

**REDUCTION OF ALKALI-SILICA EXPANSION IN  
MORTARS BY GROUND GLASS REPLACEMENT**

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## ***Abstract***

The purpose of the study was to control or reduce concrete deterioration due to alkali-silica reaction (ASR) by using waste glass. The objectives were to find out the grain size, amount, and type of glass that would most reduce the ASR expansion, and to maintain or improve the compressive strength of mortars. Spratt and Sudbury, the Ontario's ASR expansive aggregates, were used for making the mortar mixtures. Colored and clear waste glasses were collected, water washed, and crushed to the sizes, according to the Ministry of Transportation, Ontario, (MTO)'s lab manual (LS-620), for the accelerated mortar bar test method. Mortar mixtures were designed with respect to the particle (grain) size and type, and the mass proportion of glass, which was replaced or added to particular aggregate sieve fractions. The experiment was carried out in three main stages: In Phase 1 mortar mixtures were made in which white glass replaced the aggregate in sieve size fractions of #8 to #100. Mixtures with replaced glass coarser than sieve size #30 increased the expansion but the finer glass sizes showed reductions. Also mortar bars made entirely with white glass revealed that glass was not an expansive agent. This led the experiment to Phase 2 in which mixtures were made with finer sized glass. White glass, 1% - 8% by mass, sized between sieves #200 to finer than #400, were replaced and added in the Spratt aggregate. White glass finer than #400 of 2% to 8% by mass replacements showed the most reduction in the ASR expansion. Further reduction was obtained by increasing the replacement of same size glass to 16% by mass. The same replacement percentages of colored glass finer than #400 and silica fume did not reduce the expansion as much as white glass did.

Comparative test showed that ground glass was more effective in the Spratt mixtures than those made with the Sudbury aggregate. While clear glass was more effective in the Spratt mortar mixtures colored glass caused more reduction in the expansion in the Sudbury mixtures.

The ASR expansion and glass mass-surface (MS) factor were shown to have an inverse 2<sup>nd</sup> degree polynomial relationship with each other.

Replacement of #100 aggregate fraction by 2% - 16% by mass with clear glass finer than #400 is feasible to both reduce the ASR expansion over 50% and reinforce the mortar uni-axial strength by about 100%.

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## 1. Introduction

It is appropriate to call the 20<sup>th</sup> century “*Concrete Time*” because of the rapid growth of global population, urbanization and resultant high demand for construction. The abundance, availability, and economy of materials used in cement-based concrete, its strength and long term serviceability have made it a popular building material. Concrete is considered as a multi-phase system: the three states of matter are present in concrete – *solid*, i.e. cement, aggregate particles, *liquid*, i.e. water, and sometimes chemical additives (admixtures), and *air* in pores and capillaries. (Brandt, 1995).

Since the end of 19<sup>th</sup> century many investigations have been conducted on cement-based concrete and its characteristics. By using the knowledge obtained, cement-based concrete can be classified (Brandt, 1995) as:

- *Ordinary concrete* comprising Portland cement, sand, coarse grained aggregate, and water.
- *High performance and high strength concrete* having the same components, but modified for high strength.
- *Lightweight concrete* having the same components but containing low density aggregate or admixtures, which lower its density below 1800kg/m<sup>3</sup>.
- *Heavyweight concrete* made by using special heavy aggregate to increase its density above 2400kg/m<sup>3</sup>,
- *Portland cement mortar* containing Portland cement, sand, and water, and
- *Portland cement paste* made of Portland cement and water.

To produce a sound and serviceable concrete, its materials must be compatible both with each other and with the environment. Cement and aggregate are the permanent members of a concrete and its water content participates in cementing. Some interactions

between aggregate and cement may cause deterioration in the concrete. Many natural aggregates contain a quantity of amorphous silica, which reacts with alkalis such as K and Na present in the cement. This reaction is widely known as the Alkali-Silica Reaction (ASR) and its products can cause deteriorating expansion in concrete systems.

There are three main methods for coping with concrete ASR expansion: *cement replacement, use of additives, and aggregate replacement or blending*. Most studies have been concerned with the first two methods of the ASR reduction. The last, a newer method, is the subject of the present investigation. The study concentrated on incorporating crushed waste glass in mortar mixtures containing Ontario aggregates with well documented ASR potential.

## **2. Objectives**

**Fundamental goals targeted for the present study were to find out**

- the feasibility and affectivity of incorporating waste glass into mortar concrete for coping with the ASR expansion,**
- the amount of waste glass that can be used into mortar concrete for optimum results,**
- the best grain size of waste glass which can most reduce the ASR expansion,**
- differences between glass types with respect to the reduction of the ASR expansion,**
- if glass replacement or addition is more effective in reducing the ASR expansion, and**
- what is the effect of glass on the strength of mortar.**

**To initiate the research some basic knowledge of concrete, its components, and properties is required, which is discussed in the following chapter.**

### **3. Components and Properties of Cement-Based Concrete**

Concrete characteristics such as strength, durability, and serviceability are functions of its components: Water, cement, and aggregate. Their roles in concrete are as follow:

#### **3-1) Water**

Water has the following functions:

- a) To react with the cement powder resulting in cementitious products.
- b) To lubricate the fresh mixture.
- c) To cure the concrete.

Water controls the cement hydration by its amount (water/cement ratio), purity (chemical content), and temperature:

- The smaller the water/cement ratio, the greater is the concrete strength and the smaller is its porosity. On the other hand, the higher water/cement ratio increases the fluidity of concrete, which allows easier placement of wet concrete at job sites;
- The importance of water purity for concrete depends on the type of use. For instance, sea water is never used for making concrete because of the presence of damaging ions. The chemicals of the sea water may interfere with hydration during and /or after curing.
- The temperature of the water has a direct relationship to the hydration rate and early strength development. The water temperature is a consideration when high or low ambient temperatures exist during the time of placement. Effects of water used to cure concrete are not as stringent as its other effects and the purpose is to maintain high humidity in concrete and to prevent the concrete surface from drying out.

Water is also used to wash the aggregate covered by dust produced during rock crushing and stockpiling , and thus enhance the cohesion between aggregate and the cement paste (Popovics, 1992).

### **3-2) Cement or Binding Agent**

The most important and expensive part of concrete is its cement. During the last two centuries several cement types have been developed, modified, and standardized. There are five main types of cement called “Portland cement”. Different cement types have different properties such as low or high-heat hydration, early or late strength development, low or high alkalinity, strength, fineness, chemical (sulfate) resistance, fast or slow-rate setting, and so forth. To reduce the effect of alkalis present in the regular cement types, cement manufacturers may replace some percentage of it by a compatible agent such as natural pozzolan, fly ash, slag and etc., which combine with the alkalis during the cement paste hardening process. This is called “blended Portland cement” that has a lower hydration heat and an early age strength, but the ultimate strength is not reduced as long as extended moist curing is provided. There are some other hydraulic cement types which have different compositions and applications such as:

- a) High-alumina cements, whose main component is calcium aluminate, and has early stage strength, and is a good refractory.
- b) Expansive cements, which contain agent(s) that expand on hydration and are used in cases where normal concrete drying shrinkage is not desired.
- c) White Portland cements that contain low iron and magnesium content.
- d) Colored cements, which contain 3-10% inert pigment and are used for decorative purposes.



e) Oil-well cements, usually the setting-retarded Types I, II, and III Portland cements that are used for cementing oil wells drilled down to about 1800 m. For deeper wells, slow-setting cements are required, the so called oil-well cements.

f) Rapid-setting Portland cements, whose initial setting time is much shorter than the standard period of 45 minutes of the regular cements.

g) Pozzolan cements (discussed below).

h) Fly-ash containing cements (discussed below).

### **3-2-1) Pozzolan Cement**

Pozzolan (volcanic glass and ash) was combined with lime to produce cement by the Romans more than 2000 years ago around the town Pozzouli. There are two types of pozzolans: natural and artificial. The natural pozzolans are volcanic tuffs, pumice, diatomaceous earths, opaline cherts, and some shales. ASTM C618 classifies these pozzolans as Class N.

The most important artificial pozzolans are fly-ash and silica fume. The main effective property of pozzolans is their large surface area and their reactivity with the alkalis in cement. Strength of concrete containing pozzolans is typically initially lower than those containing regular Portland cement. Using pozzolans with non sulfate-resistant Portland cements generally increases the concrete resistance to aggressive agents from sea waters, acidic water, and sulfate solutions. Also, alkali-aggregate expansion in concrete can be reduced by replacing part of the cement by pozzolans. Use of pozzolans in cement showed an improvement in concrete impermeability, an increase in its fluidity (creeping), a reduction of freeze-thaw resistance in non-air-trained concretes, and an increase in concrete drying shrinkage. Considering these effects, pozzolans are useful cement replacements in cases

where deleterious chemicals or solutions are the main causes of decreasing concrete durability. Pozzolans also reduce concrete cost by reducing the amount of the more expensive cement required.

### **3-2-1-1) Fly-ash**

According to ASTM C 618, fly-ash is a finely divided residue that results from the combustion of ground or powdered coal. It is derived primarily from the inorganic portion of the source coal and has two classes of C and F. The main criterion for its classification is the percentage of calcium content. The component oxides in fly-ash are  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$  in the form of glassy aluminosilicate, which is the active part. If the total of the three oxides is equal or greater than 70%, then the fly-ash is class F and if it is between 50% and 70%, then it is class C. Their prime physical requirement is that no more than 34% of their particles should be retained on sieve No. 325 (45  $\mu\text{m}$ ).

### **3-2-1-2) Silica Fume**

Silica fume (SF) is a by-product from the production of elemental silicon and ferrosilicon alloys in electric arc furnaces. It consists of extremely fine spherical particles of amorphous silicon oxide with a specific area of about 20,000  $\text{m}^2/\text{Kg}$  and a density of 250-300  $\text{Kg}/\text{m}^3$  as compared to 1200  $\text{Kg}/\text{m}^3$  for Portland cement. These unique properties of silica fume drew engineers' attention for using it as a fractal cement substitute without loss of concrete strength.

Cement containing less than about 10%, by mass, of silica fume gives the best results. It increases concrete cohesiveness, and requires an increase in the amount of any required additives. All these changes in concrete by silica fume is because of its high surface area. Under normal curing temperatures, the strength of a silica fume concrete at 28 days is always

higher than that of a comparable concrete of Portland cement. Also, like other pozzolans, it can reduce alkali-silica expansion in concrete (Popovics , 1992).

### **3-3) Aggregates or Bulking Agents**

Aggregate in concrete is similar to pebbles and particles in conglomerate, breccia, or sandstone. Any granulate (particulate) media consisting of inert (non-cementing) rocks or stone-like solids used into concrete can be defined as “aggregate”. Aggregate is used in concrete for the purpose of filling a large part of the required volume and reducing the cement cost. There are two main aggregate types: natural and artificial. Any rock processed by either nature or crushing-sieving plants is considered a natural aggregate. Any granular material, which is a by-product or waste from industries, such as blast-furnace slag that can be used in concrete, is defined as artificial aggregate. The main aggregate properties for use in concrete are (Table 1): grain size, grain shape, grading, density, hardness, petrography (of natural aggregates) or chemical composition (of artificial ones), grain coatings, reactivity with cementing agent, porosity, and durability. Since most of the concrete volume is filled by aggregates, the service life and durability of concrete is also a function of those aggregate properties. Natural aggregates have three main geological sources: igneous, metamorphic, and sedimentary rocks. Volcanic rocks may contain some glassy silicates/silica because of their fast cooling rates. The glassy SiO<sub>2</sub>-bearing minerals are amorphous and thermodynamically unstable. When exposed to cement alkalis in concrete they tend, in the long term, to react and to produce more stable chemicals causing volumetric expansions. Sedimentary aggregates can contain some opaline chert or expansive clay minerals, which affect concrete soundness by reacting with hydroxyls. Therefore, mineralogy and chemical

<b>Concrete Property</b>	<b>Relevant Aggregate Property</b>
<b>Durability</b>	
<b>Resistance to freezing and thawing</b>	Soundness Porosity Pore structure Permeability Degree of saturation Tensile strength Texture and structure Grading Maximum size Presence of clay
<b>Resistance to wetting and drying</b>	Pore structure Modulus of elasticity
<b>Resistance to heating and cooling</b>	Coefficient of thermal expansion
<b>Abrasion resistance</b>	Hardness
<b>Cement-aggregate reaction</b>	Presence of particular constituents Maximum size
<b>Strength</b>	Strength Surface texture Cleanness Grading Particle shape Maximum size
<b>Shrinkage</b>	Modulus of elasticity Particle shape Grading Cleanness Maximum size Presence of clay
<b>Coefficient of thermal expansion</b>	Coefficient of thermal expansion Modulus of elasticity
<b>Thermal conductivity</b>	Thermal conductivity
<b>Specific heat</b>	Specific heat
<b>Unit weight</b>	Specific gravity Particle shape Grading Maximum size
<b>Modulus of elasticity</b>	Modulus of elasticity Poisson's ratio
<b>Slipperiness</b>	Tendency to polish
<b>Economy</b>	Particle shape Grading Maximum size Amount of processing required Availability
<b>Uniformity</b>	Ease of handling Uniformity

*Table 1: Aggregate properties that affect concrete (After Popovics, 1961).*

composition of aggregates are important for their long term potential ASR (Popovics , 1992).

### **3-3-1) Aggregate Size Factor**

The size distribution of aggregates used in concrete depends on the purpose of the concrete structure. Very large sized aggregate (in excess of 6 cm) may be used for mass concrete in structures such as dams. Two to three centimeter top size aggregate is used in most normal concrete in roads. The top size is dictated both by use and by the relative durability of aggregate. Smaller aggregate particles are more durable than equivalent larger particles. The proportion of the very fine particles is also strictly regulated.

The presence of aggregate finer than sieve No. 200 (75  $\mu\text{m}$ ) in concrete has important influence on concrete properties. This size, called “dust” or “fine part of aggregate”, is present in concrete in three main forms: as scattered particles throughout concrete, as coatings around coarse aggregate, and as lumps. Their presence, to some extent, has a positive effect on the final properties of the concrete but an excess of them may cause: a) a reduction in the workability, b) an increase in shrinkage, c) a decrease in air entrained content, and d) an impairment of concrete durability (Popovics , 1992).

### **3-4) Admixture/or/Additives**

To control or modify certain desirable properties of concrete, materials other than cement, water, and aggregate called “admixtures/additives (ASTM C 125)” are used in a concrete mixture. The amount and dosages of additives used depend on the design, location, and application of concrete but in all cases rarely exceeds 4% by mass (Lea, 1970). These substances are used to:

a) add more voids in concrete by air-entraining,

- b) retard or to accelerate concrete hydration and setting time,**
- c) reduce water amount,**
- d) increase fresh concrete fluidity,**
- e) increase cohesion,**
- f) resist freezing, and**
- g) to perform other miscellaneous functions (ASTM C 494).**

## **4. Concrete Durability and Deterioration**

### **4-1) Deterioration Processes**

Concrete is attacked by various chemical and physical agents under different environmental conditions. Durability, as a qualitative term, is widely used to explain and describe concrete resistance to those agents. For instance, in a cold climate, the freeze-thaw cyclic process causes concrete deterioration. In a desert climate there is a large temperature difference between days and nights, and also between the concrete surface and its inner part. That difference may be large enough to cause a thermal potential, leading to a differential expansion/contraction, spalling, and flaking on concrete faces.

Concrete used in marine structures adsorbs sea water ions such as chloride,  $\text{Cl}^-$ , which may damage it in the long term. Also canals and tanks of sewage systems in urbanized areas are made of concrete and subjected to high concentrations of sulfate or other corrosive ions, which can cause deterioration. All of these agents are similar to those that cause rock weathering in nature but over a longer period of time. Concrete, as an artificial rock, is also altered by weathering, but the important factor is its weathering rate. Concrete is designed to perform for a given period of time. If it does not maintain its designed characteristics during that period, then it has less or low durability. Therefore, concrete durability can be defined and explained by alteration rate and performance (Brandt, 1995). It should be noted that alteration means both chemical and physical changes in concrete. If the properties and chemical compositions of cement, additives, and water are known and controlled, then concrete durability must be a function of aggregate properties.

Popovics (1992) correlated aggregate properties affecting the properties of concrete (Table 1). Mechanical, geometrical, physical, and chemical characteristics of aggregate

govern the concrete strength, durability, and serviceability. Some of the main parameters are aggregate properties such as hardness, elastic and plastic moduli (mechanical), grain size, grain shape, and roundness (geometrical), electrical and thermal conductivities and transmissivities (physical), and pH, reactivity, electronegativity (chemical). Concrete deterioration due to chemical and physical factors has been the subject of study for several decades. The general causes of concrete deterioration have been classified as:

- 1) Corrosion of the steel bars in a reinforced concrete by chloride/sulfate attack;
- 2) Insufficient or improper cover on reinforcing bars;
- 3) Freeze-thaw/thermal cycles;
- 4) Carbonation that exposes steel bars to possible corrosive agents by reducing alkalinity
- 5) Shrinking aggregates, and
- 6) Alkali-aggregate reactions (AAR), that cause expansion and cracking in concrete. AAR are grouped into three types:
  - a) Alkali-silicate reaction which occurs between alkalis present in concrete pore water and phyllosilicates, producing an interlayer precipitate which takes up water, inducing expansive stresses.
  - b) Alkali-carbonate reaction (ACR) that takes place between alkalis present in concrete pore water and clay bearing dolomitic limestones. One of the theories explaining this is the initiation of dedolomitization (Eq. 1).



It has been suggested that the dolomitic crystals contain clay which became exposed when dedolimitization occurred. The exposed clay then imbibes the pore water and this causes the expansion (Hobbs, 1988).



c) **ASR** is more common and has a rate faster than the others (Hobbs, 1988). Depending on the rock type and the content of amorphous silica, the ASR causes different rates and amounts of expansion (Fig.1). The degree of silica crystallinity controls the rate and intensity of the ASR.

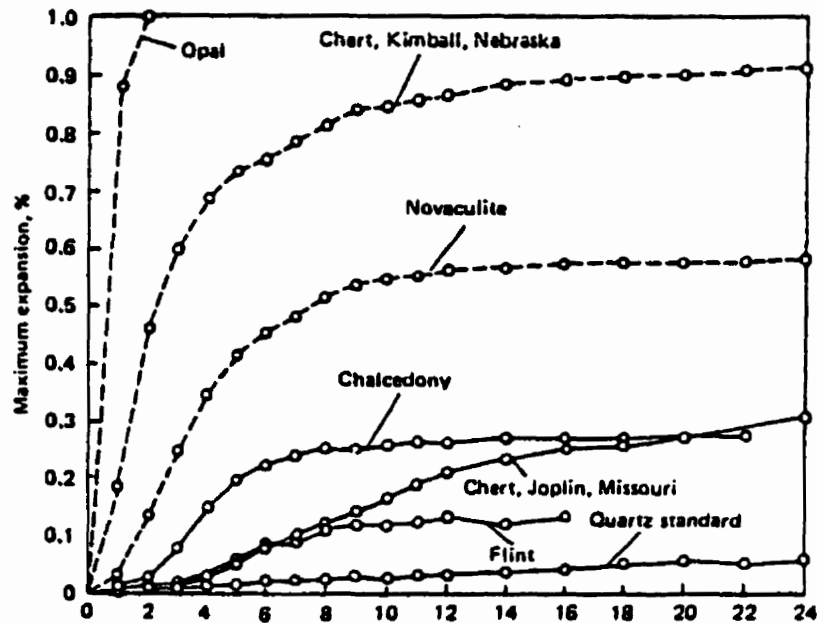


Fig. 1: Effects of different siliceous rocks and mineral on the expansion of Portland cement mortar bars containing high-alkali cement, (After Blanks & Kennedy, 1955).

Concrete, while initially being deteriorated by ASR, may still be strong enough to carry its designed loads. However, continued reaction and the resultant cracking may allow the ingress of solutions that may deteriorate it further and destroy its serviceability. This investigation concentrates on the ASR expansion and an alternate means of its reduction.

#### **4-2) Alkali-Silica Expansion**

Cracking and expansion in concrete was first observed in some of California's concrete structures and reported. It was realized that some other concrete structures constructed with the same type of cement but with different aggregates or with the same poor aggregate but with different cement types, were sound and in a good condition. The observation lead to a hypothesis that some cement constituents reacted with some components of some aggregate types under certain circumstances. To test this hypothesis 1-day moist cured concrete bars were placed in a sealed humid container. The reaction took place and was indicated by the increase in bar lengths over a period of several months. The test indicated that the cement agents responsible for the reaction with the aggregate were the alkalis i.e. sodium and potassium. When different cements were used with the reactive aggregate, the concrete bar expansions were found to be proportional to the alkalis concentration in cement (Bogue, 1955).

The US Bureau of Reclamation established an upper limit of 0.6% by mass, as an allowable maximum content of alkalis. If there is an excess of reactive silica in an aggregate, then the continuation of an ASR expansion will depend primarily on the alkali content; and conversely, if there is an excess of alkalis, then any ASR expansion will depend primarily on the quantity of reactive silica. Whenever the reactants are consumed or chemical equilibrium is established, then the ASR and its expansion will cease. The ASR will cease when there is no hydroxyl ion or when there is no humidity or aqueous media (Hobbs, 1988).

Although it was known that the ASR expansion is negligible as long as the cement alkali content stays below the upper limit, Bogue (1955) showed some inconsistencies in the relationship between alkali content and expansion. He, in support of Davis (1924), reported

that ASR expansion is mostly related to the ratio of the alkali content in cement to the amount of reactive aggregate. Then he showed that even using low alkali cement, an aggregate with small amount of reactive content could still generate large enough expansion to reject the concrete.

#### **4-3) ASR Mechanism**

Numerous researchers have tried to explain two main aspects of the ASR: the chemical products of the ASR reaction, and the ASR expansive stress generated in the cement paste. Hobbs (1988) suggested that the reaction of alkali hydroxides and opaline silica can be represented as:



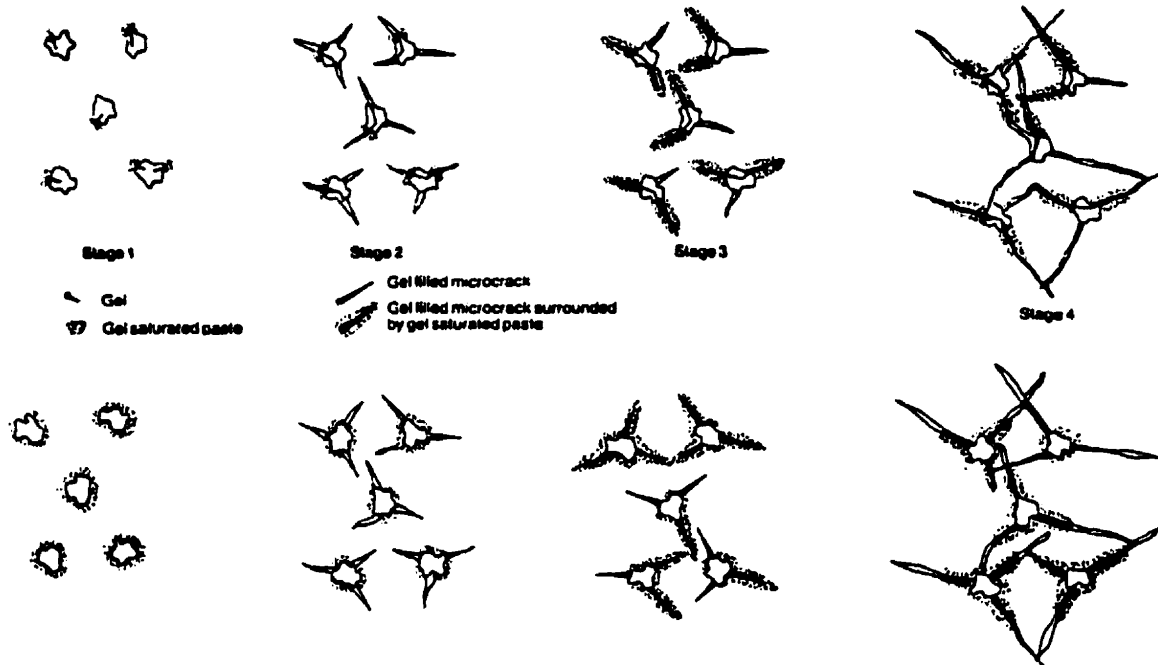
Generally two theories are used to explain the mechanism of ASR expansion and the stresses it induces on concrete:

- 1) Induced stresses by the ASR are attributed to the faster growth of the gel, which subsequently absorbs pore fluid, than its migration through the concrete pores.
- 2) Osmotic cell pressure theory, in which the development of a hydraulic pressure across an impermeable membrane is considered responsible for the ASR cracking.

The first theory necessitates a higher rate of the gel growth than the rate of the gel migration through the pore space for the cracking to occur. This causes stress build-ups and eventually the cracking (Fig.2).

The second theory assumes the formation of complex alkali-silica ions, which cannot diffuse through the hardened paste. The paste acts as a semi-impermeable membrane, across which the concentration of the complex ions provides the osmotic pressure condition. Hobbs (1988) suggested that the reaction product of  $\text{Na}_2\text{O}$ ,  $\text{CaO}$ ,  $\text{SiO}_2$ ,  $\text{H}_2\text{O}$  is a soda-lime-silicate

gel (complex) filling the paste pores and, probably as the essential material, forms the semi-permeable membrane. This model was criticized, noting that the paste can not be impassable due to the presence of extensive cracking (Hobbs, 1988).



*Fig. 2: Idealized model of the manner in which cracking can be induced by alkali-silica reaction (Hobbs 1988).*

The alkali silicates formed on the surface of the aggregate particles may osmotically attract the solution from the paste and produce local liquid pockets that may initiate hydrostatic pressure against the confining paste. Also, the complex alkali silicates ion has a greater volume than the original silica, and the hydrostatic pressure developed may disrupt the paste structure.

Vivian (1951) proposed the theory of diffusion for explaining the movement of alkalis through concrete capillaries filled by solution. He believed that opaline particles (amorphous silica) absorb water from the surrounding cement. This leads to the production of gel, which generates pressure that is proportional to the amount of water absorbed, the paste porosity,

and the capillary diameters. Based on this idea, the concrete with higher porosity must be more durable to ASR expansion than a compact concrete (Bogue, 1955).

Wilson et al (1994) disproved a widely held opinion that the ASR occurs in concrete only when the concrete pore solution has a  $\text{pH} > 12$ . They showed that a considerable amount of the ASR expansion happens at  $\text{pH} \approx 7$  (near neutral). They performed experiments on fused silica (FS), as a reference aggregate. The authors submerged mortar bars into a highly concentrated KOH and NaCl solutions at  $38^\circ \text{C}$  for a period of 150 days. They showed that the presence of alkalis in concrete pores is the main cause of the concrete ASR expansion and also to simulate situations in which concrete is subjected to sea water. The ASR expansion in mortar bars reached a certain levels after 150 days. It was shown that the concrete porosity was decreasing, along with the ASR expansion,. The explanation they offered was that the gel produced during the ASR occupies the pores and prevents further diffusion of the alkalis.

#### **4-4) ASR Expansion and Silica Content**

Ontario Ministry of Transportation (Report EM-92, 1990) presented a study about the effect of amorphous silica content on the ASR expansion. The results showed that only fused silica (FS), as a reactive silica, had a linear proportionality with the ASR expansion when substituted between 0-100% for Ottawa quartz. Expansion levels off after 80% opal substitution and cristobalite demonstrates a nonlinear proportionality. This was explained by the “Pessimum Effect (PE)”, which is defined later.

#### **4-5) ASR and Influence of Reactive Particle Size**

Concrete prism tests were performed by Locher and Sprung (1973) on Northern German flint to investigate the size influence of reactive silica particles. The results in Fig.3

show that the finer the reactive particle size, the more expansion in the mortar bars. The results indicated that the reactive aggregate sizes between 150-300  $\mu\text{m}$  led to the most expansion and with the highest rate. This is explained by the increase of total surface area as particle size decreases. Thus coarser the size fraction, the more reactive silica is required to produce the same ASR expansion. The results show that the ASR expansion is a function of the mass and size (surface area) of the amorphous silica.

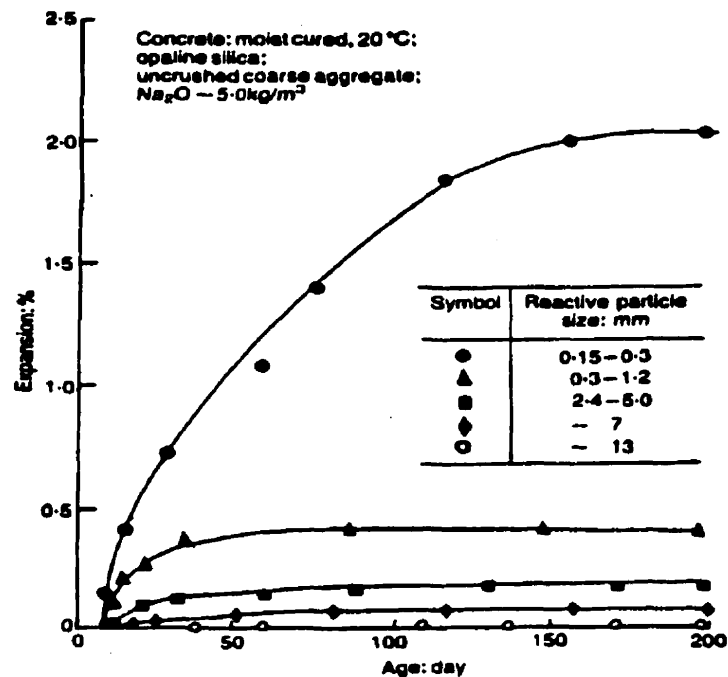


Fig. 3: Influence of the reactive particle size on the ASR expansion with time; water/cement and aggregate cement ratios are 0.41 and 3, respectively (After Hobbs, 1988).

#### 4-6) Silica Pessimum Effect

The amount of reactive aggregate that corresponds to the maximum ASR expansion in concrete is called the pessimum content. Fig.4 shows that ASR expansion and the reactant silica content have a direct relationship. If the aggregate contains less than 2.5% by mass of

reactive silica no pessimum will be observed (Hobbs, 1988). Each reactive aggregate type has its own pessimum content.

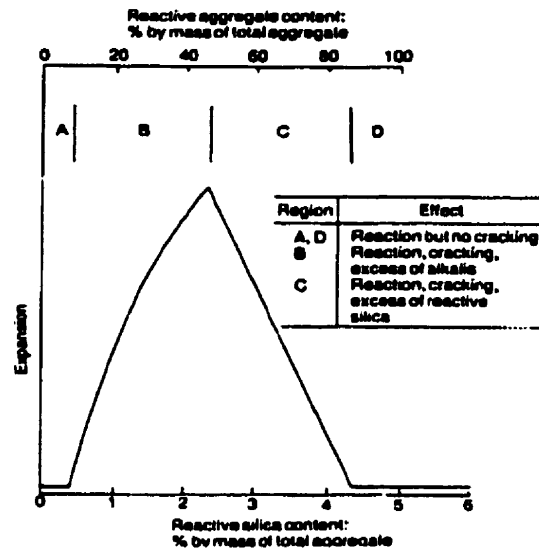


Fig. 4: Pessimism behavior; water/cement and aggregate/cement ratios are 0.4 and 2.75, respectively (After Hobbs, 1988).

#### 4-7) ASR and Concrete Strength

Atkinson (1987) explained that the infinitesimal units of alkalis and silica generate a corresponding infinitesimal tensile stress after each new reaction. In other words, the more the reaction develops, the more tension is produced. The whole (rock) system is non-linearly affected by a growing amount of stress, accelerating the ASR and its expansion. The system undergoes tensile stress that induces volumetric changes. Since the reactant silica and alkalis are present throughout the concrete, the tensile distribution has a pattern different from the distribution of mechanical stresses exerted on concrete (Brandt, 1995). Continuation of the ASR expansion in concrete causes the cracks to develop and widen and the concrete to lose its strength (Figs.5-7).

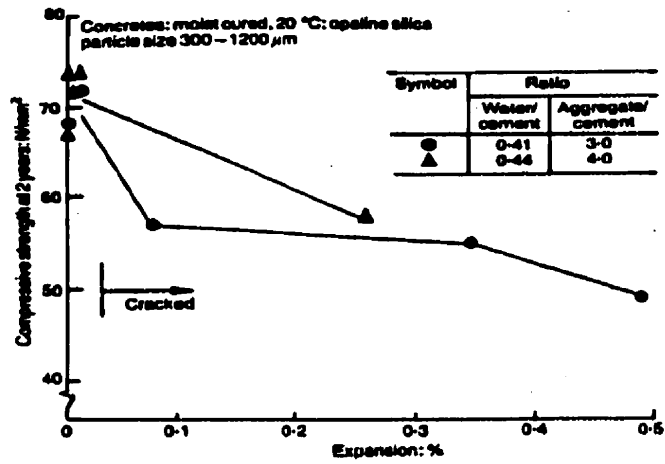


Fig. 5: Relationship between compressive strength and expansion at 2 years (After Hobbs, 1988).

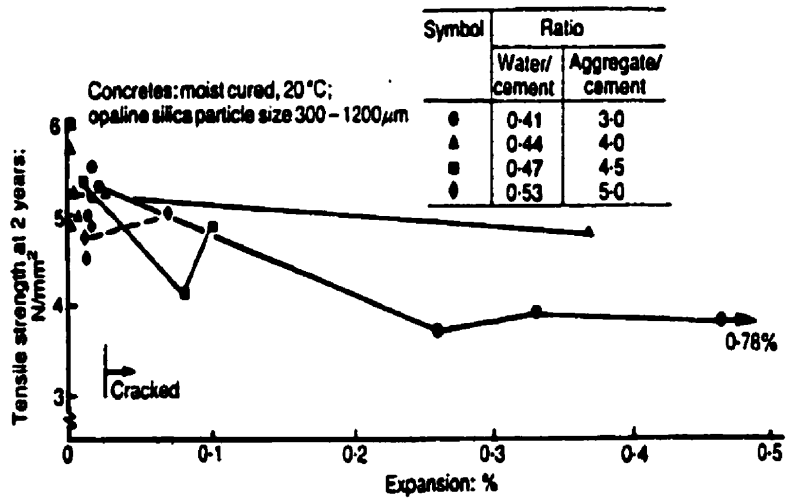


Fig. 6: Relationship between tensile strength and expansion at 2 years; uncrushed coarse aggregate (After Hobbs, 1988).



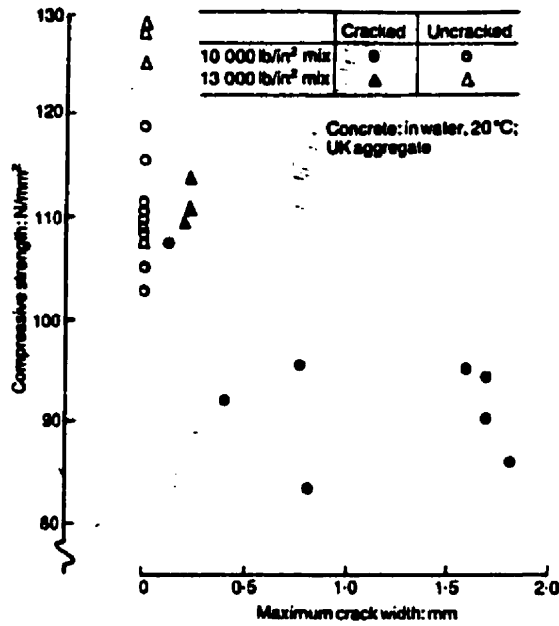


Fig. 7: Relationship between compressive strength and maximum crack width at 14 years; uncrushed aggregate (After Hobbs, 1988).

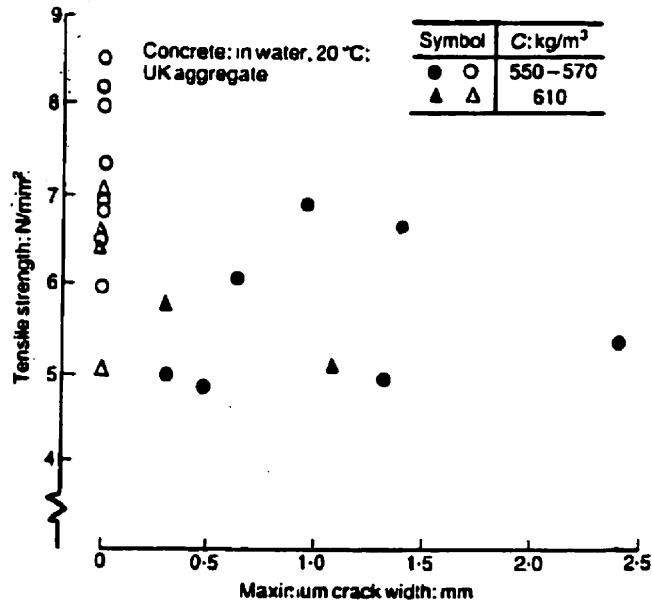


Fig. 8: Relationship between tensile strength and maximum crack width at 14 years (After Hobbs, 1988).

The examination of the data showed that the loss of strength depends on the level of expansion, which is a complex function of the content of alkalis and silica, time, moisture content, and the ambient temperature (Hobbs, 1988).

As long as there is stress, cracks develop in two dimensions: width and length. Figs. 7-8 exhibit how the compressive and tensile strengths of concrete decline as crack width increases. Thus, crack width can be used as an index of the degree of deterioration of concrete. It is worth to mention that crack properties such as its width, length, surface roughness, and so forth are important parameters for evaluating rock quality (soundness). Rock quality in rock engineering is very similar to concrete durability.

## **5. Prevention or Control of ASR Expansion**

As discussed earlier, water, cement alkalis, additives, and amorphous silica content in aggregate contribute to the ASR. Absence of all or any of these can prevent or control the ASR. Popovics (1992) showed that the ASR expansion was controlled by the content of either cement alkalis or aggregate reactive silica. He proposed 10 methods for preventing or controlling the ASR in concrete systems:

- 1) Don't use a reactive aggregate or, at least, blend it with a non-reactive material equivalent.
- 2) Don't use a high-early-strength cement.
- 3) Use cement containing alkalis less than 0.6%, calculated as sodium oxide.
- 4) Don't use additives or mixing water that contain alkalis.
- 5) Use a low cement content and a low water-cement ratio.
- 6) Replace a portion of cement with an adequate amount of certain fine powdered materials containing reactive silica, such as a pozzolan.
- 7) Increase concrete void ratio (by air entraining).
- 8) Prevent water supply to the hardened concrete.
- 9) Allow concrete to dry by leaving its surfaces uncovered.
- 10) Coat reactive aggregate grains with an impermeable material.

The permissible upper limit of alkalis in cement (0.6%, by mass) compelled the cement industries to produce alternative cements. Low-alkali cements were offered to markets but their production was more costly. Other attempts focused on replacing a part of cement with a pozzolanic silica bearing material to both save cement cost and stop or reduce the ASR expansion.

### 5-1) Cement Replacement by Pozzolanic Glass

The substitution of up to 30% pozzolanic glass for cement was investigated by Yixin et al (1998). It resulted in a considerably stronger product than a regular concrete and a reduction of about 50% in ASR expansion. Three glass sizes of 150, 75, and 38  $\mu\text{m}$  were used in the experiment. It showed that the finer the glass size, the less ASR expansion (Fig.9) and the stronger the concrete (Fig. 10). To compare the effect of glass substitution, concrete samples containing silica fume were cast. Silica fume produced the best result due to its larger surface area, or finer silica size. Their experiment also showed that concrete compressive strength obtained after 7-day accelerated testing and 21-day moist curing, exceeded the minimum limit of 4.1 MPa specified by ASTM C593 and 540C. The strength activity indexes of the volumetric replacement of 38  $\mu\text{m}$  glass by 30% were 91%, 84%, and 96% at 3-day, 7-day, and 28-day respectively, which exceeded the 75% required by ASTM C618.

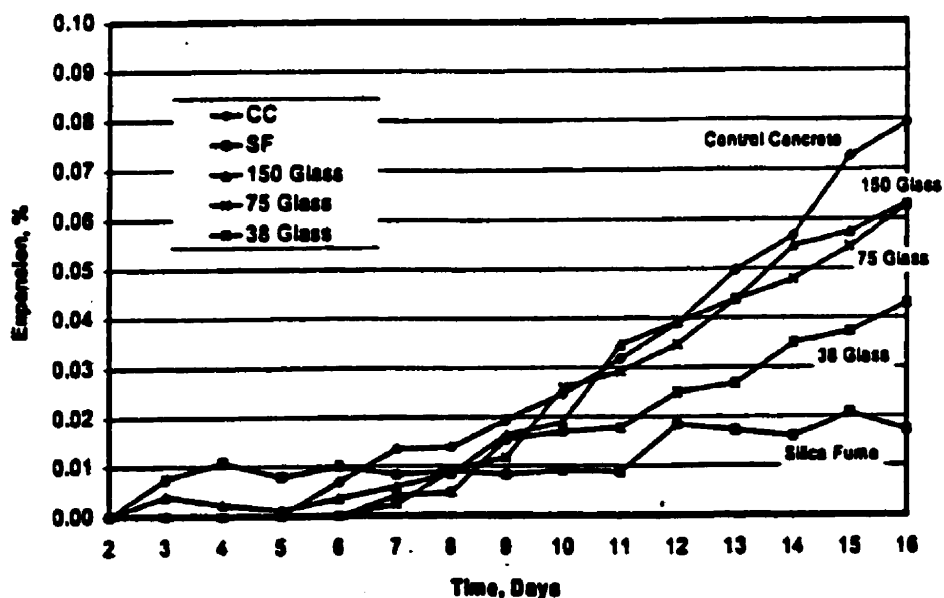


Fig. 9: Concrete expansion vs. time, days, with different glass sizes (After Yixin et al, 1998).

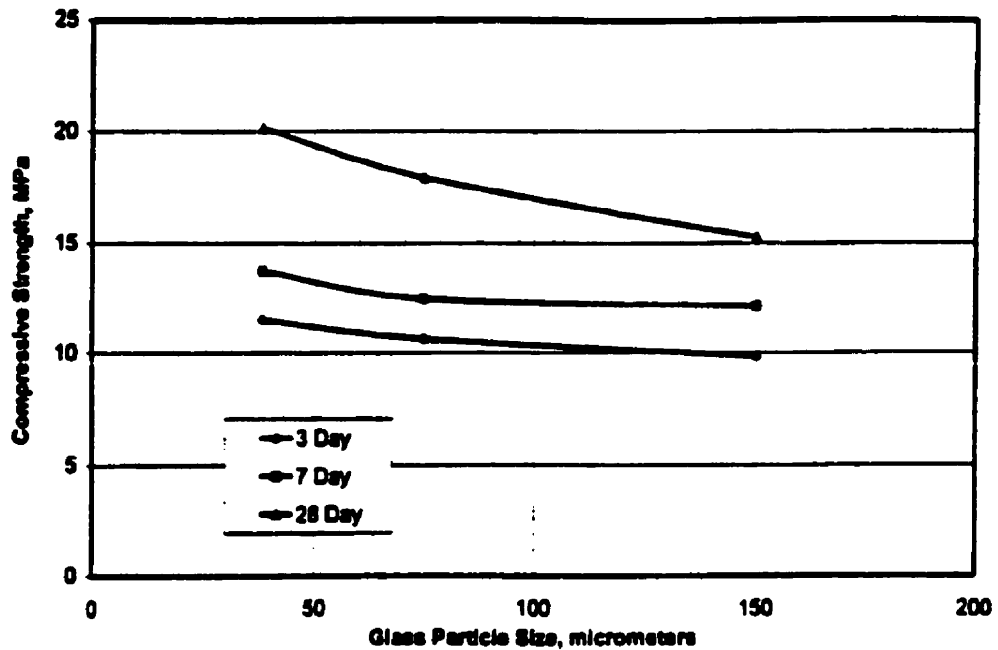


Fig. 10: Effect of glass particle size on the compressive strength of concrete (After Yixin et al, 1998).

### 5-2) Aggregate Replacement by Powdered Glass

Another study carried out by Polley et al(1998) showed the possibility of replacing aggregate up to 20% by mass with powdered glass, sized between 75 $\mu$ m ~ 1.5 mm, in a concrete made with low alkali cement. In their investigation they used some mixture of glass into aggregate and fly ash into cement. It was found that a combined replacement of both glass and fly ash could produce both higher strength and ASR reduction (Figs.11-13). The strength gain was initially slow, with only 75% of the strength of the control mix, but it increased to 84% at 28 days, 93% at 180 days, and 102% at 365 days.

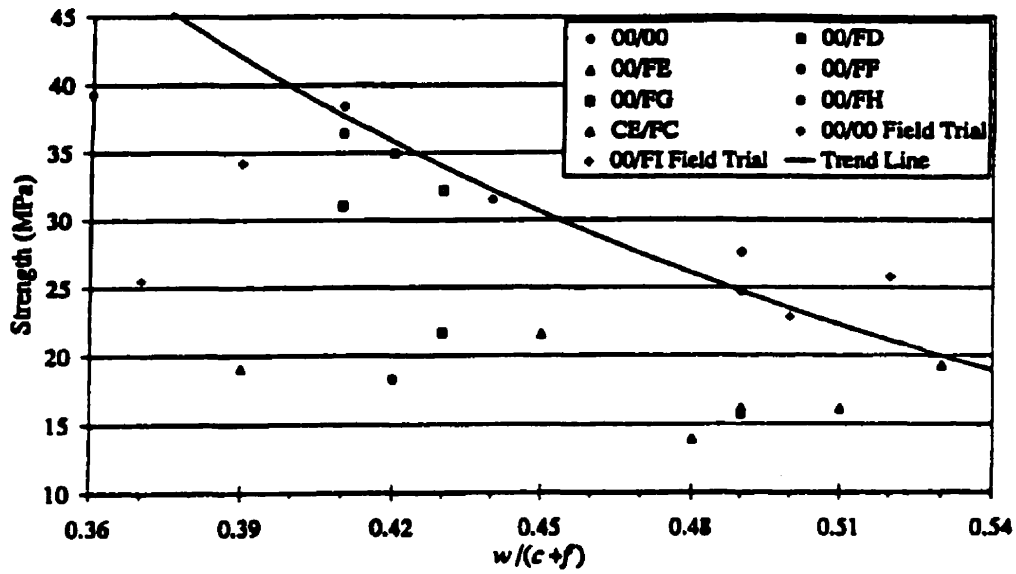


Fig. 11: Compressive strength after 365 days vs. water/cementing material (After Polley et al ,1998)

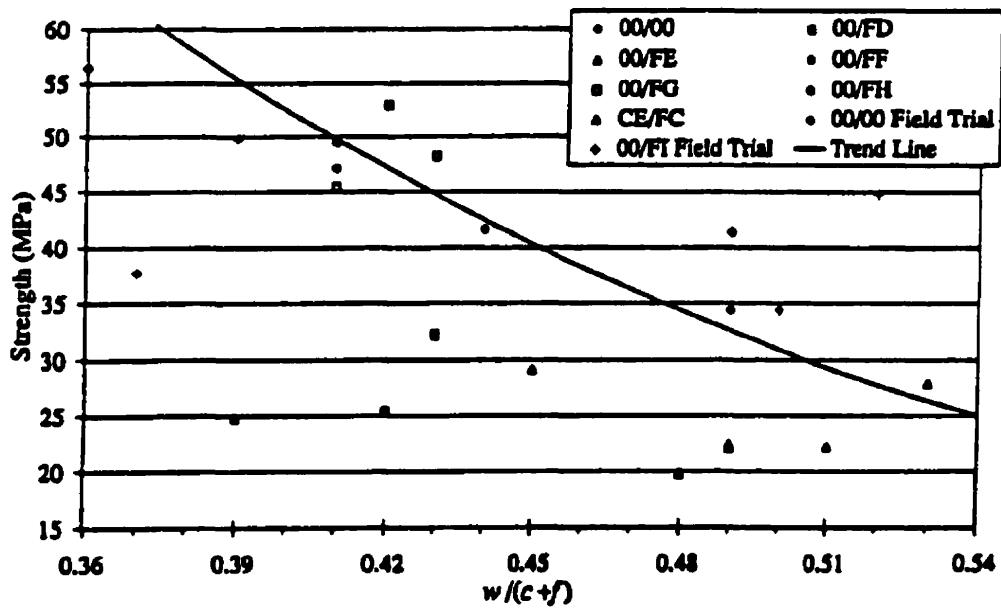


Fig. 12: Compressive strength after 28 Days vs. water/ water/cementing material (After Polley et al ,1998).

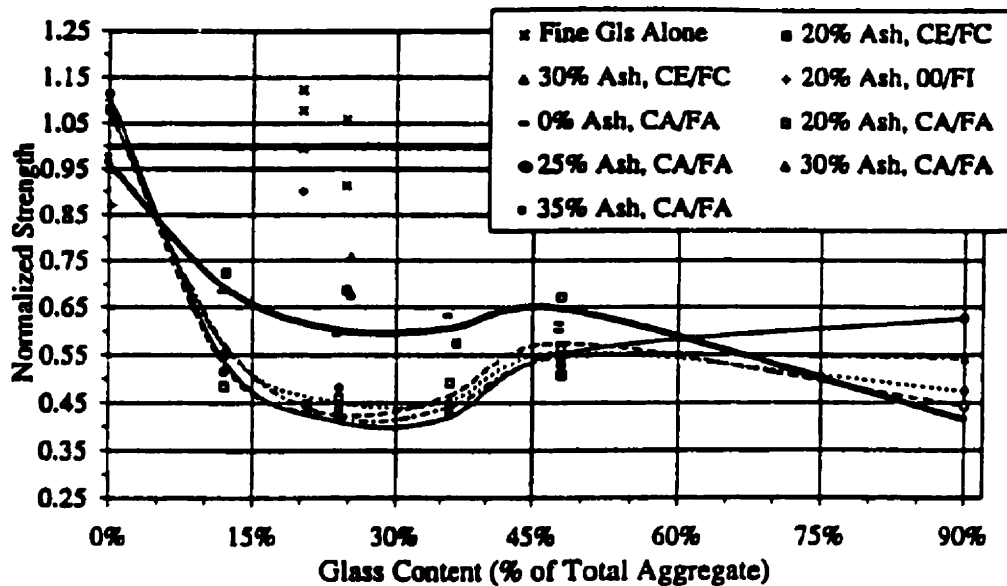


Fig. 13: Normalized compressive strength after 365 days vs. glass aggregate content (After Polley et al, 1998).

### 5-3) Chemical and Mineral Admixtures

Li et al (1998) performed an experiment to study the combined influence of chemical and mineral admixtures considering that Hudec and Banahene (1993) had shown that the ions nitrate, phosphate, lithium, and calcium were also effective in controlling the ASR expansion. They used calcium nitrite (CN), pulverized fly ash (PFA), and microsilica (MS), separately, and in combination with each other. In all cases considerable reductions were observed in the ASR expansion (Figs.14-17). They concluded that, by the addition of CN solution, the concrete hydration process was improved. Both PFA and MS could reduce ASR expansion between 20%-50% when 5-10% silica fume or 25% PFA or both were added. Mixes with MS reduced compressive strengths in the concrete by about 3%. The above mentioned studies suggested that using types of amorphous silica in concrete reduced and controlled the ASR. Also using certain sizes of glass as aggregate replacements both increased concrete strengths and reduced the ASR. Preliminary experiment conducted by

Hudec (pers. com., 1998) revealed a possibility of reducing the ASR expansion by using glass as aggregate (not cement) replacement.

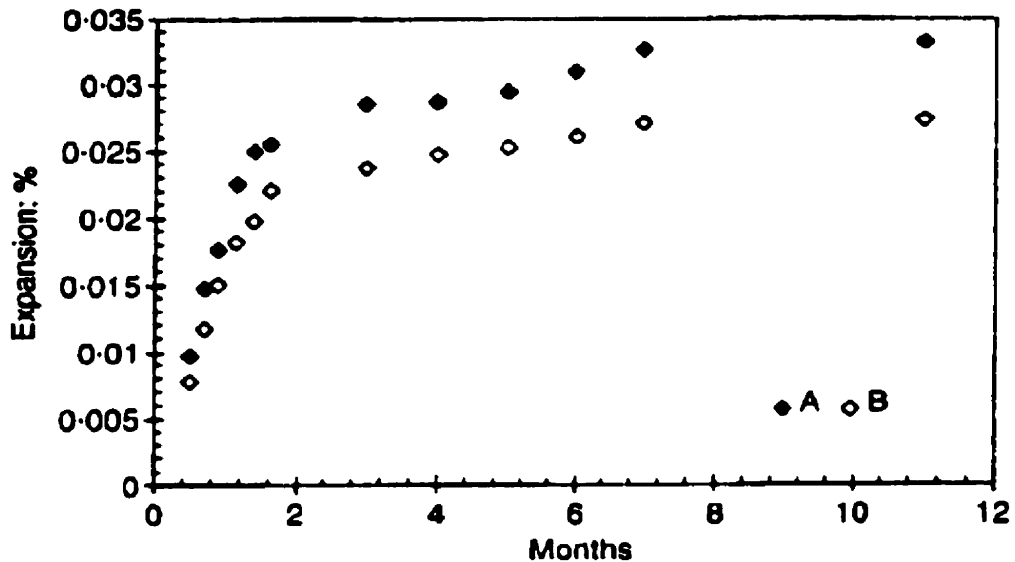


Fig. 14: Effect of PFA (A=0, B=0.25%) on the ASR expansion (After Li et al, 1998).

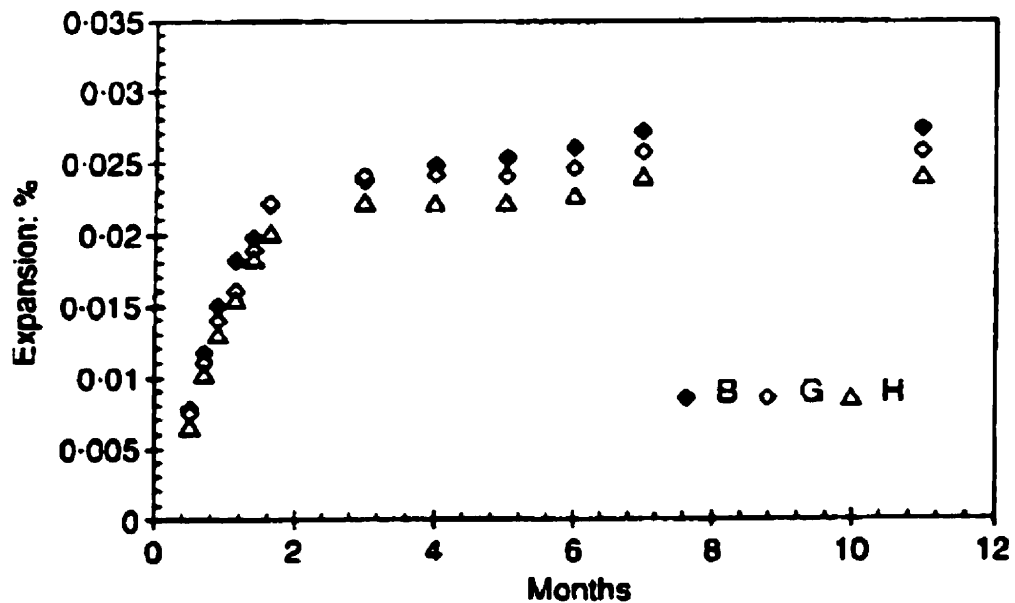


Fig. 15: Effect of CN (B=0, G=151, H=201 ml/m<sup>3</sup>) with PFA and without MS on the ASR expansion (After Li et al, 1998).



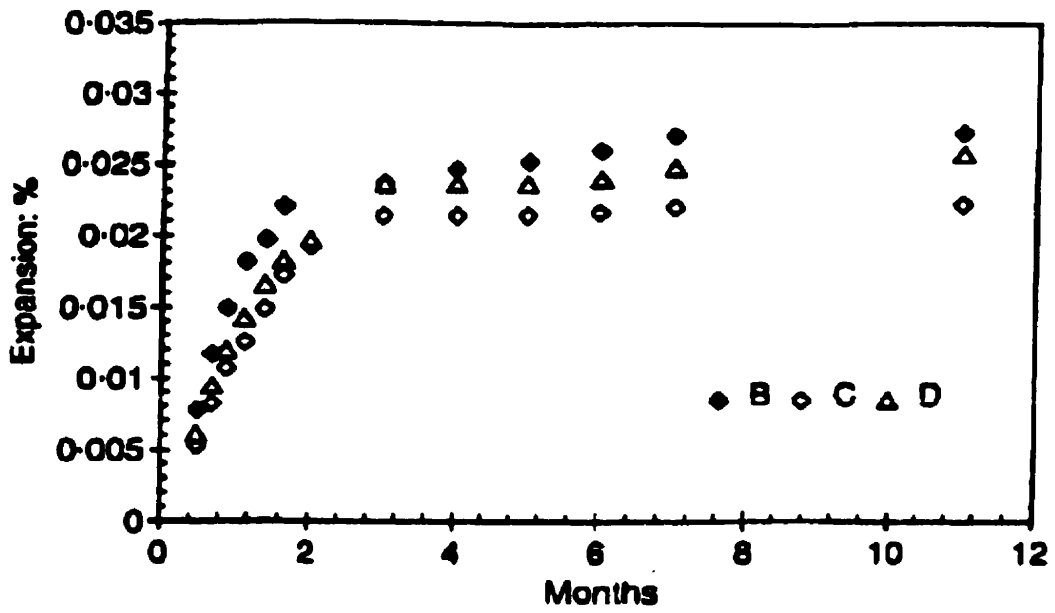


Fig. 16: Effect of MS (B=0, C=0.1%, D=0.05%) on the ASR expansion (Li, Mu, and Peng, 1998).

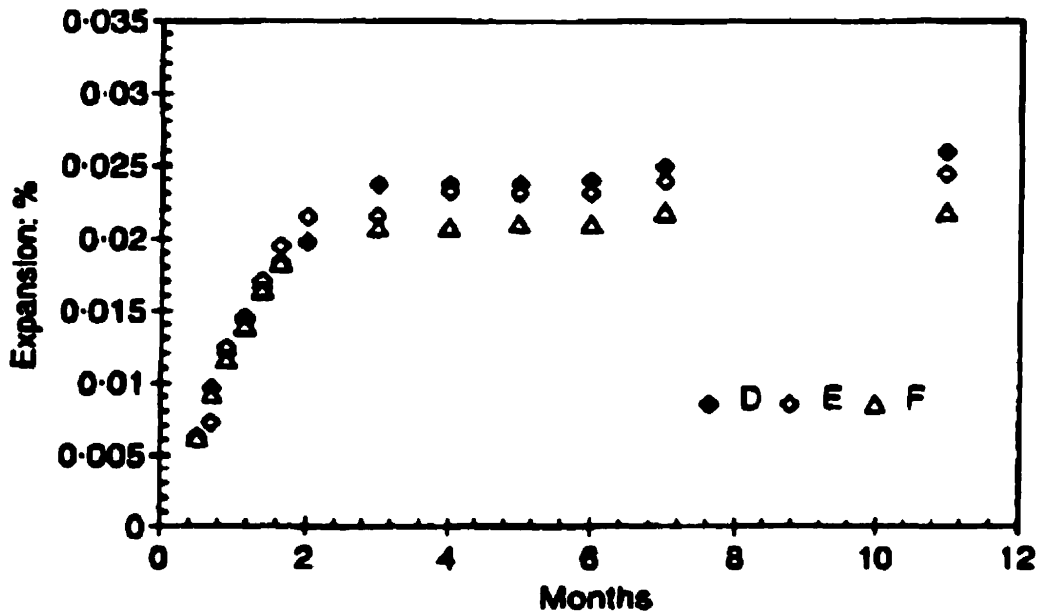


Fig. 17: Effect of CN (D=0, E=151, E=201 ml/m³) with PFA on the ASR expansion (Li, Mu, and Peng, 1998).

## 6. Experimental Design

Aggregates with ASR potential are usually tested initially using the standard mortar bar accelerated test method (MTO, LS-620). The method provides fast, continuous, and consistent reaction between aggregate's reactive silica and the alkalis. Three mortar bars dimensioned as 25mm × 25mm × 285 mm are made for each mixture design and fast cured at 80° C. The bars are measured immediately after curing without losing temperature for their initial lengths and then frequently during a period of 14 days, while being immersed in 80° C 1N NaOH solution. The change to the bar length is calculated with respect to its initial length to obtain the percentage of the ASR expansion.

### 6-1) Reference Aggregate

Experiments on concrete ASR expansion require reactive aggregate as a reference for comparing the relative expansion of each mix design. MTO has identified Spratt and Sudbury aggregates with the potential of the ASR expansion: (Fig. 18). Spratt was the main ASR aggregate used in the present study. Some tests were also performed on mortar mixes made with Sudbury aggregate and Manitoulin dolomite, as a non-reactive aggregate.

Spratt was described in MTO's report, EM-92, (1990) as a coarse to fine grained calcitic limestone in which about 15% of particles contain about 2% chalcedony with random chert.

In addition, Spratt contains illite, quartz, and pyrite. The same MTO's report discussed the discrepancy in the amount of amorphous silica measured or estimated by different methods.

Table 2 shows the percentage of total silica in Spratt

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	L.O.I	TOTAL
SPRATT	8.9	0.6	0.3	48.85	1.45	0.30	0.03	0.09	39.7	100.2
SPRATT	86.5	4.2	1.45	1.50	0	3.15	0.10	0.56	5.00	99.3

Table 2: Chemical content of Spratt aggregate analyzed by (MTO's report, EM-92, 1990). 8.9% silica is what used in calculating Mass-Surface (MS) factor (Section 8).

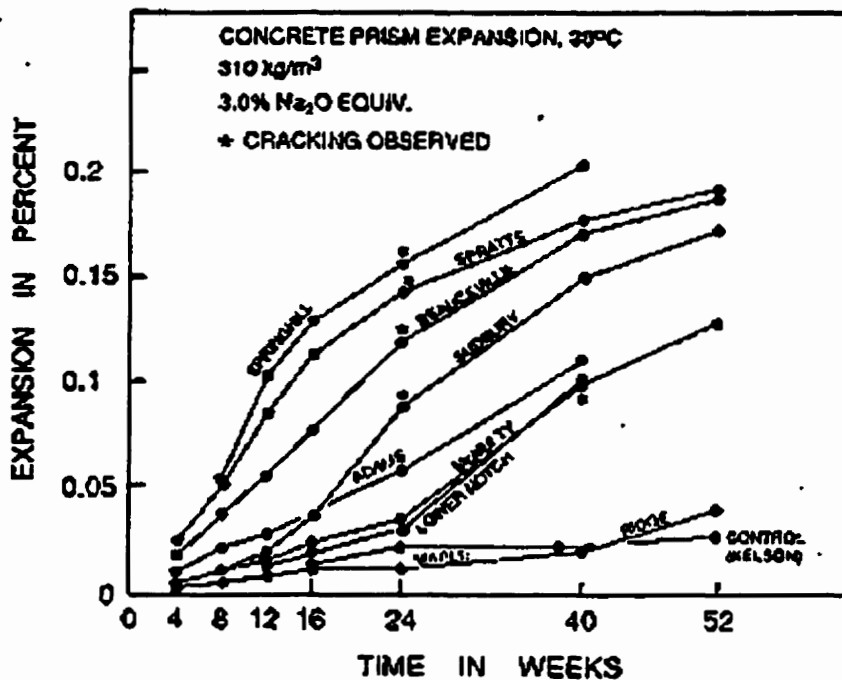


Fig. 18: Concrete prism expansion against time for mixture made with 3.0% alkalis (MTO's report, EM-92)

determined by a chemical analysis but the authors argued that several petrographers found only between 1-2% of the reactive silica (chalcedony, opal?). They explained the ASR expansion in Spratt concrete by the presence of agglomerated amorphous silica finer than 10

µm. The distribution, particle size, amount, and the amorphous nature of silica were considered as the main factors in ASR expansion in concrete made of Spratt.

The same MTO's report described Sudbury gravel as a reactive aggregate which caused deterioration of highway structures. Sudbury gravel consists of grey wacke, argillite, granite, and norite. Chert nodules from a gravel pit near Putnam, Ontario were crushed for use as a third reactive aggregate. The chert is interspersed with minor carbonate, and is light grey to light tan in colour. Manitoulin dolomite was used as a non- reactive reference aggregate. Manitoulin dolomite is a high carbonate, grey crystalline dolostone used both as high quality aggregate and as iron ore smelting flux stone. It is quarried from within the Lockport Formation, on Manitoulin island in Lake Huron.

## 6-2) Experimental Method

Study of the ASR expansion in concrete, as a part of aggregate quality assessment was traditionally performed on concrete prisms or cylinders. The prisms allow researchers to observe and to measure ASR expansion in a one-dimensional system. ASR expansion, by its nature, is a very slow rate process taking up to 2 years to become evident, depending on the ambient temperature and humidity. To reduce the time period required for the observation, MTO adopted an accelerated mortar bar method. The grading and aggregate size limits required by MTO and for mortar bars are in Table 3.

Passing Through	Retained On	Mass, %
4.75mm or sieve # 4	2.36mm or sieve # 8	10
2.36mm or sieve # 8	1.18mm or sieve # 16	25
1.18mm or sieve #16	600µm or sieve # 30	25
600µm or sieve # 30	300µm or sieve # 50	25
300µm or sieve # 50	150µm or sieve #100	15
150µm or sieve #100	Total	100%, or 990g

*Table 3 Aggregate Grading Requirement in MTO and ASTM Standards for Mortar Bars.*

The following sections of ASTM and MTO's testing procedures and specifications were used in this investigation:

ASTM C 305, practice for Mechanical Mixing Of Hydraulic Cement Pastes and Mortars,

ASTM C 490, Specification for Apparatus for Use in Measurement of Length Change of Hardened Cement Paste, Mortar, and Concrete,

ASTM C 511, Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes, and

MTO's Laboratory Testing Manual (V. II), Method LS-620. The following are the main steps of the accelerated method:

- Sizing and grading of the mortar aggregate according to Table 3
- Making standard mortar molds according to ASTM C 490
- Mixing aggregate with cement and casting the mortar bars, ASTM C305
- Maintaining relative humidity of the molding room, ASTM C511
- Preparation of an 80° C 1N NaOH solution in a proper closed system
- Fast curing the mortar bars after setting
- Measuring initial length of the mortar bars immediately after curing
- Immersing the bars in the NaOH solution
- Measuring length the bars according to a schedule
- Calculating and recording the percentage of the length changes

### **6-3) Aggregate and Glass Sources and Preparation**

Spratt and Sudbury aggregates were supplied from MTO's stockpile in Downsview, Ontario, and Manitoulin dolomite was obtained from the stockpile of Standard Aggregate Inc. in Windsor. The aggregates were crushed and sieved to sizes according to Table 3. Two

glass types, colored wine and clear juice bottles were collected, water-washed for a few hours, dried, and crushed manually by hammer. To produce finer sizes, the two glass types were crushed, by the same crusher used for aggregates, and then sieved according to Table 5. In addition, some of the glass passing through 75 $\mu$ m (#200) sieve was further pulverized using plate pulverizer and the shatter box to the sizes equal to or finer than 38 $\mu$ m (#400).

#### **6-4) Equipment**

##### **6-4-1) Molds**

Molds were designed to make six mortar bars (two sets of 3 bars) per mold, and were made from PVC plate. Mortar bars so produced had final dimensions of 25mm  $\times$  25mm  $\times$  285mm. A pair of stainless steel pins were inserted at ends of each mortar bar with an effective measurable length of 250mm between them. To aid in releasing the mortar bars from the molds after setting a demolding agent was sprayed on the mold surfaces before casting the mortars.

##### **6-4-2) Mortar Curing Containers**

Large plastic containers were used to set the mortar under a constant humidity. The containers were filled in the bottom by a small amount of water and sealed to maintain high humidity. The mortar bars were left to harden for 24 hours.

##### **6-4-3) Fast Oven Curing**

After the 24-hour hardening, the mortar bars were removed from the molds and placed in capped heat-resistant containers full of water. The containers were heated in a Blue M OV-500C2 oven at a constant temperature of 80° C for a period of 24 hours. After the fast curing, the initial length between the two pins on each bar was measured by the instrument,

described in section 6-4-4, within 15-20 seconds after its removal from the hot water, and then the bar was placed into 80° C 1N NaOH solution.

#### **6-4-4) Length Measuring Instrument and Procedure**

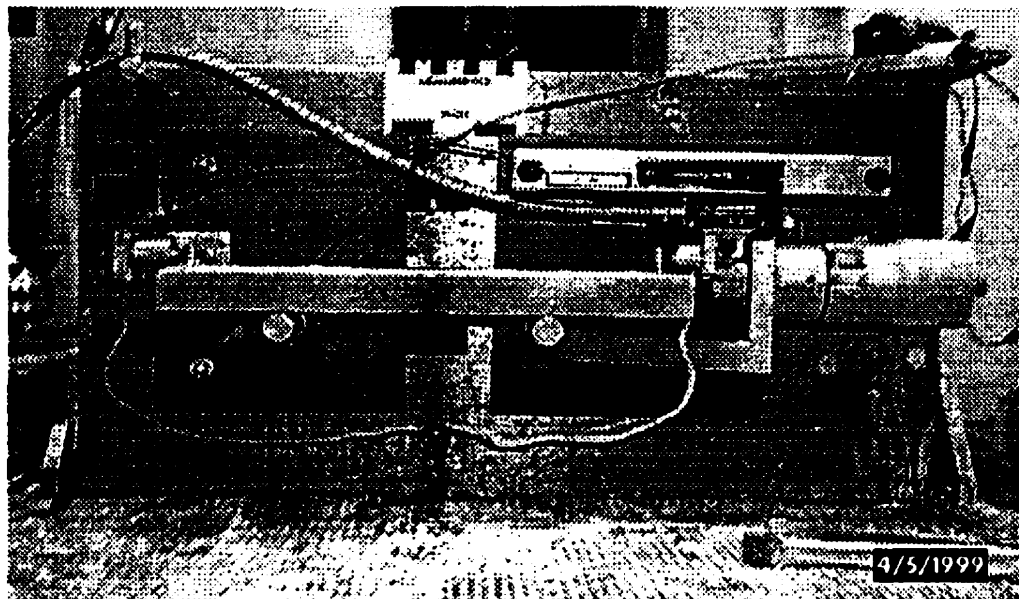
A combined system of an ACU-RITE micrometer gage sensitive to 0.001mm and connected to a Busch & Lomb Linear Variable Differential Transducer (LVDT) digital system sensitive to 0.001mm, was used for the mortar bar length measurements. To effect the measurement, the micrometer gage was manually adjusted until the both ends of the device touched the two stainless steel pins on the mortar bar. This closed the electrical circuit and caused an audible alarm system to signal the contact (Fig. 19). A PVC bar was used to calibrate the device before each measurement. To prevent cooling of the bar and to maintain the MTO's specified bar temperature, the bar length measurements were completed in a period of 15-20 sec. Also to reduce measurement errors, the bars were measured twice by switching their positions 180° in the measuring device. All the mortar bars remained in the hot 1N NaOH solution for 21 days and were periodically measured.

A PVC bar with the exact dimensions of a standard mortar bar having two 4mm-steel plates at its both ends was used for repeatability test and calibration before each measurement. By using the bar a repeatability test was performed to measure the error of the instrument. After measuring the bar length, from its both ends, for fifty times in a row the error calculated was  $\pm 0.006$  mm.

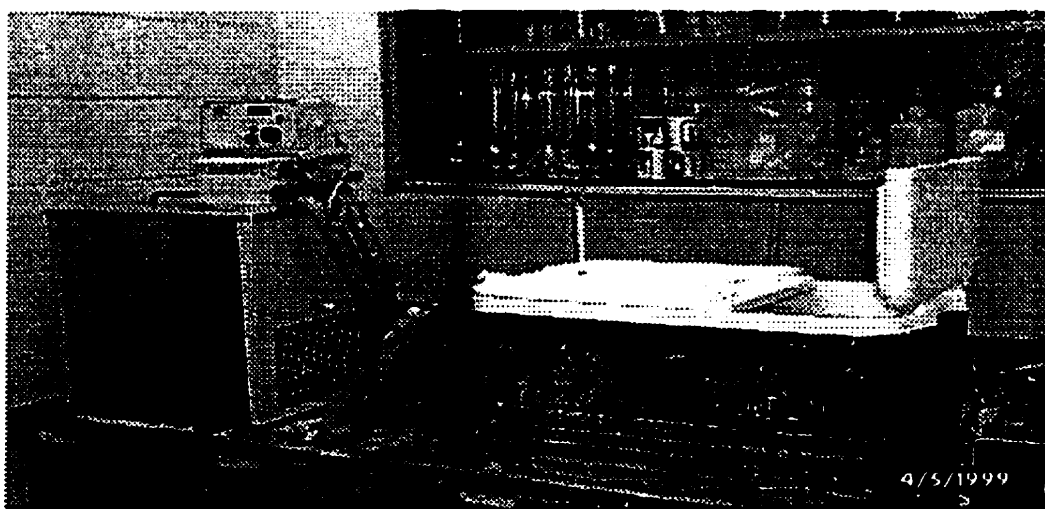
#### **6-4-5) NaOH Solution Bath**

A plastic picnic cooler (Fig. 20) was used as the reaction vessel to contain mortar bars and the 1N NaOH solution. To transfer and to circulate heat to the cooler, it was equipped by a copper tubing system, through which the antifreeze from a NESLAB constant temperature

bath was constantly circulating to maintain the solution temperature at 80° C during the whole period of the experiment. The concentration of the NaOH solution was frequently measured by a pocket Abbe refractometer, whose index number was compared to a calibration reference graph. Any minor change in the concentration of the solution due to evaporation through the cooler joints was compensated by adding a small amount of water



*Fig. 19: Measuring instrument with a mortar bar contacting the two ends (By: P. Hudec).*



*Fig. 20: 80°C 1N NaOH solution bath connected to the NESLAB antifreeze container (By: P. Hudec).*



### **6-5) Control Mortar Bars**

Control mortar bars containing no glass and made only with the Spratt aggregate were used to compare the ASR expansions with that of different mortar mix designs. Three sets were cast for three different conditions:

- 1 Fast cured and immersed to the hot NaOH solution; these bars were used to compare the ASR expansions to the experimental mortar mixture designs,
- 2 Fast cured, and
- 3 Normally cured, not subjected to hot NaOH. The last two control bars were mainly used to compare the mortar bar strengths

### **.6-6) Mix Design Concepts**

To design the mortar mixtures with glass, five points were considered:

1. According to Table 3, specified by ASTM and MTO, aggregate grain sizes (sieves) have a geometric size proportion from the coarse to the fine sizes as given below:

$$4.75\text{mm} (\#4) \approx 2 * 2.36\text{mm} (\# 8)$$

$$2.36\text{mm} (\#8) \approx 2 * 1.18\text{mm} (\#16)$$

$$1.18\text{mm} (\#16) \approx 2 * 600\mu\text{m} (\#30)$$

$$600\mu\text{m} (\#30) \approx 2 * 300\mu\text{m} (\#50)$$

$$300\mu\text{m} (\#50) \approx 2 * 150\mu\text{m} (\#100)$$

$$150\mu\text{m} (\#100) \approx 2 * 75\mu\text{m} (\#200)$$

$$75\mu\text{m} (\#200) \approx 2 * 38\mu\text{m} (\#400)$$

2. Considering a constant total unit mass and volume for a given solid (grain) and dividing its size or diameter by one half, its surface area will double. In general, if

$D_1$  = grain size

$S_1$  = surface area

$D_1 \equiv S_1$	or	$1 \equiv 1$
$(D_2 = 0.5 D_1) \equiv (S_2 = 2 S_1)$	or	$1/2 \equiv 2$
$(D_3 = 0.5 D_2) \equiv (S_3 = 2 S_2)$	or	$1/4 \equiv 4$
$(D_4 = 0.5 D_3) \equiv (S_4 = 2 S_3)$	or	$1/8 \equiv 8$
..... = .....	or	..... $\equiv$ .....
$(D_n = 0.5 D_{n-1}) \equiv (S_n = 2 S_{n-1})$	or	$1/n \equiv n$

A similar relationship between a grain size and its surface area can be calculated for any geometric shape such as a cylinder, pyramid, oval, prism, and so forth

3. The total surface area per unit mass is a geometric element of a particulate system which governs reaction rate at the interface; the larger the surface area, the faster a reaction proceeds. Total surface area will also change as the mass content changes.

4. The rate of reaction is a factor related to the concentration of reactants present at the interface and the amount of reaction product(s) which controls reactions.

5. Reactant types cause different reactions and rates. Since glass was treated as an aggregate in this experiment, its size and surface area, amount, and type were considered in all the glass mix designs. The wine green (colored) and juice clear glass types were incorporated into the mortar mixtures as both a replacement and an addition to the aggregate of a given size.

### **6-7) Chemical Tests**

To relatively and generally compare the reaction of the glass types and their crushed grain sizes, 25g of each size of each glass type was individually submerged in 25ml of the 80° C 1 N NaOH solution, according to ASTM C289-81, for a period of 14 days. The amounts of glass samples dissolved in the solution were frequently measured by photometry method. Because of water evaporation from the solution by the end of the testing period the

total amounts of the glass samples dissolved were large (Pers. Com., I. Churchill) but still the data showed the relative relationships.

### **6-8) Mortar Mixtures**

Mixture designs evolved during four distinct phases which were named Preliminary test, Phase 1, and Phase 2, and Comparative Tests.

#### **6-8-1) Preliminary Test**

Mortars were made only with Spratt, Manitoulin dolomite and clear glass, respectively, as the sole aggregate to obtain their baselines of the ASR potential and expansion.

#### **6-8-2) Phase 1**

The purpose of Phase 1 was to determine the general effect of different sizes and percentages of white glass in the Spratt mortar mixtures. The intent was to discover the best proportion and size of glass, both replacing and added to specific aggregate sizes that would result in maximum ASR reduction.

#### **6-8-3) Phase 2**

The results obtained from Phase 1 were used to select the next best mix ratios and glass sizes for further experiments and to use them with other ASR aggregates and glass types. Since the initial results showed that the finer sizes of glass were more effective in reducing the ASR expansion, the subsequent experiments continued with glass sized  $\leq 75\mu\text{m}$  (#200) added to or replacing the aggregate fraction retained on  $150\mu\text{m}$  sieve (#100). Part of the glass that passed through the  $75\mu\text{m}$  sieve (#200) was ground in the Shatter Box to obtain glass finer than the  $75\mu\text{m}$  (#200). The glass was incorporated as 1%, 2%, 4%, and 8% of the #100 fraction of the mortar aggregate by both substitution and addition. Colored glass and

silica fume were used with the same mix ratios for the purpose of comparison. To determine the effect of incorporating a higher content of powdered clear glass (finer than 38  $\mu\text{m}$  or # 400), two more mortar mixture designs with 16% and 32% glass content replacements of the #100 aggregate fraction were cast at the end of Phase 2.

#### **6-8-4) Comparative Tests**

Comparative tests were carried out with Sudbury and Manitoulin dolomite, as reactive and non-reactive aggregates, respectively, to compare their reactions with the same glass ratios used in the Spratt mixtures.

#### **6-9) Mortar Strength Comparisons**

To determine and to compare the effects of glass size and percentage on mortar strengths, at the completion of the ASR experiment, the three bars of each reacted and non-reacted mixture were sliced to 9 prisms, sizing 25mm  $\times$  25mm  $\times$  62mm, for testing their uni-axial compressive strength. The prisms were loaded by the hydraulic uni-axial compressive machine RIEHLE at a constant pacing of 0.2 R.P.M and at the range of 500 lb. The highest loads, at which the samples eventually failed, were recorded. Then the average strength for each mix design was calculated and used for the analysis.

#### **6-10) Measurement Times and Frequency**

The mortar bar lengths were measured on days 4, 7, 10, 12, 14, 17, and 21 from their initial immersion in the hot NaOH. All mixture designs reached to their highest rate of the ASR expansion by the day 14 and after that the rate decreased. The most successful Phase 2 mixtures were left in the solutions for 32 days. Those bars exhibited their 3 dimensional ASR cracks between days 27-29.

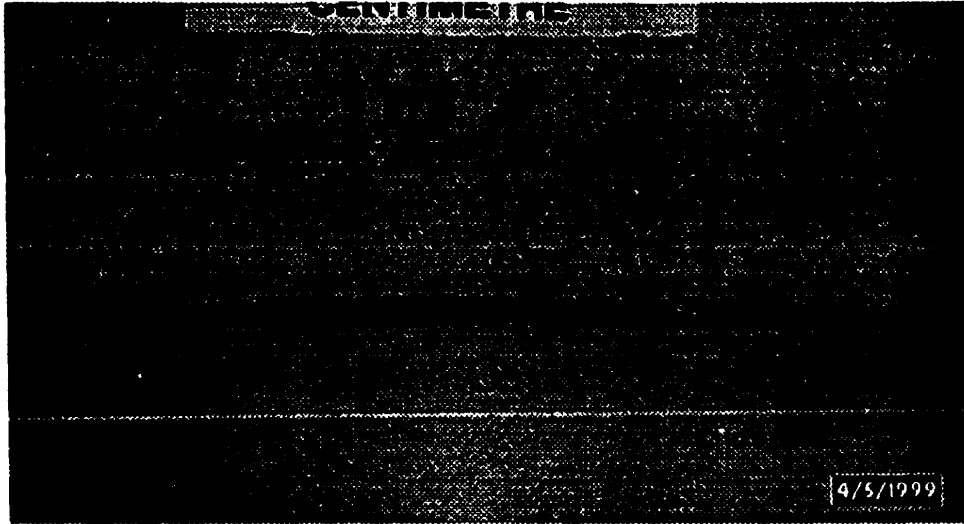
## 7. Results

### 7-1) Preliminary Tests

As seen in Table 4, Spratt had the highest ASR expansion among the three types of aggregates used in this study. Sudbury aggregate was the next most reactive while Manitoulin dolomite was inert. The mortar bars made only with white glass showed the most ASR expansion (Fig.21), so much so that after 10 days the bars did not fit in the measuring device. Large cracks developed within the clear glass bars, which showed the 3-dimensional nature of the ASR cracking, and the bar physically deformed. This large ASR expansion caused by the glass as mortar aggregate casts doubt on the theory of silica the Pessimism Effect (PE) (Hobbs, 1988). The ASR expansion was at its maximum when the glass content was at 100%, which is contrary to the theory of the PE.

Rock	Day	3	6	10	12	14	15
Spratt		0.080	0.203	0.330	0.360	0.423	0.432
Sudbury		0.030	0.038	0.038	0.083	0.095	0.104
Manitoulin dolomite		0.021	0.003	0.003	0.021	0.029	0.034
White Glass		0.018	0.433	0.515	0.705	N/A	N/A

*Table 4 : ASR expansions, %, of different Ontario aggregates and white glass.*



*Fig. 21: Deterioration and crack development in mortar bars made with white glass as an aggregate. (By: P. Hudec).*

## **7-2) Chemical Tests**

Glass grain size showed an inverse relationship to the amount of glass dissolved: the finer the glass grain size, the greater surface area and, therefore, the larger glass dissolution (Figs.22-24). Although the fine sizes of the two glass types dissolved more than their coarser sizes as seen but in Fig. 24, the ratios of dissolution to surface area index (slopes or tangents of the curves) decreased as the grain size decreased, suggesting that the rate of reaction of glass in the very fine sizes is equivalent, i.e., not as size dependent as for the coarser sizes. Fig. 24 exhibits the difference between the dissolution reactions of the colored and uncolored glass types as function of their surface area index. Since the grain sizes represent a geometric progression, sieve sizes #8, #16, #30, ..., and #200 were assigned index numbers 1, 2, 4, ..., and 32, respectively. Clear glass initially showed a higher reaction rate than the colored type, which may be a function of composition difference between the two glass types.

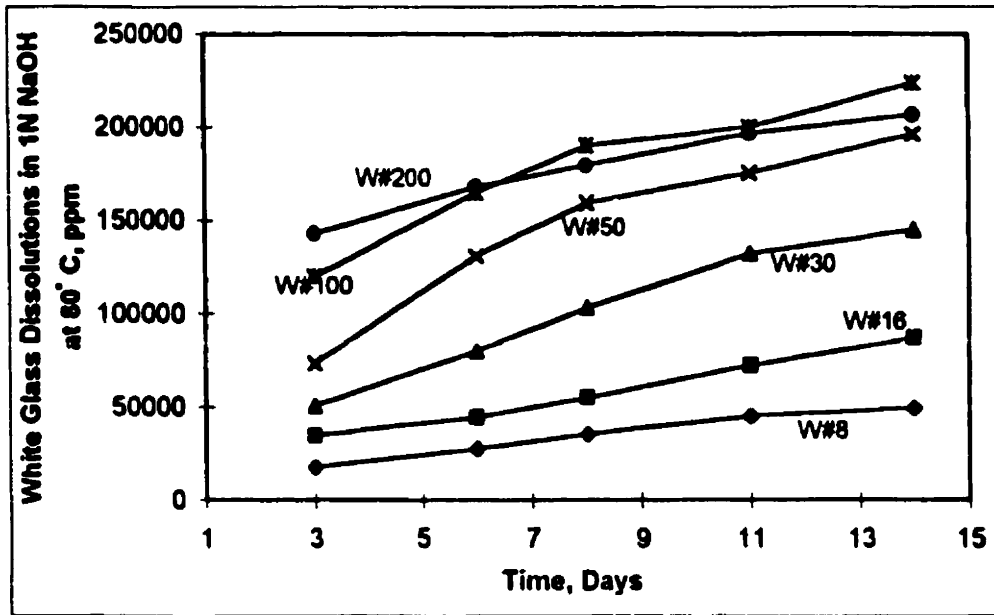


Fig. 22: Dissolution of white glass vs. time: Different sizes of glass in 1N NaOH at 80°C.

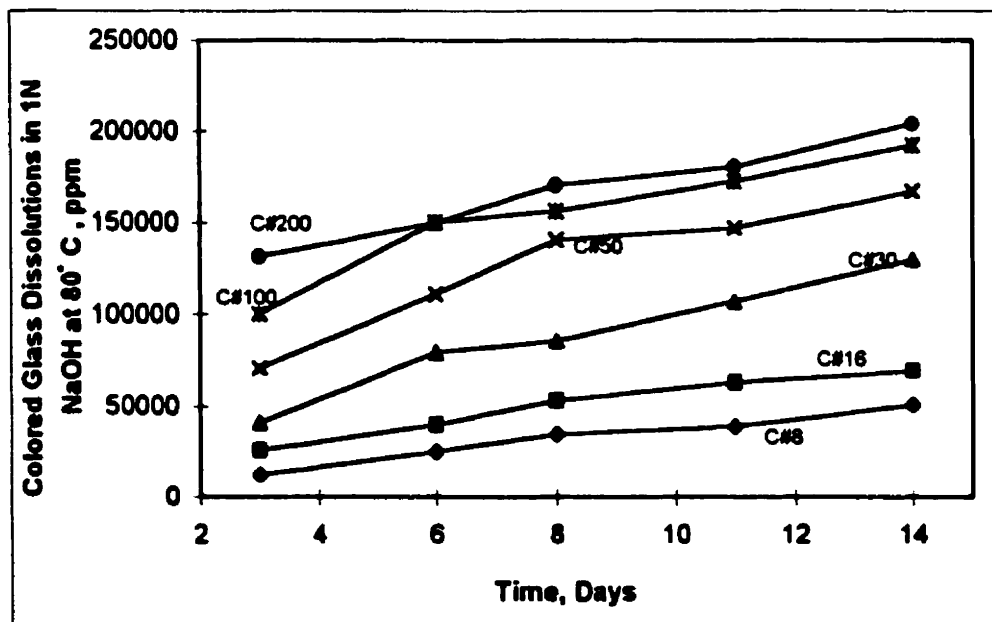


Fig. 23: Dissolution of green glass vs. time: Different sizes of glass in 1N NaOH at 80°C.

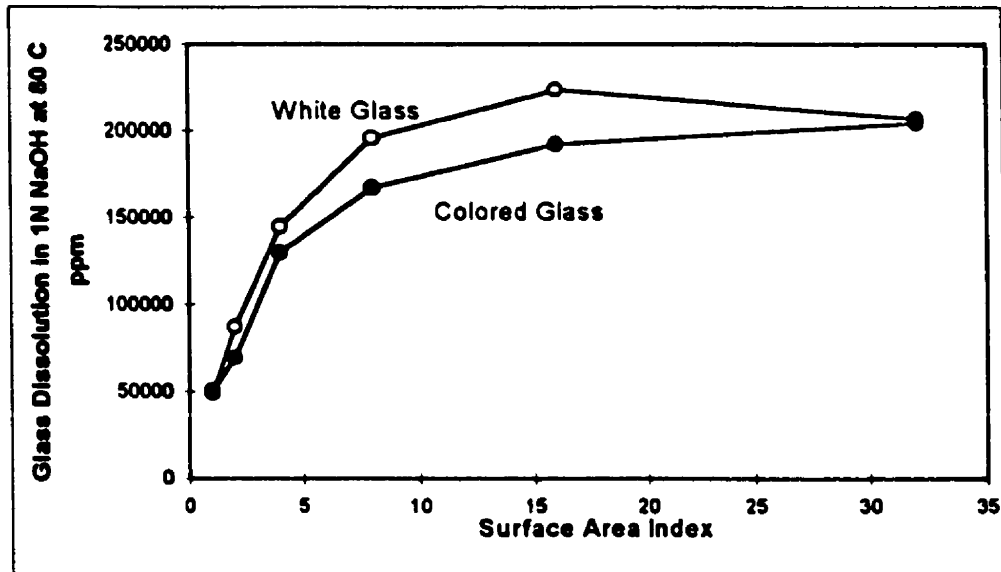


Fig. 24: Clear and colored glass dissolutions, ppm, in 1N NaOH and at 80°C, at 14 days vs. glass surface Area index.

### 7-3) Phase I

The Spratt mortar mixtures showed that the coarse-grained glass replacement or addition had, in general, no positive effect on reducing the ASR expansion; on the contrary it produced an ASR expansion that was even greater than in Spratt by itself. Table 5 shows the mixtures containing fine-grained white glass, sized of #50 and #100, that slightly reduced the Spratt ASR expansion. The order of reduction in the ASR expansions to the day 14, was: **W3<W6<W8<W1<W4<W13<W2<W7<W5<SPRATT** (Table 5). The mixtures with expansions less than SPRATT, except W13, had glass sized of #50 and #100; fine sizes. Continuation of the ASR expansion to day 21 showed that the same order of ASR expansion was not maintained. Although the total amount of change was small and statistically insignificant, (by the experimental errors), but the order after 21 days was: **W3<W6<W1<W8<SPRATT<W4<W2<W5<W7.** Even in this order, the mixtures maintained expansions less than SPRATT were those with glass sized of #50 and #100; fine sizes.



Mixes	Days	4	7	10	12	14	17	21
<b>Spratt Only</b>		<b>0.106</b>	<b>0.256</b>	<b>0.330</b>	<b>0.360</b>	<b>0.423</b>	<b>0.449</b>	<b>0.474</b>
<b>W1=1% white glass of size #100<sub>Replaced</sub></b>		<b>0.059</b>	<b>0.203</b>	<b>0.326</b>	<b>0.359</b>	<b>0.396</b>	<b>0.425</b>	<b>0.465</b>
<b>W2=2% white glass of size #100<sub>Replaced</sub></b>		<b>0.067</b>	<b>0.212</b>	<b>0.336</b>	<b>0.372</b>	<b>0.408</b>	<b>0.438</b>	<b>0.478</b>
<b>W3=4% white glass of size #100<sub>Replaced</sub></b>		<b>0.051</b>	<b>0.187</b>	<b>0.312</b>	<b>0.338</b>	<b>0.366</b>	<b>0.400</b>	<b>0.445</b>
<b>W4=7% white glass of size #100<sub>Replaced</sub></b>		<b>0.068</b>	<b>0.211</b>	<b>0.332</b>	<b>0.366</b>	<b>0.401</b>	<b>0.433</b>	<b>0.476</b>
<b>W5=2% white glass of size #50<sub>Replaced</sub></b>		<b>0.069</b>	<b>0.218</b>	<b>0.338</b>	<b>0.375</b>	<b>0.414</b>	<b>0.442</b>	<b>0.481</b>
<b>W6=3% white glass of size #50<sub>Replaced</sub></b>		<b>0.047</b>	<b>0.188</b>	<b>0.324</b>	<b>0.346</b>	<b>0.379</b>	<b>0.411</b>	<b>0.452</b>
<b>W7=5% white glass of size #50<sub>Replaced</sub></b>		<b>0.053</b>	<b>0.208</b>	<b>0.334</b>	<b>0.376</b>	<b>0.409</b>	<b>0.448</b>	<b>0.500</b>
<b>W8=8% white glass of size #50<sub>Replaced</sub></b>		<b>0.047</b>	<b>0.196</b>	<b>0.324</b>	<b>0.356</b>	<b>0.388</b>	<b>0.422</b>	<b>0.466</b>
<b>W9=4% white glass of size #30<sub>Replaced</sub></b>		<b>0.049</b>	<b>0.208</b>	<b>0.342</b>	<b>0.383</b>	<b>0.422</b>	<b>0.457</b>	<b>0.503</b>
<b>W10=5% white glass of size #30<sub>Replaced</sub></b>		<b>0.058</b>	<b>0.213</b>	<b>0.344</b>	<b>0.391</b>	<b>0.422</b>	<b>0.463</b>	<b>0.518</b>
<b>W11=7% white glass of size #30<sub>Replaced</sub></b>		<b>0.058</b>	<b>0.205</b>	<b>0.334</b>	<b>0.370</b>	<b>0.410</b>	<b>0.444</b>	<b>0.490</b>
<b>W12=10% white glass of size #30<sub>Replaced</sub></b>		<b>0.054</b>	<b>0.217</b>	<b>0.359</b>	<b>0.403</b>	<b>0.461</b>	<b>0.499</b>	<b>0.550</b>
<b>W13=8% white glass of size #16<sub>Replaced</sub></b>		<b>0.098</b>	<b>0.216</b>	<b>0.309</b>	<b>0.365</b>	<b>0.407</b>	<b>0.441</b>	<b>0.487</b>
<b>W14=9% white glass of size #16<sub>Replaced</sub></b>		<b>0.095</b>	<b>0.236</b>	<b>0.352</b>	<b>0.414</b>	<b>0.465</b>	<b>0.501</b>	<b>0.550</b>
<b>W15=11% white glass of size #16<sub>Replaced</sub></b>		<b>0.121</b>	<b>0.250</b>	<b>0.354</b>	<b>0.419</b>	<b>0.467</b>	<b>0.503</b>	<b>0.551</b>
<b>W16=14% white glass of size #16<sub>Replaced</sub></b>		<b>0.116</b>	<b>0.255</b>	<b>0.378</b>	<b>0.437</b>	<b>0.495</b>	<b>0.532</b>	<b>0.580</b>
<b>W17=16% white glass of size #8<sub>Replaced</sub></b>		<b>0.105</b>	<b>0.231</b>	<b>0.330</b>	<b>0.386</b>	<b>0.429</b>	<b>0.459</b>	<b>0.499</b>
<b>W18=17% white glass of size #8<sub>Replaced</sub></b>		<b>0.098</b>	<b>0.225</b>	<b>0.337</b>	<b>0.387</b>	<b>0.433</b>	<b>0.464</b>	<b>0.504</b>
<b>W19=19% white glass of size #8<sub>Replaced</sub></b>		<b>0.115</b>	<b>0.245</b>	<b>0.357</b>	<b>0.416</b>	<b>0.463</b>	<b>0.500</b>	<b>0.550</b>
<b>W20=22% white glass of size #8<sub>Replaced</sub></b>		<b>0.110</b>	<b>0.240</b>	<b>0.361</b>	<b>0.408</b>	<b>0.455</b>	<b>0.498</b>	<b>0.554</b>

*Table 5 : Phase I results show the ASR expansion, %, on different days. First column is the mix designs. In each mixture aggregate was replaced with clear glass in its own size fraction.*

### 7-3-1) Statistics

Student's paired t-tests were performed to statistically compare all the Phase I mixtures with the Spratt-only mixture. Table 6 shows the t-test results and their significance; The minimum significant t-test number with a degree of freedom (df) of 6, at 5% level, is  $\pm 2.447$ . The negative sign indicates that a particular mixture had an ASR expansion greater than pure Spratt while the positive sign shows the reduction of the ASR expansion in the mixture. Tables 5 and 6 show that the sizes of glass finer than #30 to #100 significantly decreased the mortar expansions. The results suggest that the effect of glass in mortar is a function of grain size (surface area) and its mass proportion.

Samples	Expansion Mean, %	Paired t-test between Spratt and samples	Significance
Spratt Only	0.343	-	-
W16:14%glass of size #16	0.399	-3.784	0.009
W15:11%glass of size #16	0.380	-3.498	0.013
W19:19%glass of size #8	0.378	-3.143	0.020
W20:22%glass of size #8	0.375	-2.750	0.033
W14:9%glass of size #16	0.373	-2.273	0.063
W12:10%glass of size #30	0.363	-1.155	0.292
W18:17%glass of size #8	0.350	-0.908	0.399
W17:16%glass of size #8	0.348	-0.908	0.400
W10:5%glass of size #30	0.344	-0.128	0.902
W9:4%glass of size #30	0.338	0.391	0.709
W7:5%glass of size #50	0.333	0.862	0.422
W5:2%glass of size #50	0.334	1.093	0.316
W11:7%glass of size #30	0.330	1.186	0.281
W2:2%glass of size #100	0.330	1.484	0.188
W13:8%glass of size #16	0.332	1.641	0.152
W4:7%glass of size #100	0.327	2.014	0.091
W1:1%glass of size #100	0.319	3.068	0.022
W8:8%glass of size #50	0.314	3.121	0.021
W6:3%glass of size #50	0.307	4.158	0.006
W3:4%glass of size #100	0.300	5.847	0.001

*Table 6: The ordered paired t-test results of Phase 1 show that there are three main groups of samples: with expansions larger than Spratt, similar to Spratt, and significantly better than Spratt.*

Phase 1 of the investigation suggested that the fine to very fine-grained glass replacing the finest fraction of mortar aggregate, sieve #100, was most effective. Also, as seen in the Figs. 22 and 23, both colored and clear glass types had higher dissolution of their finer-grained silica. But both sizes of #100 and #200 reacted similarly with the NaOH solution. This may be a real phenomenon, or may be due to the lack of accuracy in measuring (Pers. Com., I. Churchill, 1999: there was an evaporation of the solution water in the last two measurements the) the dissolution of the finer sizes.

#### **7-4) Phase 2**

All the mixtures tested in Phase 2 decreased the ASR expansions (Table 7). Decreasing the glass grain size from #200 to finer than #400 reduced the ASR expansion, as suggested by the glass dissolution test. The replacement of 16% of the sieve #100 fraction

Mixes	Days	4	7	10	12	14	17	21
Spratt Only		0.106	0.256	0.330	0.360	0.423	0.449	0.474
1% white glass sized of #200 <sub>Replaced</sub>		0.103	0.246	0.308	0.340	0.367	0.384	0.409
2% white glass sized of #200 <sub>Replaced</sub>		0.096	0.238	0.315	0.347	0.374	0.398	0.424
4% white glass sized of #200 <sub>Replaced</sub>		0.091	0.241	0.307	0.329	0.368	0.392	0.417
8% white glass sized of #200 <sub>Replaced</sub>		0.097	0.219	0.280	0.311	0.338	0.357	0.386
1% white glass sized of #200 <sub>Added</sub>		0.102	0.244	0.303	0.336	0.360	0.374	0.407
2% white glass sized of #200 <sub>Added</sub>		0.112	0.255	0.328	0.366	0.388	0.415	0.450
4% white glass sized of #200 <sub>Added</sub>		0.114	0.249	0.309	0.342	0.365	0.381	0.420
8% white glass sized of #200 <sub>Added</sub>		0.091	0.219	0.291	0.323	0.346	0.363	0.396
1% white glass finer than #200 <sub>Replaced</sub>		0.086	0.235	0.254	0.283	0.321	0.412	0.386
2% white glass finer than #200 <sub>Replaced</sub>		0.087	0.230	0.254	0.290	0.327	0.414	0.389
4% white glass finer than #200 <sub>Replaced</sub>		0.107	0.267	0.286	0.317	0.353	0.445	0.549
8% white glass finer than #200 <sub>Replaced</sub>		0.094	0.242	0.256	0.290	0.325	0.411	0.386
1% white glass finer than #200 <sub>Added</sub>		0.090	0.236	0.267	0.304	0.341	0.438	0.411
2% white glass finer than #200 <sub>Added</sub>		0.109	0.267	0.299	0.343	0.380	0.474	0.449
4% white glass finer than #200 <sub>Added</sub>		0.082	0.211	0.243	0.280	0.312	0.404	0.378
8% white glass finer than #200 <sub>Added</sub>		0.104	0.239	0.277	0.316	0.355	0.443	0.423
1% white glass finer than #400 <sub>Replaced</sub>		0.060	0.193	0.220	0.255	0.293	0.382	0.362
2% white glass finer than #400 <sub>Replaced</sub>		0.072	0.168	0.175	0.205	0.228	0.318	0.301
4% white glass finer than #400 <sub>Replaced</sub>		0.037	0.147	0.154	0.186	0.215	0.308	0.290
8% white glass finer than #400 <sub>Replaced</sub>		0.055	0.158	0.188	0.217	0.245	0.334	0.312
16% white glass finer than #400 <sub>Replaced</sub>		0.020	0.084	0.108	0.124	0.144	0.173	0.202
32% white glass finer than #400 <sub>Replaced</sub>		0.055	0.158	0.188	0.217	0.245	0.334	0.312
1% white glass finer than #400 <sub>Added</sub>		0.093	0.163	0.266	0.316	0.351	0.393	0.430
2% white glass finer than #400 <sub>Added</sub>		0.092	0.167	0.279	0.334	0.370	0.408	0.448
4% white glass finer than #400 <sub>Added</sub>		0.086	0.162	0.273	0.322	0.364	0.398	0.435
8% white glass finer than #400 <sub>Added</sub>		0.092	0.157	0.250	0.299	0.332	0.366	0.406
2% green glass finer than #400 <sub>Replaced</sub>		0.057	0.124	0.197	0.245	0.294	0.342	0.397
4% green glass finer than #400 <sub>Replaced</sub>		0.061	0.123	0.192	0.233	0.282	0.327	0.382
8% green glass finer than #400 <sub>Replaced</sub>		0.072	0.136	0.209	0.254	0.301	0.349	0.403
2% Silica. fume replaced in #100		0.046	0.129	0.212	0.264	0.306	0.340	0.257
4% Silica. fume replaced in #100		0.041	0.115	0.186	0.236	0.268	0.302	0.352
8% Silica. fume replaced in #100		0.039	0.097	0.146	0.186	0.214	0.250	0.295

Table 7 : Phase 2 results: ASR expansion, %, as a function of time. First column is the mix designs. All the aggregate replacements with glass were in fraction on the sieve #100.

(2.4% of the total aggregate) with clear glass finer than #400 decreased the ASR expansion by over 50%. As predicted from the dissolution tests, green glass did not reduce ASR expansion as much as the white glass. The ASR reduction behavior was found to be a factor of its mass proportion, as well as the mode of addition or replacement.

#### **7-5) Comparative Tests**

The results in Table 8 show that the replacement of the Sudbury aggregate by the white glass finer than #400 did not reduce the ASR expansion while 4% green glass replacement in #100 was the most effective mixture. Generally, glass replacements of this aggregate were not as effective as those in Spratt. This may be explained by the difference of mineralogy of the ASR reactive agents: Spratt contains reactive SiO<sub>2</sub> (silica) whereas Sudbury consists mainly of silicates. The alkali-silicate reaction is a much slower one, and inherently different in nature than that of the alkali-silica reaction.

Manitoulin dolomite mortar mixture, by itself, showed a relatively small ASR expansion. Dolomite is, relatively, a non-reactive aggregate and its expansion in this mortar bar tests is attributed to an amorphous silica present in the aggregate (pers. com. P. Hudec, 1999). By replacing 8% of the sieve #100 fraction with green glass this ASR expansion was reduced by about 20%. Both the glass type and its content were effective in the reduction of the ASR expansion in the Manitoulin dolomite mixtures.

This significant result indicates that the fine ground glass acts as pozzolanic/cementitious agent. Note that in coarse grain sizes, the glass acts as a reactive aggregate. Thus, finely ground glass behaves as ground granulated blast furnace slag, fly ash, or silica fume.

Mixes	Days	4	7	10	12	14	17	21
Sudbury		0.035	0.076	0.130	0.163	0.191	0.245	0.317
2% white glass finer than #400 <sub>Replaced</sub>		0.038	0.058	0.111	0.143	0.187	0.245	0.312
4% white glass finer than #400 <sub>Replaced</sub>		0.043	0.060	0.108	0.142	0.176	0.232	0.304
8% white glass finer than #400 <sub>Replaced</sub>		0.045	0.070	0.123	0.152	0.182	0.237	0.310
2% green glass finer than #400 <sub>Replaced</sub>		0.048	0.064	0.125	0.158	0.189	0.247	0.323
4% green glass finer than #400 <sub>Replaced</sub>		0.030	0.057	0.098	0.125	0.152	0.203	0.270
8% green glass finer than #400 <sub>Replaced</sub>		0.042	0.069	0.117	0.170	0.184	0.226	0.289
Manitoulin Dolomite		0.059	0.080	0.109	0.124	0.138	0.158	0.185
2% white glass finer than #400 <sub>Replaced</sub>		0.054	0.072	0.096	0.112	0.128	0.144	0.165
4% white glass finer than #400 <sub>Replaced</sub>		0.053	0.073	0.099	0.112	0.125	0.143	0.167
8% white glass finer than #400 <sub>Replaced</sub>		0.057	0.077	0.103	0.118	0.133	0.150	0.173
2% green glass finer than #400 <sub>Replaced</sub>		0.056	0.069	0.095	0.108	0.119	0.137	0.161
4% green glass finer than #400 <sub>Replaced</sub>		0.050	0.076	0.102	0.115	0.128	0.139	0.154
8% green glass finer than #400 <sub>Replaced</sub>		0.056	0.074	0.100	0.111	0.122	0.134	0.149

*Table 8 : Comparative results of the ASR expansion of Sudbury and Manitoulin aggregates. #100 size aggregate replaced with < #400 sized glass. First column is the mix designs.*

Table 9 shows the average compressive strengths of the mortar bar prisms of Phase 2 mixtures. Although cursory examination does not appear to indicate any significant trends, statistical evaluation of the data to be presented later shows that the strength of mortars is affected by addition and replacement of glass of different sizes.

Both replacements and additions of the sieve #100 fraction with glass finer than #400 obtained greater strengths than Spratt by itself. Colored glass was more effective than the clear glass. The amount of both glass types showed a direct relationship with the Spratt mortar bar strength while silica fume had an inverse trend.

Phase 2 Mixtures	Mortar Bar Average Strength, KPa
Spratt Only	262.574
1% white glass sized of #200 <sub>Replaced</sub>	304.982
2% white glass sized of #200 <sub>Replaced</sub>	278.884
4% white glass sized of #200 <sub>Replaced</sub>	293.159
8% white glass sized of #200 <sub>Replaced</sub>	261.788
1% white glass sized of #200 <sub>Added</sub>	471.637
2% white glass sized of #200 <sub>Added</sub>	359.952
4% white glass sized of #200 <sub>Added</sub>	288.345
8% white glass sized of #200 <sub>Added</sub>	270.951
1% white glass finer than #200 <sub>Replaced</sub>	424.199
2% white glass finer than #200 <sub>Replaced</sub>	407.983
4% white glass finer than #200 <sub>Replaced</sub>	382.957
8% white glass finer than #200 <sub>Replaced</sub>	307.295
1% white glass finer than #200 <sub>Added</sub>	415.104
2% white glass finer than #200 <sub>Added</sub>	399.050
4% white glass finer than #200 <sub>Added</sub>	374.278
8% white glass finer than #200 <sub>Added</sub>	326.512
1% white glass finer than #400 <sub>Replaced</sub>	339.616
2% white glass finer than #400 <sub>Replaced</sub>	234.608
4% white glass finer than #400 <sub>Replaced</sub>	231.119
8% white glass finer than #400 <sub>Replaced</sub>	265.994
16% white glass finer than #400 <sub>Replaced</sub>	368.282
32% white glass finer than #400 <sub>Replaced</sub>	453.781
1% white glass finer than #400 <sub>Added</sub>	301.146
2% white glass finer than #400 <sub>Added</sub>	293.989
4% white glass finer than #400 <sub>Added</sub>	316.903
8% white glass finer than #400 <sub>Added</sub>	303.618
2% green glass finer than #400 <sub>Replaced</sub>	354.171
4% green glass finer than #400 <sub>Replaced</sub>	330.676
8% green glass finer than #400 <sub>Replaced</sub>	346.144
2% Silica fume replaced in #100	493.633
4% Silica fume replaced in #100	375.128
8% Silica fume replaced in #100	286.223

*Table 9: The average uni-axial strengths of all the mortar bar prisms of Phase 2 mixtures; 16% was the best mixture ratio with minimum ASR expansion .*

## **7-6) X-Y Plots**

To demonstrate the relationships between reduction amounts and rates of the ASR expansions, the results were grouped and plotted by considering their:

- glass content similarity,
- glass size similarity,
- glass type similarity,
- glass addition,
- glass replacement,
- aggregate type, and
- mortar bar strengths

### **a) Glass Size Comparisons of the Spratt Mixtures**

Fig. 25 shows the grain size effect of white glass replacing the #100 aggregate fraction for Phase 2. The maximum reduction was obtained by white glass finer than #400. The expansion of the mortars containing the coarser glass sizes, although generally less than Spratt alone, were not significantly different.

Fig. 26 shows 2% by mass replacement of the #100 Spratt aggregate by white and green glass that is between #200 and finer than #400 in size, and 2% silica fume. The results show that this amount of glass and silica fume give similar and somewhat lower expansions than Spratt alone. The #200 white glass has virtually no effect.

Figs. 27 and 28, with the same glass combinations but 4% and 8%, respectively, by mass replacement show that glass finer than #400 and silica fume behave similarly, and result in significantly lower expansion. Coarser glass showed no significant effect on expansion. In all of the above, the green glass was always less effective than white glass.

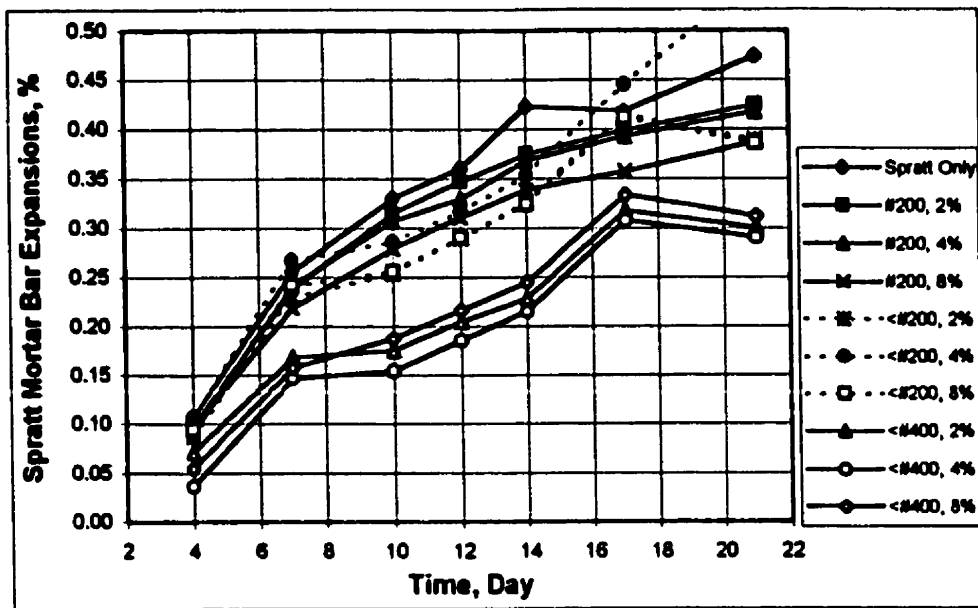


Fig. 25: Spratt mortar bar expansions, %, vs. time, day; 2%-8% Replacements of #100 aggregate by white glass of sizes #200, finer than #200, and finer than #400.

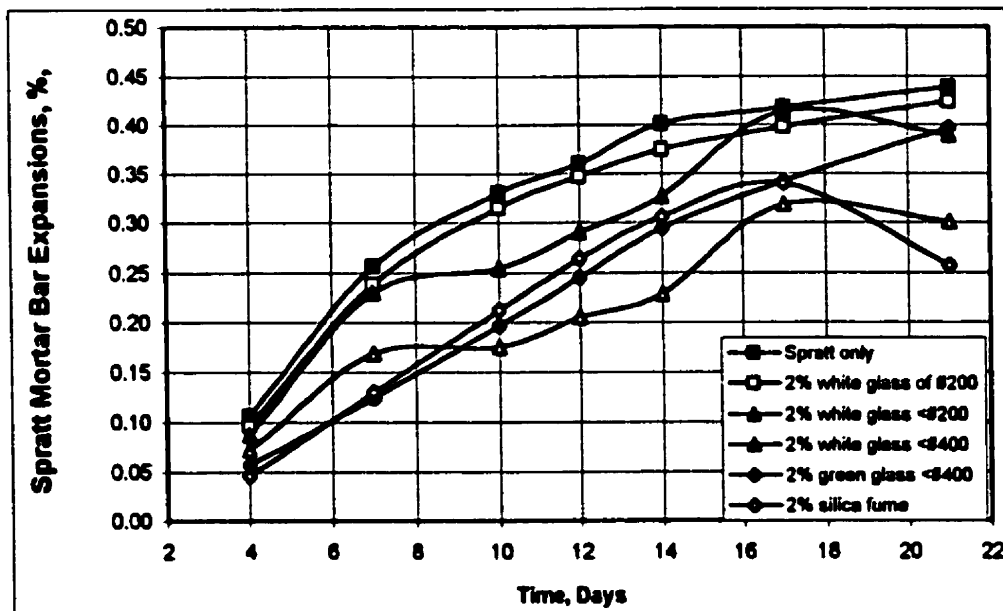


Fig. 26: Spratt mortar bar expansions, %, vs. Days; 2% replacements of #100 aggregate by silica fume and white and green glasses of sizes #200, finer than #200, and finer than #400.



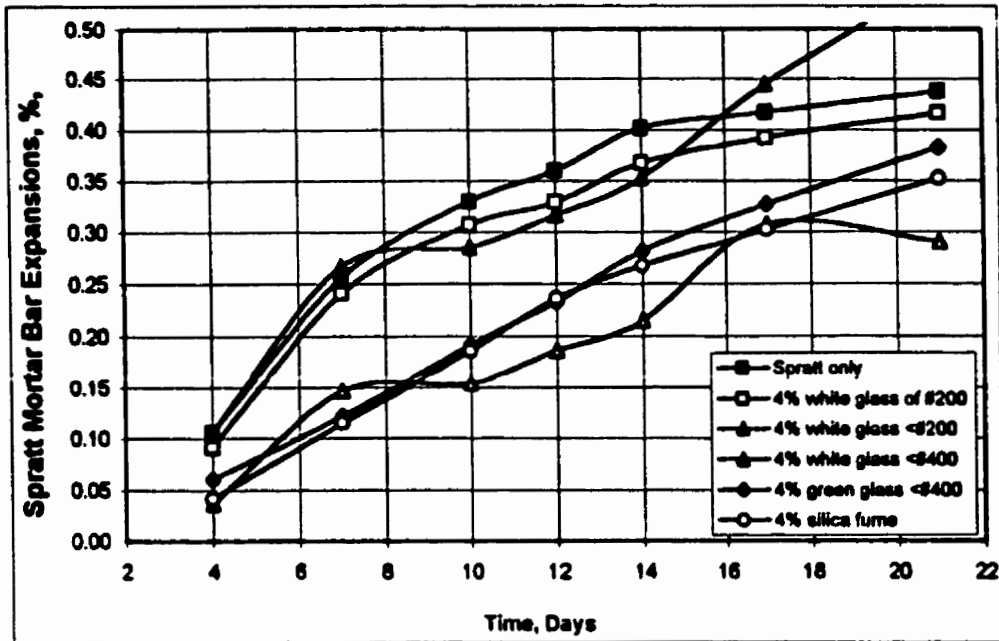


Fig. 27: Spratt mortar bar expansions, %, vs. days; 4% replacements of # 100 aggregate by silica fume and white and green glasses of sizes #200, finer than #200, and finer than #400.

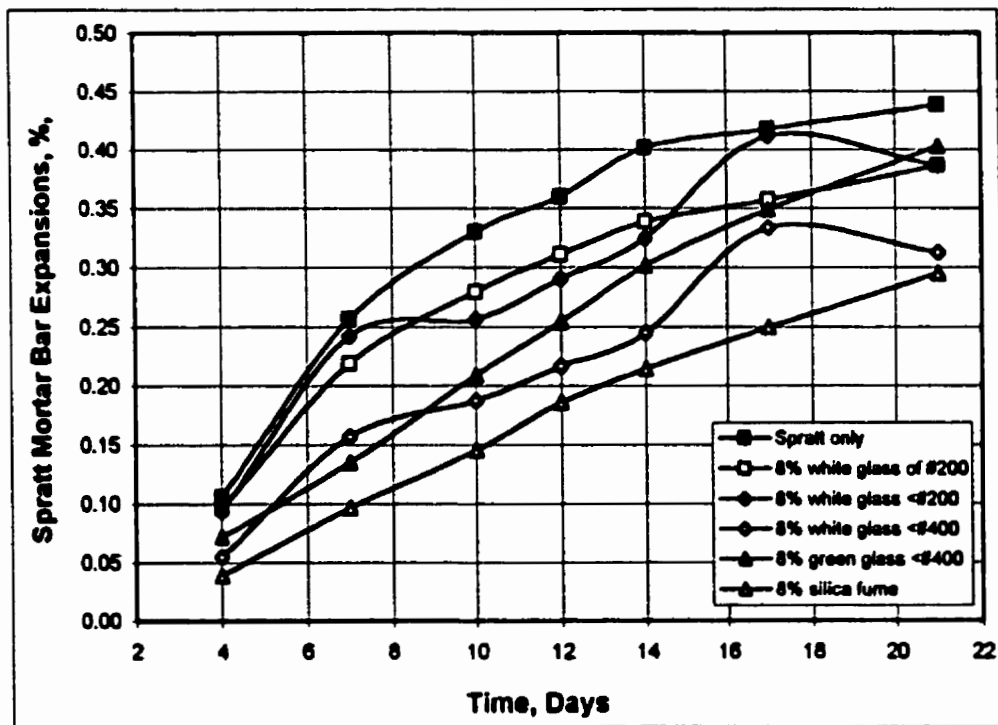


Fig. 28: Spratt mortar bar expansions, %, vs. days; 8% replacements of # 100 aggregate by silica fume and white and green glasses of sizes #200, finer than #200, and finer than #400.

## **b) Comparisons Between Glass Replacements and Additions**

Fig. 29 shows that the #100 aggregate replacements by white glass finer than #400 reduced the expansion significantly more than the addition to the mixtures. The additions only marginally improved the ASR performance of the mixtures. The replacements and the additions of 2%, 4%, and 8 % showed little difference among them in each category, i.e., similar ASR reduction performance was noted whether the mixture contained 2% or 8% glass. This is also seen in Fig 30. However, increasing the glass mass content to 16% replacement of the #100 fraction significantly reduced ASR, while 32% showed similar behavior as 8% replacement.

Fig. 31 shows that the size #200 of white glass is relatively ineffective, whether substituted for #100 aggregate or added. Both treatments reduced ASR only marginally. Much the same holds for the glass size finer than #200 (Fig. 32), although there is a small difference between the replaced versus added glass, the former being slightly more effective.

Fig. 33 shows the mass effect of white glass finer than #400. A 2<sup>nd</sup> degree polynomial line of best fit has been plotted through the points, and shows that as the mass proportion of the glass is increased from 1 to 16%, ASR expansion decreases. However, at 32% glass replacement of the #100 aggregate, rapid expansion ensues. This result suggests that at some level past 16% replacement the excess glass no longer acts as a pozzolan, but instead produces an ASR reaction. The results plotted in Figs. 34, 35, and 36 show further detail of white glass additions in the mortar mixtures.

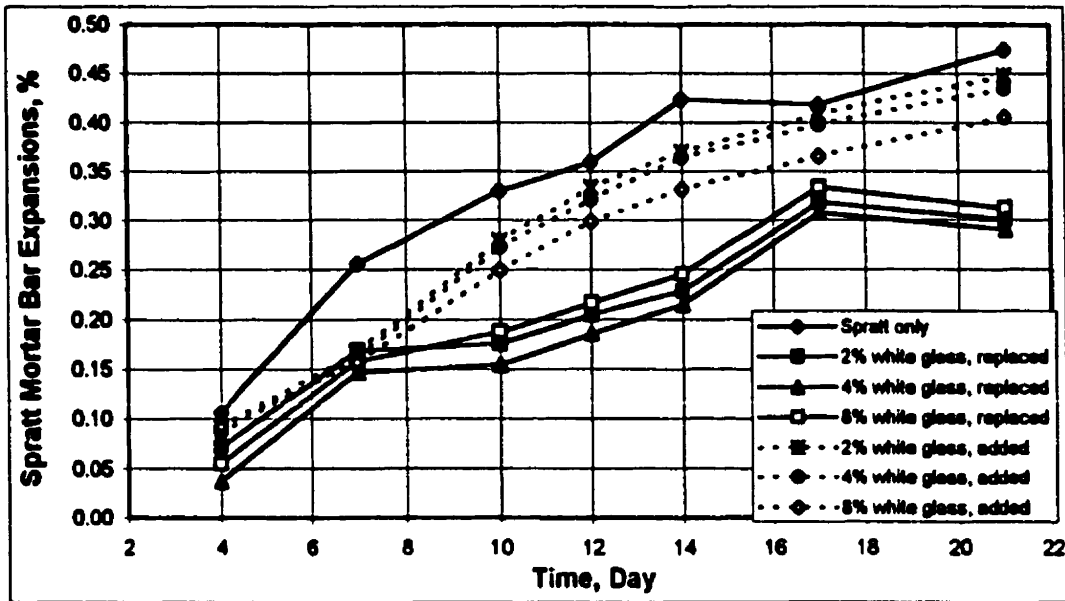


Fig. 29: Spratt mortar bar expansion, %, vs. time, day; Comparisons between 2%–8% additions and replacements of # 100 aggregate by white glass finer than # 400.

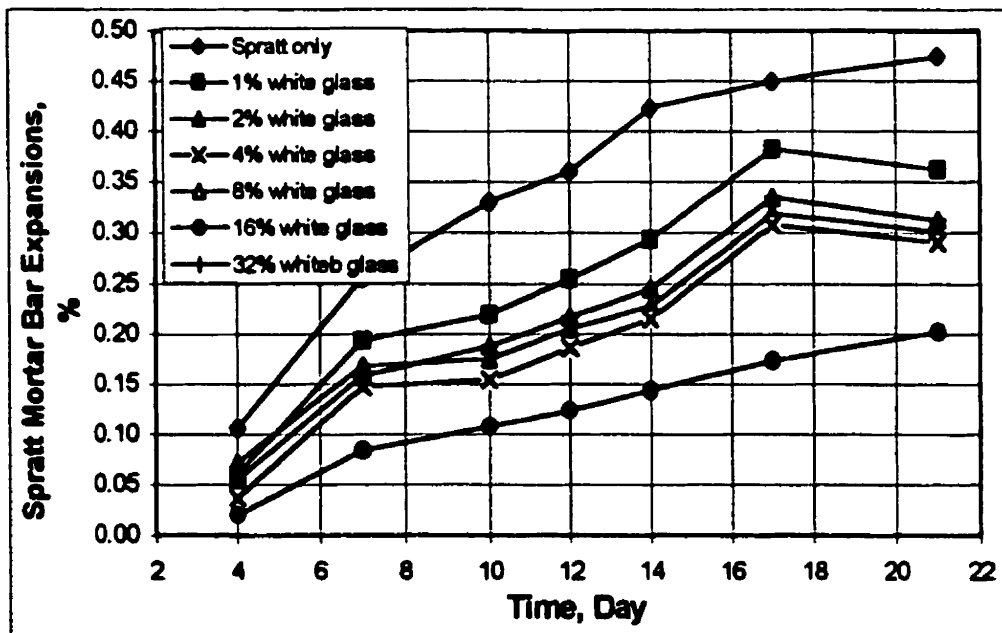


Fig. 30: Spratt mortar bar expansions, %, vs. time, day; All # 100 aggregate replacements by white glass finer than # 400.

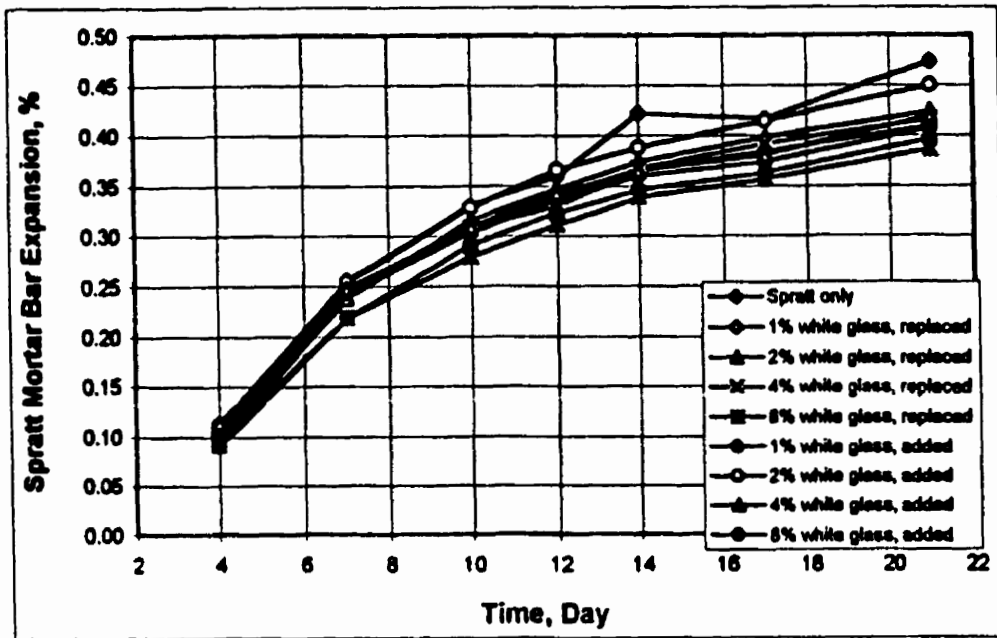


Fig. 31: Spratt mortar bar expansion, %, vs. time, day; 1%-8% replacements and additions of #100 aggregate by white glass sized of #200.

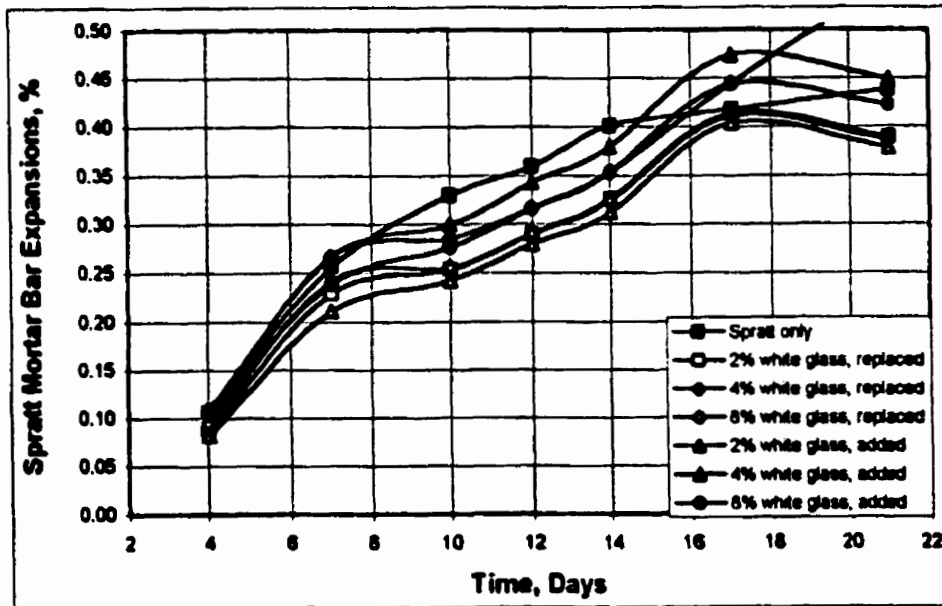


Fig. 32: Spratt mortar bar expansion, %, vs. time, day; 2%-8% replacements and additions of #100 aggregate by white glass finer than #200.

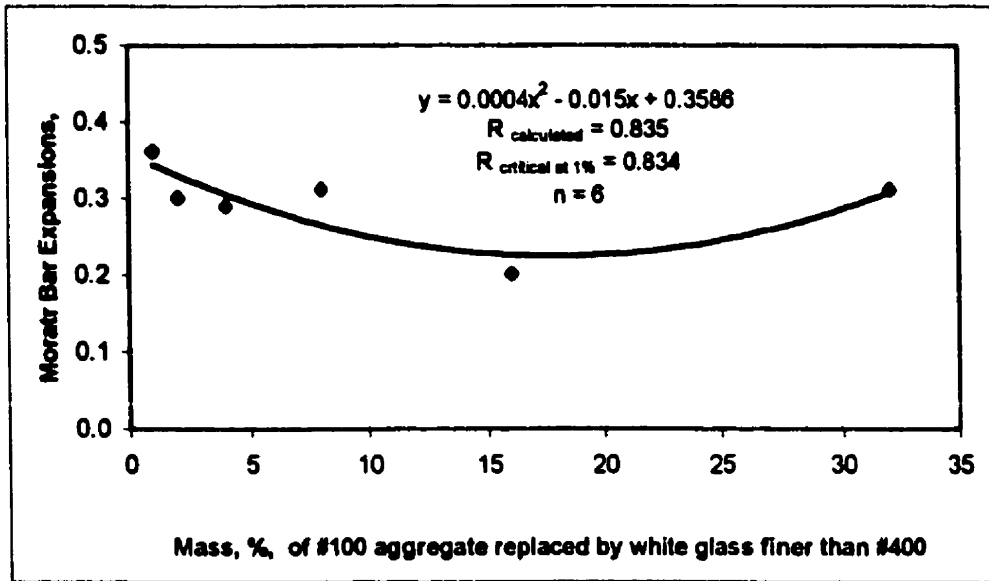


Fig. 33: Spratt mortar bar expansions % vs. mass replacement, % of #100 aggregate by white glass finer than #400, 21 days exposure to the 1N NaOH solution.

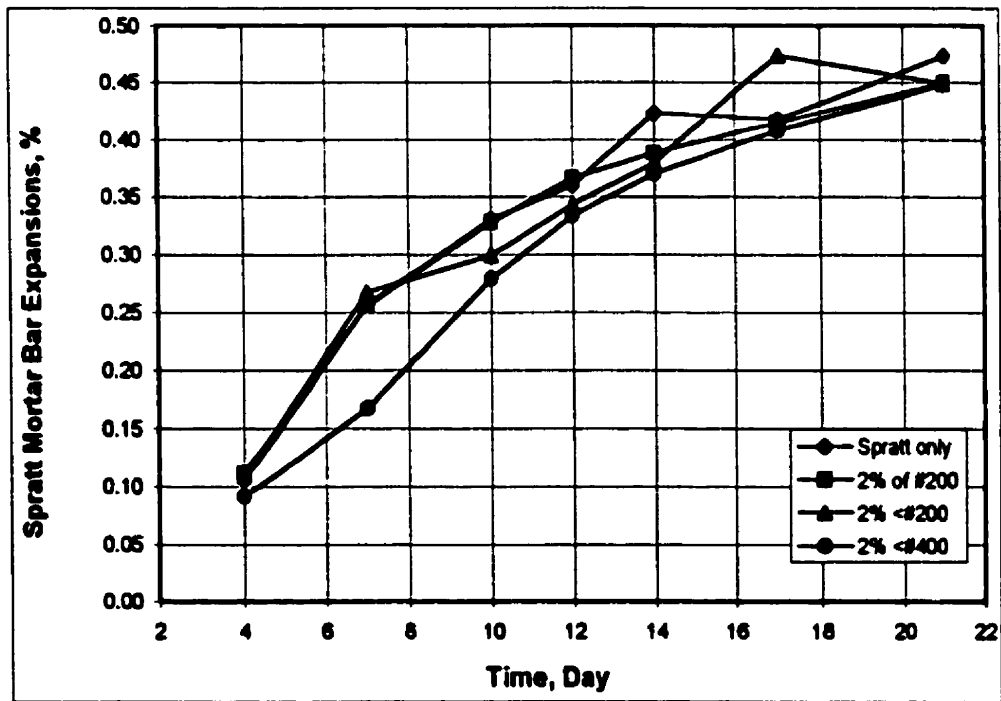


Fig. 34: Spratt mortar bar expansions, % vs. time, day; 2% additions of #100 aggregate by white glass sized of #200, finer than #200, and finer than #400.

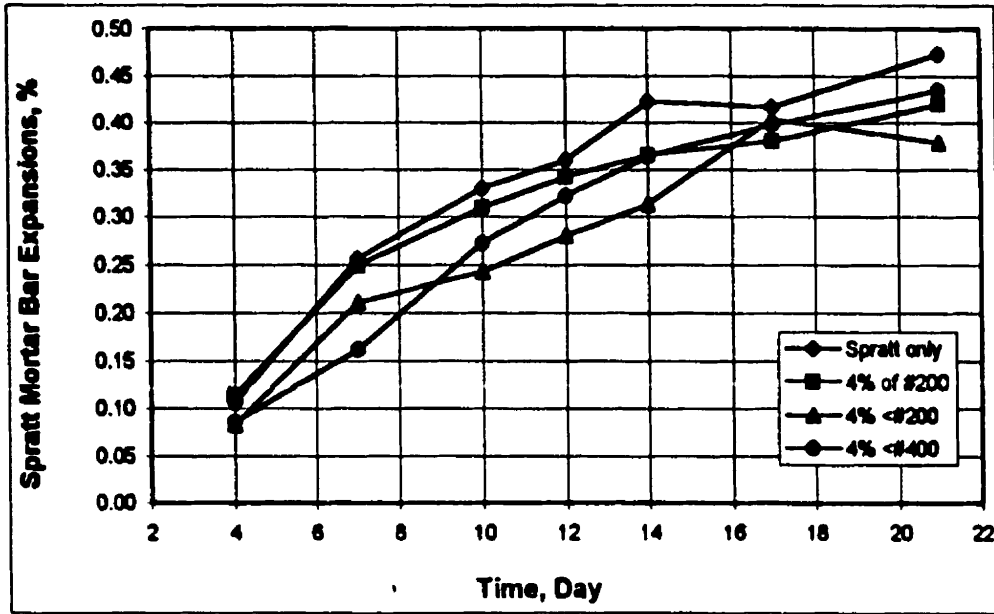


Fig. 35: Spratt mortar bar expansions, %, vs. time, day; 4% additions of #100 aggregate by white glass sized of #200, finer than #200, and finer than #400.

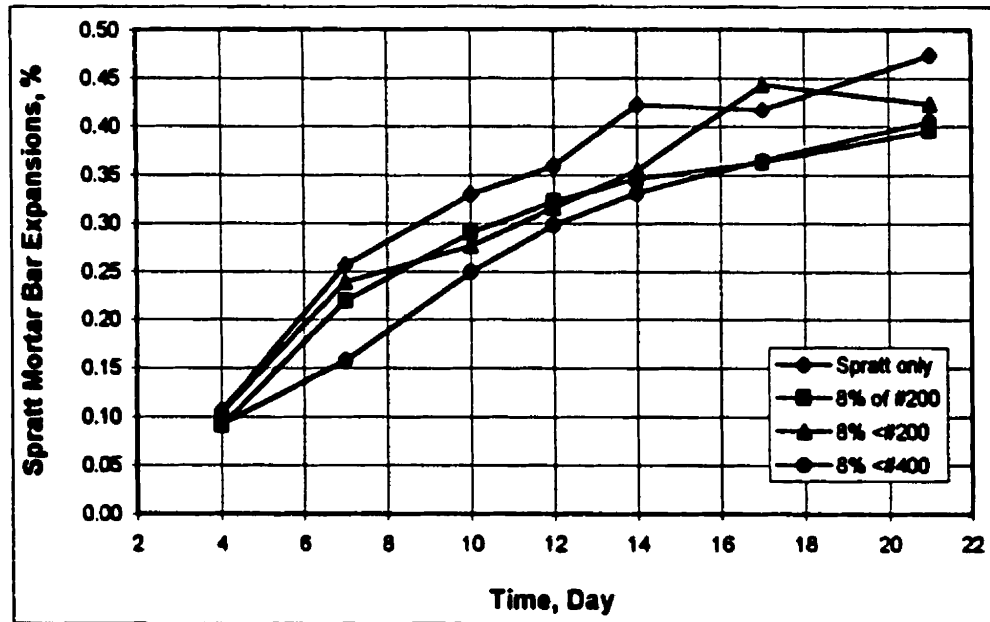


Fig. 36: Spratt mortar bar expansions, %, vs. time, day; 8% additions of #100 aggregate by white glass sized of #200, finer than #200, and finer than #400.

### c) Comparisons Between Glass Types

Fig. 37 was plotted to compare the effect of glass types on the ASR expansion. All glass was in the size range finer than #400, and all reduced the ASR expansion significantly compared to Spratt alone. The best ASR reducer was silica fume; however, the white glass was only marginally worse. The green glass, though effective, resulted in the least reduction.

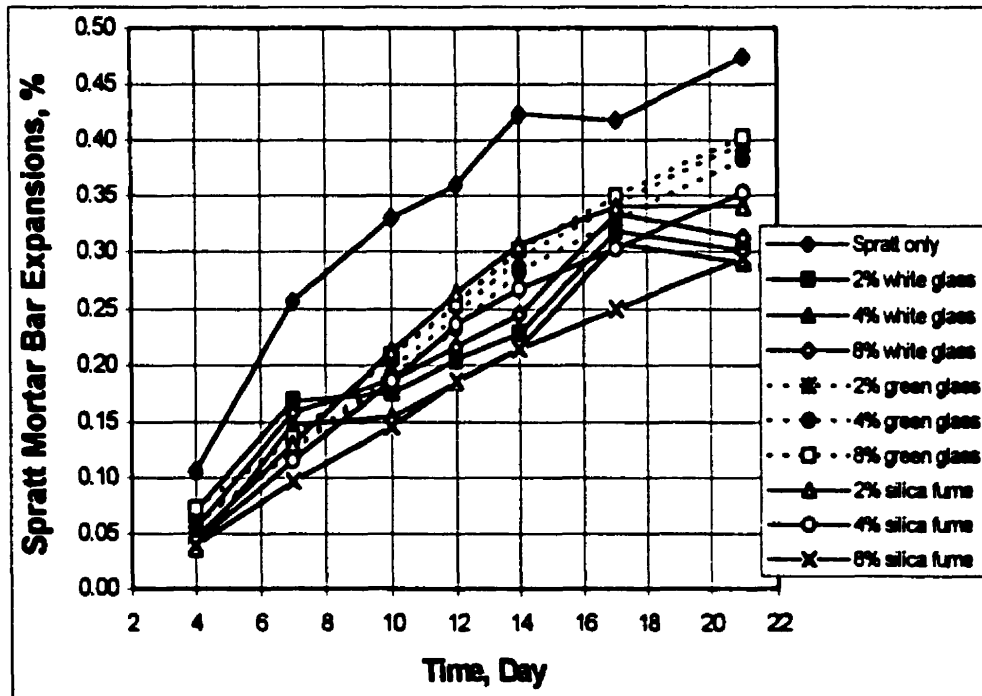
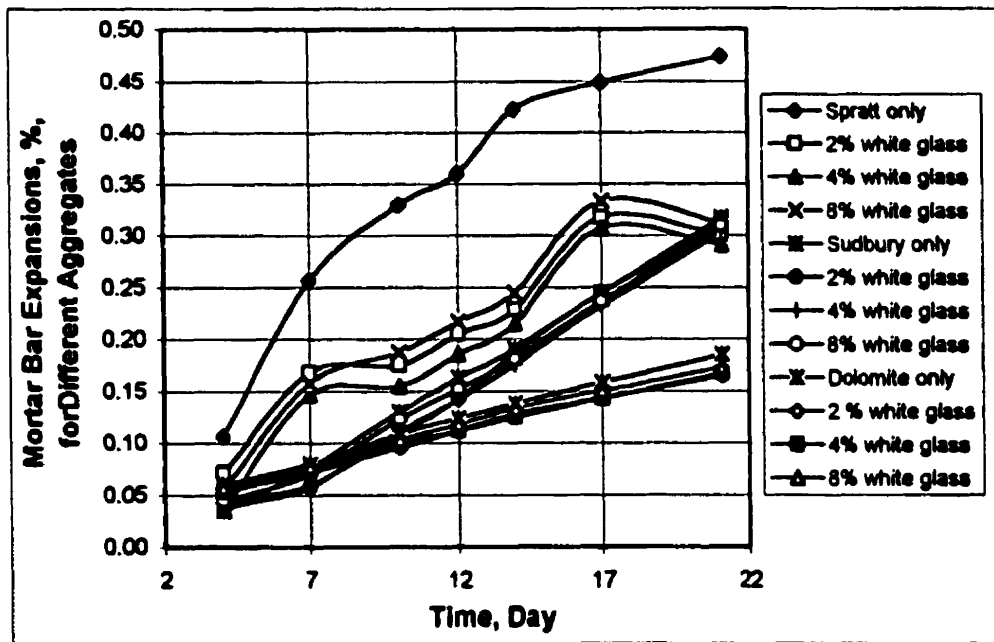


Fig. 37: Spratt mortar bar expansions, %, vs. time, day; Comparisons between three types of glass replacements in #100: white and green glasses, finer than #400, and silica fume.

**d) Comparisons of Expansion Reductions by Glass for Different Aggregates**

Figs. 38 - 41 show that the ASR reduction by white glass replacement of the #100 aggregate is very aggregate specific. It resulted in significant reduction for the Spratt aggregate, but only an insignificant one for the Sudbury aggregate. Although Manitoulin dolomite is considered to be non-reactive, glass replacement also slightly reduced its nominal expansion. Figs. 39, 40, and 41 show the effects of both glass and aggregate types.



*Fig. 38: Effect of replacing #100 fraction of Spratt, Sudbury, and Dolomite aggregates by 2%, 4%, and 8% white glass finer than #100 of on expansion of mortar bars.*



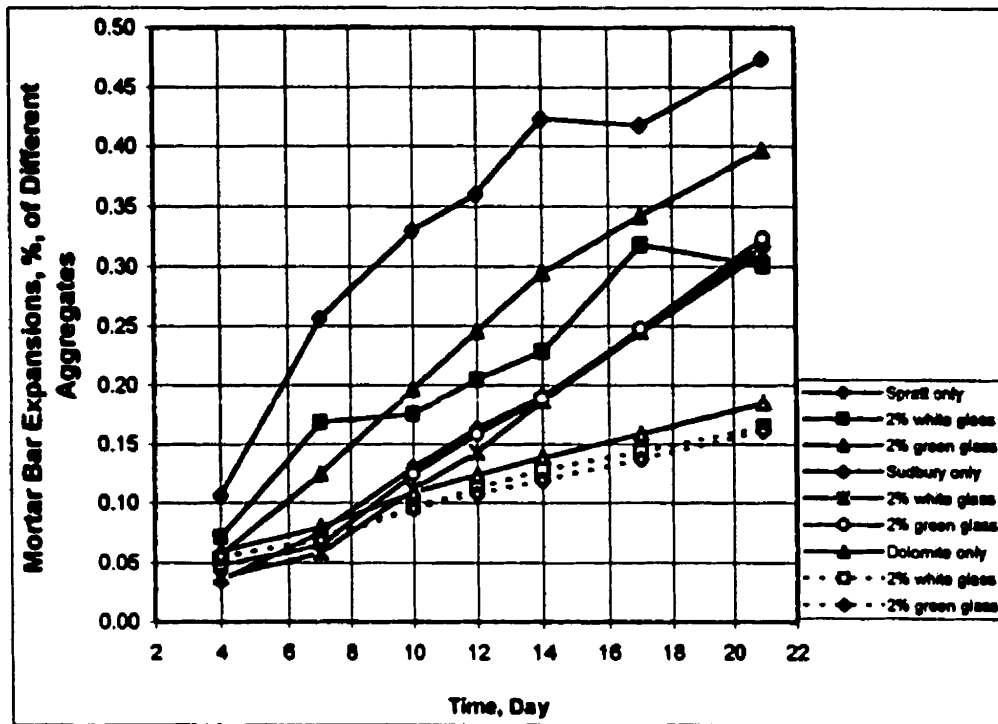


Fig. 39: Mortar bar expansions of different Aggregates, % vs. time, day; 2% replacements of #100 fraction of Spratt, Sudbury, and Dolomite aggregates by white and green glasses finer than #400.

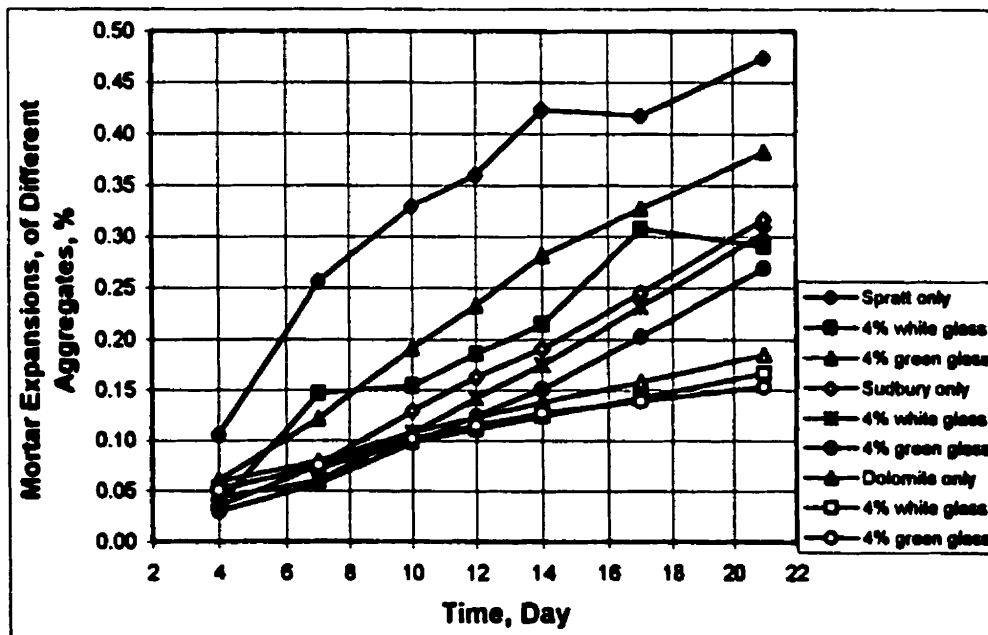


Fig. 40: Mortar bar expansions of different aggregates, % vs. time, day; 4% replacements of #100 fraction of Spratt, Sudbury, and Dolomite aggregates by white and green glasses finer than #400.

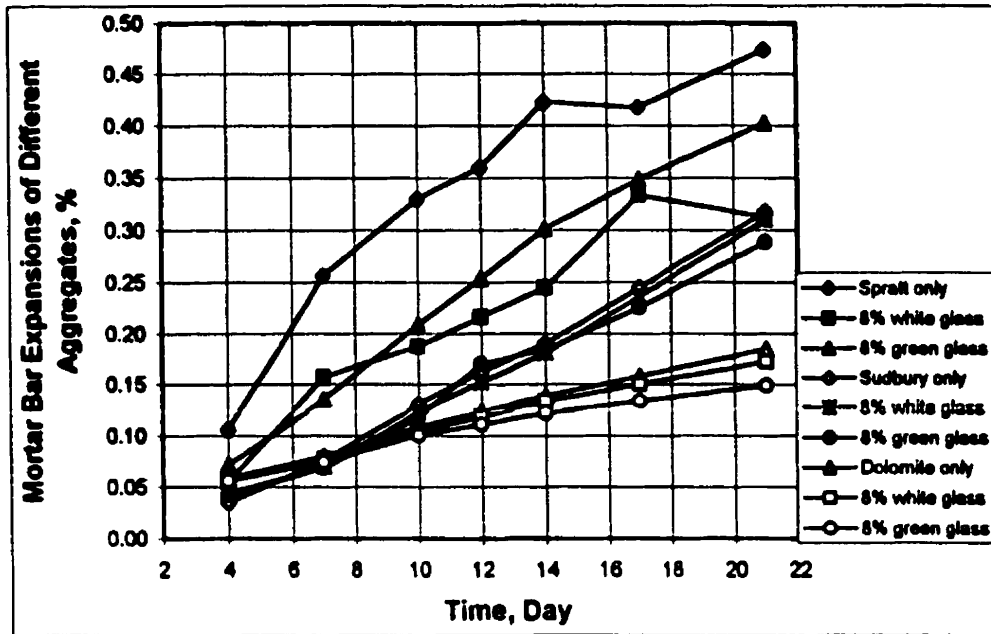


Fig. 41: Mortar bar expansions of different aggregates, %, vs. time, day; 8% replacements of #100 fraction of Spratt, Sudbury, and Dolomite aggregates by white and green glasses finer than #400.

### e) Effect of Glass on Mortar Strength

Fig. 42 shows that the mortar bar strength as a function of glass replacement and addition in the Phase 2 mixtures. Glass size rather than the glass amount appears to have a greater influence. Except of the #200 glass, where the results for addition and replacement are similar, addition of glass finer than #200 in all amounts increased the strength compared to equivalent replacement. This suggests that the glass acts as an added pozzolanic cement. Curiously, there was no increase in strength as the amount of glass in the mixture increased. Quite the opposite was observed for the #200 glass, which showed a steady decrease in strength with the increase of glass in the mixtures. This may be explained by the fact that fly ash and silica fume concretes develop their strength slower, with continued curing. These mortars were fast cured, which may not have given pozzolans a chance to fully react.

If the same strength data is plotted as function of total glass surface index (Fig. 43), a maximum strength is observed with glass size finer than #200, and an overall minimum at finer than #400 glass size for all mixes, whether added or replaced. This graph suggests that the optimum trade-off between maximum early strength and ASR reduction may be with the -#200 glass replacement.

Fig. 44 shows the relationship between the uniaxial strength and finer than #400 white glass replacement beyond the 8% shown in the previous figures. Here it is seen that the higher replacements, up to 32% of the #100 aggregate, do increase mortar strengths significantly.

Fig. 45 compares the effect of white and green glasses with that of silica fume replacements of the #100 Spratt aggregate. Increased amounts of silica fume results in uniaxial strength lowering, while no such effect is seen for glass. It should be noted that silica fume is a material much finer sized than even the finer than #400 glass, so the results may not be directly comparable, and may be explained by the slow rate of strength gain by the silica fume.

The last graph in this series, Fig. 46, shows the effect of white and green glass replacement on mortar mixtures with Spratt, Sudbury, and Manitoulin aggregate. It should be noted that the Manitoulin aggregate produces significantly stronger mortar, and that the addition of glass in low amounts tends to increase its strength, since the glass strictly as a pozzolan and is not used to control ASR. Green glass in all cases results in greater strength than white glass, although white glass is a better controller of ASR.

It should be noted that in all the strength comparisons presented above in Figs. 42 to 46, addition of glass or silica fume resulted, in general, in stronger mortars when compared to

the strength of normally cured, unreacted, no-glass mortars. Even the expanded and reacted mortars achieved greater overall strength. Glass addition then has an overall beneficial effect.

All these results exhibit that the relationship between mortar uni-axial strength and glass has a non-linear nature; Ranges of positive or negative effects by glass type, size, amount, and its addition or replacement should be considered to attain both most reduction in the ASR expansion and the uni-axial strength in the mortar bars.

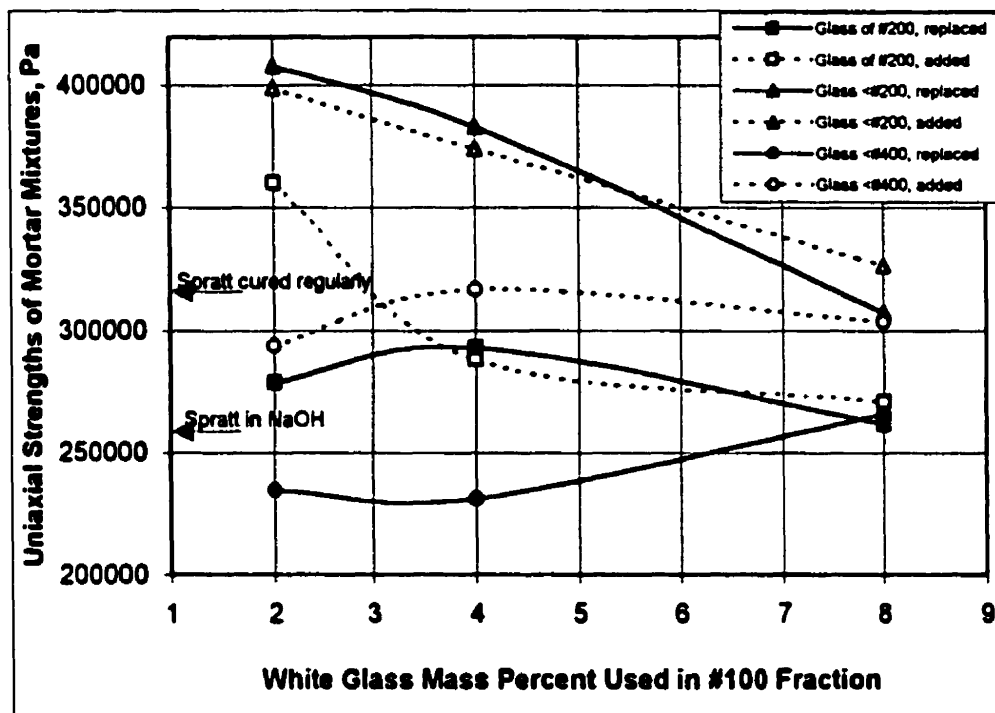


Fig. 42: Uni-axial strengths, Pa, of Phase 2 Spratt mortar mixtures vs. glass mass, %: Mass of white glass used in #100 fraction; both replacement and addition.

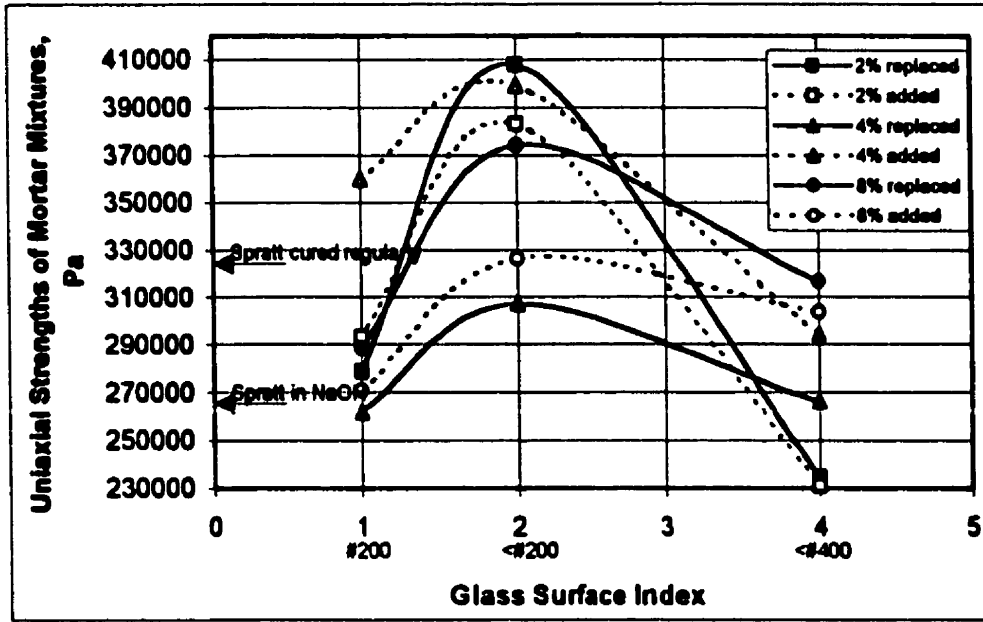


Fig. 43: Uni-axial strengths of the Phase 2 Spratt mortar bar mixtures, Pa, vs. surface index of white glass.

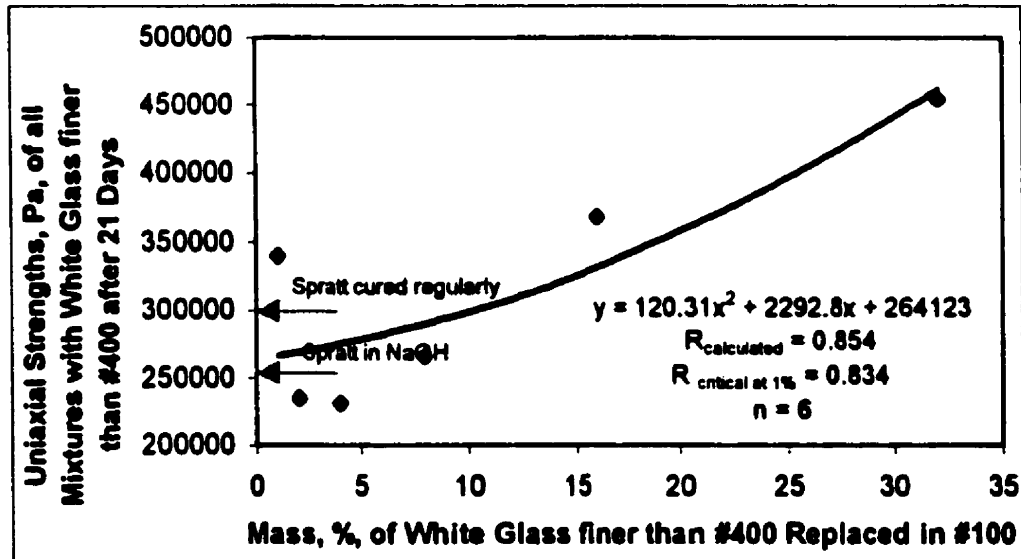


Fig. 44: Uni-axial strengths Of Spratt mortar prisms, Pa, vs. percentage of white glass finer than #400 replaced in #100 after 21 days immersion in 1 N NaOH Solution at 80°C.

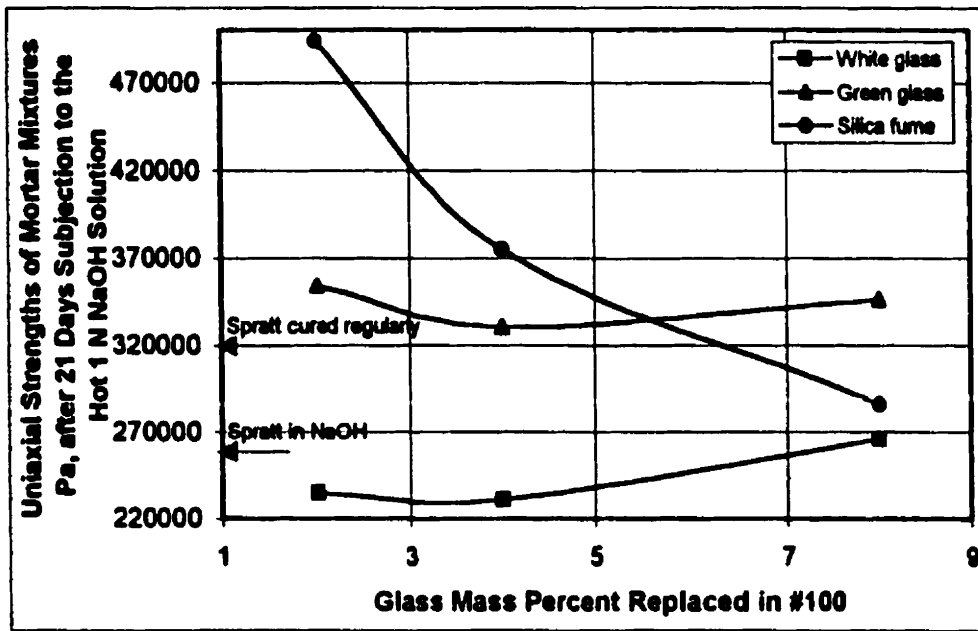


Fig. 45: Uni-axial strengths, Pa, of Spratt mortar mixtures vs. mass placement of #100 fraction by white and green glasses, finer than #400, and silica fume.

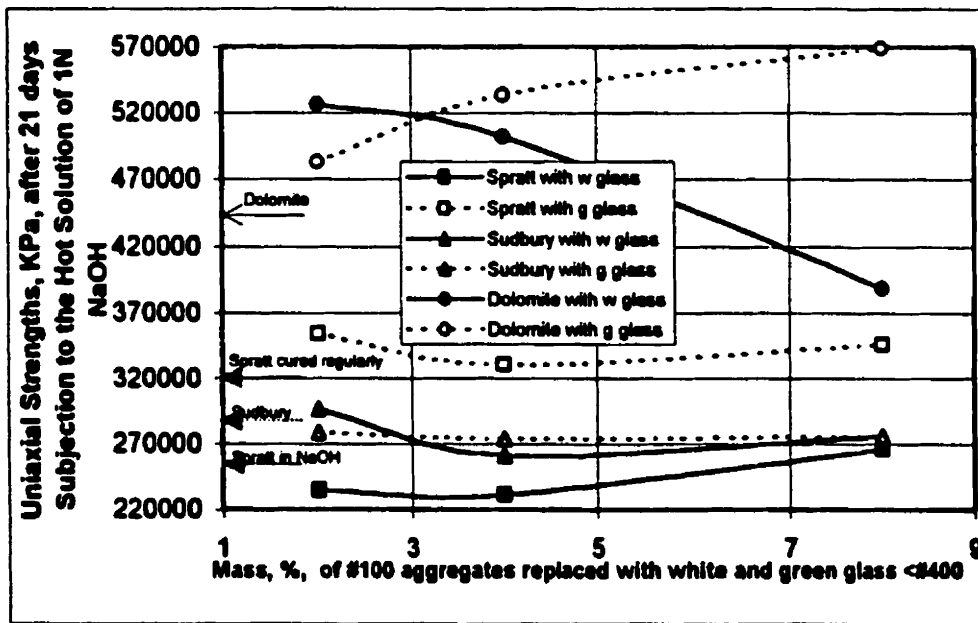


Fig. 46: Uni-axial strengths, Pa, of mortar mixtures made with different aggregates, Spratt, Sudbury, and Dolomite, vs. mass replacement of #100 fraction by white and green glasses finer than #400.

## **8. Statistics and Discussion**

### **8-1) Statistics Employed**

Statistical methods that were used to investigate and to compare the nature of relationships among the results included: Paired Student t-tests, canonical score plots, and TREE analyses.

#### **8-1-1) Significance of Glass Treatment: t-tests of Group Means**

Student's t-test is used to determine whether there exists a difference between two populations or groups, based on the differences of their means and their standard deviation.

##### **8-1-1-1) Effect of Spratt Aggregate alone and Spratt with Glass Addition / Replacement**

The mean comparison results for the Phase 2 mixtures are given in Table 10, which is arranged in order of paired 't' test significance. In paired t-tests degree of freedom (df) is calculated by  $n - 1$ , where 'n' is the number of pairs in each group. Therefore, 6 is df for the Phase 2 mixtures, whose n is the 7 measurements during the period of 21 days. Any 't' value  $\geq 2.447$  is significant for samples with  $df = 6$ . It can be seen that all mixtures except the bottom three sets show statistically lower expansion levels compared to untreated Spratt. Both additions and replacements of glass finer than #400 (35  $\mu\text{m}$ ) show significant difference at better than 0.1% level.

##### **8-1-1-2) Effect of Addition vs. Replacement and Glass Size on ASR**

Table 11 shows the significance of means between sample sets where the glass is added

compared to those where the glass replaces the #100 size Spratt aggregate, as well as the difference between glass sizes. The samples represent additions / replacements in the 1%-8% by weight range. Significant differences are observed between the ASR expansion of glass replaced vs. added.

Spratt Mixtures	Expansion Mean	T-test between Spratt and Samples	Significance
Spratt	0.34257	-	-
4%glass finer than #400R	0.19095	8.318	0.000
16%glass finer than #400R	0.12208	8.281	0.000
8%glass finer than #400R	0.21543	7.835	0.000
325glass finer than #400R	0.21543	7.835	0.000
1%glass finer than #400R	0.25218	7.597	0.000
8%glass finer than #400+	0.27185	6.617	0.001
2%glass finer than #400R	0.20968	6.393	0.001
4%glass finer than #400+	0.29125	5.831	0.001
1%glass finer than #400+	0.28736	5.818	0.001
4%glass finer than #200+	0.27298	5.775	0.001
8% glass sized of #200+	0.28981	5.170	0.002
8% glass sized of #200R	0.28393	5.033	0.002
2%glass finer than #200R	0.28448	4.987	0.002
4%glass sized of #200R	0.30652	4.804	0.003
1%glass finer than #200R	0.28259	4.714	0.003
2%glass finer than #400+	0.29986	4.582	0.004
8%glass finer than #200R	0.28639	4.237	0.005
1glass finer than #200+	0.2983	4.166	0.006
2%glass sized of #200R	0.31339	3.983	0.007
1%glass sized of #200+	0.30372	3.573	0.012
8%glass finer than #200+	0.30817	3.499	0.013
1%glass sized of #200R	0.30823	3.386	0.015
4%glass sized of #200+	0.31146	2.853	0.029
2%glass finer than #200+	0.33066	1.724	0.136
2%glass finer than #200+	0.33171	1.163	0.289
4%glass finer than #200R	0.33208	0.581	0.582

*Table 10: All the t-test numbers suggest that mixtures made with white glass finer than #400 had the maximum reduction in the ASR expansions.*

Replacement of Spratt aggregate significantly decreases the ASR expansion compared to the mortar mixtures in which glass is simply added. This may be explained by observations of other researchers, who concluded that the finer reactive aggregate is the more the ASR aggressive. Removal of the finer Spratt, and replacing it by the pozzolanic



glass results in the net reduction of ASR expansion of the mortar bars. A corollary conclusion is that simply replacement of the finer sizes of reactive aggregate with non-reactive material will improve the ASR behavior of the product. It can be also seen that there is no statistical difference between the >200 and >400 glass sizes, although the mean of the <400 glass is lower. The lack of statistical difference may be due to the large variety of mixtures being compared in each group.

ASR Expansion	Addition vs. Replacement		Glass Size			
	Added	Replaced	=200	<200	<200	<400
Mean	0.355	0.291	0.363	0.342	0.342	0.301
Variance	0.000	0.005	0.000	0.001	0.001	0.005
Observations	11	13	7	7	7	7
Pooled Variance	0.003		0.000		0.003	
df	22		12		12	
t Stat	2.953		1.957		1.507	
P(T<=t) one tail	0.004		0.037		0.079	
t Critical one tail	1.717		1.782		1.782	
P(T<=t) two-tail	0.007		0.074		0.158	
t Critical two-tail	2.074		2.179		2.179	

*Table 11: Expansion difference between glass addition and replacement by using Two-Sample t-Test.*

### 8-1-1-3) Effect of Addition vs. Replacement and Glass Size on Strength

Table 12 shows the statistical comparison of the same populations as above on the uni-axial compressive strength of the mortars. The results showed that there is no statistical difference between the strengths of mortars in which the glass has been added compared to those where it was replaced, although the latter do have a lower mean value. This is somewhat at odds with the ASR expansion results in Table 12, where the replacement by glass gave lower ASR, and should, theoretically, give higher strengths. There is a marginal statistical difference at the 5.6% level in the strength between the #200 (75  $\mu\text{m}$ ) and the #400 (35  $\mu\text{m}$ ) glass. However, there is a surprising and very significant

	Uni-axial Compressive Strength Addition vs. Replacement		Glass Size			
	Added	Replaced	=200	<200	<200	<400
Mean	3.32E+05	3.12E+05	3.18E+05	3.73E+05	3.73E+05	2.78E+05
Variance	2.31E+09	4.62E+09	5.63E+09	1.71E+09	1.71E+09	1.20E+09
Observations	11	11	7	7	7	7
Pooled Variance	3.47E+09		3.67E+09		1.45E+09	
df	20		12		12	
t Stat	0.805		-1.714		4.668	
P(T<=t) one tail	0.215		0.056		0.000	
t Critical one tail	1.725		1.782		1.782	
P(T<=t) two-tail	0.430		0.112		0.001	
t Critical two-tail	2.086		2.179		2.179	

*Table 12: Strength difference between glass addition and replacement by using Two-Sample t-Test.*

difference between the 35  $\mu\text{m}$  and finer than 35  $\mu\text{m}$  glass in their compressive strengths. The latter has a much lower strength. There is no real explanation for this anomaly, in view of the fact that silica fume, which is in the finer than 35  $\mu\text{m}$  size range, normally increases the mortar strength. It may be, as noted earlier, that pozzolans in concrete develop their full strength after more extensive curing than these samples were allowed.

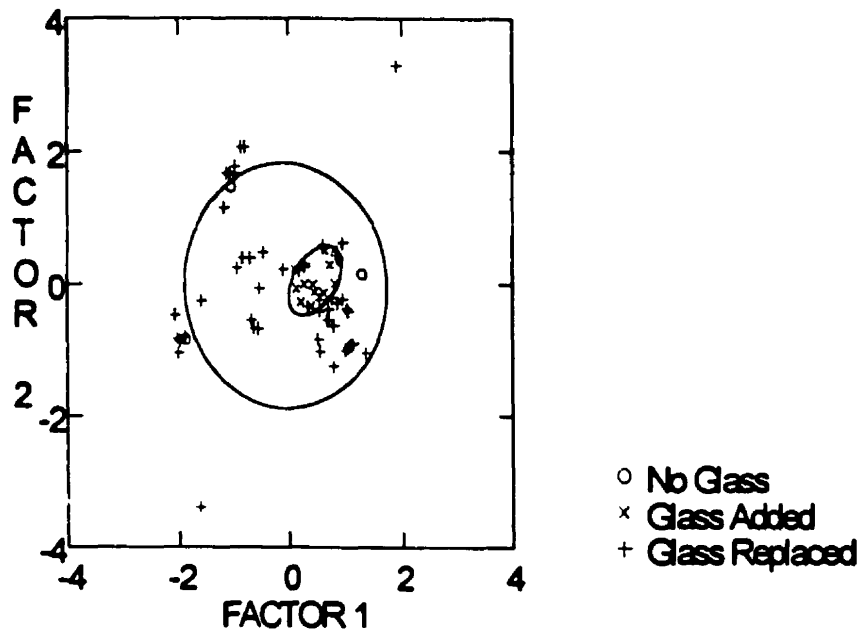
### 8-1-2) Discriminant Analysis and Canonical Scores Plots

Discriminant analysis separates the cases (mortar treatments) into two or more groups, depending on their common properties and is related to both multivariate analysis of variance and multiple regression. The analysis can be used to determine which variables are most useful for discriminating among groups, and which groups are most alike or most different.

#### a) Glass Addition/Replacement Effect on ASR Expansion

Fig. 47 shows that the results for the 14 and 21 day expansion of mortars where the glass was added are more closely clustered than those where the glass replaced the Spratt aggregate. This suggests that the behavior of the two groups is distinctly different – the

## Canonical Scores Plot

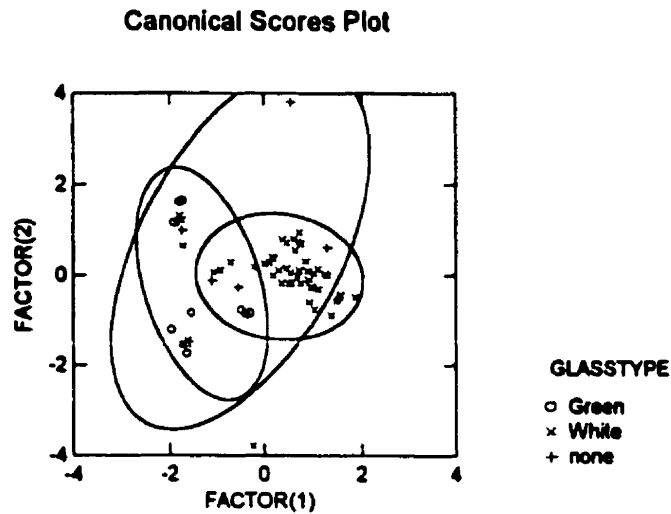


*Fig. 47 shows the differences between glass addition and replacement.*

glass-added group has a more predictable effect on ASR than the glass replacement group. An alternate explanation is that the glass replacement group is somewhat larger, and therefore a larger diversity of response may be expected. The factor difference is  $\pm 2$  suggests that the differences are not large, as is shown by the actual ASR expansions.

### **b) Effect of Glass type (colored vs. clear) on ASR Expansion**

Figure 48 corroborates that the green and white glasses behave differently in ASR expansion tests, although there is some overlap. Some of the white glass falls within the green glass envelope and vice versa. This suggests that if waste glass is to be used to reduce the ASR expansion, each type of glass must be tested in pilot tests such as this accelerated method to determine their similarities or differences. As above,  $\pm 2$  difference in their factor suggests that the difference between them is not very large.

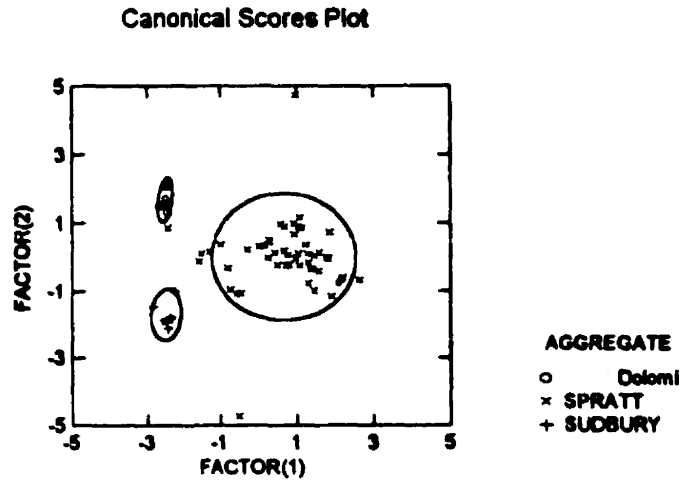


*Fig. 48 Clear and colored glass types had different effects on the mortar bars.*

### c) Aggregate Type and ASR Expansion

Figure 49 shows the canonical scores plot for the three different aggregates used in the study based on their ASR expansion at 14 and 21 days. As expected, the three aggregate types behave quite differently, both in non-treated expansion, and when glass is used as replacement of #100 size. The figure also shows that the aggregate behavior is less affected by glass replacement than by their inherent response in the ASR environment. All three aggregates occupy distinct, non-interfering clusters with large difference in their canonical factors.

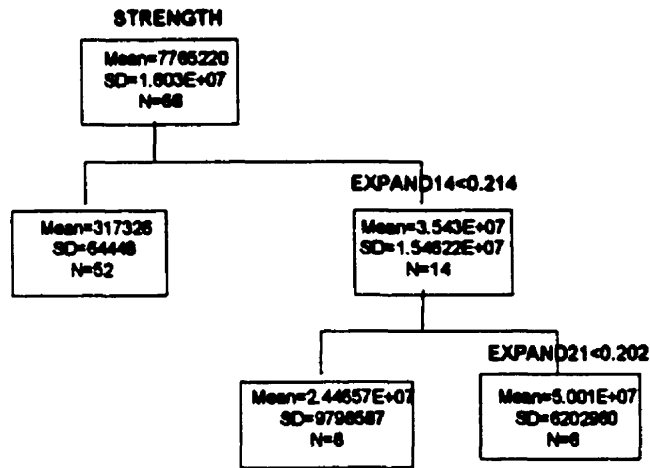
Aggregate mineralogy and chemical composition may be responsible for this distinct behavior of glass in the mortars. More investigation is required to show the presence of such an effect.



*Fig. 49 Aggregate type influences the ASR expansion behavior.*

### 8-1-3) TREES Analysis

The TREES analysis computes classification and regression trees. Classification trees can include those models in which the dependent variable (the predicted variable) is categorical. TREES produces graphical trees called mobiles. For this analysis, continuous variable of compressive strength was used. At the end of each branch is a density display showing the distribution of observations at balance at each node so that the branch is level, given the number of observations at each end. Figure 50 shows the analysis, all variables of glass type, size, percent, etc. were considered. The analysis chose the variables. At the first branch of the tree, the analysis shows that the compressive strength is related to the degree of the ASR expansion experienced at 14 days. If the expansion is greater than 0.214%, the mean strength of the samples is 3.17 E+7 Pa. For expansion less than 0.214%, the mean strength is 3.54 E+7 P. Expansion at



*Fig. 50 mortars grouped by TREE analysis, with respect to their expansions and uni-axial compressive strengths.*

21 days further subdivides this sample group so that expansions of less than 0.202% produce means compressive strength of 5.00 E+7, whereas those between 0.214 and 0.202 percent have a significantly reduced strength of 2.44 E+7 Pa. The statistics shows that although compressive strength data are rather scattered, there is a relationship between the ASR expansion and the strength reduction.

## 8-2) Mass-Surface Factor

The Mass-Surface Factor (MS) was defined as:

$(\text{Glass, \% of mixture}) / (\text{Total silica, \% in Spratt}) \times (\text{Glass Surface Index, given by its sieve size}).$

By using this formula, MS factors were calculated for all the mixtures of all the phases.

Spratt ASR expansions after 14 days were plotted vs. the calculated MS for all the mixtures with replaced glass only. Fig.51 shows the correlation between MS and the expansion with a correlation coefficient of  $R = 0.802$ , which is significant at 1%. Fig.52 exhibits the same relationship for all mixtures, including both glass addition and

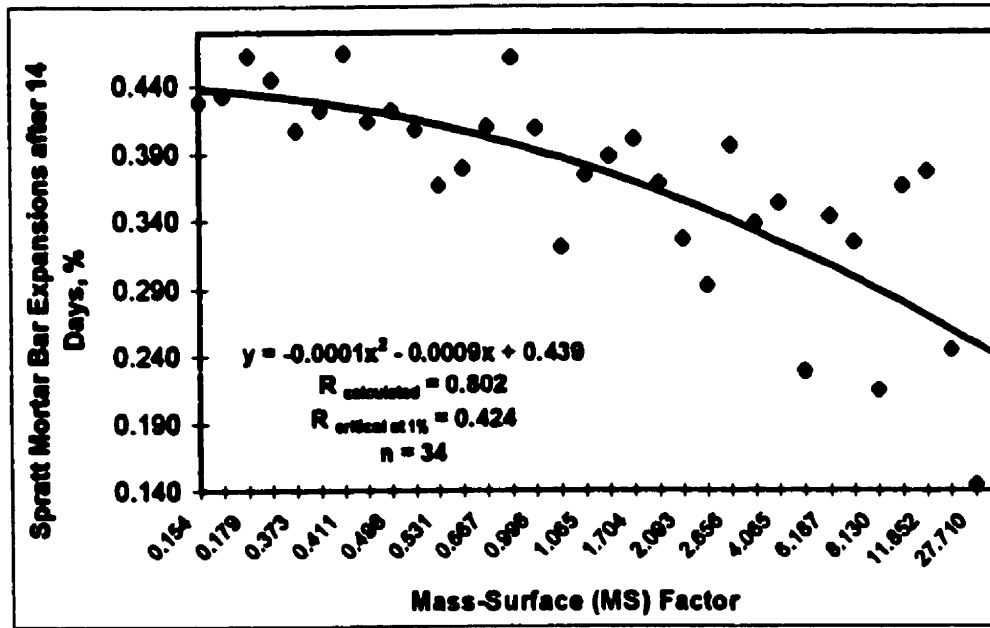


Fig. 51: Spratt mortar bar expansions after 14 Days, %, vs. Mass-Surface factors of all Mortar Mixtures; all white glass replacements of Phases 1 and 2.

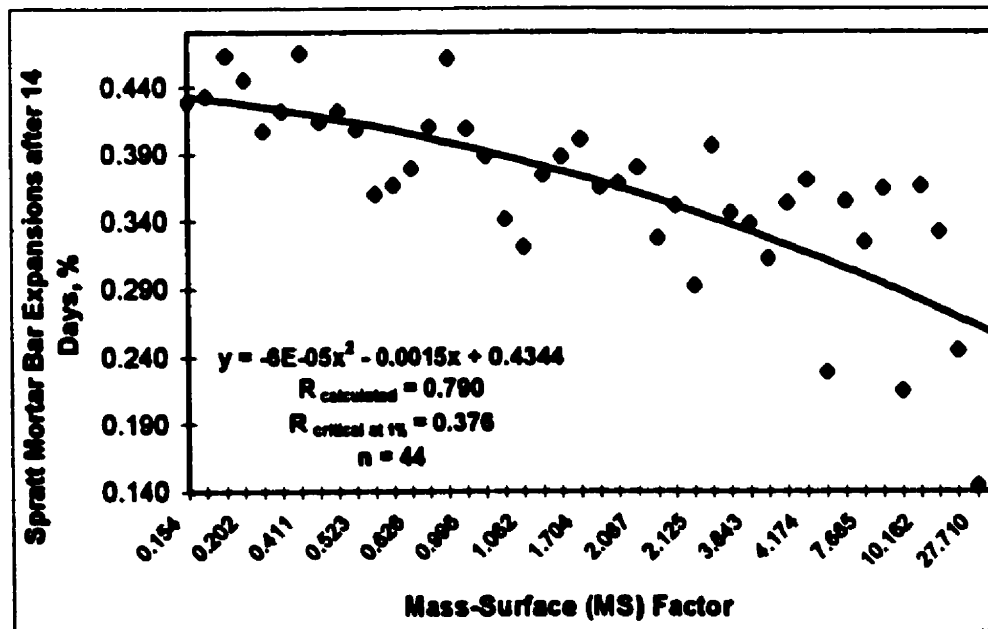


Fig. 52: Spratt mortar bar expansions after 14 days, %, vs. Mass-Surface factors of all mortar mixtures; white glass replacements and additions of Phases 1 and 2.

replacement. The correlation coefficient is slightly lower at  $R = 0.79$ , and is also at 1% significance level. The negative slopes indicate the inverse nature of MS relationship with the ASR expansion. The equations can be used to calculate the probably reduction in the ASR as a function of the mass surface factor.



## **9. Conclusion**

In this research using finely ground glass in mortar mixtures reduced the ASR expansion. Glass, as the treating agent, affected the ASR expansions as summarized below:

**1. Glass size** had two opposite effects on the ASR expansion which are directly related to its size or surface area; Glass with the sieve sizes ranging between #8 to #30 increased the expansion (Phase 1). In the coarser sizes, glass acts as a reactive aggregate. Small reduction in the ASR expansion was observed by using glass sized between sieves #30 to #100. Reducing glass size to finer than sieve #200 resulted in a significant reduction of the expansion. A reduction of over 50% was obtained by replacing 16% of the aggregate in #100 fraction with white glass finer than #400; the reduction in the ASR expansion was roughly equivalent to that of using the same amount of silica fume. The best glass size for reducing the ASR expansion is finer than sieve #400, which is close to the silica fume size. Finely ground glass acts as a pozzolan, similar to silica fume, in reducing ASR.

Fine glass replacement of the aggregate part of the mortar reduced the expansion more than its addition. This is because the sieve #100 fraction of Spratt is responsible for a significant part of its ASR expansion and its removal and replacement with the glass reduces the expansion.

**2. Glass mass** proportion governed the reduction of the ASR expansion. Replacing 4% - 16% by mass of #100 fraction of glass finer than #400 produced the maximum expansion reduction while 32% of the same glass size increased the expansion. When the mortar mixture is entirely made with glass as the aggregate, it significantly increases the ASR.

The experiment revealed that both the mass proportion of amorphous silica (glass) and its size must be considered together. According to the polynomial relationship between the mass of glass finer than #400 and the observed expansion reduction, glass replacement up to 25% of #100 may be most effective in reducing ASR.

**3. Mass-Surface Factor**, as a compound factor, showed a significant inverse relationship with the ASR expansion (strain): The larger the glass Mass-Surface Factor, the less expansion in the mortar bar. This indicated that the effectiveness of using glass in mortar mixtures is related to both its grain size and amount.

**4. Glass Types** produced different ASR expansion: Green glass was not as effective as white glass in reducing the expansion in the Spratt mortar mixtures. The effect of glass type in mortar is also related to the aggregate type; white glass reduced the expansion in the Spratt mortar bars more than green glass did while the green glass was more effective in the Sudbury mixtures. This suggests that different glass types should be tested with different expansive aggregates to obtain optimum combinations. Glass composition and aggregate mineralogy are considered responsible for such a different behavior.

**5. Mortar Bar Strength** is generally decreased by the ASR expansion. Mortar strength slightly decreased by replacement of between 1%-4% of white glass finer than #400 in sieve size #100 but replacements of 4%-32% of the same glass and size enhanced the strength. Glass mass percent between 16% - 32% caused more the ASR expansion. This might be explained by the glass' pozzolanic characteristic.

The mortar bar uniaxial strength and the ASR expansion showed a polynomial relationship, which suggested that best strengths may be achieved by 16%-25%

replacement of the #100 aggregate fraction. The strengths of Spratt mixtures with green glass were higher than mixtures with white glass.

Replacement by 2% - 4% of silica fume of the #100 Spratt fraction increased the mortar bar strength more than the glass did, but the strength decreased by a higher amount of silica fume replacement. Therefore, glass type, mass, and size control the mortar bar strength.

Glass type also influenced the mortar strength; For 2% and 4% addition, the highest, medium, and lowest strengths belonged to those mixtures with silica fume, green glass, and white glass, respectively. Therefore, glass types affect differently both mortar bar expansion and strength development.

**6. Aggregate Type** influences reactions between the aggregate and cementing component. Different aggregate materials, such as amorphous silica, and reactive silicate cause different types and rates of reactions. The Spratt mixtures with the appropriate sizes of white glass experienced maximum ASR reduction, while the same mixture designs with white glass and the Sudbury aggregate showed only minor changes in their ASR. Glass with different aggregates has different influences on the mortar bar strength. The inert and strongest Manitoulin dolomite experienced largest gains in strength with glass admixtures, confirming the pozzolanic effect of glass.

## References

- ASTM, 1994-96, "Concrete and Mineral Aggregates, Eston, USA.
- Atkinson, Barry K., 1987, "Fracture Mechanics of Rocks", Academic Press, Orlando, Florida, USA, pp. 71-211, 429-468.
- Berra, M., Maggio, R. Di, Mangialardi, T., and Paolini, A.E., 1995. "Fused quartz as a reference aggregate for alkali-silica reaction studies", *Advances in Cement Research*, 7. No. 25, pp. 21-32.
- Blanks, Robert, and F. Kennedy L., Henry, 1955, "The Technology of Cement and Concrete", John Wiley & Sons Publication, USA, pp. 299-342.
- Bogue, R.H., 1955, "Chemistry of Portland Cement" Reinhold Publishing Corporation, USA, 2<sup>nd</sup> Edition, pp. 3-70, 203-220, 691-715.
- Brandt, A.M., 1995, "Cement-Based Composites", E&FN SPON, Imprint of Chapman & Hall, London, United Kingdom, pp. 5-77, 197-217.
- Chunxian, Qian, Hangdin, Guo, and Mingshu, Tang, 1994, "Mechanism of Mineral Admixture suppressing Alkali-Silica Reaction" *Cement and Concrete Research*, Vol. 24, No. 6, pp. 1111-1120.
- Hobbs, W.D., 1988, "Alkali-Silica Reaction in Concrete", Thomas Telford, Ltd., London, Great Britain, pp. 1-155.
- Hudec, P. Peter, and Banahene, N. K, 1993 "Chemical treatments and additives for controlling alkali reactivity", *Cement and Concrete Composites*, 15, pp. 21-26.
- Lea, F.M., 1970 "Chemistry of Cement and Concrete", Edward Arnold Publishers Ltd. Glasgow, Great Britain, pp. 414-490, 557-590.
- Li, Z., mu, B., and Peng, J., 1999, "The combined influence of chemical and mineral admixtures on the alkali-silica reaction", *Magazine of Concrete Research*, 51, No. 3, pp. 163-169.
- MTO, (Ministry of Transportation, Ontario), 1990, "Report EM-92: Canadian Developments in Testing Concrete Aggregates for Alkali-Aggregate Reactivity", Engineering Materials Office, Ministry of Transportation, Ontario, pp. 1-225.
- Polley, C., Cramer, S.M., and Cruz, R. V., 1998, "Potential for using glass in Portland Cement", *Journal of materials for Civil Engineering*, Vol. 10, No. 4, pp. 210-219.
- Popovics, S., 1992, "Properties, Specifications, and Testing of Concrete Materials", Noyes Publications, Park Ridge, N.J., USA, pp. 5-340, 380- 492, 500-620

**Wilson, M., Cabrera, J.G., and Zou, Y., 1994, "The process and mechanism of alkali-silica reaction using fused silica as the reactive aggregate", *Advances in Cement Research*, 6, No. 23, pp. 117-125.**

**Yixin, Shao, Lefort, T., Moras, S., and Rodriguez, D., 1998, "Waste Glass: a possible pozzolanic material for concrete", *CANMET/ACI International Symposium on sustainable development of the cement and concrete industry*, Ottawa, Canada**

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