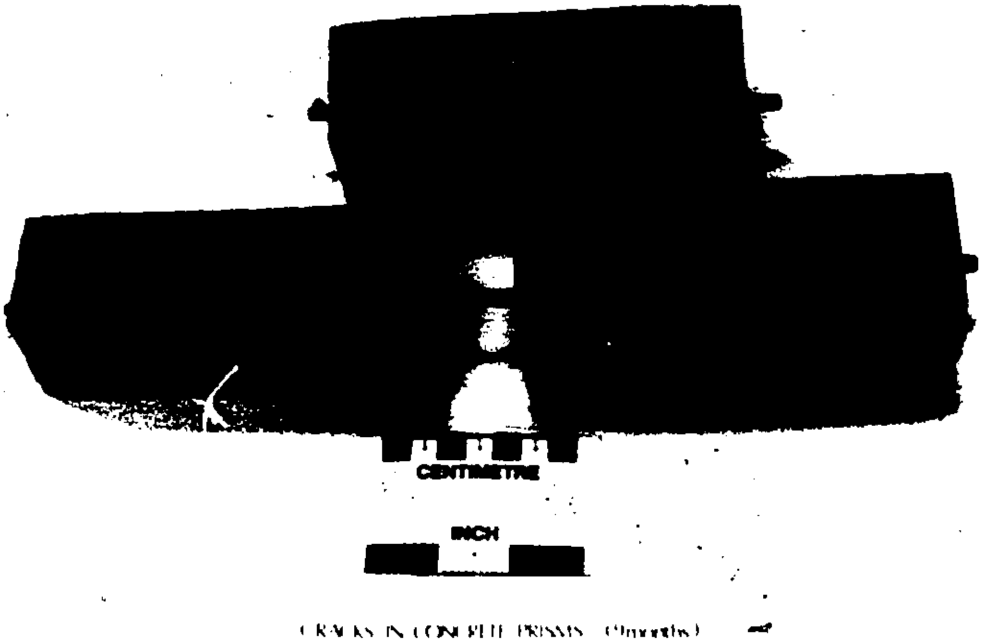


Figure 4.1: Concrete Prisms used for the standard test CSA A23.2 14A showing stainless steel studs at centre of prisms.

The aggregate/cement and water/cement ratios for all the concrete prisms were 4.00 and 0.42 respectively. The alkali content of the cement was fortified by addition of sodium hydroxide to give a cement alkali content of 1.25% Na_2O equivalent. The sodium hydroxide (NaOH) was dissolved in the mixing water prior to casting of the concrete prisms. Following casting, the prisms were labelled and cured for 28 days in water at a room temperature of about 23°C ± 2°C.

The dimensional changes of the prisms were monitored every other week for a period of one year. Three prisms were cast for each sample and the average expansion for the set of three was used in calculating the percentage change in length after every measurement.

4.2.2.3 Mortar Bar Test

Mortar bars for this test were prepared in accordance with ASTM C 227-81, however, the dimensions were modified for the available measuring devices. The size of each prism was 150mm x 50mm x 50mm, and stainless steel studs were embedded at the centre of the end of each prism. After 24 hours of casting, the prisms were demoulded and cured in water for 28 days. The alkali content of the cement was raised to about 1.25% Na_2O equivalent by dissolving sodium hydroxide (NaOH) in the mixing water. The aggregate/cement ratio of the mortar was 4.0 and the water/cement ratio was 0.42.

After curing, the initial lengths of the prisms were measured and the prisms were kept saturated and sealed in plastic bags at a room temperature of about 23°C ± 2°C. Lengths of the prisms were recorded every two weeks for a period of one year. Three prisms were used for each sample and the average change in length of the triplicate was calculated after every measurement. The test method was applied to the alkali-reactive silica and slicate rocks as well as the non-reactive aggregates.

4.2.2.4 Length measurement of prisms

The length changes of the prisms of mortar and concrete were measured with a digital caliper comparator. The caliper operates on an electrostatic capacitance detection principle. The caliper measures absolute length directly with a resolution of of 0.01mm (Figure 4.2).

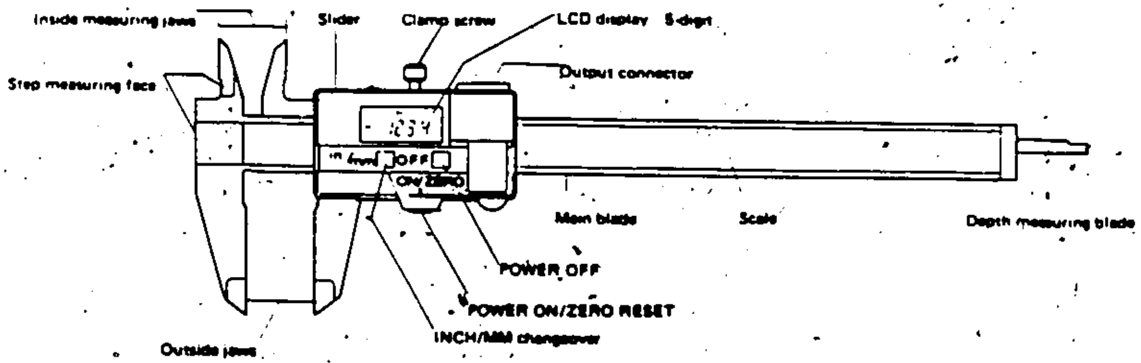


Figure 4.2: The digital caliper comparator used in measuring the length of the mortar bars and concrete prisms in the standard ASTM and CSA standard test methods.
Source: Mitoyo (1986).

To ensure accurate measurements, two supporting frames were designed and constructed for the mortar bar test and concrete prism expansion tests respectively. The frames have free sliding spaces in which the prisms could be moved to make contact with the securely fixed caliper at the studs. The measuring face of the prisms were labelled and marked clearly as shown in Figure 4.3 to ensure constant measuring spot on the studs.

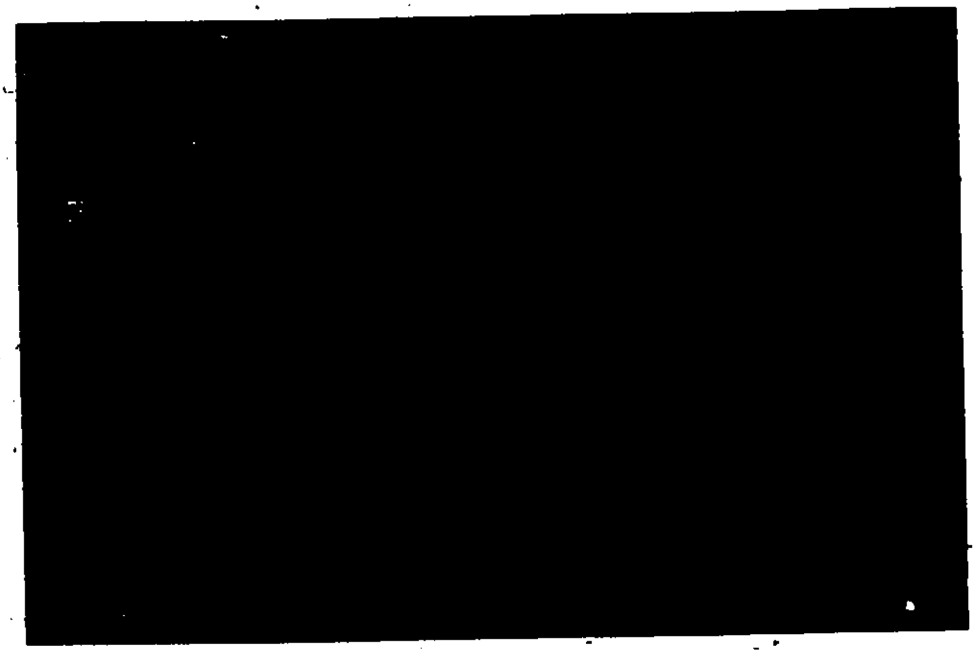


Figure 4.3: Concrete prisms fixed into supporting frames and caliper used for measuring lengths of concrete prisms.

4.2.3 LVDT comparator

The concrete and mortar cores used in this study required continuous monitoring during the experimentation period. This was carried out with the Linear Variable Differential Transformer (LVDT) at a room temperature of 23°C ± 2°C. This measuring device which was designed by Dr. Peter Hudec of the Department of

Geology and constructed by the Central Research Laboratory of the University of Windsor, is based on a similar device designed by Lama and Ventukuri (1978).

The LVDT is an electromechanical transformer which produces an electrical output proportional to the displacement of a moveable magnetic rod. It consists of three coils equally spaced on a cylindrical coil form, with one coil forming the secondary circuit (Figure 4.4). A cylindrical moveable magnetic rod inside this coil creates the magnetic flux linking the coils. The secondary coils are connected in opposite series so that the two voltages in the secondary circuit are in opposite phase and the net output of the transformer is the difference of the two voltages (Hudec, 1986). When the rod is in a centred position the net output is zero. This point is the balance point or null point. As the rod moves on either side, the voltage within the coil towards which it moves increases, giving a differential output with the corresponding sign (Ravina, 1987). This output varies linearly with the displacement of the rod (Figure 4.5). The movement of the rod requires a small driving force.

The LVDT is highly sensitive to temperature variation above room conditions; the output is also considerably affected by presence of magnetic materials. A drastic temperature rise during the test could result in a shift of the null point and a change in sensitivity.

Two in-line LVDTs attached to an aluminium board served as the comparator. The LVDTs are extended with brass rods onto

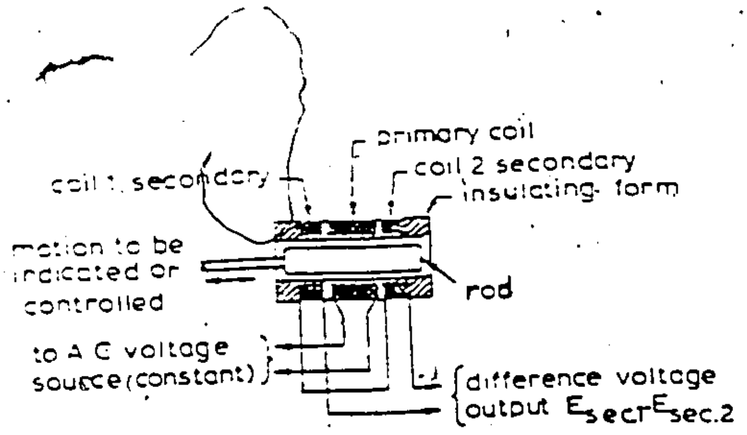


Figure 4.4: Configuration of LVDT (Lama and Vutukuri, 1978).

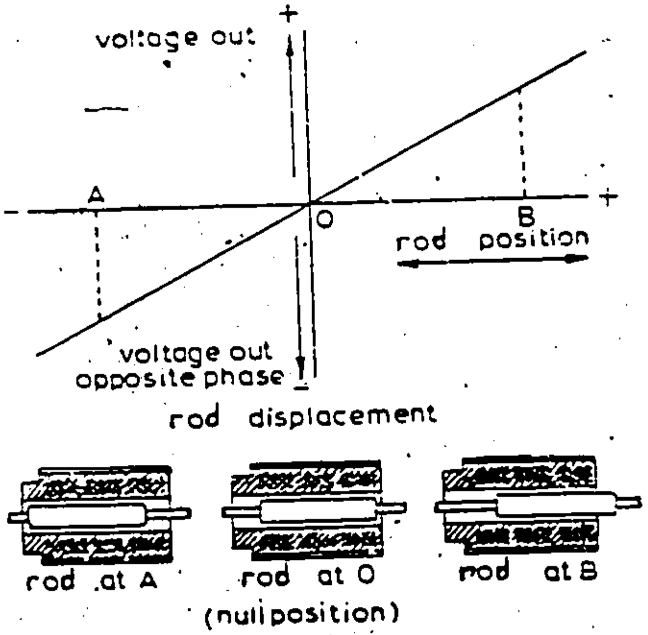


Figure 4.5: LVDT output as a function of rod position, linear graph (Lama and Vutukuri, 1978).

which hemispheric sample holders are attached (Figure 4.6). Each of the LVDTs is connected to a voltmeter which converts the voltage output to a displacement in units of millimetres or micrometres equivalent (Figures 4.7 and 4.8).

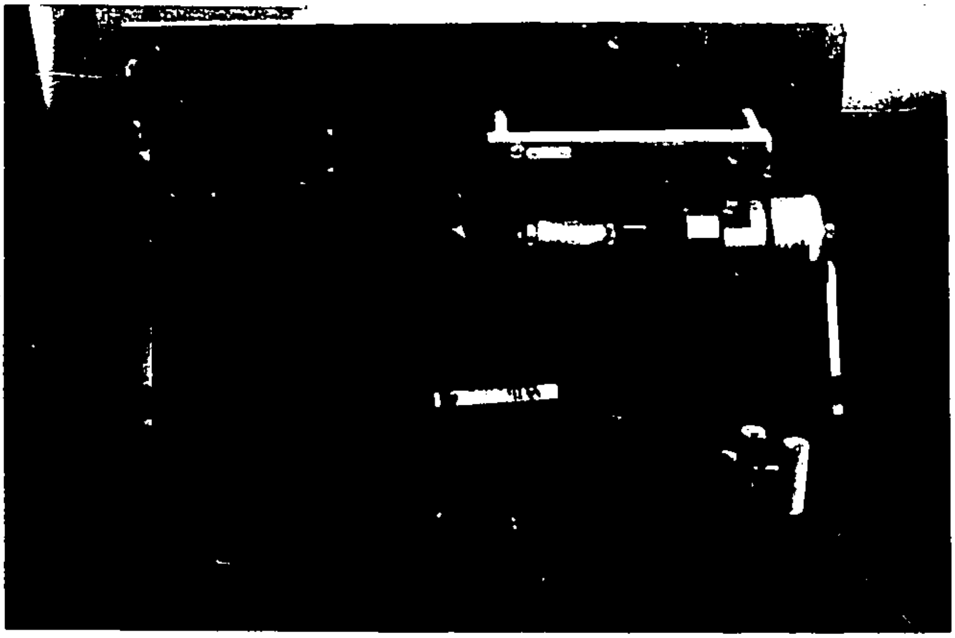


Figure 4.6: Coarse and Fine LVDT with connecting brass rods used in the study.

The scales of the LVDTs were calibrated with a 60.000mm low expansion ceramic core with a coefficient of thermal expansion (CTE) of 8.0 x 10^{-6} $^{o}C^{-1}$ and this was used as the standard core throughout the experiment. The scale of the coarse LVDT is millimetric and calibrated to 0.001mm. The fine LVDT scale is linearly related to a scale of micrometres and is calibrated to 0.0001mm equivalents. The regression equation obtained from the

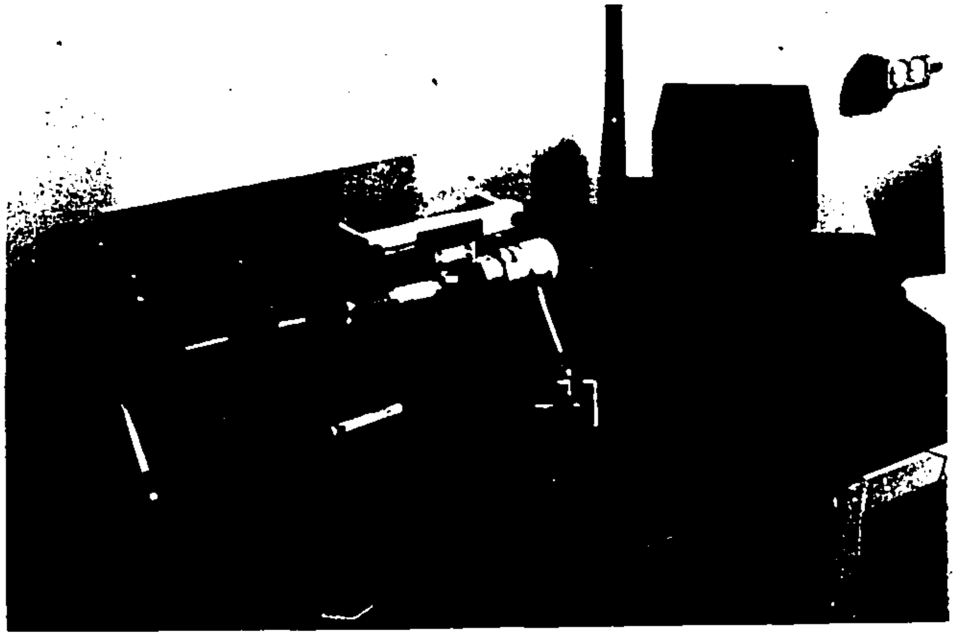


Figure 4.7: LVDT comparator used in the study for measuring core lengths.

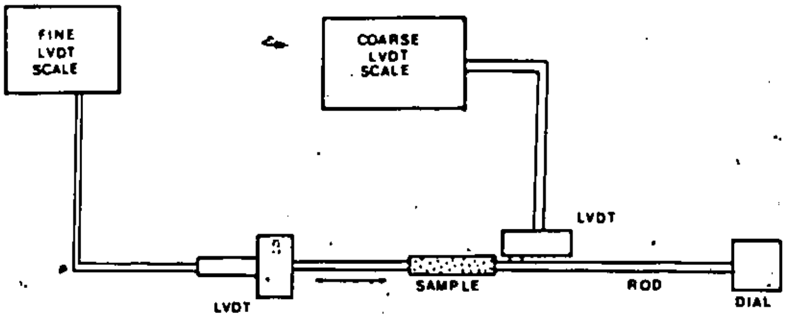


Figure 4.8: Schematic configuration of the LVDT comparator.

relationship between the two scales is used to convert the fine scale output to millimetres (Figure 4.9). The range of the fine LVDT is ±0.200mm. When the fine LVDT is out of range, the display flashes.

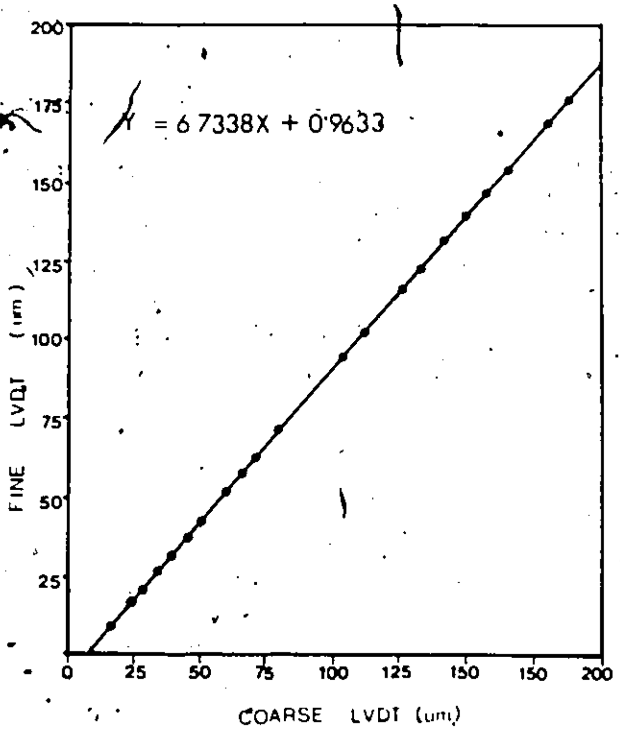


Figure4.9: Regression of fine LVDT scale on coarse LVDT scale.
Source: Ravina (1987).

4.2.4 Concrete cores testing

4.2.4.1 Preparation of cores

In both the screening and the treatment tests, eight separate blocks of concrete and mortar were cast for each set of experiments. Seven different sets of experiment were performed. Hence in all, 56 blocks of concrete were cast. Six of the concrete blocks contained reactive aggregates from different sources, while the remaining two were made with non-reactive aggregates. The fine aggregate used was sand previously described in Section 4.2.1.2. The maximum size of the coarse aggregate in each case was 10.0mm (3/8"), with the smallest size as that retained on 0.60mm (0.024") sieve size.

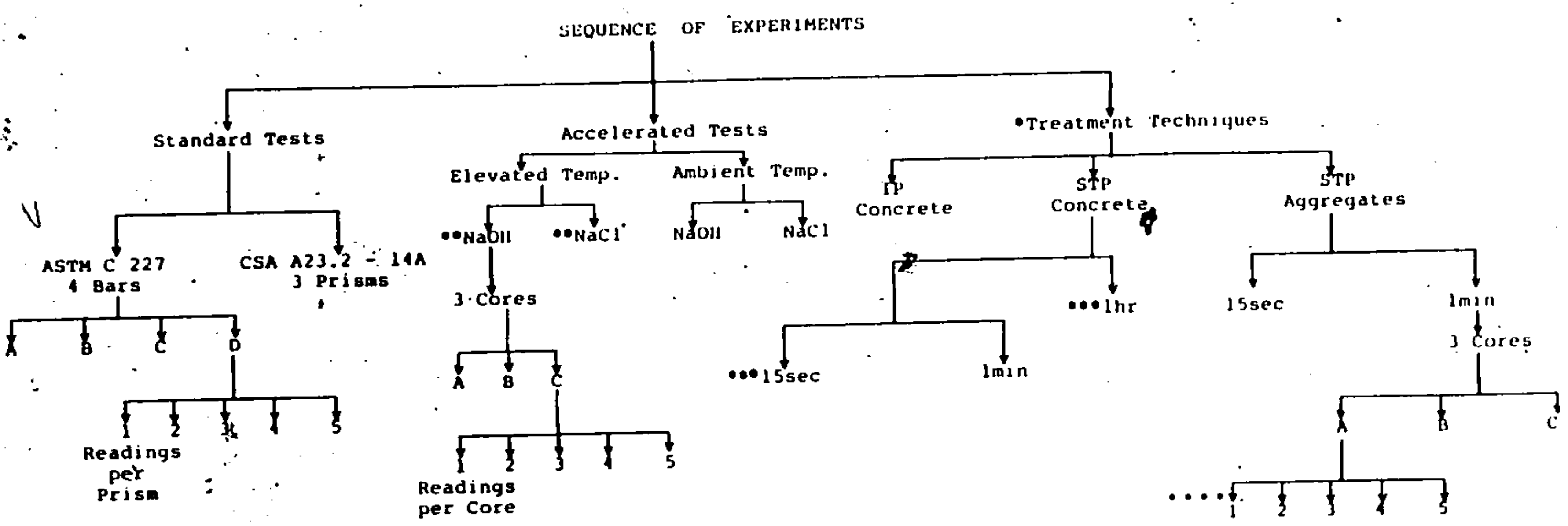
To ensure homogeneous mixes, the cement and the aggregates were mixed dry prior to addition of the water. After casting, the blocks were stored for 24 hours in plastic containers, demoulded and cured in water at a room temperature of 23°C ± 2°C for 28 days. At the end of the curing period, each of the blocks was cored to produce three cores for each set of experiments.

The cores were then trimmed and dimples made at the centre of each end to produce a length of approximately 70.0mm and a diameter of about 19.0mm. The dimples enable the samples to be held in place between the brass rods on the LVDT during measurement. There were thus 8x3 or 24 samples for each set of experiments. Figure 4.10 is the sequence of experiments performed in the study.

4.2.4.2 Accelerated method of testing on cores

(A) Ambient temperature testing

Prior to testing, each of the three samples representing a particular aggregate was labelled and the measuring end points carefully marked. The samples were then allowed to bench-dry at room temperatures for 24 hours. The initial lengths of the cores were measured. Following this measurements, the cores were



* Testing performed in 1N NaOH solution.
** Solutions used for testing.
*** Length of time of treatment in "STP" solution.
**** Similar structure for each pair set of experiments.

Figure 4.10: Sequence of experiments performed in the study.

immersed in 1N NaOH and saturated NaCl solutions separately in plastic containers (Figure 4.11) at a room temperature of about 23°C ± 2°C. Additional readings were taken every two weeks for the entire six month period of testing. The length measurement of each set of of three cores were averaged and the percentage change in length calculated.

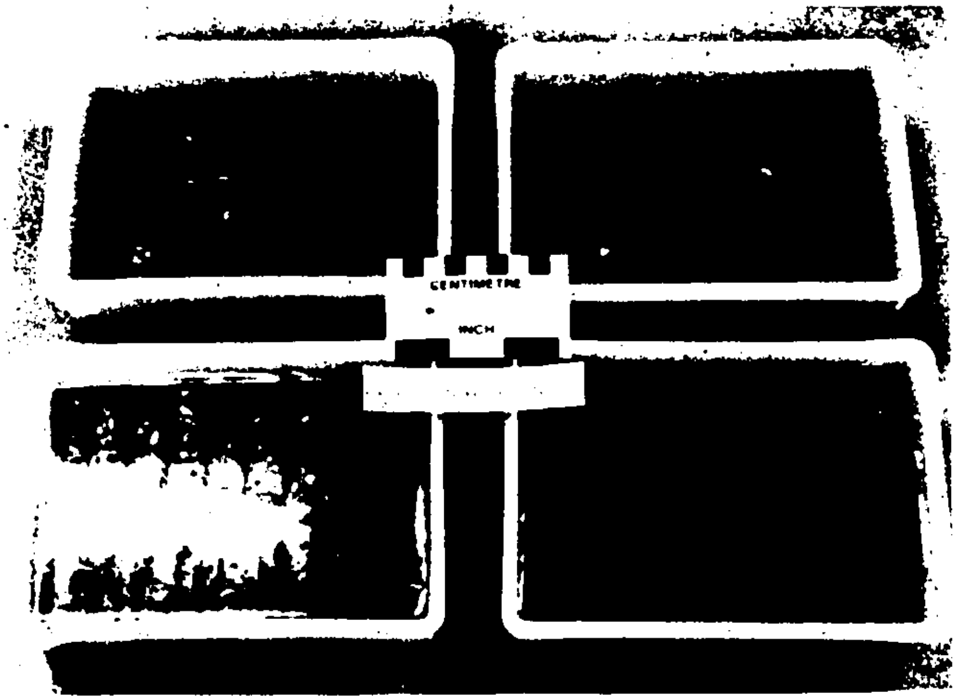


Figure 4.11: Cores of concrete immersed in solutions in plastic containers.

(B) **Elevated temperature testing**

The conditions under which the elevated temperature testing were carried out were the same as the ambient temperature method except that, in this instance, the samples were kept in an oven

(Figure 4.12) maintained at a temperature of about 80°C ± 5°C. The duration of test was only one month. Initial core lengths

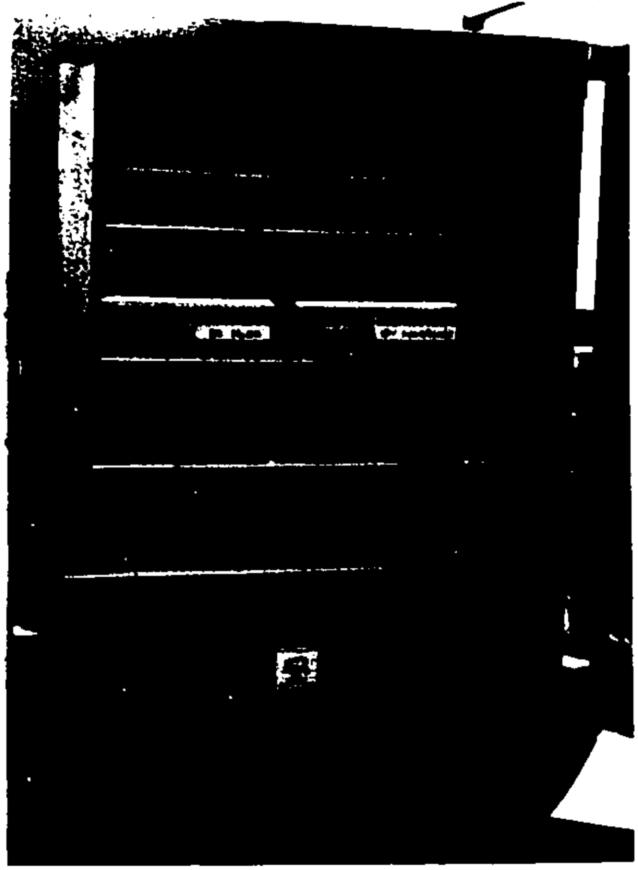


Figure 4.12: Concrete cores stored in plastic containers in the oven used in the study.

were taken prior to immersion in the two previously mentioned solutions. For the next 28 days, core lengths were recorded every two days.

4.2.5 Preventive treament and testing

4.2.5.1 Background

The treatment methods performed in this study were not strictly 'preventive' methods of alkali-aggregate reactivity as the name may imply. They were, however, measures employed to reduce the reactions in the concrete, thereby bringing any associated expansions within acceptable limits. In fact, they were treatment methods aimed at suppressing the the reactivity of the aggregates (in other words rendering them inert) by preventing ingress of aggressive solutions into the mortar or concrete.

Three methods of treatment were adopted in this study (see Figure 4.10). The first method involved treatment of cores of concrete prepared in a manner previously outlined and treating the cores with "STP" solution before testing. In the second technique, all the aggregates (both reactive and non-reactive) were treated with the "STP" solution prior to their use in casting the concrete and mortar blocks. The third method involved replacing part of the sand with the granulated "IP". The use of these chemicals stemmed from their previous performance in preventing corrosion in reinforced concrete and increased frost resistance of both rock and concrete (Hudec, 1986; Schincariol, 1986).

4.2.5.2 Treatment of cores with "STP" and testing

In the concrete core treatment technique, 9 cored samples from each concrete block were grouped into three groups with three cores each (see Figure 4.10). Two sets of three cores were immersed in 10% (by weight) solution of "STP" for 1 minute and 15 seconds respectively. The treated cores were then bench-dried at room temperature for 24 hours. The above treatment was repeated for a total of 5 cycles. At the end of the fifth cycle, the dimples at the end of the cores were cleaned and initial length of the cores taken with the LVDT. The samples were then immersed in 1N NaOH solution in plastic containers for six hours. The plastic containers with the entire contents were then placed in an oven maintained at a temperature of about 80°C ± 5°C. Length changes of the cores were recorded every two days for a period of one month.

The remaining set of cores was initially immersed in the 10% (by weight) "STP" solution for 1 hour and bench-dried. This cycle was repeated four more times - each immersion followed by bench drying.

4.2.5.3 Treatment of aggregates with "STP" and testing

One set each of all the aggregates was immersed in 10% (by weight) "STP" solution for 1 minute and 15 seconds respectively. The immersions were done five times, each immersion followed by a 24-hour bench-drying at room temperature. At the end of the cycles, the treated aggregates were used to cast blocks of concrete and mortar with the same mix design as described in Section 4.2.4.1. Following curing, 19.0mm x 70.0mm cores were obtained and tested in 1N NaOH solution for 28 days.

In each of the two test methods, the results of length changes of cores were averaged and the percent change in length calculated.

4.2.5.4 Partial replacement of sand with "IP" and testing

The "IP" is a granulated raw material of the "STP". The grain sizes are nearly uniform - passing 1.18mm (0.046") sieve size and retained on 0.60mm (0.024") sieve size. Since the grain sizes are similar to that of the sand, 5% by weight of sand was replaced by "IP" and used in casting concrete blocks with the reactive aggregates. The mix proportions were the same as before.

Core samples of 19.0mm x 70.0mm were later obtained from the blocks after 28 days of curing. Accelerated testing (ambient temperature) in both saturated salt solution, NaCl and 1N NaOH solution were performed on the cores.

4.2.6 Measurement on concrete cores

The prepared cored samples of concrete or mortar were placed between the two LVDTs. While in place, the core specimen was turned round a few times until it was within the range of measurement of the LVDTs. The LVDTs were then adjusted to fall within the required range and the scale output displayed representing the length of the core recorded. From the recorded output from the two LVDTs, the true length was obtained and percent change in length of the cores were calculated. This procedure was repeated for each of the three sets of cores representing a particular reactive aggregate.

The routine measurement of the length of each set of cores was always preceded by measurement of the standard ceramic core. The temperature and relative humidity of the room were also taken during every measurement. Figure 4.13 is a sample of the laboratory sheet used.

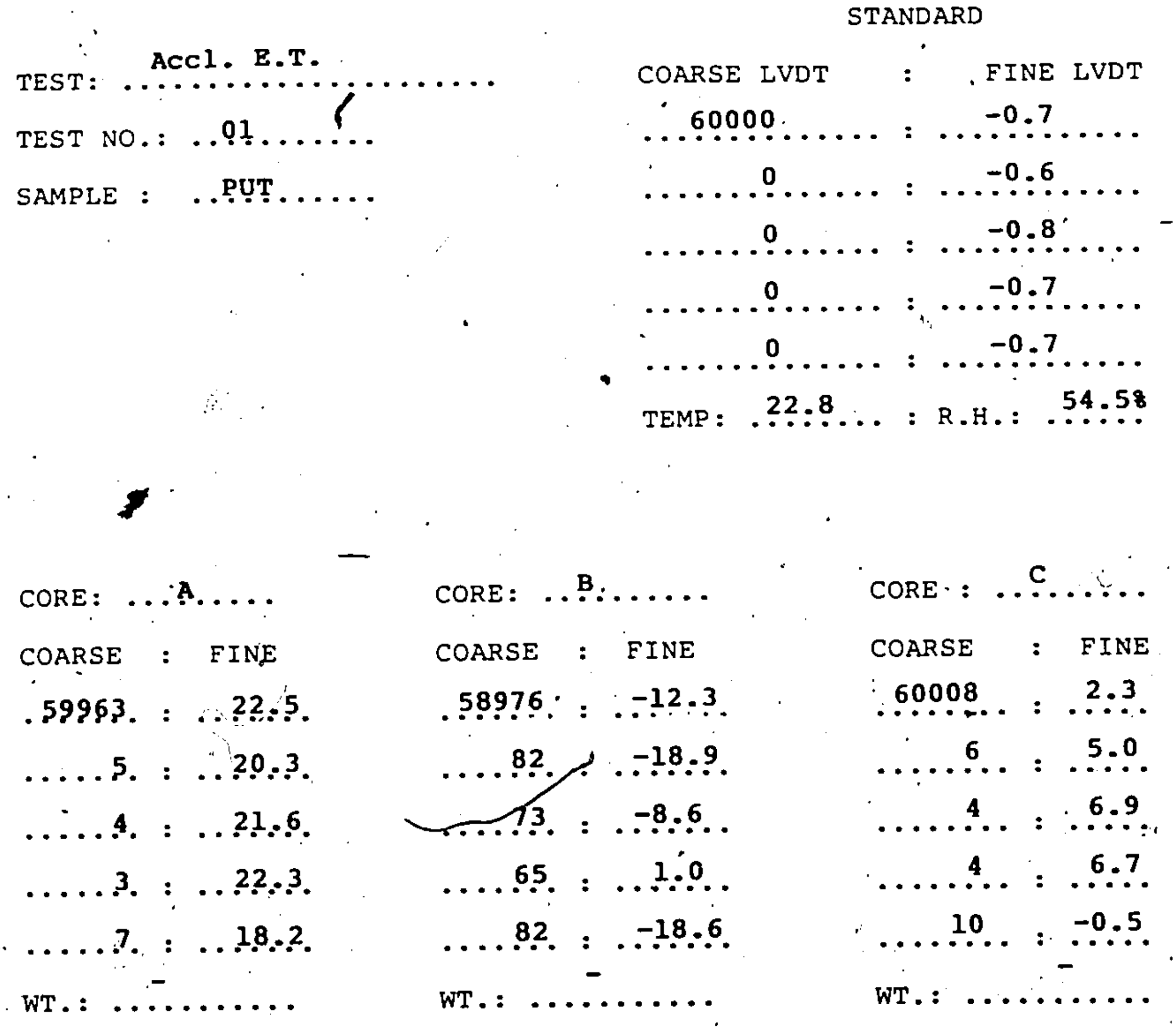
4.2.7 Precision procedures

There were some inevitable sources of errors as in many similar laboratory experiments. However, in order to reduce these errors to the barest minimum, the following measures were adopted:

(1) the length reading for a particular core was taken five times; the average of the four closest readings was used as the Length of the core; if none of the values differed by more than 5% the repeatability was considered satisfactory;

(2) the standard length of the ceramic core was redetermined after measuring every two samples at the beginning of every set of core samples; a change in reading of the fine scale greater than 1 micron required recalibration to 0.00;

(3) wet samples removed from solutions were surface-dried and



TEST: Accl. E.T.

TEST NO.: 01

SAMPLE : PUT

STANDARD

COARSE LVDT	FINE LVDT
60000	-0.7
0	-0.6
0	-0.8
0	-0.7
0	-0.7

TEMP: 22.8 : R.H.: 54.5%

CORE: A

COARSE	FINE
59963	22.5
5	20.3
4	21.6
3	22.3
7	18.2

WT.:

CORE: B

COARSE	FINE
58976	-12.3
82	-18.9
73	-8.6
65	1.0
82	-18.6

WT.:

CORE: C

COARSE	FINE
60008	2.3
6	5.0
4	6.9
4	6.7
10	-0.5

WT.:

Figure 4.13: Laboratory sample sheet for recording core lengths in the study.

the dimples at the core ends carefully cleaned prior to taking further readings.

CHAPTER 5

5.0 RESULTS AND DISCUSSIONS

5.1 Experimental results

5.1.1 Sources of error

In addition to the sources of error which have been discussed in Section 4.2.7, the other errors may be due to the slight fluctuations of the room and the oven temperatures. To reduce these errors and to ensure constant temperature of the oven, a thermometer was inserted into the oven chamber from the top portion of the oven to monitor the fluctuations. In all cases the fluctuations were an increase in temperature (about 5°C) above 80°C. Since this increase in temperature applied to all the samples in the oven, this error was considered minor and insignificant. The usual fluctuations in room temperature was ±2°C. This fluctuation was considered acceptable.

Another possible source of error was the drop in temperature of the concrete cores (from 80°C in oven to room temperature of about 23°C) during the measurement of the the core lengths on the LVDT. However, since this procedure was the same for all the cores tested under this condition, the error was considered insignificant. Any residual expansion associated with any of the elevated temperature tests are attributable to thermal expansion in the oven.

5.1.2 Statistical analysis

Eight aggregate types were used in all the tests. Statistical analyses were performed on the six reactive aggregates. The analyses included:

(i) a simple linear regression of the results of the accelerated tests (elevated temperature) on the results of the standard tests;

(ii) a simple linear regression of the results of the accelerated test (elevated temperature, 1N NaOH) on the results of the accelerated test (ambient temperature, 1N NaOH);

(iii) a simple linear regression of the results of the accelerated test (elevated temperature, 1N NaOH) on the results of the accelerated test (elevated temperature, saturated NaCl);

(iv) tests (and level of significance of all the values of the Pearson's correlation coefficient, R obtained in (i), (ii) and (iii);

(v) comparison of the 15 seconds treatment results and the 1 minute treatment results for both the treated concrete and aggregates using Student's t-test and F-test;

(vi) comparison of the performance of the treated concrete with the treated aggregate in concrete; this was done using Student's t-test and F-test;

(v) comparison of the treated concrete and aggregate with the untreated concrete and aggregate using Student's t-test and F-test.

All the statistical analyses were done using an IBM-compatible computer. The results of the statistical analyses and other parameters are tabulated in Tables 5.1, 5.2, 5.3, 5.5 and 5.7 to 5.15.

5.1.2.1 Linear correlation and regression analysis

The Pearson's 'R' correlation coefficient was used to calculate the correlations between measured variables. This coefficient measures the strength of the linear relationship between ordered pair of variables. In other words, the 'best-fit' line describing the destribution of the two variables is a straight line. The definition of the Pearson's correlation coefficient 'R' according to Davis (1973) is the ratio of the covariance of two variables to the product of their standard deviations. That is,

$$R_{xy} = \frac{\text{Covariance (Cov xy)}}{s_x \; s_y} \qquad (5.1)$$

where,

R_{xy} = correlation coefficient of variables x , y

s_x , s_y = standard deviations of the variables x , y

The Pearson's 'R' correlation coefficient lies between +1 and -1. A value of +1 describes a perfect direct relationship between two variables. A value of -1 indicates a perfect inverse (negative slope) relationship, that is, one in which one variable decreases as the other increases. Other relationships that are not perfect range between these two extremes.

A line of 'best-fit' or regression was determined for correlation of the accelerated tests (elevated temperature) and the standard tests. The objectives of the regression were:

(i) to determine whether any significant relationship existed between the accelerated tests (elevated temperature) and the standard tests;

and

(ii) to use the relationship between the accelerated tests and the critical expansion limits of the standard tests to establish limiting values of expansion for the accelerated tests.

5.1.2.2 Accuracy and significance of correlation coefficients

The one-tailed Student's t-test was used to establish whether the correlation coefficient of each of the regression lines was significant. The calculated values of t_o were used to test whether or not the sample mean correlation coefficient R (the calculated R) differed significantly from the population mean correlation coefficient of R=0. In this test, a very small value for the significance level (α) indicates that the regression parameters contribute significantly to the model. With large samples and moderately small correlations, the correlations obtained from a sample of N pairs of values is distributed normally about the true value R', with variance σ^2 given as,

$$\sigma^2 = \frac{(1 - R'^2)^2}{n - 1} \qquad (5.3)$$

where,

R' = true value of the correlation coefficient, R

n = number of degrees of freedom available for estimating the correlation coefficient.

In such a case, it is therefore usual to attach to an observed value R, a standard error given as,

$$\frac{(1 - R^2)}{\sqrt{n - 1}} \qquad (5.4)$$

This procedure is only valid under the restrictions stated above. However, for small sample size ($N < 100$), Fisher (1970) showed that the distribution is not close enough to the normal distribution to justify the use of a standard error to test the significance of R. For this reason a more accurate method was proposed by Fisher based on the distribution of t. For a correlation coefficient R, the value of the test statistic to is given as,

$$t_o = \frac{R\sqrt{n}}{\sqrt{1 - R}} \qquad (5.5)$$

The degrees of freedom n, is always taken as (N-2) where, N is the sample size. This is because there is a loss of one degree of freedom for each test statistic calculated from the sample in order to obtain R.

The above idea was used to test the significance of all the calculated values of R. For samples up to 100 pairs of observations Table G.1 of Appendix G allows this test to be applied directly from the value of R.

5.1.2.3 Comparison of means

A two-tailed Student's t-test was performed to determine whether there was a significant difference between the two treatment techniques with the "STP" - treatment of the concrete cores and treatment of the aggregates. The value of t (that is t_o) was used to test for significance between the mean expansions of the treated concrete and the mean expansions of the treated aggregates. This test and the F-test were applied to both the 15 seconds treatment as well as the 1 minute treatment for all the reactive aggregates.

In the Student's t-test, the test statistic which is used to establish whether there is a significant difference between the means according to Walpole and Myres (1978) is given by

$$t_o = ((\bar{x} - \bar{y}) - \Delta)/(s_p\sqrt{(1/n_x + 1/n_y)}) \qquad (5.2)$$

where,

$\bar{x}$ = mean of variable x

$\bar{y}$ = mean of variable y

Δ = difference between means

s_p = square root of the pool variance

n_x, n_y = number of sample size for variables x and y

The test statistic, t_o is used to test for the following hypothesis;

$H_o: \bar{x} = \bar{y}$ - no significant difference between the means

$H_a: \bar{x} \neq \bar{y}$ - significant difference between the means

D.F. (degrees of freedom) = $n_x + n_y - 2$

A confidence level of α and the degrees of freedom are used to obtain values from standard tables. Based on the values from the tables and the calculated value of t_o, the hypothesis is accepted or rejected. In order to use the Student's t-test it is necessary to establish whether the variances of the two variables are the same or differ. The F-test is used for such tests. The test statistic for the F-test is given as

$$F = \frac{s_1^2}{s_2^2} \qquad (5.3)$$

where,

$$s_1^2 > s_2^2$$

A confidence level α and degrees of freedom, ν_1 and ν_2, are used to obtain a value from the standard F-tables. The value obtained from the tables is used to establish whether the variances are the same or not.

5.2 Results of standard tests

The results of the ASTM C 227 Mortar Bar Test and CSA 14A Concrete Prism Expansion Test were used to plot a graph of percent linear expansion against time in months. Figures 5.1 and 5.2 show plots of results of alkali-reactive silica rocks (ASR) and those of alkali-reactive carbonate rocks (ACR), respectively. In each case, there is a clear distinction between the behaviour of the reactive rocks and the two non-reactive rocks NR1 and NR2. The critical limits of expansion: 0.05% in three months and 0.10% in six months for the alkali-reactive silica aggregates have been shown. For the alkali-reactive carbonate aggregates, the limit is 0.025% in one year.

From the graphs, Putnam chert (PUT) and the fine grained dolomitic limestone from Kingston (KIN) are the most reactive rocks in the two groups. On the other hand the gravel aggregates from Sudbury (SUD), and the dolomitic limestone from the 4th Lift of the MacLeod Quarry in Cornwall (C4) show less reactivity.

5.3 Comparison of standard and accelerated tests

Figures 5.3, 5.4, 5.5 and 5.6 show plots of the measured linear expansions as a function of time (in days) for the accelerated tests (elevated temperature, 1N NaOH and saturated

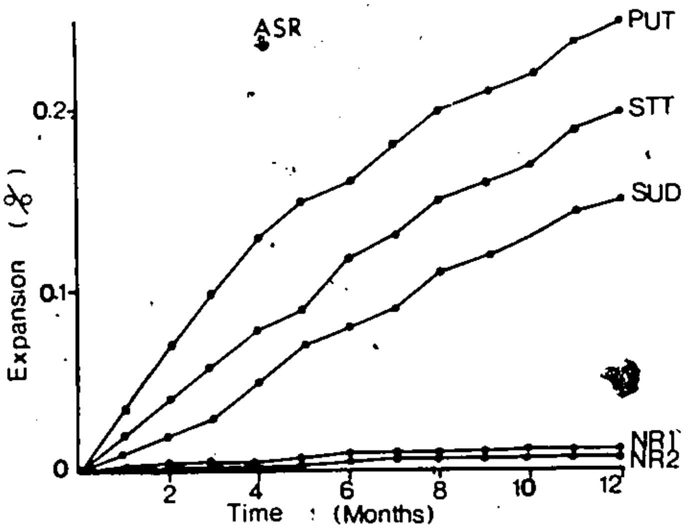


Figure 5.1: Graph of standard test ASTM C 227: Mortar Bar Test.

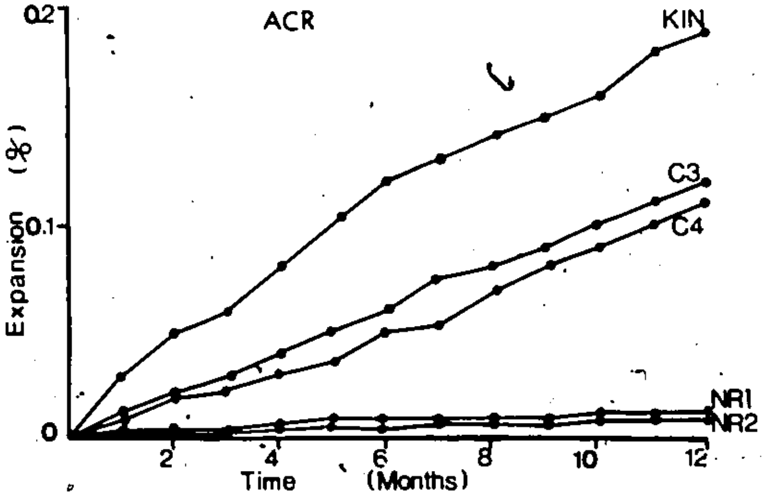


Figure 5.2 Graph of standard test CSA A23.2 14A: Concrete Prism Expansion Test

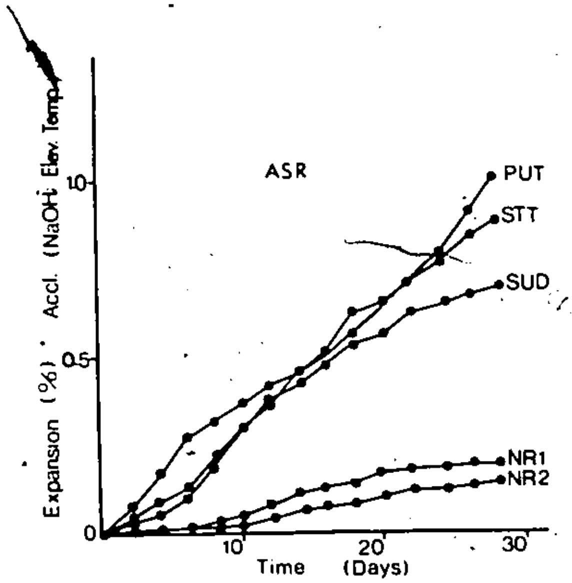


Figure 5.3: Graph of accelerated test (elevated temperature, NaOH): ASR.

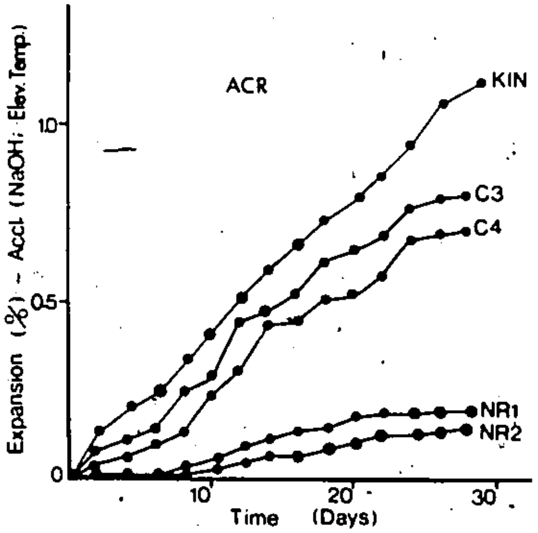


Figure 5.4 Graph of cccelerated test (elevated temperature, NaOH): ACR.

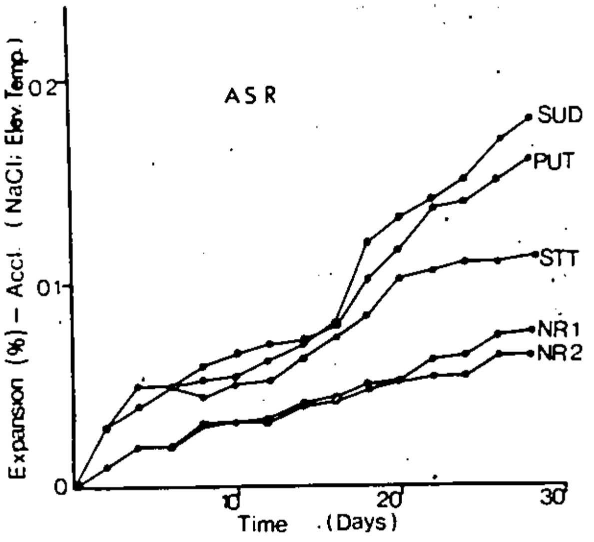


Figure 5.5: Graph of accelerated test (elevated temperature, NaCl): ASR.

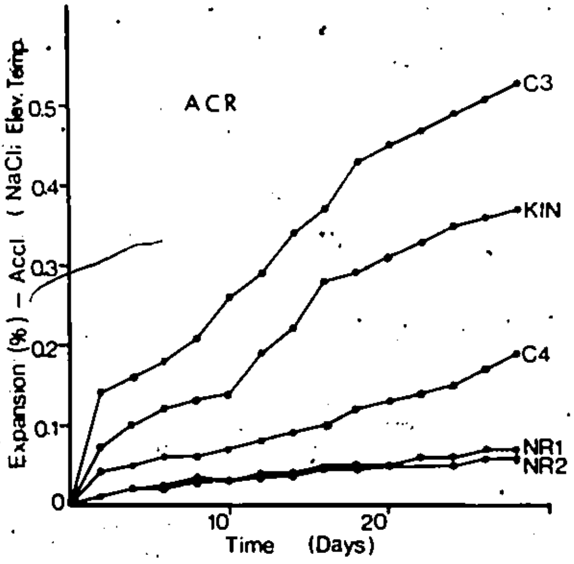


Figure 5.6: Graph of accelerated test (elevated temperature, NaCl): ACR.

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NaCl solutions). The plots cover both alkali-reactive silica and carbonate rocks. Results of the non-reactive rocks NR1 and NR2 used as controls have also been plotted alongside the reactive ones. With the exception of Putnam chert (PUT) all the curves show similarity in shape with the graphs of the standard tests (ASTM and CSA). The slight increase in the expansions of the non-reactive rocks compared to those of the standard tests is attributed to thermal expansion as mentioned already in Section 5.1.1.

5.3.1 Standard tests versus accelerated test (elevated temperature (NaOH))

Figures C.1 to C.6 of Appendix C show plots of the expansions for the accelerated test in (1N NaOH) against the expansions measured for the standard tests - ASTM C 227 and CSA 14A for the same reactive aggregates. Linear regression analyses were performed on the expansion data for the accelerated and standard tests. The boundary condition was zero expansion (%) at zero time for the two tests. Table 5.1 gives the values for the regression equations and parameters for the reactive aggregates. All the plots show good linear correlation (correlation coefficient, R $>$0.910) between the accelerated test and the standard tests for the individual aggregates. The slopes of the regression equations indicates that the expansions for the accelerated test (elevated temperature, NaOH) is at least three times that of the same aggregate in the standard tests. The expansions in the case of reactive carbonate aggregates being nearly six times as much as the expansions of the same aggregates in the standard tests.

Figure 5.7 shows correlation between accelerated test (1N NaOH) and the standard test for the alkali-reactive silica rocks as a group. Figure 5.8 shows a similar relationship for the alkali-reactive carbonate rocks. Like the individual rocks, the linear correlation for the group is also good (correlation coefficient, $R > 0.900$) and highly significant. There is nearly a perfect linear correlation between the two tests. This encouraging result suggests that the newly developed accelerated test can in fact be confidently substituted for any of the standard tests. However, this is possible only if the testing procedures for the accelerated test are strictly followed.

5.3.2 Standard tests versus accelerated test (elevated temperature (NaCl))

Figures D.1 to D.6 of Appendix D show plots of results of accelerated test (NaCl) against the standard tests. Similarly, Figures 5.9 and 5.10 show plots of the same results for the group of reactive silica rocks and reactive carbonate rocks respectively. Table 5.2 shows the regression equations and parameters for the reactive aggregates. In all cases, for the group and the individual rocks, there is a good linear correlation (correlation coefficient, $R > 0.900$) between the accelerated test (elevated temperature, NaCl) and the standard tests.

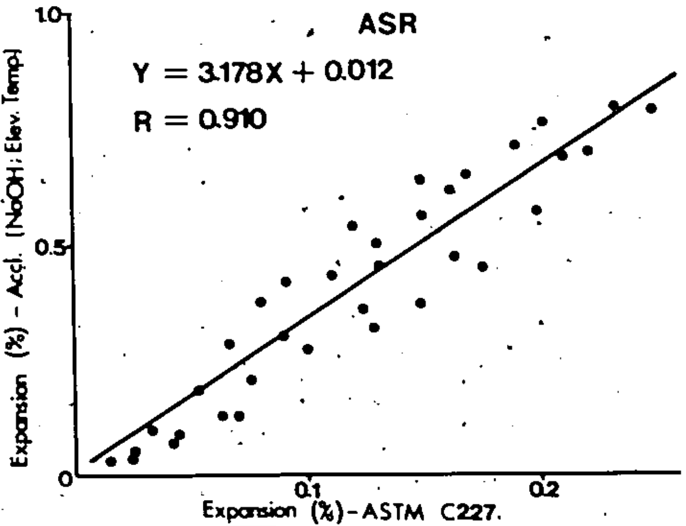

Figure 5.7: Regression curve showing correlation between standard test ASTM C 227 and accelerated test (elevated temperature, NaOH) for alkali-reactive silica group.

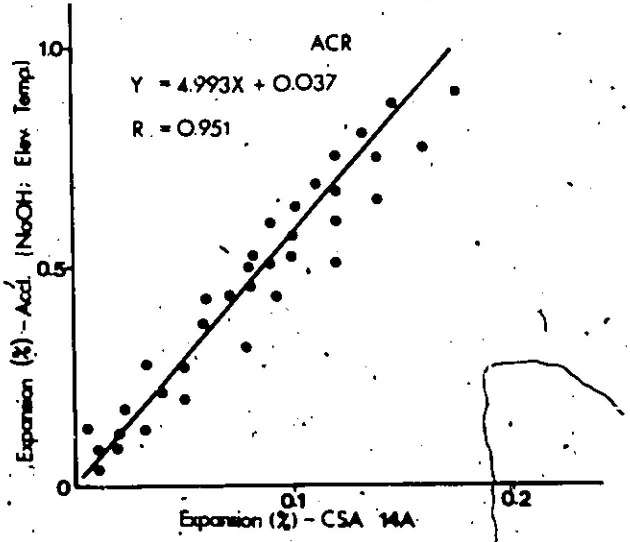

Figure 5.8 Regression curve showing correlation between standard test CSA A23.2 - 14A and accelerated test (elevated temperature, NaOH) for alkali-reactive carbonate group.

TABLE 5.1

Regression Equations and Parameters for Reactive Aggregates (Standard Test vs Accl (NaOH) Elevated Temp Test)

Sample	Variables X,Y	Regression Equation	Slope	Intercept	Number of Pairs of Variables	Correlation Coefficient r	Student's t-value	Probability (Significance Level)
PUT	Linear Expansion (Days) Linear Expansion (Months)	Y = 3.228X - 0.087	3.228	-.087	12	.982	16.441	.0001
SUD	Linear Expansion (Days) Linear Expansion (Months)	Y = 4.634X - 0.033	4.634	-.033	12	.991	21.411	.0001
STT	Linear Expansion (Days) Linear Expansion (Months)	Y = 4.271X - 0.105	4.271	-.105	12	.992	24.850	.0001
KIN	Linear Expansion (Days) Linear Expansion (Months)	Y = 5.335X - 0.078	5.335	-.078	12	.996	35.249	.0001
C3	Linear Expansion (Days) Linear Expansion (Months)	Y = 6.515X - 0.004	6.515	-.004	12	.992	24.850	.0001
C4	Linear Expansion (Days) Linear Expansion (Months)	Y = 6.298X - 0.015	6.298	-.015	12	.976	14.173	.0001
ASR	Linear Expansion (Days) Linear Expansion (Months)	Y = 3.178X + 0.012	3.178	.012	36	.910	12.798	.0001
ACR	Linear Expansion (Days) Linear Expansion (Months)	Y = 4.993X + 0.037	4.993	.037	36	.951	17.935	.0001

ASR - Alkali-Silica Reaction
ACR - Alkali-Carbonate Reaction

$t_{.01;10} = 2.764$

$t_{.01;34} = 2.326$

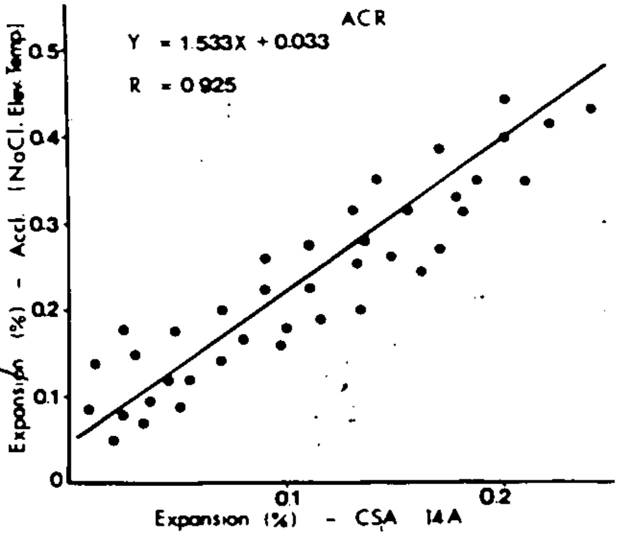

Figure 5.9~~: Regress~~ion curve showing correlation between standard test ASTM C 227 and accelerated test (elevated temperature, NaCl) for alkali-reactive silica group.

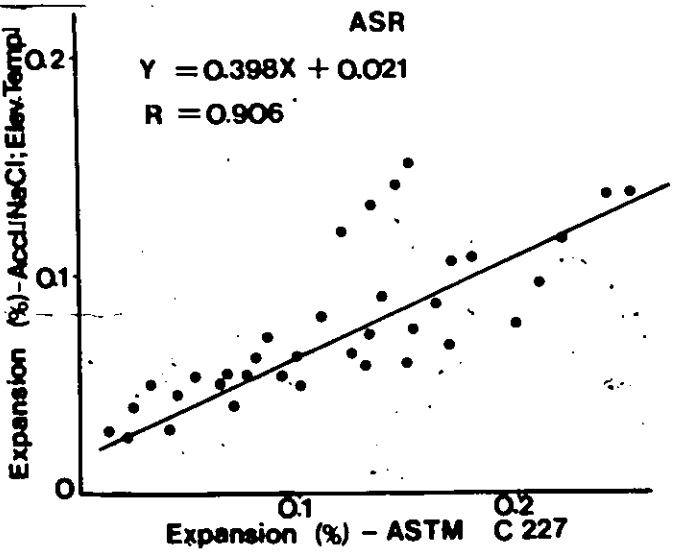

Figure 5.10: Regression curve showing correlation between standard test CSA A23.2 - 14A and accelerated test (elevated temperature, NaCl) for alkali-reactive carbonate group.

TABLE 5.2

Regression Equations and Parameters for Reactive
Aggregates (Standard vs Accelerated Test - Elevated Temperature (NaCl)

Sample	Variables X,Y	Regression Equation	Slope	Intercept	Number of Pairs of Variables	Correlation Coefficient r	Student's t-value	Probability (Significance Level)
POT	Linear Expansion (Days) Linear Expansion (Months)	Y = 0.516X - 0.005	.516	-.005	12	.938	8.557	.0001
SUD	Linear Expansion (Days) Linear Expansion (Months)	Y = 0.859X + 0.009	.859	.009	12	.958	10.564	.0001
STT	Linear Expansion (Days) Linear Expansion (Months)	Y = 0.443X + 0.014	.443	.014	12	.938	8.557	.0001
KIN	Linear Expansion (Days) Linear Expansion (Months)	Y = 1.898X - 0.006	1.898	-.006	12	.977	14.489	.0005
C3	Linear Expansion (Days) Linear Expansion (Months)	Y = 3.506X + 0.091	3.506	.091	12	.993	26.586	.0005
C4	Linear Expansion (Days) Linear Expansion (Months)	Y = 1.122X + 0,028	1.122	.028	12	.992	24.850	.0005
ASR	Linear Expansion (Days) Linear Expansion (Months)	Y = 0.398X + 0.021	.398	.021	36	.906	12.481	.0001
ACR	Linear Expansion (Days) Linear Expansion (Months)	Y = 1.533X + 0.033	1.533	.033	36	.925	14.195	.0001

ASR - Alkali-Silica Reaction
ACR - Alkali-Carbonate Reaction

$t_{.05;10} = 1.812$ $t_{.01;10} = 2.764$ $t_{.01;34} = 2.326$

Table 5.3 shows the critical expansion limits for both the standard tests and the accelerated tests (elevated temperature, NaOH and NaCl). The critical limits were obtained by substituting the limiting expansions of the standard tests (ASR: 0.05% per 3 months; 0.10% per 6 months; and ACR: 0.025% in one year) into the corresponding regression equations. This criterion was developed for the alkali-reactive silica rocks as a group and the alkali-reactive carbonate rocks as a group separately. The reference value used to obtain the critical limits in the accelerated test is the 24-day expansion. Table 5.4 is a comparison of the standard tests and the accelerated tests.

The length of testing is shorter in the accelerated tests. In addition, the accelerated tests are suitable for both alkali-reactive silica/silicate rocks and alkali-reactive carbonate rocks. Thus one test alone if performed according to the accelerated methods outlined in this study can screen all types of alkali-aggregate reaction. The small size of the concrete cores enable the hydroxide solution to penetrate the paste and the reactive aggregate easily and is one of the reasons for the acceleration of the reaction.

TABLE 5.3
Critical Limits of Expansion for Reactive Aggregates

Sample	Time	TEST / Critical Limits of Expansion (%)			
		ASTM C 227	CSA 14A	Accl. (NaOH)	Accl. (NaCl)
PUT	3 months	.050	-	.074 in 6 Days	.021 in 6 Days
	6 months	.100	-	.236 in 12 Days	.047 in 12 Days
SUD	3 months	.050	-	.199 in 6 Days	.052 in 6 Days
	6 months	.100	-	.430 in 12 Days	.095 in 12 Days
STT	3 months	.050	-	.109 in 6 Days	.036 in 6 Days
	6 months	.100	-	.322 in 12 Days	.058 in 12 Days
KIN	1 year	-	.025	.055 in 24 Days	.042 in 24 Days
C3	1 year	-	.025	.159 in 24 Days	.179 in 24 Days
C4	1 year	-	.025	.143 in 24 Days	.056 in 24 Days
ASR	3 months	.050	-	.171 in 6 Days	.041 in 6 Days
	6 months	.100	-	.330 in 12 Days	.061 in 12 Days
ACR	1 year	-	.025	.162 in 24 Days	.071 in 24 Days

ASR - Alkali-Silica Reaction
ACR - Alkali-Carbonate Reaction

TABLE 5.4

Comparison of Standard Tests and Accelerated Tests

Tests	Suitability		Length of Test
	ASR	ACR	
ASTM C 227	yes	no	3 - 6 months
CSA 14A	no	yes	1 year
Accl. (NaOH)	yes	yes	1 - 2 months
Accl. (NaCl)	yes	yes	1 - 2 months

ASR - Alkali-Silica Reaction
ACR - Alkali-Carbonate Reaction

5.4 Results of accelerated tests (ambient temperature)

5.4.1 Ambient temperature versus elevated temperature (NaOH)

Figures E.1 to E.6 of Appendix E show regression curves for relationships between accelerated tests - elevated temperature (1N NaOH) versus ambient temperature (1N NaOH). Figures 5.11 and 5.12 show the regression curves for the rock groups. In Table 5.5 the regression equations and the relevant correlation parameters for the curves are presented. The results show excellent linear correlation (correlation coefficient, $R > 0.930$) between the elevated temperature test and the ambient temperature test. A test of significance of the correlations shows that the correlation cofficients are all significant at the 95% level of significance. This means that the performance of the reactive aggregates in the elevated temperature test is almost the same as that of the ambient temperature test conditions.

5.4.2 Accelerated test (ambient temperature (NaCl))

Figure 5.13 shows a graph of percent linear expansion as a function of time (in months) for the ambient temperature test (NaCl). This graph covers all the reactive aggregates. Plots of the results of the two non-reactive aggregates NR1 and NR2 are also shown alongside with the reactive aggregates.

Table 5.6 shows the chemical composition of all the rocks (percent silica (SiO_2), lime (CaO), magnesia (MgO), and alumina (Al_2O_3). The significant feature about Figure 5.13 is that it

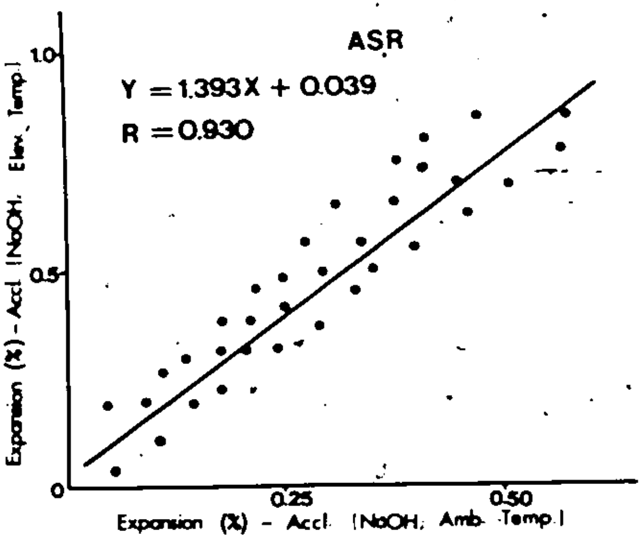

Figure 5.11: Regression curve showing correlation between accelerated test (NaOH): elevated temperature versus ambient temperature: ASR group.

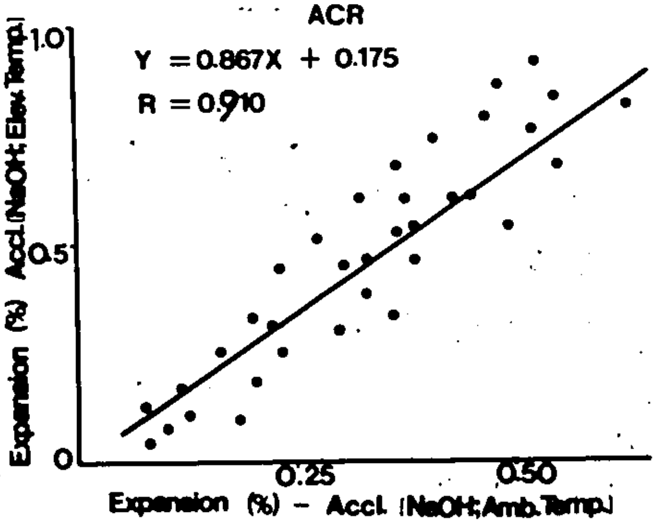

Figure 5.12: Regression curve showing correlation between accelerated test (NaOH): elevated temperature versus ambient temperature: ACR Group.

TABLE 5.5

Regression Equations and Parameters for Reactive Aggregates (Ambient (Temp) vs Elevated (Temp) (NaOH)

Sample	Variables X,Y	Regression Equation	Slope	Intercept	Number of Pairs of Variables	Correlation Coefficient r	Student's t-value	Probability (Significance Level)
PBT	Linear Expansion (Days) Linear Expansion (Weeks)	Y = 1.201X + 0.030	1.201	.030	14	.998	54.690	.0001
SUD	Linear Expansion (Days) Linear Expansion (Weeks)	Y = 1.882X - 0.064	1.882	-.064	14	.998	54.690	.0001
STT	Linear Expansion (Days) Linear Expansion (Weeks)	Y = 2.020X - 0.027	2.020	-.027	14	.997	44.621	.0001
KIM	Linear Expansion (Days) Linear Expansion (Weeks)	Y = 2.184X - 0.078	2.184	-.078	14	.999	77.402	.0005
C3	Linear Expansion (Days) Linear Expansion (Weeks)	Y = 1.001X - 0.045	1.001	-.045	14	.985	19.774	.0001
C4	Linear Expansion (Days) Linear Expansion (Weeks)	Y = 3.197X - 0.080	3.197	-.080	14	.997	44.621	.0001
ASR	Linear Expansion (Days) Linear Expansion (Weeks)	Y = 1.393X + 0.039	.867	.075	42	.930	16.002	.0001
ACR	Linear Expansion (Days) Linear Expansion (Weeks)	Y = 0.867X + 0.174	1.393	.039	42	.910	13.881	.0001

ASR - Alkali-Silica Reaction
ACR - Alkali-Carbonate Reaction

$t_{.05;12} = 1.782$ $t_{.01;12} = 2.681$ $t_{.01;40} = 2.326$

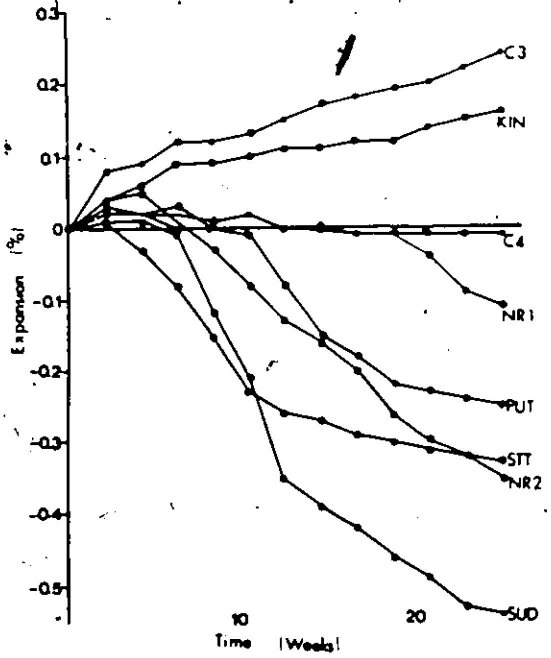

Figure 5.13: Expansion curves for rock aggregates: accelerated test: ambient temperature (NaCl).

TABLE 5.6

Chemical Composition of of Rock Samples

Samples	Type	Composition (%)		
		SiO_2	CaO + MgO	Al_2O_3
PUT	ASR	50.50	25.99	0.94
SUD	ASR	70.10	4.22	12.10
STT	ASR	* 8.34	51.89	0.50
NR2	Non-Reactive (Silicate)	51.60	20.33	6.04
KIN	ACR	7.19	48.84	2.20
C3	ACR	16.60	42.77	2.70
C4	ACR	16.50	43.09	2.66
NR1	Non-Reactive (Carbonate)	2.63	54.83	0.23

* Predominantly carbonate rock (limestone) with reactive silica.

tends to discriminate between concrete containing alkali-reactive silica/silicate rocks and concrete containing alkali-reactive carbonate rocks.

The carbonate rocks KIN, C3, C4, and the non-reactive carbonate rock NR1 have low silica contents. They tend to cause the concrete to expand while concrete containing the high silica rocks PUT, SUD, STT, and NR2 all show contraction under the same testing conditions. The results of the graph show clear distinction between the performance of concrete containing the two rock groups in a saline or brackish environment. In other words, the results suggest that alkali-reactive silica rock aggregates when used in maritime concrete structures (seawalls, bulkheads, groins, jetties, etc.) could cause contractions of the structures. If such contractions happen to be intolerable, the structure could fail. Reactive carbonate rocks, however, when used in a similar manner, could cause undesirable expansions of the concrete structure. In a saline environment where there is reason to suspect that a concrete structure will undergo undesirable elastic shrinkage, a reactive carbonate rock could be used as coarse aggregate in the concrete structure to counter the effect of the shrinkage.

Although the number of the rock samples used in the study is too small to suggest immediate conclusion the results are very suggestive and further work is required.

5.5 Accelerated tests (elevated temperature): NaOH versus NaCl

Figures F.1 to F.2 of Appendix F show plots of accelerated test (elevated temperature (1N NaOH)) against accelerated test (elevated temperature (saturated NaCl)). Figure 5.14 and 5.15 show plots of the same results for the rock groups. Table 5.7 is a summary of the regression constants, equations and test of significance for all the line of 'best-fit'. The correlation factors are high ($R > 0.900$) and the significance test shows that there is a good linear correlation between these two tests. The level of significance is as high as 99%. Thus, since these two tests individually correlate very well with the standard tests (ASTM C 227, CSA 14A) (Section 5.3.2), this suggests that either 1N NaOH or saturated NaCl can be used in the accelerated test to screen potentially reactive concrete aggregates. The slopes of the linear regression equations show that expansions of reactive aggregates in 1N NaOH solution are much greater than in saturated NaCl solution; this suggests that the hydroxide (OH^-) ion is more effective in contributing to alkali-aggregate reaction than the chloride (Cl^-) ion. An explanation for this is that, since the two solutions were each concentrated and contained the same cation (Na^+), the only major contributors to the reaction were the hydroxyl ion (OH^-) and the chloride ion (Cl^-). Thus it is fundamentally the hydroxyl ion (OH^-) which promotes alkali-aggregate reaction and not the metallic alkali ion. This

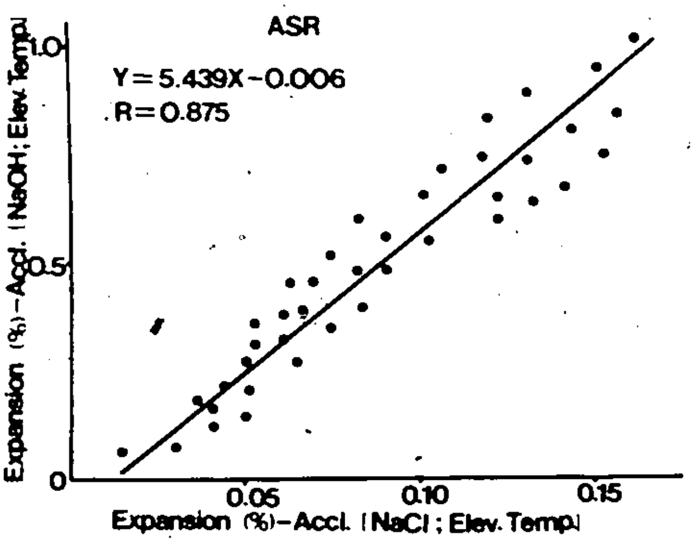

Figure 5.14: Regression curve showing correlation between accelerated tests: (NaOH) versus (NaCl): ASR group.

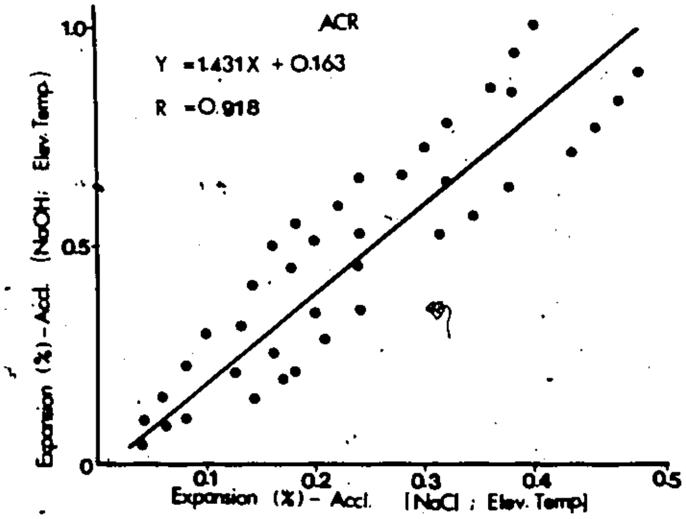

Figure 5.15: Regression curve showing correlation between accelerated tests: (NaOH) versus (NaCl): ACR group.

TABLE 5.7

Regression Equations and Parameters for Reactive Aggregates (Accelerated Tests - Elevated Temperatures (NaOH) vs(NaCl)

Sample	Variables X,Y	Regression Equation	Slope	Intercept	Number of Pairs of Variables	Correlation Coefficient r	Student's t-value	Probability (Significance Level)
PUT	Linear Expansion (Days) Linear Expansion (Days)	$Y = 6.303X - 0.055$	6.303	-.055	14	.985	19.774	.0005
SUD	Linear Expansion (Days) Linear Expansion (Days)	$Y = 4.236X + 0.004$	4.236	.004	14	.931	8.835	.0001
STT	Linear Expansion (Days) Linear Expansion (Days)	$Y = 9.273X - 0.211$	9.273	-.211	14	.969	13.587	.0005
KIN	Linear Expansion (Days) Linear Expansion (Days)	$Y = 2.973X - 0.172$	2.973	-.172	14	.985	19.774	.0005
C3	Linear Expansion (Days) Linear Expansion (Days)	$Y = 1.853X - 0.172$	1.853	-.172	14	.993	29.123	.0001
C4	Linear Expansion (Days) Linear Expansion (Days)	$Y = 4.965X - 0.124$	4.965	-.124	14	.972	14.329	.0005
ASR	Linear Expansion (Days) Linear Expansion (Days)	$Y = 5.439X - 0.006$	5.439	-.006	42	.875	11.431	.0005
ACR	Linear Expansion (Days) Linear Expansion (Days)	$Y = 1.431X + 0.163$	1.431	.163	42	.718	6.524	.0005

ASR - Alkali-Silica Reaction
ACR - Alkali-Carbonate Reaction

$t_{.05;12} = 1.782$
$t_{.05;40} = 1.645$

$t_{.01;12} = 2.681$
$t_{.01;40} = 2.326$

confirms earlier work by Diamond (1975) which showed that the basic alkali-aggregate reaction despite its name is not between the alkali ions but between the hydroxide ions (OH^-).

The result also shows that NaCl when applied as de-icing salt promotes alkali-silica and alkali-carbonate reactions in concrete containing alkali-reactive aggregates.

5.6 Results of treatment tests

5.6.1 Treated concrete cores

Figures 5.16 to 5.21 show graphs of expansion versus time in days for treated concrete cores in "STP" solution as described in Section 4.2.5.2. On each of the graphs, curves of untreated concrete core containing the aggregate, curves of treated concrete core containing the aggregate (15 seconds and 1 minute), and a curve of a corresponding concrete core containing a non-reactive aggregate have been plotted.

In all the graphs the treated concrete cores show similar expansion behaviour as the non-reactive rock aggregates. This means that after treatment, the reactive aggregates were rendered inert and behaved as the non-reactive aggregates.

The performance of the 15 seconds treatment is almost the same as that of the 1 minute treatment. In fact, the results of the Student's t-test presented in Table 5.8 shows that, there is no significant difference between the 15 seconds treatment and 1 minute treatment processes. Both lengths of treatment are equally effective in preventing alkali-aggregate reactions in concrete. Tables 5.9a and 5.9b show the reduction in expansion

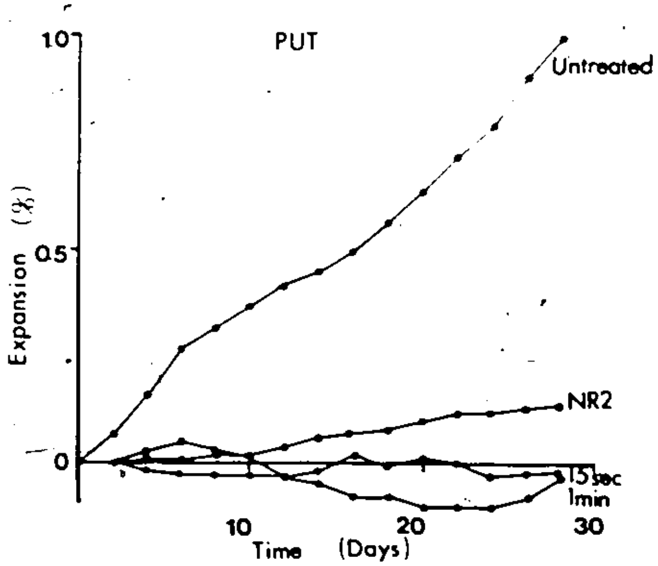

Figure 5.16 Expansion data for concrete treated with "STP": PUT.

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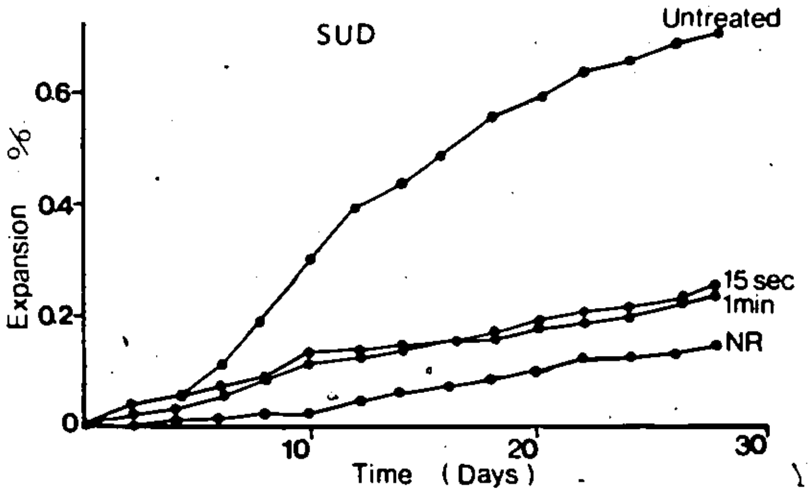

Figure 5.17 Expansion data for concrete treated with "STP": SUD.

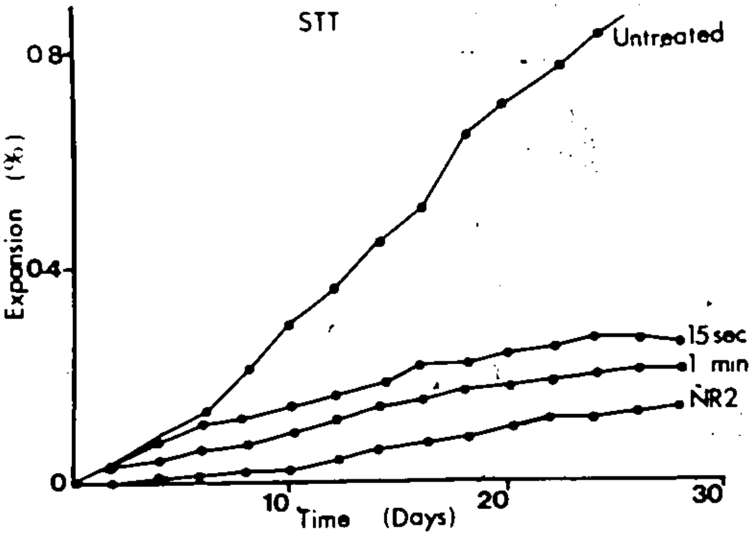

Figure 5.18: Expansion data for concrete treated with "STP": STT.

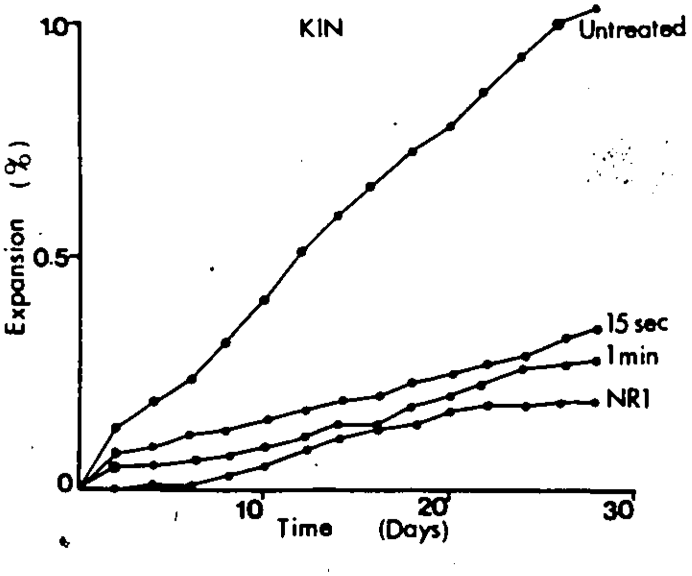

Figure 5.19 Expansion data for concrete treated with "STP": KIN.

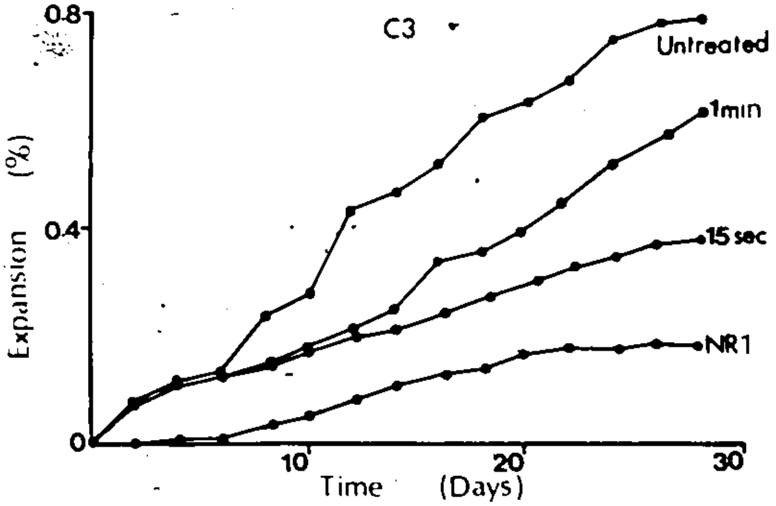

Figure 5.20: Expansion data for concrete treated with "STP": C3.

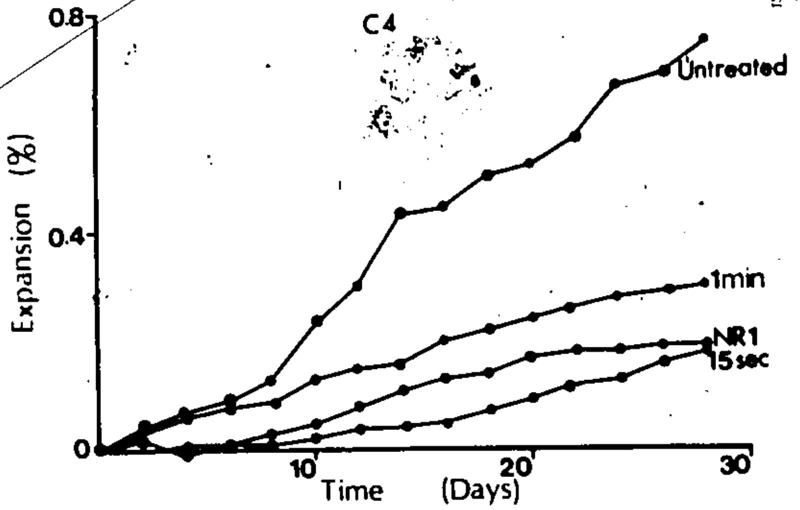

Figure 5.21: Expansion data for concrete treated with "STP": C4.

TABLE 5.8

Summary of Student's t-test for Comparing Treated Concrete Cores

Samples	Data Size	*Mean Expansion (%) 15sec	*Mean Expansion (%) 1min	Standard Deviation 15sec	Standard Deviation 1min	F-value	Student's t-value	Probability (confidence level)	Population Comparison
PUT	15	.0280	.0130	.0400	.0800	.2500	-1.2990	.0500	Same
SUD	15	.0950	.1210	.0710	.0690	1.0417	1.4476	.0100	Same
STT	15	.1710	.1230	.0850	.0680	1.5652	2.2818	.0500	Same
KIN	15	.1900	.1420	.0940	.0880	1.1429	.8442	.0500	Same
C3	15	.2180	.2910	.1130	.1860	.3699	.9784	.0500	Same
C4	15	.0640	.1360	.0580	.0950	.3778	-.1391	.0500	Same

$F_{.01;14,14} = 3.7610$; $F_{.05;14,14} = 2.5100$; $t_{.01;28} = 2.7630$; $t_{.05;28} = 2.0480$;

* Average of four measurements of three cores.

TABLE 5.9a

Comparison of "STP"-Treated Concrete with Untreated Concrete (15 Second-Treatment)

Sample	Mean Expansion (%) Untreated	Mean Expansion (%) Treated	Standard Deviation Untreated	Standard Deviation Treated	Reduction in Expansion after Treatment	Sample Size	F-value 15sec	Student's t-value 15sec	Probability (Confidence Level)	Comparison
PUT	.4807	.0280	.2985	.0400	94.1752	15	55.6875	5.8217	.0100	Different (Significant Reduction)
SUD	.3762	.1320	.2491	.0710	64.9100	15	12.4200	4.2044	.0100	Different (Significant Reduction)
STT	.4359	.1710	.3007	.0850	60.7700	15	12.5556	3.2840	.0100	Different (Significant Reduction)
KIN	.5679	.1900	.3483	.0940	66.5400	15	13.7841	4.0577	.0100	Different (Significant Reduction)
C3	.4365	.2180	.2744	.1130	50.0600	15	5.8828	2.8511	.0100	Different (Significant Reduction)
C4	.3566	.0640	.2507	.0580	82.0500	15	18.5000	4.4011	.0100	Different (Significant Reduction)
ARR (GROUP)	.4423	.1338	.0762	.0768	69.7509	90	1.0158	6.9861	.0100	Different (Significant Reduction)

$t_{.01;28} = 2.763$ $t_{.01;10} = 3.169$ $F_{.01;5;5} = 10.970$ $F_{.01;14,14} = 3.760$

ARR - Alkali-Reactive Rocks

TABLE 5.9b

Comparison of "STP"-Treated Concrete Cores with Untreated Concrete Cores
(1 Minute-Treatment)

Sample	Mean Expansion (%)		Standard Deviation		Reduction in Expansion after Treatment	Sample Size	F-value	Student's t-value	Probability (Confidence Level)	Population Comparison
	Untreated	Treated	Untreated	Treated						
PUT	.4807	.1130	.2985	.0800	76.4900	15	13.9219	4.0343	.0100	Different (Significant Reduction)
SUD	.3762	.1210	.2491	.0690	67.8400	15	12.9375	3.8213	.0100	Different (Significant Reduction)
STT	.4359	.1230	.3007	.0680	71.7800	15	19.6522	3.9318	.0100	Different (Significant Reduction)
KIN	.5679	.1420	.3483	.0880	75.1000	15	15.7532	4.5926	.0100	Different (Significant Reduction)
C3	.4365	.2910	.2744	.1860	33.3300	15	2.1763	1.6998	.0100	Different (Significant Reduction)
C4	.3566	.1630	.2507	.0950	54.2900	15	6.9889	3.1863	.0100	Different (Significant Reduction)
ARR (GROUP)	.4423	.1588	.0762	.0977	63.1383	90	1.6439	5.6141	.0100	Different (Significant Reduction)

$t_{01;28} = 2.763$ $t_{01;10} = 3.169$ $F_{01;5,5} = 10.970$ $F_{01;14,14} = 3.760$

ARR - Alkali-Reactive Rocks

after treatment of the concrete cores containing the reactive aggregates for both 15 seconds and 1 minute. A statistical analysis of the results of the untreated samples and the results of the treated samples shows that there is a significant reduction in expansion (>50-90%) after treatment for all the reactive aggregates. The results from the graph, however, show that the treatment shows much more promise with the carbonate rocks than the silica/silicate rocks.

Figures 5.22 to 5.27 show graphs of 1 hour treatment results. The curves in each case are plots of results of ambient temperature testing for six months. In each of these graphs there is quite a significant reduction in expansion (in the range of 50-90% - except C4) of the concrete cores after the 1 hour treatment (Table 5.10).

In the case of the reactive silica aggregates PUT, SUD, and STT, the behaviour is similar to that of the non-reactive aggregate. This result suggests that under ambient conditions, the treated concrete could become inert and perform well in service over a long period of time just as the non-reactive aggregates.

5.6.2 Treated aggregates

In order to determine the performance of the treated aggregates in concrete, the results of the 28-day testing were plotted against time in days. The plot for each aggregate was done together with results of untreated aggregate and a non-reactive rock. Figures 5.28 through to 5.33 show the

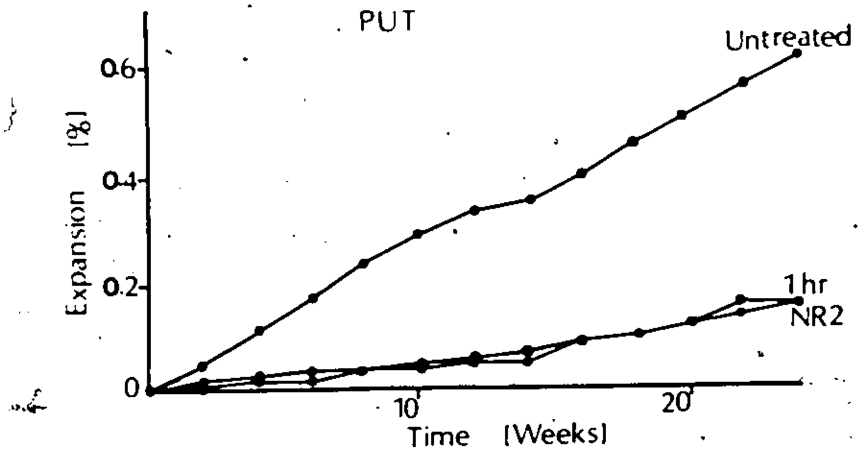

Figure 5.22: Expansion data for concrete treated with "STP": PUT (1 hr).

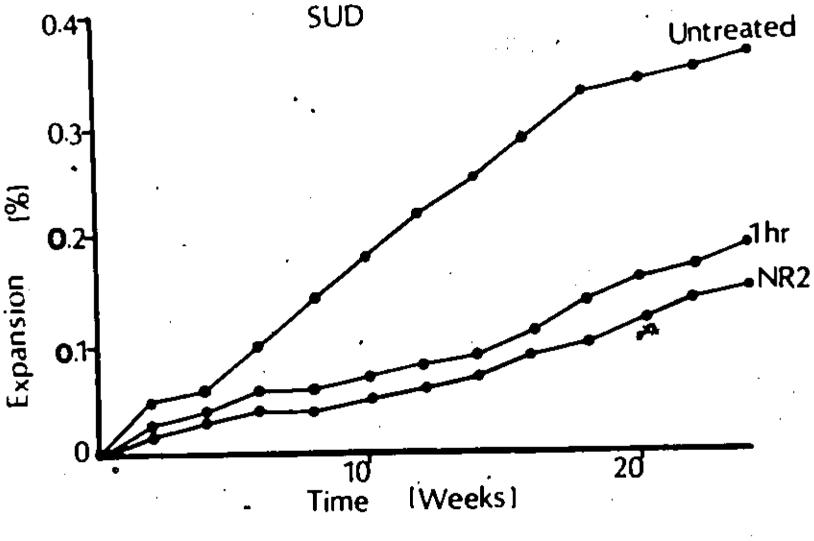

Figure 5.23: Expansion data for concrete treated with "STP": SUD (1 hr).

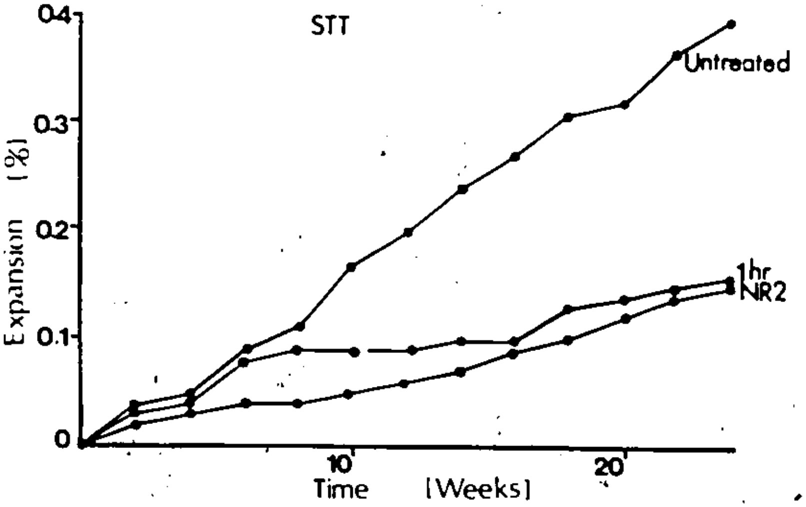

Figure 5.24: Expansion data for concrete treated with "STP": STT (1 hr).

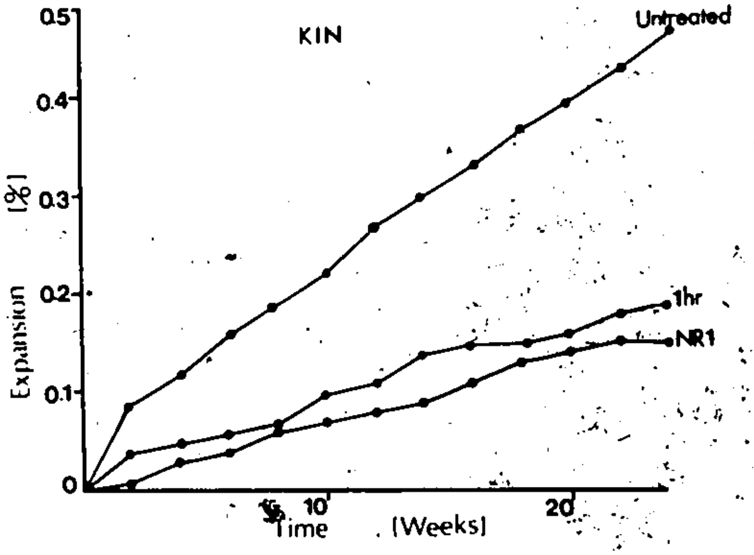

Figure 5.25: Expansion data for concrete treated with "STP": KIN (1 hr).

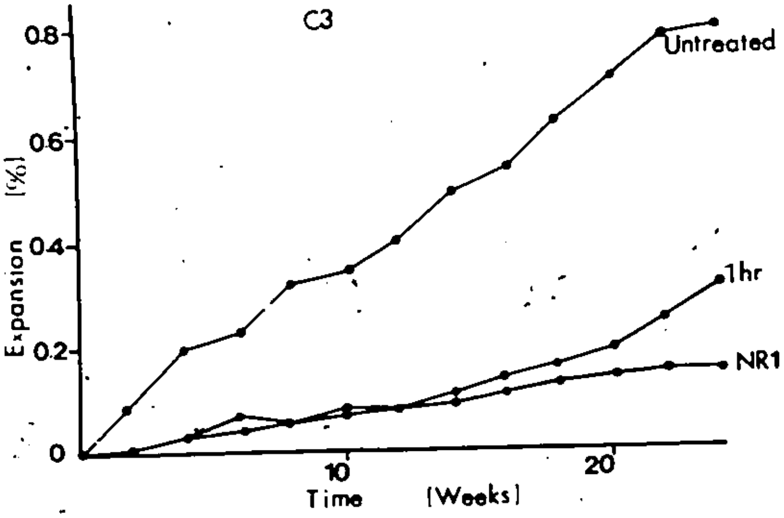

Figure 5.26: Expansion data for concrete treated with "STP": C3 (1 hr).

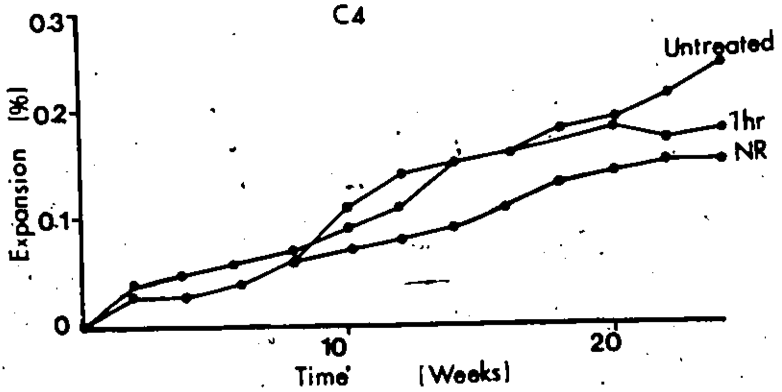

Figure 5.27: Expansion data for concrete treated with "STP": C4 (1 hr).

TABLE 5.10

Comparison of "STP"-Treated Concrete with Untreated Concrete
(1 Hour-Treatment)

Sample	*Mean Expansion		Standard Deviation		Reduction in Expansion after Treatment	Sample Size	F-value	Student's t-value	Probability (Confidence Level)	Population Comparison
	Untreated	Treated	Untreated	Treated						
PUT	.3150	.0641	.1975	.0543	79.6508	13	13	4.4142	.0500	Different (Significant Reduction)
SUD	.2067	.0887	.1286	.0601	57.0876	13	4.583	3.0009	.0500	Different (Significant Reduction)
STT	.1963	.0916	.1336	.0477	53.3367	13	7.739	2.7364	.0100	Different (Significant Reduction)
KIN	.2564	.1065	.1422	.0605	58.4633	13	5.459	3.4960	.0100	Different (Significant Reduction)
C3	.4233	.0114	.2555	.0912	97.3163	13	7.867	4.4084	.0500	Different (Significant Reduction)
C4	.1185	.1091	.0741	.0679	7.9325	13	1.375	.3477	.0100	Same (No Significant Reduction)
ARR (GROUP)	.2527	.0786	.1061	.0636	58.9645	90	2.7457	3.4365	.0100	Different (Significant Reduction)

$t_{.05;26} = 2.056$ $t_{.01;26} = 2.779$ $F_{.05;12,12} = 2.690$ $F_{.05;5,5} = 5.050$ $t_{.01;10} = 1.812$

* Average of four measurements of three cores.

individual graphs. In all the graphs (particularly the reactive silica aggregates), the treatments show considerable reduction in expansion (60-95%) compared to the untreated aggregates (Tables 5.11a and 5.11b).

In the case of PUT there is even some amount of contraction for both the 15 seconds treatment and 1 minute treatment. The reactive aggregates, after treatment behave like non-reactive aggregates. They become inert after treatment. The treatment process, shows more promise with the alkali-reactive silica rocks (ASR) than with the alkali-reactive carbonate rocks (ACR). A statistical comparison of the results of the treated and the untreated samples shows that there is a significant reduction in expansion after treatment of the aggregates. The treatment process is hence suitable for all the reactive aggregates. A comparison of the 15 seconds treatment and the 1 minute treatment shows that there is no significant difference between the two treatment times at the 95% confidence level (Table 5.12)

The mechanism by which the "STP" solution protects concrete containing reactive aggregates from chemical deterioration could be viewed as a physico-chemical phenomenon. Each time that the aggregate or concrete is immersed in the "STP" solution a precipitate forms which hardens upon drying. This precipitate blocks the accessible outer pores of the aggregate or concrete. Further treatment of the concrete or aggregate increases the amount and layer of precipitate within the pores. Eventually a tough resistant surface layer forms within the outer pores. This layer prevents any alkaline or salt solution and

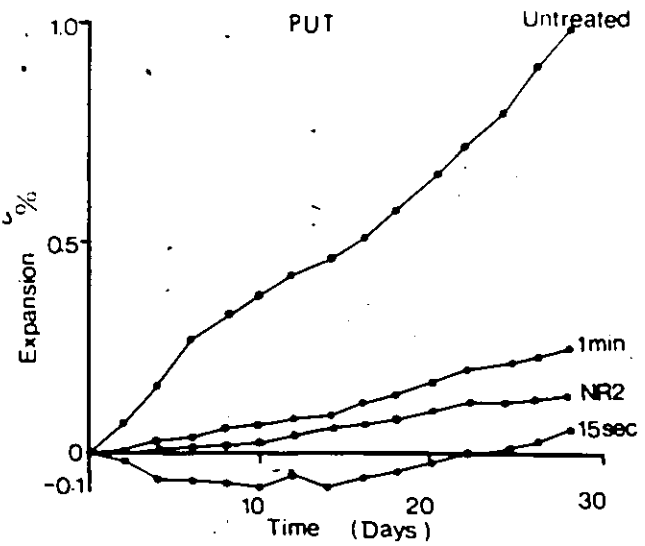

Figure 5.28 Expansion data for reactive aggregates treated with "STP": PUT.

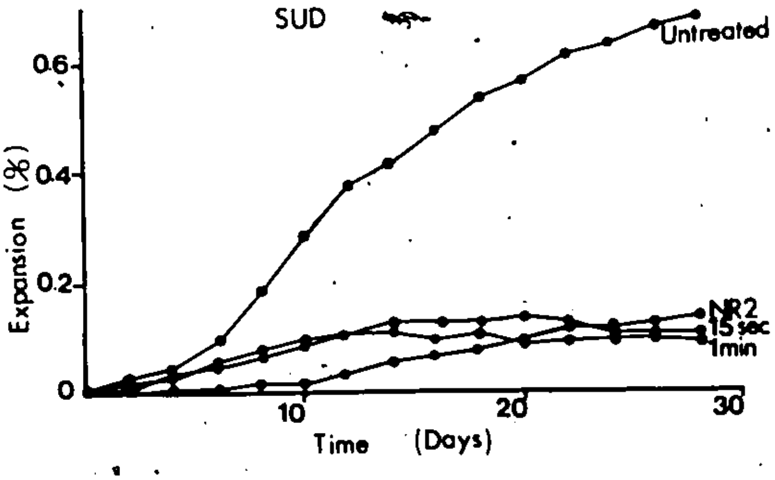

Figure 5.29:. Expansion data for reactive aggregates treated with "STP": SUD.

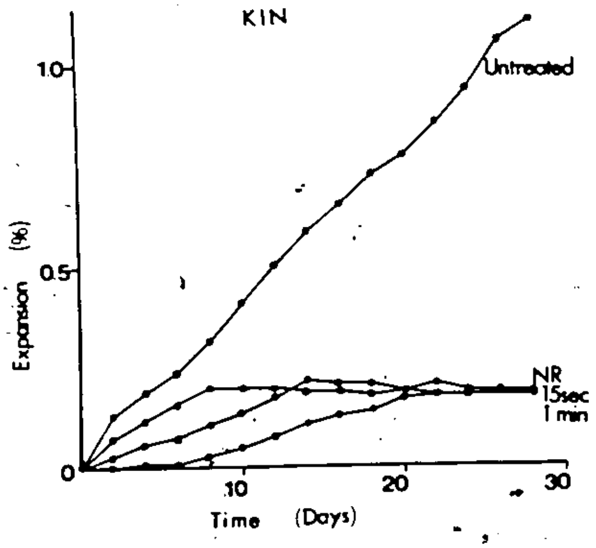

Figure 5.30: Expansion data for reactive aggregates treated with "STP": STT.

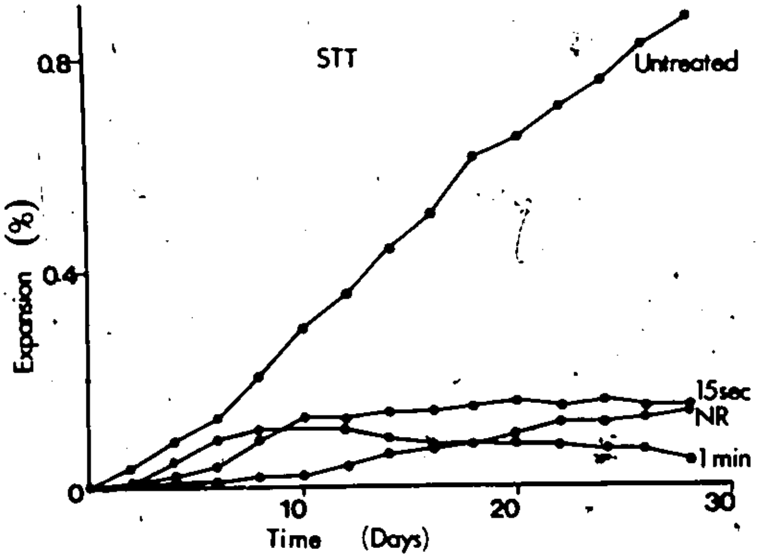

Figure 5.31 Expansion data for reactive aggregates treated with "STP": KIN.

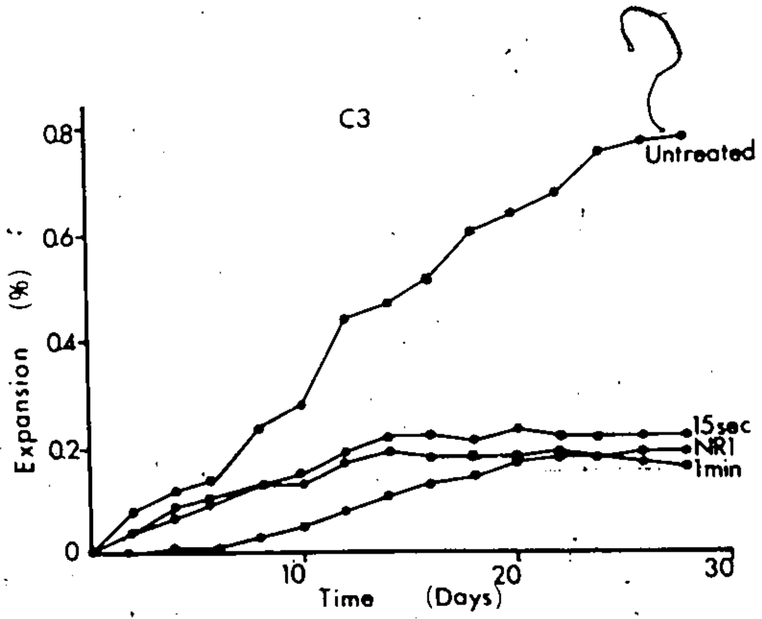

Figure 5.32 Expansion data for reactive aggregates treated with "STP": C3.

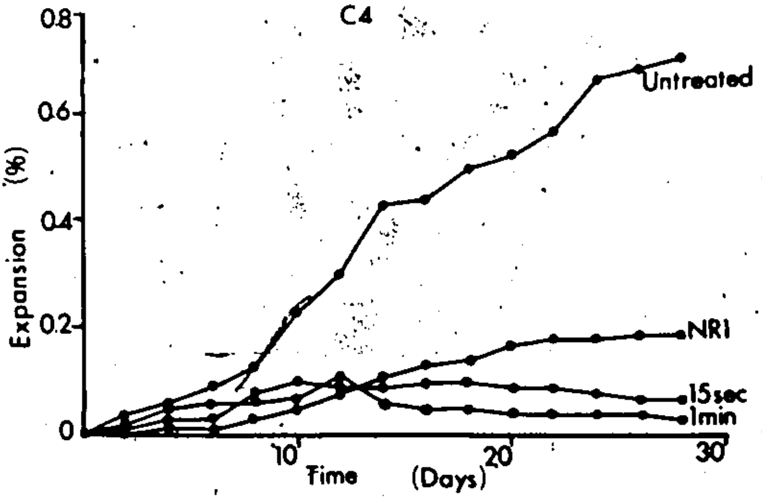

Figure 5.33: Expansion data for reactive aggregates treated with "STP": C4.

TABLE 5.11a

Comparison of "STP"-Treated Aggregates with Untreated Aggregates (15 Second-Treatment)

Sample	Mean Expansion (%)		Standard Deviation		Reduction in Expansion after Treatment	Sample Size	F-value	Student's t-value	Probability (Confidence Level)	Population Comparison
	Untreated	Treated	Untreated	Treated						
PUT	.4807	.0020	.2985	.0220	99.5839	15	178.2000	6.1938	.0100	Different (Significant Reduction)
SUD	.3762	.0950	.2491	.0430	74.7475	15	34.5000	4.3083	.0100	Different (Significant Reduction)
STT	.4359	.1070	.3007	.0580	75.4531	15	26.5882	4.1592	.0100	Different (Significant Reduction)
KIN	.5679	.1620	.3483	.0550	71.4739	15	40.4333	5.0631	.0100	Different (Significant Reduction)
C3	.4365	.1630	.2744	.0720	62.6575	15	14.4808	3.7334	.0100	Different (Significant Reduction)
C4	.3566	.0680	.2507	.0330	80.9310	15	57.1818	2.9792	.0100	Different (Significant Reduction)
ARR (GROUP)	.4423	.0995	.0762	.0608	77.4745	90	1.5676	8.6150	.0100	Different (Significant Reduction)

$t_{.01;28} = 2.763$ $t_{.01;10} = 3.169$ $F_{.01;5\,5} = 10.970$ $F_{.01;14.14} = 3.760$

ARR - Alkali-Reactive Rocks

TABLE 5.11b

Comparison of "STP"-Treated Aggregates with Untreated Aggregates (1 Minute-Treatment)

Sample	Mean Expansion (%)		Standard Deviation		Reduction in Expansion after Treatment	Sample Size	F-value	Student's t-value	Probability (Confidence Level)	Population Comparison
	Untreated	Treated	Untreated	Treated			1min	1min		
PUT	.4807	-.0520	.2985	.0370	Contraction	15	63.6429	4.0901	.0100	Different (Significant Reduction)
SUD	.3762	.0740	.2491	.0380	54.7368	15	44.3571	4.6447	.0100	Different (Significant Reduction)
STT	.4359	.0730	.3007	.0330	45.7944	15	82.1818	4.7105	.0100	Different (Significant Reduction)
KIN	.5679	.1420	.3483	.0670	66.0494	15	26.9556	5.4041	.0100	Different (Significant Reduction)
C3	.4365	.1370	.2744	.0570	55.8282	15	23.5313	4.1401	.0100	Different (Significant Reduction)
C4	.3566	.0470	.2507	.0230	51.4706	15	125.8000	3.3009	.0100	Different (Significant Reduction)
ARR (GROUP)	.4423	.0702	.0762	.0708	54.7759	90	1.1600	8.7705	.0100	Different (Significant Reduction)

$t_{.01;28} = 2.763$ $t_{.01;10} = 3.169$ $F_{.01;5,5} = 10.970$ $F_{.01;14,14} = 3.760$

AARR - Alkali-Reactive Rocks

TABLE 5.12

Summary of Student's t-test for Comparing Treated Aggregates

Samples	Data Size	*Mean Expansion (%) 15sec	*Mean Expansion (%) 1min	Standard Deviation 15sec	Standard Deviation 1min	F-value	Student's t-value	Probability (confidence level)	Population Comparison
PUT	15	.0020	-.0520	.0220	.0370	.3571	.6397	.0500	Same
SUD	15	.0950	.0740	.0430	.0380	1.2857	1.4378	.0500	Same
STT	15	.1070	.0730	.0580	.0330	3.0909	1.9630	.0100	Same
KIN	15	.1620	.1420	.0550	.0670	.6667	.8944	.0500	Same
C3	15	.1630	.1370	.0720	.0570	1.6250	1.0987	.0100	Same
C4	15	.0680	.0470	.0330	.0230	2.2000	2.0333	.0100	Same

$F_{.01;14,14} = 3.7610$; $F_{.05;14,14} = 2.5100$; $t_{.01;28} = 2.7630$; $t_{.05;28} = 2.0480$;

* Average of four measurements of three cores.

water from penetrating the concrete or aggregate. The relatively high acidity of the "STP" also neutralizes any hydroxide present in the concrete. The concentration of the hydroxide necessary to promote the alkali-aggregate reaction is reduced. The reaction is therefore prevented and the reactive aggregate becomes inert.

5.6.3 Comparison of treated concrete cores and treated aggregates

Tables 5.13 and 5.14 show a statistical comparison of the treated concrete cores and the treated aggregates. The results indicate that there is no significant difference between the performance of the treated concrete and the performance of the treated aggregate in concrete. With the exception of STT, C3, and C4 for the 1 minute treatment, the results of the two treatment procedures are the same for all the reactive aggregates. This means that if one treats a reactive aggregate with "STP" before use in concrete there will be very little variation (if any) between the performance of such concrete and treated concrete containing reactive aggregate for the same period of time.

5.6.4 Effects of "IP" on alkali-aggregate reaction

Figures 5.34 to 5.39 show graphs of linear expansion versus time in weeks for untreated concrete, concrete containing "IP", and a non-reactive silica aggregate. The treatment procedure is described in Section 4.2.4.1. From the graphs and statistical analyses, treatment of the reactive silica aggregates with "IP" shows significant reduction in expansion (>50%) (Table 5.15). In

TABLE 5.13

Comparison of Means for 15 seconds Treatment of Concrete Cores and Aggregates

Sample	Characteristics after 15 seconds treatment	Data Size	Mean Expansion (%)		Standard Deviation		F-value	Student's t-value	Probability (confidence level)	Population Comparison
			Concrete	Aggregate	Concrete	Aggregate				
PUT	Linear expansion	15	.0280	.0020	.0400	.0220	3.2000	-2.5355	.0100	Same
SUD	Linear expansion	15	.0950	.0950	.0710	.0430	2.7778	1.7378	.0100	Same
STT	Linear expansion	15	.1710	.1070	.0850	.0580	2.1176	2.4075	.0100	Same
KIN	Linear expansion	15	.1900	.1620	.0940	.0550	2.9333	.9983	.0100	Same
C3	Linear expansion	15	.2180	.1630	.1130	.0720	2.4615	1.5877	.0500	Same
C4	Linear expansion	15	.0640	.0680	.0580	.0330	3.0909	-.2309	.0100	Same

$F_{.01;14,14} = 3.7610$; $F_{.05;14,14} = 2.5000$; $t_{.01;28} = 2.7630$; $t_{.05;28} = 2.0480$.

TABLE 5.14

Comparison of Means for 1 minute Treatment of Concrete Cores and Aggregates

Sample	Characteristics after 1 minute treatment	Data Size	Mean Expansion (%)		Standard Deviation		F-value	Student's t-value	Probability (confidence level)	Population Comparison
			Concrete	Aggregate	Concrete	Aggregate				
PUT	Linear expansion	15	.0130	-.0420	.0800	.0370	4.5714	2.4119	.0100	Different
SUD	Linear expansion	15	.1210	.0740	.0620	.0380	3.4286	2.3118	.0100	Same
STT	Linear expansion	15	.1230	.0730	.0680	.0330	4.1818	2.5649	.0100	Different
KIN	Linear expansion	15	.1420	.1420	.0880	.0670	1.7111	0	.0500	Same
C3	Linear expansion	15	.2910	.1730	.1860	.0570	10.8125	2.3506	.0100	Different
C4	Linear expansion	15	.1360	.0740	.0950	.0230	18	2.4636	.0100	Different

$F_{.01;14,14} = 3.7610$; $F_{.05;14,14} = 2.5100$; $t_{.01;28} = 2.7630$; $t_{.05;28} = 2.0480$

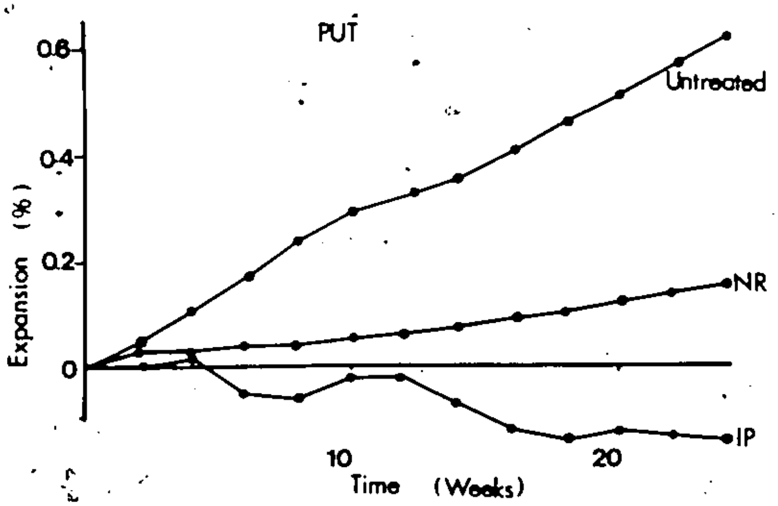

Figure 5.34 Expansion data for reactive aggregates treated with "IP": PUT.

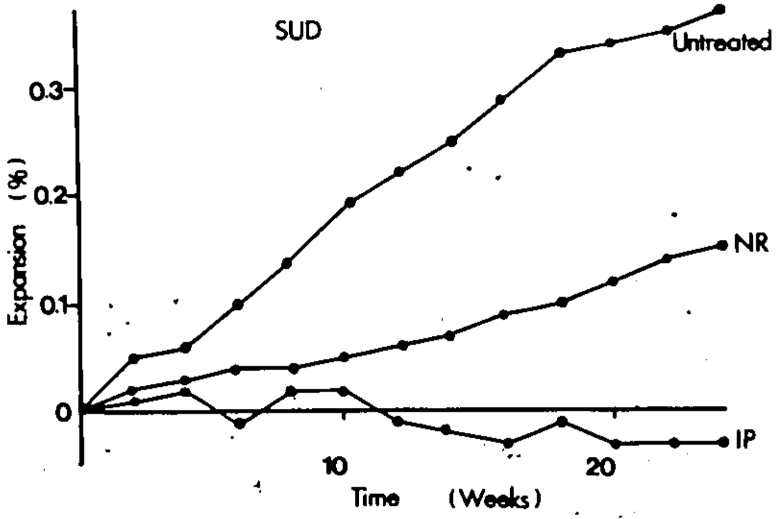

Figure 5.35: Expansion data for reactive aggregates treated with "IP": SUD.

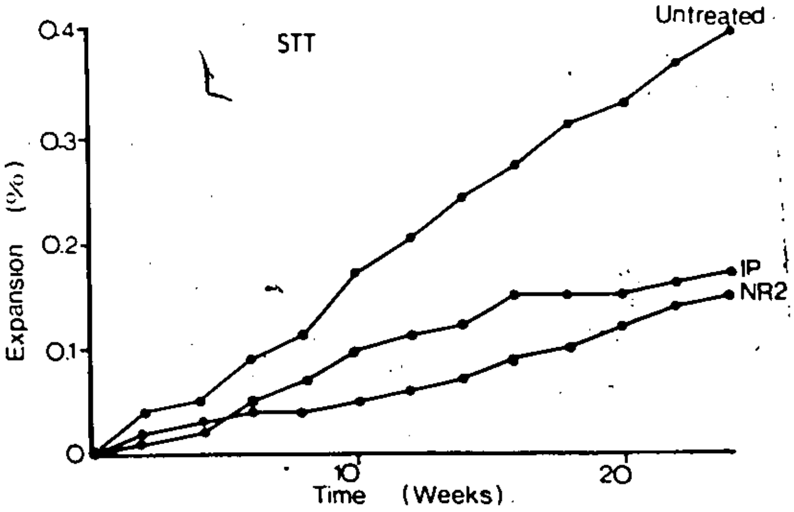

Figure 5.36: Expansion data for reactive aggregates treated with "IP": STT.

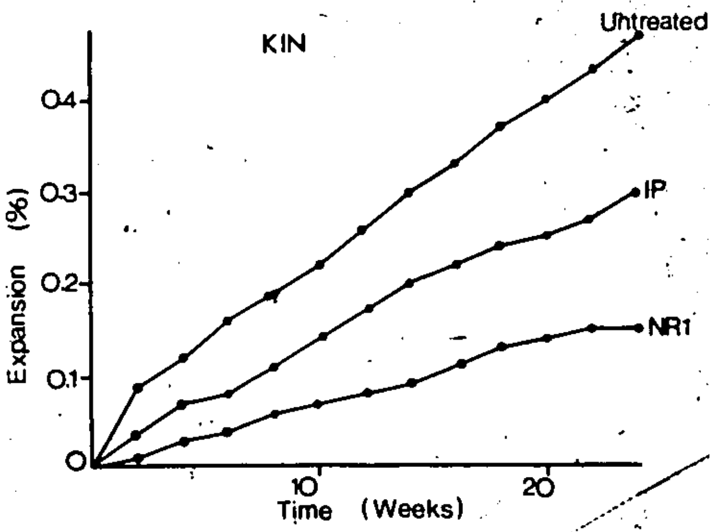

Figure 5.37: Expansion data for reactive aggregates treated with "IP": KIN.

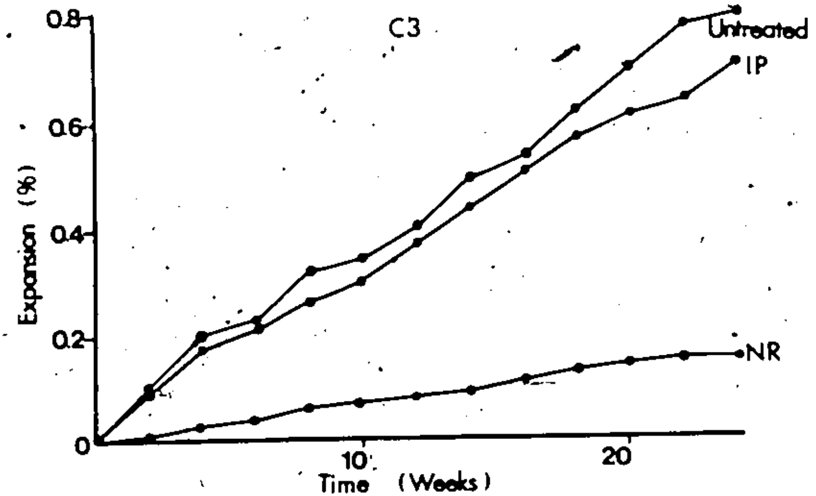

Figure 5.38: Expansion data for reactive aggregates treated with "IP": C3.

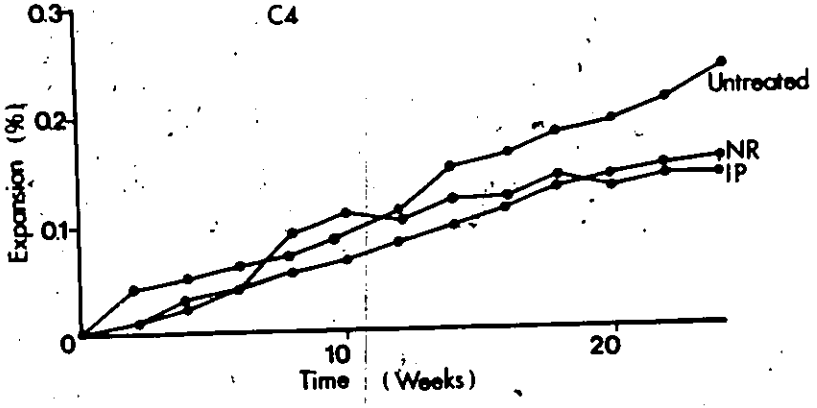

Figure 5.39: Expansion data for reactive aggregates treated with "IP": C4.

TABLE 5.15

Comparison of "IP"-Treated Concrete with Untreated Concrete Cores

Sample	*Mean Expansion		Standard Deviation		Reduction in Expansion after Treatment	Sample Size	F-value	Student's t-value	Probability (Confidence Level)	Population Comparison
	Untreated	Treated	Untreated	Treated						
PUT	.3150	-.0652	.1975	.0585	Contraction	13	1.1471	16.6238	.0500	Different (Significant Reduction)
SUD	.2067	-.0088	.1286	.0200	Contraction	13	41.2500	27.4710	.0500	Different (Significant Reduction)
STT	.1963	.0968	.1336	.0612	50.6877	13	4.8108	9.0324	.0100	Different (Significant Reduction)
KIN	.2564	.1604	.1422	.0951	37.4415	13	2.2444	2.5799	.0100	Different (Significant Reduction)
C3 n)	.4233	.3739	.2555	.2254	11.6702	13	1.2854	1.1255	.0500	Same (No Significant Reductio
C4 n)	.1185	.0892	.0741	.0520	24.7257	13	2.0370	1.4376	.0100	Same (No Significant Reduction)
ARR (GROUP)	.2527	.1077	.1061	.0854	31.1313	90	1.0354	2.3417	.0100	Different (Significant Reduction)

$t_{05\ 24} = 1.711$ $t_{01\ 11} = 2.718$ $t_{01\ 24} = 2.492$ $F_{05\ 12\ 12} = 2.690$ $F_{01\ 12\ 12} = 4.160$ $F_{05\ 5\ 5} = 5.050$ $F_{01\ 5\ 5} = 10.970$

* Average of four measurements of three cores.

fact, in the case of PUT and SUD, there is even some amount of contraction. On the other hand, the reactive carbonate rocks show poor results; the amount of expansion of the treated concrete containing KIN, C3, and C4 are almost the same as the corresponding untreated concrete. Treatment of the concrete with "IP" does not seem to work with the alkali-reactive carbonate rocks. The treatment shows more promise with the alkali-reactive silica rocks than with alkali-reactive carbonate rocks.

CHAPTER 6

6.0 SUMMARY AND RECOMMENDATIONS

6.1 Summary

The regression analyses indicate that good correlations exist between the standard tests and the two accelerated tests - that is, accelerated tests (elevated temperature, 1N NaOH) and accelerated test (elevated temperature, saturated NaCl). Results also show a good linear relationship between the accelerated test (elevated temperature, 1N NaOH) and the accelerated test (elevated temperature, saturated NaCl); and between the accelerated test (elevated temperature, 1N NaOH) and the accelerated test (ambient temperature, 1N NaOH). In all cases, the Pearson's R (correlation coefficient) obtained for the correlations were high and statistically significant.

Results of the study also indicated that alkali-aggregate reaction is manifested much better in alkaline environments than in alkali salt environments. Expansions were greater in 1N NaOH solution than in the saturated NaCl solution. This was confirmed by the slopes of the regression curves for the standard tests and the two accelerated tests as well as the slopes of the regression curves for the accelerated (1N NaOH) and the accelerated (saturated NaCl) test.

It was noted that the expansions for the accelerated test (elevated temperature, 1N NaOH) - for the 28-day testing period were greater than the expansions associated with the 1-year-long standard tests (see slopes of regression curves Figures 5.7 and

5.8). This result was noted for all the reactive aggregates. The design of the mix for the accelerated tests was the same as the standard tests. The constituents of the concrete (with the exception of the reactive aggregates) were also the same. The only parameter apart from the accelerated conditions which could have caused the variation in expansion was the size of the test prisms and the cores. The smaller size of the cores in the accelerated test enabled the hydroxide ions (OH^-) to penetrate through the cement paste to the reactive aggregates easier than through the larger sizes of the prisms. The difference was greater in the (CSA 14A) concrete prism expansion test in which the prisms were much bigger than the prisms of the (ASTM C 227) mortar bar test (Figures 5.2 and 5.8). The smaller core size in the accelerated tests promoted a faster rate of reaction in the alkali-aggregate reaction. The small core size provides a better means for screening potentially reactive aggregates.

It was observed in the study that concrete containing alkali-carbonate reactive rocks expanded while concrete containing alkali-silica reactive rocks contracted in saline environment at ambient temperature conditions. Concrete containing alkali-silica reactive rocks, however, expanded in saline solution at elevated temperatures.

Results showed that the "STP" treatment could be used to considerably improve the performance of reactive aggregates in concrete. In other words the "STP" enabled the reactive aggregates to become inert and performed in the same way in concrete as non-reactive aggregates. The shorter periods of treatment (15 seconds and 1 minute) were found to be better than the 1 hour treatment. A statistical comparison of the two methods of treatment - <u>treated concrete</u> and <u>treated aggregates</u> - indicated that there is no significant difference between the two treatment methods at the 95% confidence level. Therefore one would expect to find very little variation between the performance of reactive aggregates treated with "STP" before use in concrete and treated concrete containing reactive aggregates. The "IP" was found to be suitable for treating alkali-silica reactive aggregates only.

6.2 Conclusion

In a study of alkali-aggregate reactions in concrete, the following conclusions which are believed to be of importance to the use of reactive aggregates in routine concrete works can be drawn:

1. The newly developed accelerated tests in this study could be used to screen all reactive aggregates in preference to the standard tests ASTM C 227 and CSA 14A which are currently in use. This stems from the good and significant linear relationship between the accelerated tests (elevated temperature) and the standard tests. Two inferences could be made from the high strength of linear relationship between the accelerated test (elevated temperature) and the standard tests. First of all the results obtained suggest that the accelerated tests (elevated temperature) could be substituted for the standard tests used in this study. Thus, instead of spending one year carrying out the standard test, the accelerated test could be used to screen the same aggregates within a matter of two months. The accelerated tests, in other words, are time-saving and cost effective. Secondly, the accelerated tests have additional advantage of screening almost all potentially reactive aggregates - silica/silicate and carbonates. This is possible even in the case of late-expanders (reactive rocks which show slow initial expansion) such as the gravels of Sudbury (SUD),

which the standard test ASTM C 227 is not suitable for in most cases. The accelerated tests are therefore not aggregate-specific; they are better discriminants and less laborious than the standard tests.

2. Between the two accelerated tests used, the accelerated test (1N NaOH) gave better screening results than the accelerated test (NaCl), although the two tests correlated very well.

3. The fundamental reaction in alkali-aggregate reaction in concrete is between the hydroxide ion from the pore solution and the reactive aggregate and not the alkali ion as already shown by Diamond (1975).

4. In a saline environment at ambient temperatures, concrete containing alkali-carbonate reactive rocks will expand while concrete containing alkali-silica reactive rocks will contract. At elevated temperatures, however, concrete containing alkali-silica reactive rocks will expand.

5. Reactive aggregates could perform as non-reactive aggregates when properly treated with "STP" and "IP".

6. The performance of reactive aggregates, when treated with "STP" before use in concrete is the same as treated concrete containing reactive aggregates. In the latter case the

performance is more effective if the "STP" is applied immediately after the concrete is emplaced.

6.3 Recommendations

In the construction industry, if an aggregate is to be used for concrete works and the aggregate is suspected to be reactive, any one of the newly developed accelerated tests could be used to evaluate it. The accelerated test using 1N NaOH is much recommended.

Reactive aggregates to be used in construction of any concrete structure should first be pretreated with "STP" solution in a manner outlined in this study before use. After placement of the concrete further treatment is highly recommended.

If initial petrographic analysis identifies the suspect aggregate to be silica-reactive, then the "IP" could also be used to arrest the reaction.

Although the results presented in this study are encouraging, the data cover only six reactive aggregate samples. A large number of samples is needed for further investigation. Such investigation should be focussed on the following aspects:

(i) The effects of the accelerated tests on a large number of reactive aggregate samples from varying localities.

(ii) The effects of saturated salt solution on a large number of both reactive and non-reactive rock samples.

(iii) The effects of different "STP" concentrations on reactive aggregates in concrete.

(iv) The effects of various treatment periods (that is different length of immersion of concrete/aggregates) in "STP".

(v) The long term effect of the "STP" and the "IP" on alkali-aggreagte reaction in concrete.

(vi) Other mechanisms (chemical, physiochemical, etc.) involved in the prevention of alkali-aggregate reactions in concrete with the "STP".

In addition a study of the relationship between the pore characteristics of the aggregate and the "STP" treatment would be worthwhile to augment the information presented in this study. Results of such investigation would assist in solving other durability problems in concrete.

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APPENDIX A

SAMPLE LOCATIONS AND DESCRIPTIONS

SAMPLE LOCATIONS AND DESCRIPTIONS

Location Number	Sample	Location and Description
1	PUT	Located at New Bigging Pit near Putnam, 15km off 401 North on Putnam Road. Cobbles of chert of Middle to Devonian in age. Colour of chert is dark blue, light grey, and white. The texture is cryptocrystalline and nodular.
2	SUD	* Pioneer Construction Pit near the Airport of Sudbury, Ontario. Pit contains 75% rocks from the Huronian Supergroup. Aggregate composed of sandstone and arkosic sandstone, argillite and greywacke, quartzite and quartz, granite and diabase.
3	STT	*-Spratts Quarry, owned by Spratts Sand and Gravel Company Limited, Stittsville, Ontario. Reactive aggregate from the 2nd Lift of the quarry. Limestone of the Bobycaygeon Formation in the Simcoe Group. The limestone is hard, medium dark grey in colour, medium bedded, and calcarenite. Outcrop consists of few intercalations of slightly shaley limestone and cherty limestone.
4	KIN	Pittsburg Quarry of McGinnis and O'Conner Limited, located near Pittsburg Township on Highway 15 south of Highway 401. Limestones and dolomites of the Gull River Formation (Black River Formation, Unit A) Middle Ordovician in age; brownish grey, fine-grained, dolomitic limestones or calcitic dolomite, aphanitic calcite crystals, wackestone, biomicrite.

5	C3	The MacLeod Quarry of Cornwall Gravel Company in the Township of Cornwall, about 2.5km east of Eamer. Ottawa Limestone of the Middle Black River Formation, Unit CC2 and CC3; Middle Ordovician in Age. Limestone, medium grey, medium crystalline to aphanitic; massive bedded; alternating calcarenite and calcilutite; calcite crystals and shaley partings.
6	C4	The MacLeod Quarry of Cornwall Gravel Company in the Township of Cornwall, about 2.5km east of Eamer. Ottawa Limestone of the Lower Black River Formation, Unit CC1; Middle Ordovician. Limestone and dolomite; medium to dark grey; medium crystalline to aphanitic.
7	NR1	Inland Lime and Stone Quarry owned by the Inland Steel Corporation. Quarry located 9.6km east on US41 from junction of M95 near Humbolt and 1.12km west on Marquette County Road, in the State of Michigan. **Limestone, whitish-grey, medium crystalline to aphanatic; hard with few crystals of calcite; biomicrite.
8	NR2	Sand and Gravel Pit of Geo. E. White and Sons Company located 2km northeast of Leamington. Medium- to fine-grained Quatrenary sand; glacial deposit interstratified with sand granules and pebbles.

* Information supplied by the Materials Division of the Ministry of Transport and Communications, Toronto.

** Formation unknown.

APPENDIX B

PROPERTIES OF SAMPLES

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

Source New Bigging Pit, Putnam, Ontario. Lab No. 1

Type Crushed Rock (PUT) Size Fraction – Date June, 1987.

LITHOLOGIC DESCRIPTION	MTC Type	Weight g	Percent of total
Chert – cherty carbonates, dark blue, light grey, nodular;	Fair	252.50	25.51
Carbonates – cherty limestone, light grey, whitish in colour;	Fair	612.30	61.84
Carbonates – crystalline, white, medium-to fine-grained, hard;	Good	125.20	12.65
TOTAL		990.00	100.00

Percent Good 12.65 x 1 .... 12.65

Percent Fair 87.35 x 3 .... 262.05

Percent Poor – .... –

Percent Deleterious – .... –

Percent crushed 100.00

Percent Flats and Elongate... –

PETROGRAPHIC NUMBER

BASIC...................... 274.70

CONCRETE & HOT MIX......... –

GRANULAR "A" & 5/8" Cr..... –

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

Source Pioneer Construction Pit, Sudbury, On Lab No. 1

Type Gravel (SUD) Size Fraction - Date June, 1987

LITHOLOGIC DESCRIPTION	MTC Type	Weight g	Percent of total
Sandstone - medium hard, medium-grained,	Good	99.00	9.90
Gneiss, schist - hard;	Good	75.30	7.40
Quartzite - hard, medium-grained;	Good	141.00	14.10
Greywacke, arkose - medium-grained, hard;	Good	328.00	32.80
Volcanic - hard and slightly weathered;	Good	120.00	12.00
Granite, diabase - hard;	Good	140.00	14.00
Argillite - light grey, fine-grained;	Fair	99.00	9.90
TOTAL		1002.00	100.00

Percent Good... 90.10 x 1 ... 90.10

Percent Fair... 9.90 x 3 ... 29.7

Percent Poor... - ... -

Percent Deleterious... - ... -

Percent crushed 100.00

Percent Flats and Elongate... -

PETROGRAPHIC NUMBER

BASIC........................ 120.60

CONCRETE & HOT MIX......... -

GRANULAR "A" & 5/8" Cr..... -

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

Source Spratts Quarry, Stittsville, Ontario Lab No. 1

Type Crushed Rock (STT) Size Fraction - - Date June, 1987.

LITHOLOGIC DESCRIPTION	MTC Type	Weight g	Percent of total
Carbonates - hard, medium dark grey, good, medium-grained limestone;	Good	425.43	42.29
Carbonates - hard, sandy, medium dark grey, limestone;	Good	501.50	50.25
Carbonates - slightly shaley limestone;	Fair	65.54	6.52
Carbonates - cherty limestone;	Fair	5.32	0.52
Carbonates - shaley limestone;	Poor	7.40	0.74
TOTAL		1005.00	100.00

Percent Good. 92.54 x 1 ..... 92.54

Percent Fair.. 7.05 x 3 ..... 21.15

Percent Poor.. 0.74 x 6 ..... 4.40

Percent Deleterious .... -

Percent crushed 100.00

Percent Flats and Elongate... -

PETROGRAPHIC NUMBER

BASIC........................ 118.09

CONCRETE & HOT MIX......... -

GRANULAR "A" & 5/8" Cr..... -

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

Source Pittsburg Quarry, Kingston, Ontario Lab No. 1

Type Crushed Rock (KIN) Size Fraction - Date June, 1987

LITHOLOGIC DESCRIPTION	MTC Type	Weight g	Percent of total
Carbonates - brownish grey, hard, fine-grained, dolomitic limestone;	Good	691.00	69.30
Carbonates - wackestone, sandy, hard;	Good	185.00	18.60
Carbonates - medium grey, fine-grained, slightly shaley limestone;	Fair	121.10	12.10
TOTAL		997.00	100.00

Percent Good 87.90 x 1 .... 87.90

Percent Fair 12.10 x 3 .... 36.30

Percent Poor .... -

Percent Deleterious .... -

Percent crushed 100.00

Percent Flats and Elongate... -

PETROGRAPHIC NUMBER

BASIC........................ 124.20

CONCRETE & HOT MIX......... -

GRANULAR "A" & 5/8" Cr..... -

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

Source MacLeod Quarry, Cornwall, Ontario Lab No. 1

Type Crushed Rock (3rd Lift) Size Fraction - Date June, 1987

LITHOLOGIC DESCRIPTION	MTC Type	Weight g	Percent of total
Carbonates - good, hard, medium grey, medium crystalline limestone;	Good	800.00	84.20
Carbonates - sandy, hard, dark grey limestone;	Good	53.00	5.60
Carbonates - sandy, medium hard, dolomitic limestone;	Good	31.00	3.30
Carbonates - slightly shaley, grey limestone;	Fair	66.00	6.90
TOTAL		950.00	100.00

Percent Good.. 93.10 x 1 .... 93.10

Percent Fair.... 6.90 x 3 .... 20.70

Percent Poor............... -

Percent Deleterious........ -

Percent crushed 100.00

Percent Flats and Elongate... -

PETROGRAPHIC NUMBER

BASIC...................... 113.80

CONCRETE & HOT MIX......... -

GRANULAR "A" & 5/8" Cr..... -

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

Source MacLeod Quarry, Cornwall, Ontario. Lab No. 1

Type Crushed Rock (4TH Lift) Size Fraction - Date June, 1987

LITHOLOGIC DESCRIPTION	MTC Type	Weight g	Percent of total
Carbonates - good, Hard, grey, medium crystalline, limestone;	Good	800.00	85.11
Carbonates - hard, sandy, grey limestone;	Good	71.00	7.55
Carbonates - slightly shaley, dark grey limestone;	Fair	69.00	7.34
TOTAL		940.00	100.00

Percent Good 92.66 x 1 .... 92.66

Percent Fair 7.34 x 3 .... 22.02

Percent Poor - .... -

Percent Deleterious - .... -

Percent crushed 100.00

Percent Flats and Elongate... -

PETROGRAPHIC NUMBER

BASIC.................... 114.68

CONCRETE & HOT MIX.........

GRANULAR "A" & 5/8" Cr..... -

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

Source Inland Pit and Gravel, Humbolt, Mich Lab No. 1

Type Crushed Rock (NR 1) Size Fraction - Date June, 1987

LITHOLOGIC DESCRIPTION	MTC Type	Weight g	Percent of total
Carbonates - hard, light grey, medium-grained limestone;	Good	99.50	9.13
Carbonates - slightly weathered, medium-grained limestone;	Good	158.60	14.55
Carbonates - sandy, hard, limestone;	Good	186.70	17.13
Carbonates - sandy, medium hard, medium-grained, light grey limestone;	Good	554.00	50.83
Carbonates - soft, slightly shaley limestone;	Fair	91.20	8.37
TOTAL		1090.00	100.00

Percent Good.......... 91.64 x 1 .... 91.64

Percent Fair.......... 8.37 x 3 .... 25.11

Percent Poor.......... - .... -

Percent Deleterious........ - .... -

Percent crushed 100.00

Percent Flats and Elongate... -

PETROGRAPHIC NUMBER

BASIC........................ 116.75

CONCRETE & HOT MIX......... -

GRANULAR "A" & 5/8" Cr..... -

TABLE B.1

Physical Properties of Rock Aggregates Used

Data	PUT	SUD	STT	KIN	C3	C4	NR1
P. N.	274.700	120.600	118.090	124.200	113.800	114.680	116.75
BSG	2.545	2.669	2.639	2.679	2.567	2.578	2.57
ASG	2.503	2.656	2.631	2.649	2.538	2.543	2.52
% Absp.	1.651	.466	.433	1.120	1.142	1.357	2.10
L.A.	6.330	12.600	18.300	14.170	16.380	15.740	16.75

P.N. - Petrographic Number (MTC)
B.S.G. - Bulk Specific Gravity
A.S.G. - Apparent Specific Gravity
% Absp. - Absorption (%)
L.A. - Los Angeles Abrasion Test

TABLE B.2

Chemical Analyses of Samples used in Study

Constituent	PUT	SUD	STT	KIN	C3	C4	NR1	NR2
SiO_2	50.50	70.10	8.34	7.19	16.60	16.50	2.63	51.60
Al_2O_3	.94	12.10	.50	2.20	2.70	2.66	.23	6.04
CaO	25	2.10	50.10	41.10	33.40	33.70	47.20	18.60
MgO	.99	2.12	1.79	7.74	9.37	9.39	7.63	1.73
Na_2O	.08	2.99	.01	.04	.13	.12	.01	1.16
K_2O	.28	2.02	.04	.32	.91	.90	.04	1.29
Fe_2O_3	3.49	6.80	.26	1.20	1.37	1.35	.20	4.04
MnO	.03	.08	.02	.02	.04	.04	.01	.07
TiO_2	.06	.41	.02	.09	.14	.13	.02	.28
P_2O_5	.02	.09	.20	.03	.04	.04	.01	.08
LIO	18.90	1	37.80	39.50	35.50	35.40	41.50	15.20
SUM	100.40	99.90	99.20	99.50	100.30	100.30	99.40	100.20

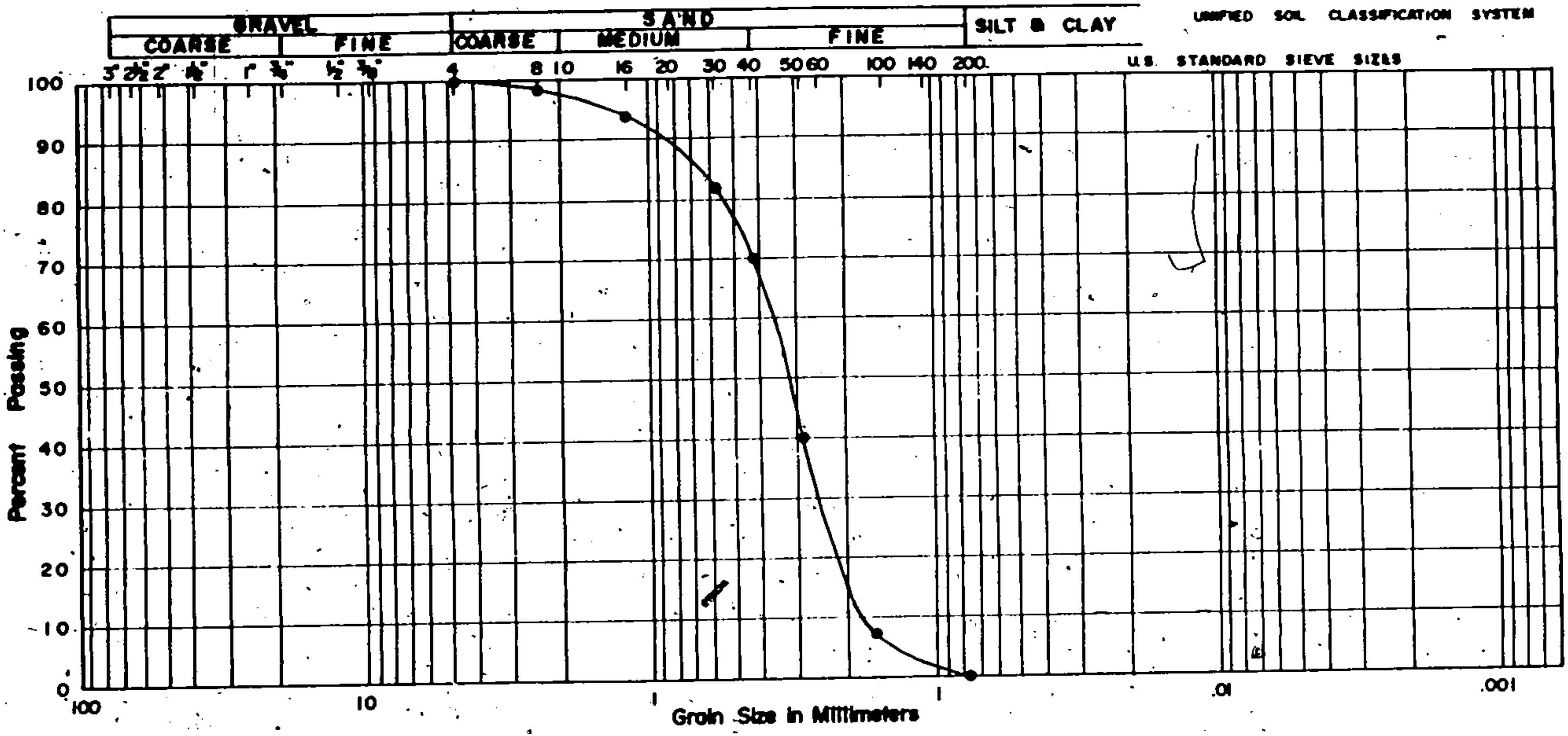


Figure B.1 : Particle Size Distribution of Sand

APPENDIX C

RESULTS OF CORRELATION AND REGRESSION ANALYSIS BETWEEN STANDARD AND ACCELERATED TESTS (ELEVATED TEMPERATURE, NaOH)

(INDIVIDUAL ROCK AGGREGATES)

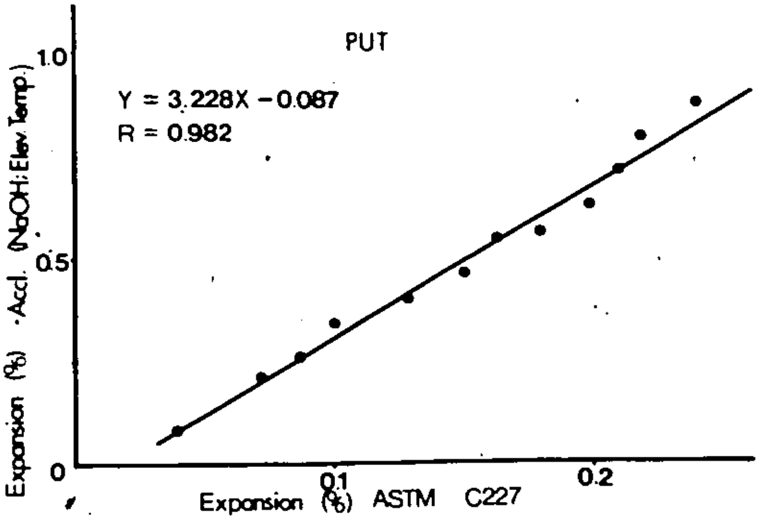


Figure C.1 PUT

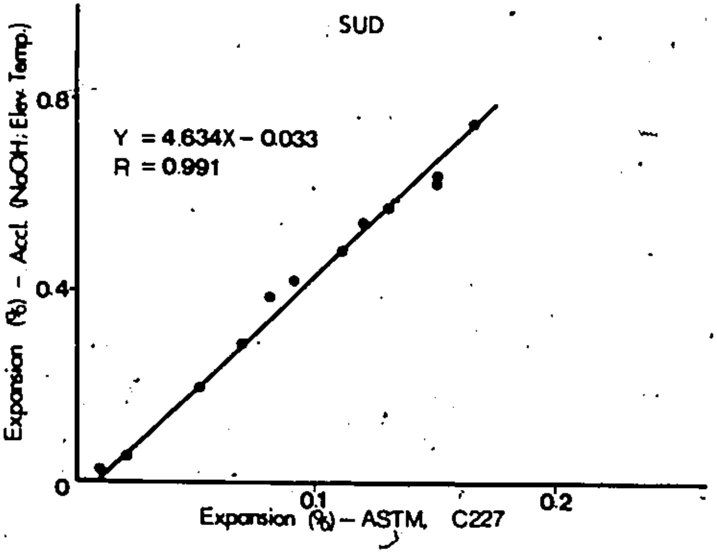


Figure C.2 SUD

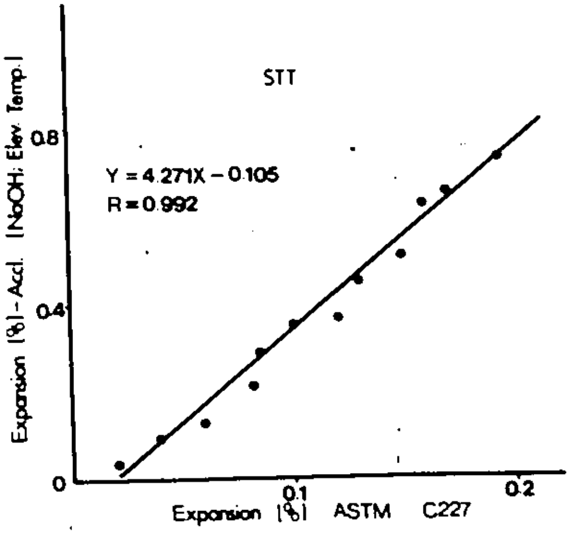


Figure C.3 STT

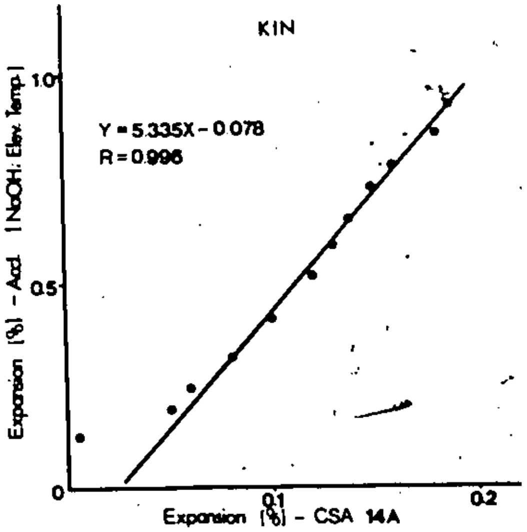


Figure C.4 KIN

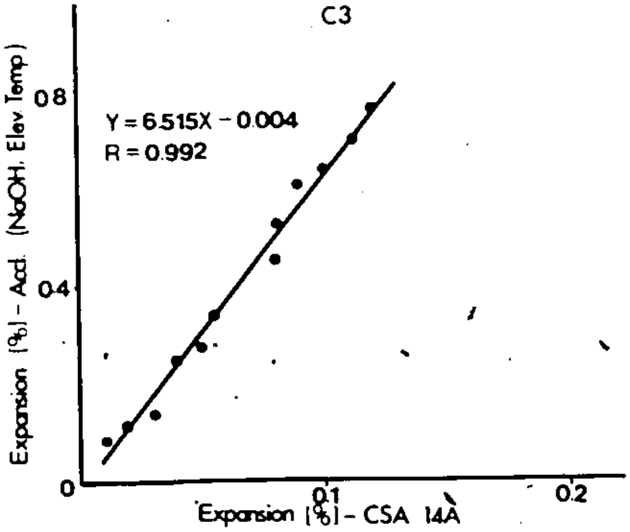
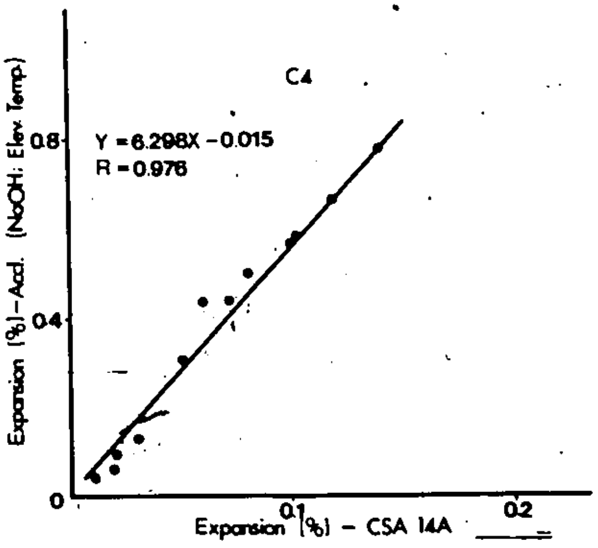


Figure C.5 C3



Fîugre C.6 C4

APPENDIX D

RESULTS OF CORRELATION AND REGRESSION ANALYSIS BETWEEN STANDARD AND ACCELERATED TESTS (ELEVATED TEMPERATURE, NaCl)

(INDIVIDUAL ROCKS AGGREGATES)

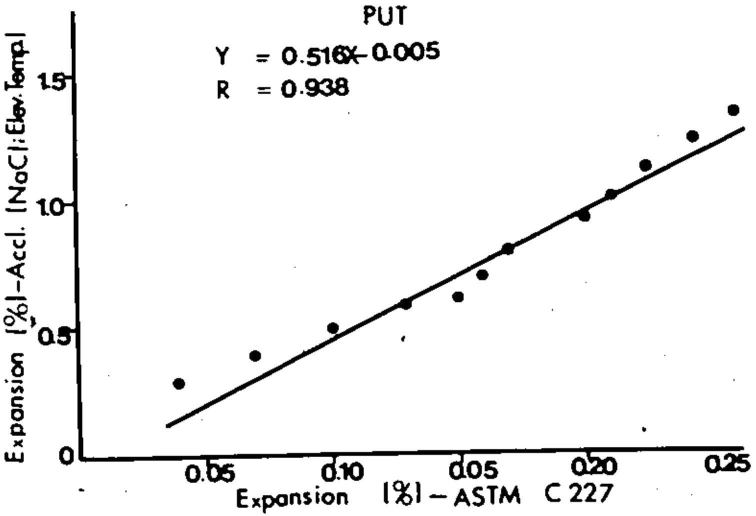


Figure D.1 PUT

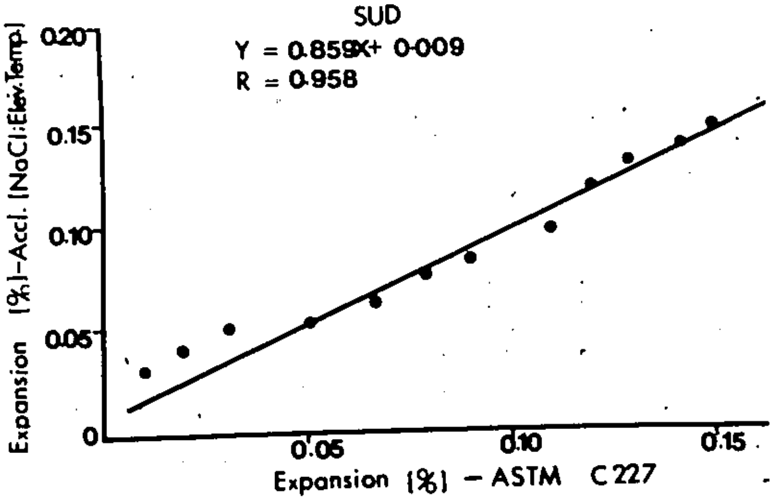


Figure D.2 SUD

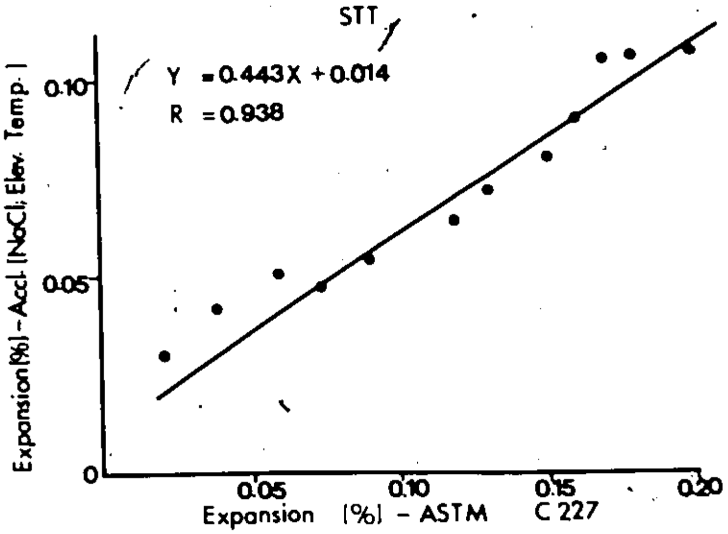


Figure D.3 STT

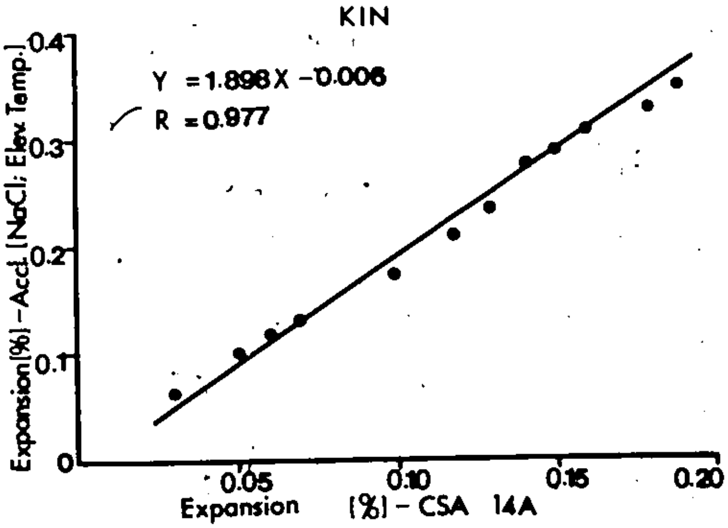


Figure D.4 KIN

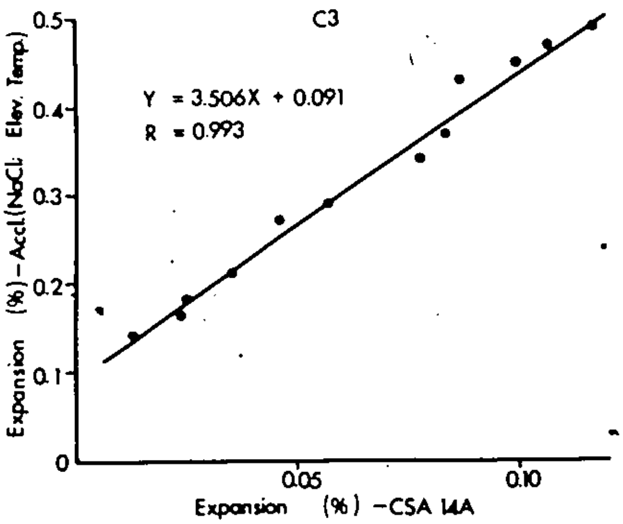


Figure D.5 C3

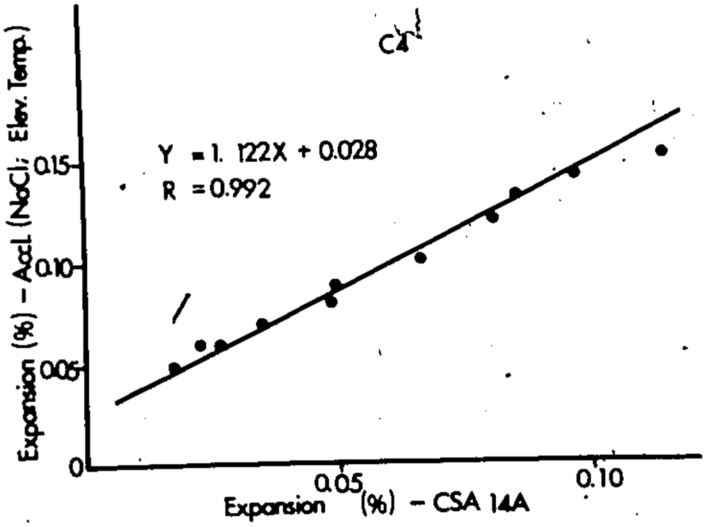


Figure D.6 C4

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APPENDIX E

RESULTS OF CORRELATION AND REGRESSION ANALYSIS BETWEEN ACCELERATED TESTS: (ELEVATED TEMPERATURE VS AMBIENT TEMPERATURE: NaOH)

(INDIVIDUAL ROCK AGGREGATES)

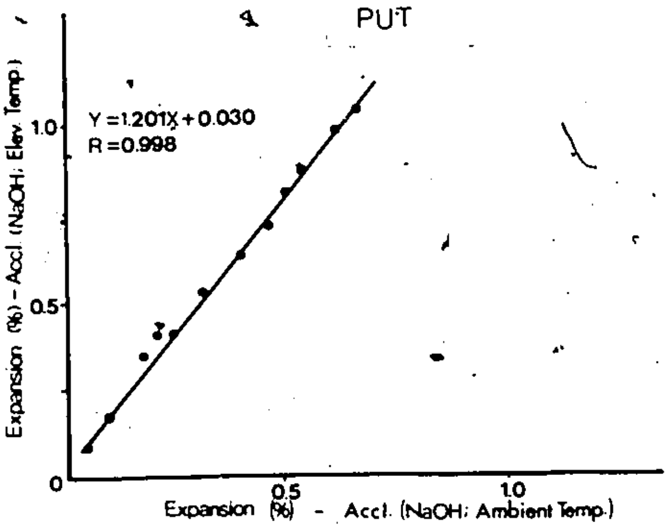

Figure E.1 PUT

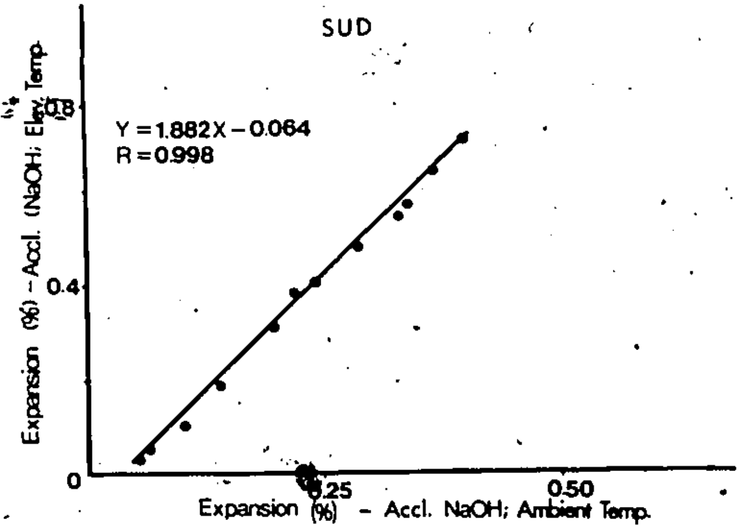

Figure E.2 SUD

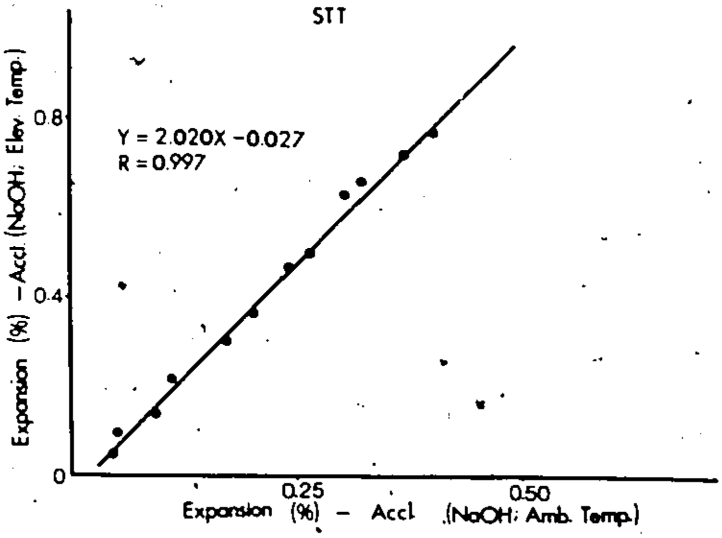

Figure E.3 STT

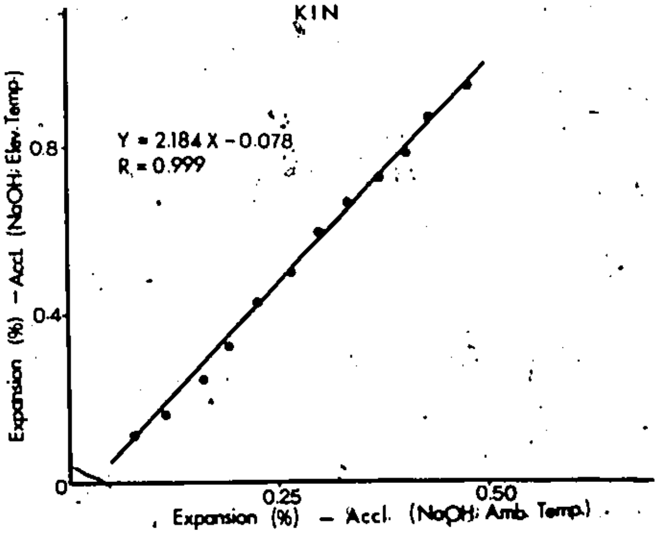

Figure E.4 KIN

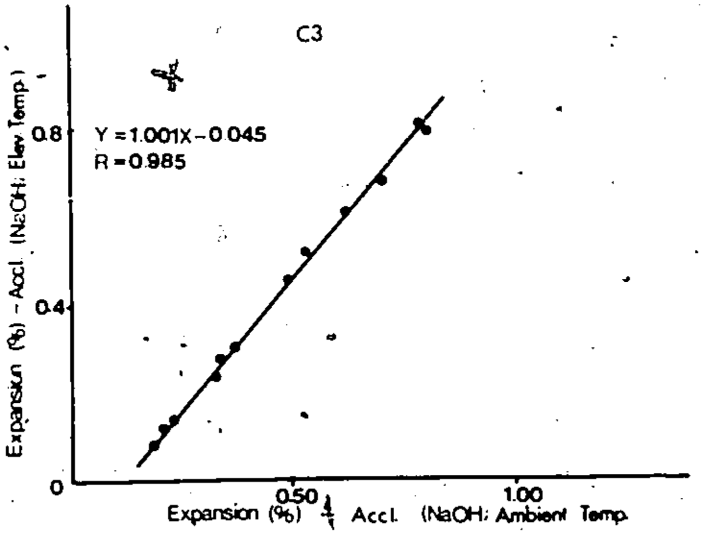

Figure E.5 C3

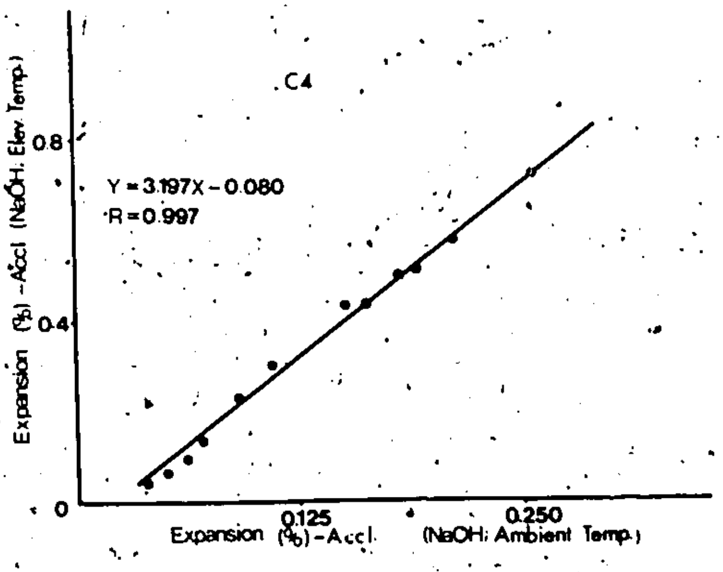

Figure E.6 C4

APPENDIX F

RESULTS OF CORRELATION AND REGRESSION ANALYSIS BETWEEN ACCELERATED TESTS: ELEVATED TEMPERATURE: (NaOH) VS (NaCl)

(INDIVIDUAL ROCK AGGREGATES)

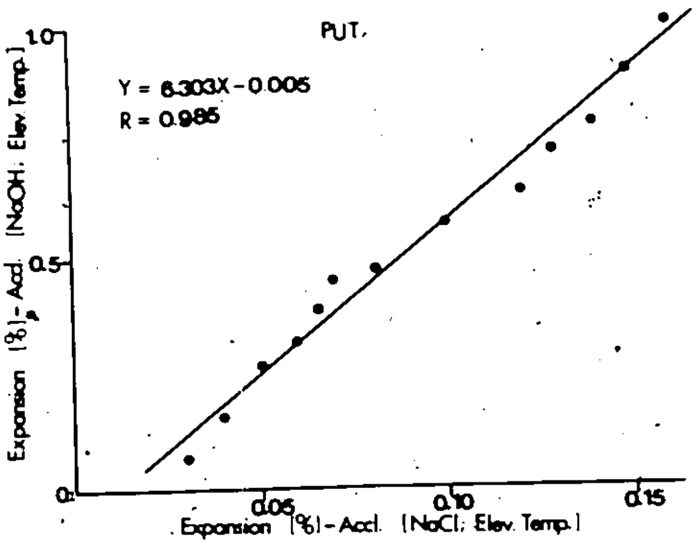

Figure F.1 PUT

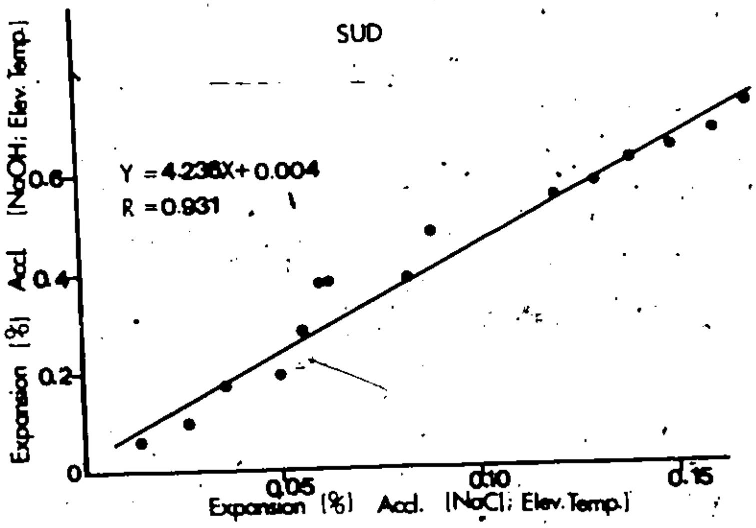

Figure F.2 SUD

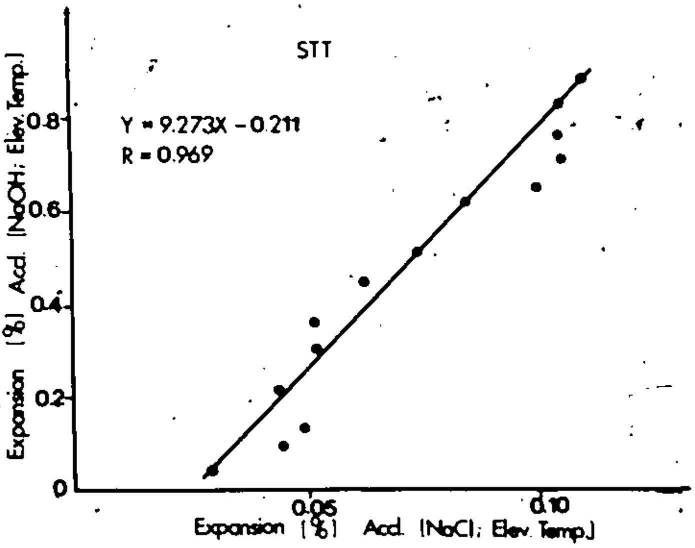

Figure F.3 STT

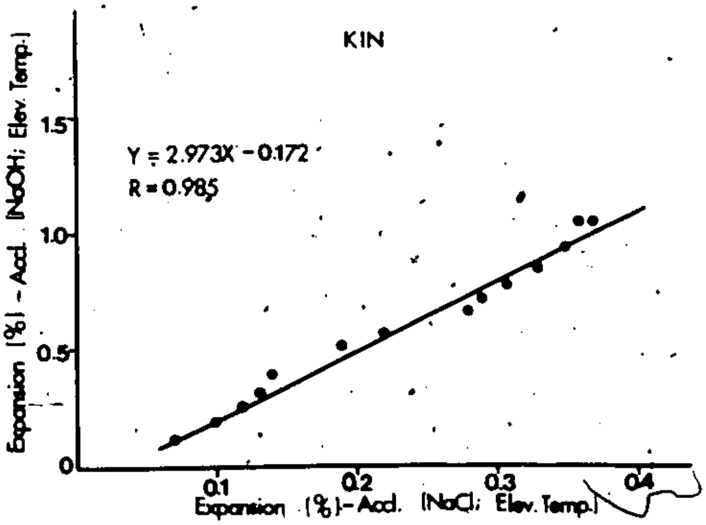

Figure F.4 KIN

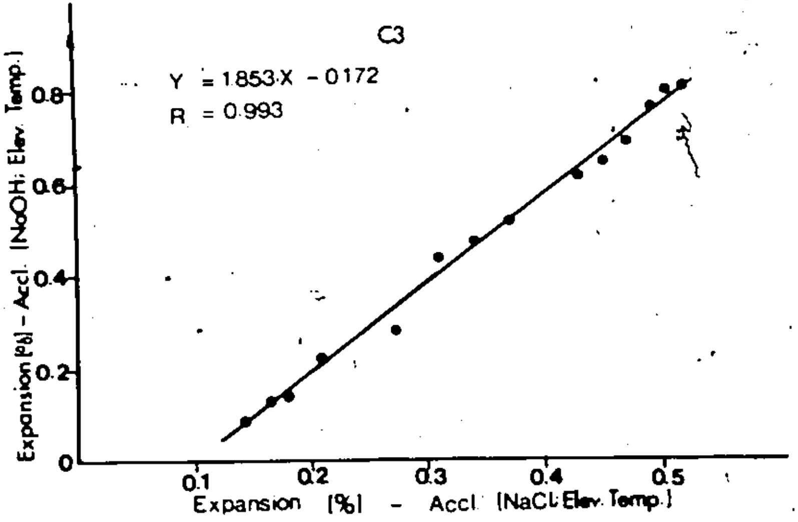

Figure F.5 C3

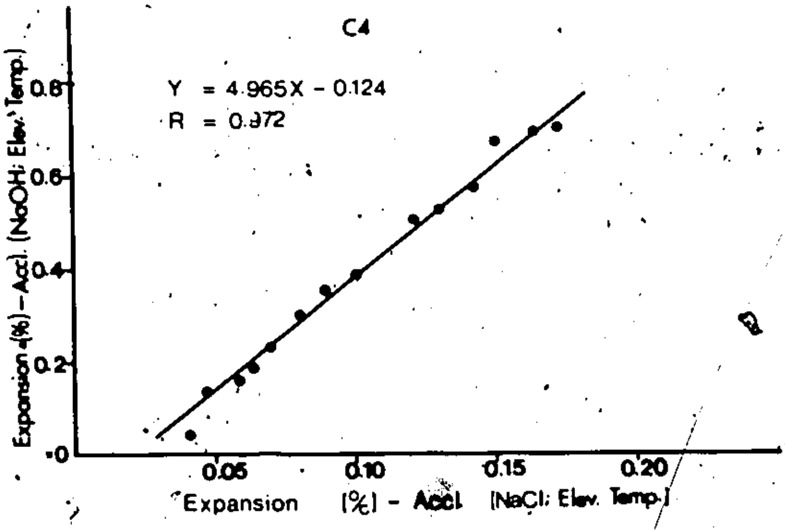

Figure F.6 C4

APPENDIX G

EXPANSION DATA FOR ALL TESTS IN THE STUDY

TABLE G.1

Results of standard test - ASTM C 227
Linear expansions (%) - Mortar Bar Test

Time (Months)	Mortar bars containing rock samples PUT	SUD	STT	NR1	NR2
0	0	0	0	0	0
1	.0416	.0137	.0225	.0010	.0007
2	.0730	.0240	.0432	.0026	.0016
3	.1022	.0325	.0621	.0034	.0020
4	.1300	.0533	.0755	.0043	.0025
5	.1477	.0670	.0932	.0058	.0031
6	.1638	.0804	.1236	.0079	.0049
7	.1756	.0855	.1320	.0094	.0065
8	.2037	.1082	.1531	.0098	.0070
9	.2134	.1183	.1623	.0103	.0075
10	.2235	.1332	.1689	.0112	.0082
11	.2390	.1447	.1857	.0119	.0087
12	.2447	.1508	.2033	.0122	.0092

TABLE G.2

Results of standard test - CSA A23.2 14A
Linear expansions (%) - Concrete Prism Expansion Test

Time (Months)	Concrete prisms containing rock samples KIN	C3	C4	NR1	NR2
0	0	0	0	0	0
1	.0[illegible]42	.0127	.0122	.0010	.0007
2	.0473	.0226	.0176	.0026	.0016
3	.0582	.0251	.0232	.0034	.0020
4	.0764	.0345	.0271	.0043	.0025
5	.1014	.0459	.0346	.0058	.0031
6	.1152	.0577	.0485	.0079	.0049
7	.1286	.0781	.0501	.0094	.0065
8	.1345	.0843	.0667	.0098	.0070
9	.1463	.0868	.0806	.0103	.0075
10	.1571	.0987	.0855	.0112	.0082
11	.1782	.1068	.0971	.0119	.0087
12	.1878	.1172	.1145	.0122	.0092

TABLE G.3

Results of accelerated test (elevated temperature, NaOH)
(Linear expansions (%))

Time	Concrete cores containing rock samples							
Days	PUT	SUD	STT	KIN	C3	C4	NR1	NR2
0	0	0	0	0	0	0	0	0
2	.0713	.0339	.0358	.1250	.0843	.0416	.0044	.0042
4	.1608	.0488	.0894	.1885	.1204	.0592	.0069	.0053
6	.2710	.0995	.1247	.2412	.1395	.0891	.0098	.0132
8	.3214	.1853	.2069	.3211	.2405	.1269	.0277	.0154
10	.3722	.2856	.3026	.4120	.2781	.2339	.0529	.0237
12	.4228	.3750	.3620	.5057	.4366	.3010	.0834	.0425
14	.4462	.4226	.4492	.5903	.4692	.4252	.1122	.0583
16	.4965	.4832	.5115	.6595	.5203	.4366	.1275	.0668
18	.5726	.5393	.6190	.7246	.6068	.5018	.1420	.0756
20	.6352	.5655	.6517	.7781	.6403	.5158	.1692	.0952
22	.7181	.6149	.7097	.8594	.6718	.5684	.1765	.1147
24	.7938	.6351	.7631	.9422	.7602	.6682	.1798	.1233
26	.9100	.6670	.8328	1.0579	.7876	.6859	.1846	.1321
28	1.0191	.6875	.8802	1.1129	.7912	.6955	.1889	.1386

TABLE G.4

Results of accelerated test (elevated temperature, NaCl)
(Linear expansion (%))

Time (Days)	Concrete cores containing rock samples PUT	SUD	STT	KIN	C3	C4	NR1	NR2
0	0	0	0	0	0	0	0	0
2	.0297	.0274	.0264	.0669	.1363	.0415	.0104	.0101
4	.0376	.0362	.0445	.0951	.1588	.0458	.0200	.0196
6	.0501	.0509	.0470	.1200	.1824	.0584	.0200	.0204
8	.0605	.0534	.0438	.1269	.2110	.0571	.0330	.0315
10	.0633	.0528	.0520	.1386	.2699	.0677	.0324	.0304
12	.0703	.0621	.0517	.1930	.2899	.0755	.0347	.0322
14	.0708	.0700	.0626	.2206	.3420	.0890	.0410	.0400
16	.0774	.0801	.0735	.2767	.3734	.1017	.0439	.0415
18	.1035	.1201	.0849	.2934	.4278	.1156	.0502	.0483
20	.1174	.1319	.1052	.3057	.4521	.1322	.0515	.0534
22	.1360	.1399	.1064	.3307	.4664	.1419	.0620	.0539
24	.1392	.1480	.1066	.3467	.4881	.1504	.0641	.0536
26	.1514	.1646	.1059	.3580	.5062	.1681	.0737	.0637
28	.1587	.1821	.1126	.3681	.5252	.1815	.0755	.0638

TABLE G:5

Results of accelerated test (ambient temperature, NaOH)
(Linear expansions (%))

Time (Weeks)	Concrete cores containing rock samples							
	PUT	SUD	STT	KIN	C3	C4	NR1	NR2
0	0	0	0	0	0	0	0	0
2	.0462	.0485	.0377	.0901	.1088	.0383	.0112	.0176
4	.1058	.0589	.0482	.1188	.1969	.0455	.0246	.0276
6	.1710	.0988	.0863	.1590	.2269	.0564	.0362	.0356
8	.2389	.1372	.1051	.1881	.3165	.0720	.0550	.0423
10	.2941	.1832	.1678	.2225	.3410	.0933	.0719	.0513
12	.3297	.2203	.1997	.2648	.4005	.1124	.0793	.0595
14	.3504	.2505	.2376	.2966	.4882	.1492	.0938	.0702
16	.3960	.2902	.2678	.3285	.5273	.1592	.1122	.0884
18	.4631	.3322	.3089	.3665	.6202	.1796	.1282	.0981
20	.5108	.3438	.3229	.3956	.6991	.1882	.1393	.1161
22	.5667	.3530	.3663	.4323	.7767	.2112	.1464	.1392
24	.6219	.3701	.4032	.4705	.8003	.2355	.1540	.1534

TABLE G.6

Results of accelerated test (ambient temperature, NaCl)
(Linear expansions (%))

Time (Weeks)	Concrete cores containing rock samples							
	PUT	SUD	STT	KIN	C3	C4	NR1	NR2
0	0	0	0	0	0	0	0	0
2	.0184	.0117	.0091	.0309	.0803	.0189	.0312	.0348
4	.0151	.0126	-.0246	.0615	.0877	.0155	.0148	.0492
6	.0264	-.0064	-.0733	.0865	.1240	.0127	.0006	.0132
8	-.0033	-.1212	-.1457	.0923	.1189	.0109	-.0007	-.0273
10	-.0086	-.2138	-.2301	.0978	.1284	.0113	-.0016	-.0749
12	-.0759	-.3484	-.2547	.1067	.1449	-.0025	-.0027	-.1255
14	-.1451	-.3915	-.2690	.1094	.1667	-.0047	-.0043	-.1621
16	-.1769	-.4216	-.2867	.1152	.1790	-.0059	-.0086	-.2006
18	-.2231	-.4597	-.2990	.1213	.1922	-.0064	-.0111	-.2600
20	-.2331	-.4895	-.3109	.1361	.1983	-.0071	-.0347	-.2981
22	-.2436	-.5293	-.3189	.1451	.2170	-.0082	-.0895	-.3178
24	-.2522	-.5365	-.3247	.1566	.2382	-.0089	-.1063	-.3487

TABLE G.7

Results of "STP"-treated concrete containing reactive aggregates.
(Linear expansion (%))

Time	PUT				Time	SUD			
(Days)	Untreated	Treated			(Days)	Untreated	Treated		
		15secs	1min	1hour			15secs	1min	1hour
0	0	0	0	0	0	0	0	0	0
2	.0713	-.0089	.0143	.0070	2	.0339	.0296	.0206	.0004
4	.1608	-.0562	.0265	.0160	4	.0488	.0504	.0322	.0422
6	.2710	-.0552	.0417	.0190	6	.0995	.0700	.0515	.0608
8	.3214	-.0708	.0611	.0405	8	.1853	.0896	.0807	.0585
10	.3722	-.0808	.0732	.0378	10	.2856	.1263	.1114	.0667
12	.4228	-.0492	.0756	.0499	12	.3750	.1303	.1159	.0782
14	.4462	-.0763	.0906	.0452	14	.4226	.1365	.1291	.0904
16	.4965	-.0576	.1166	.0849	16	.4832	.1462	.1450	.1078
18	.5726	-.0377	.1385	.0993	18	.5393	.1571	.1520	.1360
20	.6352	-.0218	.1662	.1194	20	.5655	.1745	.1670	.1570
22	.7181	-.0033	.1961	.1561	22	.6149	.1957	.1759	.1672
24	.7938	.0116	.2143	.1575	24	.6351	.2123	.1939	.1876
26	.9100	.0327	.2332	-	26	.6670	.2185	.2058	-
28	1.0191	.0574	.2507	-	28	.6875	.2490	.2306	-

TABLE G.7 (contd.)

Time	STT				Time	KIN			
(Days)	Untreated	Treated			(Days)	Untreated	Treated		
		15secs	1min	1hour			15secs	1min	1hour
0	0	0	0	0	0	0	0	0	0
2	.0358	.0404	.0332	.0270	2	.1250	.0749	.0465	.0394
4	.0894	.0750	.0437	.0369	4	.1885	.0926	.0471	.0484
6	.1247	.1111	.0575	.0843	6	.2412	.1170	.0561	.0588
8	.2069	.1210	.0684	.0847	8	.3211	.1314	.0680	.0695
10	.3026	.1409	.0931	.0885	10	.4120	.1541	.0922	.0902
12	.3620	.1590	.1078	.0907	12	.5057	.1692	.1139	.1058
14	.4492	.1817	.1346	.1021	14	.5903	.1914	.1374	.1382
16	.5115	.2147	.1520	.1014	16	.6595	.2029	.1441	.1470
18	.6190	.2330	.1693	.1263	18	.7246	.2329	.1752	.1494
20	.6517	.2409	.1811	.1403	20	.7781	.2541	.1995	.1627
22	.7097	.2508	.1912	.1502	22	.8594	.2646	.2308	.1812
24	.7631	.2740	.2005	.1585	24	.9422	.2927	.2602	.1938
26	.8328	.2652	.2078	-	26	1.0579	.3231	.2729	-
28	.8802	.2626	.2074	-	28	1.4129	.3470	.2794	-

TABLE G.7 (contd.)

Time (Days)	C3 Untreated	C3 Treated			Time (Days)	C4 Untreated	C4 Treated		
		15secs	1min	1hour			15secs	1min	1hour
0	0	0	0	0	0	0	0	0	0
2	.0843	.0665	.0741	.0183	2	.0416	.0465	.0307	.0271
4	.1204	.1159	.1115	.0275	4	.0592	-.0069	.0560	.0361
6	.1395	.1299	.1288	.0700	6	.0891	-.0011	.0766	.0385
8	.2405	.1384	.1474	.0592	8	.1269	.0122	.0865	.0559
10	.2781	.1669	.1775	.0829	10	.2339	.0217	.1257	.1056
12	.4366	.1992	.2125	.0832	12	.3010	.0376	.1462	.1407
14	.4692	.2099	.2472	.1103	14	.4252	.0409	.1608	.1449
16	.5203	.2348	.3357	.1354	16	.4366	.0538	.1951	.1623
18	.6068	.2657	.3622	.1559	18	.5018	.0687	.2158	.1705
20	.6403	.2986	.3977	.1845	20	.5158	.0921	.2360	.1836
22	.6798	.3261	.4556	.2477	22	.5684	.1170	.2581	.1734
24	.7602	.3494	.5341	.3068	24	.6682	.1304	.2764	.1801
26	.7876	.3747	.5695	-	26	.6859	.1582	.2856	-
28	.7912	.3909	.6162	-	28	.6955	.1842	.2993	-

TABLE G.8

Results of concrete containing "STP"-treated aggregates
(Linear expansions (%))

Time		PUT		Time		SUD	
Days	Untreated	Treated		(Days)	Untreated	Treated	
		15secs	1min			15secs	1min
0	0	0	0	0	0	0	0
2	.0713	.0037	.0209	2	.0339	.0083	.0203
4	.1608	.0299	-.0192	4	.0488	.0437	.0323
6	.2710	.0467	-.0260	6	.0995	.0998	.0609
8	.3214	.0295	-.0323	8	.1853	.0725	.0841
10	.3722	.0098	-.0334	10	.2856	.0943	.1027
12	.4228	-.0267	-.0342	12	.3750	.1140	.1116
14	.4462	-.0224	-.0459	14	.4226	.1252	.1070
16	.4965	.0178	-.0746	16	.4832	.1279	.0093
18	.5726	-.0070	-.0754	18	.5393	.1258	.1046
20	.6352	.0111	-.1026	20	.5655	.1425	.0889
22	.7181	-.0019	-.0968	22	.6149	.1302	.0941
24	.7938	-.0252	-.0969	24	.6351	.1132	.0971
26	.9100	-.0164	-.0780	26	.6670	.1129	.1035
28	1.0191	-.0219	-.0820	28	.6875	.1193	.0931

TABLE G.8 (contd.)

Time (Days)	STT Untreated	STT Treated 15secs	STT Treated 1min	Time (Days)	KIN Untreated	KIN Treated 15secs	KIN Treated 1min
0	0	0	0	0	0	0	0
2	.0358	.0076	.0066	2	.1250	.0679	.0278
4	.0894	.0153	.0542	4	.1885	.1216	.0568
6	.1247	.0381	.0939	6	.2412	.1548	.0842
8	.2069	.0884	.1135	8	.3211	.1947	.1104
10	.3026	.1344	.1110	10	.4120	.1945	.1378
12	.3620	.1312	.1097	12	.5057	.1972	.1746
14	.4492	.1443	.1035	14	.5903	.1862	.2176
16	.5115	.1370	.0754	16	.6595	.1851	.2054
18	.6190	.1474	.0814	18	.7246	.1792	.2086
20	.6517	.1598	.0788	20	.7781	.1936	.1919
22	.7097	.1527	.0785	22	.8594	.2055	.1826
24	.7631	.1558	.0714	24	.9422	.1920	.1776
26	.8328	.1473	.0645	26	1.0579	.1851	.1809
28	.8802	.1474	.0529	28	1.1129	.1754	.1757

TABLE G.8 (contd.)

Time (Days)	C3			Time (Days)	C4		
	Untreated	Treated			Untreated	Treated	
		15secs	1min			15secs	1min
0	0	0	0	0	0	0	0
2	.0843	.0367	.0434	2	.0416	.0088	.0196
4	.1204	.0879	.0673	4	.0592	.0262	.0525
6	.1395	.1124	.0964	6	.0891	.0274	.0583
8	.2405	.1265	.1269	8	.1269	.0812	.0589
10	.2781	.1456	.1251	10	.2339	.1015	.0716
12	.4366	.1865	.1739	12	.3010	.0878	.1055
14	.4692	.2176	.1923	14	.4252	.0859	.0605
16	.5203	.2236	.1761	16	.4366	.1024	.0469
18	.6068	.2134	.1837	18	.5018	.0975	.0449
20	.6403	.2248	.1756	20	.5158	.0902	.0409
22	.6798	.2176	.1863	22	.5684	.0854	.0357
24	.7602	.2160	.1750	24	.6682	.0783	.0375
26	.7876	.2217	.1685	26	.6859	.0743	.0361
28	.7912	.2189	.1640	28	.6955	.0703	.0314

TABLE G.9

Results of "IP"-treated concrete.
(Linear expansions (%))

Time (Weeks)	Concrete containing rock samples							
	PUT	SUD	STT	KIN	C3	C4	NR1	NR2
0	0	0	0	0	0	0	0	0
2	.0014	.0100	.0132	.0407	.0895	.0083	.0112	.0176
4	.0172	.0164	.0173	.0708	.1710	.0231	.0246	.0276
6	-.0493	-.0129	.0501	.0789	.2079	.0442	.0362	.0356
8	-.0549	.0152	.0649	.1094	.2574	.0856	.0550	.0423
10	-.0208	.0221	.1003	.1388	.2956	.1101	.0719	.0513
12	-.0220	-.0094	.1052	.1720	.3646	.1044	.0793	.0595
14	-.0687	-.0169	.1236	.2003	.4416	.1182	.0938	.0702
16	-.1167	-.0291	.1465	.2149	.5031	.1191	.1122	.0884
18	-.1374	-.0114	.1527	.2395	.5653	.1430	.1282	.0981
20	-.1243	-.0330	.1539	.2492	.6069	.1251	.1393	.1161
22	-.1330	-.0314	.1642	.2687	.6425	.1389	.1464	.1392
24	-.1388	-.0334	.1667	.3021	.7148	.1393	.1540	.1534

APPENDIX H

TABLE OF VALUES OF THE CORRELATION COEFFICIENT FOR DIFFERENT LEVELS OF SIGNIFICANCE

TABLE H.1

VALUES OF THE CORRELATION COEFFICIENT FOR DIFFERENT LEVELS OF SIGNIFICANCE

n.	P = ·1.	·05.	·02.	·01.
1	·98769	·996917	·9995066	·9998766
2	·90000	·95000	·98000	·990000
3	·8054	·8783	·93433	·95873
4	·7293	·8114	·8822	·91720
5	·6694	·7545	·8329	·8745
6	·6215	·7067	·7887	·8343
7	·5822	·6664	·7498	·7977
8	·5494	·6319	·7155	·7646
9	·5214	·6021	·6851	·7348
10	·4973	·5760	·6581	·7079
11	·4762	·5529	·6339	·6835
12	·4575	·5324	·6120	·6614
13	·4409	·5139	·5923	·6411
14	·4259	·4973	·5742	·6226
15	·4124	·4821	·5577	·6055
16	·4000	·4683	·5425	·5897
17	·3887	·4555	·5285	·5751
18	·3783	·4438	·5155	·5614
19	·3687	·4329	·5034	·5487
20	·3598	·4227	·4921	·5368
25	·3233	·3809	·4451	·4869
30	·2960	·3494	·4093	·4487
35	·2746	·3246	·3810	·4182
40	·2573	·3044	·3578	·3932
45	·2428	·2875	·3384	·3721
50	·2306	·2732	·3218	·3541
60	·2108	·2500	·2948	·3248
70	·1954	·2319	·2737	·3017
80	·1829	·2172	·2565	·2830
90	·1726	·2050	·2422	·2673
100	·1638	·1946	·2301	·2540

For a total correlation, n is 2 less than the number of pairs in the sample; for a partial correlation, the number of eliminated variates also should be subtracted.

Source: Fisher (1970).

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