THE EFFECT OF PRODUCT FORM AND SILICA CONTENT OF SILICA FUME ON ITS ABILITY TO CONTROL ALKALI-SILICA REACTION

by

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ABSTRACT

The effects that the form and silica content of silica fume (SF) have on resistance to alkali-silica reaction (ASR) expansion were investigated using: 1) concrete prism expansion, 2) accelerated mortar bar expansion, and 3) paste pore solution analysis. The mixtures tested included 0%, 4%, 8%, and 12% silica fume replacement by mass of cement.

At 4% SF replacement, performance did vary for different product forms. At higher levels of replacement (i.e. 8% and 12%), there were no differences in the results from the concrete prism expansion or paste pore solution analysis for the various silica fume forms tested. The accelerated mortar bar test results at all levels of replacement indicated that undensified and slurried SFs are significantly better at controlling ASR expansion than are densified or pelletized SFs. Preliminary results show that silica fumes with lower than standard amorphous silica contents cannot control ASR at the levels of replacement tested in this program.

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The following abbreviations are used in this thesis:

ACI	AMERICAN CONCRETE INSTITUE
ASR	ALKALI-SILICA REACTION
ASTM	AMERICAN STANDARDS FOR TESTING MATERIALS
CSA	CANADIAN STANDARDS ASSOCIATION
C-S-H	CALCIUM-SILICA HYDRATES
HRWRA	HIGH-RANGE-WATER-REDUCING ADMIXTURE
NaOH	SODIUM HYDROXIDE
Na_2O_e	EQUIVALENT ALKALI CONTENT ($=Na_2O + 0.658\ K_2O$)
OPC	ORDINARY PORTLAND CEMENT
SCM	SUPPLEMENTARY CEMENTING MATERIAL
SF	SILICA FUME
SiO_2	SILICA
w/cm	WATER TO CEMENTITIOUS MATERIAL RATIO

1 INTRODUCTION

In the past decade, major advancements have been made in producing both high-strength and high-performance concrete. Much of this progress can be attributed to the use of silica fume (SF) as a supplementary cementing material (SCM), as well as high-range water-reducing admixtures. As research has continued to prove that silica fume concrete can be stronger and more durable than concrete made solely with ordinary Portland cement, the market for silica fume in concrete applications has increased greatly. In fact, the ability of silica fume to increase both strength and durability properties of concrete has resulted in silica fume being the most touted concrete admixture of the past decade (Marsh, 1994).

Condensed silica fume is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the manufacture of ferro-silicon alloys and silicon metal (Malhotra, 1993). It is a highly-reactive pozzolan due to three of its most notable characteristics, namely (ACI, 1994):

- an average particle diameter of 0.1μm (approximately 100 times smaller than average Portland cement particles),
- a high amorphous silica composition (typically > 90% SiO_2), and
- a very high surface area of 20,000 m^2/kg (as compared to Portland cement values of 300-500 m^2/kg).

As-produced silica fume also has a very low bulk density, typically ranging from 130-430 kg/m^3 (Hooton et al., 1998). This fact creates economic difficulties in the transport of SF from silicon alloy furnace sites to cement or concrete plants, and also makes it hard to handle. Commercial suppliers have responded by processing silica fume using different methods of densification, compaction, or slurrying in order to improve the handling and transport properties of the material. Final bulk densities have been reported to be as high as 600 to 700 kg/m^3 for some densified products with agglomerations found up to 1mm in diameter (Hooton et al., 1998). This fact would not be a problem as long as the silica fume can be redispersed during concrete mixing or when interground to form blended cement. However, if this is not the case, two characteristics (small particle size and high surface area) which make the silica fume such a good pozzolan will be greatly reduced. It is possible that the full potential performance of the silica fume concrete will not be achieved. Performance of the resulting mixtures may also be variable. There also exists the possibility that the presence of undispersed agglomerates could cause additional problems. Not much is known about the possible deleterious effects as published data relating delivery form of silica fume to performance in concrete are lacking (ACI, 1994).

Investigation of the performance of silica fumes with varying SiO_2 contents is also of interest both in terms of economics and efficiency. Currently, both CSA A23.5 (CSA, 1998) and ASTM C1240 require a minimum silica content of 85%. In addition, the CSA

A23.5 limits the use of silica fume in Canada to materials recovered from the production of silicon or ferrosilicon alloys containing at least 75 percent silicon. The Guide for the Use of Silica Fume in Concrete: Section 2.8 (ACI 234R-96) further states the following regarding amorphous silica content of silica fume:

> It is sometimes assumed that the higher the SiO_2 content of a silica fume, the more reactive the silica fume will be in concrete. However, the committee does not have data to relate performance directly to SiO_2 content. Higher SiO_2 content implies that there are fewer of the non-SiO_2 components. ... Silicon and ferrosilicon (75%) silica fumes contain higher amorphous SiO_2 contents than the other silica fumes.

Published research findings indicate that only limited information is available relating the durability of silica fume concrete mixtures to the product form and amorphous silica content of the silica fume used. The term durability refers to a concrete's ability "to withstand the processes of deterioration to which it can be expected to be exposed", (Neville 1996). One such deterioration mechanism is alkali-silica reaction (ASR), a reaction between the thermodynamically unstable silica in some aggregates and the hydroxyl ions in the pore solution.

This report will first discuss the literature relevant to these issues. It will secondly present the method, results, and analysis of a research program carried out to investigate the effects of amorphous silica content and product form on silica fume's ability to control alkali-silica reaction.

2 LITERATURE REVIEW

2.1 ALKALI-SILICA REACTION

Alkali-silica reaction is one form of alkali-aggregate reaction. Alkali-silica reaction is in fact a reaction between the hydroxyl ions in the pore solution and thermodynamically unstable silica in the aggregate. Sodium and potassium alkalis are involved in this deleterious process in 2 ways. Firstly, they add to the high concentrations of hydroxyl ions required to:

(1) start an acid-base reaction with the acidic silanol (Si-OH) found in poorly-crystalline hydrous silica in the aggregate, as follows:

$$\equiv Si - OH + OH^- \rightarrow \equiv Si - O^- + H_2O$$

(2) further break up the silica to form a concentrated solution of silicate ions (SiO^{4+}) as aqueous H_2SiO_4 (Dent Glasser and Kataoka, 1981) as follows:

$$\equiv Si - O - Si \equiv + 2OH^- \rightarrow 2 \equiv Si - O^- + H_2O \rightarrow H_2SiO_{4(aq)}$$

Secondly, the alkalis will react with the Si-O$^-$ to form an alkali-silica gel, which will imbibe water and swell:

$$\equiv Si - O^- + Na^+ \rightarrow Si - O - Na$$
$$\equiv Si - O^- + K^+ \rightarrow Si - O - K$$

"The reaction may lead to local volume expansion, cracking, loss of strength, and in extreme cases, to the complete destruction of the concrete", (Diamond, 1975). Differing hypotheses on how this expansion occurs have been proposed by Hansen (1944) with the osmotic pressure theory and by McGowan and Vivian (1952) with the mechanical pressure theory. The former suggests that a semi-permeable membrane is formed by the cement paste surrounding reactive silica grains. This membrane would allow water molecules to flow through it, but not the larger alkali-silicate complex, thus forming an osmotic pressure cell that exerts hydrostatic pressure on the surrounding cement paste, resulting in cracking. The latter authors propose that the aggregate is surrounded by a solid alkali-silicate layer that physically absorbs water to form a swelling gel which causes internal stresses to form with subsequent expansion and cracking. The possibility that both osmotic and mechanical pressures could be generated from the gel imbibing water, depending on whether the alkali-silicate complex is fluid or solid, was introduced by Powers and Steinour (1955) and supported by Diamond (1989). Dent Glasser (1979) has also suggested that the insolubility of the gel may in fact cause it to behave like a semi-permeable membrane. It should be mentioned that the presence of calcium also been found to play an important role in alkali-silica reaction (Thomas and Bleszynski, 2000), but an in-depth discussion of this topic is beyond the scope of this report. It has been noted by Hornain (1996), that apart from ambient conditions such as relative humidity and temperature, the occurrence of ASR primarily depends on the ratio between the reactive silica and equivalent alkali content of the surrounding solution. In fact, there is a pessimum ratio around 4.5 at which the observed expansion is maximum (Dent Glasser & Kataoka, 1981).

Degradation of concrete by ASR can be visually identified by map cracking, surface discolouration, expansion causing deformations, relative movements and displacements, gel exudations, and even spalling, delaminations, popouts, and misalignment of components. Verification of ASR as the process responsible for damage can be accomplished by inspection of samples petrographically using optical or scanning electron microscopy.

Several options are available to prevent damage due to ASR from occuring in new concrete construction. Avoiding the use of deleteriously reactive aggregates, through the use of petrographic analysis, physical testing, and evaluation of prior field performance is one solution (Hooton, 1995). Caution must be used, though, since damage attributed to alkali-aggregate reaction has developed in several instances where an aggregate had been previously identified as inert (Thomas, 1996). A reduction of the alkali loading on the concrete can also be achieved through the use of low alkali cement and limited cement content. Both field and laboratory concretes have indicated that using low-alkali cement is often not enough to avoid the occurrence of ASR (Stark, 1980; Lane, 1987), especially when the concrete alkali content can potentially increase from certain exposure conditions such as drying or temperature gradients, alkali release from aggregates, or alkali ingress from external sources (Van Aardt and Visser, 1977; Stark, 1978; 1980; Stark and Bhatty, 1986; Way and Cole, 1982; Oberholster, 1992; Thomas et al., 1992; Zhongi and Hooton, 1993). SCMs can also help improve the ASR resistance of concrete through the production of a dense and impermeable matrix which will inhibit the movement of water and alkalis, and by combining free alkalis in chemical reactions (Kropp, 1995).

2.2 SILICA FUME

2.2.1 Nature of Silica Fume

Silica fume is a by-product of the silicon and ferrosilicon alloy production industry. The chemical composition of silica fume is greatly influenced by the type of alloy produced and the composition of the quartz and coal, the two major components of burden of the submerged electric arc furnace (Malhotra, 1987). Silica fume is made of extremely fine spherical particles with an average diameter of 0.1 μm (i.e. approximately 100 times smaller than average Portland cement particles). It is composed of amorphous silica (typically > 90% SiO_2) with a very high surface area approaching 20,000 m^2/kg as compared with typical values in the range of 300-500 m^2/kg for Portland cement (ACI, 1994).

The various ways in which silica fume works to improve the properties of concrete are generally well understood. It achieves this both through chemical and physical means. As mentioned previously, silica fume is a very efficient pozzolanic material. "The chemical effect is the pozzolanic reaction that is a result of the high surface area of the silica fume coupled with its main component, amorphous silica (SiO_2)", (Li, 1996). In fact, the extremely small particle size means that an average dosage of about 40kg/m^3 will have around one square kilometre of surface area capable of reacting with the calcium hydroxide released as the cement hydrates (Lewis, 1996). Silica fume reacts with the calcium hydroxide released by the hydrating cement to increase the quantity of calcium silicate hydrates (C-S-H) in the hardening concrete. The C-S-H formed by the reaction is both more dense and stronger than that formed during the hydration of cement (Young, 1992). This can be partially explained by the fact that the C-S-H product formed contains less non-evaporable water than that formed during normal hydration of cement (Cheng-Yi and Feldman, 1985).

Physically, immediately upon mixing, silica fume acts as a filler between the cement particles as long as there is a sufficient amount of superplasticizer in the mix to overcome the surface force effects (Detwiler and Mehta, 1989). Furthermore, silica fume particles act as nucleation sites for hydration, pozzolanically improve the interfacial transition zone around aggregates, and pozzolanically react to infill and subdivide original pore space, giving fewer capillary pores and more of the finer gel pores (Hooton et al., 1998). Silica fume essentially permits the development of a much stronger, less porous, and more durable concrete.

2.2.2 The Effect of Silica Fume on Expansion due to ASR

Several specifications and guidelines allow for the use of SCMs in concrete with potentially reactive aggregate to control ASR. However, the recommendations on the use of these materials for this purpose vary tremendously. This lack of consensus is a direct result of the conflicting results reported on this matter. "Much of the controversy is centered around the alkalis in the SCMs and whether they are potentially available for reaction", (Thomas and Bleszynski, 2000). Thus, there is already controversy surrounding silica fume's ability to control expansion due to ASR, even before the issues of product form and SiO_2 content are considered. A brief summary of the broader issue of the effect of silica fume on expansion due to ASR will be provided in this section. For a more extensive information, the reader is referred to other reviews which are being published. (Thomas and Bleszynski, 2000).

Silica fume causes certain physical and chemical changes to fresh and hardened concrete properties that will have a direct effect on concrete's susceptibility to ASR. The first is related to the reduction in permeability. This implies a reduction of mobility of the ions present in the pore solution, as well as the mobility of the pore solution itself. A decrease in ionic diffusion and water permeability can slow the rate of reaction and also retard the rate at which any reaction product can imbibe water and thus expand.

The second involves reduced pore solution alkalinity. This is primarily the result of the incorporation of alkalis into the pozzolanic reaction products. As described in a previous section, SF will react with the calcium hydroxide produced during cement hydration to form supplementary C-S-H. This is beneficial since C-S-H entraps alkalis, thus the more C-S-H present, the lower the amount of free alkalis available for alkali silica reaction to occur. The alkali hydroxides are essentially removed from the pore solution before they have a chance to react with any susceptible aggregates present (Diamond, 1983; Page and Vennesland, 1983). Furthermore, a silica fume paste has a lower global Ca:Si ratio than an identical paste which does not contain silica fume. As the Ca:Si ratio of C-S-H decreases, its capacity to entrap alkalis increases; therefore, a paste containing SF would have more alkalis entrapped in the C-S-H and less alkalis left in the pore solution (Durand et al., 1990).

Other mechanisms which have been proposed as to why silica fume increases a concrete's ability to resist ASR expansion include the consumption of $Ca(OH)_2$, improved $Ca(OH)_2$ distribution at the aggregate/cement interface, and self-desiccation. The roles that these changes play are beyond the scope of this report, and as such will not be discussed in depth.

2.2.3 Silica Content of Silica Fume

As mentioned previously, silica fume is a by-product of ferrosilicon and silicon alloy manufacturing from coal and high-purity quartz in a submerged-arc electric furnace. The product is referred to as silica fume because of how it is formed; during the process, SiO gas oxidizes and condenses to form extremely fine spherical particles of SiO_2 (amorphous or glassy silica) which are highly reactive. Table 2.2.1 summarizes data from Neville (1996) and explains the relationship between the alloy being produced and the silica content of the resulting silica fume.

Table 2.2.1 - Typical Silica Content for Various Alloys

Nominal Silicon Content of Alloy	Typical Silica Content of Resulting SF
> 98%	94-98%
90%	90-96%
75%	86-90%
50%	≈ 80%

It is evident that the higher the silicon content in the alloy, the higher the silica content in the resulting silica fume. Neville (1996) also mentions that it is important to know the provenance of any silica fume to be used in concrete since the same furnace can produce different alloys. However, steady production of a given alloy will result in a silica fume with consistent properties.

Three chemical requirements of silica fume are specified by the CSA A23.5 standard, namely 1) SiO_2 content, 2) SO_3 content, and 3) loss of ignition. Isabelle (1986) noted that the most important of these requirements is the minimum SiO_2 content, which has been placed at 85%. It has been found that silica fume having at least 85% SiO_2 generally performs well whereas those having a lesser amount do not give satisfactory results (Isabelle, 1986). It is also of interest to note that silica fumes from current Canadian sources have SiO_2 contents well in excess of the specified 85% minimum (Isabelle, 1986).

The published data relating silica fume concrete performance to silica content are extremely limited. The majority of the related information found involved work performed by Duchesne and Berube (1994b). Included in the SCMs examined in the study were a high-silica, low-alkali silica fume and a low-silica,high-alkali silica fume. They found that 10% of the low-silica, high-alkali silica fume was not sufficient to control ASR expansion of Spratt aggregate (siliceous limestone) when tested by the CSA-A23.2-14A Concrete Prism Method. In the paste pore solution analysis work performed by the same authors, it was found that a 5% low-silica, high-alkali silica fume paste did not show any reduction in alkali concentration with respect to the control specimens, even at 545 days of age. Reductions were observed for the 10% low-silica, high-alkali mixture when compared to the neat cement paste, but these reductions were very similar to those experienced with the 5% high-silica,low-alkali mixture. It is important to note the silica fume with low silica content also had a very high alkali content, and as such, it is not possible to ascribe its poor performance solely to the low silica content.

Findings are also reported by Wolsiefer et al. (1995) on a study involving silica fumes with SiO_2 contents ranging from 79 to 95%. Mixtures were made at w/cm of 0.40, 0.35, 0.30, and 0.22 and were tested for compressive and flexural strengths, drying shrinkage, and rapid chloride permeability. There was no significance difference in performance and lower SiO_2 levels did not require higher silica fume dosages for comparable performance. As this literature survey indicated that only limited information was available on this topic, it is recognized that further work in this area is indeed warranted. It is hoped that the parts of this study which investigate specifically the effectiveness of low-silica silica fumes will provide more insight on this matter.

2.2.4 Forms of Silica Fume

As introduced previously, silica fume is available commercially in various product forms. The ACI has recognized the existence of four different forms, namely:

- As-produced silica fume,
- Slurried silica fume,
- Densified silica fume, and
- Pelletized silica fume.

As-produced silica fume is also commonly referred to as undensified silica fume. This is the form in which the fume is collected in deducting systems as a direct by-product of silicon metal and ferro-silicon alloy production. The bulk density of this form of fume can range from 130-430 kg/m^3 but it is more common to experience values in the middle of this range. Because of its extreme fineness, handling and transporting undensified silica fume can present problems. When employed as a very fine powder, it is most often used for pre-bagged materials, as well as for mortars and grouts (Lewis, 1996). This raw silica fume can be processed in various ways to create product forms which facilitate handling, transportation, and use.

Slurried silica fume is formed of an aqueous suspension of undensified silica fume in water, generally at a 50:50 ratio by mass. Typical densities range from 1300 to 1400kg/m^3 (Neville, 1996). Its liquid nature is intended to make it easier to handle than in powder form. Unfortunately, the slurry form also makes transportation uneconomical since it requires the shipment of an equal mass of water. "To optimize its quality and stability, slurry is produced at the filtering unit as soon as possible after silica fume has been collected", (Lewis, 1996). Even so, during use, periodic agitation is often required to achieve a uniform distribution of the fume within the slurry (Neville, 1996). Slurry products containing different chemical admixtures are also commercially available (ACI, 1994).

Silica fume is also often densified. This procedure is accomplished through mechanical means, such as compaction in a cone-shaped auger end extrusion system, or by using compressed air (Hooton et al., 1998). For the latter process, undensified fume is loaded into a silo through which compressed air is blown. The air causes the particles to tumble and agglomerate, with the heavier agglomerates falling to the silo bottom where they are subsequently removed. After densification, the material is no longer as "dusty", has a fine granular appearance, and handling is much more user-friendly (Lewis, 1996). The forces holding the particles together should be easily overcome with proper concrete mixing with typical proprietary silica fumes of bulk densities ranging from 480 to 640 kg/m^3. However, "beyond about the 720 kg/m^3 level, it may become increasingly difficult to disperse densified silica fume particles within concrete", (ACI, 1994). Densified fumes are used in various applications including formulated products, pre-cast operations, and ready-mix concrete.

Finally, undensified silica fume is also sometimes converted to pelletized form. This is produced by mixing silica fume with a small quantity of water to form a solid agglomerate, often in an inclined rotating drum. Pelletized fume is not suitable for direct use in concrete since the agglomerates will not disperse without physical grinding (ACI, 1994). As such, pelletized fume is typically interground to form blended cements.

2.2.4.1 Dispersion of Silica Fume

Even before considering the impact of the use of various product forms of silica fume described in the previous section, the issue of adequate dispersion of any type of silica fume throughout a concrete mixture must be addressed. If silica fume is not dispersed adequately throughout a mixture, performance may be variable and the improvement to concrete properties may be less dramatic, especially with respect to durability (Hooton et al., 1998). Furthermore, undispersed clumps of silica fume could potentially act as alkali-reactive, or frost susceptible, aggregates (Lagerblad and Utkin, 1995).

Various factors can have an impact on the ability of a silica fume to adequately disperse throughout a concrete mixture. The results of ultrasonic dispersion tests performed by St. John (1994) on fumes of varying density found that silica fumes with bulk densities of greater than 500 kg/m^3 were unlikely to be redispersed in a concrete mixer. As well as bulk density, both method and form of densification are issues of concern. Blended cement producers should address these problems when designing their intergrinding systems. For example, work done by Gudmundsson and Moller (1997) in Iceland has found that air-compacted silica fume is not always as effectively interground with the clinker as pelletized SF. The actual mixing process must also be considered. This includes batching sequence, mixer efficiency, and mixing time (Hooton et al., 1998). Lagerblad and Utkin (1993; 1995) have found the use of proper concrete mixing to be of even greater importance than the use of superplasticizers, and recommend a dry pre-mixing of silica fume with coarse aggregate. They also emphasize that the size of the smallest aggregate grain size should be twice that of SF granules to achieve good crushing. "Mixing procedures may vary in line with the production facility but the general rule is to mix thoroughly, ensuring maximum dispersion of the microsilica (SF) within the concrete. To this end, microsilica concretes should incorporate a plasticiser or a superplasticiser to aid in dispersion", (Lewis 1996). Superplasticizers will aid in the dispersion of small agglomerations, and should be used as a minimal measure to address the issue of proper silica fume dispersion. This fact is highlighted by results such as those reported by Gudmundsson and Moller (1997) from a study on the effect superplasticizers have on the distribution of silica fume in mortar and concrete. Samples were made with eight different plasticisers and yet the thin sections examined petrographically showed there was no effect of the superplasticizers on the amount of SF clusters present in the samples.

The fact remains that more and more evidence of the presence of silica fume agglomerations in silica fume mortars and concretes both in the field and in the laboratory. It seems that the widely held assumption that if agglomerates are present that they will be broken up by intermixing to be small enough to pack between cement grains is simply not correct in the case of some silica fumes (St. John, 1994). Many researchers have come to the conclusion that the mean particle size of SF actually varies between 1 and 50 μm, and not 0.1 to 0.2 μm as is normally quoted in the literature (Kolderup, 1977; Aitcin, 1983; De Larrard, 1992; St. John, 1994). The "microspheres" of silica fume can be held in clusters by a combination of Van der Waals forces, fused spheres, entanglement of fused spheres and single or linked chains. Work done by St. John (1994) showed that some particles can be fused together during the manufacturing process. "Once a silica fume with an unfavourable amount of fusion is agglomerated, it is impossible to de-agglomerate it sufficiently for use in concrete and mortars", (St. John, 1994). A standardized procedure to measure dispersibility of silica fume, such as measuring the ultrasonic dispersivity, should be implemented.

Researchers have reported cases where silica fume agglomerations have allegedly caused ASR in both laboratory and field studies (Shayan et al., 1994; Lagerblad and Utkin, 1995). Some authors have found that these "lumps" of silica fume can actually behave as reactive aggregate particles (Pettersson, 1992; Bonen and Diamond; 1992). In these cases, the reaction and/or the reaction product seem typical of ASR. The potential of the agglomerates to cause expansive ASR will depend on their amount, size, and whether sufficient alkali and moisture is present (St. John, 1994).

It is evident that in order for silica fume to work in a concrete mixture to its full potential, it is imperative that silica fume particles be well dispersed in a concrete mixture (Malhotra, 1987). It is crucial that both suppliers and producers be aware of the potential consequences of inadequate dispersion of silica fume, so they will take care to use proper admixtures and mixing techniques. This is also equally true for laboratory testing of mixtures incorporating silica fume. The true effect of silica fume on the resulting properties of a paste, mortar, or concrete mixture will not be realized in a testing program that does not pay attention to details such as mixing processes, SF bulk density, product form of silica fume, and use of appropriate admixtures.

2.2.4.2 Performance of Various Forms of Silica Fume

> Each of the different forms in which silica fume is available has operational advantages, but all forms can be successfully used; claims of significant beneficial effects of one or other of these forms upon the resulting concrete have not been substantiated. – (Neville, 1996)

Some previous work has been performed testing concrete mixtures containing different product forms of silica fume. Much of the research reported in the literature is directed towards properties other than ASR resistance. Cohen and Olek (1989) compared the performance of concretes with 10% replacement of slurried, uncompacted, and densified silica fumes at 0.35 w/cm in terms of compressive strength, freezing and thawing resistance, and resistance to chloride permeability. Their findings showed "no reason to advocate for or against the use of any specific form of silica fume as there were no significant differences observed in the engineering properties of concretes containing either of the three forms of silica fume", (Cohen and Olek, 1989). From this same work, the researchers also noted that in terms of fresh properties, the densified form of silica fume was the easiest to handle during mixing and also showed the best finishability, and that the slurried silica fume had the highest demand for HRWRA and air-entraining admixture. Fidjestol (1992) performed a study relating frost resistance to product form of silica fume. He reported a slight reduction in frost resistance with increasing bulk density, ranging from 200 kg/m^3 to 800 kg/m^3, of the silica fume incorporated in the concrete. The same study found detrimental effects of increasing densification of silica fume on resulting compressive strengths. Work done by Wolsiefer et al. (1995) showed different results. They report on a study where eleven different product forms of SF at w/cm of 0.40, 0.35, 0.30, and 0.22 were tested for compressive and flexural strengths, drying shrinkage, and rapid chloride permeability. The performance of the concretes in terms of mechanical properties and durability characteristics (as determined by RCPT) was comparable, regardless of the silica fume product form used.

In some studies the effect of product form of SF on ASR resistance was examined. Concrete prism expansion tests performed by Berube and co-workers (1998) indicated that pelletizing the silica fume before mixing with the clinker at the grinding stage did not reduce its effectiveness against ASR, provided the grinding process is effective in dispersing the silica fume. Conflicting results were reported by Lagerblad and Utkin (1993). They tested concretes in terms of ASR and freezing and thawing, using sodium chloride to accelerate deterioration in both cases. For both tests, they found that the concretes with badly dispersed silica fume grains developed ASR and disintegrated rapidly. They concluded that "in real structures, badly dispersed silica granules can only cause damage under certain conditions" based on the finding that the granules turned to alkali-silica gel quite quickly (before the concrete hardened) and only became expansive with a sufficient supply of alkalis and water.

3 EXPERIMENTAL TEST PROCEDURES

Several test procedures were carried out on various mortar and concrete mixtures to investigate the effects that form and silica content of silica fume have on resistance to deterioration due to alkali-silica reaction. The details of these test procedures are outlined in this chapter. The various materials employed, as well as the various mixture designs used, are also described.

3.1 MATERIALS

All specimens tested in this program were made with high-alkali, CSA Type 10 cement, (similar to ASTM Type I). The equivalent alkali content of this cement is 0.98%, and a complete chemical analysis is provided in Table 3.1.1 and Appendix A. This cement met all the requirements for use in both the accelerated mortar bar (CSA A23.2-25A) and concrete prism (CSA A23.2-14A) tests.

A total of 7 types and/or sources of silica fumes were examined. The first series consists of five silica fumes, chosen to represent the range of product forms currently in use in North America. The second series involves two silica fumes from the same source, but different silica contents. The chemical analyses of the silica fumes and the ordinary Portland cement are presented in Table 3.1.1 and Appendix A. A list outlining the two series of silica fumes and certain relevant characteristics is provided in Table 3.1.2.

Table 3.1.1 - Chemical Analyses for Cementitious Materials

MATERIAL	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	CaO	MgO	LSO$_3$	K$_2$O	Na$_2$O	Na$_2$O$_{eq}$
OPC	19.82	5.13	2.2	62.72	2.64	3.15	1.08	0.27	0.98
Series 1: product form									
Pelletized (PEL)	88.85	0.25	0.08	0.44	0.18	0.21	0.62	0.07	0.48
Densified #1 (DEN1)	94.83	0.22	0.06	0.94	0.34	0.28	0.66	0.17	0.60
Densified #2 (DEN2)	90.73	0.39	1.11	0.52	3.37	0.27	0.96	0.20	0.83
Undensified (UND)	95.52	0.15	0.04	0.30	0.15	0.22	0.75	0.10	0.59
Slurried (SLU)	94.54	0.23	0.03	0.39	0.08	0.21	0.50	0.08	0.41
Series 2: silica content									
Low -Silica (LS)	68.21	1.55	12.27	4.57	1.16	1.02	1.37	0.26	1.16
Normal-Silica (NS)	88.40	0.60	5.42	0.84	0.73	0.71	1.12	0.24	0.98

Table 3.1.2 - Silica Fume Properties

SILICA FUME	Source	SiO$_2$ content	Loose Bulk Density (kg/m^3)	% Na$_2$O$_e$
Series 1: product form				
Undensified (UND)	Can-1	95.52	270	0.59
Pelletized (PEL)	Can-1	88.85	557	0.48
Densified #1 (DEN1)	Can-2	94.83	689	0.60
Densified #2 (DEN2)	US-3	90.73	643	0.83
Slurried (SLU)	US-4	94.54	-	0.41
Series 2: silica content				
Normal Silica (NS)	US-5	88.40	218	0.98
Low Silica (LS)	US-5	68.21	233	1.16

It should be noted that these silica fumes are not all from the same source. The code CAN refers to a Canadian source and US refers to a U.S. source, while the numbering refers to the five different cement suppliers from which the silica fumes were received. Other researchers have maintained that for this type of work, the different forms of SF represented should be created from the same origin for valid assessments to be made

(Cohen and Olek. 1989). These silica fumes were chosen to reflect the products which are commercially available, through both source and form. As such, all the silica fumes employed came directly from plants either as finished products or in the state in which they would be prior to intergrinding as an ingredient in silica fume blended cement. It should also be mentioned that the low-silica silica fume (LS) does not meet the 85% minimum silica content required by CSA A23.5 or ASTM 1240, and as such, is not currently marketed for use in ready-mixed concrete.

There is currently no standard method for measuring the loose bulk density of silica fume. For this study, this was determined by filling and weighing a calibrated 400 ml brass cup with silica fume. The cup was always filled in 2 layers, with 4 tamps per layer, and extra material was struck off at the top. This procedure was performed 5 times for each fume to obtain an average loose bulk density for the material, as presented in Table 3.1.2.

Deleteriously reactive aggregate from the Spratt quarry near Ottawa, Ontario was used in the mortar and concrete test specimens. It is a crushed, siliceous limestone which is deleteriously reactive and often employed as a standard aggregate for ASR tests (CSA A23.1-94, Appendix B). It should be noted that it is the chert siliceous component of this aggregate that is reactive. This aggregate was obtained from the Engineering Materials Office of the Ontario Ministry of Transportation (MTO).

3.2 CONCRETE PRISM EXPANSION TEST

Expansion testing of concrete prisms followed the procedure outlined in CSA A23.2-14A (similar to ASTM C 1293) standard. In this test, concrete prisms are cast with 420 kg/m^3 of high-alkali Portland cement and the mix water is dosed with NaOH to raise the cement alkalis to 1.25% Na_2O_{eq}. Prisms are subsequently cast and measured for length change while exposed to 100% r.h. and 38°C. Although the test procedure is primarily intended to assess the potential expansivity of aggregates, it has been found to be a useful tool in evaluating the effectiveness of SCMs in controlling ASR in specimens containing aggregates which are known to be reactive. "Current experience suggests that a testing period of 2 years is sufficient for the evaluation of SCMs, with an expansion limit criterion of 0.04%", (CSA A23.1-94, App. B). For the purpose of this report, the most recent data possible are presented, yet further monitoring of the prisms will continue to a minimum of 2 years. Such long term expansion measurements are required to ensure that the fume does not merely delay the onset of ASR.

For each concrete mixture studied, three 75x75x300 mm prisms were cast. Mixtures were cast with each of the varying product form silica fumes at 4%, 8%, and 12% levels of cement replacement by mass. The specific concrete mixture proportions used for each 7.5 L mixture are outlined in Table 3.2.1. It should be noted that the amount of sodium hydroxide included in the mix was adjusted to accommodate the level of replacement of

Portland cement with silica fume, as the alkali contribution of silica fume is not included for calculation purposes.

A note should be made at this point regarding an error in the batching process resulted in 25% more NaOH being added to the mixtures than was required by the standard procedures. This resulted in a somewhat higher total alkali content in the mixtures than was targeted, as shown in Table 3.2.1. Even so, the data from the prisms are still valid for the purposes of comparing between the ability of the various forms of silica fume to control expansion due to ASR.

Table 3.2.1 - Prisms Mix Designs

MATERIALS	LEVEL OF REPLACEMENT			
	0%	4%	8%	12%
Cement (kg)	3.15	3.02	2.90	2.77
Silica Fume (kg)	0.00	0.13	0.25	0.38
C.Aggregate 10-20mm (kg)	5.13	5.11	5.09	5.08
C.Aggregate 10-5mm (kg)	2.56	2.56	2.55	2.54
Sand (kg)	5.13	5.11	5.09	5.08
Water (kg)	1.42	1.42	1.42	1.42
w/cm	0.45	0.45	0.45	0.45
NaOH (g)	14.10	13.53	12.97	12.41
Target Alkalis (kg/m^3)	5.25	5.04	4.83	4.62
Actual Alkalis (kg/m^3)	5.57	5.34	5.13	4.90

The prisms were demoulded 24 hours after casting, and were immediately covered with damp rags so the specimens would not dry out. The initial length measurement of the prisms was taken within one hour of demoulding. After the length was measured, each set of 3 prisms was placed in a storage container. These storage containers consisted of a 25 litre plastic pail with an airtight lid. In the bottom of each pail, a piece of plastic mesh was placed on three 40mm high PVC pipe spacers, and water was added to approximately a 25mm depth. The sides of the pail were covered with filter paper that extended down into the water.

The prisms in their storage containers were then placed in a room maintained at 38 ± 2°C. Subsequent readings were taken at 1, 2, 3, 8, 13, 18, 26, 39, and 52 weeks. Further readings will be taken every 3 months up to the minimum 2 years of monitoring. Prior to a reading being taken, the pails were removed from storage and maintained at 23 ± 2°C for 16 ± 4 hours. It should be noted that the mass of all specimens was also recorded with each length reading.

3.3 ACCELERATED EXPANSION OF MORTAR BARS DUE TO ASR

The accelerated expansion of mortar bars due to ASR was studied in accordance with CSA A23.2-25A-M94 (similar to ASTM C 1260-94). This test is basically the same as the method developed by Oberholster and Davies (1986). Questions have been raised as to whether this test is appropriate for evaluating the effectiveness of supplementary cementing materials against alkali-silica reaction. Recent work has shown that the specified conditions are suitable to accelerate the pozzolanic reactions of SCMs, ensuring that this test is a reasonable evaluation method (Berra et al., 1996; Berube et al., 1995; Berra et al., 1994). As such, the accelerated mortar bar test has been included in the Canadian Standard for Supplementary Cementing Materials, CSA A23.5-98, as an optional requirement to assess the ability of supplementary cementing materials such as silica fume to control expansion due to ASR. The test method requires that the SCM in question be tested at various replacement levels and that the reactive aggregate used must produce an expansion of at least 0.30% after 14 days in a high-alkali Portland cement mixture. The Spratt aggregate used in this study fits this requirement.

It should be noted that this study was carried out to give preliminary indications of the effects that the form and silica content of silica fume have on its ability to control expansion due to ASR. It is recognized that the test conditions are quite severe, but it has been found that at 14 days, a expansion limit of 0.10% correlates well with the 0.040% concrete prism limit after 2 years when studying SCMs (Thomas and Innis, 1999; Berube, et al., 1995).

The grading and proportioning of the Spratt aggregate was carried out according to the CSA standard and all aggregate was washed prior to use. The casting was carried out following ASTM C305-94. A ratio of water to cement to aggregate of 0.50 : 1.00 : 2.25 was employed. The specific mix proportions used to cast the 3 mortar bar specimens for each mixture tested are presented in Table 3.3.1. These mixtures included a 4%, 8%, and 12% cement replacement mixture for each of the 7 silica fumes examined.

Three 25x25x250 mm gauge length mortar bars were cast for each mixture in the study. The specimens were demoulded after 24±2 hours. They were then placed in water at 23°C and heated to 80°C. After 24 hours, an initial length measurement (the zero reading) was then taken. All length measurements were carried out using a digital length comparator. The specimens were subsequently placed in a standard 1 molar NaOH host solution, pre-heated to 80°C. It should be noted that the solution was titrated before use to ensure that the hydroxyl ion concentration was within ± 0.1 mol/L of 1M. Also, the solution level was maintained at roughly 25mm above the samples. Further readings were taken at 1, 3, 7, 11, 14, 21, and 28 days after NaOH immersion.

Table 3.3.1 - Mortar Bar Mix Designs

MATERIALS	LEVEL OF REPLACEMENT			
	0%	**4%**	**8%**	**12%**
Cement (g)	440	422.4	404.8	387.2
Silica Fume (g)	0	17.6	35.2	52.8
Aggregate (g)	990	990	990	990
Water (g)	220	220	220	220
w/cm	0.5	0.5	0.5	0.5
Superplasticizer (g)*	0	0	2.5	3

* sulfonate-naphthalene superplasticizer was used in liquid form

3.4 PORE SOLUTION COMPOSITION

This work was done in order to investigate the effects that the product form and silica content of silica fume have on pore solution composition. Aspects to be investigated include the solid and liquid phase partition of alkalis, alkali binding properties, and alkali dilution effects.

For each SF type, pastes were prepared at 4%, 8%, and 12% mass replacement at a water-to-cementitious materials ratio of 0.5. A 100% ordinary Portland cement mixture was also cast for control purposes. The paste specimens were mixed in a high shear blender (Waring stainless steel, 3.81 litre capacity). No superplasticizers or water-reducers were included in the mixtures. Eight cylinders (50mm diameter x 100mm high) were filled in 2 layers and sealed with parafilm and a plastic lid. After casting, the specimens were slowly rotated about their ends at 12rpm for 24 hours to avoid bleeding and segregation prior to set.

Pore solution was extracted from the specimens at 1, 3, 7, 28, and 90 days of age and analysed for chemical composition. The pore solution was expressed from the samples using a high-pressure apparatus, originally described by Barneyback and Diamond (1981). It should be noted that Duchesne and Berube (1994a) have shown that the alkali concentration of pore solution is not affected by the pressure at which a sample is expressed. Further analysis will be performed on specimens at 1 and 2 years of age. The specimens were stored at 23°C and 100% r.h. to help prevent moisture loss until they were tested. Once the pore solution was collected, it was immediately tested for OH^- ion concentration using automatic H_2SO_4 titration with a Metrohm Titrino DMS automatic titrator. The samples were also tested later for Na^+ and K^+ ion concentrations using flame photometry. Specific mix proportions for the pastes cast in this study are presented in Table 3.4.1.

Table 3.4.1 - Paste Specimen Mix Designs

MATERIALS	**LEVEL OF REPLACEMENT**			
	0%	**4%**	**8%**	**12%**
Cement (g)	2600	2496	2392	2288
Silica Fume (g)	0	104	208	312
Water (g)	1300	1300	1300	1300
w/cm	0.5	0.5	0.5	0.5

4 EXPERIMENTAL RESULTS AND DISCUSSION

The results from this program are presented in Chapter 4. First the effect of the product form, involving mixtures made with the series #1 silica fumes as outlined in Section 3.1, are examined, followed by a discussion of the issue of silica content by analysing the results from mixtures containing the series #2 silica fumes. Tables and plots of results exhibited in this section of the report either present average values or sample values representative of general findings. Detailed calculations and results for individual samples for certain tests are located in the appendices, as will be later cited.

4.1 ACCELERATED EXPANSION OF CONCRETE PRISMS DUE TO ASR

4.1.1 Effect of Product Form of Silica Fume

Results presented in this report are as recent as possible. Monitoring of the prisms will continue to a minimum of 2 years. Currently, CSA A23.1-94, Appendix B recommends a testing period of 2 years with an expansion limit criterion of 0.04% for the evaluation of SCMs. Specific plots and data for individual specimens of each mixture are presented in Appendix B. Although this study is not complete, some preliminary observations can be made from the results obtained to date.

As mentioned in Chapter 3, concrete prisms were cast at 4%, 8%, and 12% replacement of Portland cement by silica fume with the varying product form silica fumes. The prism expansion evolution for these levels of replacement are shown in Figures 4.1.1, 4.1.2, and 4.1.3, respectively.

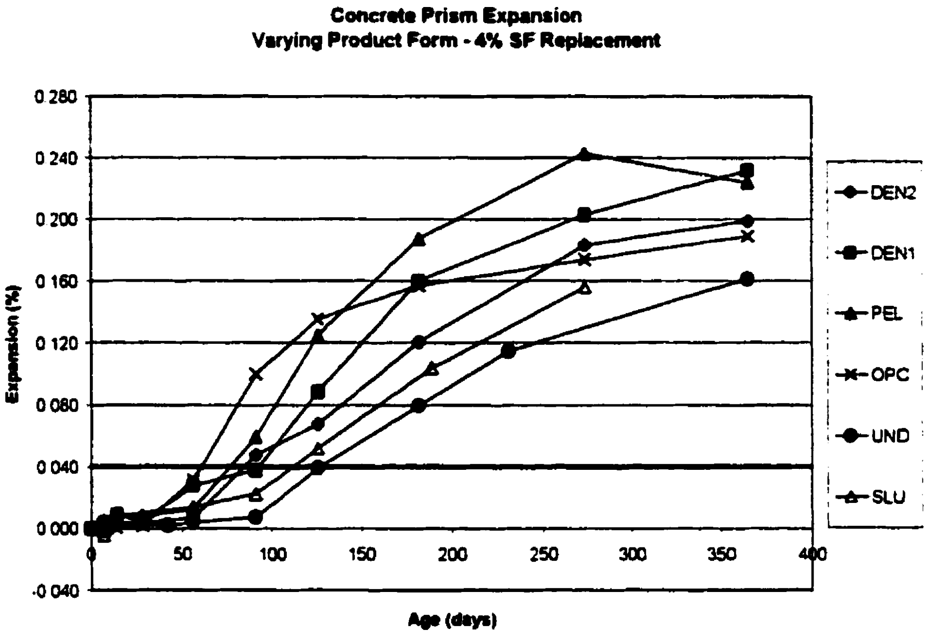

Figure 4.1.1 : Expansion of concrete prisms containing 4% silica fume replacement

As mentioned in Section 3.2, an error was made when preparing mixture designs and too much NaOH was added to all of concrete prism mixtures. As such, the concrete prism data reported in this study should only be used for relative, comparative purposes. However, it is of interest to note that the average expansion of the OPC prisms after 52 weeks (0.189%) falls within one standard deviation of the average expansion after 52 weeks of OPC prisms containing Spratt aggregate (μ = 0.170%, σ = 0.021%) as determined in a inter-laboratory study reported by Fournier and Malhotra (1996).

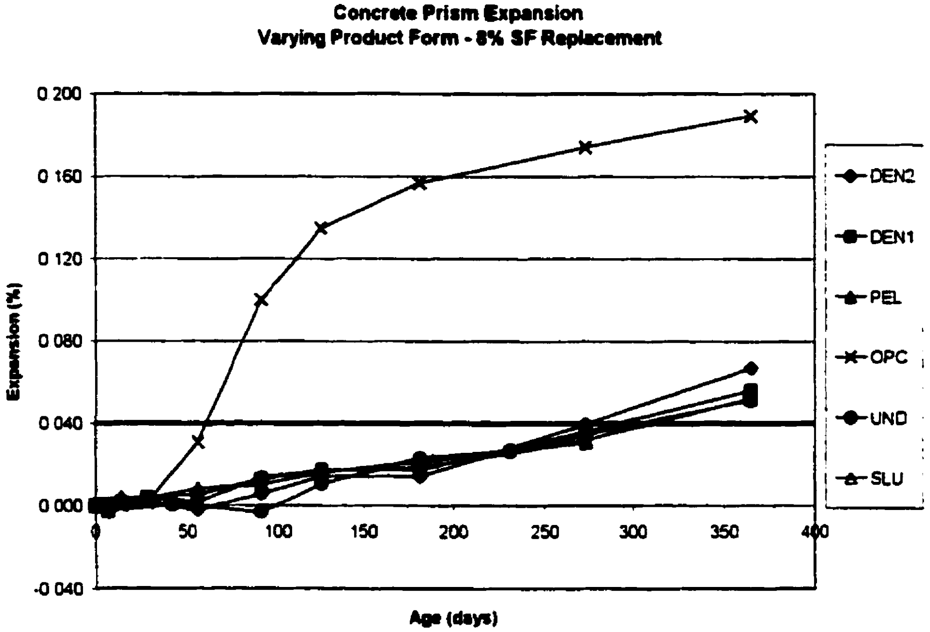

Figure 4.1.2 : Expansion of concrete prisms containing 8% silica fume replacement

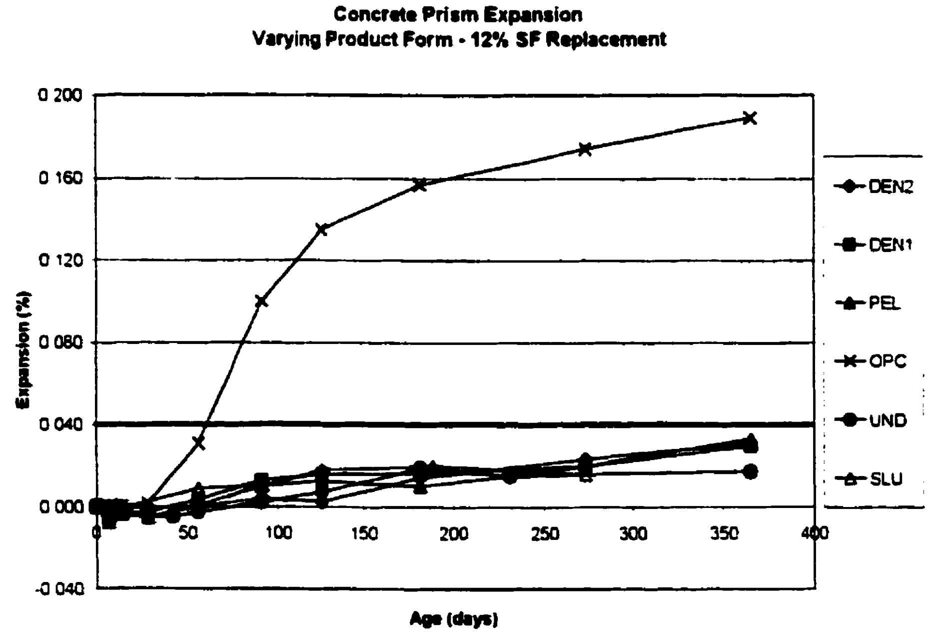

Figure 4.1.3 : Expansion of concrete prisms containing 12% silica fume replacement

In many cases, the prisms exhibited some initial negative expansion, most likely due to autogenous shrinkage. When comparing the mixtures containing silica fume, it is evident that as the replacement percentage of each silica fume was increased, the expansion decreased. However, Figure 4.1.1 shows that 4% silica fume did not reduce long term expansion when compared to that experienced by the OPC control prisms. The ordinary Portland cement control mixture exceeded the expansion limit criterion of 0.04% shortly after 56 days. Extensive surface cracking, extruded gel, and white streaking were also observed on the OPC specimens after 90 days. After 1 year of testing, the rate of the OPC prism expansion seems to be slowing. The 4% PEL, DEN1, and DEN2 silica fume prisms exceeded the limit criterion almost exactly at 90 days. These three sets of prisms all experienced minimal expansion up to around 56 days, after which the rate of expansion drastically increased and has continued relatively steadily to date. Although it took longer for these mixtures to surpass the limit than the OPC mixture did, these prisms later achieved higher expansions than the control mixture prisms. Other researchers have reported the occurrence of this pessimum effect where the use of silica fume at low replacement levels can actually result in higher expansions due to ASR. "With very reactive aggregates, greater expansions than for control specimens without SCM (pessimum effect) can be obtained for concretes made with a low CSF content, i.e. 5%", (Duschene and Berube, 1994). The trend of expansion of 4% PEL, 4% DEN1, and 4% DEN2 prisms also do not seem to have levelled off, even after 1 year of testing.

Unfortunately, due to a delay in receiving materials, there is not as much long-term data available for the mixtures incorporating the undensified and slurried silica fumes. However, it is evident from Figure 4.1.1, that the 4% Slurried and Undensified silica fume prisms expanded beyond the limit criterion at approximately 126 days. The delay in the onset of expansion for these prism sets was longer than that of the PEL-4%, DEN1-4%, and DEN2-4% mixtures. It was after 90 days that the prisms with 4% of undensified and slurried silica fume began to expand at a significant rate.

Although all the prisms made with 4% replacement by silica fume of Portland cement failed the test criterion, there is a noticeable difference in performance between some of the product forms of silica fume employed. This was not the case, however, at the 8% and 12% levels of replacement, after 1 year of testing. Figure 4.1.2 presents the expansion of prisms with time for concrete with 8% SF, and after 1 year of testing, the prisms made with the pelletized and both of the densified silica fumes had all surpassed the expansion limit. Again, the data available for the undensified and slurried silica fume prisms is not as advanced as the others. The latest recorded readings were at 126 days (0.016%) for the slurried SF and 231 days (0.027%) for the undensified SF. At these ages, the prisms were still well below the 0.040% limit criterion, however, the rates and levels of expansion to date seem to be following the same trend as the prisms made with the other three silica fumes. In essence, at this point, there is no distinguishable difference in performance of the different product forms in terms of concrete prism expansion at an 8% level of replacement. Also, there is no significant change in the rate of expansion experienced to date by any of the concrete prisms with 8% replacement of cement by silica fume .

Similar observations can be made for the prisms made with 12% silica fume. As is evident in Figure 4.1.3, there is no significant difference between the expansion experienced by the prisms made with the different product forms to date. This occurrence is further discussed in conjunction with the results of the mortar bar and paste specimen testing, in Section 4.4. The 12% SF concrete prisms also have not exhibited a significant change in the rate of expansion to date. Figure 4.1.3 also shows that 12% silica fume is sufficient to maintain expansion below the limit criterion after 1 year, no matter what form was employed. Further monitoring to 2 years of exposure will reveal whether some or all of these 12% SF mixtures will pass the expansion limit criterion for SCMs as recommended by CSA A23.1, Appendix B. It is expected that the prisms will exceed the expansion limit criterion since the dosage of NaOH included in these mixtures was 25% higher than specified in the standard. However, as previously mentioned and as is evident by the preceding discussion, useful comparisons and observations can be drawn from these results even with this error.

4.1.2 Effect of Silica Content of Silica Fume

Concrete prisms were not cast with the low-silica silica fume (LS) and the control silica silica fume (NS) from the same producer. It was originally thought that the conditions used for the concrete prism test might not be severe enough for any useful data to be obtained. In the interests of a complete and thorough study, it is most likely that these prisms will be cast and monitored to a minimum of 2 years at a later date.

4.2 ACCELERATED EXPANSION OF MORTAR BARS DUE TO ASR

Although this is traditionally a 14 day test, all expansions were monitored to 28 days. Full expansion data tables and plots are exhibited in Appendix C.

4.2.1 Effect of Product Form of Silica Fume

Figures 4.2.1, 4.2.2, and 4.2.3 show the performance of mortar bars with 4%, 8%, and 12% SF respectively. At 14 days, the expansion of the OPC control specimens seems high at 0.505%. However, this average expansion is within 2 standard deviations of the mean 14 day expansion of Spratt aggregate (μ = 0.416%, σ = 0.06%) as determined in a multi-laboratory study of the accelerated mortar bar test (ASTM C1260) and reported by Rogers (1999).

The ordinary Portland cement control specimens had exceeded the 0.10% expansion limit criterion after 4 days. All of the 4% SF specimens had expansions of 0.10% or greater by 7 days. After 11 days, all of the 8% SF specimens had also failed the test limit. With 12% SF, only the specimens containing either the undensified or slurried form of silica fume had average expansions below 0.10% after 14 days of testing. The specimens made with the two densified silica fumes just barely exceeded the 0.10% limit; however, the 12%

pelletized silica fume specimens still performed poorly with an expansion of almost 0.20% at 14 days.

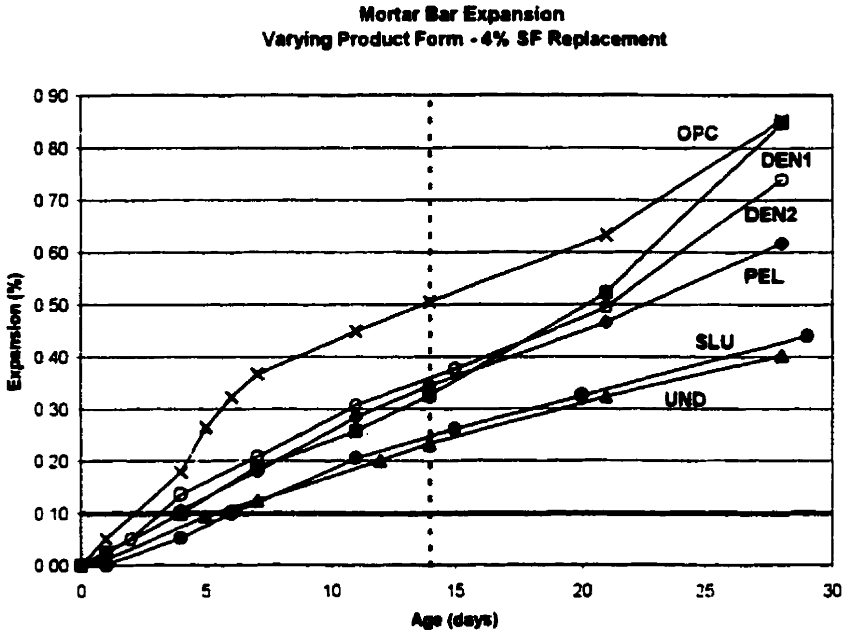

Figure 4.2.1 : Expansion of mortar bars containing 4% silica fume replacement

There was no delay of the onset of expansion with any of the sets of mortar bars containing 4% silica fume. Of the mortar mixtures with 8% SF, only PEL-8% expanded significantly immediately and increased steadily. The expansion of UND-8% began after 7 days, while the other three silica fumes tested (DEN1, DEN2, and SLU) exhibited a large increase in the rate of expansion at approximately 4 days. All of the 12% SF specimens experienced a delay in the onset of expansion. For PEL-12%, DEN1-12%, and DEN2-12%. the onset of expansion occurred at approximately 7 days, while with SLU-12% and

UND-12%, significant expansion began after 11 days. These trends are actually quite different from those observed with the concrete prisms.

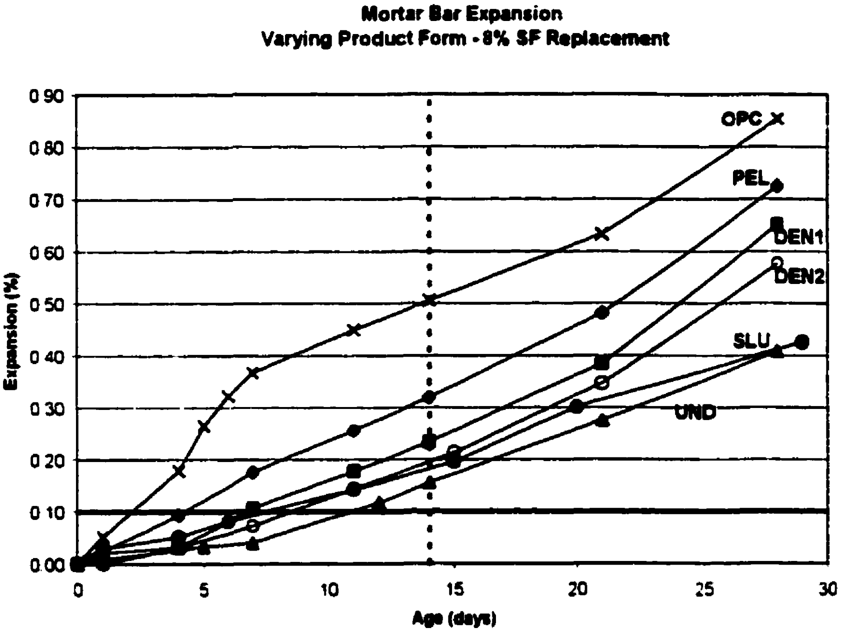

Figure 4.2.2 : Expansion of mortar bars containing 8% silica fume replacement

The above discussion of the accelerated mortar bar test results makes it evident that differences were observed in performance between the various product forms of silica fume tested, even with the 12% replacement of cement mortar mixtures. At all 3 levels of replacement of cement, the slurried and undensified silica fume mixtures performed fairly similarly in terms of ultimate expansion and rates at which this expansion was achieved; these two forms of silica fume were consistently better at controlling mortar bar expansion than the other three forms tested. There was no significant difference in the expansion results observed for mortars with the 4% replacement of cement by the pelletized or either of the two densified silica fume mixtures, up to 21 days. With 8% and 12% silica fume content, the pelletized SF mortar bars expanded the most, followed by the DEN1 mortar bars and then the DEN2 mortar bars. Further discussion of these observations will be made in Section 4.4.

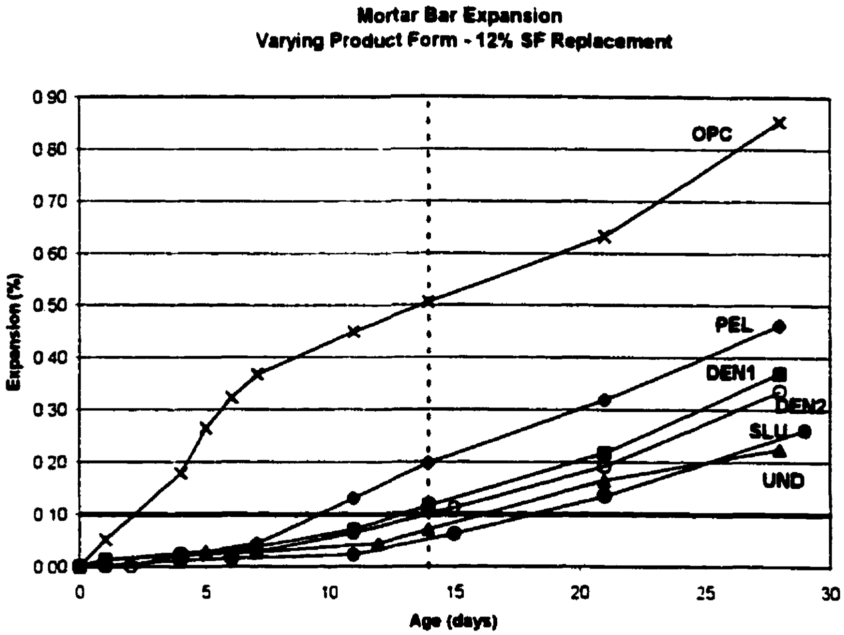

Figure 4.2.3 : Expansion of mortar bars containing 12% silica fume replacement

It is also important to note that the degree of expansion decreased as the level of silica fume increased for all silica fume forms tested if the results are only examined up to 14 days, (details in Appendix C). However, for specimens prepared with pelletized silica fume, the 8% replacement samples exhibited greater expansion after 28 days than did the 4% replacement of cement by pelletized silica fume samples. Samples of these bars have been saved to be examined by scanning electron microscope in the hopes of determining why this happened. Potentially, there could be more silica fume clusters of undispersed grains in the 8% mortar bars, which may have provided more reaction sites for ASR to occur.

4.2.2 Effect of Silica Content of Silica Fume

Mortar bars were also cast with the series #2 silica fumes to investigate the effect that the silica content of silica fume has on its ability to control expansion under the accelerated mortar bar test conditions. The degree of expansion decreased as the level of silica fume increased for the two silica fumes tested in this part of the study, with one exception, (details in Appendix C). After 28 days of monitoring, the 8% low-silica silica fume mortar bars had expanded slightly more than the 4% low-silica silica fume mortar bars.

Figures 4.2.4, 4.2.5, and 4.2.6 present the 28 day expansion results for the mortar bars cast with 4%, 8%, and 12% levels of replacement with the series #2 silica fumes respectively. It is evident from all three figures that the mortar bars containing the low-silica silica fume experienced no delay in onset of expansion. At all three levels of replacement, the LS mortar bars expanded at a faster rate and to a higher ultimate expansion than did the bars containing NS silica fume. Also, even the 12% LS mortar bars failed the expansion limit of 0.010% after 14 days. In the case of the bars made with the NS silica fume, the mortar mixtures with 4% replacement failed the limit criterion after 7 days and with 8% replacement just exceeded the limit at 14 days. The mortar bars made with 12% NS passed the expansion criterion.

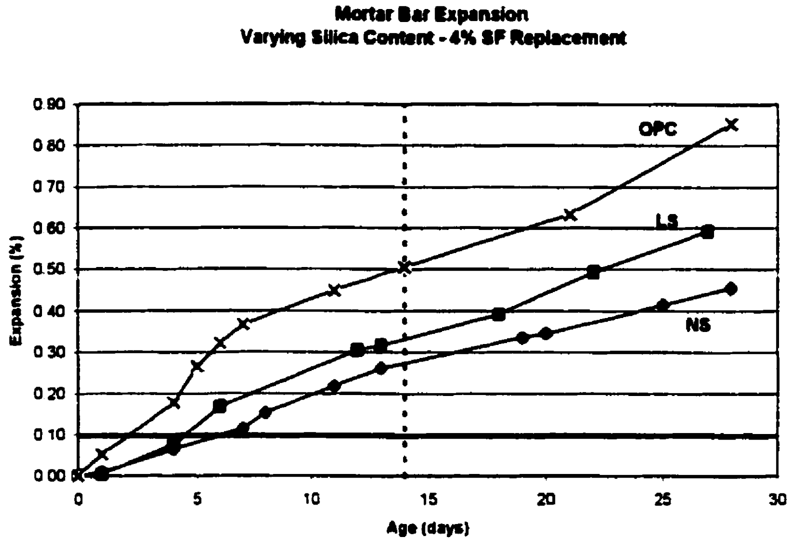

Figure 4.2.4 : Expansion of mortar bars containing 4% silica fume replacement

Based on the results of the accelerated mortar bar test, it appears that the lower silica content does affect a silica fume's ability to control mortar bar expansion. It should be noted, however, that the test conditions are very severe in this procedure, and as such, these results should not fully discount the possible effectiveness of low-silica silica fumes at controlling ASR expansion. Often, the accelerated mortar bar test is not enough to determine the effectiveness of SCMs against ASR unless the mechanisms involved can be explained or shown to be similar to those that occur under a more realistic procedure, such as the concrete prism test (Berube et al., 1995). As such, it would be extremely beneficial to cast concrete prisms using the NS and LS silica fumes from this study. Also, it would be of great interest to test mortar bars made with higher replacement levels (i.e.

>12%) of the LS silica fume to see if that level of replacement of Portland cement would be sufficient for the mixture to pass the 0.10% ASTM expansion limit criterion.

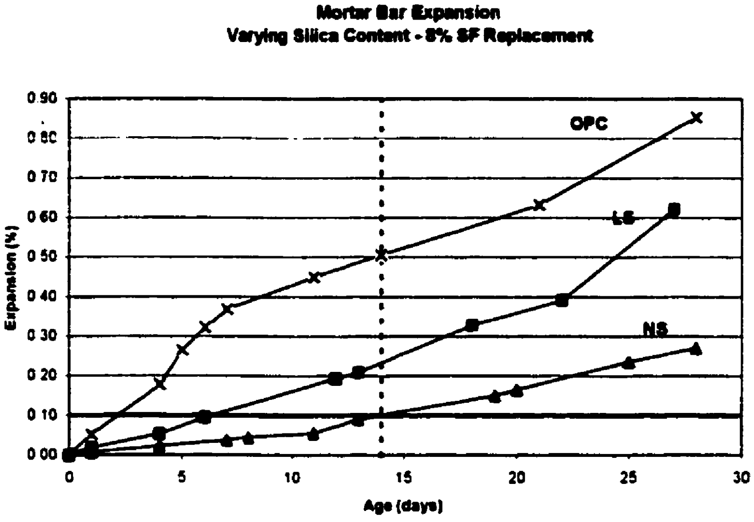

Figure 4.2.5 : Expansion of mortar bars containing 8% silica fume replacement

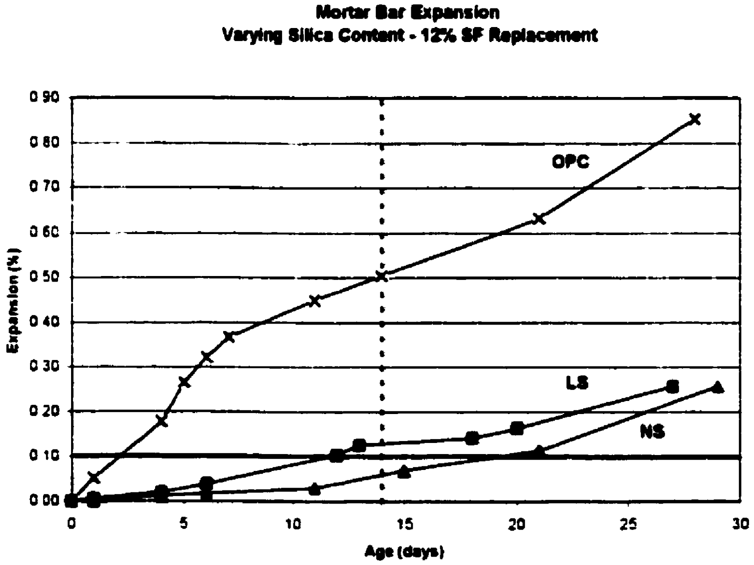

Figure 4.2.6 : Expansion of mortar bars containing 12% silica fume replacement

4.3 PASTE SPECIMEN PORE SOLUTION COMPOSITION

4.3.1 Effect of Product Form of Silica Fume

This section highlights key findings of the paste specimen pore solution study. Pore solution was extracted from samples at 1, 3, 7, 28, 90, and 365 days, and analyzed for OH^-, Na^+, and K^+ concentrations. In some cases, solutions were also extracted and tested at intermediate ages, between 90 days and 1 year of age, for the mixtures where the 1 year data would not be available for this report. Complete experimental data and plots are provided in Appendix D.

By studying paste specimens, the effects of cementitious materials on the pore solution alkalinity can be examined since the only source of alkalis in the procedure is directly from the cement and silica fume. Thus, the study of the pore solution composition and, particularly, the effect of the partial replacement of cement with silica fume on the OH^- ion concentration in the pore solution can be an effective tool to reveal the ability of different forms of silica fume in countering alkali-silica reaction (Berra et al., 1996). It should be noted that the presence of reactive aggregate in concrete or mortars will decrease the pore water alkalinity as OH^- ions are consumed during the reaction (Diamond et al., 1981; Thomas et al., 1991). Similar experience has also been reported with apparently "inert" aggregates (Thomas, 1994).

Figure 4.3.1 shows that generally a good balance was found between the alkali ion concentration and the OH^- concentration. Therefore, further analyses were simply performed using the alkali ion concentration data as determined by flame photometry. In the few cases where there was not enough pore solution remaining to determine the alkali concentration, the OH^- concentration was employed for data analysis purposes.

It should be noted that, in a few instances, the hydroxyl content as determined by titration and the alkali content as determined by flame photometry differed by more than 5%. Normally, this would indicate the presence of another significant ion, such as sulphates, in the system. However, in this study, the differences were never consistently to one side or the other. It is more likely that the differences can be attributed to experimental errors such as pipetting, evaporation of solution between time of titration and flame photometry, and problems that were found to occur with the flame photometry equipment. In order to eliminate some of this error, it is recommended in future studies that the flame photometry analysis be performed as soon as possible after the pore squeeze has been performed since even good sealing techniques did not seem to stop evaporation from the solution containers. It is suggested that samples be weighed immediately after collection and directly before testing to monitor this effect.

Several broad observations can be made from the first five plots presented in Appendix D. These figures compare the effects of increased levels of silica fume replacement on the

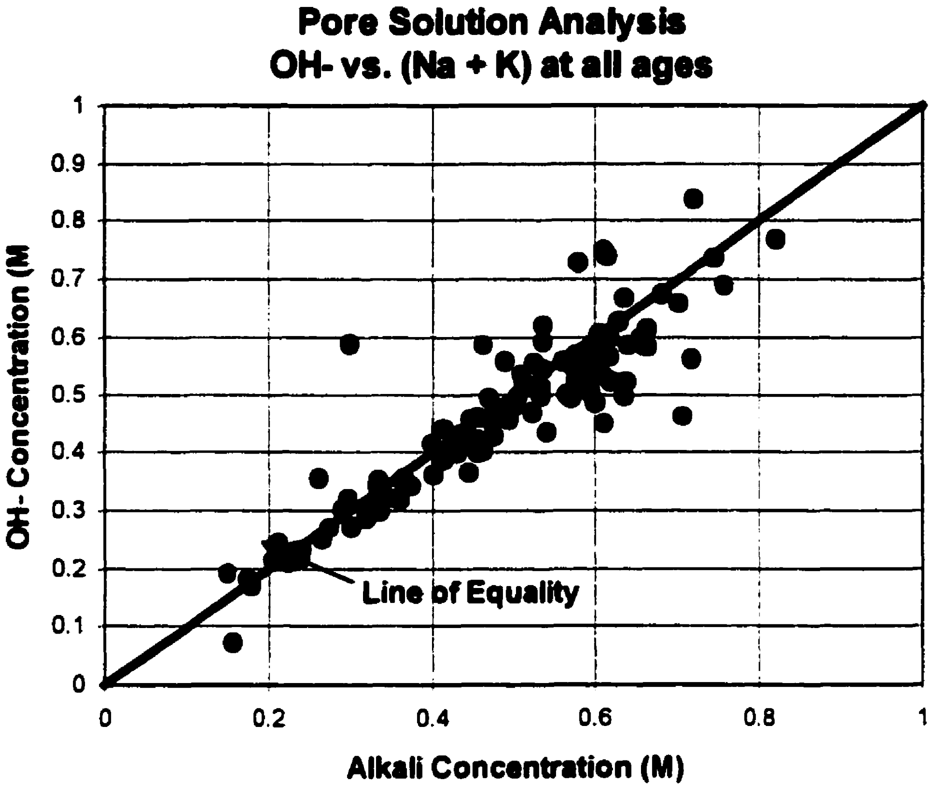

Figure 4.3.1 : Balance between ionic species in pore solution

evolution of pore solution alkalinity for each fume tested in the varying product form series. Generally, silica fume addition at all replacement levels, for all product forms and ages tested, reduced the alkali concentration when compared to that of the neat cement paste. The only exception to this trend was found with the 4% pelletized silica fume mixture where the alkali concentration at 90 days was higher than that of the OPC at 90 days. Also, an increase in the replacement level of silica fume resulted in a larger decrease in the alkali concentration at 7, 28, and 90 days for all series #1 silica fumes. This trend did not hold for data at 1 and 3 days.

The next three plots compare the different forms of silica fume at similar replacement levels. Figures 4.3.2, 4.3.3, and 4.3.4 present the results for the 4%, 8%, and 12% levels of replacement respectively. Examination of Figure 4.3.2 indicates that at a 4% level of replacement, the product form of silica fume does cause differences in the resulting pore solution alkalinity of paste specimens, which confirms the concrete prism and mortar bar expansion results. In contrast, Figure 4.3.3 shows no significant difference in the concentration of alkalis in the specimens made with the various product forms of silica fume with 8% replacement. Similar results were observed for the 12% replacement by silica fume of Portland cement mixtures, as is evident in Figure 4.3.4.

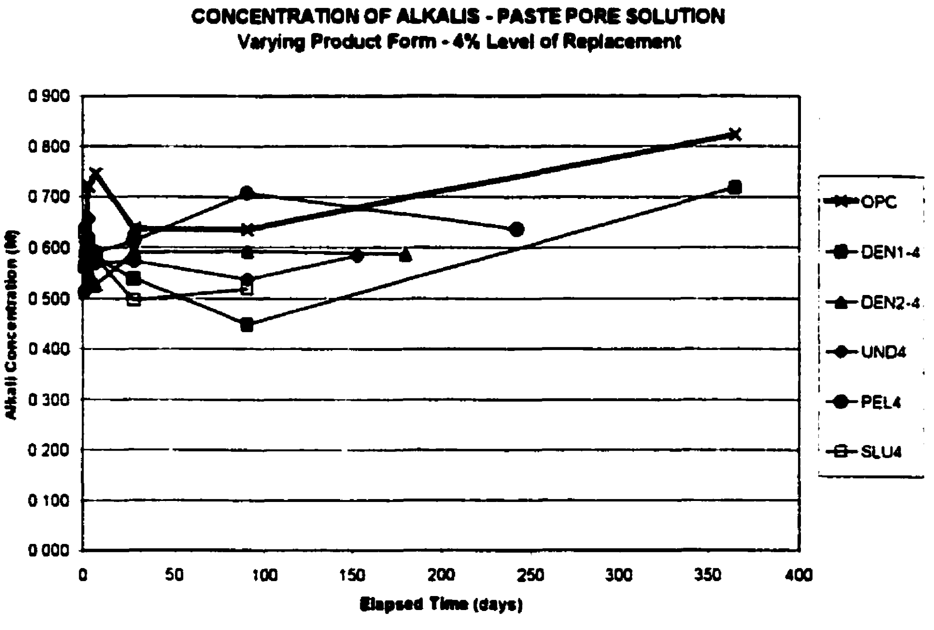

Figure 4.3.2 : Effect of product form of silica fume on pore solution alkalinity with time at 4% level of replacement

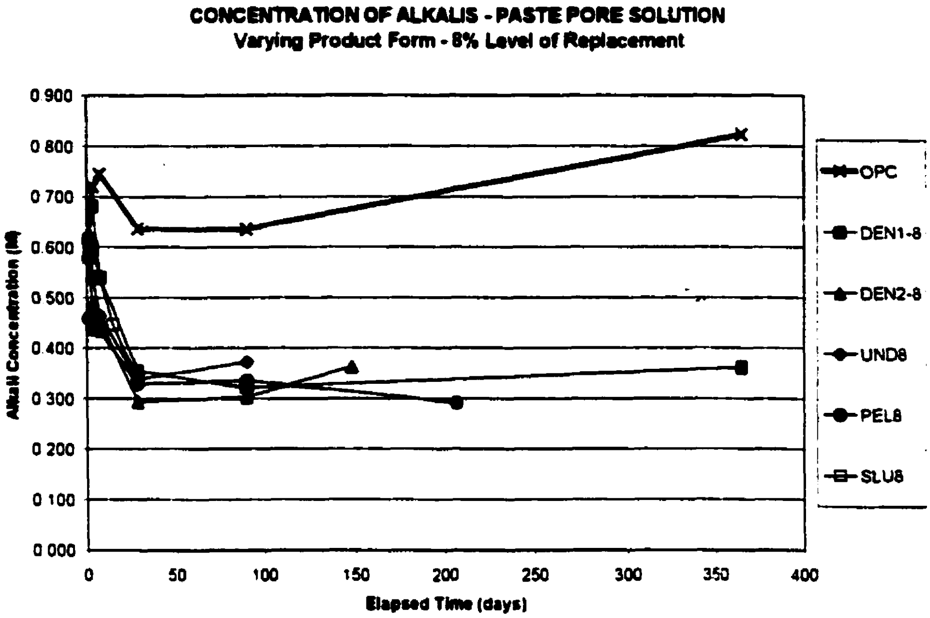

Figure 4.3.3 : Effect of product form of silica fume on pore solution alkalinity with time at 8% level of replacement

Potentially, at higher levels of replacement such as 8 and 12%, the system is essentially swamped with silica fume to a degree that the difference in the quantity of exposed, reactive surface area that exists between the different forms of silica fume no longer matters, at least up to 1 year. This implies that there could be similar performance obtained by different forms of silica fume at lower replacement levels. For example, a 4% undensified SF concrete mixture may be able to control ASR expansion as well as a 6% pelletized or densified concrete mixture. Further work correlating a form of silica fume's performance to the average reactive surface area would definitely be useful.

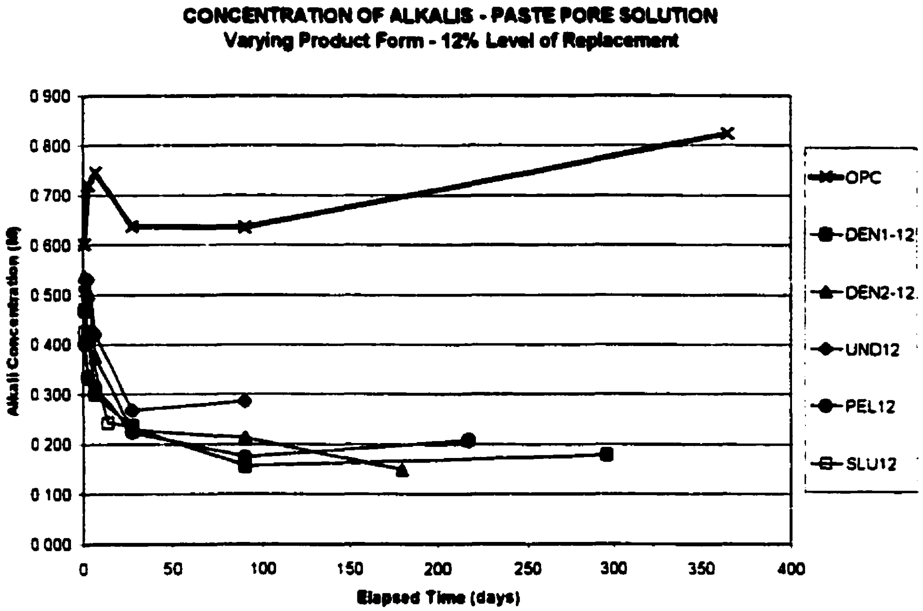

Figure 4.3.4 : Effect of product form of silica fume on pore solution alkalinity with time at 12% level of replacement

Figure 4.3.5 and 4.3.6 present plots of alkalinity versus level of replacement for the various product forms of silica fume at 28 and 90 days of age respectively. The theoretical effect of an inert diluent has also been plotted on this figure. All the product forms tested at all replacement levels cause a significantly greater decrease in pore solution alkalinity than would an inert diluent except in the case of the 4% pelletized silica fume paste.

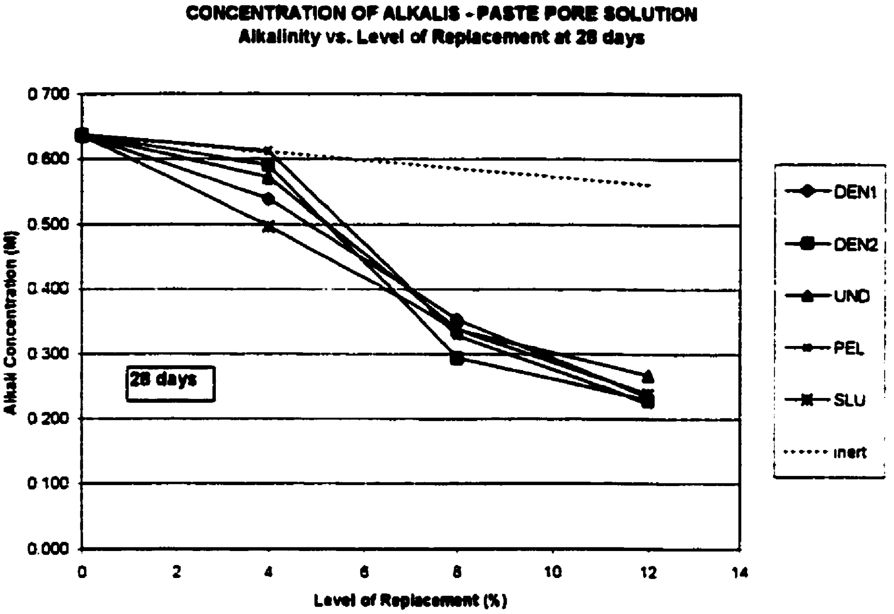

Figure 4.3.5 : Effect of SF level of replacement and product form on pore solution alkalinity at 28 days

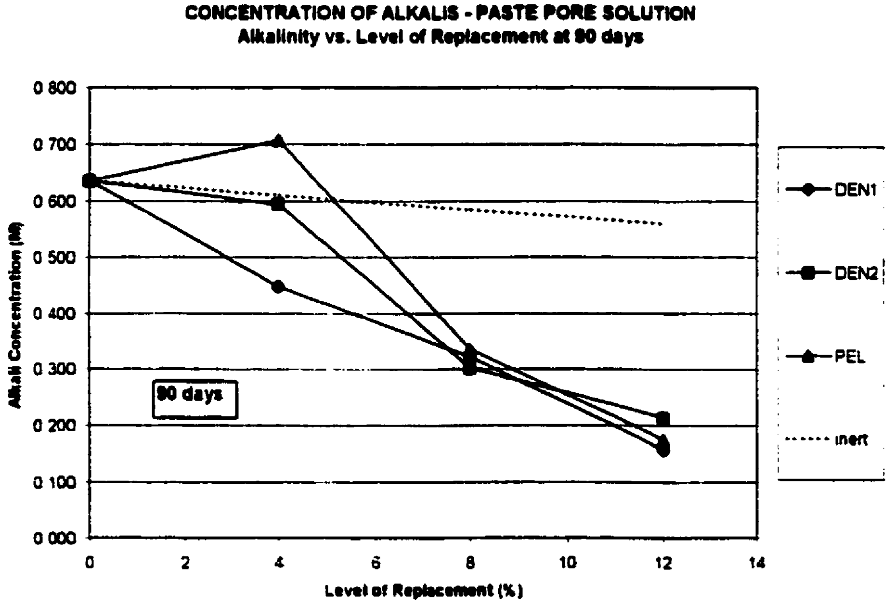

Figure 4.3.6 : Effect of SF level of replacement and product form on pore solution alkalinity at 90 days

4.3.2 Effect of Silica Content of Silica Fume

The pore solution analysis of the pastes made with the NS silica fume gave fairly straightforward results. At all ages tested to date, the addition of the silica fume lowered the pore solution alkalinity when compared to that of the neat cement paste. Also, an increased level of silica fume replacement of Portland cement caused an even greater decrease in the alkali level of the pore solution, (details in Appendix D).

The results of the pore solution analysis of the low-silica silica fume pastes were not as clear. An increase in the replacement level of LS silica fume resulted in a larger decrease in the alkali concentration for the pastes analyzed at 28 days and later ages, (details in Appendix D). Also, at 90 days, the alkali concentration of the pore solution from the 4% LS paste was higher than the sample from the OPC sample at the same age.

Figures 4.3.7, 4.3.8, and 4.3.9 present the pore solution analysis results comparing the 4%, 8%, and 12% replacement mixtures respectively for both silica fumes. It is evident from all three figures that a change in amorphous silica content of the silica fume does affect the resulting pore solution alkalinity. This effect is much more dramatic at the 4% level of replacement, but there is still a significant difference even with the 12% SF samples. It may be that silica fumes with lower SiO_2 do not have the capacity to bind as much of the alkalies in the formation of supplementary C-S-H as do silica fumes with higher amorphous silica contents. However, there may be some point of equivalency

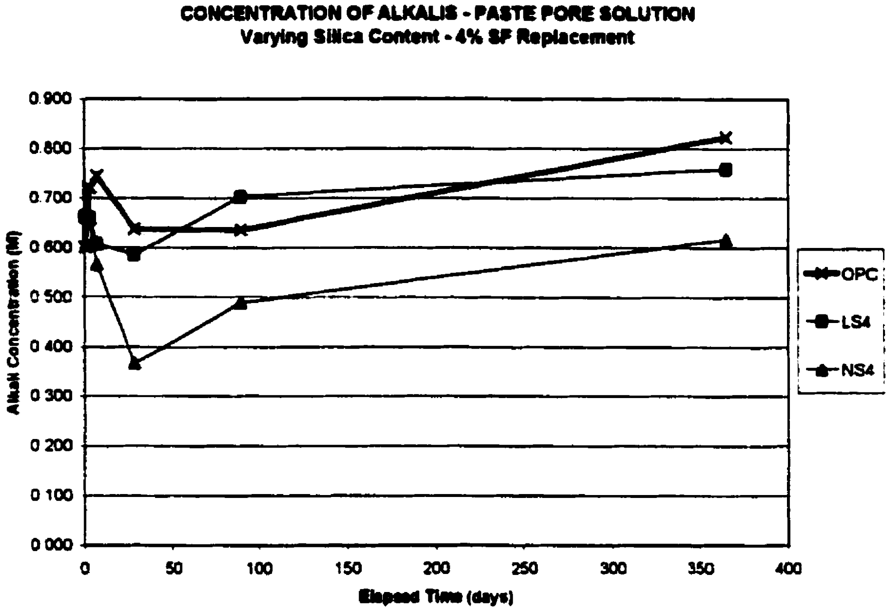

Figure 4.3.7 : Effect of SiO_2 of silica fume on pore solution alkalinity with time at 4% level of replacement

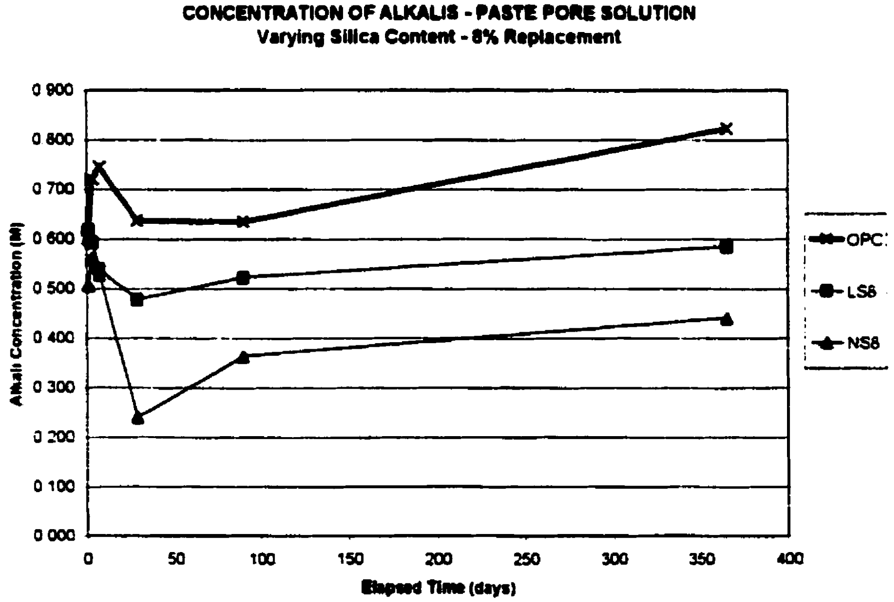

Figure 4.3.8 : Effect of SiO_2 of silica fume on pore solution alkalinity with time at 8% level of replacement

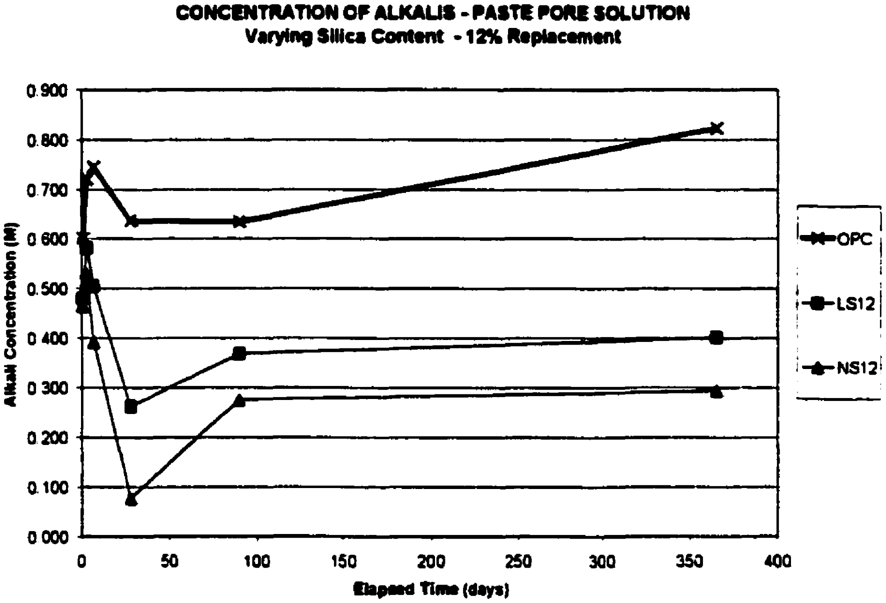

Figure 4.3.9 : Effect of SiO_2 of silica fume on pore solution alkalinity with time at 12% level of replacement

between a higher replacement level of SF with lower SiO_2 and lower replacement level of SF with higher SiO_2. Further work should be performed to investigate this possibility.

Figure 4.3.10 shows the effect of level of SF replacement on the alkali concentration of the paste samples determined at 90 days. It is of interest to note that the 4% low-silica paste specimen had a higher alkali concentration than that which would be expected to occur with 4% of an inert diluent. The use of lower grade silica fumes at low replacement levels appears to be ineffective.

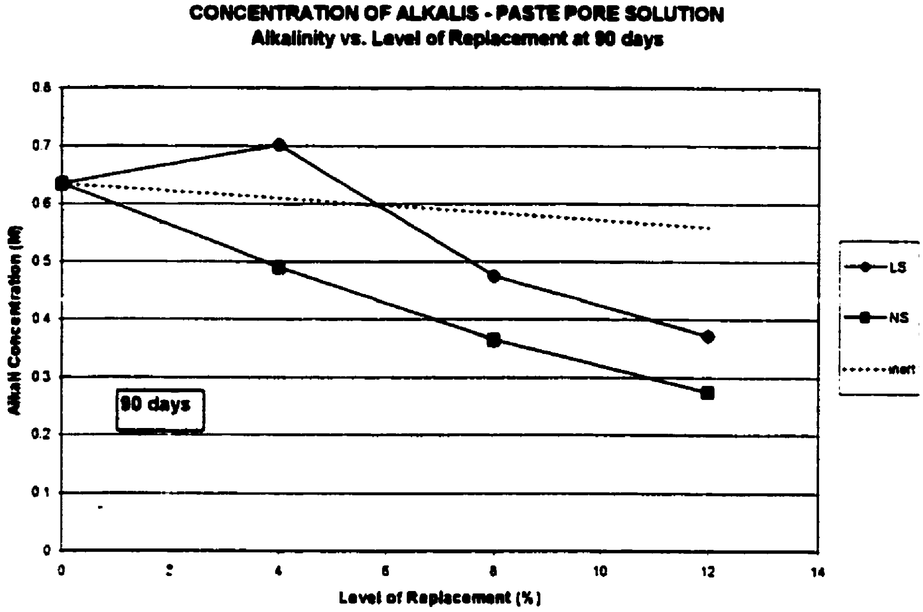

Figure 4.3.10 : Effect of SF level of replacement and SiO_2 content on pore solution alkalinity at 90 days

4.4 SUMMARY OF RESULTS

4.4.1 Effect of Product Form of Silica Fume

In Table 4.4.1, the performance of the various product forms of silica fume is ranked in terms of the three studies performed in this research program. The number 1 indicates the best performance and number 6 indicates the worst performance comparatively. The numbers in italics simply mean that the results available are not as advanced as the others, so those rankings are based on trends to date.

Table 4.4.1 - Summary of Results

Form Of SF	Concrete Prism Expansion (after 180 days)			Mortar Bar Expansion (after 28 days)			Paste Pore Solution Study (after 90 days)		
	4%	8%	12%	4%	8%	12%	4%	8%	12%
UND	1	1	1	1	1	1	3	1	*2*
PEL	6	1	1	3	5	5	6	1	1
DEN1	5	1	1	5	4	4	2	1	1
DEN2	3	1	1	4	3	3	4	1	1
SLU	*2*	*1*	*1*	2	2	2	*1*	*1*	*1*
OPC	4	6	6	6	6	6	5	6	6

Some issues warrant further discussion in terms of a combination of the results of all three studies performed in this program. The first issue was mentioned earlier in this report. No significant difference in performance was observed in terms of concrete prism testing or pore solution alkalinity between the various product forms used at 8 and 12% replacement, while differences were observed at 4% replacement. However, for the mortar bar testing, noticeable differences in performance were found between the various forms at all levels of replacement. One possible contributing factor to these occurences could be the difference in mixers used to cast the paste specimens, mortar bars, and concrete prisms. The paste specimens were cast in a high-speed, high-shear, blender mixer which possibly had the ability to break apart and better disperse the silica fume, no matter what form was used. Also, when casting the concrete prisms, there is a very short dry blend period (i.e. 20 seconds) where the silica fume and cement are being intermixed with the sand and two sizes of coarse aggregate. This blending could help break up any silica fume agglomerations present and better disperse the SF so that performance may be more similar. There is no such dry blend period for the mortar bar casting and there is no large coarse aggregate to provide as strong of a grinding action during mixing.

Comparison of Figures 4.1.1 and 4.1.2 lead to further possible explanations. The other factor that could have influenced these results is the severe test conditions (80°C, 1.0 M NaOH) which are employed in the mortar bar test. These extreme conditions could force an observable difference in performance between different mixtures, even when comparing different high-performance mixtures. This is in contrast to the conditions used in the concrete prism test (38°C, moist storage). The potential does exist, however, that differences may be noticed at 8 and 12% replacement levels with the concrete prism results at later ages, i.e. approaching 2 years or more. In other words, possibly the trends observed in the accelerated mortar bar test results have not yet had time to manifest in the concrete prism test. Alternatively, it could be that product form may never cause

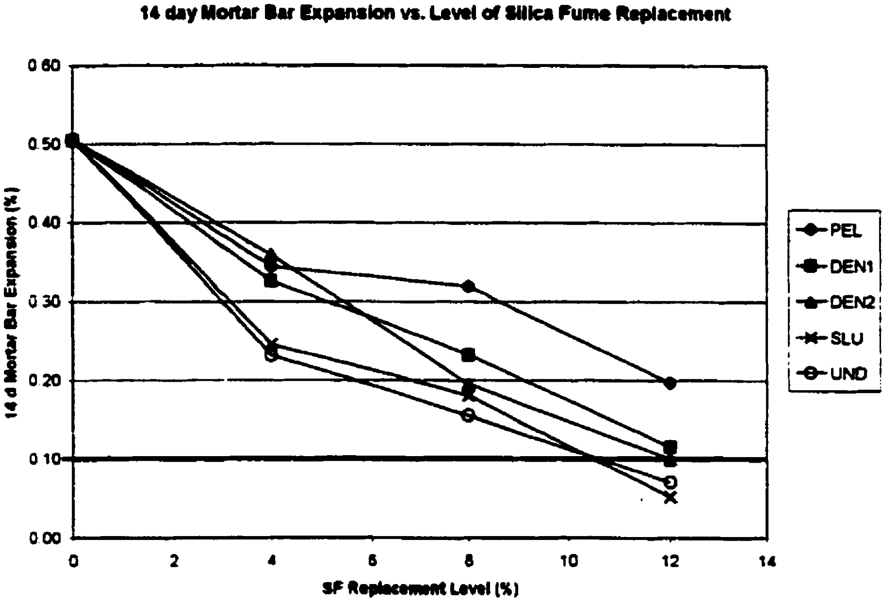

Figure 4.1.1 : Effect of SF level of replacement and product form on 14 day mortar bar expansion

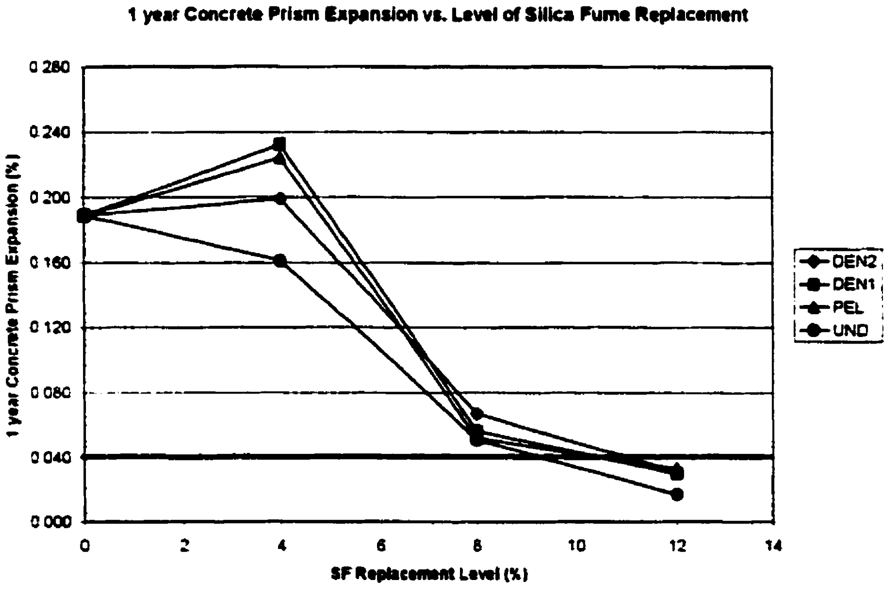

Figure 4.1.2 : Effect of SF level of replacement and product form on 1 year concrete prism expansion

differences in the concrete prism test results at 8 or 12% replacement. In the concrete prism test there is a finite, internal supply of alkalis available for ASR to occur. In contrast, the mortar bar test conditions give a nearly unlimited, external source of alkalis available for reaction. It could be that there are SF agglomerations present in both the mortar bars and the concrete prisms, and the degree to which these clusters are present is linked to the form of silica fume used. In the case of the mortar bars, there is a sufficient supply of alkali available to cause these agglomerations to react and cause ASR expansion to varying degrees for the various product forms studied. For the concrete prism test, the alkalis may have been exhausted, and as such, no difference in performance at 8 and 12% replacement for the varying product forms was observed. A final possible explanation could be the influence of cross-section size. An agglomeration present in a mortar bar would have relatively more significant effects on expansion results than an agglomeration of the same size present in a concrete prism, since mortar bars are significantly smaller in dimensions than concrete prisms.

It is interesting to compare the performance of the two densified fumes in the three studies. DEN2 was better at controlling mortar bar and prism expansions than DEN1, but DEN1 consistently had lower pore solution alkalinity than DEN2. DEN1 had a higher bulk density than DEN2. As such, it could be harder to disperse evenly through a mixture, and thus not be able to control expansion as well as DEN2. In the paste pore solution study, a high-speed, high-shear mixer was used, which would help better disperse even a

SF of high density. Also, DEN1 has a much lower Na_2O_{eq} than DEN2. It is most likely that the higher alkali content of DEN2 explains why the paste samples made with DEN2 had higher pore solution alkalinities than those made with DEN1, even though DEN2 was better at controlling the ASR expansion of Spratt aggregate.

The pelletized silica fume consistently performed poorly. At times, its inclusion in a mixture gave results no better or worse than those found with the OPC control samples (Figures 4.1.1, 4.3.2, 4.3.4, and 4.3.5). It should be reiterated that unground pelletized silica fume is not marketed for use in industry, nor is it recommended for use as an SCM in concrete in ACI C234R-96. It was simply included to evaluate an extreme case. It is interground with cement clinker to form blended silica fume cements. These results do emphasize though the importance of stringent grinding techniques and quality control monitoring of the resulting grain sizes. If many pellets of SF go through the intergrinding process without getting broken down, the properties of the concrete in which the blended SF is used could very well be equal or even worse than those of an OPC concrete in terms of controlling ASR. To add SF without any improvement in performance would be an inefficient use of materials. It could also result in large repair costs later on if the mixture does not have as good durability as was desired for the exposure conditions.

Specimens containing the undensified or slurried silica fumes consistently performed better in the accelerated mortar bar test, as well as at a 4% replacement level in both the concrete prism and pore solution studies. These forms of silica fume are simply more conducive to adequate dispersion throughout a mixture and make it easier for all the benefits of silica fume to be realized

4.4.2 Effect of Silica Content of Silica Fume

To summarize the results in terms of the effect of SiO_2 content on silica fume's ability to control alkali-silica reaction is quite simple; the research work performed in this program indicates that mixtures containing lower grade silica fumes will be susceptible to ASR expansion. This was true for the three levels of replacement tested in this study, namely 4%, 8%, and 12%. All three levels of replacement failed the accelerated mortar bar test expansion criterion. Also, the long-term alkali concentrations in the pore solution of the cement pastes were quite high, even with 12% replacement by low-silica silica fume of OPC, (0.40 M after 1 year). As mentioned previously, concrete prisms should be cast and monitored to confirm these results. It would also be of interest to test lower grade silica fumes at higher levels of replacement, such as 15%; however, even if expansion due to alkali-silica reaction can be controlled by low-silica silica fumes at higher levels of replacement, there are several other practical problems that could still prohibit these high levels of replacement from being used in the field. One main problem would be the fact that many organizations have limits on the maximum allowable silica fume replacement in concrete due to the increased potential for placing problems during construction. It should also be considered that low-silica silica fume would perhaps be effective when used in combination which other supplementary cementing materials. In all, more research will have to be done of the use of low-silica silica fumes in terms of control of ASR, as well as other durability issues, before it is considered for use in practice.

5 CONCLUSIONS

The following conclusions are drawn from the results obtained to date in this study. In the case of the concrete prism expansion results, these conclusions are indeed preliminary as the prisms must be monitored for at least another year according to the recommendations of the CSA.

5.1 EFFECT OF PRODUCT FORM OF SILICA FUME

1. With all forms of silica fume tested, 4% replacement was not sufficient to control ASR expansion of Spratt aggregate with high-alkali cement. At a 4% level of replacement, the product form of silica fume does cause differences in the concrete prism expansion up to 1 year, the accelerated mortar bar test results, and the resulting pore solution alkalinity of paste specimens. At this level of replacement, the undensified and slurried forms of silica fume consistently performed the best, while the pelletized form of silica fume performed poorer than the other mixtures.

2. Concrete prisms containing 8% or 12% silica fume expand similarly up to 1 year, regardless of the product form of silica fume. In addition, the alkalinity of paste pore solutions containing 8% or 12% silica fume replacement by mass were similar, regardless of the product form of silica fume.

3. The product form of silica fume caused differences in results of the accelerated mortar bar test at all levels of replacement. The undensified and slurried forms of silica fume were best at mitigating the expansion due to ASR. The pelletized form of silica fume performed poorer than all other mixtures, as was expected.

4. All mortar bar mixtures failed to control deleterious ASR expansion of Spratt aggregate, with the exception of the 12% replacement with undensified and slurried silica fume mixtures.

5.2 EFFECT OF SILICA CONTENT OF SILICA FUME

1. Mortar bar mixtures containing low-silica silica fume at levels of replacement up to 12% failed to control ASR expansion of Spratt aggregate.

2. Pore solution alkalinity of paste specimens containing 4% low-silica silica fume were comparable to those of the OPC paste specimens at all ages, up to 1 year.

3. The long-term alkali concentrations of low-silica silica fume paste specimens remained high at both 8% (≅ 0.600 M at 1 year) and 12% (≅ 0.400 M at 1 year).

4. Based on the preliminary results of this study, it appears that, at typical rates of replacement, the lower silica content does affect a silica fume's ability to control expansion due to alkali-silica reaction.

6 RECOMMENDATIONS

1. Continue monitoring concrete prism expansion to a minimum of 2 years.

2. Perform 2 year pore solution analysis of paste specimens.

3. Examine samples of mortar bars and paste specimens, which have been saved and stored under vacuum, using scanning electron microscopy.

4. Perform thermo-gravimetric analysis on samples of paste specimens that have been saved and stored under vacuum.

5. Repeat this study using blended silica fume cements made with different forms of silica fume.

6. Test concrete prisms at 4%, 8%, and 12% replacement of OPC by mass of silica fume using the low-silica and control silica silica fumes.

7. Test mortar bars made with higher replacement levels (i.e. >12%) of the low-silica silica fume to see if higher levels of replacement of Portland cement would be sufficient for the mixture to pass the ASTM expansion limit criterion.

8. Test mortar bars made with the low-silica silica fume in combination with fly ash and/or slag to see if these ternary blends pass the ASTM expansion limit criterion.

9. Perform flame photometry analysis as soon as possible after a pore solution sample has been collected since even good sealing techniques did not seem to stop evaporation from the solution containers. It is suggested that samples be weighed immediately after collection and directly before testing to monitor evaporation.

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APPENDIX A

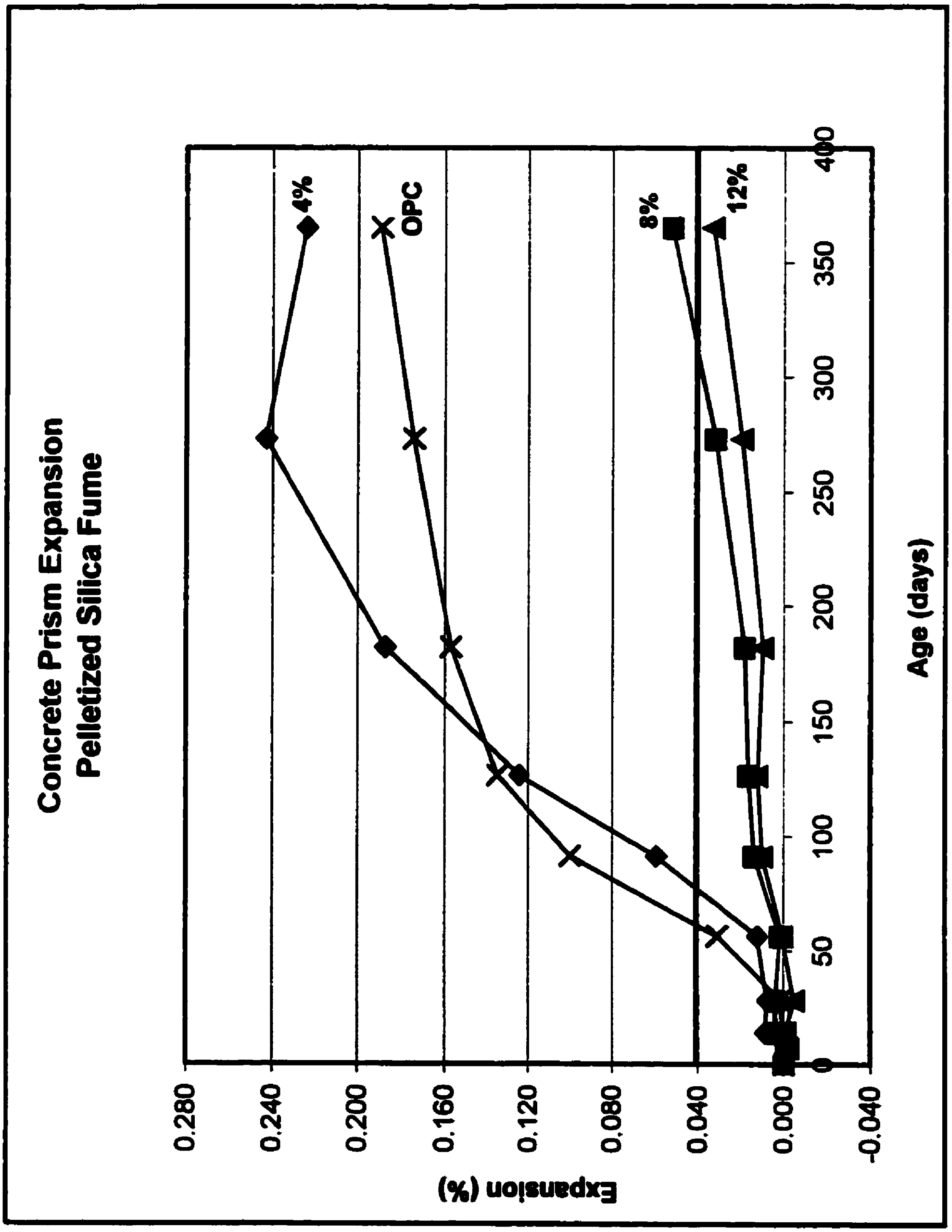
CHEMICAL ANALYSIS OF CEMENTITIOUS MATERIALS

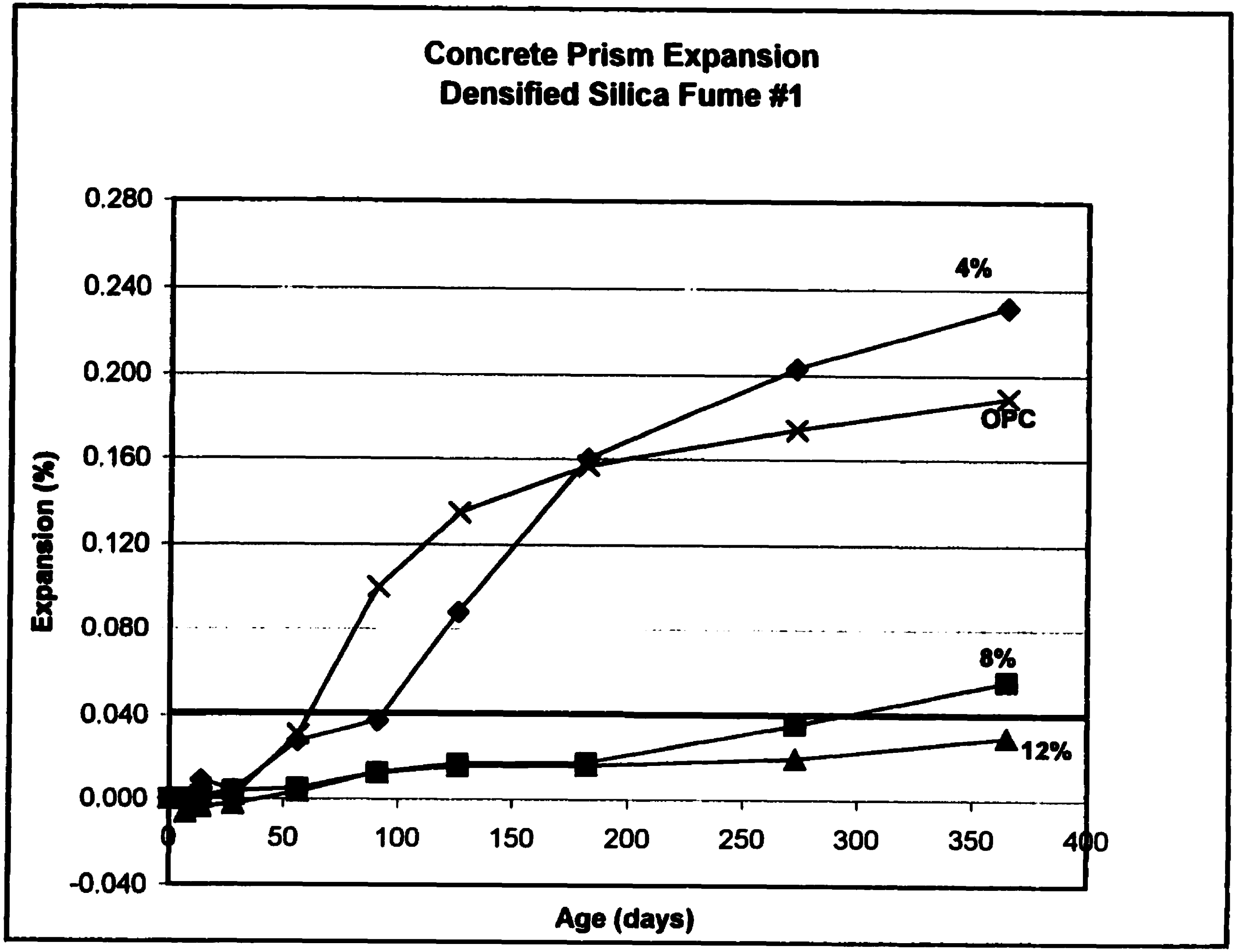
Chemical Analysis of Cementitious Materials

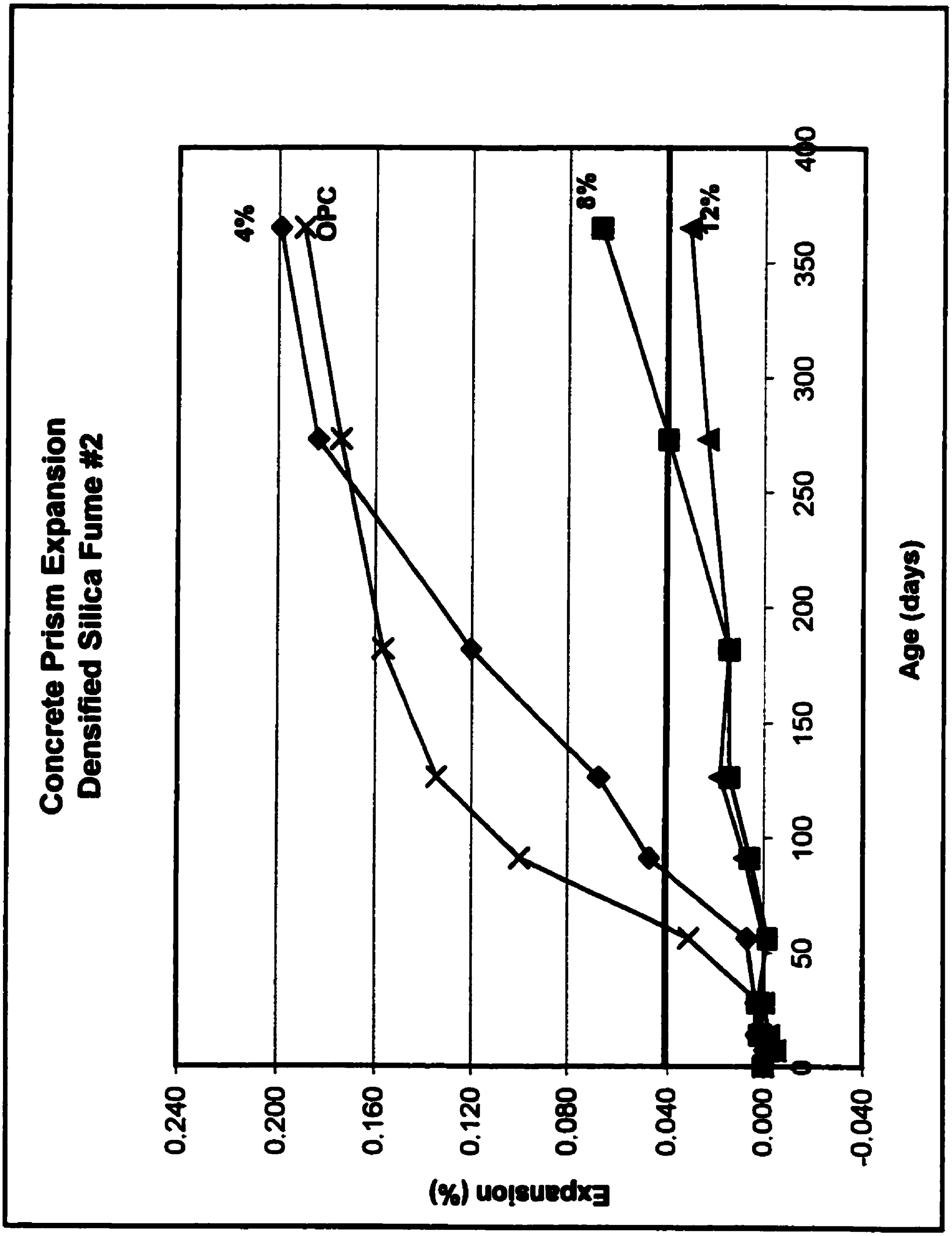
MATERIAL	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	LSO_3	K_2O	Na_2O	TiO_2	P_2O_5	Mn_2O_3	SrO	LOI	TOTAL	Eq. Alk.
OPC	19.82	5.13	2.20	62.72	2.64	3.15	1.08	0.27	0.26	0.19	0.04	0.09	2.16	99.75	0.98
Low Silica SF	68.21	1.55	12.27	4.57	1.16	1.02	1.37	0.26	0.05	0.08	0.73	0.09	5.59	96.94	1.16
Normal Silica SF	88.40	0.60	5.42	0.84	0.73	0.71	1.12	0.24	0.02	0.05	0.10	0.03	3.24	101.50	0.98
Pelletized SF	88.85	0.25	0.08	0.44	0.18	0.21	0.62	0.07	0.01	0.09	0.02	0.01	10.01	100.85	0.48
Densified SF #1	94.83	0.22	0.06	0.94	0.34	0.28	0.66	0.17	0.01	0.13	0.01	0.02	3.26	100.92	0.60
Densified SF #2	90.73	0.39	1.11	0.52	3.37	0.27	0.96	0.20	0.01	0.09	0.05	0.03	2.62	100.36	0.83
Undensified SF	95.52	0.15	0.04	0.30	0.15	0.22	0.75	0.10	0.01	0.11	0.01	0.01	2.11	99.50	0.59
Slurried SF	94.54	0.23	0.03	0.39	0.08	0.21	0.50	0.08	0.01	0.16	0.01	0.01	4.02	100.28	0.41

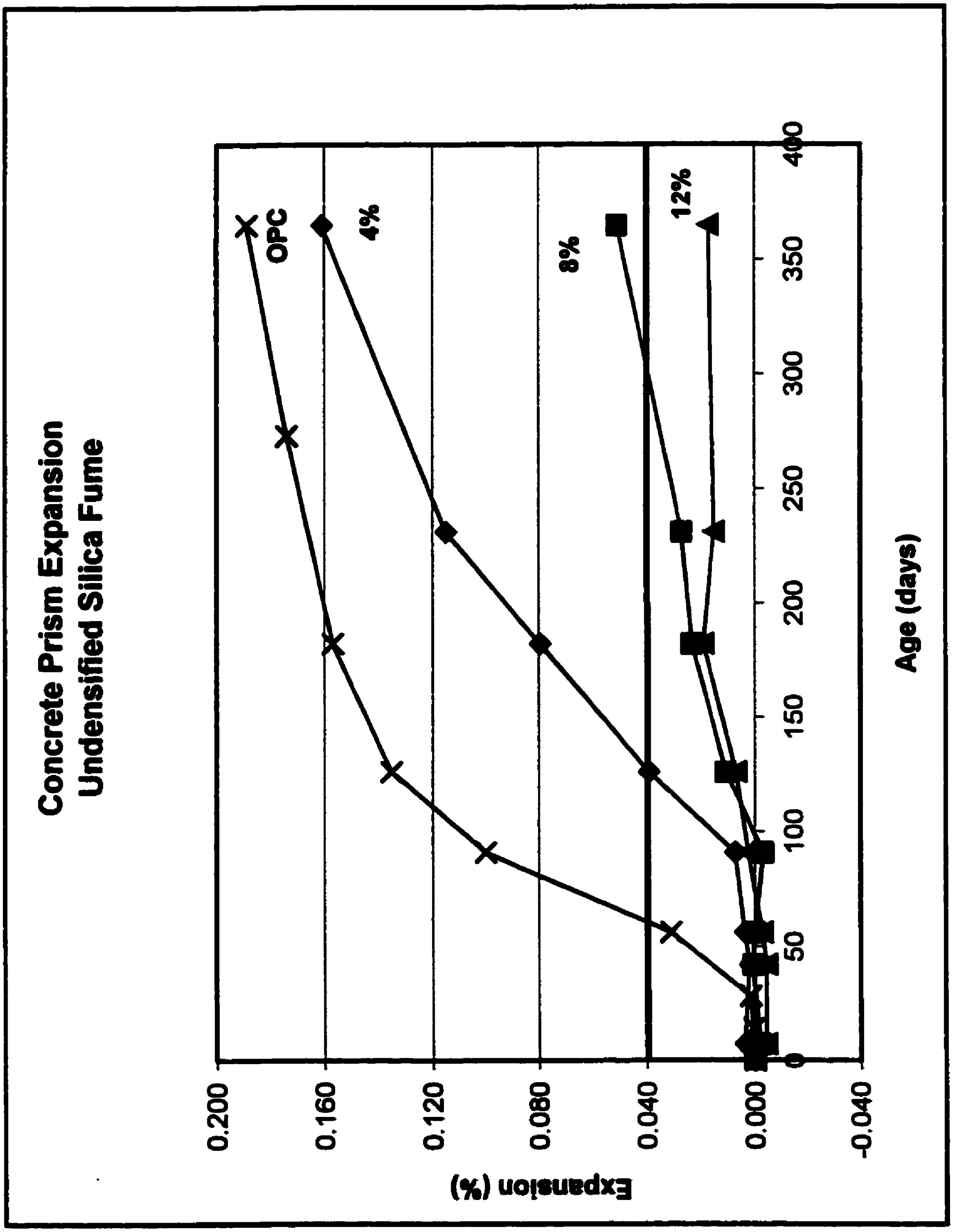
APPENDIX B

CONCRETE PRISM EXPANSION DATA AND PLOTS

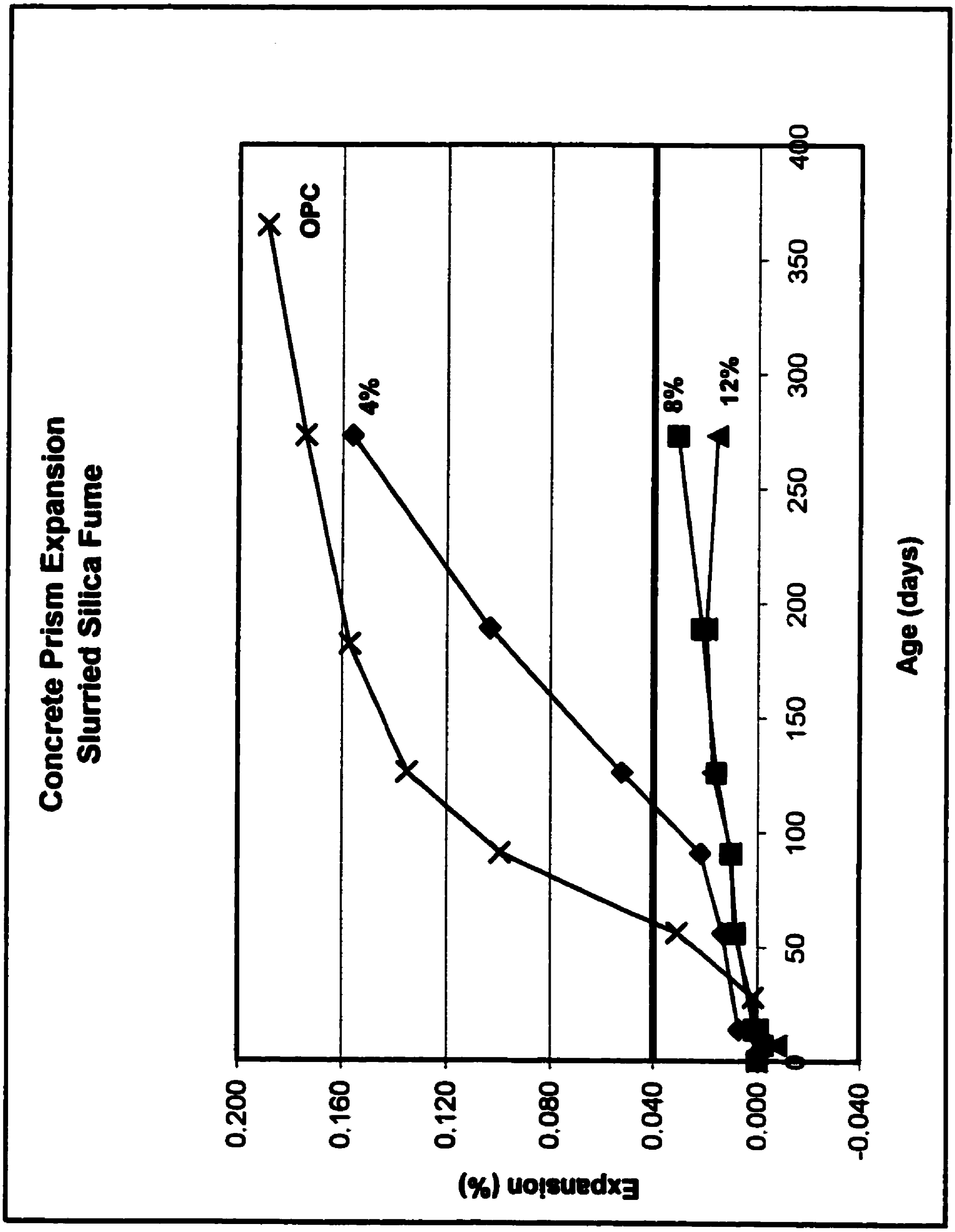

Concrete Prism Expansion
Pelletized Silica Fume
Expansion (%)
0.280
0.240
0.200
0.160
0.120
0.080
0.040
0.000
-0.040
Age (days)
0
50
100
150
200
250
300
350
400
4%
OPC
8%
12%

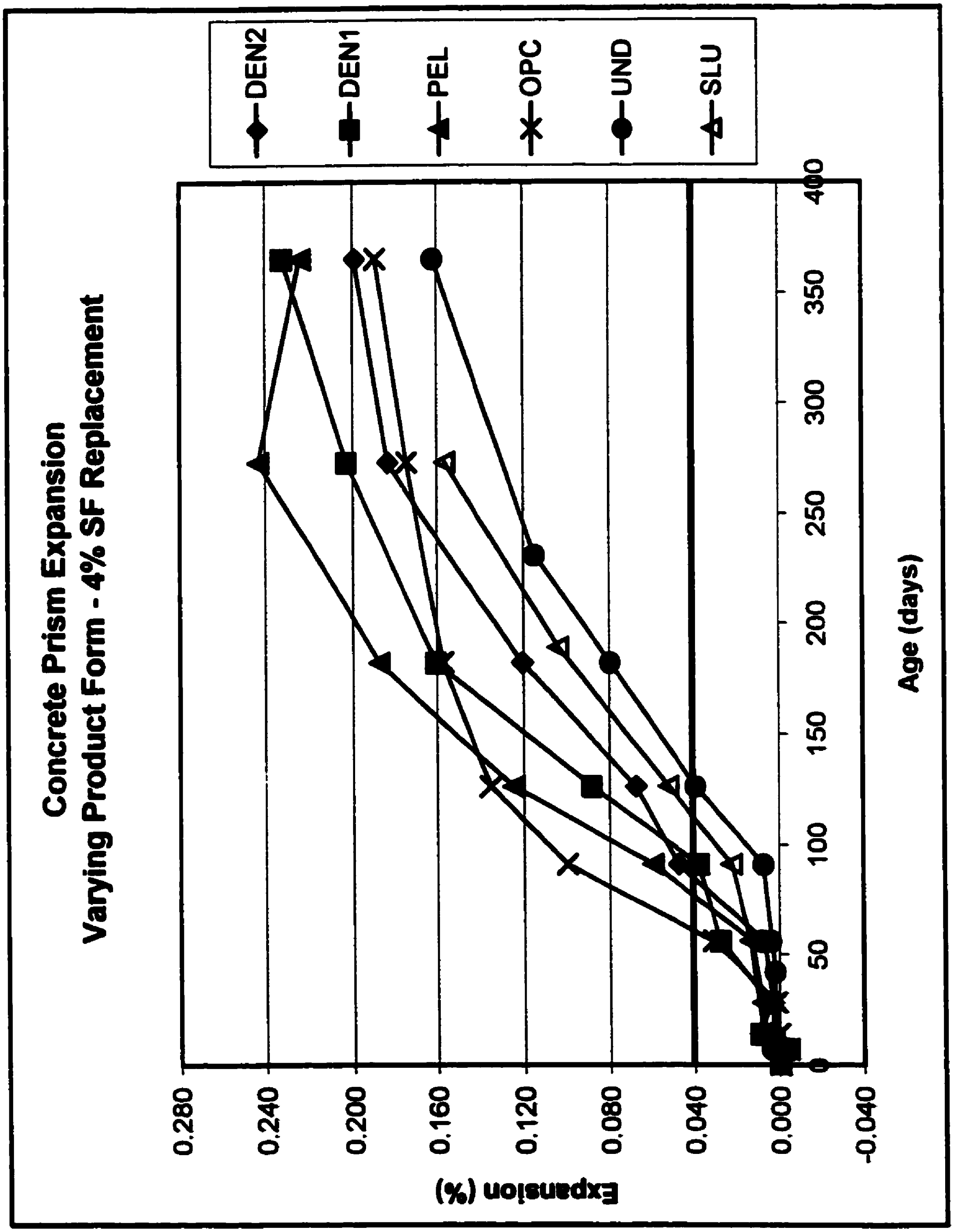

Concrete Prism Expansion
Densified Silica Fume #1
Expansion (%)
0.280
0.240
0.200
0.160
0.120
0.080
0.040
0.000
-0.040
0
50
100
150
200
250
300
350
400
Age (days)
4%
OPC
8%
12%

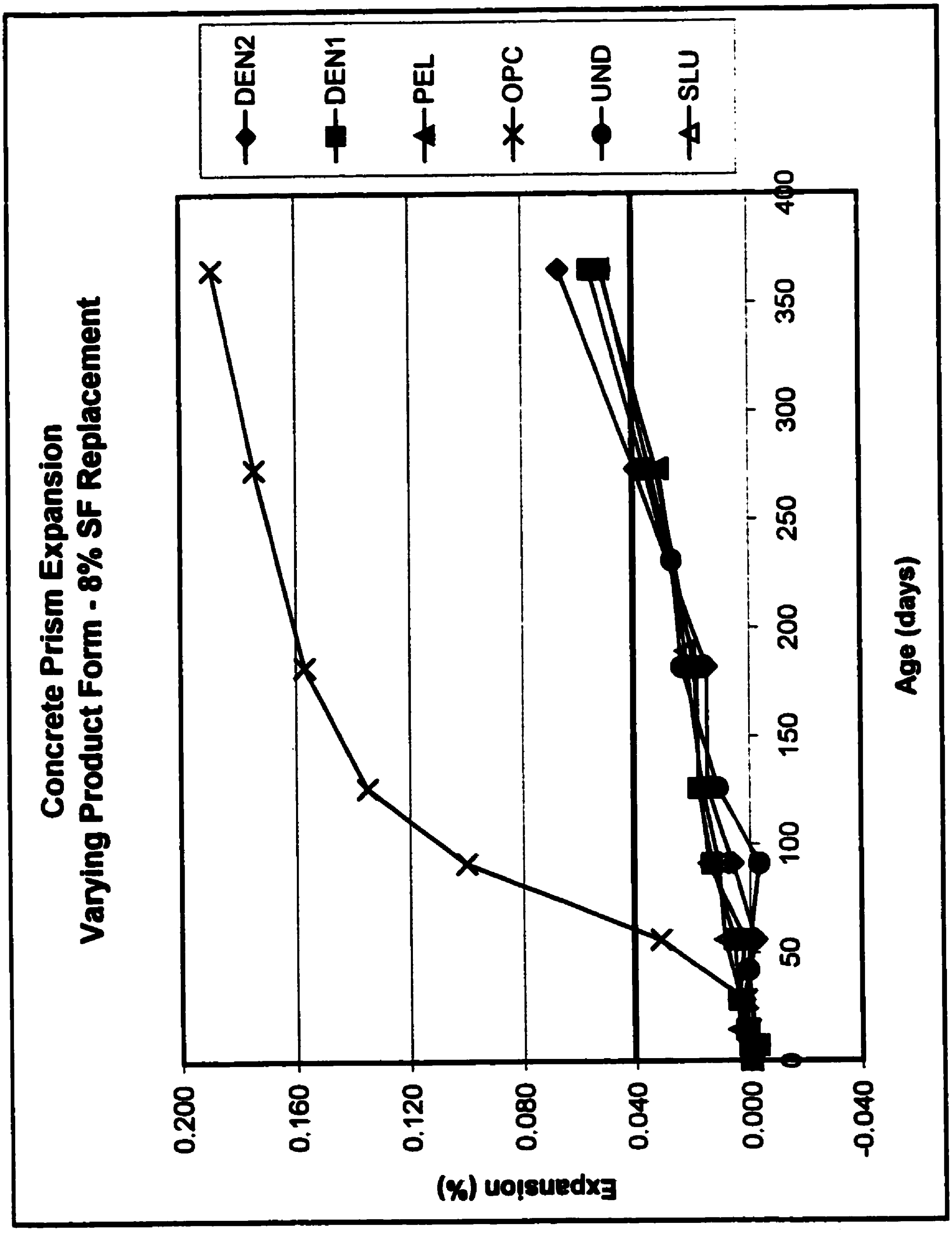

Concrete Prism Expansion
Densified Silica Fume #2
Expansion (%)
0.240
0.200
0.160
0.120
0.080
0.040
0.000
-0.040
Age (days)
0
50
100
150
200
250
300
350
400
4%
OPC
8%
12%

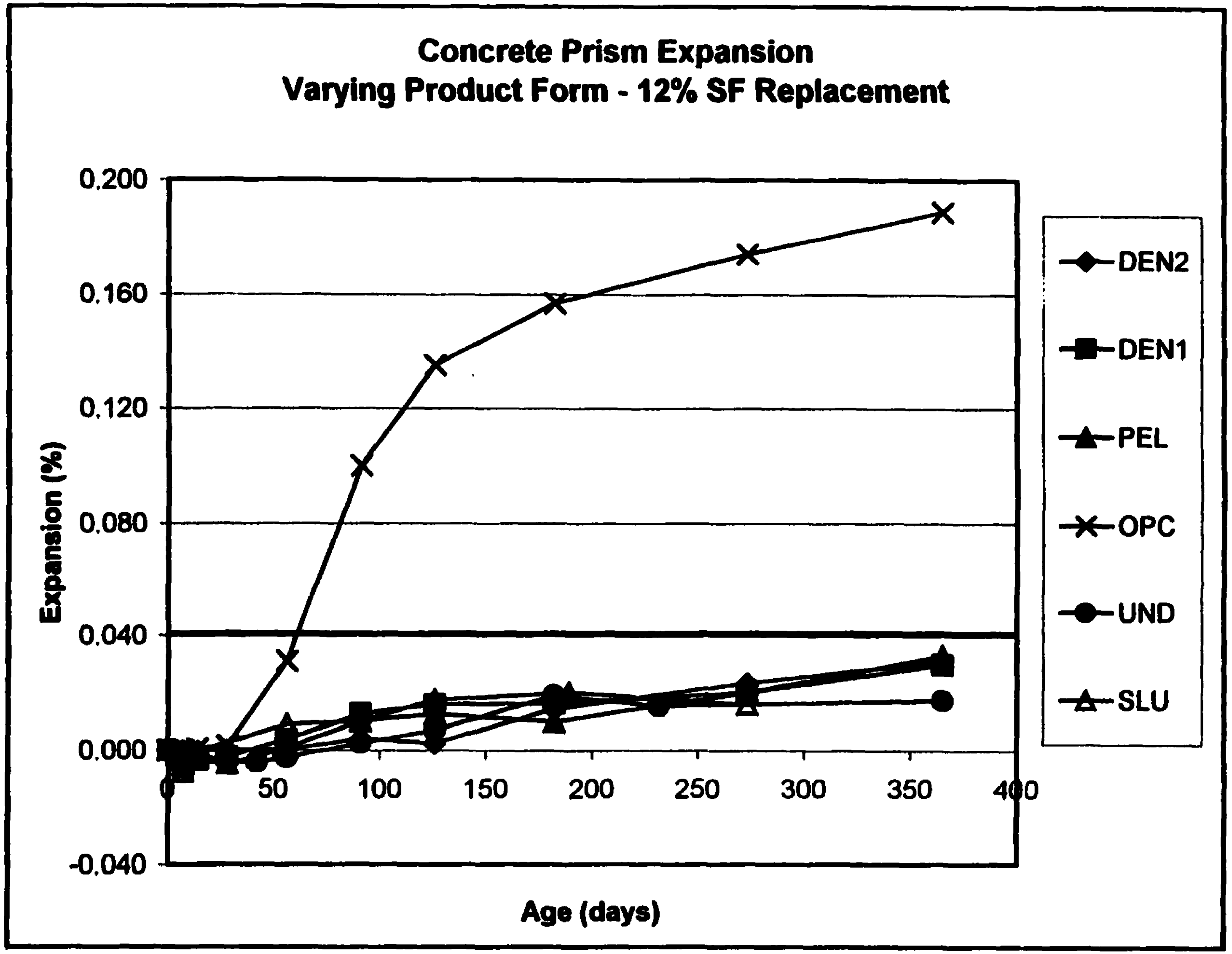


Concrete Prism Expansion
Undensified Silica Fume

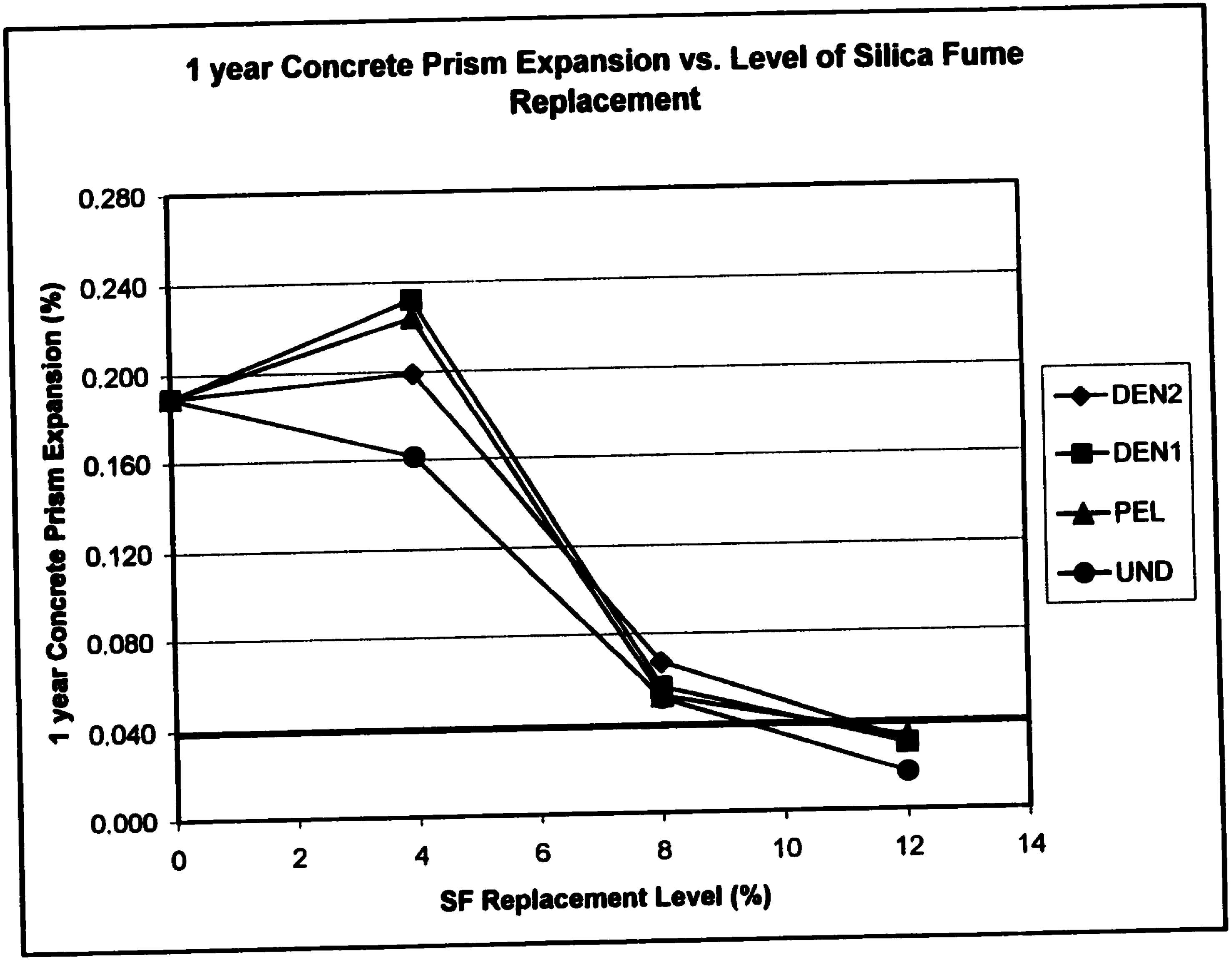

Concrete Prism Expansion
Slurried Silica Fume
Expansion (%)
0.200
0.160
0.120
0.080
0.040
0.000
-0.040
Age (days)
0
50
100
150
200
250
300
350
400
OPC
4%
8%
12%


Concrete Prism Expansion
Varying Product Form - 4% SF Replacement
DEN2
DEN1
PEL
OPC
UND
SLU
Expansion (%)
0.280
0.240
0.200
0.160
0.120
0.080
0.040
0.000
-0.040
Age (days)
0
50
100
150
200
250
300
350
400


Concrete Prism Expansion
Varying Product Form - 8% SF Replacement
DEN2
DEN1
PEL
OPC
UND
SLU
Expansion (%)
0.200
0.160
0.120
0.080
0.040
0.000
-0.040
Age (days)
0
50
100
150
200
250
300
350
400



Concrete Prism Expansion
Varying Product Form - 12% SF Replacement


1 year Concrete Prism Expansion vs. Level of Silica Fume Replacement
1 year Concrete Prism Expansion (%)
0.280
0.240
0.200
0.160
0.120
0.080
0.040
0.000
0
2
4
6
8
10
12
14
SF Replacement Level (%)
DEN2
DEN1
PEL
UND

Mix PEL 4% **Cast Date** 21-Jul-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	22-Jul-98	17.838	0.000	17.557	0.000	18.398	0.000	0.000
7	29-Jul-98	17.836	-0.001	17.552	-0.002	18.393	-0.002	-0.002
14	05-Aug-98	17.855	0.007	17.589	0.013	18.416	0.007	0.009
28	19-Aug-98	17.858	0.008	17.577	0.008	18.418	0.008	0.008
56	23-Sep-98	17.862	0.010	17.571	0.006	18.455	0.023	0.013
91	22-Oct-98	17.990	0.061	17.706	0.060	18.543	0.058	0.059
126	25-Nov-98	18.207	0.148	17.846	0.116	18.674	0.110	0.125
182	21-Jan-99	18.425	0.235	17.955	0.159	18.818	0.168	0.187
273	24-Apr-99	18.594	0.302	18.066	0.204	18.955	0.223	0.243
365	21-Jul-99	18.532	0.278	18.026	0.188	18.917	0.208	0.224

Mix PEL 8% **Cast Date** 21-Jul-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	22-Jul-98	22.300	0.000	24.405	0.000	23.095	0.000	0.000
7	29-Jul-98	22.295	-0.002	24.405	0.000	23.092	-0.001	-0.001
14	05-Aug-98	22.311	0.004	24.414	0.004	23.105	0.004	0.004
28	19-Aug-98	22.314	0.006	24.414	0.004	23.102	0.003	0.004
56	23-Sep-98	22.311	0.004	24.444	0.016	23.058	-0.015	0.002
91	22-Oct-98	22.333	0.013	24.438	0.013	23.135	0.016	0.014
126	25-Nov-98	22.339	0.016	24.446	0.016	23.142	0.019	0.017
182	21-Jan-99	22.344	0.018	24.450	0.018	23.147	0.021	0.019
273	24-Apr-99	22.375	0.030	24.493	0.035	23.169	0.030	0.032
365	21-Jul-99	22.437	0.055	24.529	0.050	23.223	0.051	0.052

Mix PEL 12% **Cast Date** 21-Jul-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	22-Jul-98	25.414	0.000	26.028	0.000	25.395	0.000	0.000
7	29-Jul-98	25.411	-0.001	26.022	-0.002	25.388	-0.003	-0.002
14	05-Aug-98	25.407	-0.003	26.018	-0.004	25.405	0.004	-0.001
28	19-Aug-98	25.410	-0.002	26.011	-0.007	25.379	-0.006	-0.005
56	23-Sep-98	25.416	0.001	26.030	0.001	25.395	0.000	0.001
91	22-Oct-98	25.442	0.011	26.048	0.008	25.424	0.012	0.010
126	25-Nov-98	25.446	0.013	26.051	0.009	25.434	0.016	0.013
182	21-Jan-99	25.441	0.011	26.051	0.009	25.420	0.010	0.010
273	24-Apr-99	25.473	0.024	26.074	0.018	25.440	0.018	0.020
365	21-Jul-99	25.501	0.035	26.108	0.032	25.478	0.033	0.033

Mix DEN1 4% **Cast Date** 22-Jul-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	23-Jul-98	19.285	0.000	19.545	0.000	19.345	0.000	0.000
7	30-Jul-98	19.280	-0.002	19.542	-0.001	19.354	0.004	0.000
14	06-Aug-98	19.300	0.006	19.567	0.009	19.377	0.013	0.009
28	20-Aug-98	19.280	-0.002	19.552	0.003	19.376	0.012	0.004
56	24-Sep-98	19.359	0.030	19.646	0.040	19.380	0.014	0.028
91	22-Oct-98	19.377	0.037	19.642	0.039	19.439	0.038	0.038
126	26-Nov-98	19.497	0.085	19.774	0.092	19.567	0.089	0.088
182	22-Jan-99	19.649	0.146	19.980	0.174	19.748	0.161	0.160
273	24-Apr-99	19.761	0.190	20.058	0.205	19.881	0.214	0.203
365	22-Jul-99	19.835	0.220	20.116	0.228	19.961	0.246	0.232

Mix DEN1 8% **Cast Date** 22-Jul-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	23-Jul-98	21.741	0.000	22.036	0.000	22.204	0.000	0.000
7	30-Jul-98	21.741	0.000	22.038	0.001	22.204	0.000	0.000
14	06-Aug-98	21.746	0.002	22.041	0.002	22.205	0.000	0.002
28	20-Aug-98	21.748	0.003	22.059	0.009	22.203	0.000	0.004
56	24-Sep-98	21.747	0.003	22.057	0.008	22.216	0.005	0.005
91	22-Oct-98	21.771	0.012	22.073	0.015	22.233	0.012	0.013
126	26-Nov-98	21.785	0.018	22.077	0.016	22.249	0.018	0.017
182	22-Jan-99	21.789	0.020	22.077	0.016	22.248	0.018	0.018
273	24-Apr-99	21.836	0.038	22.119	0.033	22.292	0.035	0.036
365	22-Jul-99			22.189	0.061	22.331	0.051	0.056

Mix DEN1 12% **Cast Date** 22-Jul-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	23-Jul-98	18.797	0.000	20.064	0.000	19.665	0.000	0.000
7	30-Jul-98	18.772	-0.010	20.048	-0.006	19.659	-0.002	-0.006
14	06-Aug-98	18.785	-0.005	20.051	-0.005	19.661	-0.002	-0.004
28	20-Aug-98	18.786	-0.004	20.058	-0.002	19.665	0.000	-0.002
56	24-Sep-98	18.821	0.010	20.083	0.008	19.649	-0.006	0.004
91	22-Oct-98	19.148	0.140	20.084	0.008	19.709	0.018	0.013
126	26-Nov-98	18.834	0.015	20.094	0.012	19.718	0.021	0.016
182	22-Jan-99	18.846	0.020	20.091	0.011	19.712	0.019	0.016
273	24-Apr-99	18.846	0.020	20.110	0.018	19.722	0.023	0.020
365	22-Jul-99	18.863	0.026	20.138	0.030	19.749	0.034	0.030

Mix DEN2 4% Cast Date 29-Jul-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	30-Jul-98	22.600	0.000	22.448	0.000	22.137	0.000	0.000
7	06-Aug-98	22.597	-0.001	22.440	-0.003	22.145	0.003	0.000
14	13-Aug-98	22.610	0.004	22.451	0.001	22.147	0.004	0.003
28	27-Aug-98	22.613	0.005	22.450	0.001	22.147	0.004	0.003
56	24-Sep-98	22.624	0.010	22.460	0.005	22.154	0.007	0.007
91	27-Oct-98	22.679	0.032	22.657	0.084	22.206	0.028	0.048
126	12-Apr-98	22.761	0.064	22.607	0.064	22.325	0.075	0.068
182	29-Jan-99	22.898	0.119	22.731	0.113	22.460	0.129	0.121
273	30-Apr-99	23.033	0.173	22.869	0.168	22.658	0.208	0.183
365	29-Jul-99	23.091	0.196	22.903	0.182	22.682	0.218	0.199

Mix DEN2 8% Cast Date 29-Jul-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	30-Jul-98	19.078	0.000	18.809	0.000	17.979	0.000	0.000
7	06-Aug-98	19.070	-0.003	18.806	-0.001	17.970	-0.004	-0.003
14	13-Aug-98	19.080	0.001	18.801	-0.003	17.997	0.007	0.002
28	27-Aug-98	19.081	0.001	18.807	-0.001	17.996	0.007	0.002
56	24-Sep-98	19.068	-0.004	18.808	0.000	17.975	-0.002	-0.002
91	27-Oct-98	19.084	0.002			18.002	0.009	0.006
126	12-Apr-98	19.105	0.011	18.848	0.016	18.020	0.016	0.014
182	29-Jan-99	19.112	0.014	18.847	0.015	18.016	0.015	0.015
273	30-Apr-99	19.180	0.041	18.901	0.037	18.083	0.042	0.040
365	29-Jul-99	19.250	0.069			18.142	0.065	0.067

Mix DEN2 12% Cast Date 29-Jul-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	30-Jul-98	19.715	0.000	17.804	0.000	19.917	0.000	0.000
7	06-Aug-98	19.703	-0.005	17.785	-0.008	19.910	-0.003	-0.005
14	13-Aug-98	19.709	-0.002	17.791	-0.005	19.917	0.000	-0.003
28	27-Aug-98	19.716	0.000	17.800	-0.002	19.917	0.000	0.000
56	24-Sep-98	19.718	0.001	17.805	0.000	19.912	-0.002	0.000
91	27-Oct-98	19.737	0.009			19.934	0.007	0.008
126	12-Apr-98	19.760	0.018	17.848	0.018	19.964	0.019	0.018
182	29-Jan-99	19.752	0.015	17.840	0.014	19.953	0.014	0.015
273	30-Apr-99	19.776	0.024	17.860	0.022	19.975	0.023	0.023
365	29-Jul-99	19.792	0.031	17.884	0.032	19.991	0.030	0.031

Mix UND 4% **Cast Date** 24-Nov-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	25-Nov-98	23.744	0.000	26.013	0.000			0.000
7	03-Dec-98	23.762	0.007	26.014	0.000			0.004
14								
42	06-Jan-99	23.754	0.004	26.013	0.000			0.002
56	19-Jan-99	23.753	0.004	26.023	0.004			0.004
91	23-Feb-99	23.771	0.011	26.023	0.004			0.007
126	30-Mar-99	23.832	0.035	26.121	0.043			0.039
182	26-May-99	23.919	0.070	26.236	0.089			0.080
231	07-Jul-99	24.008	0.106	26.323	0.124			0.115
365	25-Nov-99	24.123	0.152	26.441	0.171			0.161

Mix UND 8% **Cast Date** 24-Nov-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	25-Nov-98	20.971	0.000	21.254	0.000	18.973	0.000	0.000
7	03-Dec-98	20.960	-0.004	21.254	0.000	18.969	-0.002	-0.002
14								
42	06-Jan-99	20.981	0.004	21.249	-0.002	18.973	0.000	0.001
56	19-Jan-99	20.956	-0.006	21.258	0.002	18.984	0.004	0.000
91	23-Feb-99	20.978	0.003	21.241	-0.005	18.955	-0.007	-0.003
126	30-Mar-99	21.008	0.015	21.279	0.010	18.992	0.008	0.011
182	26-May-99	21.031	0.024	21.334	0.032	19.007	0.014	0.023
231	07-Jul-99	21.042	0.028	21.321	0.027	19.035	0.025	0.027
365	25-Nov-99	21.107	0.054	21.377	0.049	19.099	0.050	0.051

Mix UND 12% **Cast Date** 24-Nov-98

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	25-Nov-98	20.904	0.000	23.560	0.000	20.619	0.000	0.000
7	03-Dec-98	20.888	-0.006	23.550	-0.004	20.614	-0.002	-0.004
14								
42	06-Jan-99	20.890	-0.006	23.552	-0.003			-0.004
56	19-Jan-99	20.897	-0.003	23.552	-0.003	20.614	-0.002	-0.003
91	23-Feb-99	20.913	0.004	23.559	0.000	20.629	0.004	0.002
126	30-Mar-99	20.925	0.008	23.580	0.008	20.631	0.005	0.007
182	26-May-99	20.959	0.022	23.597	0.015	20.670	0.020	0.019
231	07-Jul-99	20.939	0.014	23.606	0.018	20.653	0.014	0.015
365	25-Nov-99	20.943	0.016	23.611	0.020	20.660	0.016	0.017

Mix SLU 4% **Cast Date** 04-Mar-99

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	05-Mar-99	21.641	0.000	21.823	0.000	20.268	0.000	0.000
7	15-Mar-99	21.632	-0.004	21.805	-0.007	20.263	-0.002	-0.004
14	23-Mar-99	21.662	0.008	21.841	0.007	20.286	0.007	0.008
28								
56	30-Apr-99	21.671	0.012	21.849	0.010	20.314	0.018	0.014
91	03-Jun-99	21.687	0.018	21.880	0.023	20.333	0.026	0.022
126	07-Sep-99	21.750	0.044	21.963	0.056	20.409	0.056	0.052
189	09-Sep-99	21.877	0.094	22.091	0.107	20.543	0.110	0.104
273	13-Dec-99	21.988	0.139	22.218	0.158	20.694	0.170	0.156
365								

Mix SLU 8% **Cast Date** 04-Mar-99

Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	05-Mar-99	21.842	0.000	20.012	0.000	20.110	0.000	0.000
7	15-Mar-99	21.837	-0.002	20.005	-0.003	20.103	-0.003	-0.003
14	23-Mar-99	21.838	-0.002	20.015	0.001	20.119	0.004	0.001
28								
56	30-Apr-99	21.863	0.008	20.034	0.009	20.130	0.008	0.008
91	03-Jun-99	21.872	0.012	20.039	0.011	20.132	0.009	0.011
126	07-Sep-99	21.883	0.016	20.049	0.015	20.153	0.017	0.016
189	09-Sep-99	21.902	0.024	20.064	0.021	20.166	0.022	0.022
273	13-Dec-99	21.923	0.032	20.092	0.032	20.182	0.029	0.031
365								

Mix SLU 12% **Cast Date** 04-Mar-99

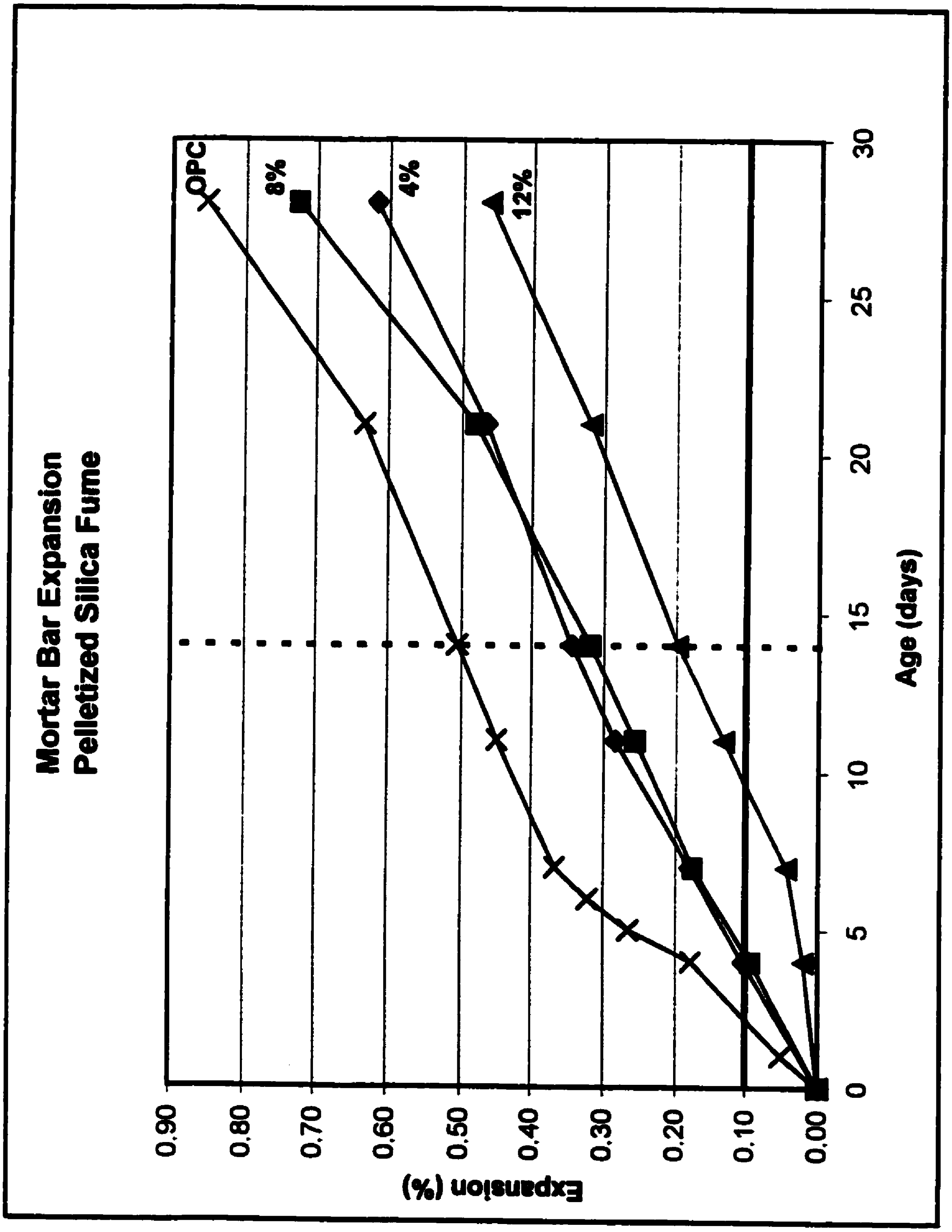
Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	05-Mar-99	21.332	0.000	21.018	0.000			0.000
7	15-Mar-99	21.308	-0.010	21.002	-0.006			-0.008
14	23-Mar-99	21.323	-0.004	21.024	0.002			-0.001
28								
56	30-Apr-99	21.352	0.008	21.043	0.010			0.009
91	03-Jun-99	21.353	0.008	21.048	0.012			0.010
126	07-Sep-99	21.370	0.015	21.068	0.020			0.018
189	09-Sep-99	21.371	0.016	21.079	0.024			0.020
273	13-Dec-99	21.366	0.014	21.062	0.018			0.016
365								

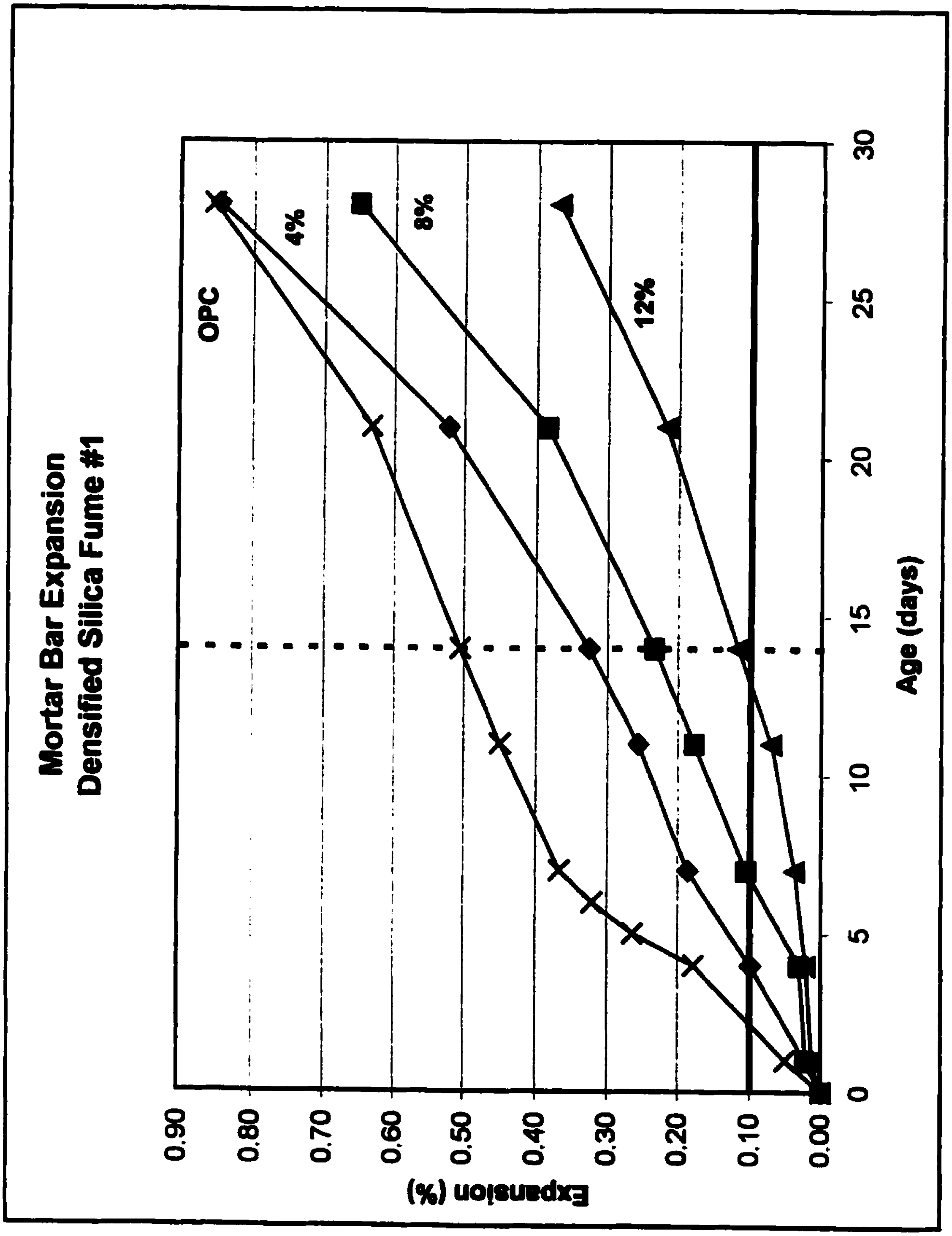
Mix OPC **Cast Date** 21-Jul-98

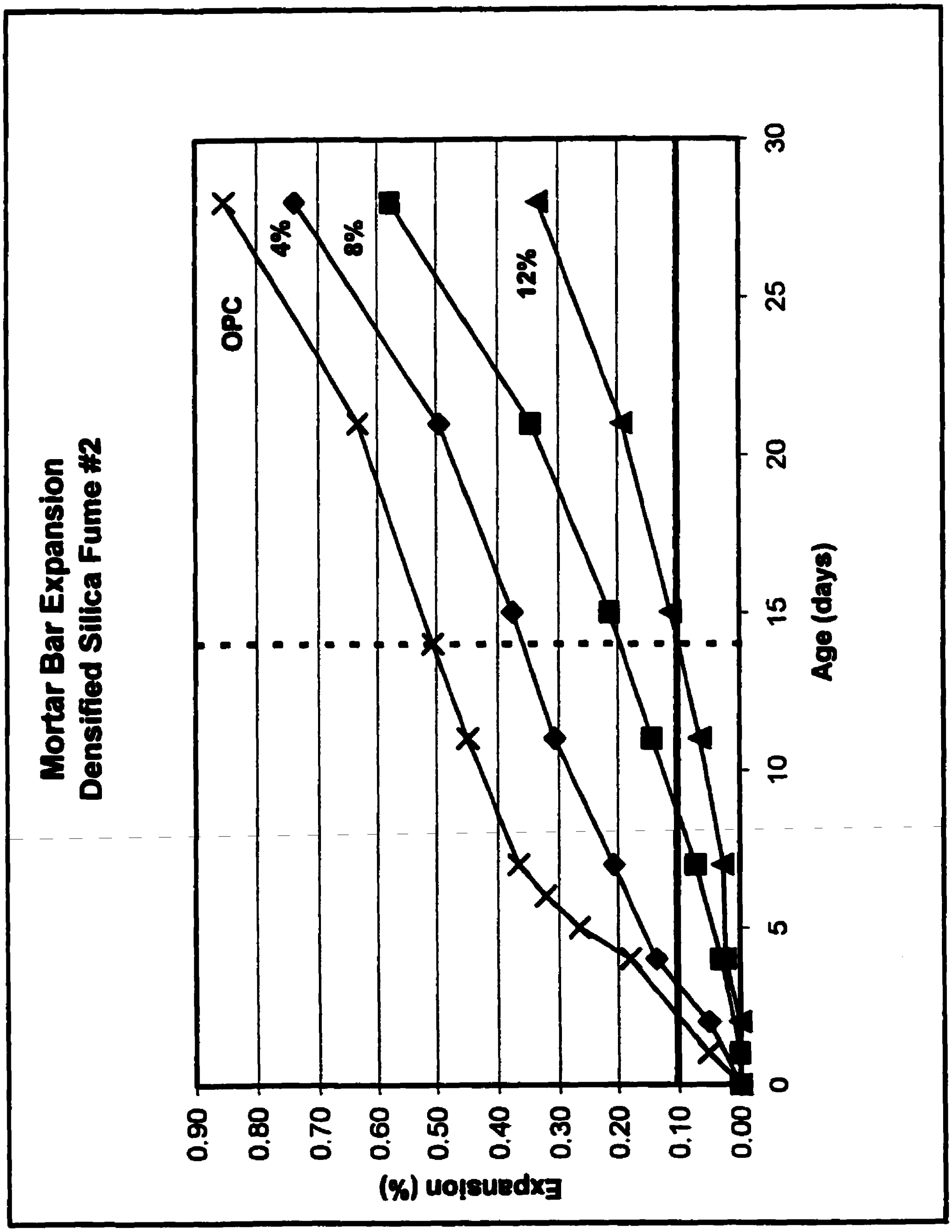
Days	Date	length A	% exp.	length B	% exp.	length C	% exp.	avg % exp.
0	22-Jul-98	18.244	0.000	21.377	0.000	20.333	0.000	0.000
7	29-Jul-98	18.240	-0.002	21.377	0.000	20.338	0.002	0.000
14	05-Aug-98	18.250	0.002	21.369	-0.003	20.338	0.002	0.000
28	19-Aug-98	18.249	0.002	21.365	-0.005	20.352	0.008	0.002
56	23-Sep-98	18.328	0.034	21.450	0.029			0.031
91	22-Oct-98	18.513	0.108	21.629	0.101	20.561	0.091	0.100
126	25-Nov-98	18.607	0.145	21.705	0.131	20.654	0.128	0.135
182	21-Jan-99	18.666	0.169	21.745	0.147	20.719	0.154	0.157
273	24-Apr-99	18.668	0.170	21.823	0.178	20.768	0.174	0.174
365	21-Jul-99	18.699	0.182	21.864	0.195	20.808	0.190	0.189

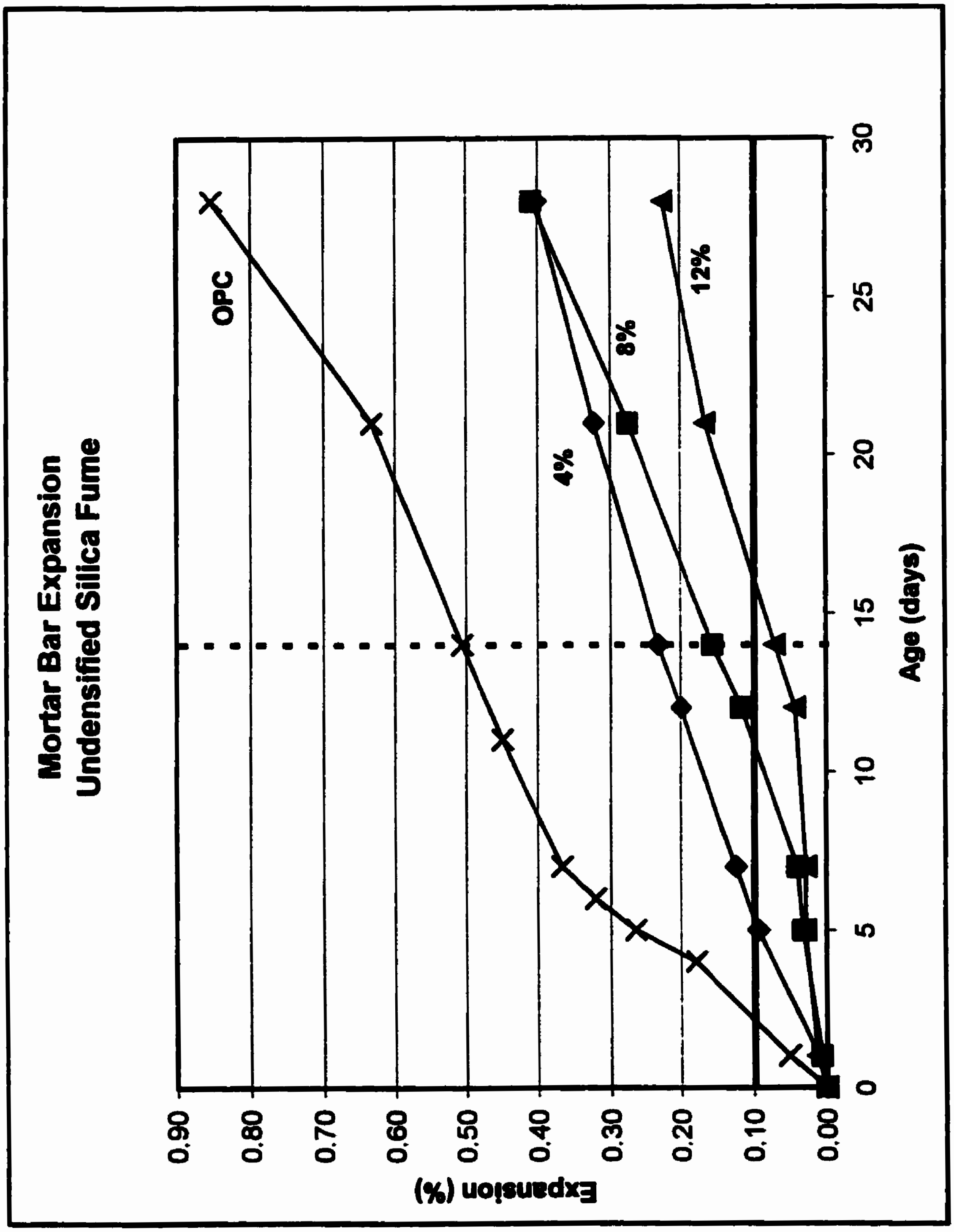
APPENDIX C

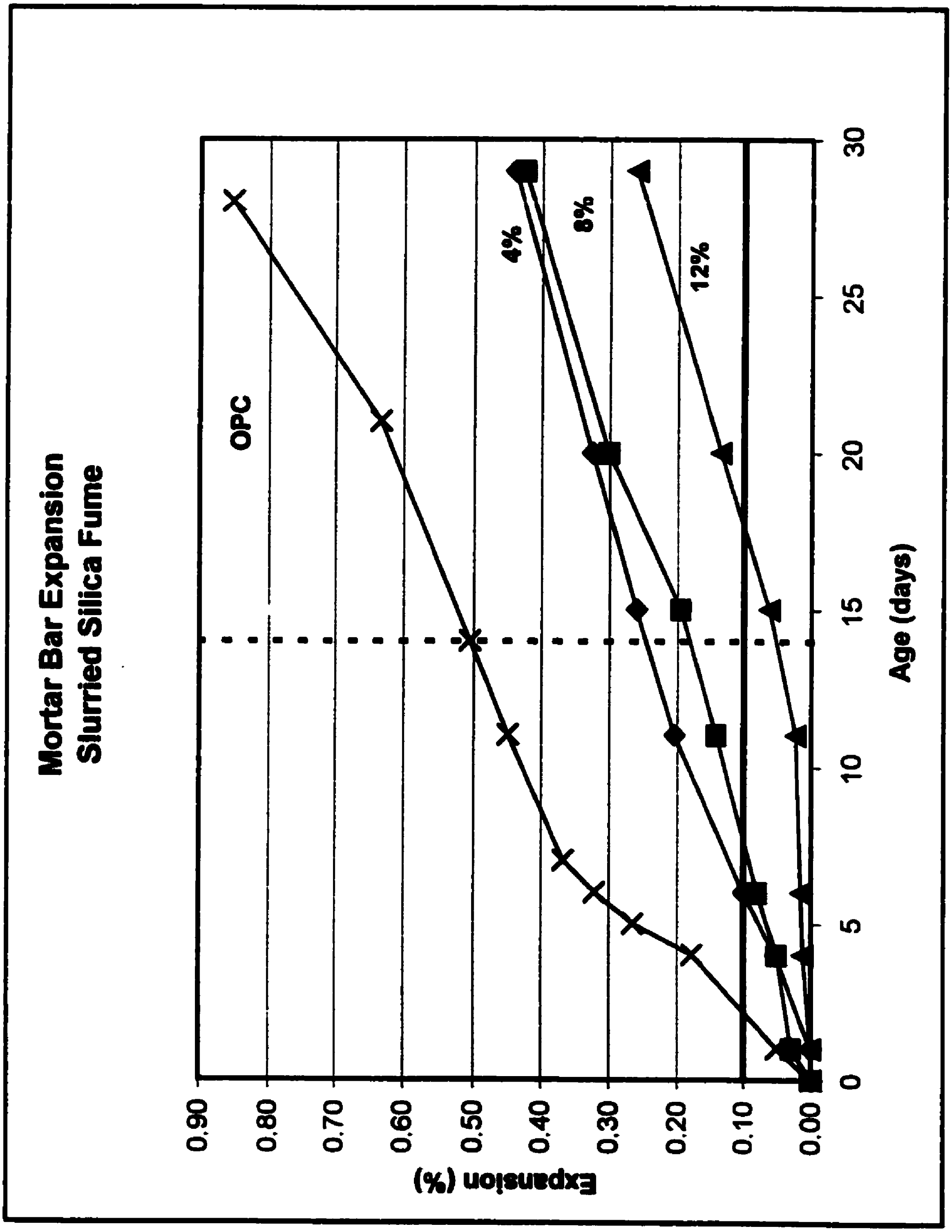
MORTAR BAR EXPANSION DATA AND PLOTS

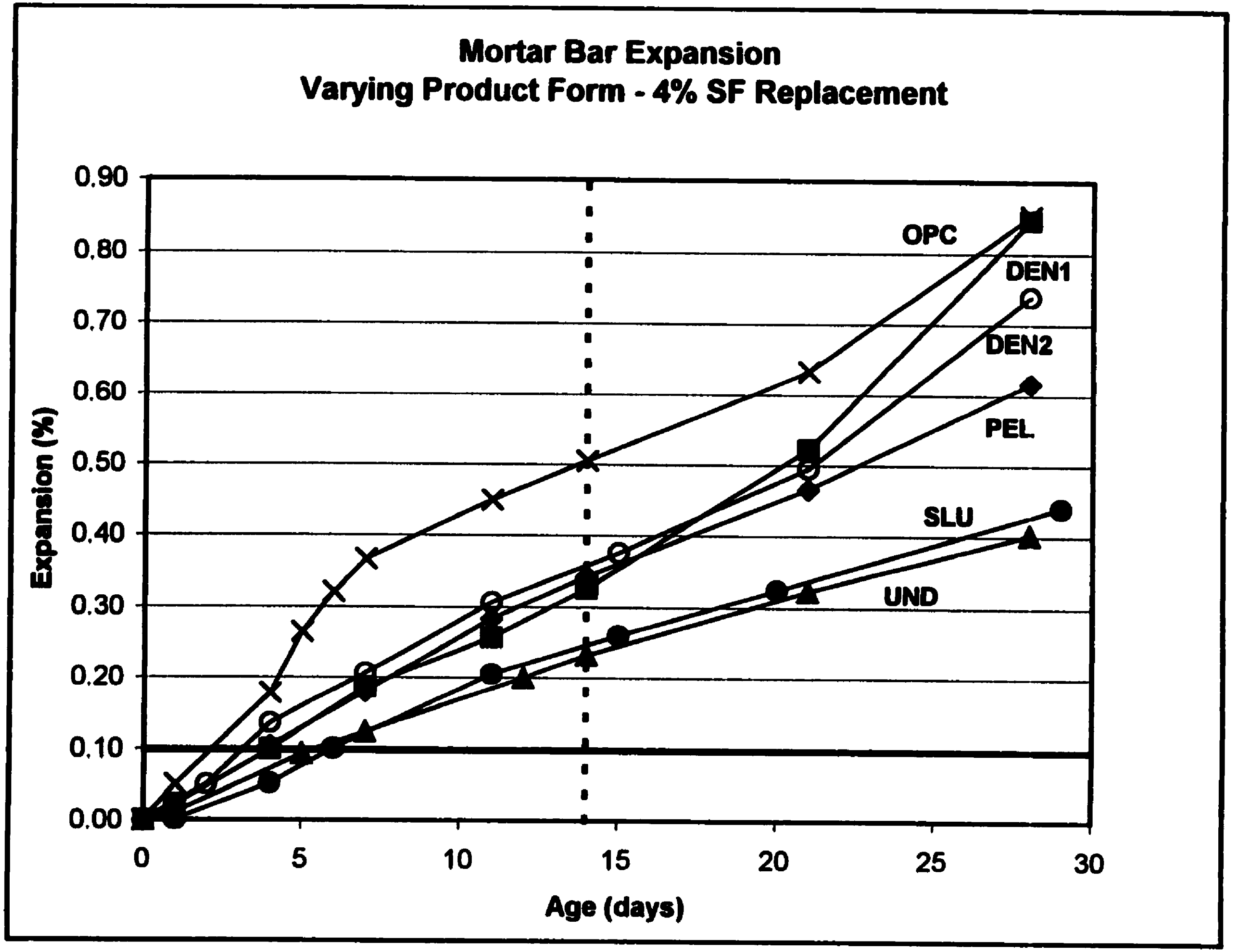

Mortar Bar Expansion
Pelletized Silica Fume
Expansion (%)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Age (days)
0
5
10
15
20
25
30
OPC
8%
4%
12%

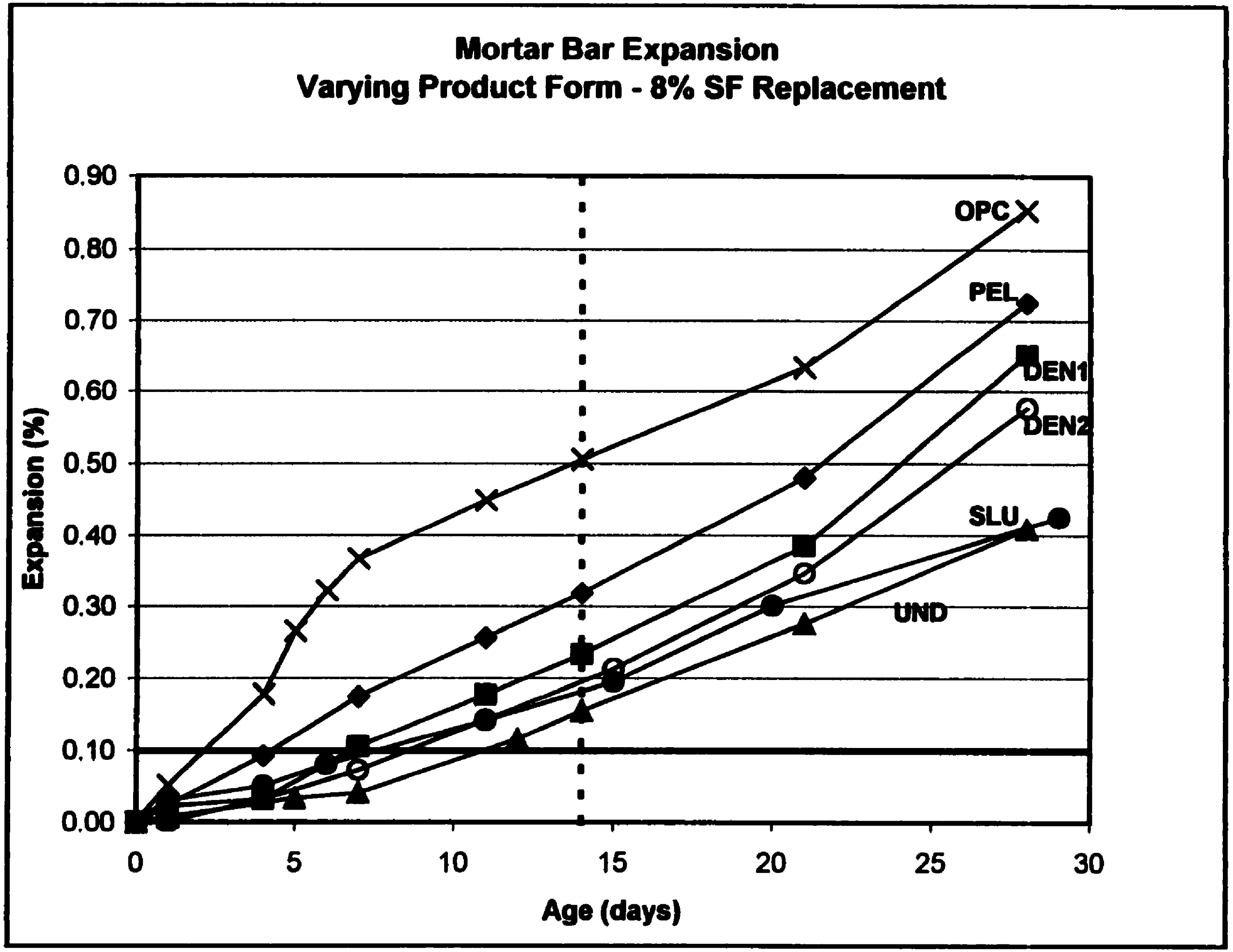

Mortar Bar Expansion
Densified Silica Fume #1
Expansion (%)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Age (days)
0
5
10
15
20
25
30
OPC
4%
8%
12%


Mortar Bar Expansion
Densified Silica Fume #2
Expansion (%)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Age (days)
0
5
10
15
20
25
30
OPC
4%
8%
12%

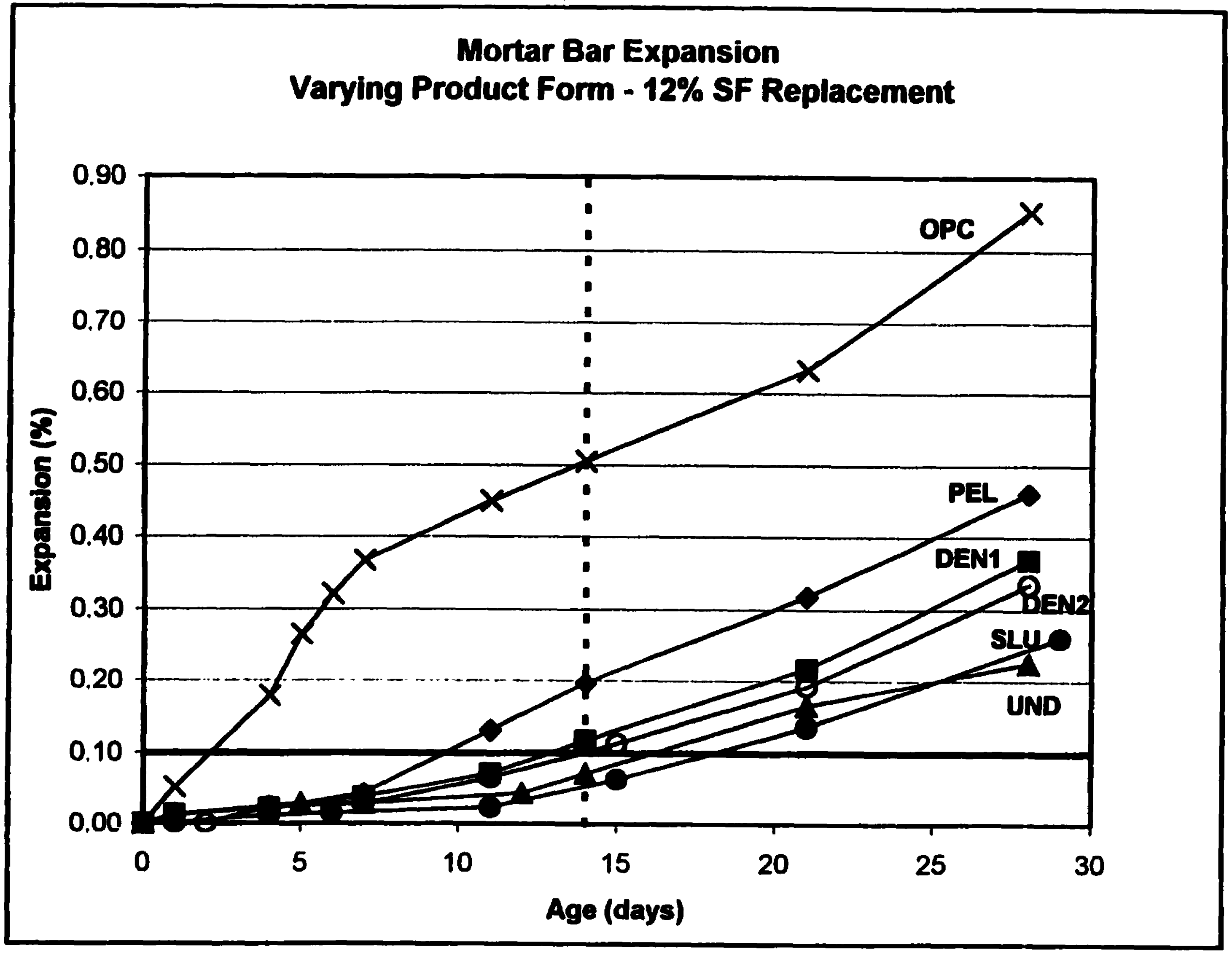

Mortar Bar Expansion
Undensified Silica Fume
OPC
4%
8%
12%
Expansion (%)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Age (days)
0
5
10
15
20
25
30

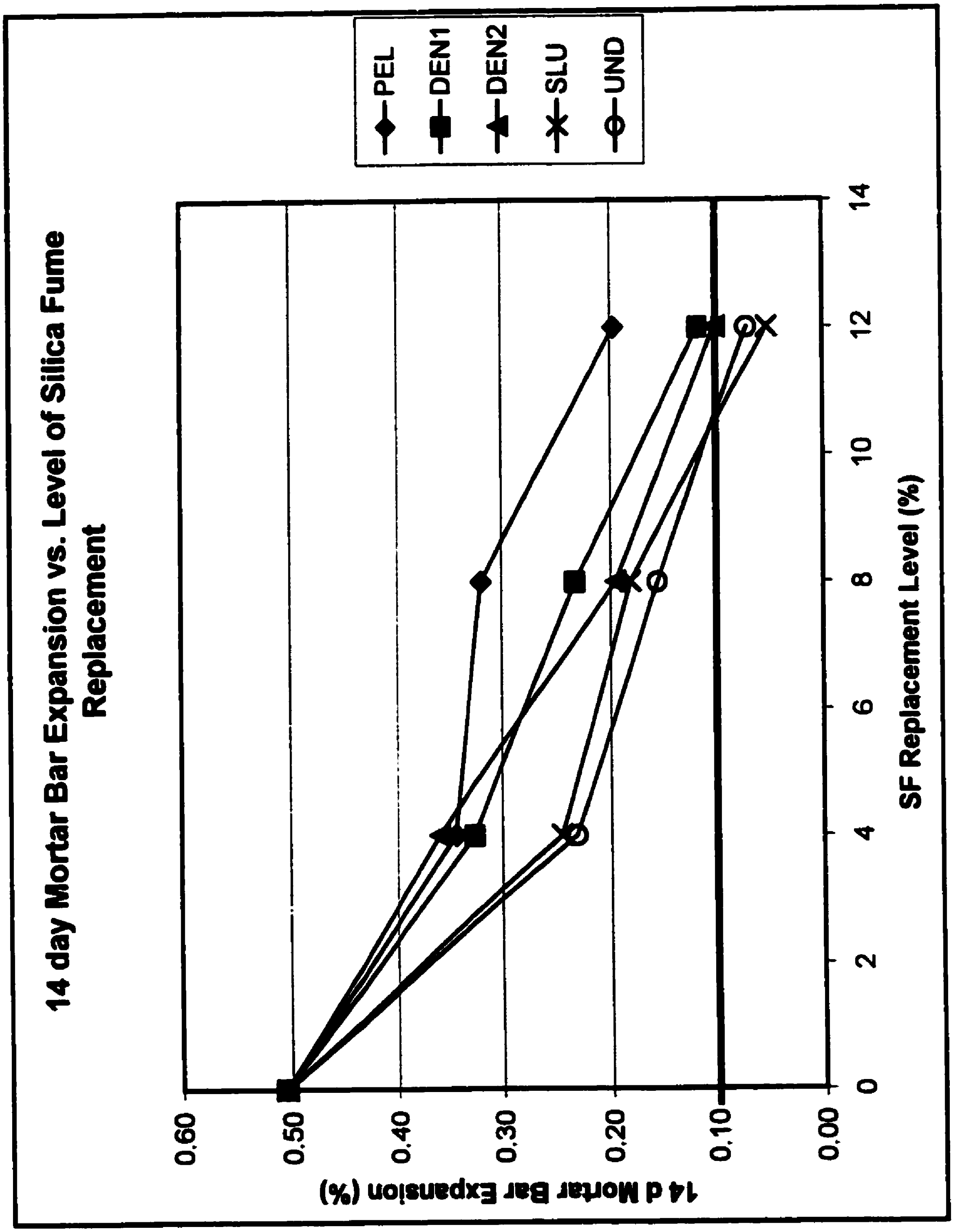

Mortar Bar Expansion
Slurried Silica Fume
Expansion (%)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Age (days)
0
5
10
15
20
25
30
OPC
4%
8%
12%

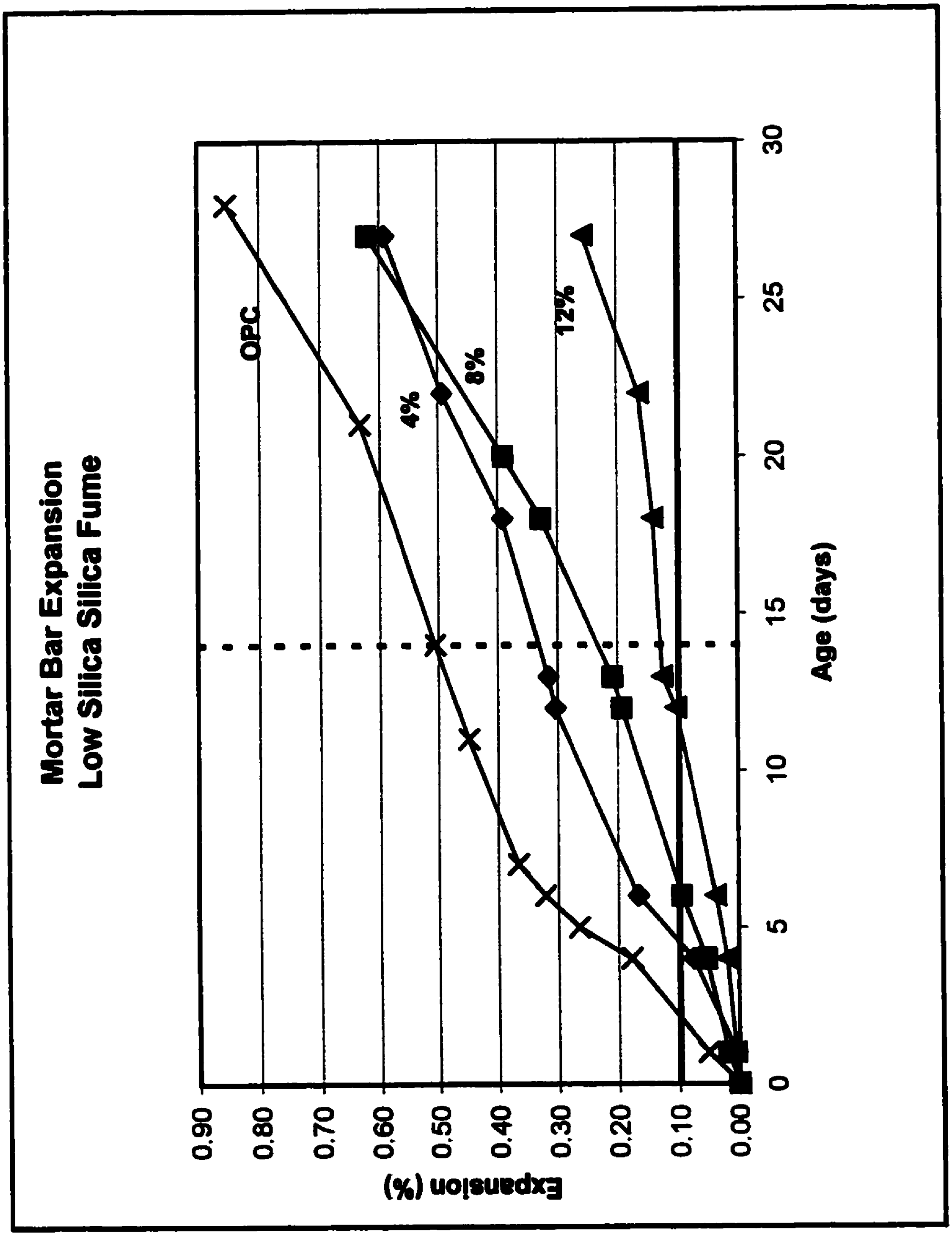

Mortar Bar Expansion
Varying Product Form - 4% SF Replacement
Expansion (%)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Age (days)
0
5
10
15
20
25
30
OPC
DEN1
DEN2
PEL
SLU
UND

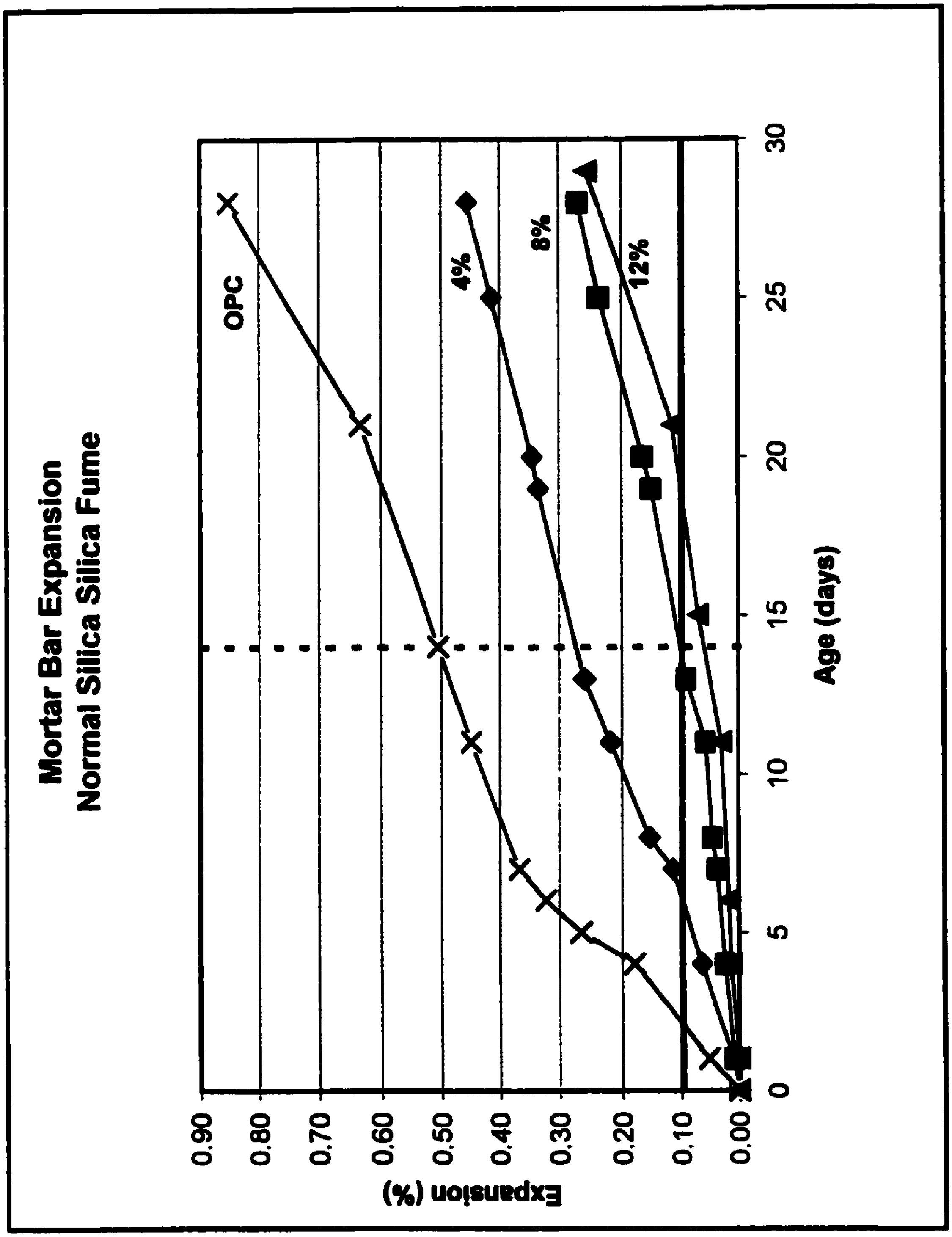


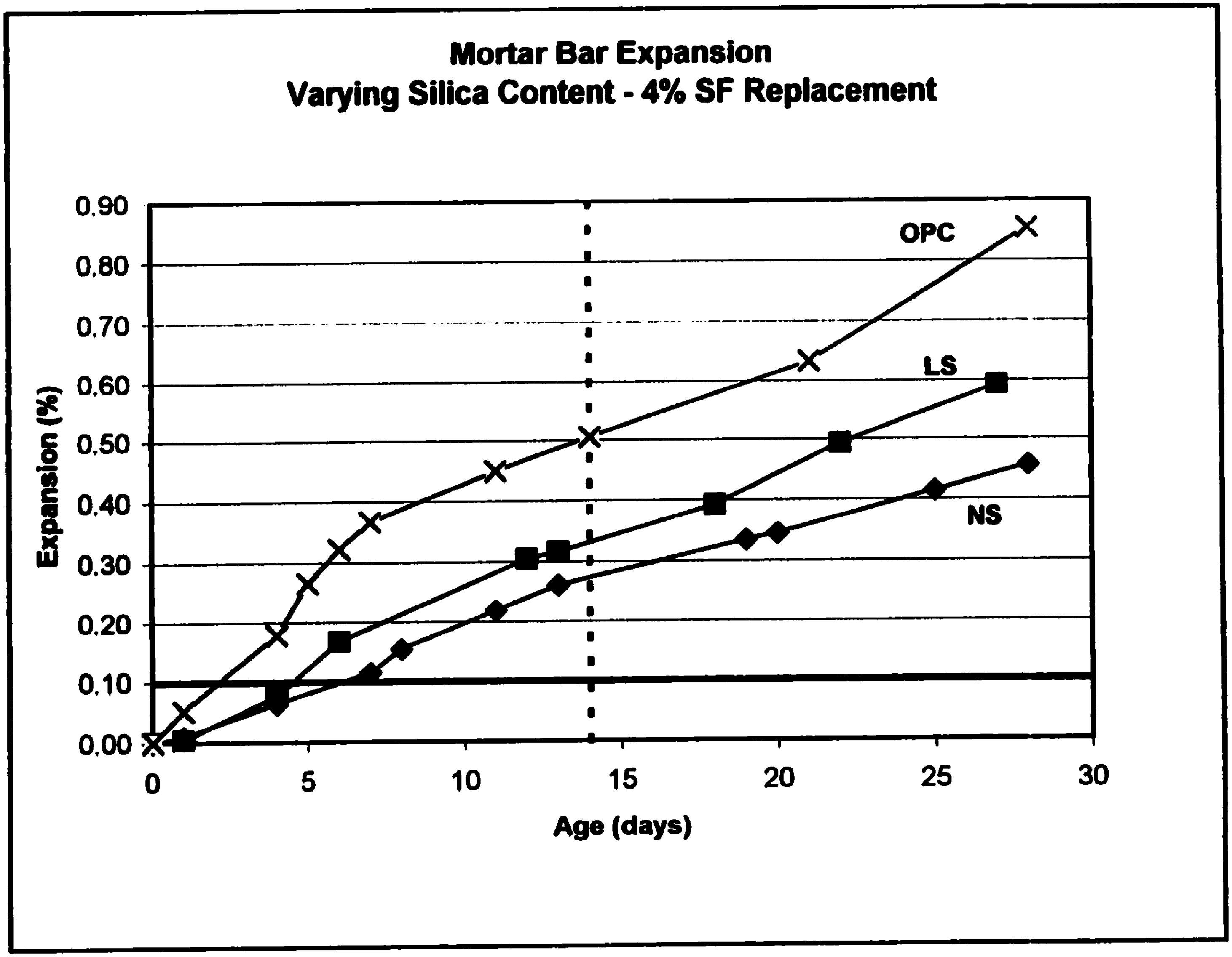
Mortar Bar Expansion
Varying Product Form - 8% SF Replacement

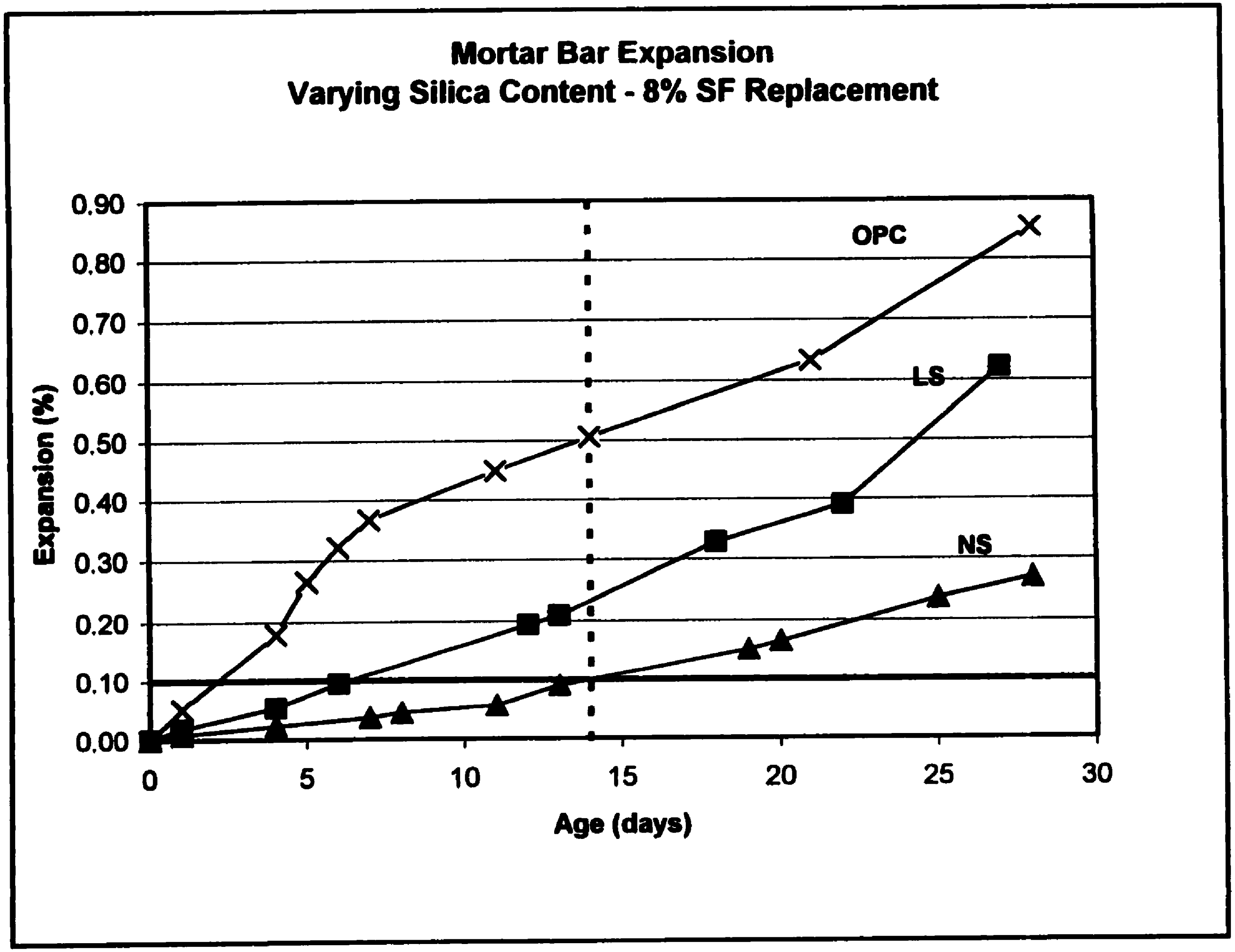

Mortar Bar Expansion
Varying Product Form - 12% SF Replacement
Expansion (%)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Age (days)
0
5
10
15
20
25
30
OPC
PEL
DEN1
DEN2
SLU
UND

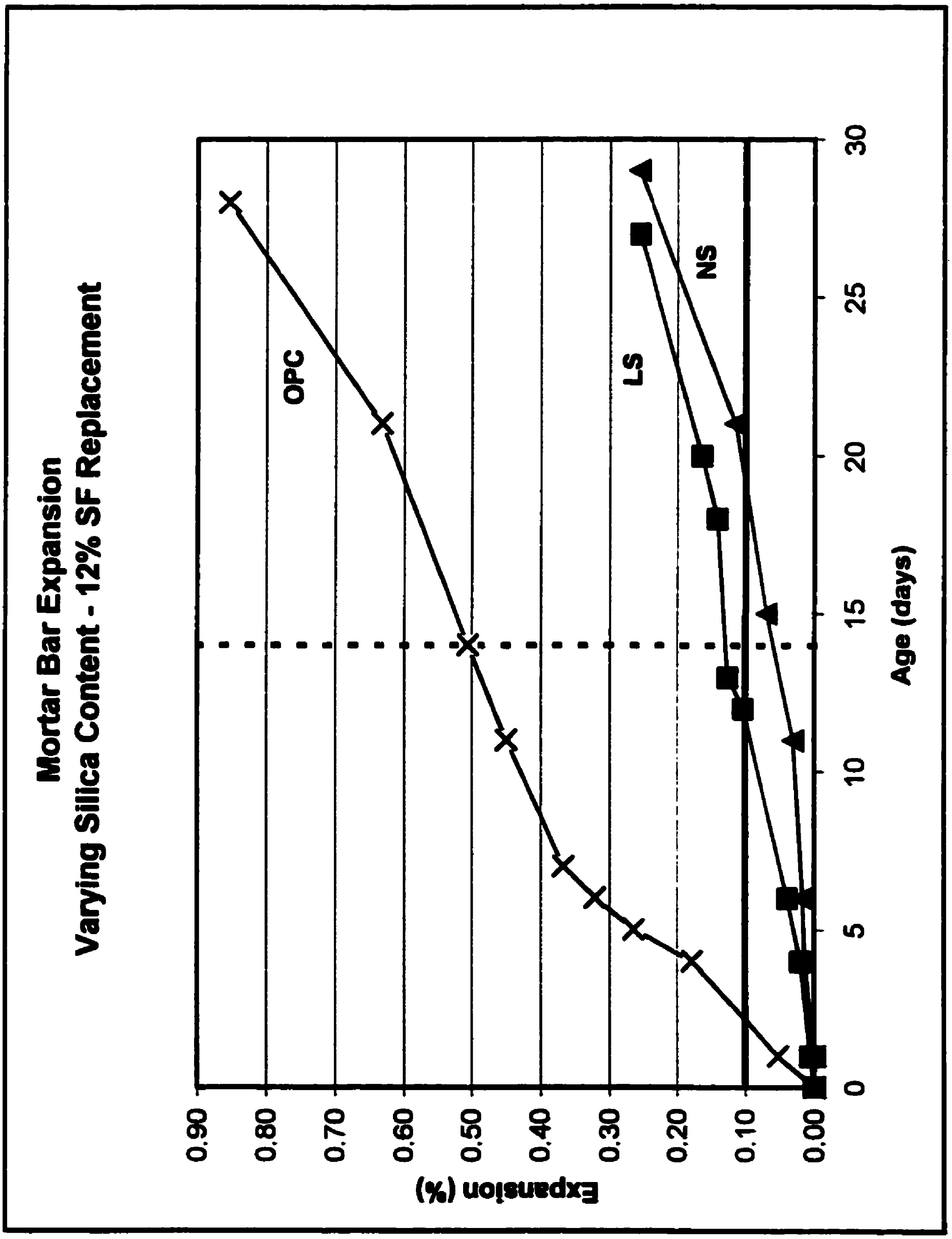

14 day Mortar Bar Expansion vs. Level of Silica Fume Replacement
PEL
DEN1
DEN2
SLU
UND
14 d Mortar Bar Expansion (%)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
SF Replacement Level (%)
0
2
4
6
8
10
12
14


Mortar Bar Expansion
Low Silica Silica Fume
Expansion (%)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Age (days)
0
5
10
15
20
25
30
OPC
4%
8%
12%


Mortar Bar Expansion
Normal Silica Silica Fume
Expansion (%)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Age (days)
0
5
10
15
20
25
30
OPC
4%
8%
12%


Mortar Bar Expansion
Varying Silica Content - 4% SF Replacement
Expansion (%)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
5
10
15
20
25
30
Age (days)
OPC
LS
NS


Mortar Bar Expansion
Varying Silica Content - 8% SF Replacement
Expansion (%)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
5
10
15
20
25
30
Age (days)
OPC
LS
NS


Mortar Bar Expansion
Varying Silica Content - 12% SF Replacement
Expansion (%)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Age (days)
0
5
10
15
20
25
30
OPC
LS
NS

Mortar Bar Expansion Data

Mix 4% PEL **Cast** 07-Oct-96

		BAR # 1			BAR # 2			BAR # 3			Average
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Expansion (%)
0	09-Oct-96	441.87	2.817	0.000	438.01	1.532	0.000	438.33	1.144	0.000	0.000
1	10-Oct-96										
4	13-Oct-96	447.82	3.075	0.103	443.35	1.786	0.102	443.46	1.412	0.107	0.104
7	16-Oct-96	449.25	3.398	0.232	444.98	1.909	0.151	445.33	1.538	0.158	0.180
11	20-Oct-96	450.25	3.654	0.335	445.38	2.173	0.256	445.97	1.796	0.261	0.284
14	23-Oct-96	450.90	3.798	0.392	446.46	2.326	0.318	446.94	1.946	0.321	0.344
21	30-Oct-96	452.77	4.104	0.515	448.06	2.628	0.438	448.20	2.252	0.443	0.465
28	06-Nov-96	453.77	4.483	0.666	448.82	3.003	0.588	449.41	2.635	0.596	0.617

Mix 8% PEL **Cast** 07-Oct-96

		BAR # 1			BAR # 2			BAR # 3			Average
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Expansion (%)
0	09-Oct-96	422.50	3.162	0.000	432.24	1.579	0.000	421.37	2.108	0.000	0.000
1	10-Oct-96										
4	13-Oct-96	425.85	3.386	0.090	436.25	1.814	0.094	425.04	2.343	0.095	0.093
7	16-Oct-96	428.02	3.597	0.174	437.54	2.017	0.175	427.02	2.546	0.176	0.175
11	20-Oct-96	429.18	3.791	0.252	438.86	2.217	0.255	427.71	2.760	0.262	0.256
14	23-Oct-96	430.20	3.950	0.315	440.00	2.368	0.316	428.45	2.918	0.325	0.319
21	30-Oct-96	431.64	4.359	0.479	441.59	2.768	0.476	430.39	3.328	0.488	0.481
28	06-Nov-96	433.91	4.977	0.726	443.86	3.372	0.717	431.83	3.935	0.732	0.725

Mortar Bar Expansion Data

Mix 12% PEL **Cast** 07-Oct-98

		BAR # 1			BAR # 2			BAR # 3			Average
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Expansion (%)
0	09-Oct-98	420.65	1.474	0.000	427.35	2.268	0.000	413.72	2.552	0.000	0.000
1	10-Oct-98										
4	13-Oct-98	423.58	1.515	0.016	430.49	2.316	0.019	417.13	2.613	0.024	0.020
7	16-Oct-98	424.43	1.574	0.040	431.02	2.383	0.046	417.78	2.660	0.043	0.043
11	20-Oct-98	425.53	1.795	0.128	432.63	2.592	0.130	418.93	2.888	0.134	0.131
14	23-Oct-98	426.57	1.970	0.198	433.89	2.750	0.193	419.99	3.050	0.199	0.197
21	30-Oct-98	428.10	2.276	0.321	435.00	3.049	0.312	421.41	3.357	0.322	0.318
28	06-Nov-98	429.05	2.641	0.467	436.46	3.401	0.453	422.47	3.712	0.464	0.461

Mix 4% DEN1 **Cast** 14-Oct-98

		BAR # 1			BAR # 2			BAR # 3			Average
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Expansion (%)
0	16-Oct-98	454.75	2.184	0.000	444.19	1.333	0.000	446.2	1.891	0.000	0.000
1	17-Oct-98		2.243	0.024		1.391	0.023		1.949	0.023	0.023
4	20-Oct-98	458.30	2.435	0.100	448.16	1.581	0.099	450.16	2.139	0.099	0.100
7	23-Oct-98	459.69	2.648	0.186	449.95	1.798	0.186	451.50	2.357	0.186	0.186
11	27-Oct-98	460.64	2.824	0.256	450.97	1.974	0.256	452.56	2.541	0.260	0.257
14	30-Oct-98	461.45	2.999	0.326	451.67	2.146	0.325	453.21	2.710	0.326	0.326
21	06-Nov-98	462.98	3.495	0.524	453.02	2.626	0.517	454.62	3.204	0.525	0.522
28	13-Nov-98	466.82	4.319	0.854	456.46	3.412	0.832	458.77	4.028	0.855	0.847

Mortar Bar Expansion Data

Mix 8% DEN1 **Cast** 14-Oct-98

		BAR # 1			BAR # 2			BAR # 3			Average
Day	**Date**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Expansion (%)**
0	16-Oct-98	432.63	1.425	0.000	435.68	1.570	0.000	428.18	1.022	0.000	0.000
1	17-Oct-98		1.483	0.023		1.621	0.020		1.072	0.020	0.021
4	20-Oct-98	434.94	1.500	0.030	437.54	1.650	0.032	430.30	1.098	0.030	0.031
7	23-Oct-98	437.18	1.709	0.114	439.69	1.831	0.104	432.31	1.269	0.099	0.106
11	27-Oct-98	438.65	1.881	0.182	440.86	2.014	0.178	433.72	1.450	0.171	0.177
14	30-Oct-98	439.30	2.020	0.238	441.72	2.152	0.233	434.29	1.594	0.229	0.233
21	06-Nov-98	441.07	2.393	0.387	443.28	2.522	0.381	436.03	1.985	0.385	0.384
28	13-Nov-98	443.82	3.050	0.650	446.05	3.171	0.640	438.50	2.678	0.662	0.651

Mix 12% DEN1 **Cast** 14-Oct-98

		BAR # 1			BAR # 2			BAR # 3			Average
Day	**Date**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Expansion (%)**
0	16-Oct-98	424.31	2.044	0.000	429.89	1.804	0.000	420.27	2.075	0.000	0.000
1	17-Oct-98		2.072	0.011		1.831	0.011		2.112	0.015	0.012
4	20-Oct-98	426.08	2.091	0.019	431.62	1.859	0.022	421.42	2.133	0.023	0.021
7	23-Oct-98	427.60	2.137	0.037	433.10	1.898	0.038	423.22	2.169	0.038	0.037
11	27-Oct-98	429.07	2.222	0.071	434.47	1.978	0.070	424.35	2.253	0.071	0.071
14	30-Oct-98	429.67	2.326	0.113	435.34	2.098	0.118	424.90	2.370	0.118	0.116
21	06-Nov-98	430.97	2.567	0.209	436.66	2.344	0.216	426.27	2.635	0.224	0.216
28	13-Nov-98	432.26	2.938	0.358	438.11	2.719	0.366	427.68	3.035	0.384	0.369

Mortar Bar Expansion Data

Mix 4% UND **Cast** 19-Oct-98

Day	Date	BAR # 1 Weight (g)	BAR # 1 Length (mm)	BAR # 1 Expansion (%)	BAR # 2 Weight (g)	BAR # 2 Length (mm)	BAR # 2 Expansion (%)	BAR # 3 Weight (g)	BAR # 3 Length (mm)	BAR # 3 Expansion (%)	Average Expansion (%)
0	21-Oct-98	450.55	1.142	0.000	464.08	1.91	0.000	461.51	1.766	0.000	0.000
1	22-Oct-98	451.00	1.169	0.011	465.07	1.937	0.011	461.62	1.796	0.012	0.011
5	26-Oct-98	455.11	1.368	0.090	469.45	2.152	0.097	465.60	2.000	0.094	0.094
7	28-Oct-98	454.64	1.450	0.123	468.00	2.228	0.127	464.84	2.070	0.122	0.124
12	02-Nov-98	455.11	1.641	0.200	469.12	2.423	0.205	465.79	2.250	0.194	0.199
14	04-Nov-98	455.32	1.713	0.228	469.48	2.512	0.241	465.97	2.333	0.227	0.232
21	11-Nov-98	457.19	1.944	0.321	470.88	2.744	0.334	467.50	2.554	0.315	0.323
28	18-Nov-98	458.47	2.139	0.399	472.60	2.950	0.416	469.27	2.748	0.393	0.403

Mix 8% UND **Cast** 19-Oct-98

Day	Date	BAR # 1 Weight (g)	BAR # 1 Length (mm)	BAR # 1 Expansion (%)	BAR # 2 Weight (g)	BAR # 2 Length (mm)	BAR # 2 Expansion (%)	BAR # 3 Weight (g)	BAR # 3 Length (mm)	BAR # 3 Expansion (%)	Average Expansion (%)
0	21-Oct-98	431.62	1.229	0.000	431.40	2.908	0.000	448.93	1.087	0.000	0.000
1	22-Oct-98	431.88	1.246	0.007	431.67	2.921	0.005	449.30	1.107	0.008	0.007
5	26-Oct-98	435.11	1.308	0.032	434.80	2.990	0.033	452.61	1.173	0.034	0.033
7	28-Oct-98	435.50	1.330	0.040	435.01	3.001	0.037	452.64	1.191	0.042	0.040
12	02-Nov-98	436.73	1.531	0.121	435.88	3.201	0.117	453.74	1.362	0.110	0.116
14	04-Nov-98	437.10	1.632	0.161	436.44	3.300	0.157	454.46	1.453	0.146	0.155
21	11-Nov-98	439.19	1.943	0.266	438.47	3.595	0.275	456.54	1.751	0.266	0.275
28	18-Nov-98	440.96	2.290	0.424	440.47	3.929	0.408	458.39	2.071	0.394	0.409

Mortar Bar Expansion Data

Mix 12% UND **Cast** 19-Oct-98

		BAR # 1			BAR # 2			BAR # 3			Average
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Expansion (%)
0	21-Oct-98	443.10	1.370	0.000	427.78	2.021	0.000	440.18	1.309	0.000	0.000
1	22-Oct-98	443.86	1.402	0.013	428.50	2.053	0.013	440.93	1.341	0.013	0.013
5	26-Oct-98	445.78	1.442	0.029	430.63	2.098	0.031	442.92	1.378	0.028	0.029
7	28-Oct-98	446.10	1.440	0.028	430.63	2.090	0.028	443.32	1.380	0.028	0.028
12	02-Nov-98	447.34	1.471	0.040	431.83	2.143	0.049	444.62	1.411	0.041	0.043
14	04-Nov-98	447.74	1.533	0.065	432.49	2.223	0.081	444.93	1.473	0.066	0.071
21	11-Nov-98	449.48	1.764	0.158	434.16	2.464	0.177	446.72	1.704	0.158	0.164
28	18-Nov-98	450.76	1.902	0.213	435.55	2.629	0.243	448.09	1.852	0.217	0.224

Mix DEN2 4% **Cast** 13-Jul-99

		BAR # 1			BAR # 2			BAR # 3			Average
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Expansion (%)
0	15-Jul-99	416.70	2.262	0.000	421.67	2.992	0.000				0.000
2	17-Jul-99	418.15	2.389	0.051	423.05	3.119	0.051				0.051
4	19-Jul-99	421.35	2.611	0.140	426.56	3.323	0.132				0.136
7	22-Jul-99	422.65	2.794	0.213	427.73	3.492	0.200				0.206
11	26-Jul-99	422.92	3.050	0.315	428.17	3.739	0.299				0.307
15	30-Jul-99	424.41	3.228	0.386	429.81	3.907	0.366				0.376
21	05-Aug-99	426.16	3.53	0.507	431.54	4.195	0.481				0.494
28	12-Aug-99	428.07	4.16	0.759	432.66	4.79	0.719				0.739

Mortar Bar Expansion Data

Mix DEN2 8% **Cast** 13-Jul-99

		BAR # 1			BAR # 2			BAR # 3			Average
Day	**Date**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Expansion (%)**
0	15-Jul-99	416.68	0.920	0.000	417.72	1.990	0.000	415.03	2.200	0.000	0.000
1	17-Jul-99	416.88	0.944	0.010	418.29	2.011	0.008	416.00	2.231	0.012	0.000
4	19-Jul-99	420.52	1.002	0.033	421.58	2.066	0.030	418.92	2.273	0.029	0.031
7	22-Jul-99	420.96	1.109	0.076	422.23	2.170	0.072	419.88	2.370	0.068	0.072
11	26-Jul-99	421.29	1.280	0.144	422.61	2.350	0.144	420.22	2.548	0.139	0.142
15	30-Jul-99	422.96	1.460	0.216	424.10	2.528	0.215	421.49	2.717	0.207	0.213
21	05-Aug-99	423.73	1.791	0.348	425.82	2.864	0.350	423.22	3.047	0.339	0.346
28	12-Aug-99	426.74	2.380	0.584	427.60	3.441	0.580	424.92	3.611	0.564	0.576

Mix DEN2 12% **Cast** 13-Jul-99

		BAR # 1			BAR # 2			BAR # 3			Average
Day	**Date**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Expansion (%)**
0	15-Jul-99	422.02	2.290	0.000	412.09	1.310	0.000	416.79	1.810	0.000	0.000
2	17-Jul-99	423.00	2.327	0.015	412.76	1.349	0.016	417.71	1.848	0.015	0.000
4	19-Jul-99	424.42	2.349	0.024	414.87	1.370	0.024	419.57	1.869	0.024	0.024
7	22-Jul-99	425.69	2.359	0.028	416.04	1.380	0.028	420.88	1.879	0.028	0.028
11	26-Jul-99	426.02	2.450	0.064	416.18	1.472	0.065	421.32	1.971	0.064	0.064
15	30-Jul-99	427.46	2.570	0.112	417.66	1.593	0.113	422.55	2.084	0.110	0.112
21	05-Aug-99	429.09	2.770	0.192	419.19	1.792	0.193	423.91	2.282	0.189	0.191
28	12-Aug-99	430.26	3.126	0.334	420.64	2.155	0.338	425.33	2.636	0.330	0.334

Mortar Bar Expansion Data

Mix SL 4% **Cast** 25-May-99

		BAR # 1			BAR # 2			BAR # 3			Average
Day	**Date**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Expansion (%)**
0	27-May-99	433.28	0.819	0.000	429.61	-2.175	0.000	418.43	-0.497	0.000	0.000
1	28-May-99	433.10	0.822	0.001	429.78	-2.174	0.000	418.67	-0.496	0.000	0.001
4	31-May-99	436.30	0.939	0.048	432.95	-2.048	0.051	422.10	-0.348	0.060	0.053
6	02-Jun-99	437.57	1.056	0.095	434.28	-1.935	0.096	423.43	-0.219	0.111	0.101
11	07-Jun-99	438.72	1.317	0.199	435.12	-1.689	0.194	424.27	0.051	0.219	0.204
15	11-Jun-99	439.17	1.452	0.253	435.79	-1.548	0.251	424.84	0.196	0.277	0.260
20	16-Jun-99	439.23	1.609	0.316	436.10	-1.397	0.311	425.23	0.372	0.348	0.325
29	25-Jun-99	440.76	1.902	0.433	437.49	-1.119	0.422	426.66	0.663	0.464	0.440

Mix SL 8% **Cast** 25-May-99

		BAR # 1			BAR # 2			BAR # 3			Average
Day	**Date**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Weight (g)**	**Length (mm)**	**Expansion (%)**	**Expansion (%)**
0	27-May-99	416.16	0.58	0.000	437.85	-0.511	0.000	432.19	0.275	0.000	0.000
1	28-May-99	415.91	0.654	0.030	437.89	-0.439	0.029	432.46	0.352	0.031	0.030
4	31-May-99	418.44	0.702	0.049	440.8	-0.379	0.053	434.97	0.4	0.050	0.051
6	02-Jun-99	420.19	0.791	0.084	442.44	-0.297	0.086	436.81	0.453	0.071	0.080
11	07-Jun-99	421.42	0.946	0.146	443.60	-0.159	0.141	438.03	0.618	0.137	0.141
15	11-Jun-99	422.91	1.082	0.201	445.03	-0.027	0.194	439.14	0.754	0.192	0.195
20	16-Jun-99	423.32	1.353	0.309	445.61	0.229	0.296	439.82	1.018	0.297	0.301
29	25-Jun-99	424.75	1.681	0.440	447.00	0.531	0.417	441.06	1.319	0.418	0.425

Mortar Bar Expansion Data

Mix SL 12% **Cast** 25-May-99

		BAR # 1			BAR # 2			BAR # 3			Average Expansion (%)
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	
0	27-May-99	460.30	-0.518	0.000	457.57	0.756	0.000				0.000
1	28-May-99	460.27	-0.517	0.000	457.45	0.759	0.001				0.001
4	31-May-99	461.35	-0.488	0.012	458.99	0.784	0.011				0.012
6	02-Jun-99	462.78	-0.480	0.015	460.23	0.792	0.014				0.015
11	07-Jun-99	464.52	-0.461	0.023	462.15	0.813	0.023				0.023
15	11-Jun-99	450.93	-0.269	0.100	428.13	0.819	0.025				0.062
21	16-Jun-99	465.90	-0.199	0.128	463.55	1.110	0.142				0.135
29	25-Jun-99	467.32	0.119	0.255	464.83	1.420	0.266				0.260

Mix OPC **Cast** 14-Oct-98

		BAR # 1			BAR # 2			BAR # 3			Average Expansion (%)
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	
0	16-Oct-98	459.32	2.032	0.000	443.66	2.677	0.000	443.76	0.97	0.000	0.000
1	17-Oct-98		2.152	0.048		2.801	0.050		1.112	0.057	0.051
4	20-Oct-98	465.40	2.451	0.168	449.71	3.134	0.183	449.05	1.429	0.184	0.178
5	21-Oct-98	462.88	2.668	0.254	447.62	3.348	0.268	447.39	1.648	0.271	0.265
6	22-Oct-98	463.90	2.800	0.307	447.86	3.491	0.326	448.11	1.798	0.331	0.321
7	23-Oct-98	464.21	2.907	0.350	448.61	3.607	0.372	448.36	1.916	0.378	0.367
11	27-Oct-98	465.55	3.103	0.428	449.90	3.813	0.454	449.55	2.130	0.464	0.449
14	30-Oct-98	466.18	3.239	0.483	450.45	3.952	0.510	450.12	2.277	0.523	0.505
21	06-Nov-98	467.68	3.546	0.606	452.00	4.274	0.639	451.82	2.603	0.653	0.633
28	13-Nov-98	470.70	4.099	0.827	454.70	4.809	0.853	454.84	3.169	0.880	0.853

Mortar Bar Expansion Data

Mix NS 4% Cast 04-May-99

Day	Date	BAR # 1			BAR # 2			BAR # 3			Average Expansion (%)
		Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	
0	06-May-99	457.12	-1.266	0.000	431.58	-0.542	0.000	424.95	-0.078	0.000	0.000
1	07-May-99	457.76	-1.240	0.010	432.12	-0.511	0.012	425.30	-0.064	0.006	0.009
4	10-May-99	461.41	-1.097	0.068	435.98	-0.376	0.066	429.02	0.066	0.058	0.064
7	13-May-99	463.39	-0.965	0.120	437.80	-0.250	0.117	430.90	0.183	0.104	0.114
8	14-May-99	463.01	-0.870	0.158	437.03	-0.156	0.154	430.46	0.292	0.148	0.154
11	17-May-99	463.88	-0.708	0.223	438.09	0.017	0.224	431.58	0.443	0.208	0.218
13	19-May-99	464.09	-0.606	0.264	438.35	0.112	0.262	432.79	0.558	0.254	0.260
19	25-May-99	466.50	-0.41	0.342	440.02	0.303	0.338	432.92	0.732	0.324	0.335
20	26-May-99	465.29	-0.386	0.352	439.87	0.33	0.349	433.01	0.761	0.336	0.345
25	31-May-99	466.49	-0.21	0.422	440.71	0.499	0.416	434.39	0.932	0.404	0.414
28	03-Jun-99	466.36	-0.106	0.464	440.9	0.6	0.457	434.16	1.037	0.446	0.456

Mix NS 8% Cast 04-May-99

Day	Date	BAR # 1			BAR # 2			BAR # 3			Average Expansion (%)
		Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	
0	06-May-99	446.89	2.663	0.000	453.78	1.154	0.000	449.67	-1.146	0.000	0.000
1	07-May-99	447.26	2.680	0.007	454.10	1.171	0.007	450.03	-1.121	0.010	0.008
4	10-May-99	448.34	2.727	0.026	455.53	1.210	0.022	451.17	-1.094	0.021	0.023
7	13-May-99	450.00	2.761	0.039	457.16	1.249	0.038	452.58	-1.061	0.034	0.037
8	14-May-99	450.52	2.774	0.044	457.09	1.272	0.047	452.53	-1.037	0.044	0.045
11	17-May-99	450.26	2.819	0.062	457.46	1.290	0.054	453.17	-1.017	0.052	0.056
13	19-May-99	450.84	2.909	0.098	457.42	1.360	0.082	453.29			0.090
19	25-May-99	452.30	3.062	0.160	459.2	1.523	0.148	454.46	-0.790	0.142	0.150
20	26-May-99	452.60	3.098	0.174	459.69	1.561	0.163	454.9	-0.754	0.157	0.165
25	31-May-99	453.27	3.269	0.242	460.77	1.739	0.234	455.74	-0.568	0.231	0.236
28	03-Jun-99	453.91	3.333	0.268	461.48	1.825	0.268	456.75	-0.465	0.272	0.270

Mortar Bar Expansion Data

Mix **NS 12%** **Cast** **04-May-99**

		BAR # 1			BAR # 2			BAR # 3			Average Expansion (%)
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	
0	27-May-99	410.99	-0.175	0.000	421.58	0.440	0.000	428.50	0.570	0.000	0.000
1	28-May-99	411.15	-0.171	0.002	421.46	0.443	0.001	428.48	0.567	-0.001	0.000
4	31-May-99	413.10	-0.140	0.014	423.43	0.471	0.012	430.40	0.601	0.012	0.013
6	02-Jun-99	413.92	-0.130	0.018	424.47	0.480	0.016	431.39	0.609	0.016	0.017
11	07-Jun-99	415.09	-0.096	0.032	425.72	0.511	0.028	432.94	0.641	0.028	0.029
15	11-Jun-99	415.53	0.005	0.072	426.33			432.96	0.733	0.065	0.069
21	16-Jun-99	416.29	0.136	0.124	427.01	0.721	0.112	433.81	0.833	0.105	0.114
29	25-Jun-99	417.35	0.485	0.264	428.20	1.091	0.260	434.92	1.183	0.245	0.257

Mix **LS 4%** **Cast** **11-May-99**

		BAR # 1			BAR # 2			BAR # 3			Average Expansion (%)
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	
0	13-May-99	441.12	3.084	0.000	453.57	2.280	0.000	445.79	-0.621	0.000	0.000
1	14-May-99	441.38	3.098	0.006	454.08	2.293	0.005	446.22	-0.616	0.002	0.004
4	17-May-99	444.61	3.279	0.078	457.15	2.470	0.076	449.51	-0.432	0.076	0.077
6	19-May-99	446.32	3.511	0.171	459.21	2.698	0.167	451.24	-0.212	0.164	0.167
12	25-May-99	448.35	3.857	0.309	461.51	3.046	0.306	453.33	0.125	0.298	0.305
13	26-May-99	448.96	3.880	0.318	462.30	3.071	0.316	453.99	0.160	0.312	0.316
18	31-May-99	449.59	4.083	0.400	463.07	3.267	0.395	454.41	0.330	0.380	0.392
22	04-Jun-99	450.06	4.344	0.504	463.44	3.505	0.490	455.92	0.593	0.486	0.493
27	09-Jun-99	451.78	4.605	0.608	464.65	3.746	0.586	456.44	0.835	0.582	0.592

Mortar Bar Expansion Data

Mix LS 8% **Cast** 11-May-99

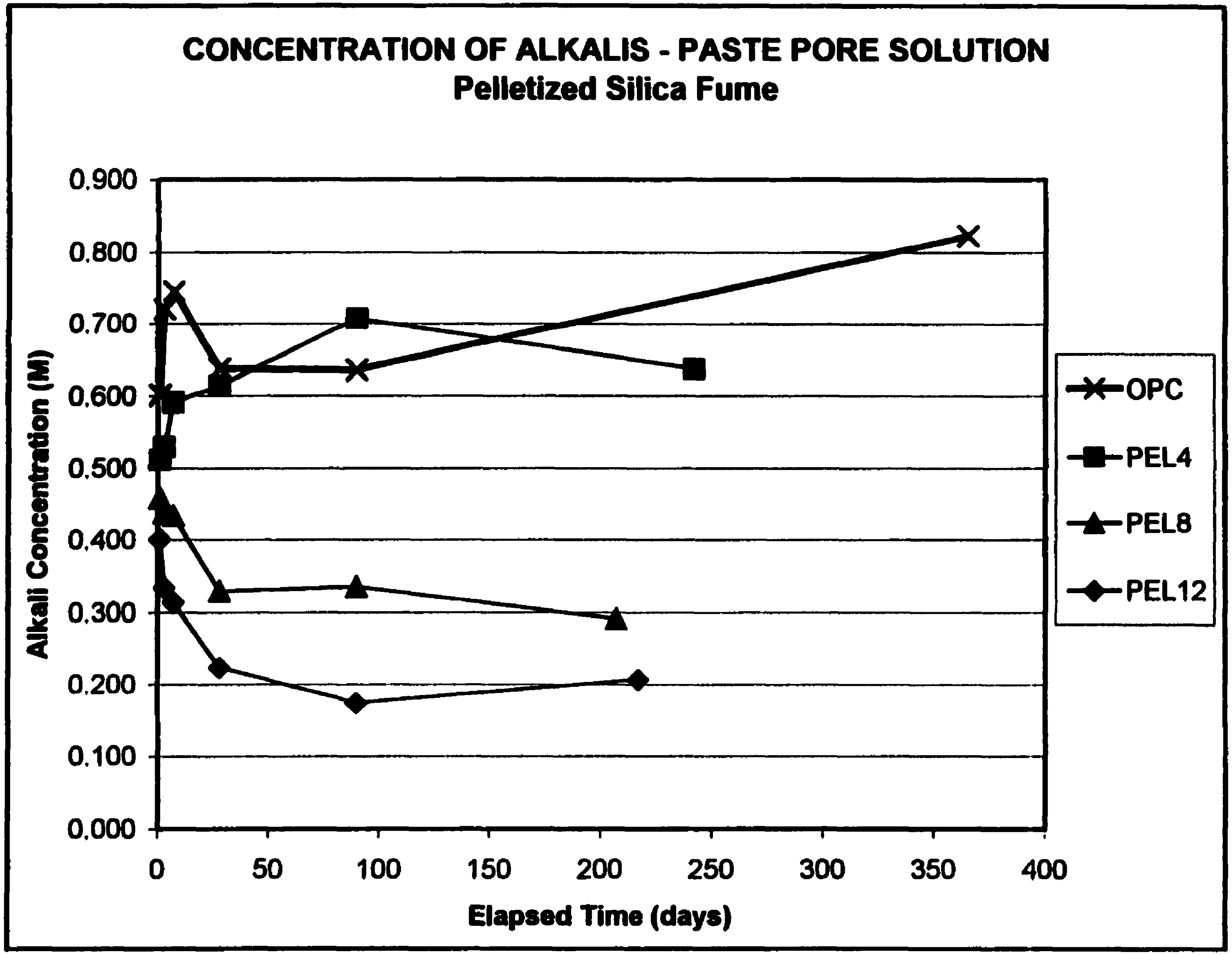
		BAR # 1			BAR # 2			BAR # 3			Average
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Expansion (%)
0	13-May-99	435.80	3.361	0.000	437.66	-1.001	0.000	432.45	0.770	0.000	0.000
1	14-May-99	436.02	3.392	0.012	437.49	-0.947	0.022	432.06	0.822	0.021	0.018
4	17-May-99	440.34	3.502	0.056	442.02	-0.860	0.056	436.84	0.893	0.049	0.054
6	19-May-99	440.94	3.600	0.096	442.56	-0.778	0.089	437.71	1.020	0.100	0.095
12	25-May-99	442.62	3.853	0.197	444.35	-0.528	0.189	442.73			0.193
13	26-May-99	442.88	3.892	0.212	444.72	-0.489	0.205	439.94	1.288	0.207	0.208
18	31-May-99	444.14	4.192	0.332	446.05	-0.187	0.326	441.39	1.581	0.324	0.327
20	02-Jun-99	444.53	4.352	0.396	446.41	-0.034	0.387	441.76	1.739	0.388	0.390
27	09-Jun-99	446.96	4.939	0.631	448.99	0.538	0.616	443.93	2.308	0.615	0.621

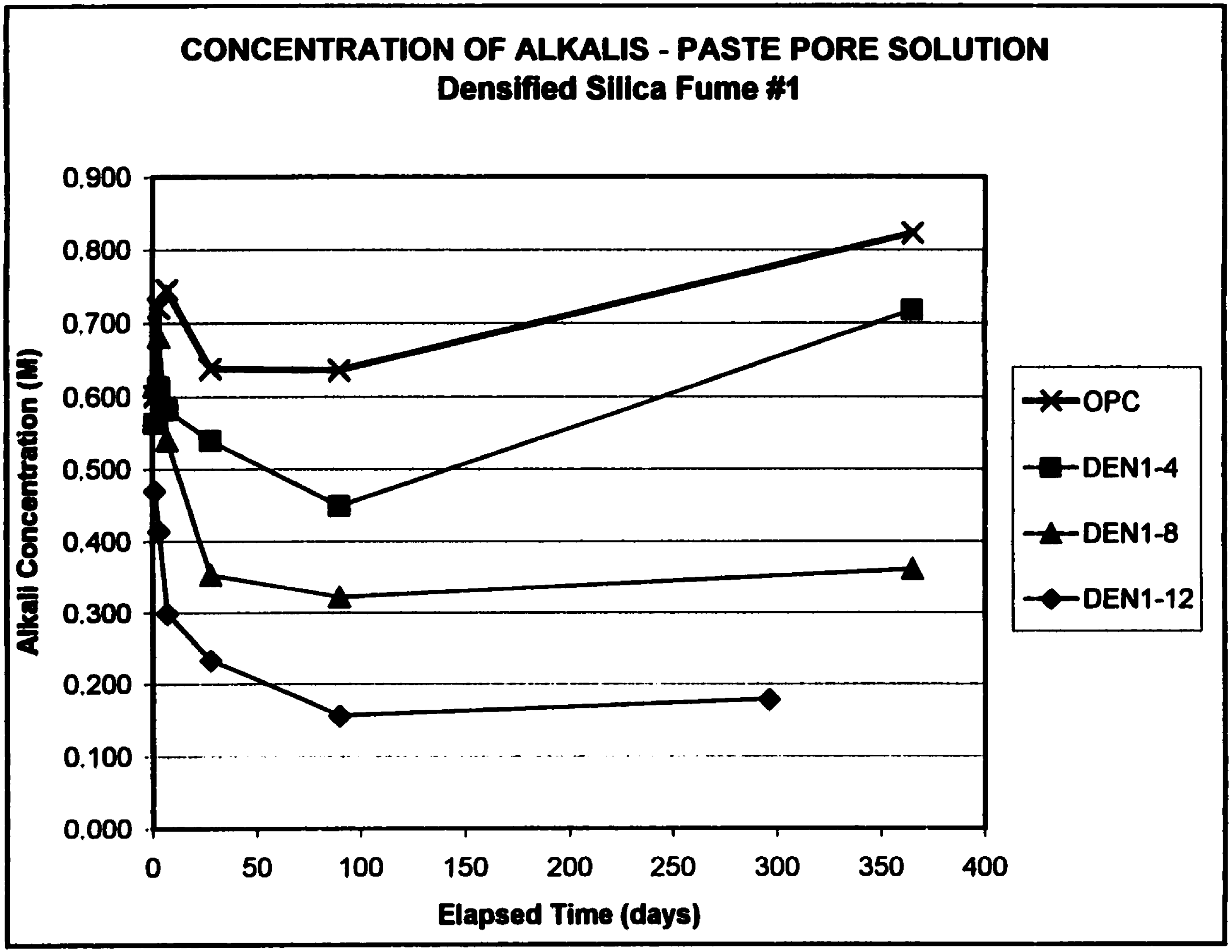
Mix LS 12% **Cast** 11-May-99

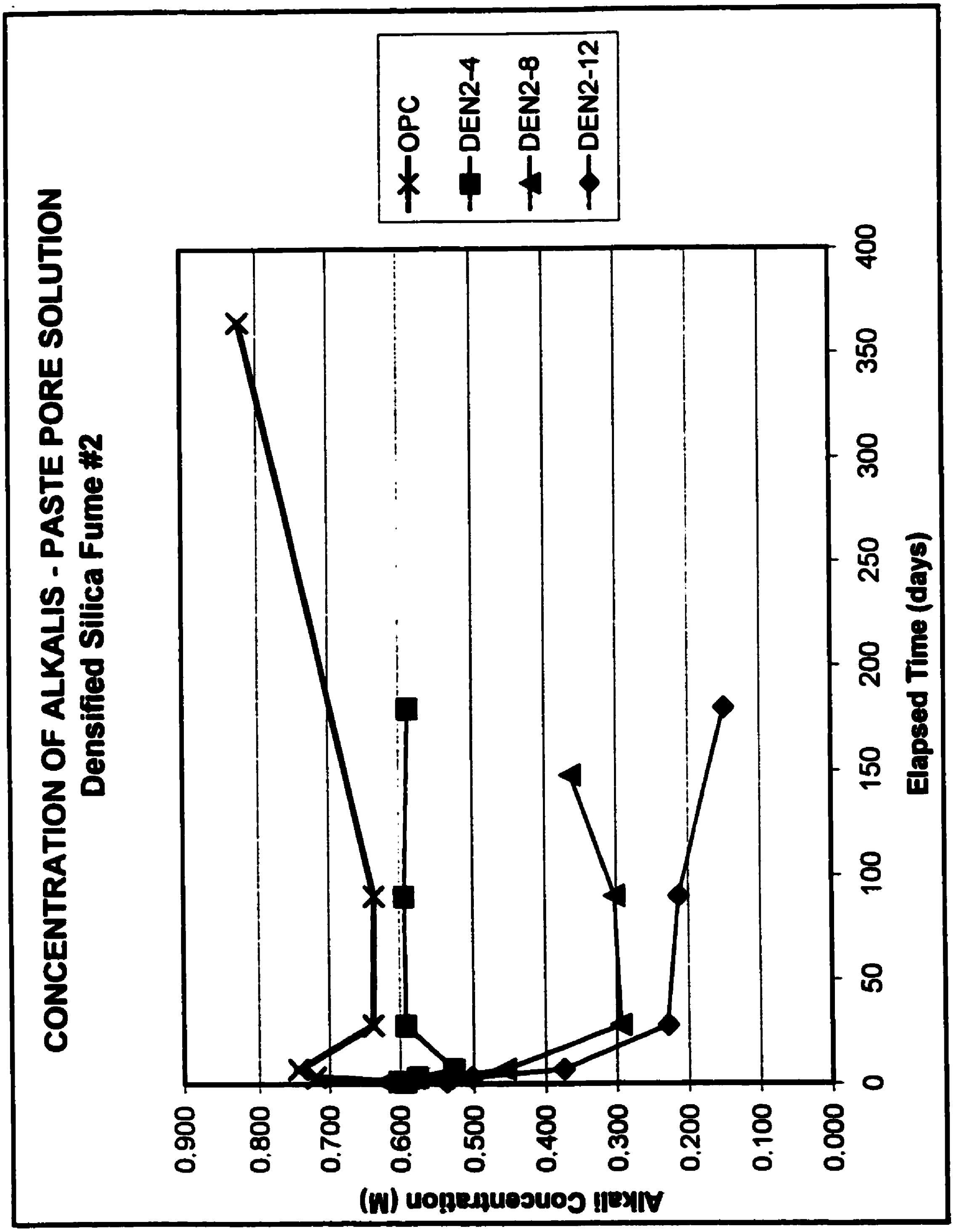
		BAR # 1			BAR # 2			BAR # 3			Average
Day	Date	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Weight (g)	Length (mm)	Expansion (%)	Expansion (%)
0	13-May-99	431.80	0.439	0.000	423.23	-0.521	0.000	445.67	0.581	0.000	0.000
1	14-May-99	432.05	0.443	0.002	422.94	-0.497	0.010	445.75	0.591	0.004	0.005
4	17-May-99	435.60	0.477	0.015	426.47	-0.452	0.028	448.97	0.619	0.015	0.019
6	19-May-99	435.71	0.526	0.035	426.05	-0.404	0.047	448.31	0.660	0.032	0.038
12	25-May-99	451.32	0.783	0.138	427.90	-0.302	0.088	451.28	0.796	0.086	0.104
13	26-May-99	450.93	0.819	0.152	428.13	-0.269	0.101	437.94			0.126
18	31-May-99	452.30	0.924	0.194	429.22	-0.169	0.141	439.11	0.799	0.087	0.141
20	02-Jun-99	452.98	0.981	0.217	430.10	-0.107	0.166	440.40	0.851	0.108	0.163
27	09-Jun-99	453.93	1.219	0.312	431.02	0.118	0.256	440.52	1.079	0.199	0.256

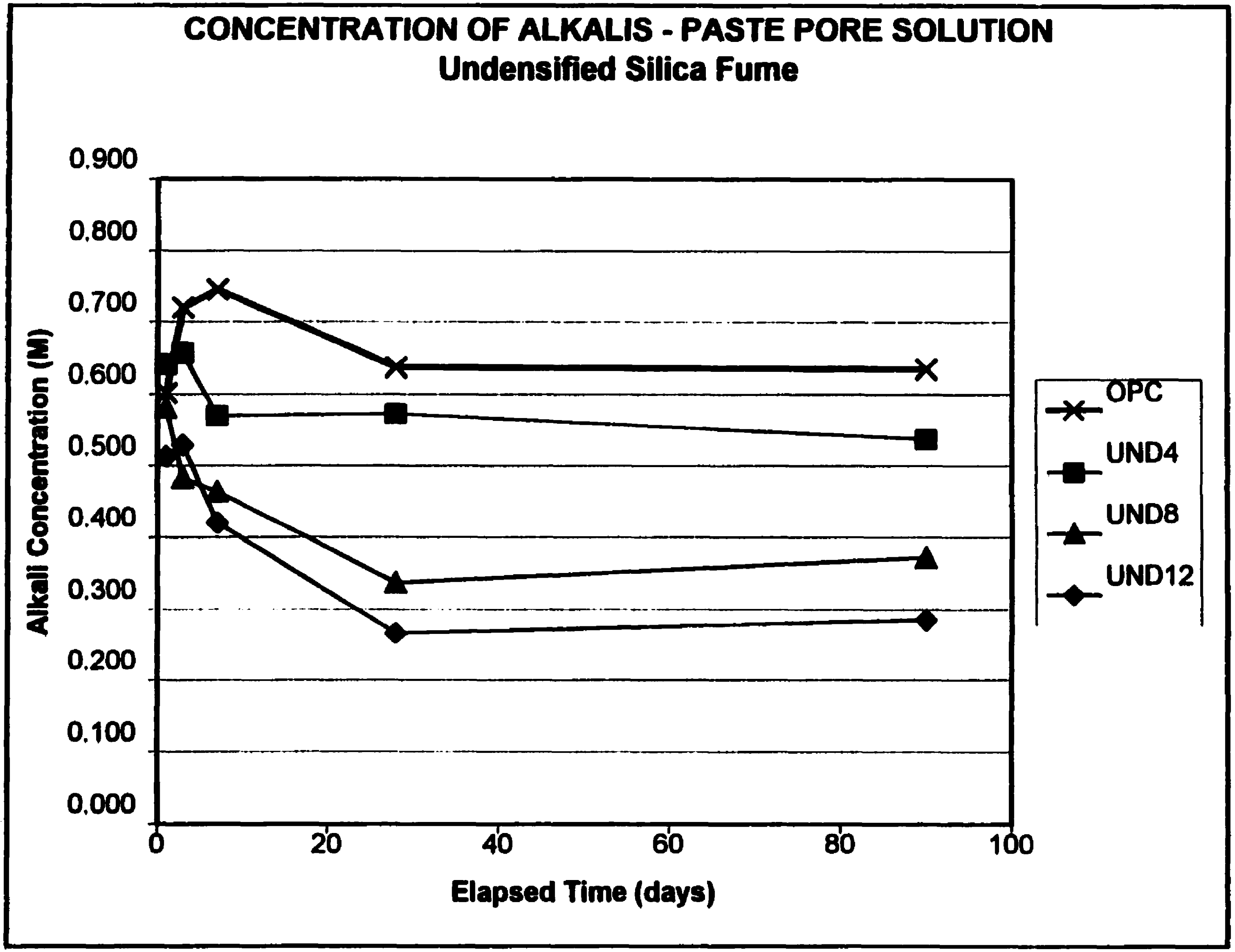
APPENDIX D

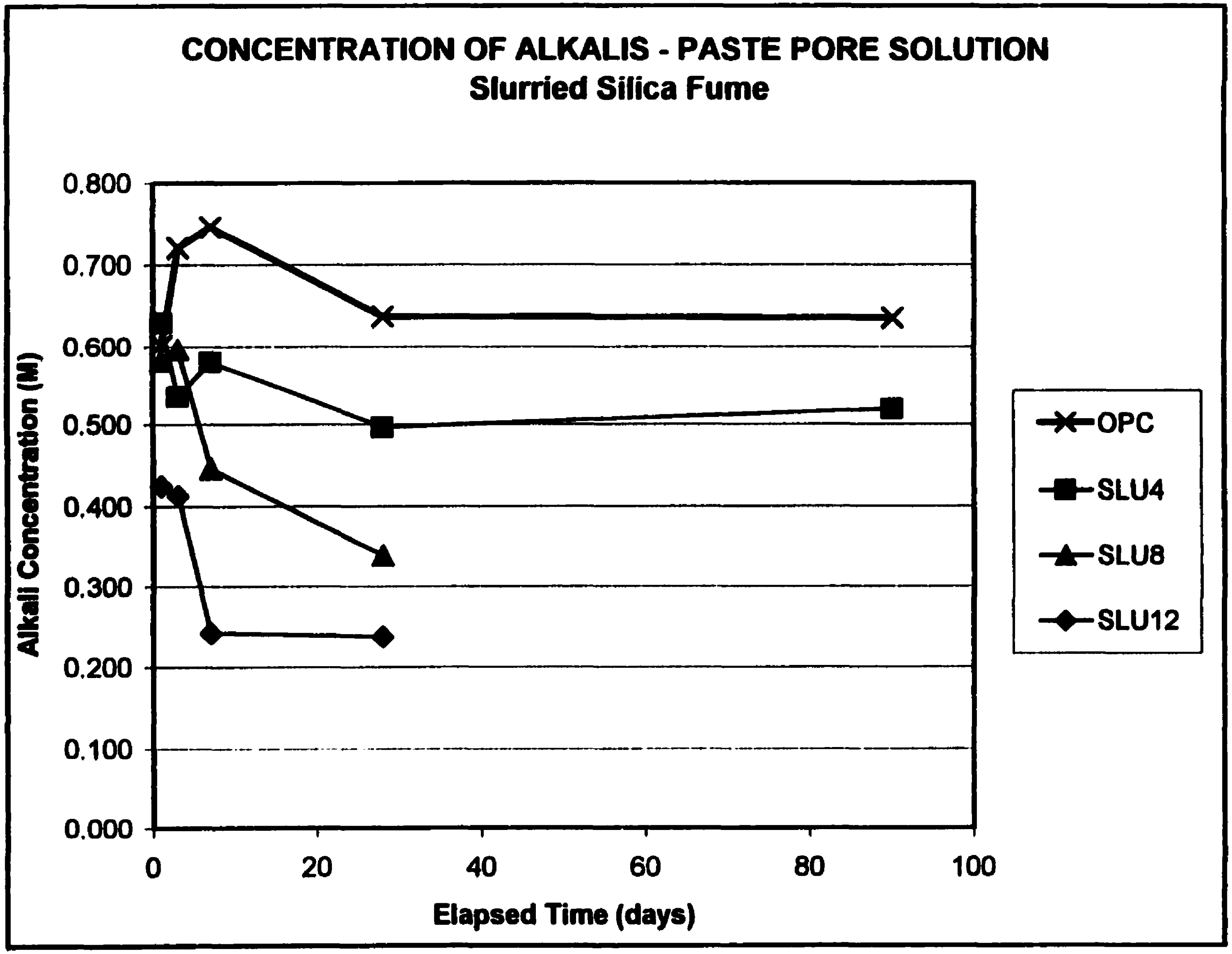
PASTE PORE SOLUTION COMPOSITION DATA AND PLOTS

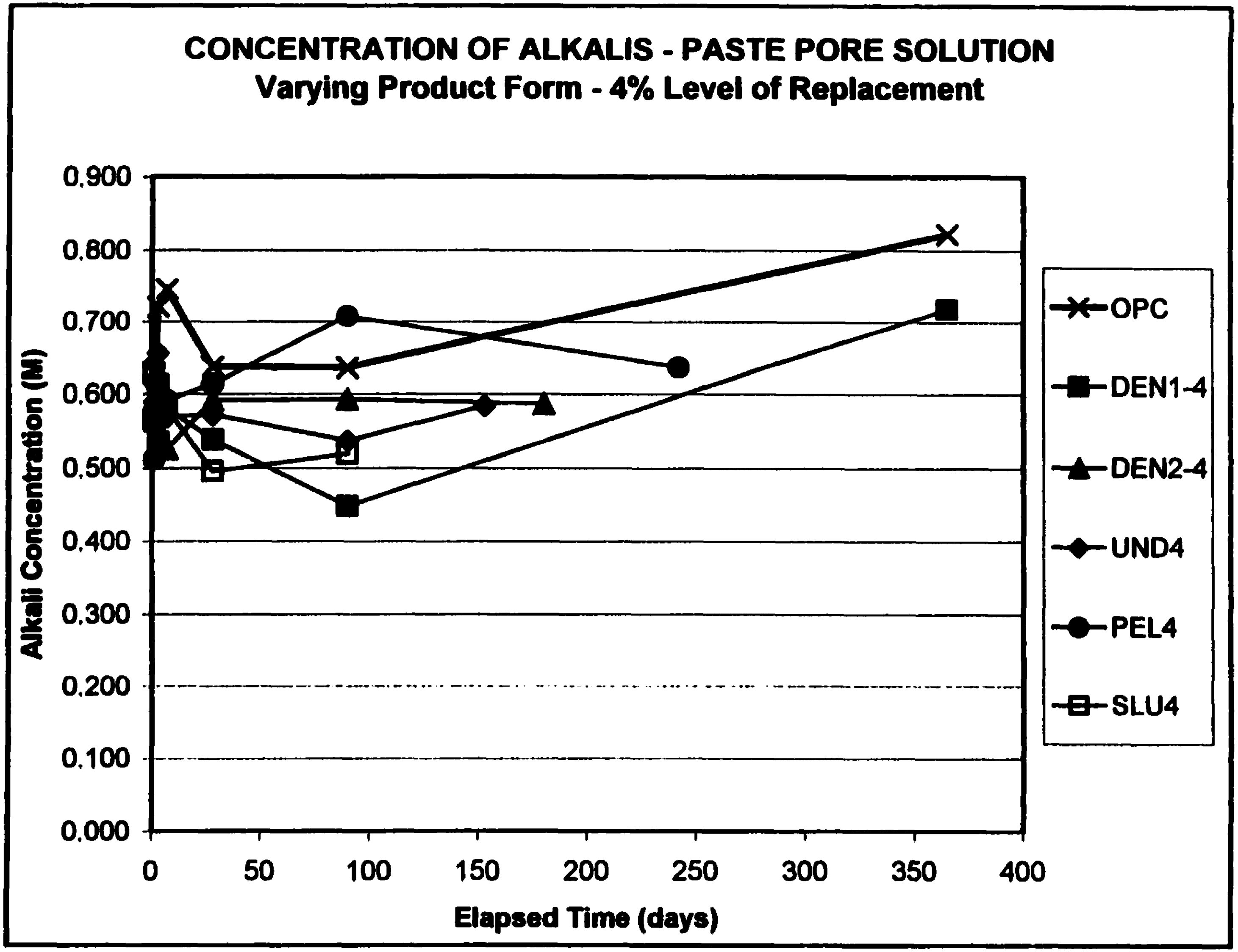

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Pelletized Silica Fume
Alkali Concentration (M)
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
50
100
150
200
250
300
350
400
Elapsed Time (days)
OPC
PEL4
PEL8
PEL12


CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Densified Silica Fume #1
Alkali Concentration (M)
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
50
100
150
200
250
300
350
400
Elapsed Time (days)
OPC
DEN1-4
DEN1-8
DEN1-12

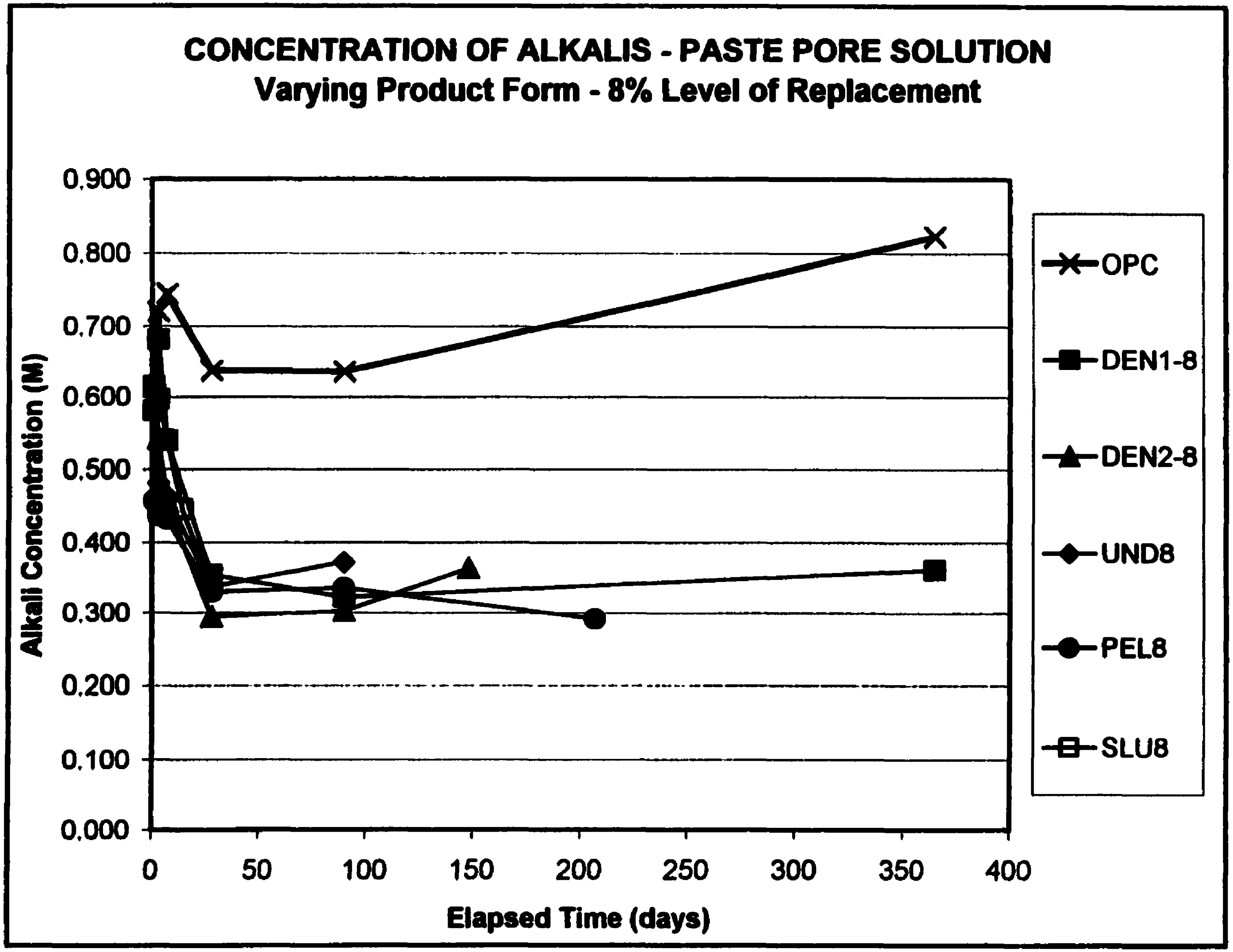

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Densified Silica Fume #2
OPC
DEN2-4
DEN2-8
DEN2-12
Alkali Concentration (M)
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Elapsed Time (days)
0
50
100
150
200
250
300
350
400

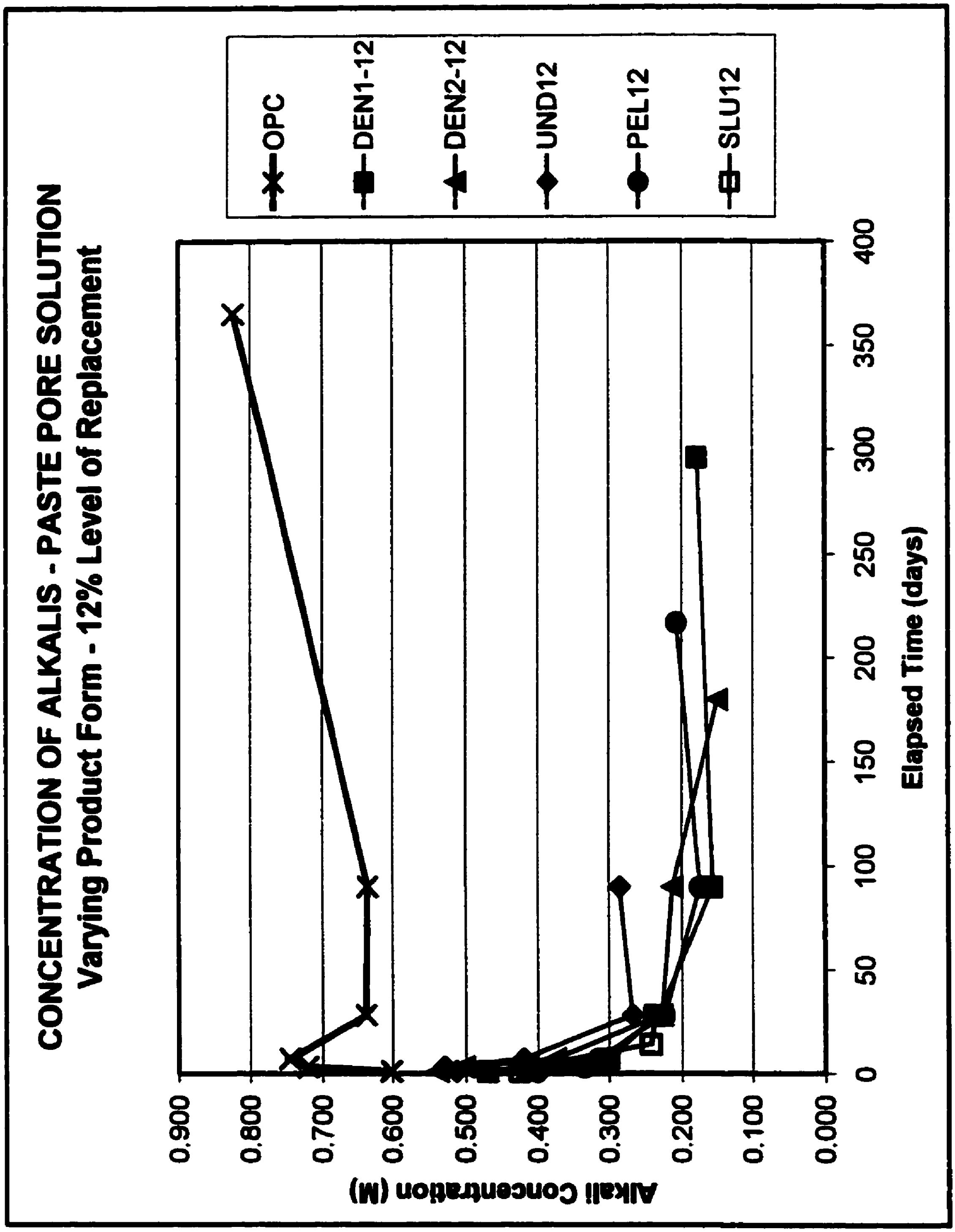

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Undensified Silica Fume
Alkali Concentration (M)
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
20
40
60
80
100
Elapsed Time (days)
OPC
UND4
UND8
UND12

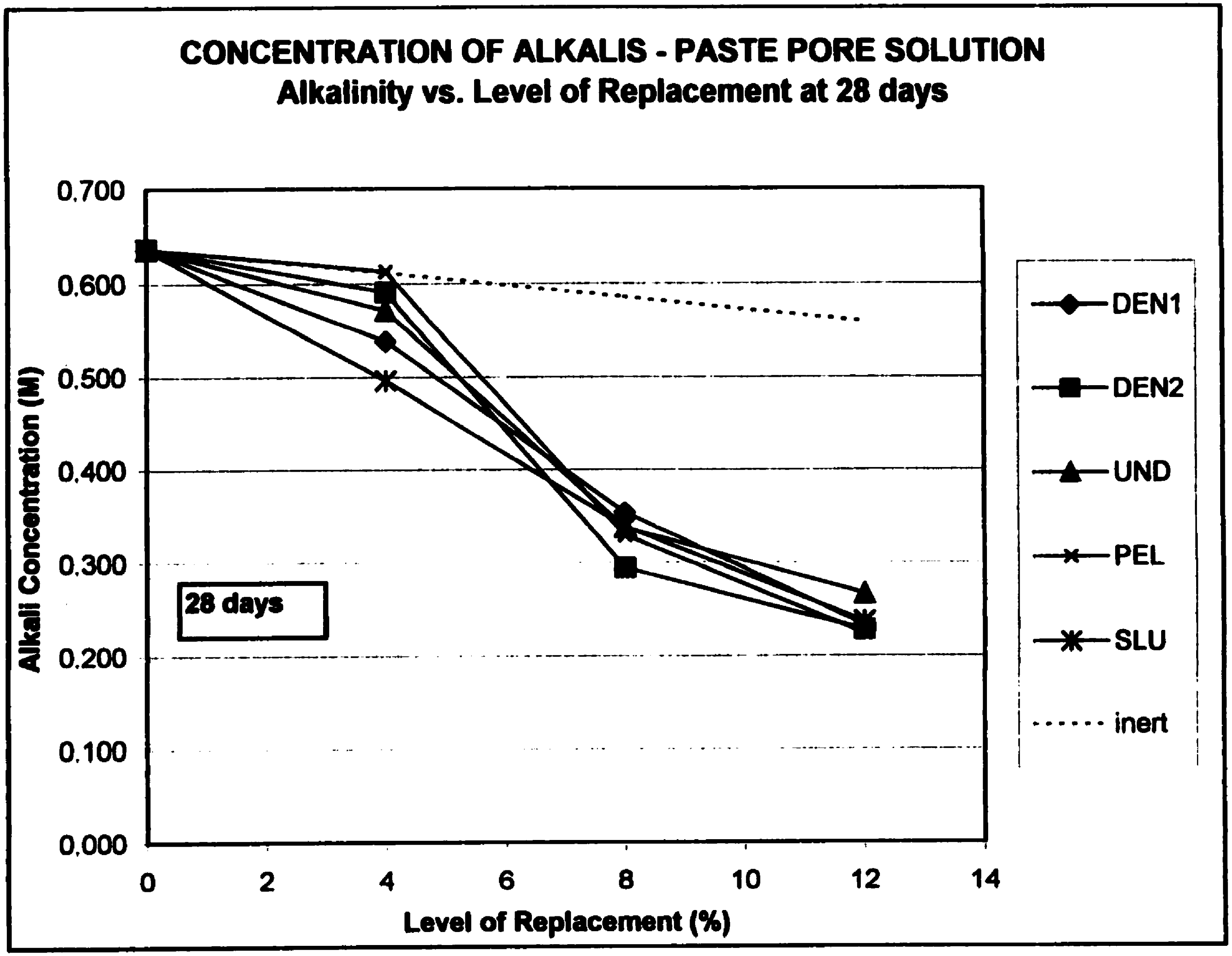

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Slurried Silica Fume
Alkali Concentration (M)
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
20
40
60
80
100
Elapsed Time (days)
OPC
SLU4
SLU8
SLU12

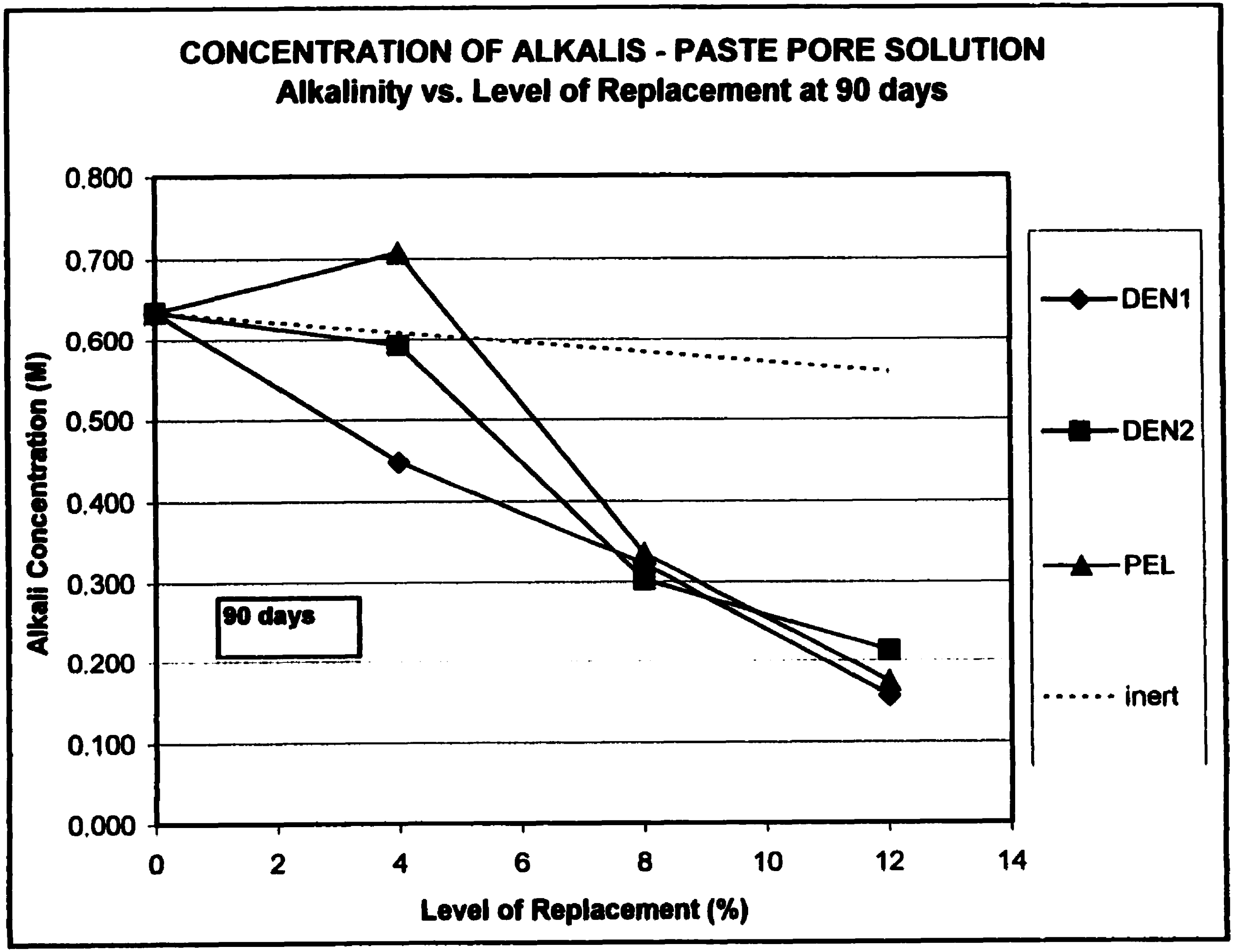


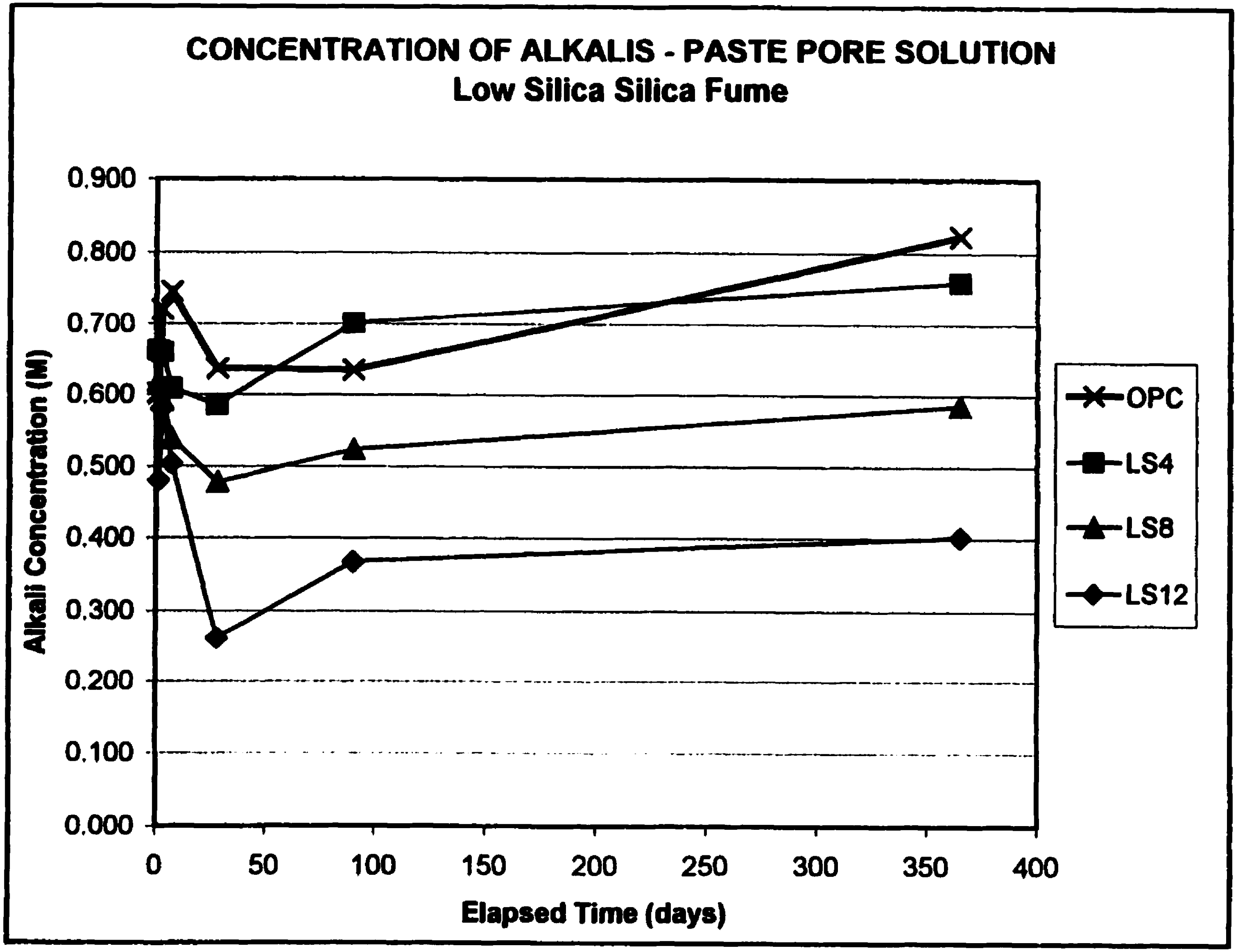
CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Varying Product Form - 4% Level of Replacement

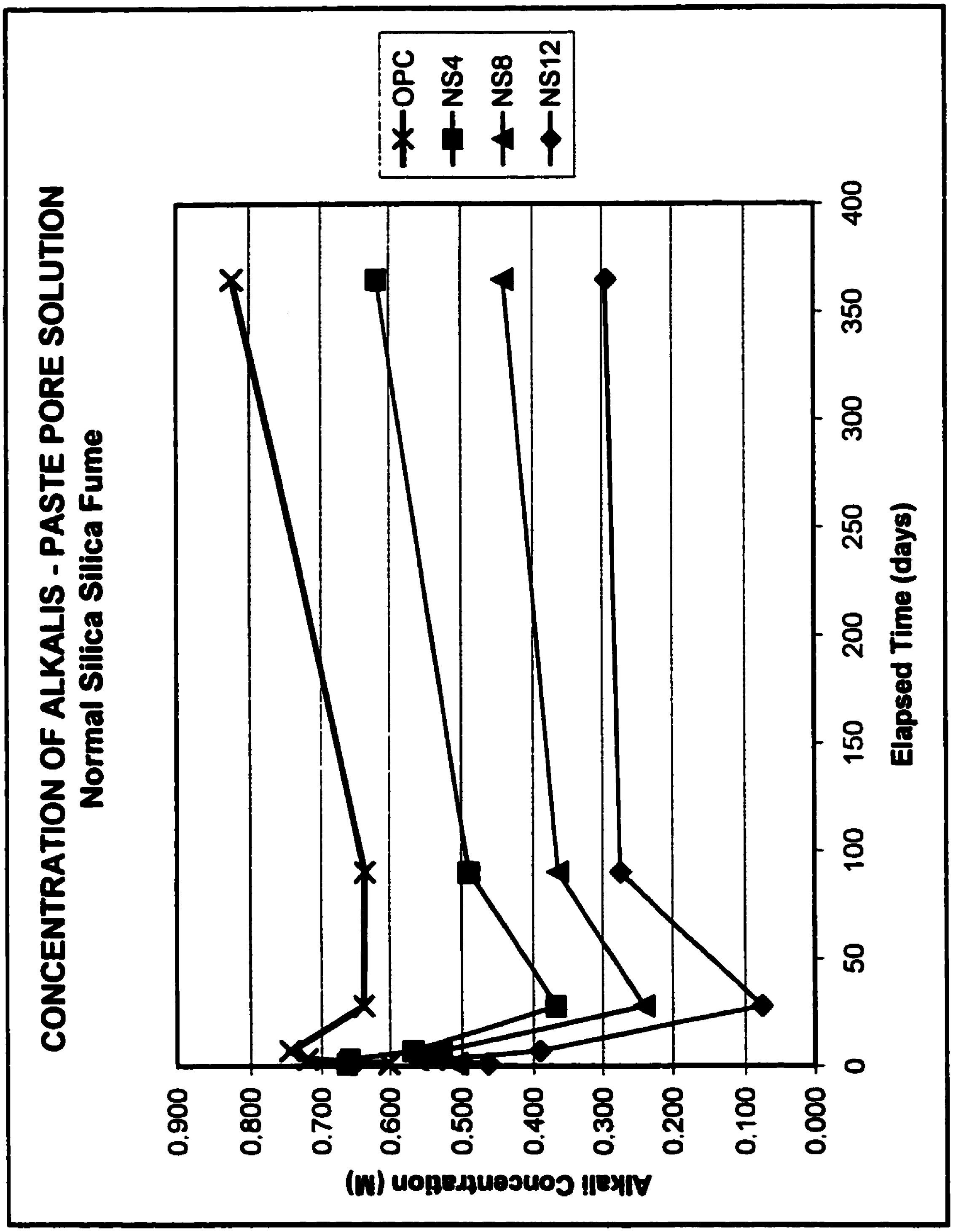

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Varying Product Form - 8% Level of Replacement

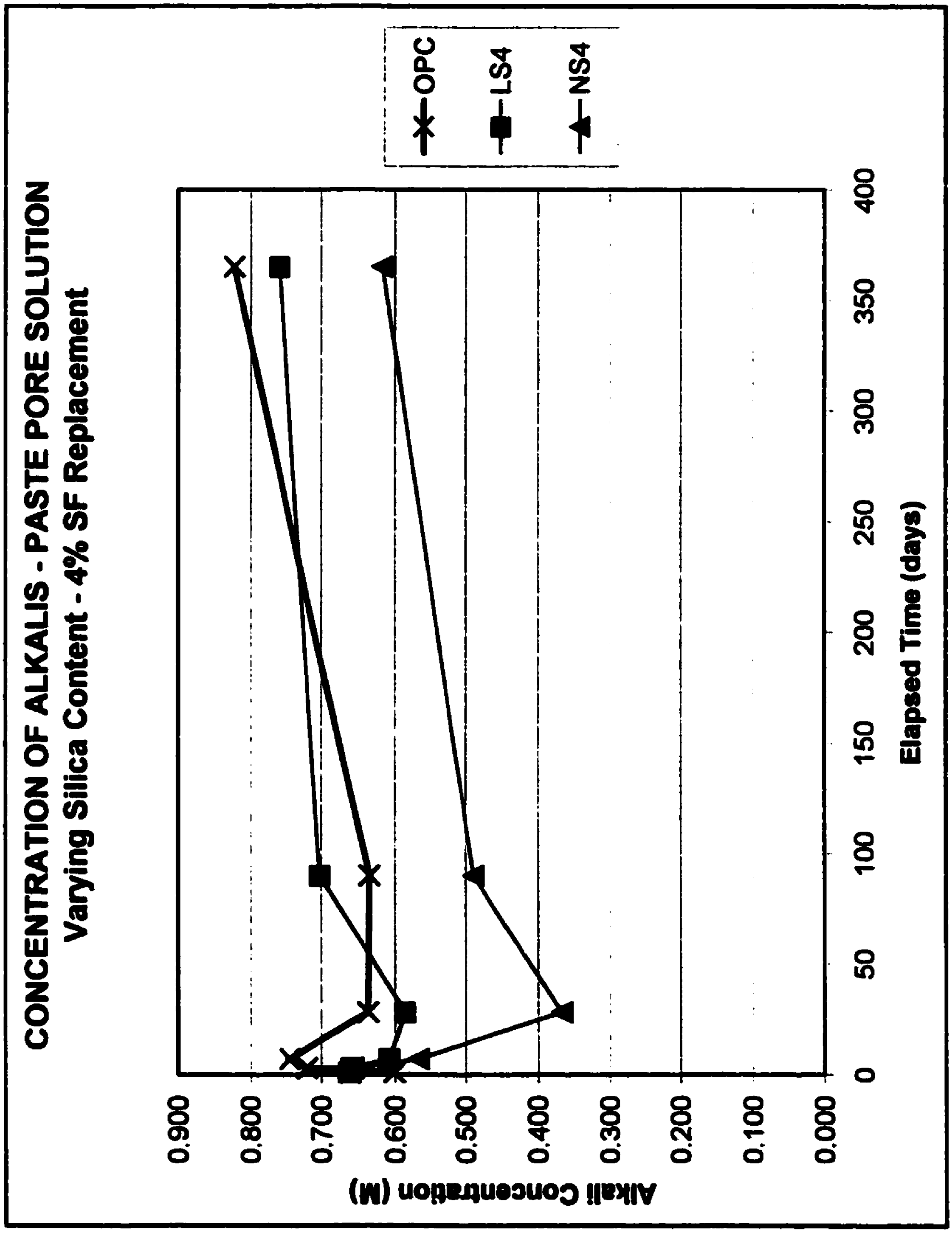

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Varying Product Form - 12% Level of Replacement
Alkali Concentration (M)
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
50
100
150
200
250
300
350
400
Elapsed Time (days)
OPC
DEN1-12
DEN2-12
UND12
PEL12
SLU12

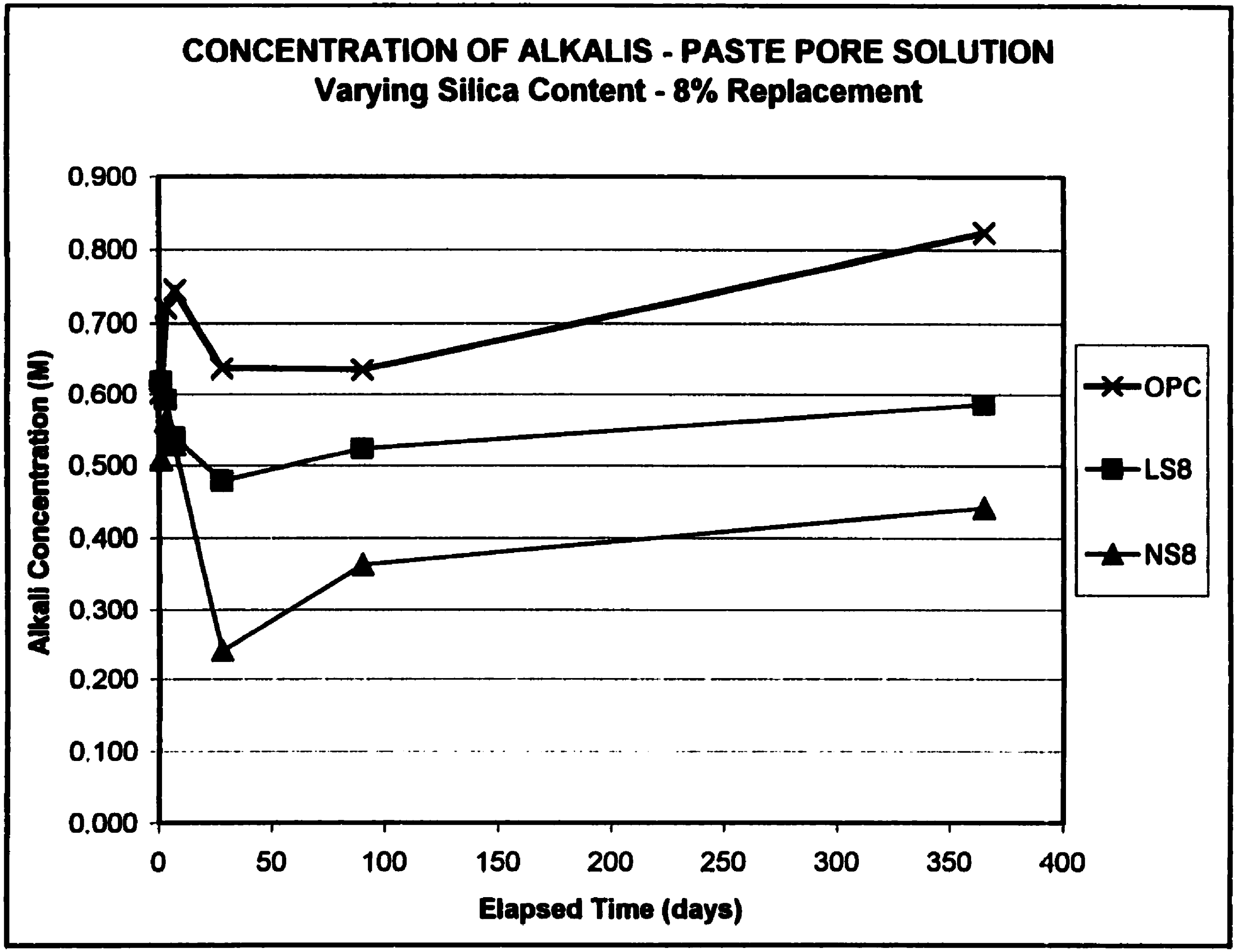

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Alkalinity vs. Level of Replacement at 28 days
Alkali Concentration (M)
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
Level of Replacement (%)
0
2
4
6
8
10
12
14
28 days
DEN1
DEN2
UND
PEL
SLU
inert

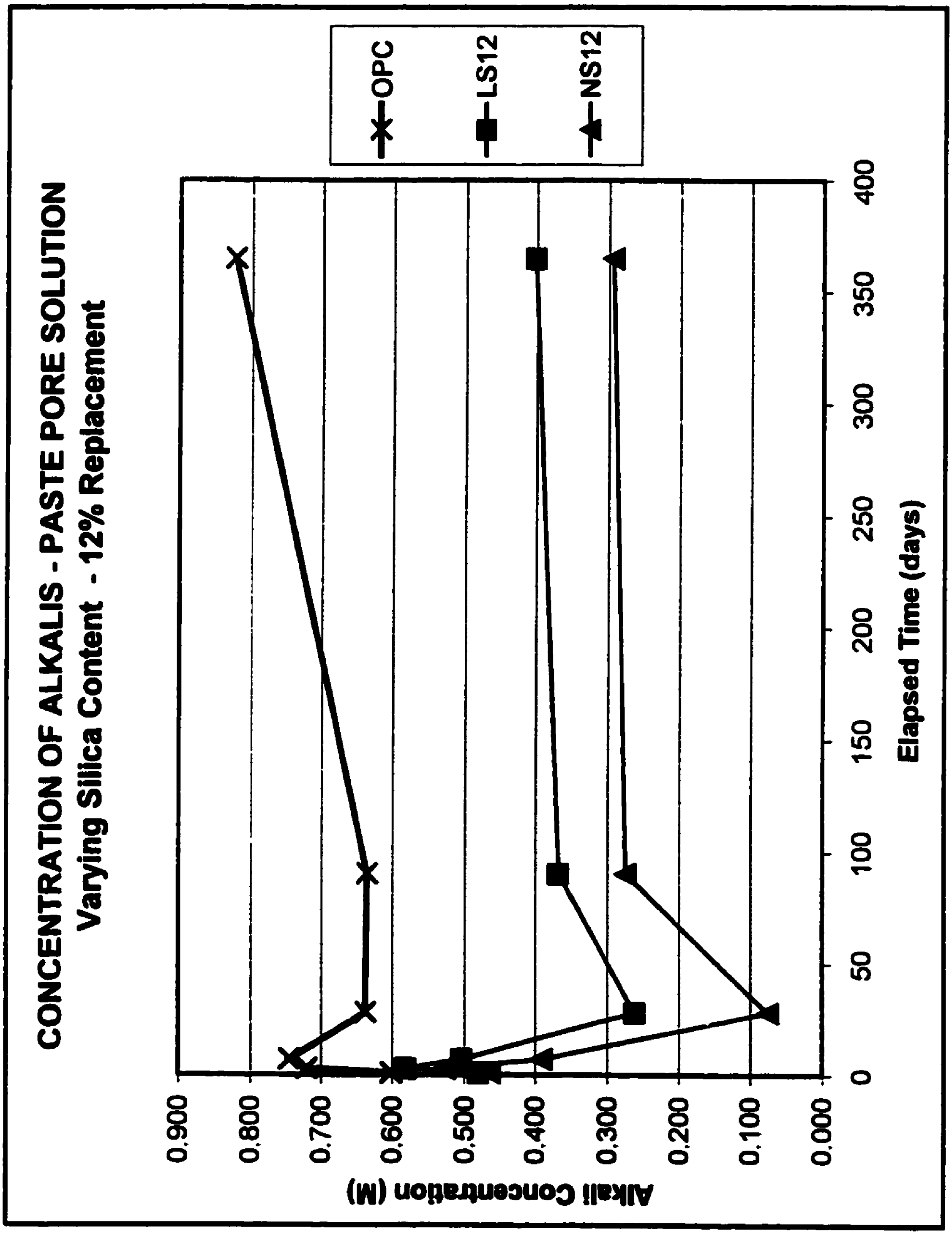

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Alkalinity vs. Level of Replacement at 90 days
Alkali Concentration (M)
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
2
4
6
8
10
12
14
Level of Replacement (%)
90 days
DEN1
DEN2
PEL
inert

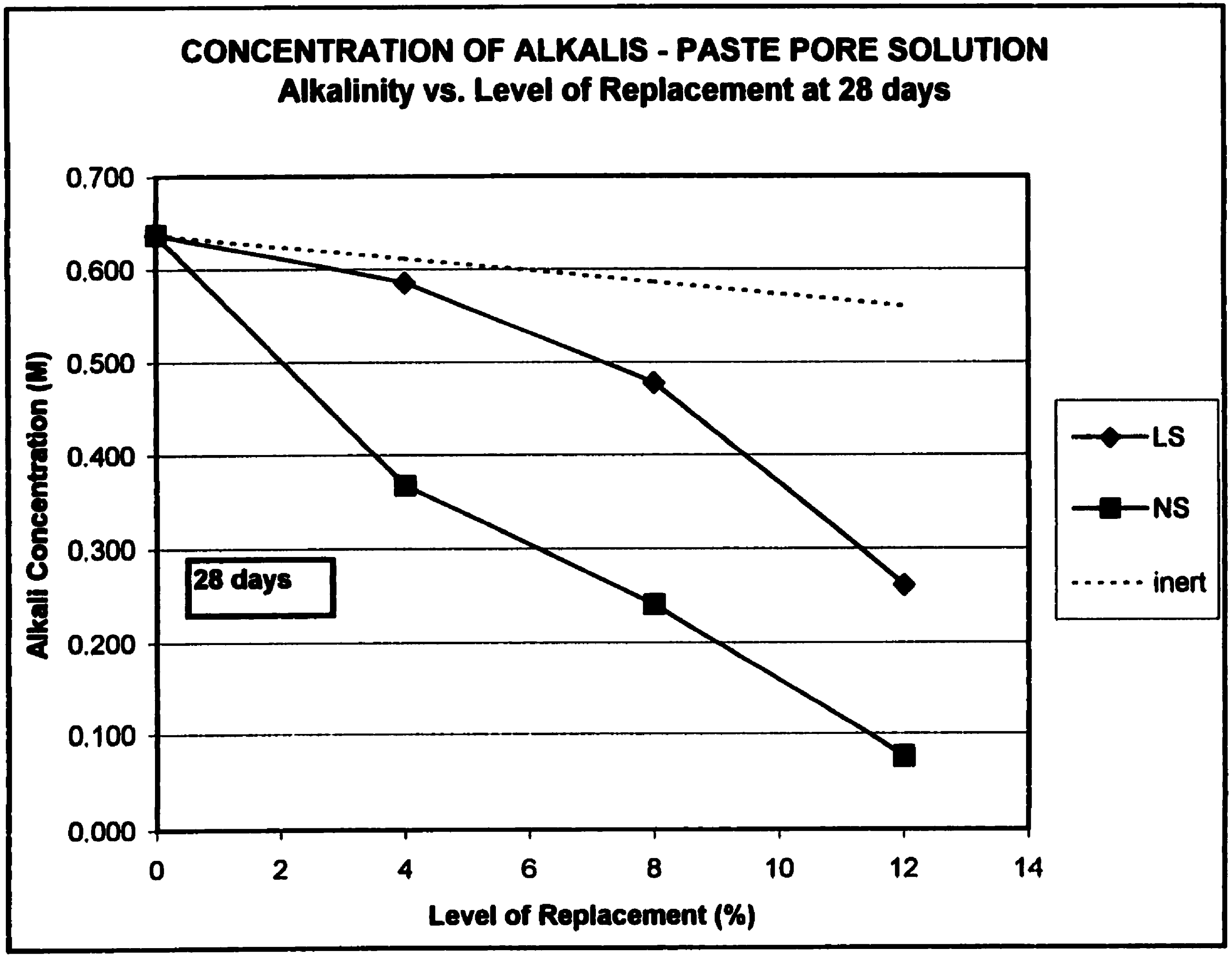

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Low Silica Silica Fume
Alkali Concentration (M)
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
0
50
100
150
200
250
300
350
400
Elapsed Time (days)
OPC
LS4
LS8
LS12

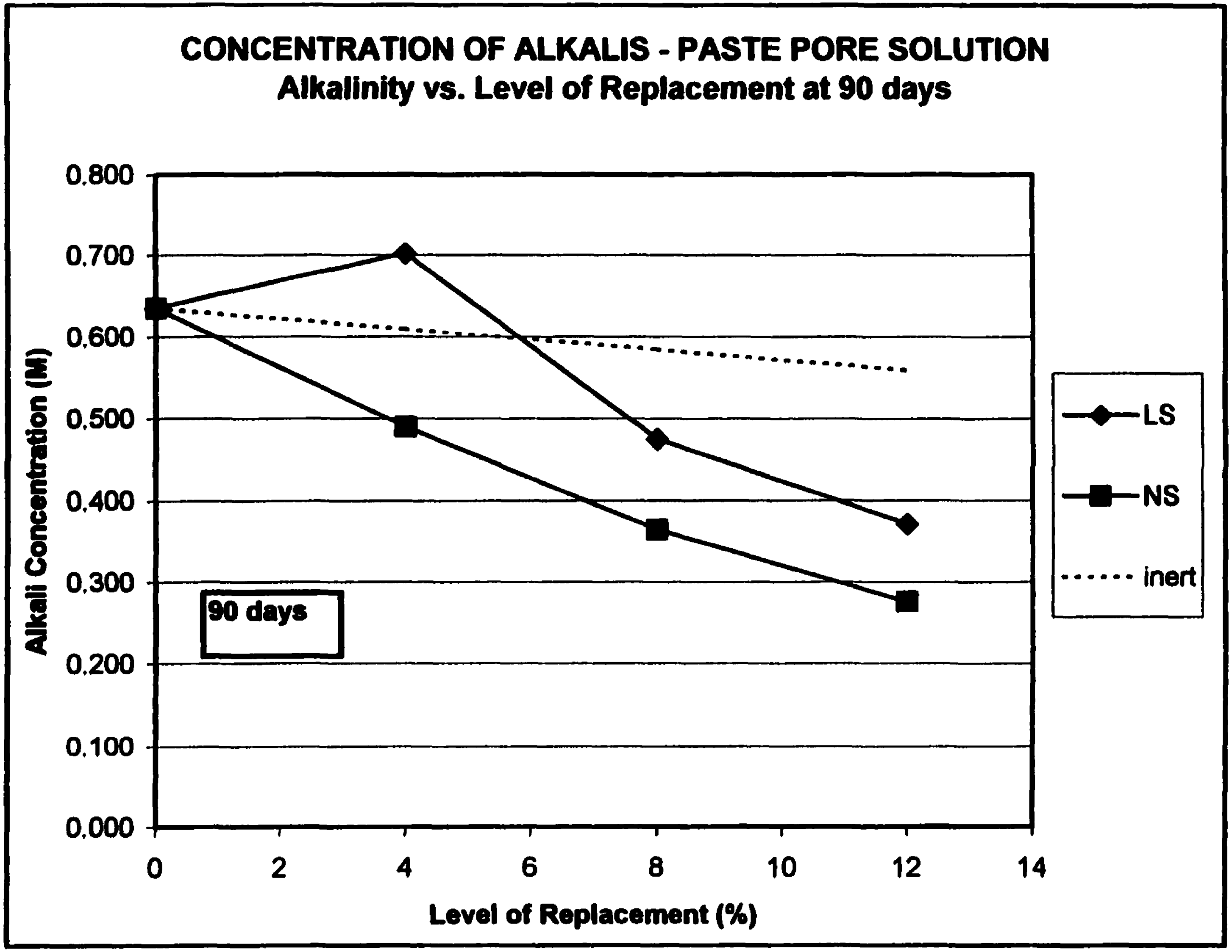

CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Normal Silica Silica Fume
Alkali Concentration (M)
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
50
100
150
200
250
300
350
400
Elapsed Time (days)
OPC
NS4
NS8
NS12


CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Varying Silica Content - 4% SF Replacement
Alkali Concentration (M)
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
Elapsed Time (days)
0
50
100
150
200
250
300
350
400
OPC
LS4
NS4


CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Varying Silica Content - 8% Replacement
Alkali Concentration (M)
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
50
100
150
200
250
300
350
400
Elapsed Time (days)
OPC
LS8
NS8


CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Varying Silica Content - 12% Replacement
Alkali Concentration (M)
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
50
100
150
200
250
300
350
400
Elapsed Time (days)
OPC
LS12
NS12


CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Alkalinity vs. Level of Replacement at 28 days
Alkali Concentration (M)
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
28 days
0
2
4
6
8
10
12
14
Level of Replacement (%)
LS
NS
inert


CONCENTRATION OF ALKALIS - PASTE PORE SOLUTION
Alkalinity vs. Level of Replacement at 90 days
Alkali Concentration (M)
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
2
4
6
8
10
12
14
Level of Replacement (%)
90 days
LS
NS
inert

Mix Name	Cast Date	1 day				
		[OH-]	[Na+]	[K+]	[Na+ & K+]	[Na+/K+]
OPC	98/06/22	0.584	0.121	0.481	0.602	0.252
DEN1-4	98/06/29	0.555	0.114	0.449	0.563	0.254
DEN1-8	98/07/07	0.739	0.133	0.482	0.615	0.276
DEN1-12	98/09/22	0.493	0.103	0.367	0.470	0.281
LS4	98/07/28	0.582	0.140	0.523	0.663	0.268
LS8	98/07/28	0.596	0.134	0.484	0.618	0.277
LS12	98/07/27	0.474	0.101	0.380	0.481	0.266
NS4	98/08/11	0.613	0.140	0.523	0.663	0.268
NS8	98/08/11	0.495	0.110	0.397	0.507	0.277
NS12	98/08/18	0.583	0.100	0.364	0.464	0.275
DEN2-4	99/01/25	0.554	0.126	0.467	0.593	0.270
DEN2-8	99/02/23	0.521	0.131	0.490	0.621	0.267
DEN2-12	99/01/12	0.510	0.114	0.423	0.537	0.270
UND4	99/02/23	0.585	0.132	0.509	0.641	0.259
UND8	99/05/10	0.567	0.124	0.456	0.580	0.272
UND12	99/05/10	0.521	0.110	0.403	0.513	0.273
PEL4	98/11/10	0.532	0.106	0.406	0.512	0.261
PEL8	98/12/14	0.458	0.102	0.357	0.458	0.286
PEL12	98/12/15	0.413	0.091	0.310	0.401	0.294
SLU4	99/05/25	0.624	0.133	0.496	0.629	0.268
SLU8	99/06/08	0.524	0.127	0.453	0.580	0.280
SLU12	99/06/08	0.406	0.099	0.326	0.425	0.304
Mix Name	Cast Date	3 days				
		[OH-]	[Na+]	[K+]	[Na+ & K+]	[Na+/K+]
OPC	98/06/22	0.836	0.152	0.568	0.720	0.268
DEN1-4	98/06/29	0.748	0.135	0.478	0.613	0.281
DEN1-8	98/07/07	0.672	0.152	0.529	0.681	0.287
DEN1-12	98/09/22	0.440	0.094	0.320	0.414	0.294
LS4	98/07/28	0.601	0.131	0.475	0.606	0.276
LS8	98/07/28	0.567	0.129	0.463	0.592	0.279
LS12	98/07/27	0.542	0.129	0.453	0.582	0.285
NS4	98/08/11	0.585	0.140	0.518	0.658	0.270
NS8	98/08/11	0.561				
NS12	98/08/18	0.552	0.114	0.414	0.528	0.275
DEN2-4	99/01/25	0.547	0.123	0.454	0.577	0.271
DEN2-8	99/02/23	0.432	0.117	0.425	0.542	0.275
DEN2-12	99/01/12	0.502				
UND4	99/02/23	0.596	0.138	0.518	0.656	0.266
UND8	99/05/10	0.483	0.129	0.472	0.601	0.273
UND12	99/05/10	0.529	0.131	0.480	0.611	0.273
PEL4	98/11/10	0.511	0.115	0.415	0.530	0.277
PEL8	98/12/14	0.430	0.102	0.335	0.437	0.304
PEL12	98/12/15	0.339	0.080	0.254	0.334	0.315
SLU4	99/05/25	0.505	0.114	0.421	0.535	0.271
SLU8	99/06/08	0.503	0.128	0.467	0.595	0.274
SLU12	99/06/08	0.386	0.097	0.316	0.413	0.307

Mix Name	Cast Date	7 days				
		[OH-]	[Na+]	[K+]	[Na+ & K+]	[Na+/K+]
OPC	98/06/22	0.735	0.161	0.584	0.745	0.276
DEN1-4	98/06/29	0.727	0.128	0.453	0.581	0.283
DEN1-8	98/07/07	0.619	0.119	0.421	0.540	0.283
DEN1-12	98/09/22	0.318	0.071	0.229	0.300	0.310
LS4	98/07/28	0.559	0.132	0.476	0.608	0.277
LS8	98/07/28	0.543	0.120	0.419	0.539	0.286
LS12	98/07/27	0.479	0.115	0.390	0.505	0.295
NS4	98/08/11	0.567				
NS8	98/08/11	0.511	0.116	0.412	0.528	0.282
NS12	98/08/18	0.391				
DEN2-4	99/01/25	0.468	0.114	0.412	0.526	0.277
DEN2-8	99/02/23	0.398	0.105	0.351	0.456	0.299
DEN2-12	99/01/12	0.342	0.085	0.290	0.375	0.293
UND4	99/02/23	0.498	0.122	0.447	0.569	0.273
UND8	99/05/10	0.399	0.098	0.366	0.464	0.268
UND12	99/05/10	0.420	0.100	0.357	0.457	0.280
PEL4	98/11/10	0.527	0.131	0.460	0.591	0.285
PEL8	98/12/14	0.396	0.101	0.332	0.433	0.304
PEL12	98/12/15	0.314				
SLU4	99/05/25	0.522	0.123	0.458	0.580	0.268
SLU8*	99/06/08	0.362	0.118	0.328	0.446	0.360
SLU12*	99/06/08	0.231	0.063	0.179	0.242	0.352

* values reported for these samples are at 14 days of age

Mix Name	Cast Date	28 days				
		[OH-]	[Na+]	[K+]	[Na+ & K+]	[Na+/K+]
OPC	98/06/22	0.522	0.138	0.499	0.637	0.277
DEN1-4	98/06/29	0.589	0.124	0.415	0.539	0.299
DEN1-8	98/07/07	0.318	0.088	0.266	0.354	0.331
DEN1-12	98/09/22	0.227	0.062	0.171	0.233	0.363
LS4	98/07/28	0.586	0.067	0.233	0.300	0.288
LS8	98/07/28	0.426	0.111	0.367	0.478	0.302
LS12	98/07/27	0.353	0.064	0.198	0.262	0.323
NS4	98/08/11	0.353	0.081	0.286	0.367	0.283
NS8	98/08/11	0.214	0.058	0.183	0.241	0.317
NS12	98/08/18	0.076				
DEN2-4	99/01/25	0.465	0.134	0.457	0.591	0.293
DEN2-8	99/02/23	0.294				
DEN2-12	99/01/12	0.215	0.059	0.169	0.228	0.349
UND4	99/02/23	0.491	0.127	0.445	0.572	0.285
UND8	99/05/10	0.323	0.080	0.257	0.337	0.311
UND12	99/05/10	0.245	0.066	0.201	0.267	0.326
PEL4	98/11/10	0.448	0.141	0.472	0.613	0.299
PEL8	98/12/14	0.297	0.081	0.248	0.329	0.327
PEL12	98/12/15	0.208	0.059	0.165	0.224	0.358
SLU4	99/05/25	0.455	0.112	0.384	0.496	0.292
SLU8	99/06/08	0.296	0.082	0.256	0.338	0.320
SLU12	99/06/08	0.218	0.063	0.174	0.237	0.362

Mix	Cast	90 days				
Name	Date	[OH-]	[Na+]	[K+]	[Na+ & K+]	[Na+/K+]
OPC	98/06/22	0.665	0.140	0.495	0.635	0.283
DEN1-4	98/06/29	0.454	0.107	0.341	0.448	0.314
DEN1-8	98/07/07	0.284	0.082	0.240	0.322	0.342
DEN1-12	98/09/22	0.069	0.045	0.111	0.156	0.405
LS4	98/07/28	0.656	0.163	0.539	0.702	0.301
LS8	98/07/28	0.452	0.116	0.359	0.475	0.323
LS12	98/07/27	0.343	0.094	0.277	0.371	0.338
NS4	98/08/11	0.554	0.117	0.373	0.490	0.313
NS8	98/08/11	0.351	0.093	0.271	0.364	0.343
NS12	98/08/18	0.269	0.048	0.227	0.275	0.211
DEN2-4	99/01/25		0.138	0.456	0.593	0.302
DEN2-8	99/02/23	0.272	0.079	0.224	0.303	0.350
DEN2-12	99/01/12	0.242	0.058	0.156	0.213	0.369
UND4	99/02/23	0.494	0.127	0.410	0.537	0.310
UND8	99/05/10	0.353	0.090	0.282	0.372	0.319
UND12	99/05/10	0.221	0.072	0.213	0.285	0.338
PEL4	98/11/10	0.461	0.168	0.539	0.707	0.312
PEL8	98/12/14	0.350	0.087	0.248	0.335	0.351
PEL12	98/12/15	0.179	0.049	0.125	0.174	0.392
SLU4	99/05/25	0.519				
SLU8	99/06/08					
SLU12	99/06/08					

Mix	Age of	Intermediate Age (close to 180 days)				
Name	PS (days)	[OH-]	[Na+]	[K+]	[Na+ & K+]	[Na+/K+]
OPC						
DEN1-4						
DEN1-8						
DEN1-12	296	0.168	0.051	0.127	0.178	0.402
LS4						
LS8						
LS12						
NS4						
NS8						
NS12						
DEN2-4	180	0.553	0.138	0.449	0.587	0.307
DEN2-8	148	0.314	0.093	0.270	0.363	0.344
DEN2-12	180	0.189	0.041	0.108	0.149	0.381
UND4	153	0.544	0.138	0.446	0.584	0.309
UND8						
UND12						
PEL4	242	0.495	0.150	0.486	0.636	0.309
PEL8	207	0.299	0.077	0.214	0.291	0.360
PEL12	217	0.211	0.058	0.149	0.207	0.389
SLU4						
SLU8						
SLU12						

Mix Name	Cast Date	1 year				
		[OH-]	[Na+]	[K+]	[Na+ & K+]	[Na+/K+]
OPC	98/06/22	0.766	0.187	0.636	0.823	0.294
DEN1-4	98/06/29	0.561	0.171	0.546	0.717	0.313
DEN1-8	98/07/07	0.317	0.094	0.267	0.361	0.352
DEN1-12	98/09/22					
LS4	98/07/28	0.687	0.176	0.583	0.759	0.302
LS8	98/07/28	0.541	0.145	0.440	0.585	0.330
LS12	98/07/27	0.360	0.104	0.298	0.402	0.349
NS4	98/08/11	0.566	0.145	0.472	0.617	0.307
NS8	98/08/11	0.416	0.112	0.329	0.441	0.340
NS12	98/08/18	0.294				
DEN2-4	99/01/25					
DEN2-8	99/02/23					
DEN2-12	99/01/12					
UND4	99/02/23					
UND8	99/05/10					
UND12	99/05/10					
PEL4	98/11/10					
PEL8	98/12/14					
PEL12	98/12/15					
SLU4	99/05/25					
SLU8	99/06/08					
SLU12	99/06/08					