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EVALUATE THE USE OF MINERAL ADMIXTURES IN CONCRETE TO MITIGATE ALKALI-SILICA REACTIVITY

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EVALUATE THE USE OF MINERAL ADMIXTURES IN CONCRETE TO MITIGATE ALKALI-SILICA REACTIVITY

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16. Abstract

The increased use of mineral admixtures in portland cement concrete demands a better understanding of their properties and effects on hardened concrete. One of several beneficial advantages of mineral admixtures like flyash and silica fume is their potential for controlling deleterious expansion due to the alkali-silica reaction (ASR) in concrete. The objective of this investigation was to investigate the effects of portland cement, aggregates, and mineral admixtures on the alkali-silica reaction in concrete with and without air entrainment. The experimental program utilized aggregates from two sources, portland cement with different alkali contents, flyashes, silica fume and natural pozzolanic materials. The mitigation of the alkali-silica reaction by addition of mineral admixtures was evaluated using ASTM C 227, "Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar - Bar Method)."

The test results show that the effect of mineral admixtures on ASR expansion is highly variable and depends on the chemical makeup of the mineral admixture, alkali content of the cement, and replacement rates of cement by mineral admixture.

Creep characteristics of pozzolan based concrete were also studied. Four mineral admixtures were used as a partial replacement of portland cement. Air entraining admixture was used in some of the mixes. The results show that the creep characteristics of concrete are not adversely affected by the use of mineral admixtures.

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INTRODUCTION

1.1 BACKGROUND

With the increased use of mineral admixtures in concrete, a better understanding of their properties and their effect on hardened concrete is needed. One of the several advantages of mineral admixtures like flyash and silica fume is their control or reduction of alkali-silica reactivity expansion. The objective of the research described in this report was to determine how to use mineral admixtures in concrete to mitigate alkali-silica reactivity (ASR) expansion.

Alkali-silica reactivity was first recognized in California more than 50 years ago. Since then, the number of concrete deterioration cases linked to ASR has increased rapidly throughout the world. Intensive research (references 1-23) has been conducted worldwide to find solutions to this problem. Using only nonreactive aggregate is a very trivial, impractical solution. Thomas Stanton's[1, 2] work at the Transportation Laboratory in Sacramento, California, led to the specification of low alkali cement [less than 0.60% equivalent alkalies content - (Na_20 + 0.658 K_20)] beginning in 1940. It was concluded at that time that the use of low alkali cement would effectively mitigate expansion due to ASR. But it was found that this was only a partial solution to a complex problem.

A practical and economical means of controlling ASR expansion in concrete is by the use of pozzolanic mineral admixtures such as flyash, ground granulated blast furnace slag, natural pozzolans, rice hull ash, and silica fume. A number of studies have been completed on the use of these and other pozzolanic materials to mitigate ASR expansion. Despite much detailed research, however, there are several aspects of the role of mineral admixtures in ASR that are not fully understood. For example, there is not a single, universally accepted explanation of the mechanism of ASR expansion. Further, the reported effects of pozzolanic additions on ASR expansion is variable. The effect appears to depend on the type of reactive aggregate, the type of mineral admixture, alkali content of the cement and replacement rates of cement by pozzolan.

In California, the problem of ASR may have been aggravated by the adoption of sand equivalent and cleanness value specifications for fine and coarse aggregates (California Test 217 and 227, respectively). These tests were designed to eliminate clay coatings on the aggregate. However, clay size sand particles are also measured as detrimental clay. When these fine particles are formed from reactive aggregates, they act as a pozzolanic material, helping to mitigate the ASR expansion.

Since 1985, the California Department of Transportation has specified 15% replacement of portland cement with a pozzolanic mineral admixture when the aggregate to be used is identified as deleterious or potentially deleterious by ASTM C 289, “Standard Test Method for Potential Reactivity of Aggregates." With the implementation of this specification, it has become important that time dependent characteristics (creep) of concrete made with pozzolan be investigated and defined as completely as possible.

1.2 LITERATURE SURVEY ON ALKALI SILICA REACTION (ASR) EXPANSION

The mechanism of the alkali-silica reaction (ASR) and expansion has created a great deal of interest among researchers throughout the world. Extensive work has been carried out to explain the physical and chemical mechanisms involved in alkali-silica reaction expansion as well as the manner and extent to which mineral admixtures influence ASR expansion. Several theories have been proposed to explain the mechanism by which ASR causes expansion within the concrete.

In 1955, Powers and Steinour[3] postulated that an alkali-silica complex is expansive and that a lime-alkali-silica complex is non-expansive. They also explained the role of $Ca(OH)_2$ in ASR expansion. According to them, the attack of sodium and calcium hydroxides on reactive silica forms a layer of non-expansive lime-alkali-silica complex which separates the unreacted silica from the lime and alkali in the concrete pore solution. During further attack on the silica, lime and/or alkali external to the non-expansive layer determines the type of complex produced in the silica grain. If the ratio of lime to alkali is high, then non-swelling gel is formed. If the lime to alkali ratio is low, then expansive alkali-silica gel is formed, resulting in expansion and, eventually, cracking of the concrete.

In 1989, Chatterji[13] presented an alternate hypothesis to explain the mechanism of ASR expansion. He did not accept the non-expansive nature of a lime-alkali-silica complex. His explanation was based on the net amount of material which diffuses into a reactive grain. The attack of OH^- on the silica grains is by the penetration of cations (i.e., Na^+, K^+, and Ca^{++}) to the reaction sites. The cations follow the penetration of the OH^- ions into reactive silica grains. The smaller K^+ and/or Na^+ ions will penetrate in greater numbers than the larger Ca^{++}. The Ca^{++} ion concentration in the vicinity of the reactive grains controls the rate at which silica diffuses out of the grains. The higher the concentration of Ca^{++} ions in the environment, the lower the rate at which silica diffuses out of the grain and the higher the rate at which cations like Na^+, K^+, and Ca^{++} penetrate into the grains. Expansion occurs when the amount of cations entering a grain exceeds the amount of silica (SiO_2) diffusing out. In summary, a concentration of lime [$Ca(OH)_2$] around the grain controls the relative rates of diffusion in and out of the reactive grains. Experiments by Struble[23] and Kilgour[12] support Chatterji's hypothesis that the presence of calcium hydroxide is essential to the ASR process.

Wang and Gillot[14] presented another hypothesis which basically agrees with the Powers-Steinour hypothesis[3] but with some significant changes. In explaining the mechanism, the function of lime [$Ca(OH)_2$] in the alkali-silica reaction and expansion is emphasized. They reported two main functions of lime in causing expansion; lime acts as a buffer to maintain a higher pH; i.e., a high concentration of hydroxyl ions in pore solutions, and calcium ions may exchange for alkali ions on silica gel, leading to further production of expansive alkali-silica gel. Four steps involved in the alkali-silica reaction and expansion are also explained.

Many papers have been written presenting various explanations of the ASR expansion phenomenon. They have presented comparisons of various properties of mortars with and without pozzolanic substitution. Some of the observations are summarized below.

A long term study (16 years) by Bhatty, et al[6] found that the amount of alkali retained in the paste depends on the nature and amount of pozzolan used in blended cement. They found that 95% of the total alkali can be retained in the blended cement paste compared to only 15% of the total alkali in portland cement paste. The amount of alkali retained in blended cement pastes increased as the amount of calcium hydroxide decreased. The decrease in the amount of calcium hydroxide was caused by the reaction with pozzolan and subsequent formation of calcium silicate hydrate.

Nixon and Page[15] reviewed the progress made in explaining the phenomena associated with alkali-aggregate reactions in terms of pore solution composition. They discussed the role of pozzolanic materials in mitigating the expansion due to alkali-aggregate reaction.

Lonquet, et al[18] found that in cement paste the hydroxyl, sodium and potassium ion concentrations increased to a maximum between 7 and 28 days and then remained constant or decreased slightly. The calcium concentration in the pore solution decreased with time.

Page and Vennesland,[9] and Diamond[10] reported the results of substituting silica-fume for different proportions (0-30%) of high alkali portland cements. The results indicate that marked reductions in sodium, potassium and hydroxyl ion concentrations of the pore solution can be achieved with silica fume even at low levels of cement substitution (5-10%). A fine, highly pozzolanic flyash with a low alkali content substituted for a portion of high alkali cement will also be very effective in mitigating the alkali-aggregate reaction.

Diamond[16] reported the effect of time in relation to the effectiveness of ashes. Their results showed that flyashes begin mitigating the alkali aggregate reaction expansion after 28 days.

Gillott[17] reported that for ASR the reaction increases with temperature from a minimum at 10°C to a maximum at 38°C. Beyond 38°C, the reaction slows until no significant expansion can be observed at 60°C. Working with synthetic glasses, he showed that the nature of the cations has a marked effect on the expansive behavior of these materials when used as aggregate in mortar.

Josef Farbiarz, et al[11] presented data to show that the degree of alkali-aggregate reactivity in concrete increases as the alkali content of portland cement increases. Further, they observed that there is a cement replacement percentage below which the flyash actually increases expansion and above which the flyash begins to mitigate expansion.

1.3 SCOPE OF RESEARCH

The objectives of the study were as follows:

1. Evaluate the effectiveness of mineral admixtures in preventing excessive expansion in PCC concrete due to reactive aggregates available in California.
2. Determine length changes in concrete due to alkali reactivity with various California aggregates.
3. Provide further information on the adequacy of the existing flyash specification to ensure satisfactory performance of concrete containing flyash, particularly its ability to resist alkali-silica reaction expansion.
4. Establish practical guidelines in a form useful to field engineers for the selection and use of flyash and other pozzolanic materials in concrete for the mitigation of alkali-silica reaction expansion.
5. Measure the creep strain of concrete containing mineral admixtures.
6. Determine whether the current guidelines for creep and shrinkage of conventional concrete are applicable to concrete containing mineral admixtures.

CHAPTER 2

EXPERIMENTAL PROGRAM

2.1 EXPERIMENTAL PROGRAM

Four sets of mortar samples were made during the period from January 1987 to August 1991. The first two sets were cast using Pyrex aggregate meeting the grading requirement of ASTM C 441. The third set was made using natural aggregates (Packway and Cal-Mat). The portland cement used was from a single lot of Kaiser Type II cement with 0.25% alkali content (Na_2O equivalent). Portland cements with 0.60% and 1.0% alkali contents were prepared in the laboratory by adding sodium and potassium carbonates to the above cement. Mortar bars of size 25.4 x 25.4 x 285 mm were prepared, stored in sealed containers at 37.8 ± 1.7°C and measured for length changes as described in ASTM C 227. The fourth set of mortar samples was made using Pyrex glass aggregate and a different Type II portland cement..

2.2 MATERIALS, TEST PROCEDURE AND RESULTS — SET 1

A total of 23 mortar mixes was made in Set 1. Three bars were cast from each mix. Pyrex glass aggregate complying with the grading given in ASTM C 441-89 was used in the mixes. Mix proportions were 400 grams of portland cement and pozzolan, 900 grams of graded Pyrex glass and sufficient water to produce a measured flow of 100 to 115 as determined in accordance with test method ASTM C109. The water/cement ratio varied from 0.56 to 0.63. Five pozzolanic materials were used at 15% and 30% replacement of portland cement by weight. One each of Class F and Class C flyashes and three natural pozzolanic materials described as Class N were used. The physical and chemical properties of these materials are presented in Table 1. The sources of the mineral admixtures are presented in Table 2. The length changes of the mortar bars were measured at 14 to 180 days of storage. The test results are reported in Table 3. Figures 1.1 to 1.6 show the lineal expansion with time.

CONTROL SAMPLES (NO MINERAL ADMIXTURE)

Control samples were cast from portland cement of different alkali contents. Expansion of samples made with 0.6% and 1.0% alkali cement was measured as 0.0367% and 0.2200% at 14 days, respectively. Expansion of mortar bars increased with storage time and increase in cement alkali content. The expansion at 6 months was observed to be 0.018%, 0.200%, and 0.468% for cements with alkali contents of 0.25%, 0.60%, and 1.0%, respectively. Early expansion, at 60 days, of mortar samples made with cement of alkali contents of 0.6% and 1.0% were measured to be 0.152% and 0.433%, respectively.

FLYASH (CLASS F)

The results show that expansion increases with time and increase in alkali content. At 15% replacement of cement, the expansion at 6 months was observed to be 0.025%, 0.23%, and 0.30% for cements with alkali contents of 0.25%, 0.60%, and 1.0%, respectively. Early expansion, at 60 days, of 1.0% alkali cement with 15% replacement was measured to be 0.26%. There is a reduction of expansion at 1.0% alkali content, but at 0.25% and 0.60% alkali contents, there is no change in expansion at 60 days when compared to control samples. However, at 30% replacement of cement with an alkali content of 0.6%, expansion was 0.06% at 180 days.

FLYASH (CLASS C)

At 15% replacement of cement, the expansion at 6 months was observed to be 0.21%, 0.37% and 0.42% for cements with alkali contents of 0.25%, 0.60% and

1.0%, respectively. Early expansion, at 60 days, was observed to be 0.30% and 0.37% for 0.60% and 1.0% alkali cements, respectively. At 30% replacement of cement with an alkali content of 0.6%, expansion was 0.35% at six months. There is an increase in expansion in all cases when compared to the control samples.

NATURAL POZZOLAN (CLASS N)

Lassenite, Cushenbury, and Carson City pozzolans were used as part replacement of portland cement in mortar mixes. At 15% replacement of cement by Lassenite pozzolan, the expansion at 6 months were observed to be 0.022%, 0.027%, and 0.095% for cements with alkali content of 0.25%, 0.60%, and 1.0%, respectively. At 15% replacement of cement by Cushenbury pozzolan, expansion at 6 months was observed to be 0.045%, 0.030%, and 0.042% for cements with alkali contents of 0.25%, 0.60% and 1.0%, respectively. With 30% replacement, very low six month expansions of 0.017% and 0.023% were measured for cement with an alkali content of 0.6% for Lassenite and Cushenbury pozzolans, respectively. The chemical composition of Lassenite and Cushenbury pozzolans showed that they had low calcium oxide contents (less than 2%) and high silicon dioxide (SiO_2) content (more than 70%).

The opposite trend was observed with Carson City pozzolan replacement of cement. With 15% replacement, six month expansion was measured to be 0.023%, 0.183%, and 0.308% for cements with alkali contents of 0.25%, 0.60% and 1.0%, respectively. These values showed that 15% replacement is not effective in lowering the expansion. However, at the 30% replacement level, a very low expansion of 0.03% was measured at six months. This pozzolan had a high total alkali content of 6.8% (Na_2O equivalent).

2.3 MATERIALS, TEST PROCEDURE AND RESULTS — SET 2

A total of 43 mixes was made in Set 2. A water/cement ratio of 0.51 was used for the mortar mixes.

A total of five pozzolanic materials was used for 15% and 30% replacement of portland cement by mass. Two were Class F flyashes, two were natural pozzolans (Class N), and one was a Class C flyash. The physical and chemical properties of these materials are included in Table 1. The samples were stored in sealed containers at 37.8 ± 1.7°C in accordance with ASTM C 227.

The length changes of these samples were measured for various times up to 18 months. The test results are presented in Table 4. Figures 2.1 through 2.6 illustrate the lineal expansion with time.

CONTROL (NO MINERAL ADMIXTURE)

The test results showed that expansion of control mortar bars increases with time and increase in alkali content of the cement. The expansion at 180 days was observed to be -0.006%, 0.068% and 0.293% for cements with alkali contents of 0.25%, 0.60% and 1.0%, respectively. The early expansion up to 60 days was observed to be rapid and then continued increasing gradually to 18 months.

FLYASH (CLASS F)

At 15% replacement of cement by Bridger flyash, the expansion at 180 days was observed to be 0.020%, 0.085% and 0.165% for cements with alkali contents of 0.25%, 0.60% and 1.0%, respectively. The expansion gradually increased with time to 540 days. At 1.0% alkali content, there was reduction in six month expansion from 0.293% to 0.165% by replacing 15% of cement.

With 30% replacement of cement, the expansion at 180 days was recorded to be 0.03% for cement with alkali content of 0.6%. This expansion value is less than half that of 15% replacement and the control value.

With 15% replacement of cement by Valmy flyash, the samples showed much more expansion than the control samples at all cement alkali levels. The expansion at 180 days was observed to be 0.181%, 0.244% and 0.325% for cements with alkali contents of 0.25%, 0.60% and 1.0%, respectively. Early expansion was observed to be rapid and this was followed by a steady increase. Even with low alkali (0.25%) cement, the expansion increased from 0.006% to 0.181% with the use of Valmy flyash replacement. A 30% replacement of cement with alkali content of 0.6% showed expansion of 0.276%, which is still higher than at 15% replacement. This increase in expansion may be due to the fact that the chemical composition of Valmy flyash shows a high percentage of calcium oxide – see Table 1.

FLYASH (CLASS C)

With a 15% replacement of cement by 4th Street Rock flyash, the expansion at 180 days was recorded to be 0.159%, 0.264% and 0.220% for cements with alkali contents of 0.25%, 0.60% and 1.0%, respectively. Early expansion up to 120 days was observed to be very high, as can be seen in Figure 2.4. There was a rapid increase in expansion with the use of 4th Street Rock flyash, which has a calcium oxide (CaO) content of 31%. The expansion with 30% replacement of cement (alkali content of 0.6%) was observed to be 0.278% at 180 days. This expansion is greater than that for 15% replacement of cement and also much greater than that for the control samples This shows that replacement of portland cement with this Class C flyash increases expansion in proportion to the addition rate of this Class C flyash.

POZZOLAN (CLASS N)

Lassenite and Cushenbury, natural pozzolanic materials, were also used for partial replacement of portland cement. The expansion at 180 days with 15% replacement of cement by Lassenite was measured to be -0.013%, -0.002% and 0.035% for cements with alkali contents of 0.25%, 0.60% and 1.0%, respectively. The expansion values at 180 days with 15% replacement of cement by Cushenbury were -0.006%, -0.007% and 0.027% for cements with alkali content of 0.25%, 0.60% and 1.0%, respectively. With 30% replacement of cement by Lassenite and Cushenbury, shrinkage of -0.005% and -0.011%, respectively, were observed at 180 days. The above results show that these Class N pozzolanic materials are effective in controlling ASR expansion.

2.4 COMPARISON OF TEST RESULTS OF SET 1 AND SET 2

Set 1 samples were made with a constant flow and a water/cement ratio varying from 0.56 to 0.63. Set 2 samples were cast at a constant water cement ratio of 0.51 but with different flows. All Set 1 mixes contained more water than Set 2 mixes. A comparison of the two sets of samples shows higher expansions in Set 1 samples than Set 2 samples. This suggests that a higher water cement ratio yields greater expansion when all other variables remain the same.

When expansion results are compared, it can be seen that the two sets of samples are very similar with regard to the different pozzolanic materials and their various replacements of portland cement. Control samples made with portland cement with alkali contents of 0.6% and above showed expansion greater than 0.1%. Expansion was rapid for the first 90 days and then increased gradually from 90 to 180 days. Class F flyashes at replacement levels of 30% were found to be effective in reducing expansion with a cement alkali content of 0.60%. Valmy flyash, with a high CaO content, was an exception, showing a greater expansion than that of the control samples when cement was replaced in proportions of 15% or 30%. Expansion increased with an increase in cement replacement . Class C flyash up to 30% replacement level showed high expansion for cements with alkali contents of 0.25%, 0.60% and 1.0% in both sets of samples. Class N pozzolanic materials were observed to be very effective in reducing ASR expansion in both sets of samples.

2.5 MATERIALS, TEST PROCEDURE AND RESULTS — SET 3

Type II Kaiser portland cement with an alkali content of 0.60% (Na_2O equivalent) was used for making 51 mortar mixes. Two bars were made from each mix. Two types of natural aggregate were used, Packway (Burney pit) which was classified as potentially deleterious and Cal-Mat (Upland pit) which was innocuous per ASTM C 289. The grading of these aggregates was in accordance with ASTM C 227. A control mix (no pozzolan) of 300 grams of portland cement and 675 grams of aggregate was made. Six pozzolanic materials were used at 15% and 30% replacement of portland cement (by mass). Two were Class F flyashes, two were Class N natural pozzolanic materials, one was Class C flyash and one was silica fume. The flow of these mixes was held in the range of 105-120 with a varying water/cement ratio. The samples were made and stored in accordance with the test procedure outlined in ASTM C 227. The length changes were recorded at durations of 14 days, and 1, 2 ,3 ,4 ,6 ,7 ,9 ,12 , and 21 months of storage. The test results are presented in Table 5. Figures 3.1 to 3.7 show the relationship between lineal expansion and time.

CONTROL (NO POZZOLAN)

The expansion of the mortar bars at 640 days with Packway and Cal-Mat aggregates was recorded to be 0.0535 and 0.0345%, respectively. Packway aggregate, which is considered a potentially deleterious aggregate, showed higher expansion than Cal-Mat, an innocuous aggregate. Initial expansion up to 270 days was observed to be rapid followed by a slow increase to 640 days (Figure 3.1).

FLYASH (CLASS F)

The expansion of mortar bars made with Packway aggregate using Navajo Ash and Bridger Ash at 15% replacement of cement was recorded to be 0.049% and 0.058% at 640 days, respectively. The expansion of mortar bars made with Cal-Mat aggregate and Bridger Ash at 15% replacement of cement was observed to be 0.056% at 640 days. The expansion of samples with 30% replacement of cement with Bridger ash using Packway or Cal-Mat aggregate was measured to be 0.039%.

NATURAL POZZOLANS (CLASS N)

The mortar samples with Packway aggregate showed expansion of 0.051% and 0.052% using Cushenbury Volcanic ash and Lassenite pozzolan, respectively, with 15% replacement of cement at 640 days. The expansion of mortar bars made with Cal-Mat aggregate and Lassenite pozzolan (15% replacement of cement) showed expansion of 0.044% at 640 days. The expansion of mortar bars made with Packway and Cal-Mat aggregates and using Lassenite pozzolanic material at 30% replacement of cement was recorded to be 0.066% and 0.067%, respectively, at 640 days. The above expansion results show that expansion with 30% replacement of cement with Lassenite was slightly greater than with 15% replacement with either aggregate (Figure 3.5).

FLYASH (CLASS C)

The expansion of samples made with Packway and Cal-Mat aggregates and 15% 4th Street Rock pozzolan in place of cement was 0.067% and 0.057%, respectively, at 640 days. A 30% replacement of cement with 4th Street Rock pozzolan when using the above two aggregates showed a lower expansion of 0.0370% and 0.051%, respectively, at 640 days.

2.6 MATERIALS, TEST PROCEDURE AND RESULTS — SET 4

Kaiser Permanente Type II portland cement, graded standard sand (ASTM C 778) and Pyrex glass aggregate of size #8 to #16 were used for making four mortar mixes. Six samples were made from each mix. In three mixes, the flyash (Class F), silica fume and hydrated lime were added at the rate of 10% by mass of portland cement. The chemical and physical properties of the portland cement, Western Flyash (Laughlin), silica fume and hydrated lime are reported in Table 6. The proportions of the four mixes are presented in Table 7. The samples were prepared according to the procedure given in ASTM C 227. The samples were then divided into three groups and each group was maintained under one of the following storage conditions:

1. Immersed in 1N NaOH (sodium hydroxide) solution at 23 ± 1.7°C.
2. Immersed in 1N NaOH (sodium hydroxide) solution at 80 ± 1.7°C (According to ASTM C-9 Proposal P 214).
3. Kept over water (not touching water) at 80 ± 1.7°C.

The containers with the samples were sealed and maintained at the above temperatures for the duration of the testing. The length measurements were recorded at room temperature at 4, 7, 10, 19, 33, 40, and 47 days of storage. The difference between the initial length of the specimen and the length after each period of storage was calculated. The results reported in Table 8 are the average of two specimens. Figures 4.1 to 4.4 show the relationship between lineal expansion and storage time.

CONTROL SAMPLES

Mortar bar samples immersed in 1N NaOH solution showed a large expansion in a short period of 4 days, both at 23°C and 80°C, and then a gradual additional increase. The expansion at 4 days was measured as 0.18% and 0.19% at 23°C and 80°C, respectively. The expansion at 47 days was observed to be 0.42% and 0.36% at 23°C and 80°C, respectively. The above results showed that at 47 days, samples stored at 80°C showed less expansion than those at 23°C. The samples kept over water at 80°C showed a much lower expansion at 47 days than samples immersed in 1N NaOH solution.

EFFECT OF LIME ADDITION

Addition of hydrated lime to the mortar mix increased the expansion substantially in comparison to the control samples. The expansion of samples immersed in 1N NaOH solutions for 47 days was 0.52% and 0.45% at 23°C and 80°C, respectively. The early expansion at 4 days was also very high, 0.34% and 0.37% at 23°C and 80°C, respectively. Samples stored over water for 47 days showed expansion of 0.17%, which is less than that for those in NaOH solution but much higher than that for the control samples.

The above results show that immersion in 1N NaOH solution increases the expansion and that an increase in temperature from 23°C to 80°C lowers the expansion as was observed in the control samples.

EFFECT OF FLYASH ADDITION

The mortar bar samples containing flyash that were immersed in 1N NaOH solution showed 47 day expansions of 0.48% and 0.42% at 23°C and 80°C, respectively. The early expansion at 4 days was observed to be high (0.28% and 0.31%) at the above temperatures. The expansion of samples kept over water at 80°C was 0.21% at 47 days. However, early expansion at 4 days was only 0.02%. Results of lime addition and flyash addition are similar in that the expansions are greater than that measured for the control samples. The above results show that immersing the samples in 1N NaOH solution increased expansion and greater expansion was observed at 23°C than at 80°C. Additionally, 1N NaOH solution also helps accelerate the alkali-silica reaction from the earliest stage, resulting in greater expansion at 4 days (see Figure 4.3).

EFFECT OF SILICA FUME ADDITION

Mortar bar samples containing silica fume showed expansion of 0.12% and 0.06% when immersed in 1N NaOH solution for 47 days at 23°C and 80°C, respectively. When kept over water at 80°C, the samples showed 0.06% expansion at 47 days. The results in Table 8 show that silica fume addition proved very effective in reducing expansion even in the presence of the 1N NaOH solution.

CHAPTER 3

DISCUSSION OF TEST RESULTS

This section discusses the results of the tests in terms of ASTM C 441 and ASTM C 33 specifications, which contain guidelines for the interpretation of results obtained from mortar bar tests.

3.1 DISCUSSION OF RESULTS OF SETS 1 AND 2

CONTROL (NO POZZOLAN)

It was generally believed that use of low alkali portland cement (alkali content up to 0.60% Na_2O equivalent) would help mitigate ASR expansion. The results of this study show that this may not be enough to control ASR expansion in hardened concrete made with reactive aggregate. Mortar samples made with portland cement with an alkali content of 0.25% shows expansion of 0.018% at 180 days. However, it is observed that with Pyrex glass aggregate and 0.60% alkali cement, the expansion increased to more than 0.1% in a short period of 60 days and it continued to increase to 0.20% at 180 days (see Table 3, control samples). With 1.0% alkali content, the expansion of the bars at 14 days was measured to be 0.22%, which is more than the 0.2% expansion observed at 180 days for 0.6% alkali content cement. This shows that decreasing the alkali content of the portland cement from 1.0% to 0.6% is effective in reducing expansion but may not be a sufficient remedy. It was observed that after showing high early expansion with 1.0% alkali content cement in Set 2, the expansion rate is much lower from 60 days to the end of the test (i.e., 540 days). The above results indicate that the alkali-aggregate reaction is very rapid in its early stages and then slows down in the case of Pyrex glass.

FLYASH (CLASS F)

The data show that increasing the alkali content of the portland cement from 0.25% to 0.6% to 1.0% results in greater expansion. The results show that 15% replacement of portland cement with Class F flyash is not effective in reducing the expansion. However, 30% replacement of 0.6% alkali cement with these flyashes proved very effective in lowering the expansion. While such trends were quite consistent with most of the Class F flyashes used, the results in the case of Valmy Class F flyash were different. These samples showed early large expansion with all levels of alkali content in the portland cement and with up to 30% cement replacement. This flyash had the same effect on expansion as the 4th Street Rock, which is a Class C flyash. The Valmy flyash contained a relatively high percentage (14%) of calcium oxide (CaO).

Another observation was that with the use of flyash as a replacement material, the early expansion (up to 14 days) was high. The rate of expansion then gradually decreased and finally ceased (see figures 1.2, 2.2 and 2.3).

In this study, the flyashes used had a total alkali content in the range of 2.0% to 3.0% Na_2O equivalent. The extent to which these alkali's are released and then contribute to expansion was not determined.

Based on these test results, it can be stated that a Class F flyash with a high percentage of calcium oxide (more than 10%) is not effective in inhibiting ASR expansion when used as a replacement for 30% of the portland cement. These observations are based on portland cement with alkali contents up to 1.0% and flyash total alkali contents up to 3.0%.

FLYASH (CLASS C)

Large expansion of mortar bars was observed using 4th Street Rock flyash at 15% and 30% replacement levels with portland cement alkali contents up to 1.0%.

A 30% replacement of portland cement resulted in the same or greater expansion values as those measured with 15% replacement of cement. Expansion was rapid up to 90 days and then increased gradually. A chemical analysis of the flyash showed a high percentage of calcium oxide (about 31%) (see Table 1).

The results indicate that replacement of portland cement with Class C flyash can adversely affect ASR expansion. The most probable reason is the high percentage of calcium oxide in the flyash. Based on these findings, Class C flyash (and other high calcium oxide pozzolan) should not be used as partial replacement of portland cement to mitigate the expansion caused by the alkali-silica reaction.

NATURAL POZZOLANS (CLASS N)

Lassenite and Cushenbury, which are Class N natural pozzolanic materials, were found to be very effective in controlling expansion. Expansion was virtually eliminated at all alkali levels. With 15% replacement of portland cement having an alkali content of 1.0%, expansion was well below 0.1% even after 540 days. A 30% replacement reduced the expansion even more than the 15% replacement. A possible explanation for this could be the high silica, low lime (CaO) and low alkali contents of these pozzolans as can be seen in Table 1.

The Carson City pozzolanic material was not found to be effective in controlling expansion at a 15% replacement. However, it was effective at 30% replacement of cement with 0.6% alkali content. The chemical analysis of Carson City pozzolanic material showed that it had a very high total alkali content of 6.8% Na_2O equivalent. This may be a possible explanation for its lack of effectiveness in controlling expansion with 15% replacement of portland cement.

3.2 DISCUSSION OF RESULTS OF SET 3

Cal-Mat aggregate was known to be an innocuous aggregate. Packway aggregate, which was described as potentially deleterious when tested in accordance with ASTM C 289, was found to also be an innocuous aggregate when tested in accordance with ASTM C 227. The control test samples made with these aggregates showed very low expansion which leads to the above finding. The portland cement used in making the mortar mixes had 0.6% alkali content (Na_2O equivalent). The test results with pozzolanic replacements showed that none of the pozzolanic materials produced any appreciable change in expansion results when compared to the control samples. The expansion of these samples at up to 640 days was measured to be less than 0.1%. With 15% replacement of portland cement with pozzolanic materials, the samples showed slightly more expansion than the control samples. The small increase in expansion could be due to the reaction between the portland cement alkalies and the reactive silica of the pozzolanic materials. Even with the addition of Class C flyash (high CaO content), the sample did not show any abnormal expansion values of the type observed in Sets 1 and 2. This observation confirms that both aggregates used in the mortar mixes were innocuous.

3.3 DISCUSSION OF RESULTS OF SET 4

The test results of control samples immersed in 1N NaOH solution show much higher expansion than those kept over water. This indicates that the supply of

Na^+ and OH^- ions from an outside source contribute to expansion (see Table 8). Lime or flyash addition (about 10% of portland cement by mass) to the mortar mix exacerbates expansion. From these results, it appears that the presence of lime in the pore solution of the cement matrix aggravates the alkali-aggregate reaction and results in greater expansion. This observation has been made by other investigators as well[13,14]. Silica fume addition (10% of portland cement by mass) was found to be very effective in reducing expansion. A comparison of the results shows that expansion was much lower in silica fume samples than in control samples even in the presence of large quantities of Na^+ and OH^- ions in solution. The explanation appears to be that lime released by the hydration of cement reacts with the silica of the silica fume, resulting in lower lime content. Also, addition of silica fume reduces the amount of available alkalies in the cement matrix system. Fine particles of silica fume can also react with some of the available alkalies, thereby resulting in a reduction in alkalies available for reaction with the silica present in the aggregates. It appears that some or all of the above factors may be contributing to the mitigation of expansion achieved by the use of silica fume.

An increase in temperature of 1N NaOH immersion solution from 23°C to 80°C resulted in a lower expansion of the mortar bar samples. It is possible that the solubility of lime, which is lower at higher temperatures, is having an effect on expansion (solubility in water at 40°C = 1.41×10^{-1}; 80°C = 9.4×10^{-2}). Since expansion is enhanced by immersion of mortar samples in 1N NaOH solution, this aspect of ASTM C-9 Proposed P214 is beneficial for an accelerated test. However, in light of lower expansion results at 80°C than at 23°C, it may be appropriate that a test be conducted at 38°C, the temperature used in ASTM C 227.

CHAPTER 4

SUMMARY RECOMMENDATIONS AND FUTURE RESEARCH

4.1 SUMMARY OF RESULTS AND CONCLUSIONS

1. Based on tests using portland cement with alkali contents up to 1.0%, expansion due to alkali-silica reaction (ASR) is directly related to the alkali content of the portland cement. The higher the alkali content in the cement, the greater the ASR expansion.

2. The ASTM C 150 limit of 0.6% alkali content (Na_2O equivalent) in portland cement may be too high to entirely mitigate deleterious expansion due to alkali-aggregate reaction.

3. The calcium oxide content of the mineral admixtures plays a critical role in the degree of ASR expansion in concrete. It seems to act as a catalyst, promoting the ASR and resulting in greater expansion.

4. In general, Class F flyashes (ASTM C 618) are effective in controlling/reducing ASR expansion when used to replace up to 30% of the portland cement (by mass).

5. Flyash with more than 10% calcium oxide was found to be unsuitable for mitigating ASR expansion, even at the 30% replacement level.

6. Natural pozzolanic materials with low lime content (<2% CaO) and low alkali content (less than 3.0%) are very effective in preventing deleterious expansion in concrete due to alkali-silica reaction when used at the 15% replacement level.

7. Silica fume, when added to the mortar samples in small amounts (10% of cement by mass), is quite effective in inhibiting ASR expansion, even in the adverse condition of 1N NaOH solution.

8. Alkali ions (Na^+, K^+) entering into the mortar/concrete matrix from an outside source will contribute to higher ASR expansion.

9. Lowering the temperature of the storage solution (1N NaOH) in test ASTM C 9 Proposal P 214 from 80°C to 23°C resulted in increased expansion. Thus, 80°C as specified in the method is not the best temperature for an accelerated test.

10. A pozzolan that reduces expansion with a cement of 1.0% alkali will not necessarily reduce expansion with a cement of 0.6% alkali content.

4.2 RECOMMENDATION

As a result of this study, the following guidelines are recommended for selection of materials and their proportions to prevent damage in concrete due to alkali-silica reaction expansion. Based on these guidelines, a specification for ASR mitigation in concrete is presented in 4.3.

1. Making concrete with a low-alkali cement (less than 0.6% Na_2O equivalent) does not guarantee prevention of alkali-silica reaction expansion in concrete. Therefore, it is recommended that a mineral admixture be used when aggregate is reactive.

2. Mineral admixtures with very low lime (less than 2%) and alkali content less than 3% can be effectively used to mitigate ASR expansion in concrete, at 15% replacement of portland cement by mass.

3. Mineral admixtures containing less than 10% calcium oxide (CaO) and total alkalies less than 3.0% can be effectively used at 30% (by mass) minimum replacement of portland cement, when using potentially deleterious or deleterious aggregate in concrete.

4.3 PROPOSED SPECIAL PROVISIONS FOR MITIGATING ALKALI-SILICA REACTIVITY EXPANSION IN CONCRETE

When aggregate is determined to be potentially deleterious or deleterious, a mineral admixture will be added to the portland cement concrete. Mineral admixture shall be silica fume or conform to ASTM C 618 Type N or F, except that the loss on ignition shall not exceed 4% and calcium oxide content shall not exceed 10%.

Silica fume shall be a finely divided material delivered in slurry or powdered form meeting the requirements of ASTM C1240 with reduction of mortar expansion of 80% minimum using the portland cement from the proposed mix design.

Mineral admixture shall be incorporated into the concrete mix in one of the following proportions:

A. Silica Fume - An amount equal to at least 10% of the specified portland cement mass shall be added.

B. Class N or F Pozzolan - If the Pozzolan has 2% or less calcium oxide and 3% or less total alkali, an amount equal to at least 15% of the specified cement mass shall be added.

C. If the mineral admixture does not meet the above conditions in A or B, an amount equal to at least 30% of the specified cement mass shall be added.

If Type II Modified or Type IV or Type V cement is used, the cement mass may be reduced by up to 15% of the minimum mass specified (see Section 90-1.01)[25], but not more than the mass of the mineral admixture added. If Type III cement or other measures are specified to attain high early strength, no reduction in the mass of the cement will be allowed.

4.4 RECOMMENDATIONS FOR FUTURE RESEARCH

Alkali-silica reactivity (ASR) in concrete is a complex and very challenging problem. Some aspects of this problem have been addressed in this report, but more research is needed on the following:

1. This project did not effectively evaluate mineral admixtures in combination with actual reactive aggregates as intended, and mineral admixture proportions between 15% and 30% were not examined. These two aspects should be investigated further to improve the special provisions.
2. Investigate further the effectiveness of silica fume in controlling ASR expansion.
3. Evaluate the use of chemical admixtures like lithium hydroxide for prevention of alkali-aggregate reactivity expansion in concrete.
4. Explore the use of chemically treated reactive aggregate in concrete in mitigating ASR expansion.
5. Identify and explain the destructive reaction process of reactive aggregate in concrete.

CHAPTER 5

CREEP STUDY OF CONCRETE CONTAINING MINERAL ADMIXTURES

5.1 BACKGROUND

The effective use of concrete demands a detailed knowledge of its many properties. One such property is creep, the time dependent increase in strain due to sustained stress. There is a great deal of information available on the creep characteristics of portland cement concrete. However, information regarding concrete made using pozzolans is very limited.

With the implementation of mineral admixture substitution for portland cement in concrete in Caltrans specifications, it has become desirable that the time-dependent characteristics of concrete made using pozzolans be investigated and defined as completely as possible.

If the creep is predicted accurately and design compensations are made, the result will be better distribution of stresses in reinforced concrete structures. Unfortunately, when the deformations and deflections due to creep are excessive, or design compensations are not made, the result can be expensive repairs and possible loss of prestress in concrete members.

5.2 EXPERIMENTAL PROGRAM - CREEP

TEST PROCEDURE AND RESULTS

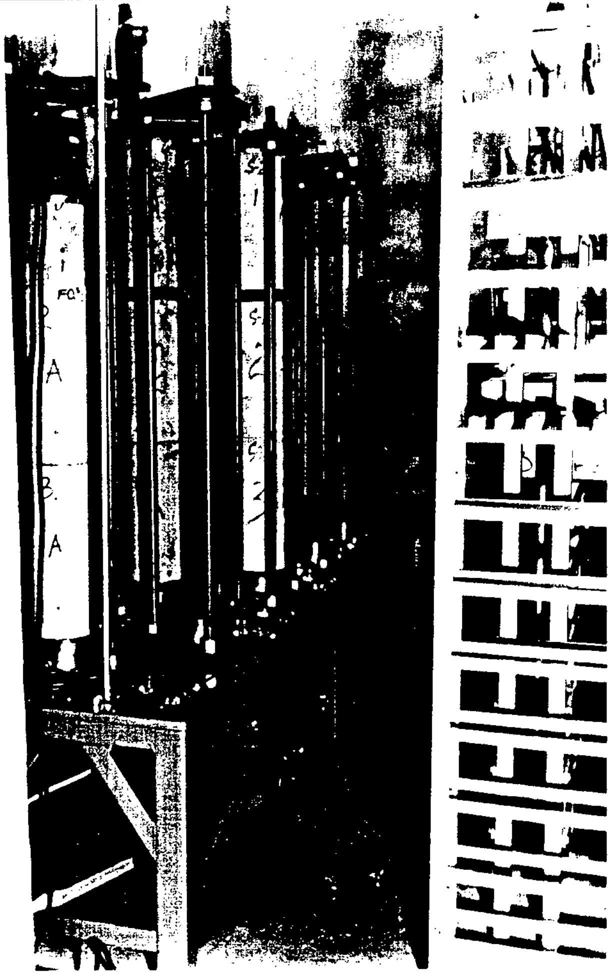
A total of nine concrete mixes were made with or without replacement of portland cement by pozzolanic materials. Kaiser portland cement Type II and Teichert-Perkins coarse (25 mm maximum size) and fine aggregates were used in the concrete mixes. Four pozzolanic materials were used at 15% or 30% replacements of portland cement by weight. The air entraining admixture

(AEA) "Darex" was used in some of the mixes. The water/binder ratio of the concrete mixes ranged from 0.45 to 0.51, and the slump was about 75 mm. The mix proportions are reported in Table 9. The percentage of air in the concrete mixes with and without air entraining agent were in the range of 5.7-6.0 and 1.0-1.4, respectively.

The concrete test specimens used in this study were cylinders 355 mm long and 152 mm in diameter. They were fabricated in steel molds. The specimens were demolded after 24 hours and then cured in the fog room for the next 6 days. Each specimen had three sets of gauge pins cast in place 254 mm apart at intervals of 120° around the circumference. A set of three cylinders comprise one "creep test." In addition to the creep specimens, an identical cylinder was made from the same concrete for measuring drying shrinkage. After 7 days of fog curing, the specimens were stored in the controlled environment loading room and loaded. The temperature in the room was maintained at 21 ± 1°C and at a relative humidity of 50 ± 5%. All loading and unloading operations and strain measurements were performed in this controlled environment room.

The loading equipment consists of a hydraulic system which permits a large number of specimens to be loaded. The basic system consists of a motor, an oil injection pump, an accumulator, an electronically controlled pressure supply system, pressure pistons (cells) and associated piping and loading racks.

Each loading rack can accommodate a stack of three 355 mm long specimens. The load is applied at the lower end of the rack through the floating circular plate of the hydraulic cylinder. Oil is pumped through tubing to each cylinder and the pressure is transmitted to the specimen through a rubber piston cup and the metal floating plate. The pressure is supplied by an American Bosch diesel fuel injection pump driven by a $^3/_8$ HP electric motor. The loading rack hydraulic pressure system is shown in Photograph 1. This pump is capable of relatively high pressure with low displacement. A larger displacement, manually operated pump was added to the system to reduce the time required to load the test cylinders initially. After approaching the desired pressure, the manual pump is shut off and the electronic pressure regulator is activated to bring the loading cell to the final sustained stress with the injector pump. A nitrogen-filled hydraulic accumulator is also included in the system. This device has a diaphragm with gas on one side at a static pressure of 4.9 MPa. It is connected to the fluid pressure system on the other side. The accumulator eliminates pulse surges from the injector pump into the fluid system and loading pistons. Should any power or regulator failure occur, the accumulator prevents any substantial loss in pressure until necessary repairs are made. Nine stacks of three specimens each can be accommodated simultaneously in the equipment. The hydraulic pressure is kept constant at the preset level by a Honeywell automatic regulator.



The experimental program for this study consisted of measurements on 9 sets of three cylinders each. Nine concrete cylinders (one for each mix) were used to obtain shrinkage data.

After the specimens were properly centered, the hydraulic pressure was raised to produce a stress of 8.3 MPa.

Following loading, strain measurements were made periodically using a Whitmore strain gauge. The specimens were loaded for a period of 633 days. The temperature and humidity in the room were monitored during the entire period of the project. Strain increments were obtained by comparing test measurements with initial measurements before load application. The total strain measurements reported represent average values for the three sides of three specimens, hence the average value of nine readings (except in cases where gage points were lost) was used to establish the total strain of a rack set for each mix that was tested

5.3 RELIABILITY OF DATA

The strain increments were determined by averaging readings of three gauges on each of three test cylinders. It was observed that occasionally the data did not fit the expected pattern of strain increments due to creep and shrinkage. One reason for this erratic behavior was determined to be loose gauge pins.

5.4 TEST RESULTS AND DISCUSSION

The creep, shrinkage and total strain of the concrete with and without mineral admixtures under sustained load were studied in this experimental program.

Some of the concrete samples contained the air entraining admixture "Darex." The tabular and graphical representation of these results are presented herein to facilitate the interpretation and understanding of the data. The mix proportions and physical properties of the concrete are shown in Table 9.

The main focus of this testing was to determine the effect of mineral admixtures on creep and shrinkage. The effect of air entraining agent in concrete with and without mineral admixture was also studied.

In this experimental work, the induced strains were measured in terms of total strain, instantaneous strain, and shrinkage strain. In Figure 5.1, it may be seen that the total strain is the summation of the instantaneous strain and the time dependent strains, including creep and shrinkage. The creep strain, ε_{ct}, can be determined by subtracting the instantaneous strain, ε_e, and the shrinkage strain, ε_{st}, from the total strain ε_t as shown in illustration A. Thus, the following relationship is assumed to be valid:

$$\varepsilon_t = \varepsilon_e + \varepsilon_{ct} + \varepsilon_{st}$$

or,

$$\varepsilon_{ct} = \varepsilon_t - (\varepsilon_e + \varepsilon_{st})$$

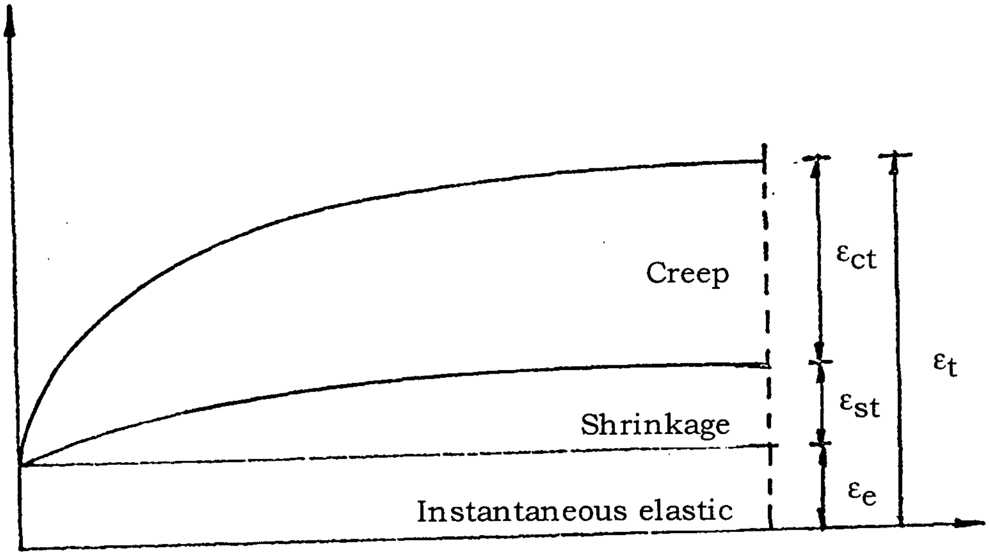


Illustration A. Typical Strain Profiles Constant Uniaxial Stress Loading

TOTAL STRAIN

Total strain results, which include the instantaneous strain, creep and shrinkage are presented in Table 10. Strain variations with time for the nine mixes are illustrated in Figures 5.2 through 5.10. The total strain values of the concrete samples under the sustained load of 8.3 MPa gradually increase with time to 640 days, as can be seen in Table 10.

It was observed that the total strain values for the concrete containing mineral admixture were generally higher than those for the control samples (no mineral admixture). The only exception was the concrete with 15% Pozzolanic International flyash. Concrete samples made with mineral admixtures and air entraining agent (Darex) also showed higher total strain as compared to control samples with air entraining agent.

SHRINKAGE STRAIN

Shrinkage results for the companion concrete samples are reported in Table 11. The 640 day shrinkage time curves are shown in Figures 5.2 through 5.10. Shrinkage of the samples gradually increased with time.

A comparison of the results shows that shrinkage of the samples containing mineral admixture was observed to be higher than the control samples. It was also observed that an increase in the amount of cement replaced by flyash, increased the shrinkage. With the addition of air entraining agent to the mixes with mineral admixtures, the shrinkage values were not conclusive when compared to samples without an air entraining agent.

Creep results of the concrete samples with and without mineral admixtures are presented in Table 12. The creep versus time curves are shown in Figures 5.2 to 5.9. Creep strain of the samples gradually increases with time to 640 days. Test results show that mineral admixtures had no adverse effect on creep characteristics of concrete samples. Also, addition of air entraining agent (AEA) makes no appreciable change in the creep properties of concrete with or without mineral admixtures.

5.5 SUMMARY OF RESULTS

The creep and shrinkage of the concrete samples made with and without mineral admixtures and air entraining agent were studied in this experimental program. A summary of the results follows:

1. The use of mineral admixtures as replacement of cement in concrete up to 30% by weight increased the shrinkage of the concrete. A greater replacement of cement by pozzolanic materials resulted in greater shrinkage of the concrete.
2. No conclusive shrinkage data was obtained regarding the use of air entraining admixture in concrete.
3. Creep of concrete samples containing mineral admixture replacement of portland cement up to 30% was determined to be lower than conventional concrete (no mineral admixture). Addition of an air entraining admixture to the concrete does not change its creep characteristics.

5.6 CONCLUSION

The use of mineral admixtures in concrete for partial replacement of portland cement (up to 30% by mass) does not adversely affect the creep characteristics of concrete. Therefore, the current guideline for creep of conventional concrete can be safely used for concrete containing mineral admixtures.

ADDENDUM

Materials Specification Implementation

Based on the results obtained from this report, Standard Specification for Materials (Section 90-4.02) has been amended by the following special provision.

8-2. ADMIXTURES

Section 90-4.02, "Materials," of the Standard Specifications is amended by adding the following material to those listed:

Silica Fume – ASTM Designation: C 1240, with reduction of mortar expansion of 80%, minimum, using the portland cement from the proposed mix design.

Section 90-4.08, " Required Use of Mineral Admixtures," of the Standard Specifications is amended by adding the following before the first paragraph:

Mineral admixture will be required in the manufacture of concrete containing aggregate that is determined to be "deleterious" or "potentially deleterious" as specified in Section 90-2.02, "Aggregates." The calcium oxide content of mineral admixtures shall not exceed 10%. Where Section 90-1.0l, "Description," specifies a maximum cement content in kilograms per cubic meter, the total mass of portland cement and mineral admixture per cubic meter shall not exceed the specified maximum cement content. The concrete shall conform to one of the following:

1. The concrete containing "Type IP (MS) Modified" cement shall conform to the provisions in Section 90-2.01, "Portland Cement," except that the mineral admixture used in the manufacture of "Type IP (MS) Modified" cement shall

have a calcium oxide content not exceeding 2%, and an alkali content not exceeding 4%. The amount of cement shall be sufficient to satisfy the specified minimum cement content.

2. When the calcium oxide content in a mineral admixture does not exceed 2%, the portland cement in the concrete shall conform to the provisions in Section 90-2.01, "Portland Cement," with an amount not less than 85% of the amount required to satisfy the specified minimum cement content. The concrete shall also contain the mineral admixture in an amount not less than 15%, by mass, of the amount of cement required to satisfy the specified minimum cement content. The mineral admixture shall conform to the requirements in ASTM Designation C 618, Class N or F, except that the alkali content shall not exceed 4%.
3. When the calcium oxide content in a mineral admixture is between 2% and 10%, the portland cement in the concrete shall conform to the provisions in Section 90-2.01, "Portland Cement," with an amount not less than 85% of the amount required to satisfy the specified minimum cement content. The concrete shall also contain the mineral admixture in an amount not less than 30%, by mass, of the amount of cement required to satisfy the specified minimum cement content. The mineral admixture shall conform to the requirements in ASTM Designation: C 618, Class N or F, except that the alkali content shall not exceed 4%.
4. The portland cement in the concrete shall conform to the provisions in Section 90-2.01, "Portland Cement," with an amount required to satisfy the specified minimum cement content. The concrete shall also contain a mineral admixture in an amount not less than 10%, by mass, of the amount

of cement required to satisfy the specified minimum cement content. The mineral admixture shall conform to these provisions for silica fume.

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TABLE 1

PHYSICAL AND CHEMICAL PROPERTIES OF PORTLAND CEMENT AND MINERAL ADMIXTURES (USED FOR SETS 1, 2, & 3)

Compounds (%)	Kaiser Portland Cement Type II (RE-1037) (Dec 86)	Pozzolanic International (Bridger A&R) (Class F)	Carson City Volcanic Ash (Class N)	Navajo Ash (Class F)	Western Ash (Valmy) (Class F)	Lassenite (Class N)	Cushenberry Volcanic Ash (Class N)	Southwest 4th Street Rock (Class C)
SiO_2	21.35	64.5	71.5	58.6	57	71	84.6	35
Al_2O_3	3.74	16.6	12.9	22	17	15.1	1.65	19.6
Fe_2O_3	3.63	5.15	2.2	5.4	5	5.97	0.04	6.62
CaO	65.2	5.65	1.5	8.03	14	1.75	1.52	31
MgO	0.85	1.83	0.2	1.55	2.8	0.84	0.07	5.14
SO_3	3.1	0.64	0.13	0.58	0.8	0.61	0.61	1.91
Total Alkalies (Na_2O+0.658 K_2O)	0.3	2.62	6.84	2.06	---	2.81	0.28	1.69
Loss on Ignition, (%)	1.13	0.53	3.17	1.06	---	0.98	3.57	0.5
Insoluble Residue, (%)	---	65.5	---	70	---	84.4	82.5	25.6
Fineness,(% Passing 325 Mesh Sieve)	---	65	---	---	67.2	---	65.5	85
Specific Gravity	3.15	2.47	2.4	---	---	2.36	2.19	2.7

TABLE 2

SOURCE OF MINERAL ADMIXTURES USED IN THE PROJECT

Material	Source of Material (Supplier)
Portland Cement Type II	Kaiser Permanente Cement
Bridger Fly Ash (Class F) (Rock Springs, Wyoming)	Pozzolanic International 2448 76th Avenue, S.E., Suite 222 Merser Island, Washington 98040
Valmy Fly Ash (Class F) Valmy, Nevada	Western Ash Company 3640 South 19th Avenue Phoenix, Arizona 85036
Navajo Fly Ash (Class F) Page, Arizona	Western Ash Company 3640 South 19th Avenue Phoenix, Arizona 85036
Fourth Street Rock (Type C)	Southwest Type C Distributors 3442 Covey Court Napa, CA 94558
Lassenite (Type N)	Diatomics Mineral Corporation 601 University Avenue, Ste. 165 Sacramento, CA 95825
Cushenberry Volcanic Ash (Type N)	Cushenberry Cement Company 5808 Highway 18 Lucerne Valley, CA 92356
Carson City Volcanic Ash (Type N)	Basalite 2600 Boeing Carson City, Nevada 89701
Silica Fume	Master Builders 23700 Chagrin Blvd. Cleveland, Ohio 44122

TABLE 3

SUMMARY OF EXPANSION RESULTS OF SAMPLES (SET 1)

Mineral admixture	% replacement of portland cement (by weight)	% alkali content of cement	flow	w/c ratio	% Expansion					
					14 days	30 days	60 days	90 days	120 days	180 days
Control	--	0.25	109	0.58	-0.0133	-0.0017	0.0050	0.0017	0.0067	0.0183
(No mineral	--	0.60	113	0.61	0.0367	0.0933	0.1517	0.1683	0.1800	0.2000
admixture)	--	1.00	111	0.59	0.2200	0.3850	0.4333	0.4533	0.4250	0.4683
Bridger Flyash	15	0.25	113	0.57	-0.0100	0.0133	0.0133	0.0100	0.0133	0.0250
Class F	15	0.60	110	0.57	0.0567	0.1100	0.1717	0.1967	0.2150	0.2300
	15	1.00	108	0.57	0.1583	0.2183	0.2550	0.2800	0.2850	0.2950
	30	0.60	113	0.58	0.0050	0.0217	0.0367	0.0417	0.0483	0.0633
4th St. Rock	15	0.25	112	0.58	-0.0067	0.0050	0.0200	0.0333	0.0967	0.2050
Flyash	15	0.60	114	0.58	0.0950	0.2133	0.3050	0.3417	0.3617	0.3700
Class C	15	1.00	112	0.56	0.2267	0.3333	0.3733	0.4050	0.4050	0.4167
	30	0.60	114	0.61	0.1167	0.1817	0.2833	0.2950	0.3200	0.3450
Carson City	15	0.25	111	0.59	-0.0067	0.0033	0.0117	0.0100	0.0117	0.0233
Volcanic Ash	15	0.60	112	0.59	0.0183	0.0467	0.0967	0.1267	0.1550	0.1833
Class N	15	1.00	106	0.59	0.1467	0.2067	0.2583	0.2867	0.2933	0.3083
	30	0.60	112	0.63	-0.0017	0.0050	0.0200	0.0167	0.0200	0.0300
Cushenbury	15	0.25	104	0.60	-0.0017	0.0117	0.0267	0.0250	0.0300	0.0450
Volcanic Ash	15	0.60	101	0.57	-0.0017	0.0100	0.0167	0.0150	0.0183	0.0300
Class N	15	1.00	104	0.61	0.0133	0.0233	0.0333	0.0267	0.0317	0.0417
	30	0.60	104	0.63	-0.0017	0.0067	0.0150	0.0117	0.0150	0.0233
Lassenite	15	0.25	102	0.60	-0.0100	-0.0017	0.0100	0.0067	0.0100	0.0217
Ash	15	0.60	110	0.61	-0.0067	0.0033	0.0117	0.0100	0.0167	0.0267
Class N	15	1.00	105	0.60	0.0283	0.0467	0.0633	0.0750	0.0800	0.0950
	30	0.60	105	0.63	-0.0100	-0.0017	0.0050	0.0033	0.0083	0.0167

<u>NOTE:</u>

(1) (-) indicates shrinkage of sample

(2) Reported results are an average of three samples

(3) Samples were made on 2/3/87

TABLE 4

SUMMARY OF EXPANSION RESULTS OF SAMPLES (SET 2)

Mineral admixture	% replacement of portland cement (by weight)	% alkali content of cement	flow	% Expansion								
				14 days	30 days	60 days	90 days	120 days	180 days	270 days	360 days	540 days
Control	--	0.25	110	-0.0040	-0.0032	-0.0034	-0.0045	-0.0045	-0.0058	0.0100	0.0092	0.0150
(No mineral	--	0.60	108	0.0078	0.0259	0.0545	0.0633	0.0660	0.0678	0.0780	0.0782	0.0824
admixtures)	--	1.00	127	0.2152	0.2675	0.2949	0.2940	0.2920	0.2930	0.3057	0.3049	0.3082
Bridger Flyash	15	0.25	114	-0.0020	-0.0060	-0.0033	0.0023	0.0073	0.0203	0.0417	0.0477	0.0521
Class F	15	0.60	124	0.0260	0.0503	0.0717	0.0820	0.0843	0.0853	0.1050	0.1050	0.1072
	15	1.00	134	0.1083	0.1253	0.1463	0.1587	0.1563	0.1650	0.1750	0.1763	0.1773
	30	0.60	129	0.0073	0.0113	0.0223	0.0243	0.0273	0.0343	0.0503	0.0533	0.0598
Valmy Flyash	15	0.25	121	-0.0223	-0.0113	0.0380	0.1043	0.1657	0.1813	0.2040	0.2030	0.2042
Class F	15	0.60	107	0.0873	0.1777	0.2380	0.2403	0.2550	0.2440	0.2697	0.2643	0.2693
	15	1.00	115	0.2357	0.2633	0.2970	0.3113	0.3187	0.3253	0.3386	0.3413	0.3413
	30	0.60	130	0.1347	0.1933	0.2517	0.2733	0.2863	0.2760	0.3057	0.3047	0.3151
4th St. Rock	15	0.25	130	0.0017	0.0060	0.0460	0.1137	0.1540	0.1590	0.1823	0.1790	0.1883
Flyash	15	0.60	129	0.0987	0.1940	0.2600	0.2703	0.2747	0.2643	0.2887	0.2900	0.2965
Class C	15	1.00	136	0.1297	0.1520	0.2020	0.2123	0.2150	0.2197	0.2300	0.2357	0.2357
	30	0.60	>140	0.1310	0.1823	0.2470	0.2677	0.2860	0.2780	0.3043	0.3047	0.3116
Lassenite	15	0.25	92	-0.0050	-0.0030	-0.0040	-0.0037	-0.0037	-0.0133	0.0100	0.0083	0.0127
Ash	15	0.60	84	0.0000	0.0020	0.0040	0.0037	0.0027	-0.0020	0.0197	0.0187	0.0224
Class N	15	1.00	95	0.0133	0.0133	0.0223	0.0263	0.0277	0.0347	0.0437	0.0443	0.0408
	30	0.60	73	0.0000	-0.0050	-0.0023	-0.0023	-0.0030	-0.0047	0.0090	0.0098	0.0140
Cushenbury	15	0.25	102	-0.0107	-0.0017	-0.0110	-0.0073	-0.0070	-0.0063	0.0090	0.0093	0.0177
Volcanic Ash	15	0.60	93	-0.0003	-0.0010	0.0017	0.0027	0.0057	-0.0073	0.0176	0.0133	0.0203
Class N	15	1.00	107	0.0170	0.0153	0.0133	0.0183	0.0203	0.0274	0.0380	0.0387	0.0375
	30	0.60	82	-0.0010	-0.0017	-0.0013	-0.0013	0.0013	-0.0107	0.0080	0.0150	0.0153

<u>NOTE:</u>

(1) (-) indicates shrinkage of sample

(2) Reported results are an average of three samples

(3) Samples were made on 2/2/89

(4) W/C ratio for all samples=0.51

TABLE 5

SUMMARY OF EXPANSION RESULTS OF SAMPLES (SET 3)

Aggregate	Mineral admixture	Class	% repl. of portland cement (by weight)	flow	W/C ratio	% EXPANSION (days)									
						14	30	60	90	120	180	210	270	360	640
PACKWAY	CONTROL		--	116	0.529	.0248	.0125	.0088	.0098	.0110	.0275	.0363	.0528	.0543	.0535
	4th St. Rock Flyash	C	15	115	0.512	.0090	.0175	.0205	.0205	.0305	.0385	.0495	.0670	.0695	.0665
			30	116	0.487	-.0290	-.0030	.0000	.0010	.0100	.0140	.0250	.0380	.0400	.0370
	Cushenbury Volcanic Ash	N	15	109	0.570	.0000	.0155	.0165	.0145	.0220	.0315	.0355	.0520	.0540	.0510
	Navajo Volcanic Ash	N	15	122	0.534	.0050	.0070	.0075	.0090	.0185	.0255	.0330	.0505	.0510	.0490
	Silica Fume		15	107	0.765	.0085	.0165	.0125	.0175	.0290	.0395	.0380	.0600	.0645	.0595
			30	105	1.047	.0000	.0025	.0075	.0065	.0215	.0245	.0230	.0483	.0451	.0371
	Lassenite Ash	N	15	107	0.575	.0020	.0060	.0060	.0085	.0180	.0255	.0330	.0530	.0535	.0515
			30	111	0.643	.0110	.0150	.0200	.0220	.0400	.0400	.0470	.0690	.0720	.0660
	Bridger Flyash	F	15	114	0.542	.0100	.0125	.0125	.0145	.0240	.0320	.0415	.0585	.0605	.0580
			30	120	0.517	-.0140	-.0240	-.0100	-.0055	.0060	.0090	.0245	.0390	.0425	.0390
CAL-MAT	CONTROL		--	112	0.533	-.0170	.0015	-.0055	-.0055	.0100	.0095	.0135	.0370	.0375	.0345
	4th St. Rock Flyash	C	15	115	0.505	-.0030	.0020	.0080	.0100	.0165	.0170	.0270	.0575	.0580	.0565
			30	119	0.503	.0060	.0190	.0170	.0250	.0370	.0370	.0500	.0600	.0610	.0510
	Lassenite Ash	N	15	112	0.587	-.0125	.0015	.0015	.0010	.0200	.0200	.0220	.0475	.0475	.0435
			30	110	0.665	.0025	.0070	.0065	.0040	.0250	.0230	.0245	.0850	.0705	.0670
	Bridger Flyash	F	15	115	0.520	.0050	.0150	.0160	.0140	.0280	.0280	.0420	.0580	.0600	.0560
			30	114	0.542	-.0050	.0015	.0020	-.0050	.0160	.0140	.0215	.0460	.0430	.0385

NOTE: **(1) (-) indicates shrinkage of sample**
(2) Samples were made between 10/7/87 and 10/29/87

TABLE 6

PHYSICAL AND CHEMICAL PROPERTIES OF PORTLAND CEMENT AND MINERAL ADMIXTURES (USED FOR SET 1)

Compounds	Western Fly Ash Laughlin	Master Builders Silica Fume	Kaiser Portland Cement Type II	Chemstone Hydrated Lime
SiO_2	58.00	96.00	21.70	---
Al_2O_3	21.15	---	3.08	---
Fe_2O_3	6.05	---	3.75	---
CaO	8.80	---	65.00	95.10
MgO	1.58	---	0.99	0.35
SO_3	0.69	0.41	2.66	0.06
Total Alkalies (%)	3.15	---	0.31	---
Ignition Loss (%)	0.54	2.7	1.87	27.89
Fineness (% passing 325 mesh)	---	---	---	30.17

TABLE 7

MIX PROPORTIONS OF MORTAR BAR SAMPLES (SET 4)

Mix No.	Mix I.D.	Portland Cement (g)	Hydrated Lime (g)	Flyash (g)	Silica Fume (g)	Graded Standard Sand (g)	Pyrex Glass (g)	Water (mL)	Water/ Binder Ratio
1	Control	400	—	—	—	720	480	213	0.53
2	Lime	400	40	—	—	680	480	213	0.48
3	Flyash	400	—	40	—	680	480	213	0.48
4	Silica Fume	400	—	—	40	680	480	234	0.53

NOTE: (1) Pyrex glass aggregate of ASTM Sieve size #8 to #16 was used.
(2) Graded Standard sand (used for ASTM C109 test)

TABLE 8

SUMMARY OF EXPANSION RESULTS OF SAMPLES (SET 4)

		% EXPANSION						
MIX #	STORAGE CONDITION	4 DAYS	7 DAYS	10 DAYS	19 DAYS	33 DAYS	40 DAYS	47 DAYS
1-CONTROL	1N-NaOH Solution-23°C	0.18	0.23	0.26	0.30	0.36	0.38	0.42
	1N-NaOH Solution-80°C	0.19	0.20	0.22	0.28	0.30	0.35	0.36
	Over Water-80°C	0.02	0.03	0.04	0.07	0.04	0.09	0.10
2-HYDRATED LIME	1N-NaOH Solution-23°C	0.34	0.40	0.40	0.40	0.46	0.48	0.52
	1N-NaOH Solution-80°C	0.37	0.36	0.37	0.36	0.39	0.45	0.45
	Over Water-80°C	0.03	0.08	0.09	0.14	0.10	0.15	0.17
3-FLYASH	1N-NaOH Solution-23°C	0.28	0.35	0.37	0.39	0.43	0.45	0.48
	1N-NaOH Solution-80°C	0.31	0.31	0.32	0.35	0.37	0.42	0.42
	Over Water-80°C	0.02	0.12	0.14	0.19	0.17	0.22	0.21
4-SILICA FUME	1N-NaOH Solution-23°C	0.02	0.04	0.04	0.05	0.08	0.10	0.12
	1N-NaOH Solution-80°C	0.01	0.01	0.01	0.01	0.02	0.07	0.06
	Over Water-80°C	0.00	0.01	0.00	0.04	0.01	0.05	0.06

<u>NOTE:</u>

(1) Reported results are an average of two samples.

TABLE 9

MIX PROPORTIONS AND PROPERTIES OF CONCRETE (CREEP STUDY)

Mix #	Mineral Type & Percentage	Mineral Admixture (kg)	Portland Cement (kg)	SSD Sand (kg)	SSD Rock (kg)	Water (kg)	Water/Binder Ratio (W/B)	Slump (mm)	Air Entrainment		
									AEA	Amount (mL)	% Air
1	No admixture (control)	---	22.1	38.7	69.7	8.6	0.46	76	---	---	1
2	15% Pozzolanic Int'l (Class F)	3.3	18.8	38.5	69.1	8.8	0.47	76	---	---	1
3	30% Pozzolanic Int'l. (Class F)	6.6	15.5	38.1	68.6	8.4	0.45	76	---	---	-1
4	15% Lassenite (Class N)	3.3	18.8	38.5	69.1	9.8	0.51	76	---	---	1.2
5	15% Silica Fume	3.3	18.8	38.3	68.9	10.2	0.46	96	---	---	1.2
6	No admixture (control)	---	22.1	36.9	66.4	8.7	0.46	71	Darex	27	6
7	15% Pozzolanic Int'l (Class F)	3.3	18.8	36.6	65.8	8.7	0.46	76	Darex	36	6
8	15% Lassenite (Class N)	3.3	18.8	36.6	65.8	9.3	0.49	71	Darex	30	5.5
9	15% 4th St. Rock (Class C)	3.3	18.8	36.7	66.0	8.6	0.46	71	Darex	40	5.7

NOTE: Sand = Teichert Perkins Sand
Rock = Teichert Perkins Aggregate, 25.4 mm max.
Darex = Air Entraining Agent manufactured by Sika Corporation

TABLE 10

SUMMARY OF TOTAL STRAIN RESULTS OF CONCRETE SAMPLES

	DAYS OF CURING -->	7	14	21	28	60	90	120	180	270	360	640
	DAYS OF LOADING -->	**0**	**7**	**14**	**21**	**53**	**83**	**113**	**173**	**263**	**353**	**633**
Mix #	**Mix ID**	**TOTAL STRAIN (mm/mm)**										
1	Control, No Mineral Admixtures	0.00052	0.00085	0.00096	0.00103	0.00123	0.00140	0.00152	0.00162	0.00172	0.00176	0.00187
2	15% Pozz. Int'l.	0.00045	0.00061	0.00081	0.00089	0.00115	0.00130	0.00140	0.00147	0.00156	0.00159	0.00166
3	30% Pozz. Int'l.	0.00062	0.00101	0.00128	0.00130	0.00160	0.00189	0.00187	0.00202	0.00209	0.00218	0.00226
4	15% Lassenite	0.00050	0.00107	0.00108	0.00118	0.00138	0.00161	0.00162	0.00173	0.00187	0.00196	0.00209
5	15% Silica Fume	0.00065	0.00112	0.00119	0.00135	0.00154	0.00160	0.00166	0.00181	0.00173	0.00203	0.00216
6	Control, No Mineral Admixture+Darex	0.00039	0.00070	0.00128	0.00098	0.00130	0.00159	0.00162	0.00173	0.00177	0.00183	0.00193
7	15% Pozz. Int'l.+ Darex	0.00055	0.00121	0.00135	0.00138	0.00170	0.00184	0.00201	0.00214	0.00205	0.00224	0.00227
8	15% Lassenite + Darex	0.00040	0.00089	0.00107	0.00125	0.00148	0.00169	0.00177	0.00193	0.00190	0.00203	0.00214
9	15% 4th St. Rock + Darex	0.00039	0.00078	0.00092	0.00102	0.00143	0.00147	0.00154	0.00174	0.00162	0.00180	0.00192

NOTE: Total Strain = Instantaneous Strain (Elastic Modulus) + Shrinkage Strain + Creep.

TABLE 11

SUMMARY OF SHRINKAGE STRAIN RESULTS OF CONCRETE SAMPLES

	DAYS OF CURING->	7	14	21	28	60	90	120	180	270	360	640
	DAYS OF LOADING->	0	7	14	21	53	83	113	173	263	353	633
Mix #	Mix ID	SHRINKAGE (mm/mm)										
1	Control, No Mineral Admixtures	0.00000	0.00000	0.00004	0.00004	0.00014	0.00028	0.00034	0.00039	0.00041	0.00047	0.00042
2	15% Pozz. Int'l.	0.00000	0.00003	0.00006	0.00010	0.00020	0.00034	0.00043	0.00046	0.00051	0.00051	0.00049
3	30% Pozz. Int'l.	0.00000	0.00007	0.00008	0.00021	0.00031	0.00050	0.00051	0.00060	0.00070	0.00071	0.00071
4	15% Lassenite	0.00000	0.00025	0.00037	0.00045	0.00051	0.00075	0.00078	0.00088	0.00094	0.00100	0.00107
5	15% Silica Fume	0.00000	0.00010	0.00017	0.00019	0.00037	0.00039	0.00037	0.00049	0.00047	0.00055	0.00057
6	Control, No Mineral Admixture+Darex	0.00000	0.00014	0.00026	0.00035	0.00060	0.00076	0.00077	0.00079	0.00081	0.00084	0.00088
7	15% Pozz. Int'l.+ Darex	0.00000	0.00005	0.00009	0.00017	0.00024	0.00054	0.00059	0.00058	0.00067	0.00067	0.00071
8	15% Lassenite + Darex	0.00000	0.00013	0.00014	0.00027	0.00027	0.00059	0.00060	0.00081	0.00080	0.00065	0.00076
9	15% 4th St. Rock + Darex	0.00000	0.00018	0.00056	0.00067	0.00078	0.00095	0.00076	0.00100	0.00099	0.00090	0.00105

NOTE: Total Strain = Instantaneous Strain (Elastic Modulus) + Shrinkage Strain + Creep.

TABLE 12

SUMMARY OF CREEP STRAIN RESULTS OF CONCRETE SAMPLES

	DAYS OF CURING->	7	14	21	28	60	90	120	180	270	360	640
	DAYS OF LOADING->	0	7	14	21	53	83	113	173	263	353	633
Mix #	Mix ID	SHRINKAGE (mm/mm)										
1	Control, No Mineral Admixtures	0.00000	0.00032	0.00040	0.00046	0.00057	0.00060	0.00066	0.00072	0.00080	0.00077	0.00093
2	15% Pozz. Int'l.	0.00000	0.00013	0.00030	0.00033	0.00030	0.00051	0.00052	0.00056	0.00060	0.00063	0.00072
3	30% Pozz. Int'l.	0.00000	0.00032	0.00059	0.00047	0.00068	0.00078	0.00075	0.00080	0.00077	0.00086	0.00094
4	15% Lassenite	0.00000	0.00033	0.00021	0.00024	0.00037	0.00035	0.00035	0.00035	0.00043	0.00047	0.00053
5	15% Silica Fume	0.00000	0.00037	0.00051	0.00052	0.00056	0.00064	0.00064	0.00067	0.00061	0.00083	0.00093
6	Control, No Mineral Admixture+Darex	0.00000	0.00017	0.00023	0.00023	0.00032	0.00044	0.00046	0.00055	0.00058	0.00060	0.00066
7	15% Pozz. Int'l.+ Darex	0.00000	0.00061	0.00071	0.00067	0.00071	0.00076	0.00088	0.00102	0.00084	0.00102	0.00101
8	15% Lassenite + Darex	0.00000	0.00036	0.00054	0.00058	0.00081	0.00071	0.00077	0.00073	0.00070	0.00098	0.00098
9	15% 4th St. Rock + Darex	0.00000	0.00020	-0.00003	-0.00002	0.00026	0.00033	0.00039	0.00034	0.00024	0.00050	0.00048

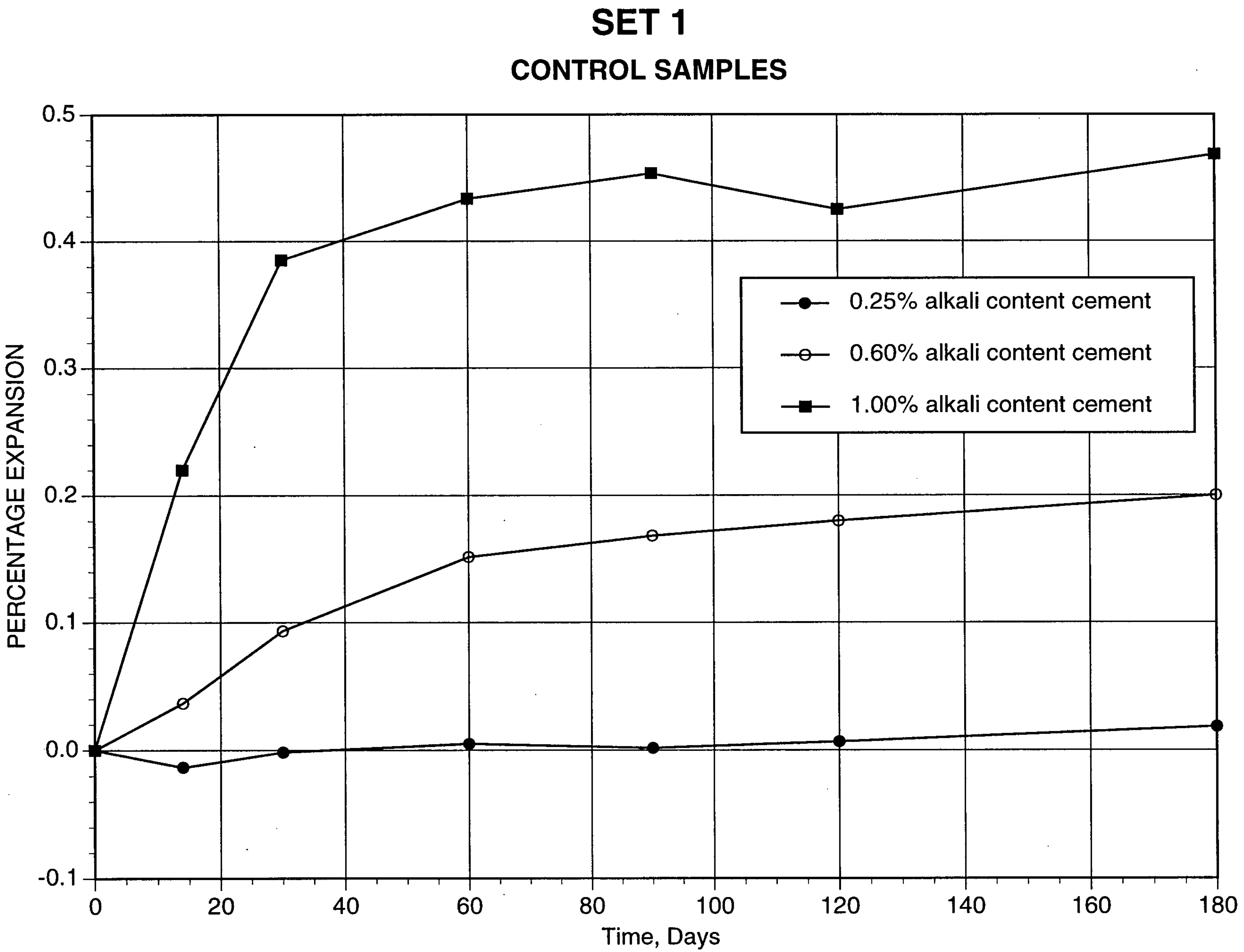
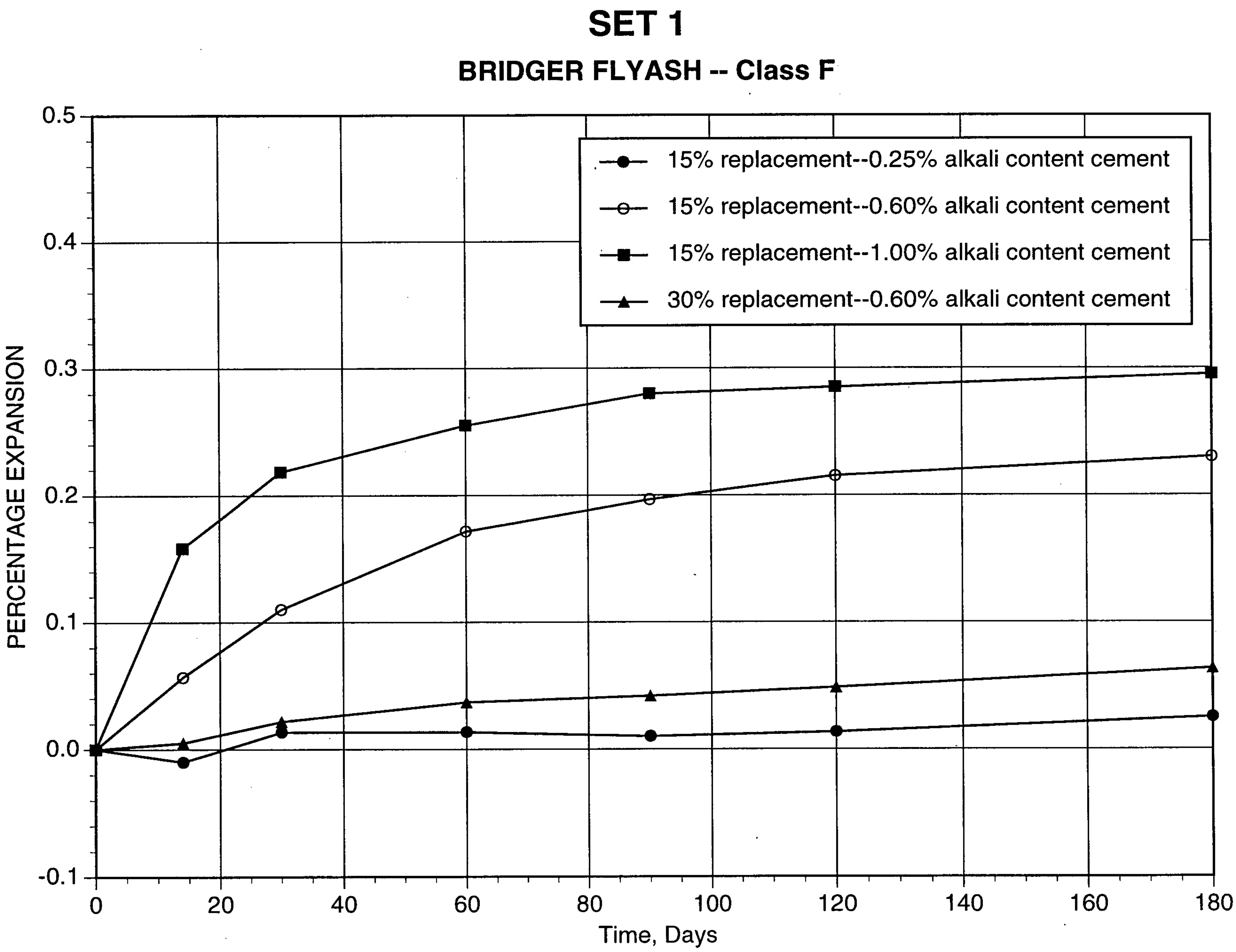


FIGURE 1.1 : EXPANSION VS TIME



SET 1

BRIDGER FLYASH -- Class F

FIGURE 1.2 : EXPANSION VS TIME

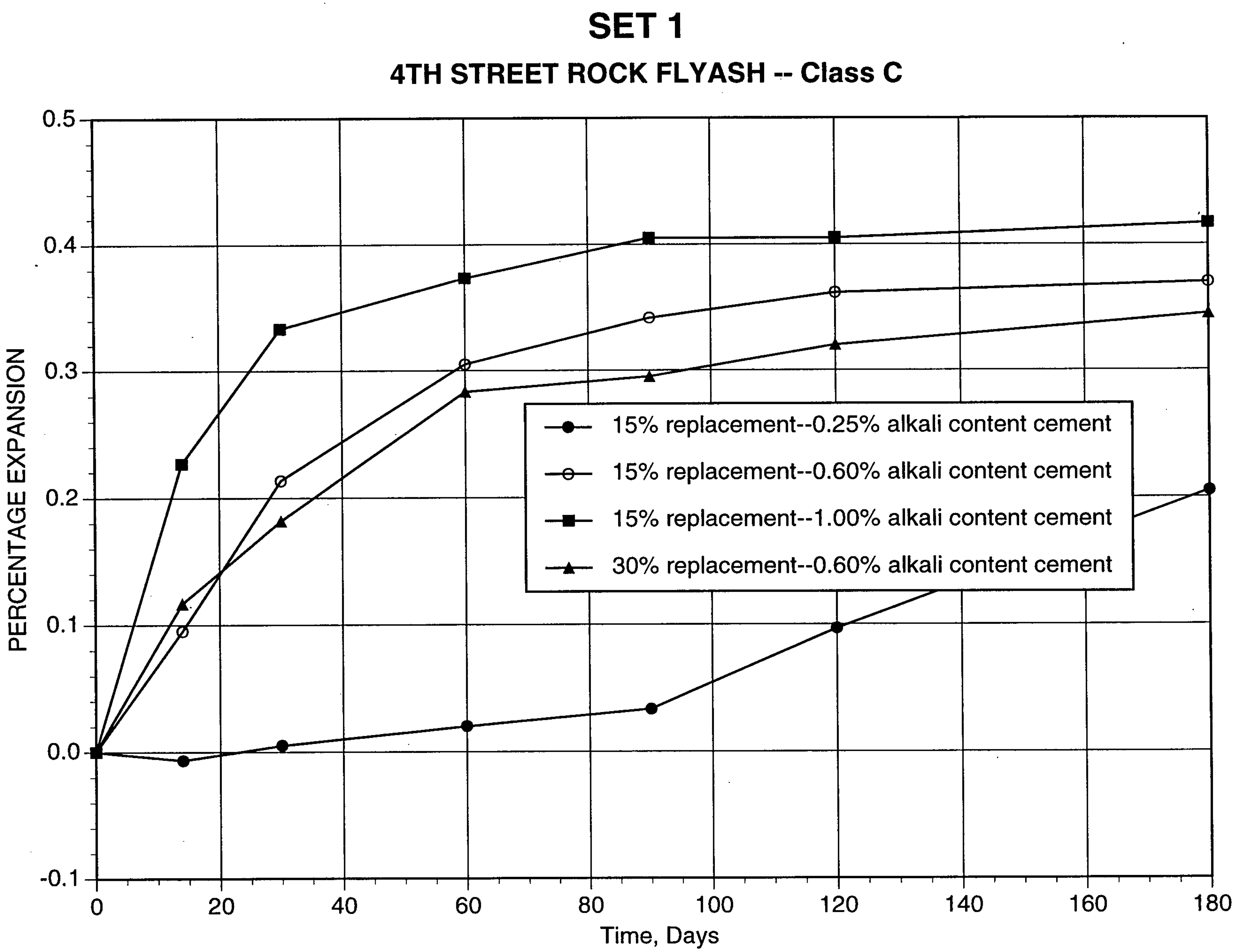


FIGURE 1.3 : EXPANSION VS TIME

SET 1

LASSENITE ASH -- Class N

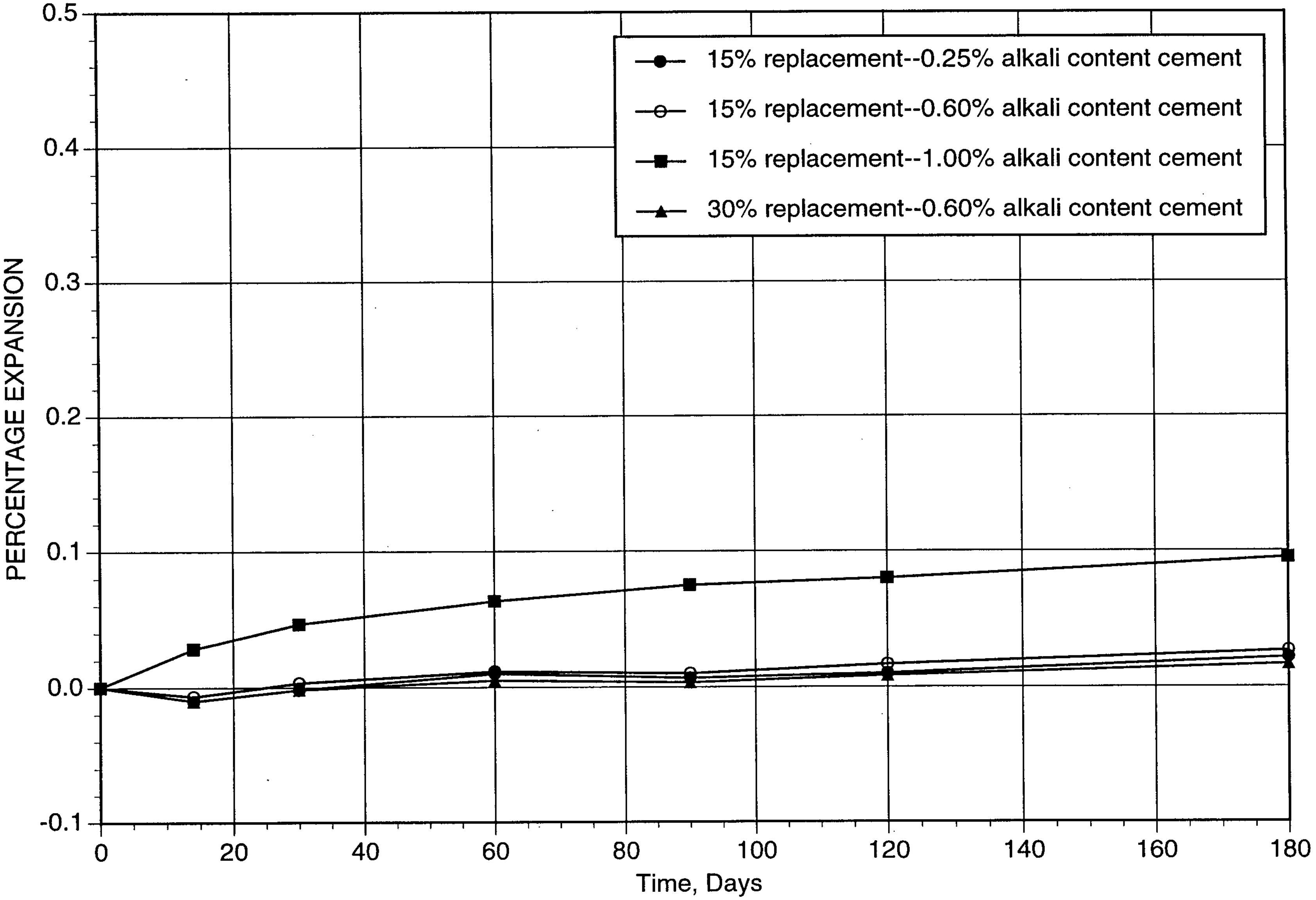


FIGURE 1.4 : EXPANSION VS TIME

SET 1

CUSHENBURY VOLCANIC ASH -- Class N

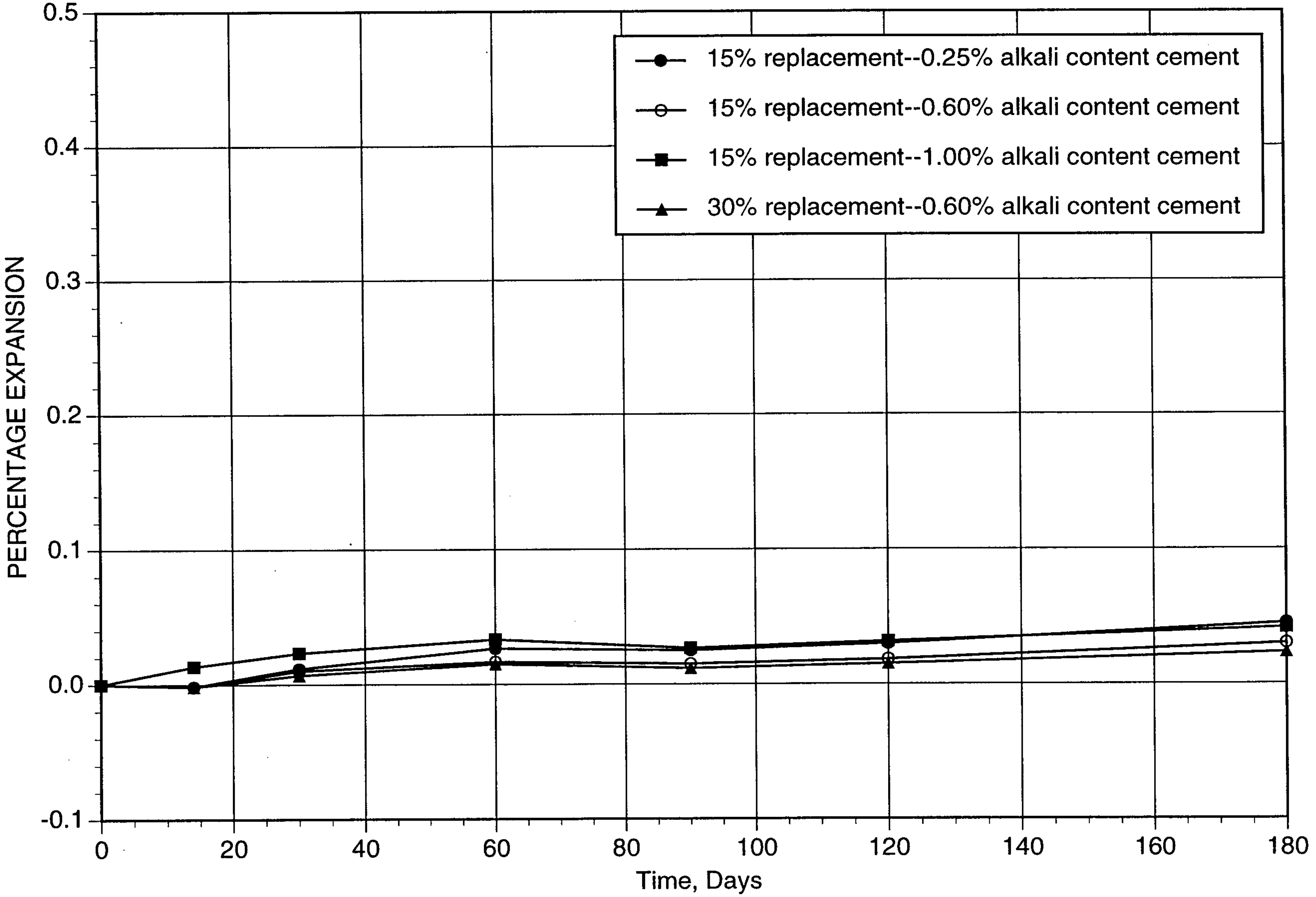


FIGURE 1.5 : EXPANSION VS TIME

SET 1

CARSON CITY VOLCANIC ASH -- Class N

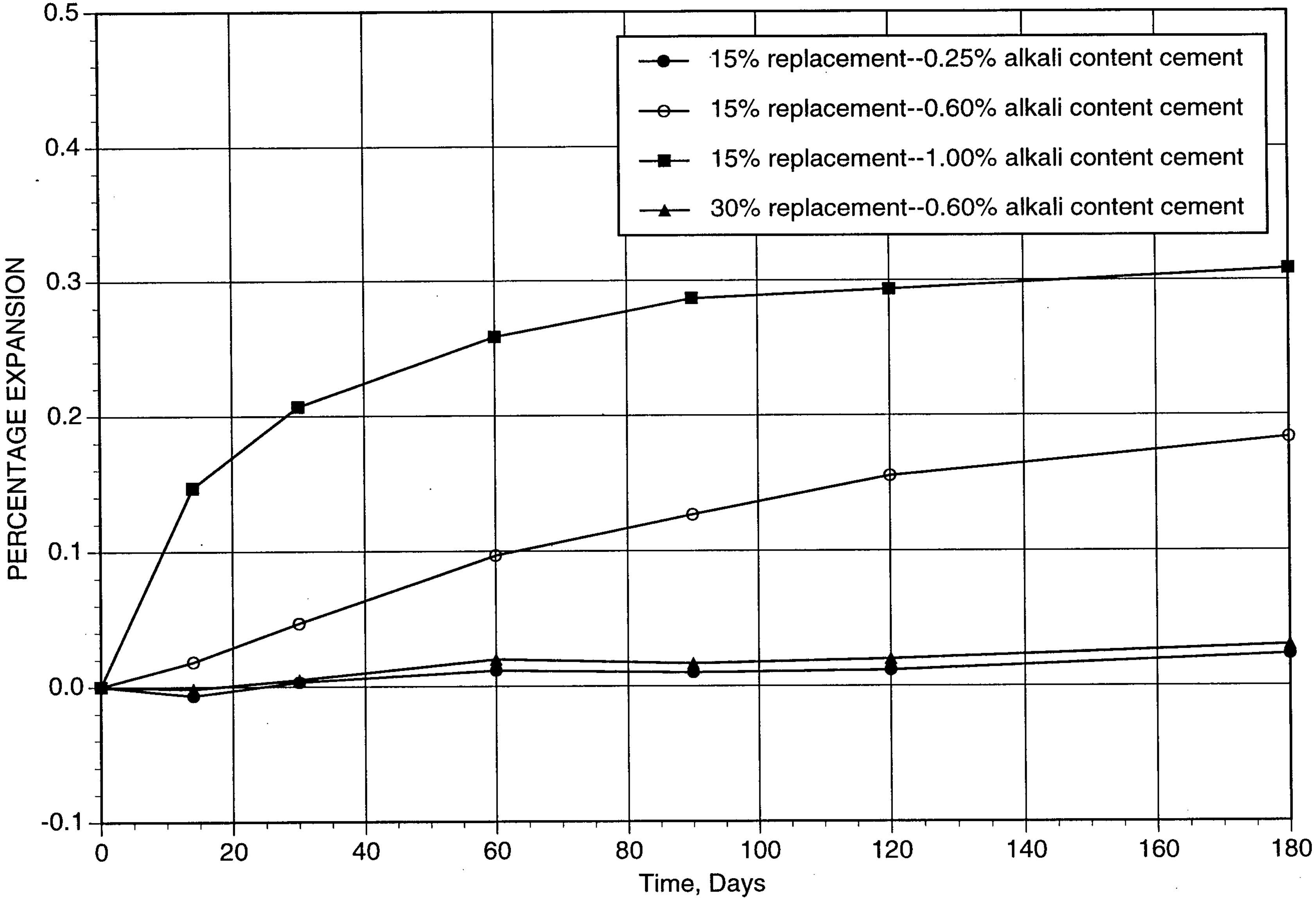


FIGURE 1.6 : EXPANSION VS TIME

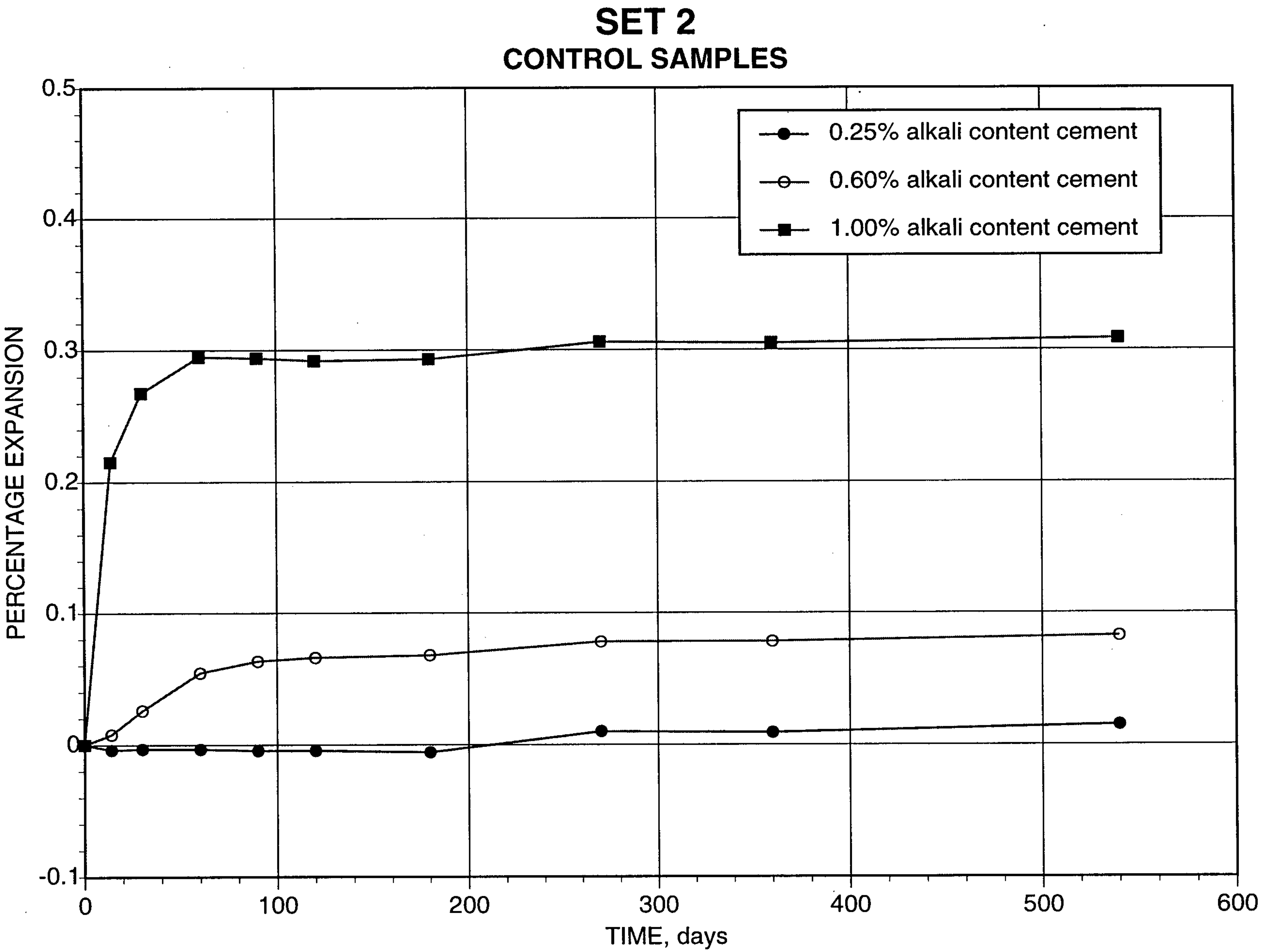


FIGURE 2.1 : EXPANSION VS. TIME

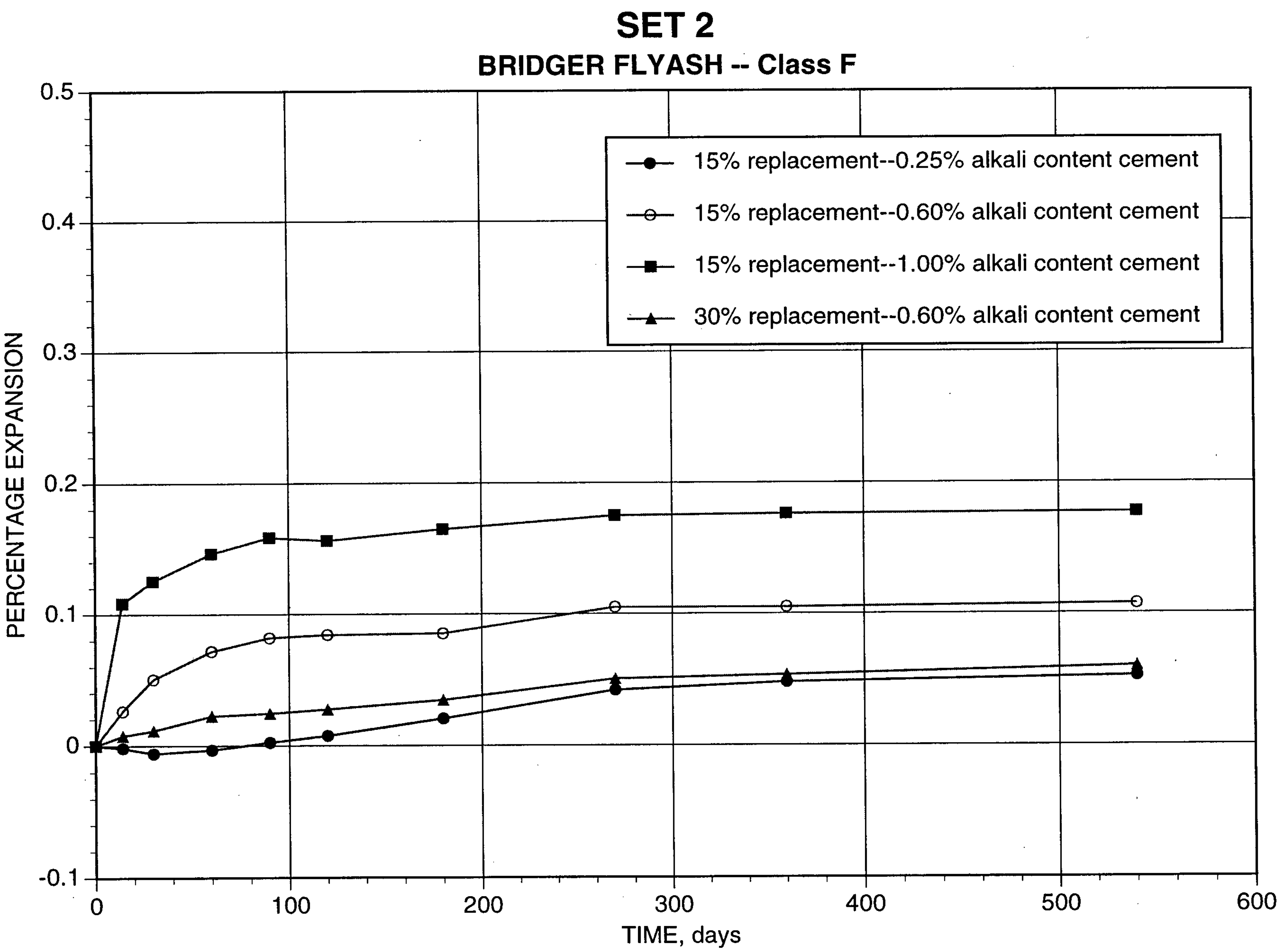


FIGURE 2.2 : EXPANSION VS. TIME

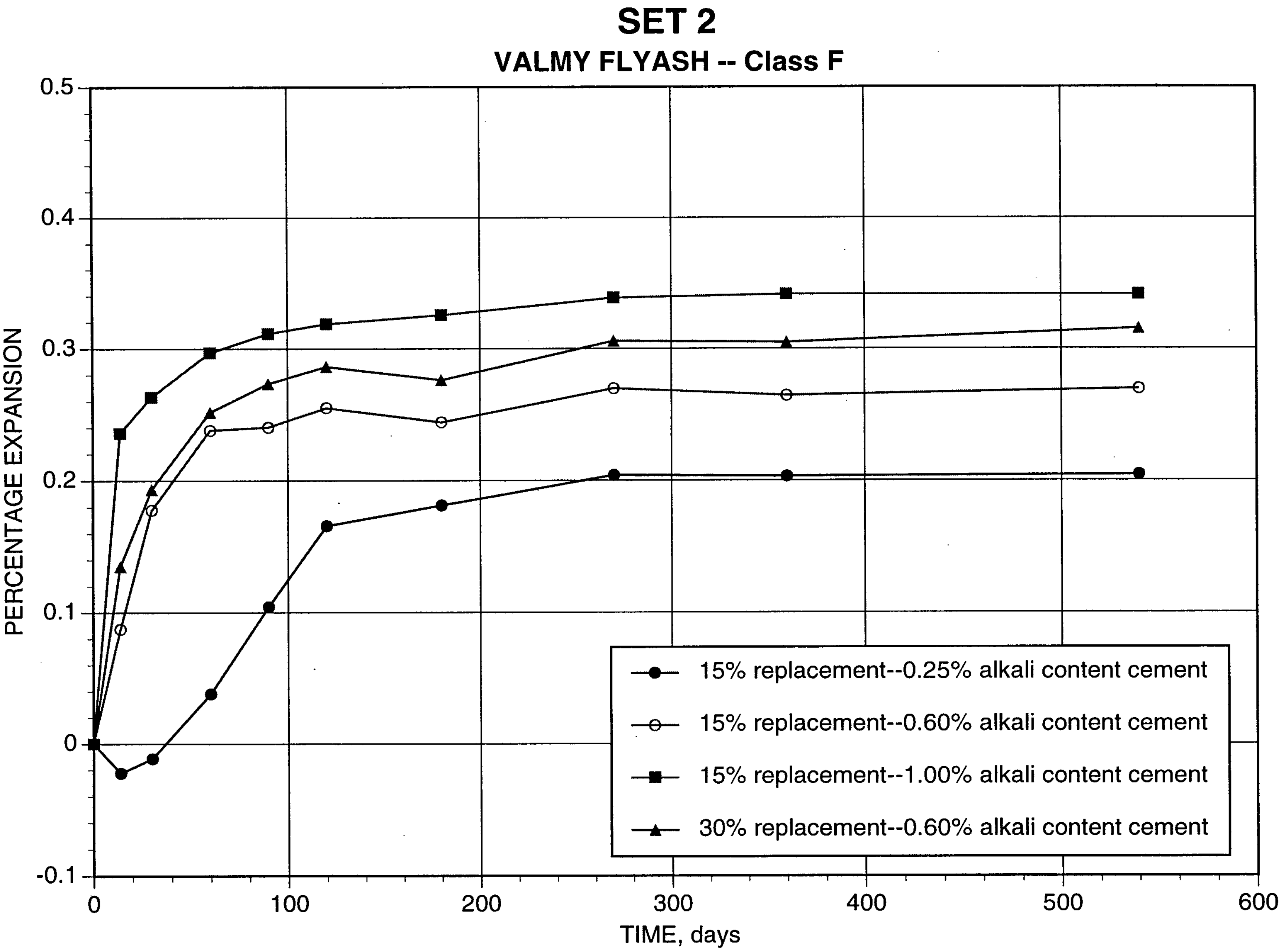


FIGURE 2.3 : EXPANSION VS. TIME

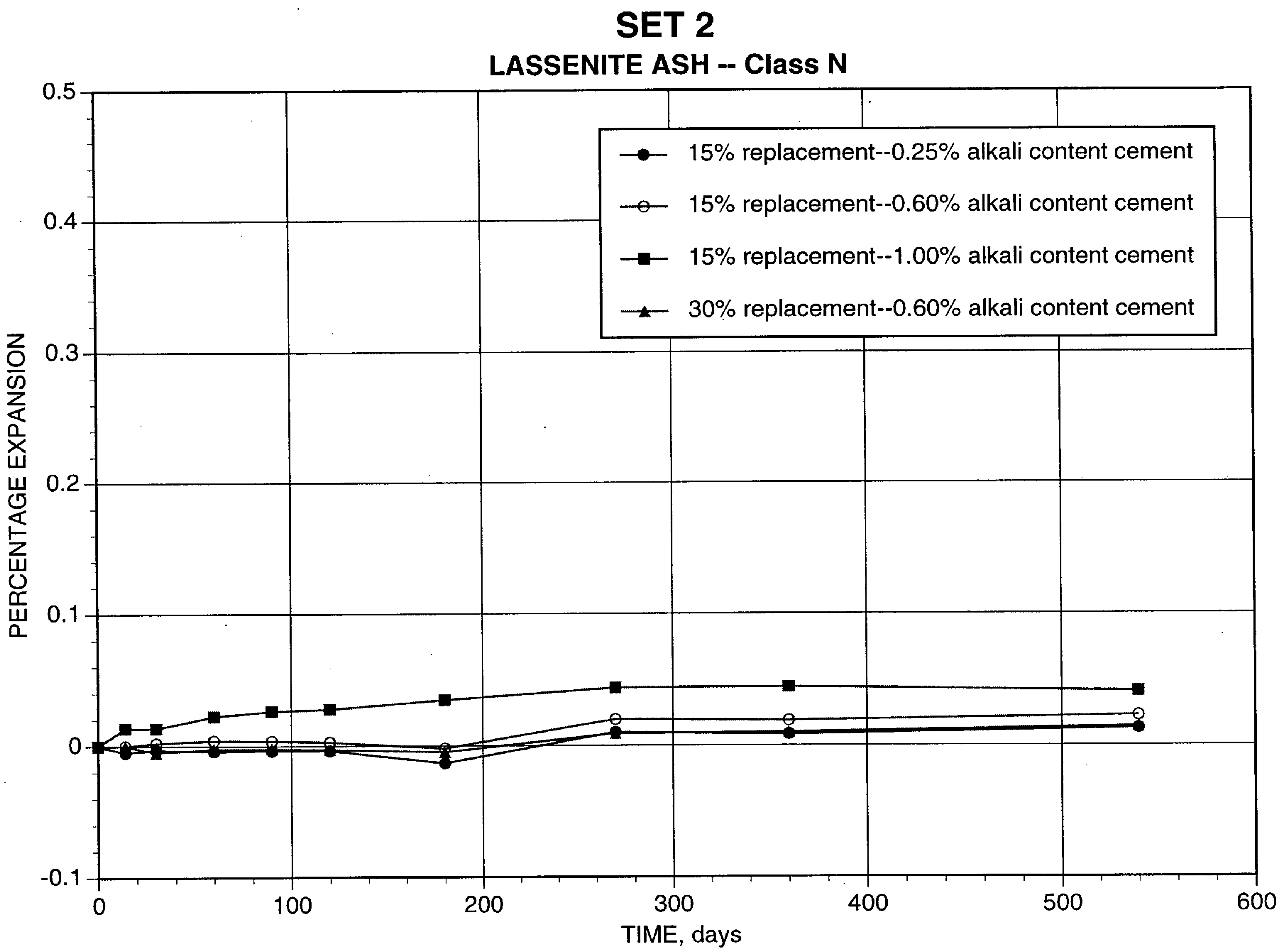
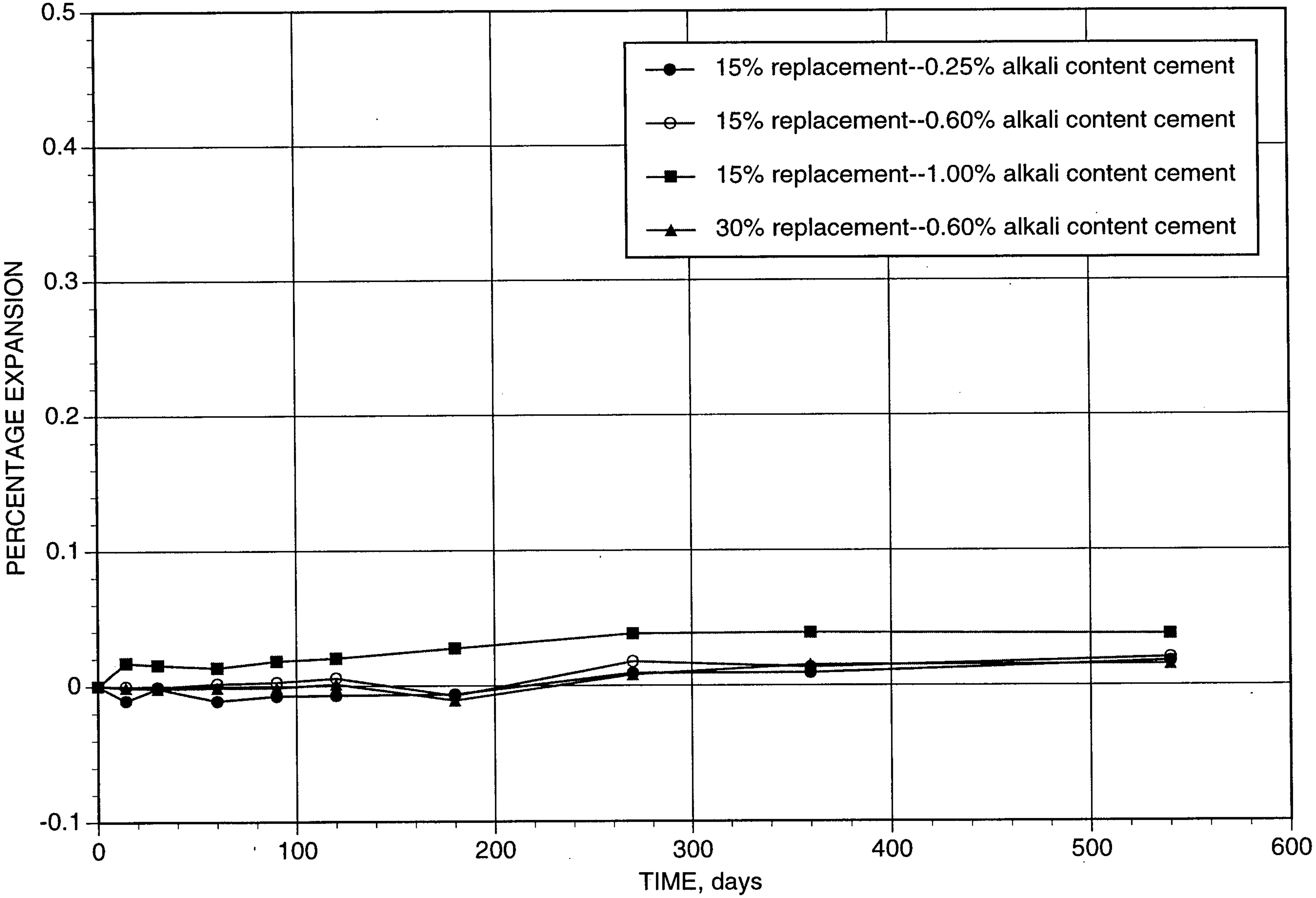


FIGURE 2.5 : EXPANSION VS. TIME



SET 2

CUSHENBURY VOLCANIC ASH -- Class N

FIGURE 2.6 : EXPANSION VS. TIME

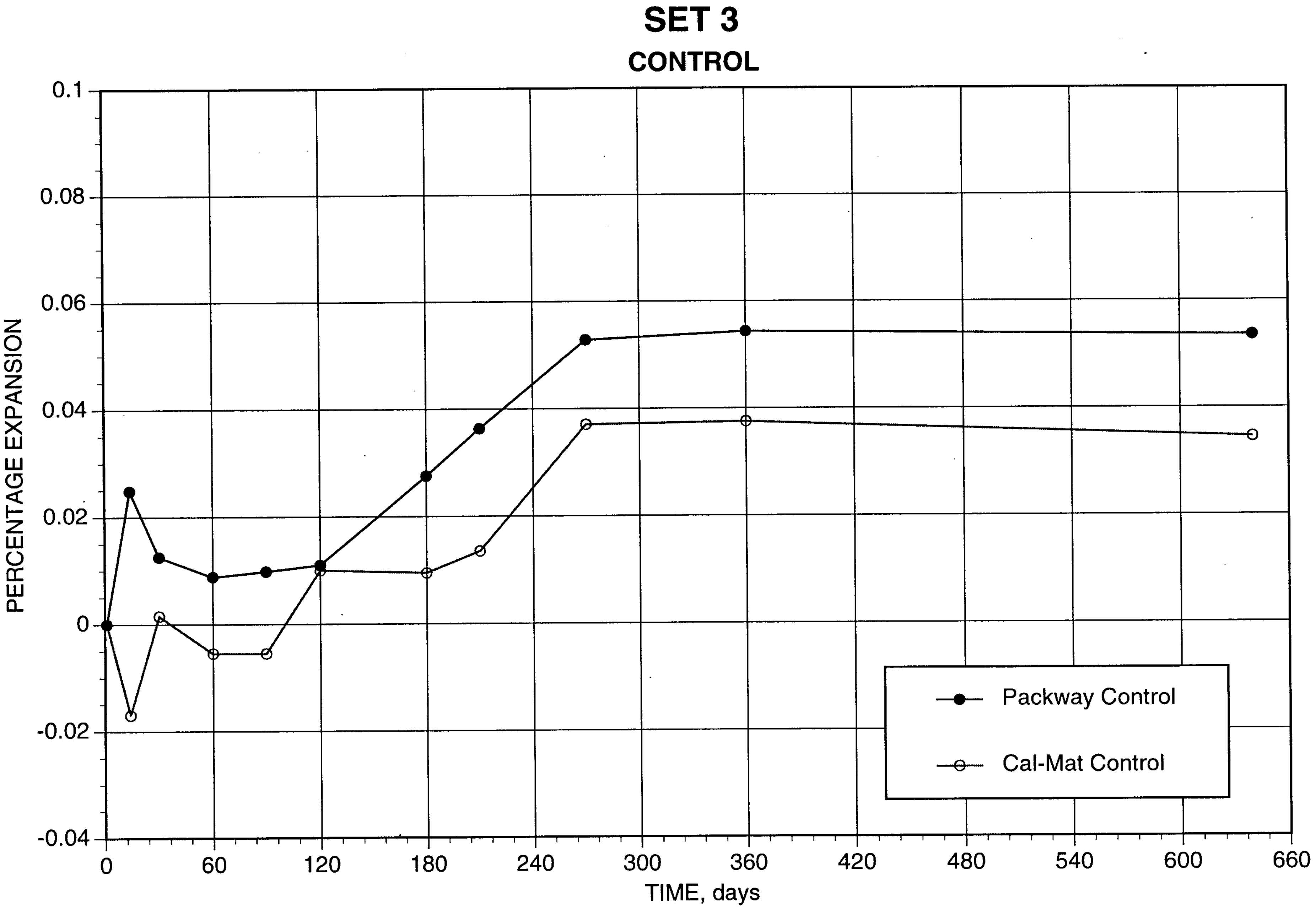
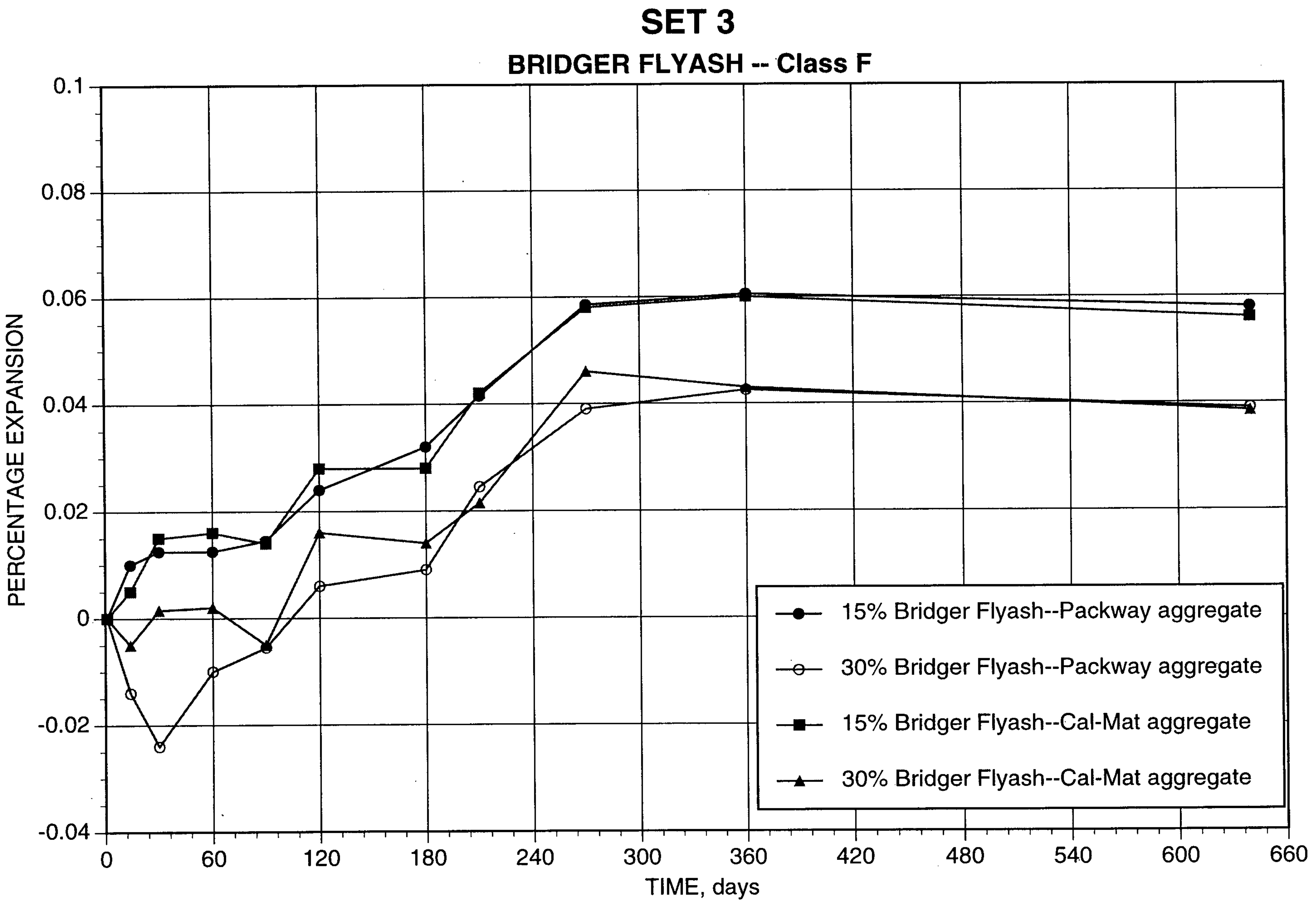


FIGURE 3.1 : EXPANSION VS. TIME



SET 3

BRIDGER FLYASH -- Class F

FIGURE 3.2 : EXPANSION VS. TIME

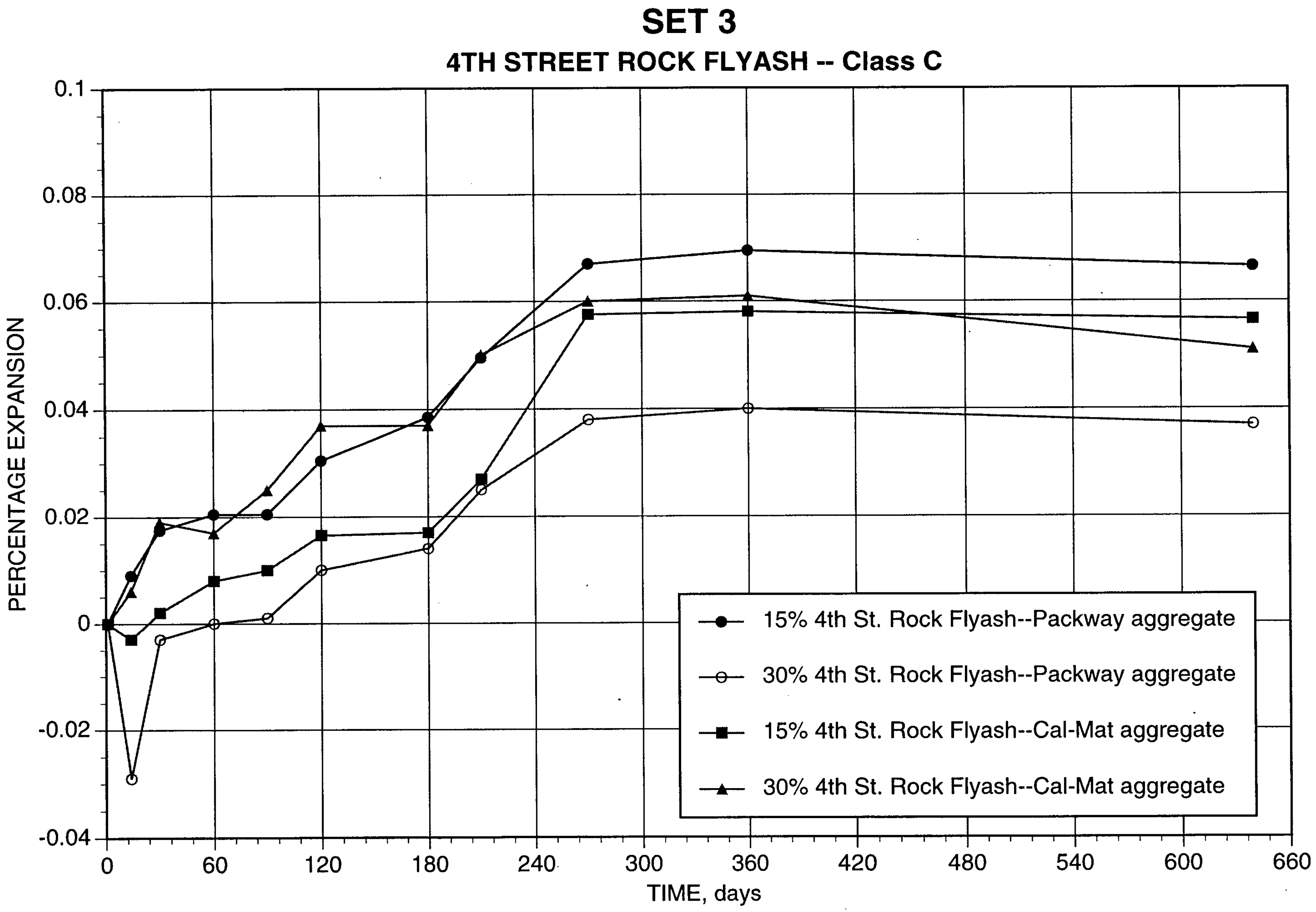


FIGURE 3.3 : EXPANSION VS. TIME

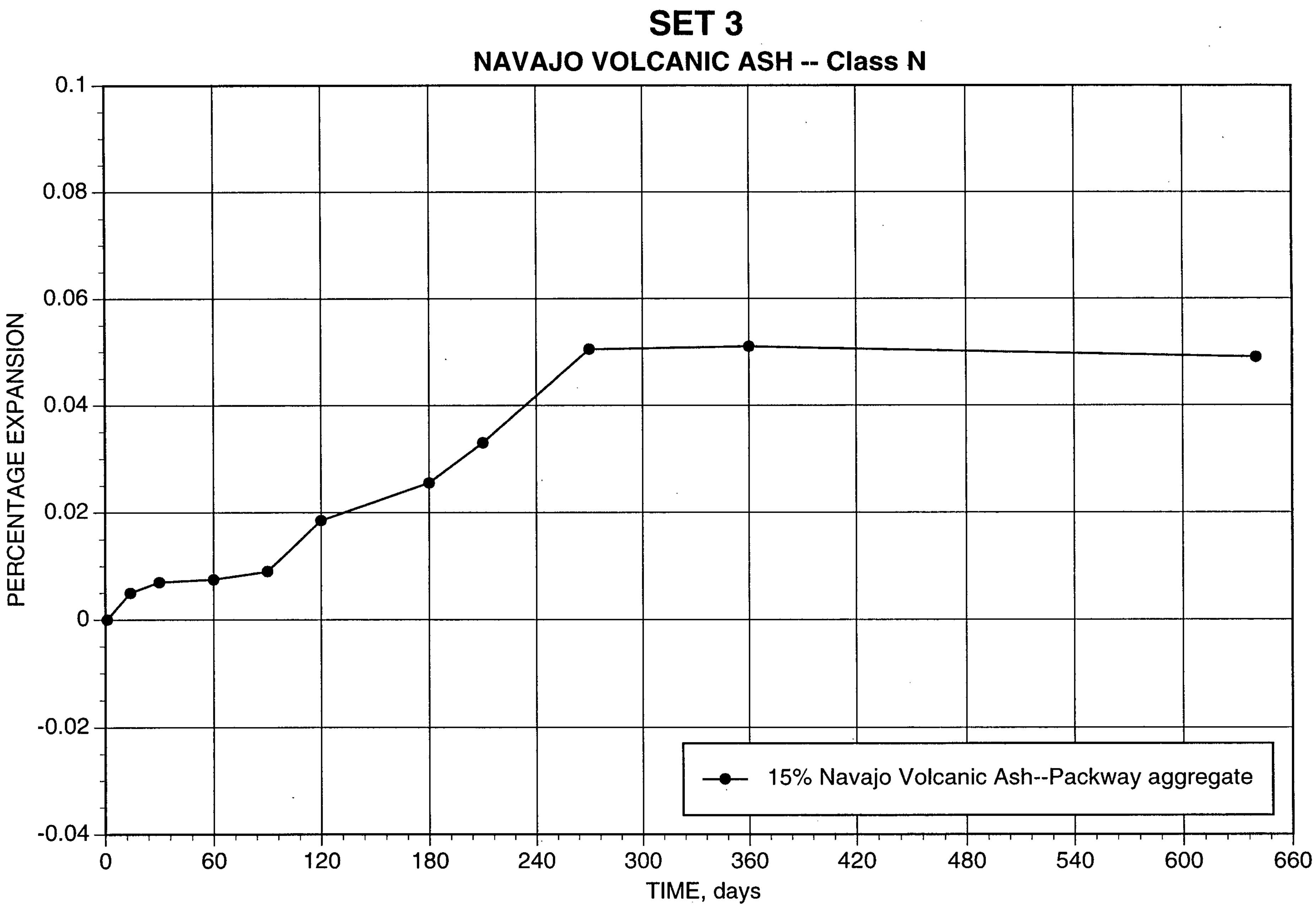


FIGURE 3.4 : EXPANSION VS. TIME

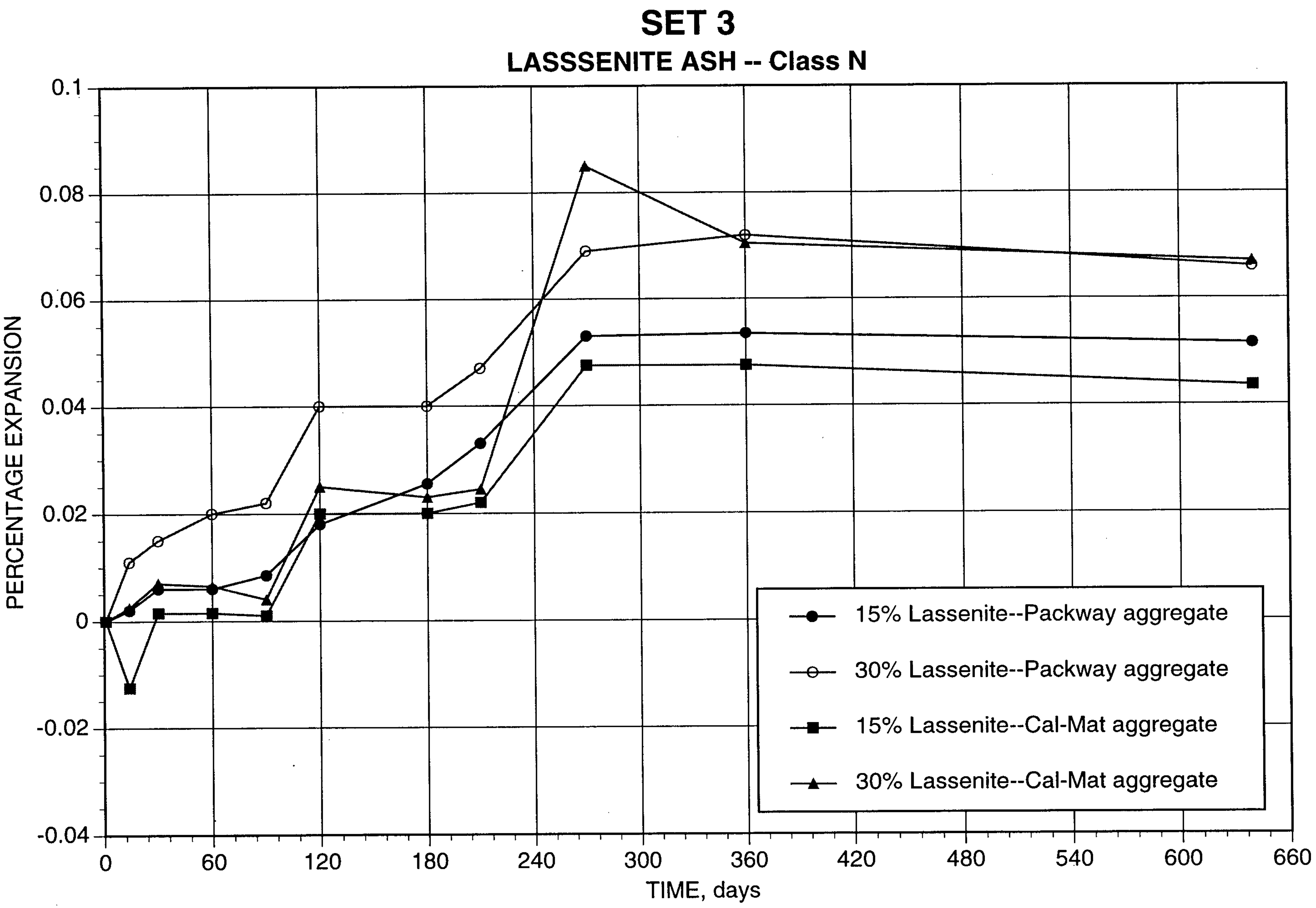
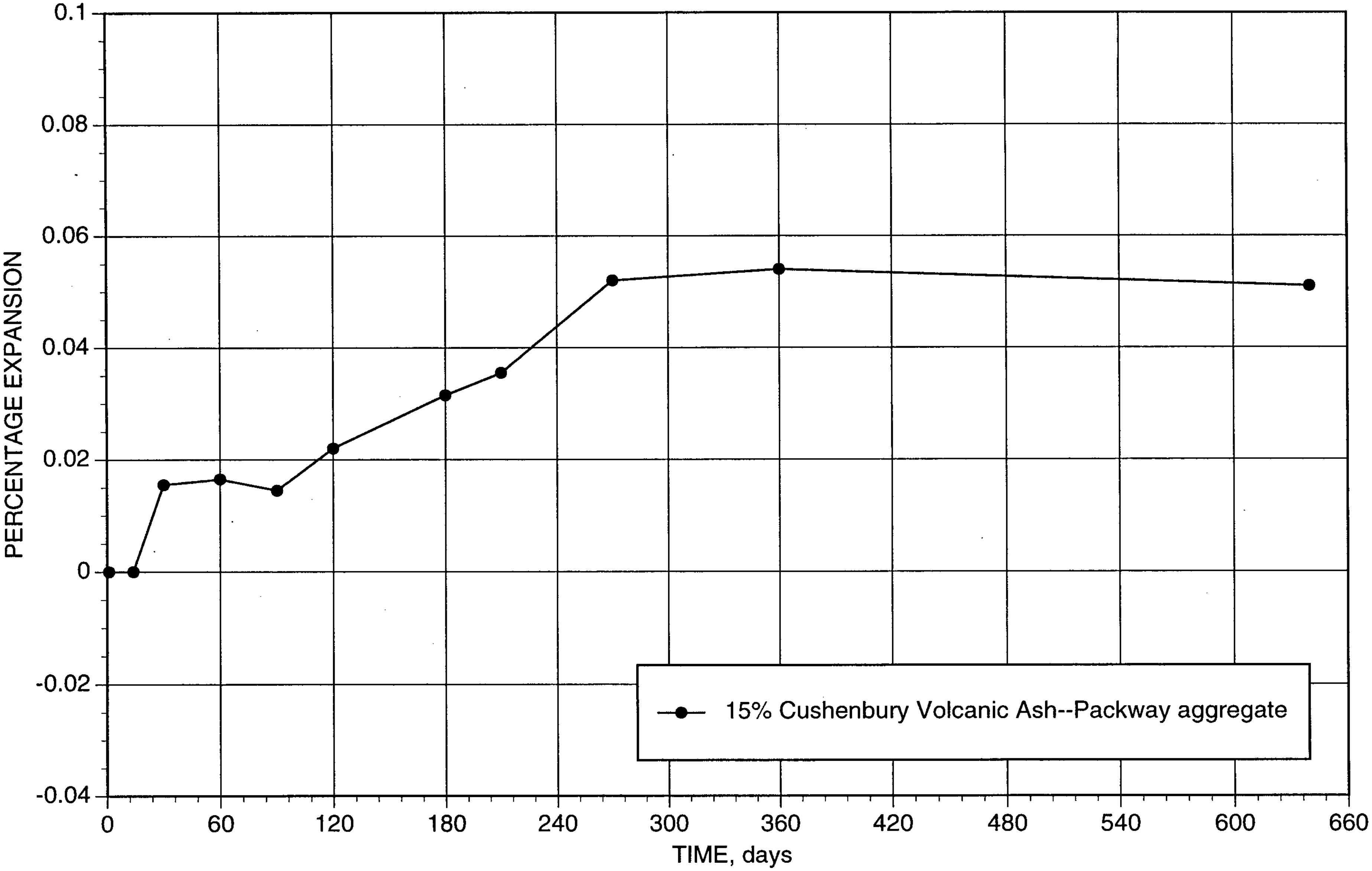


FIGURE 3.5 : EXPANSION VS. TIME



SET 3

CUSHENBURY VOLCANIC ASH -- Class N

FIGURE 3.6 : EXPANSION VS. TIME

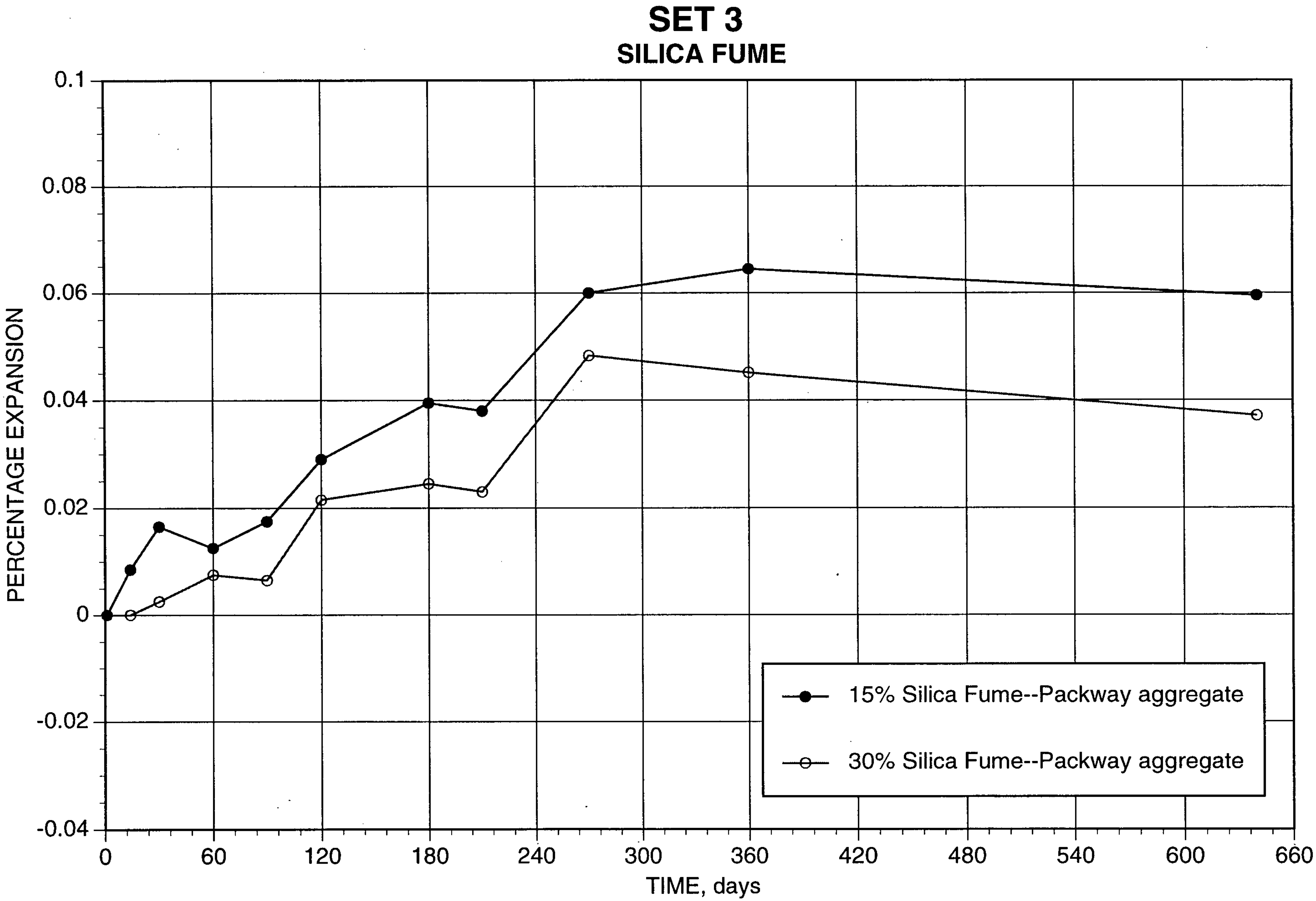


FIGURE 3.7 : EXPANSION VS. TIME

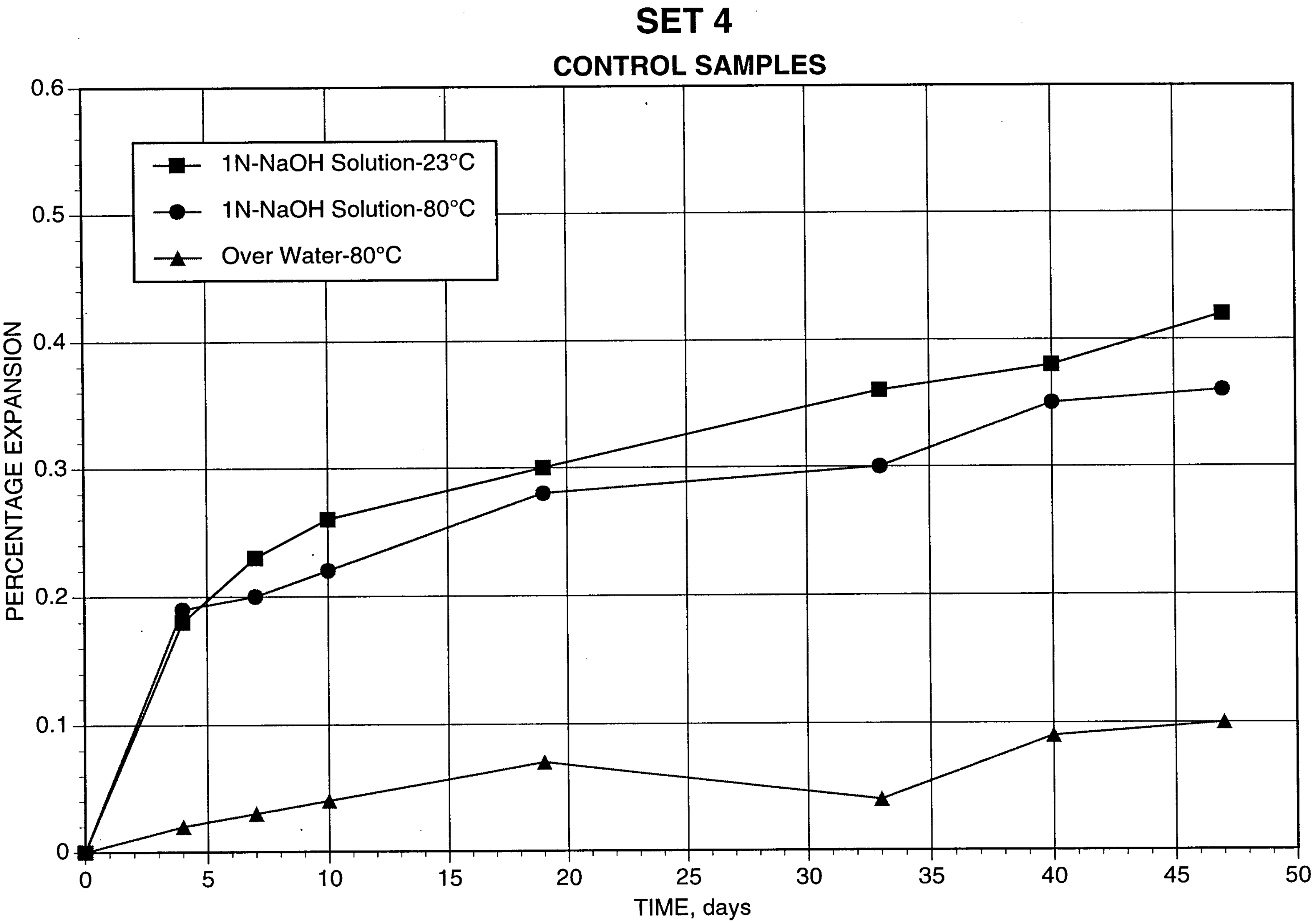


FIGURE 4.1 : EXPANSION VS TIME

SET 4

HYDRATED LIME

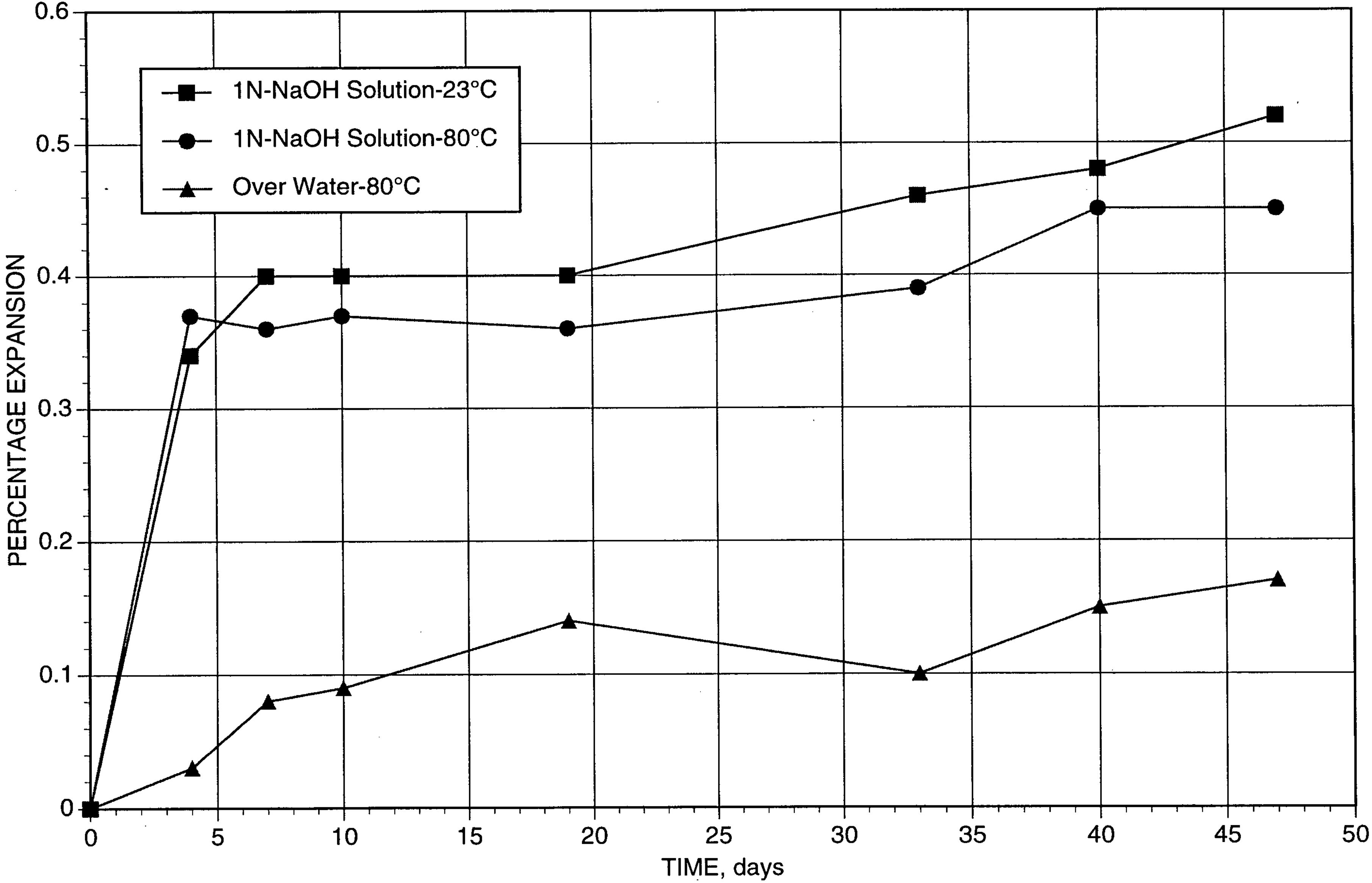


FIGURE 4.2 : EXPANSION VS TIME

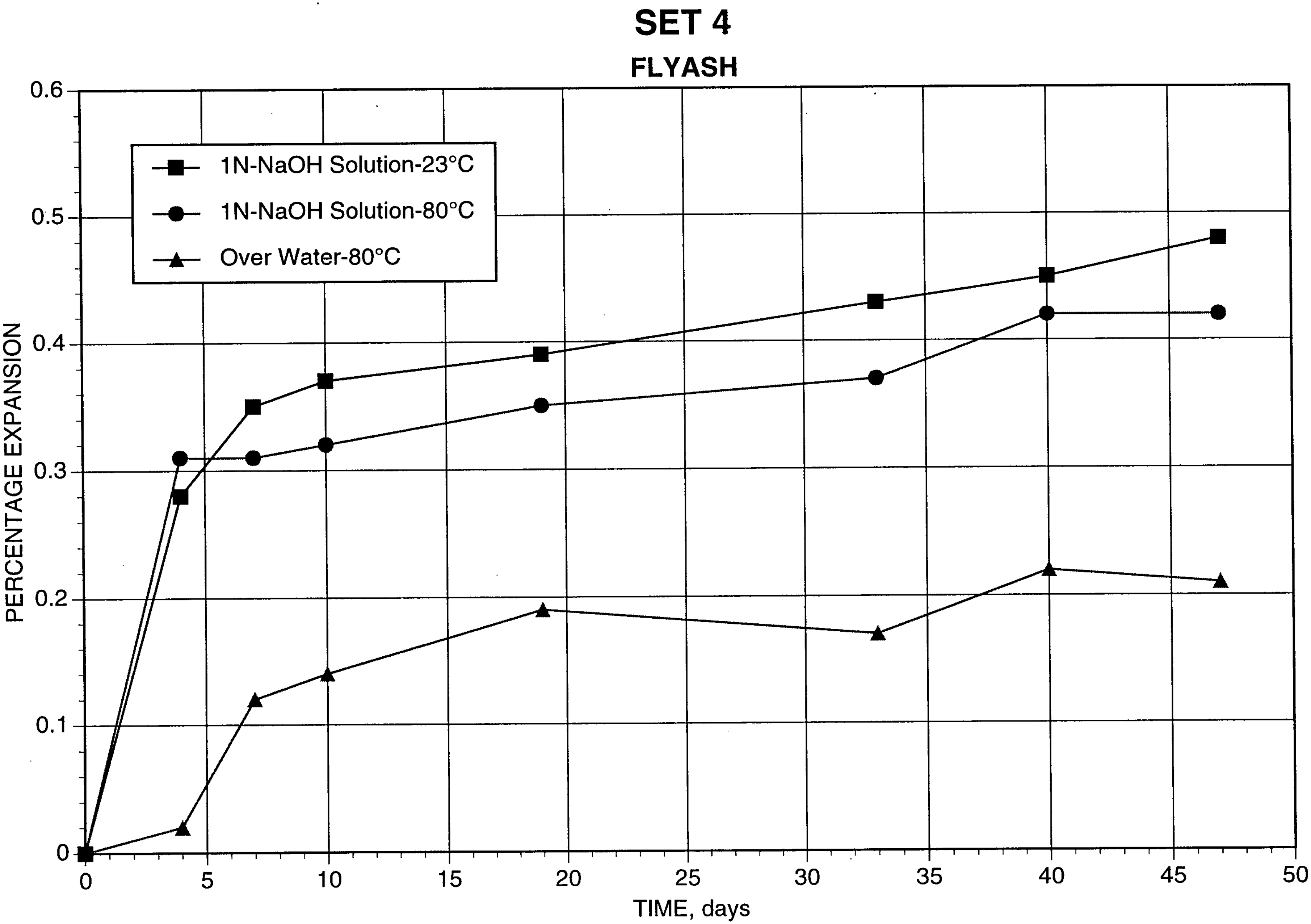


FIGURE 4.3 : EXPANSION VS TIME

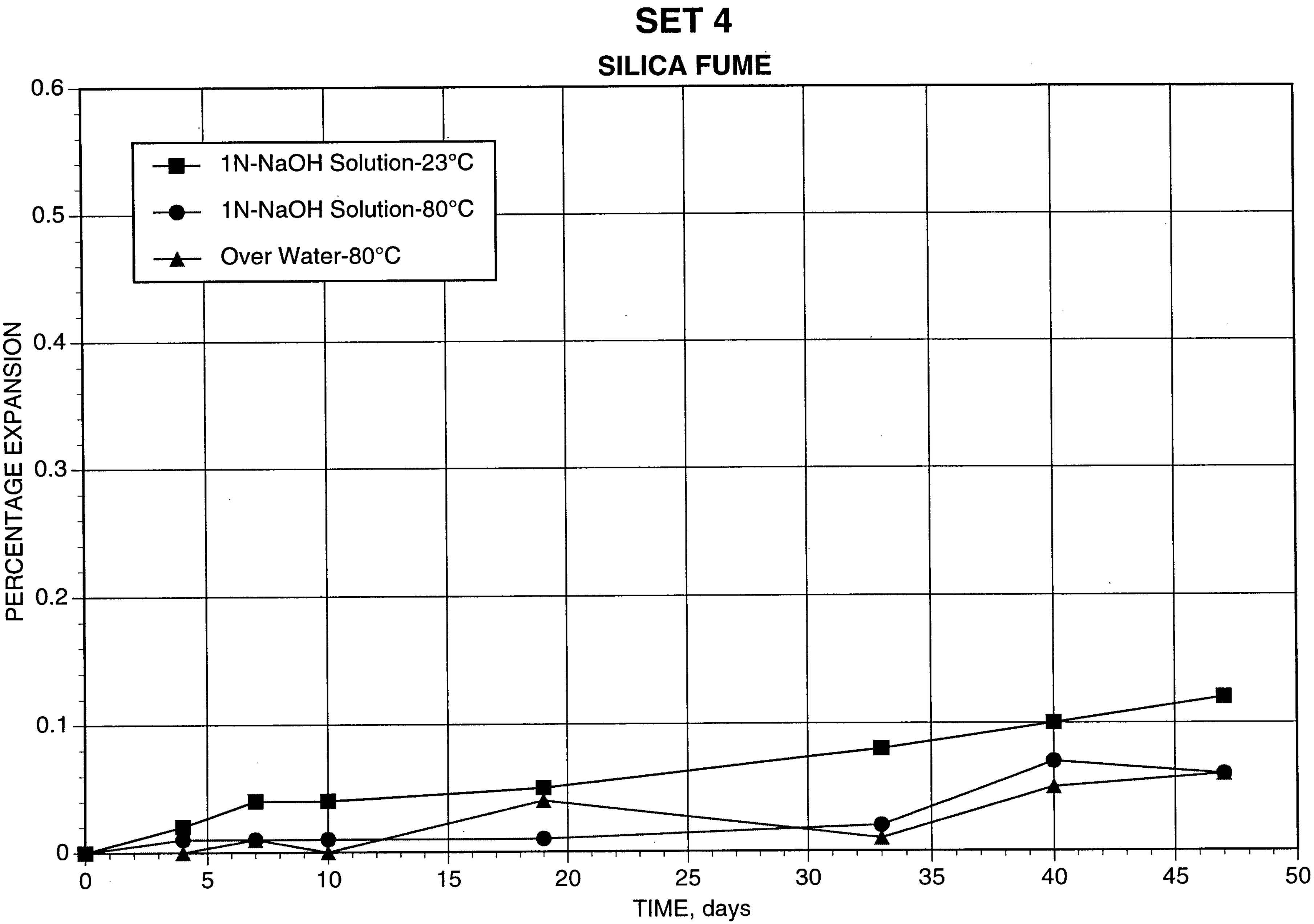


FIGURE 4.4 : EXPANSION VS TIME

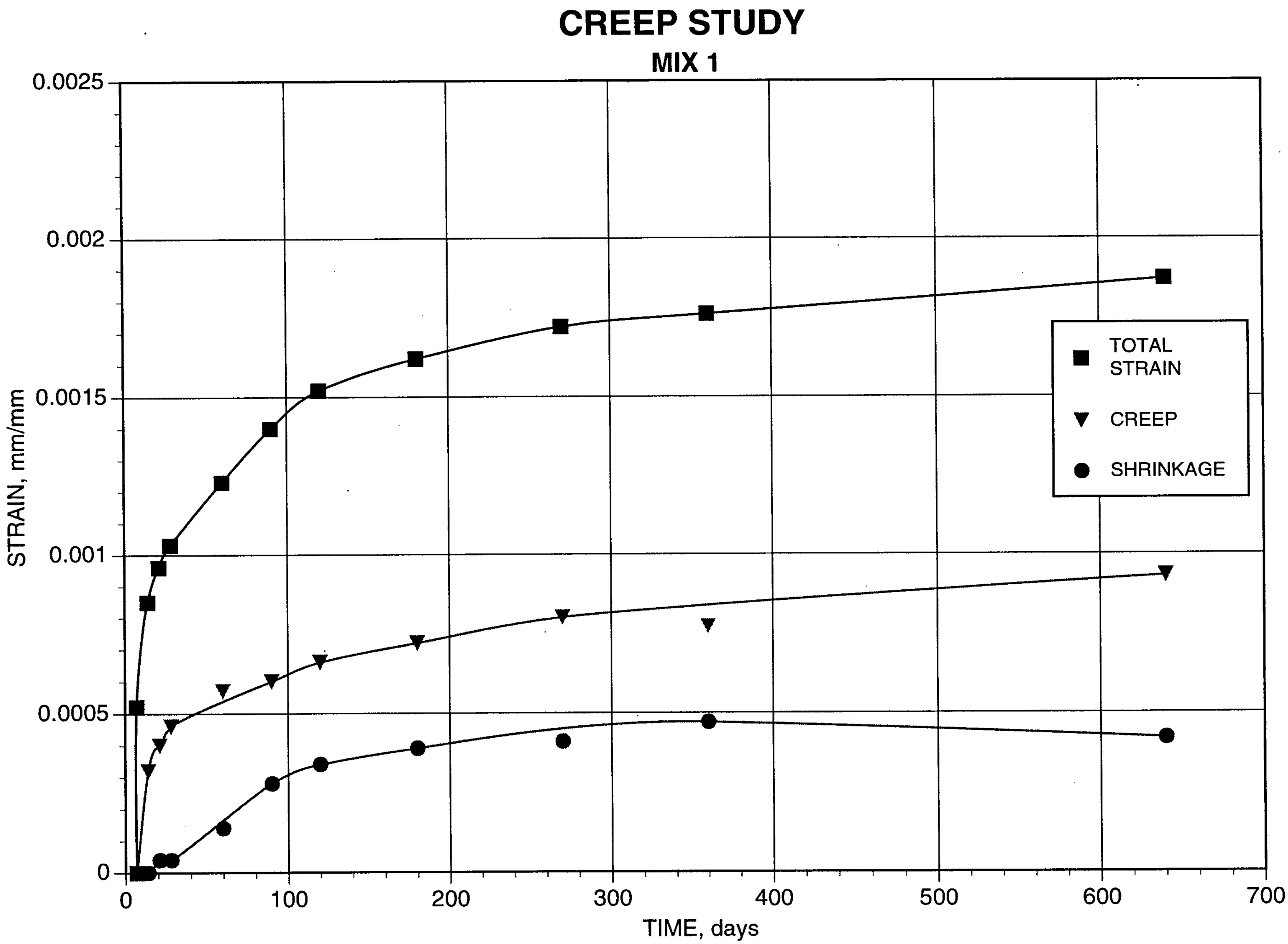


FIGURE 5.1 : STRAIN-TIME CURVE

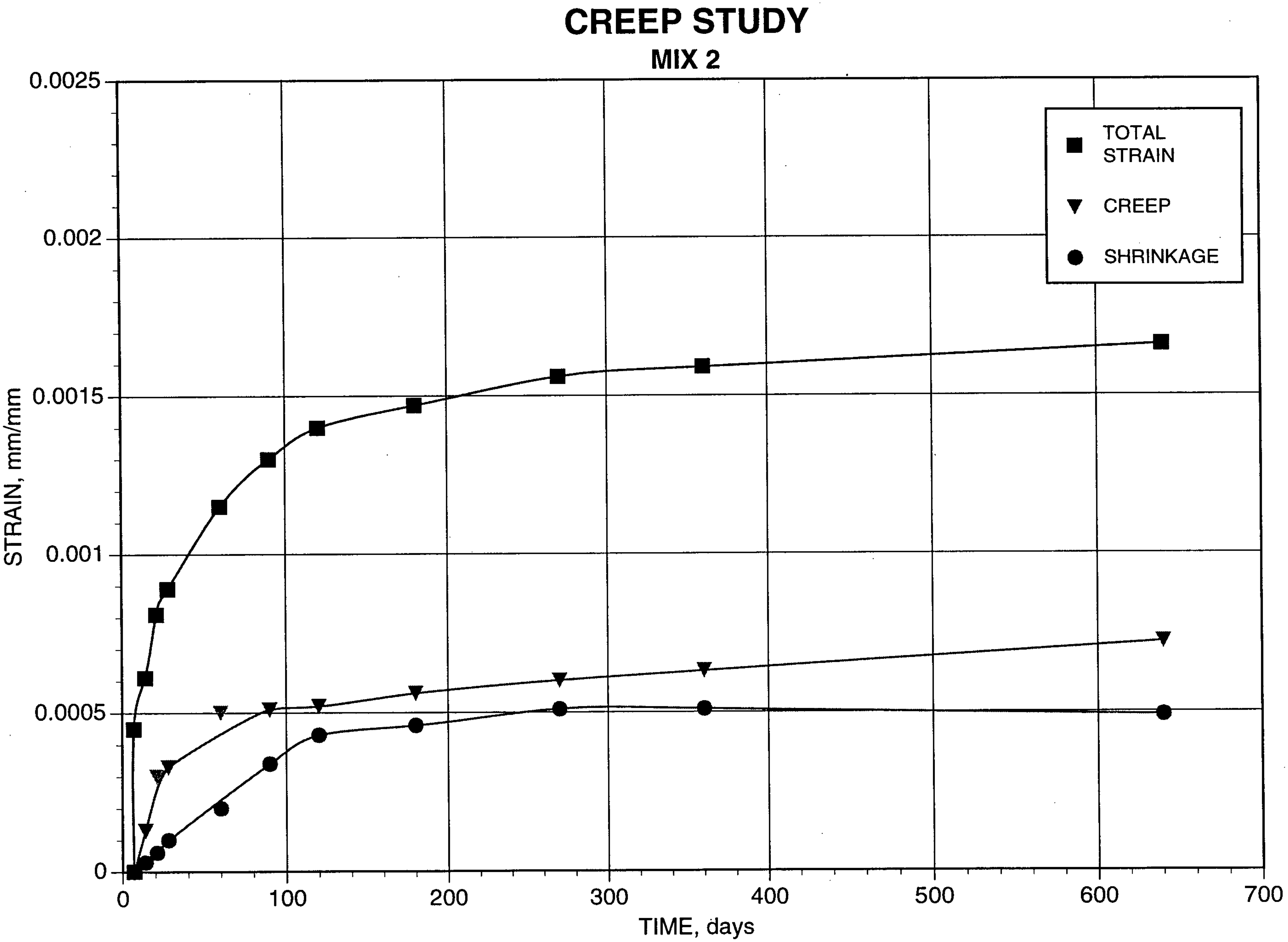


FIGURE 5.2 : STRAIN-TIME CURVE

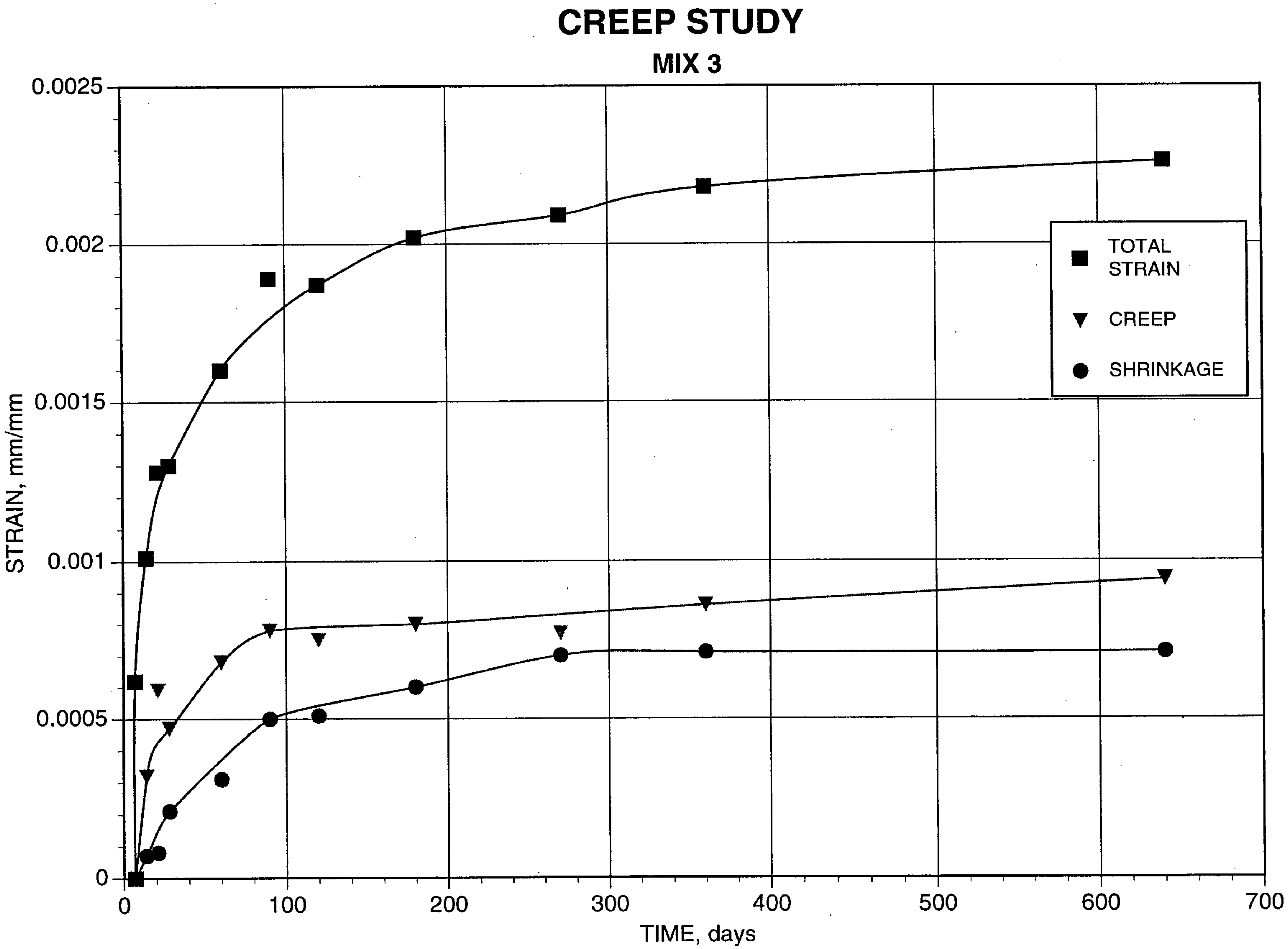


FIGURE 5.3 : STRAIN-TIME CURVE

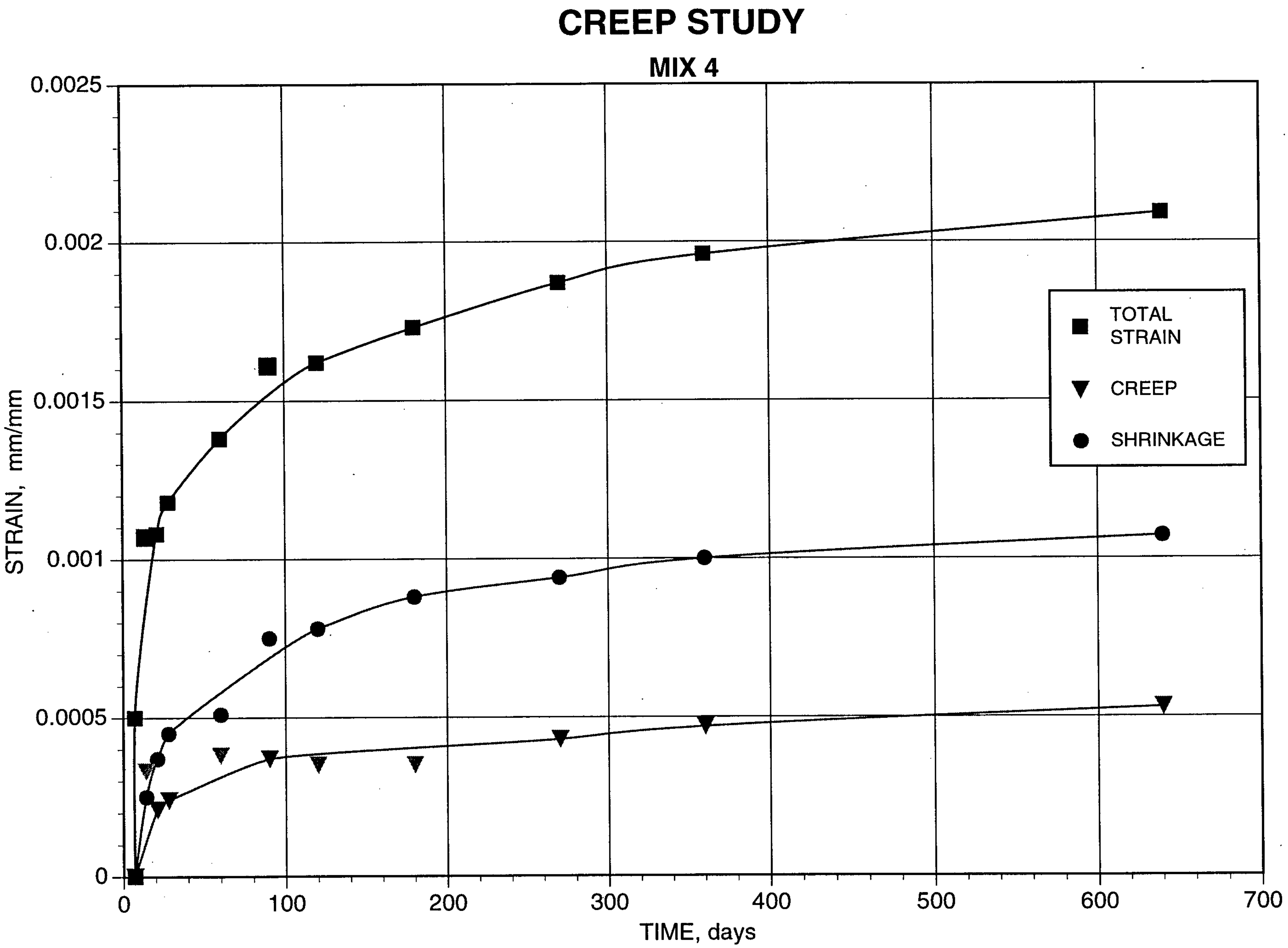


FIGURE 5.4 : STRAIN-TIME CURVE

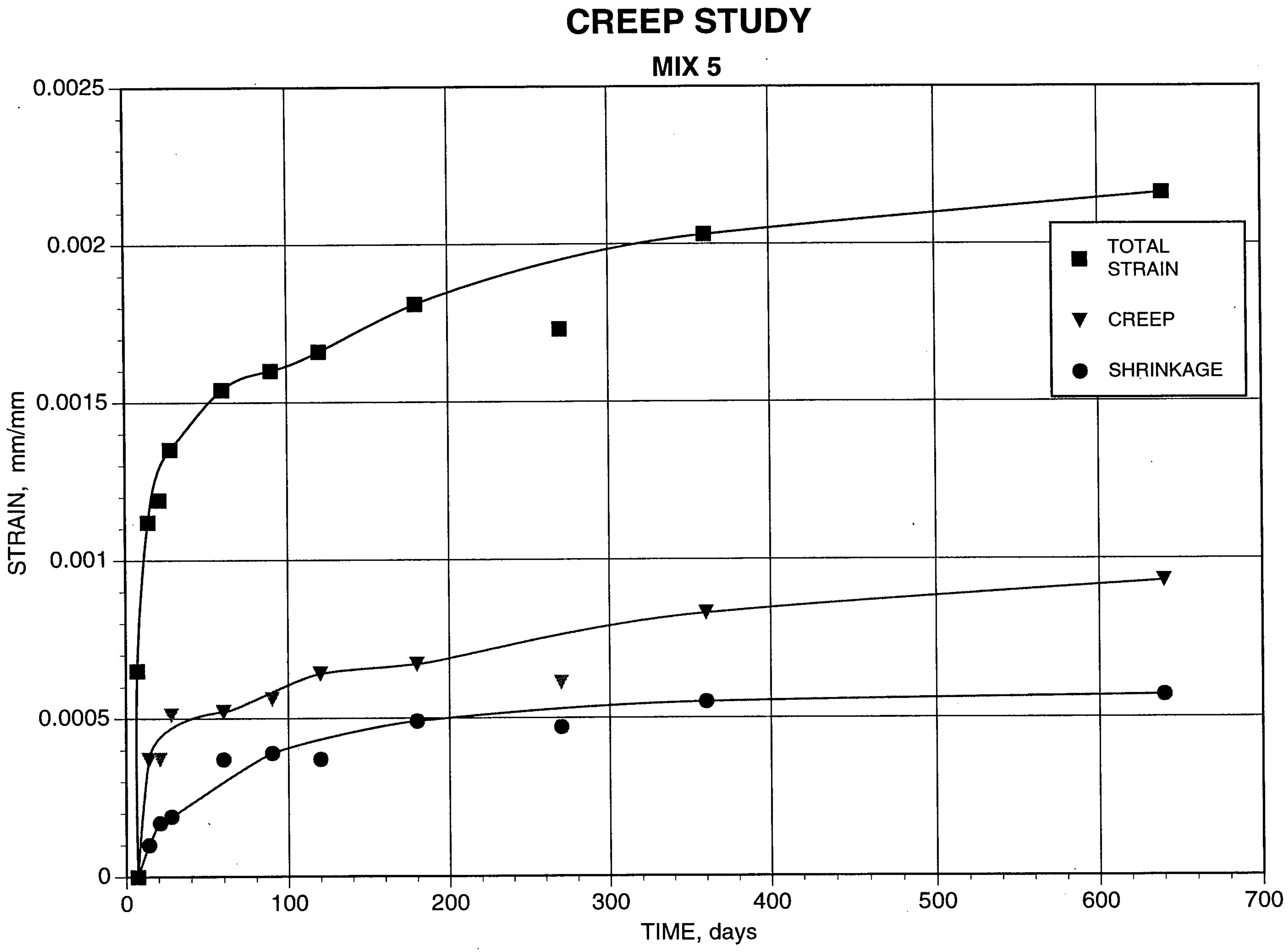


FIGURE 5.5 : STRAIN-TIME CURVE

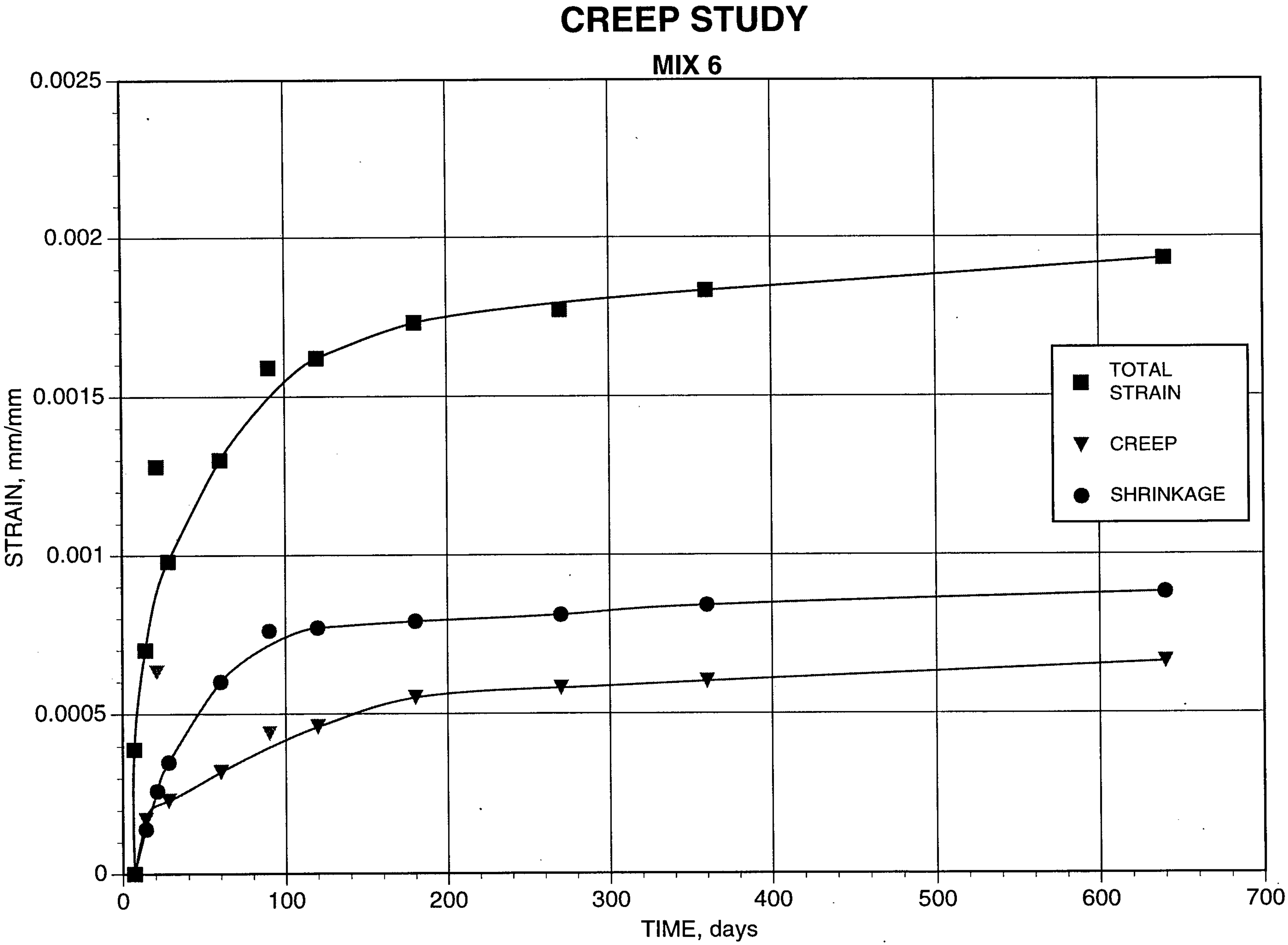


FIGURE 5.6 : STRAIN-TIME CURVE

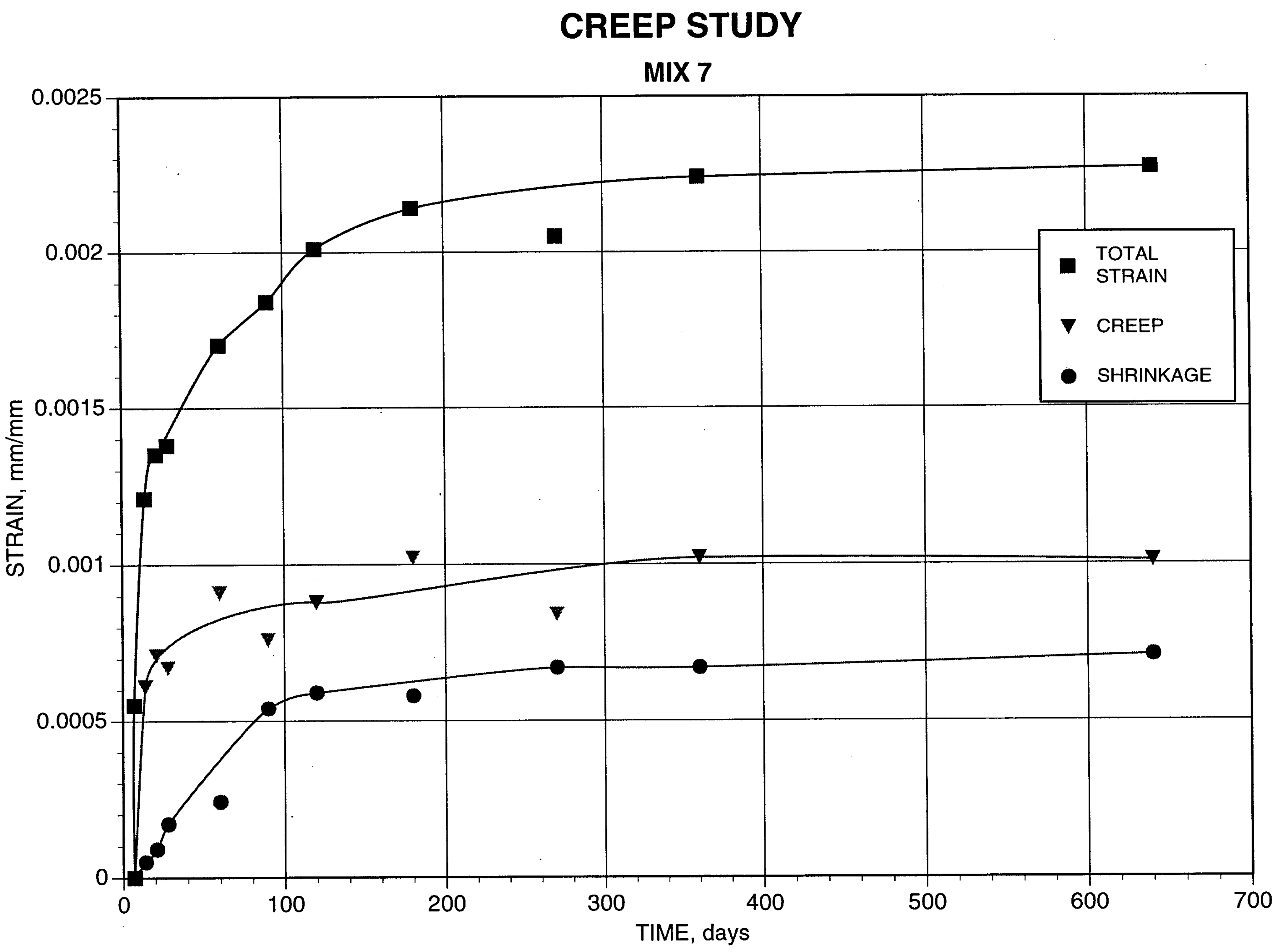


FIGURE 5.7 : STRAIN-TIME CURVE

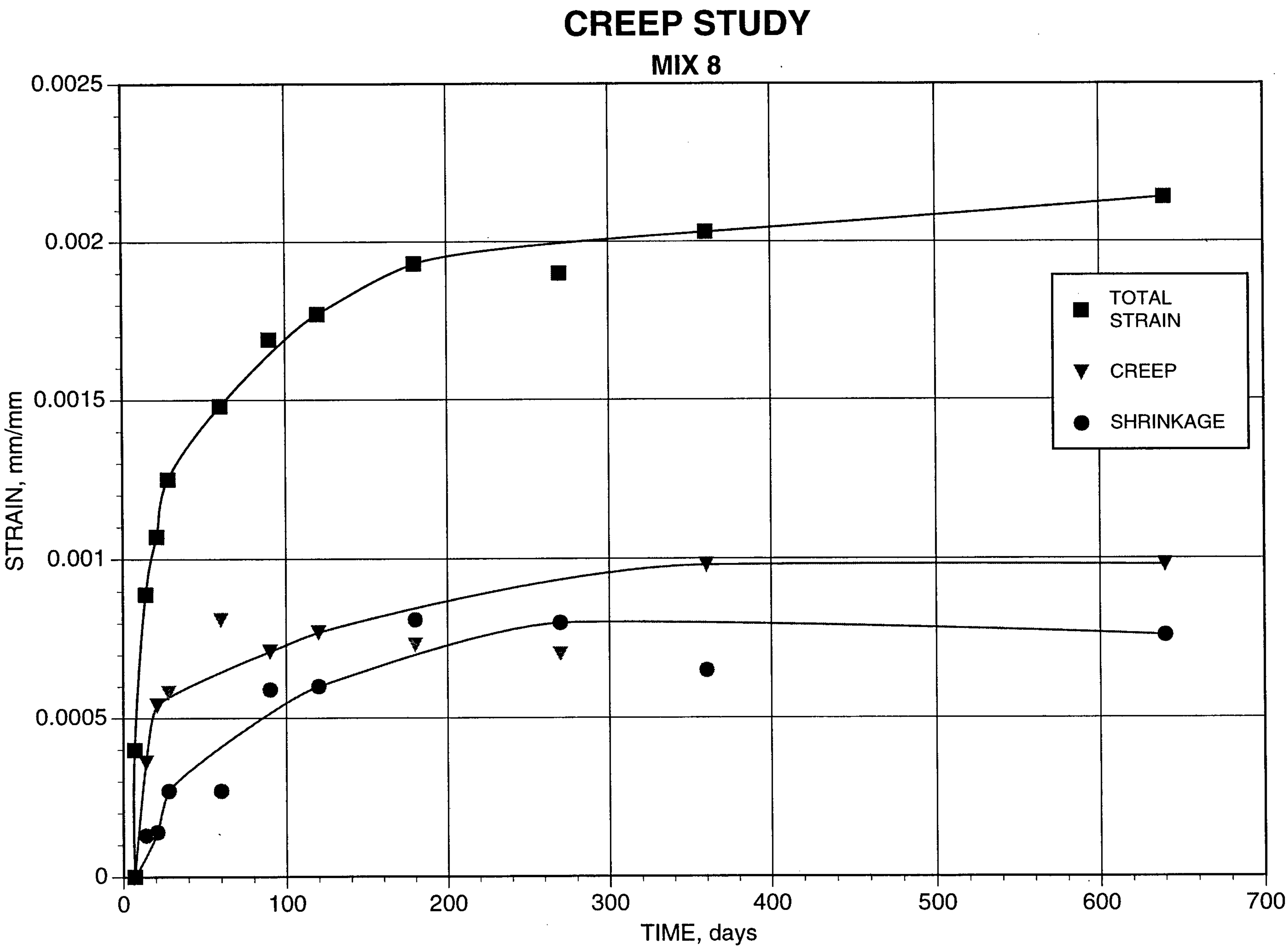


FIGURE 5.8 : STRAIN-TIME CURVE

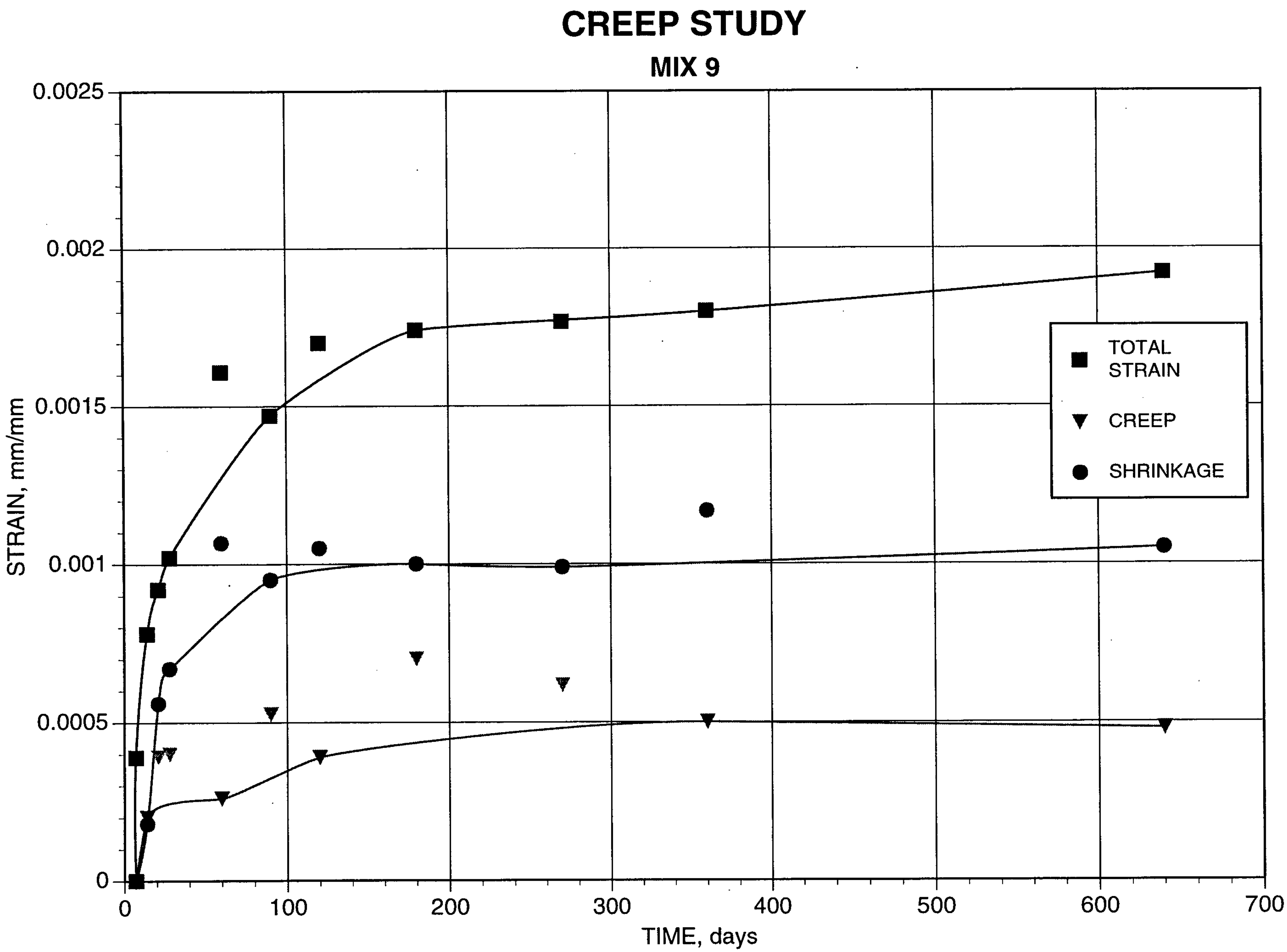
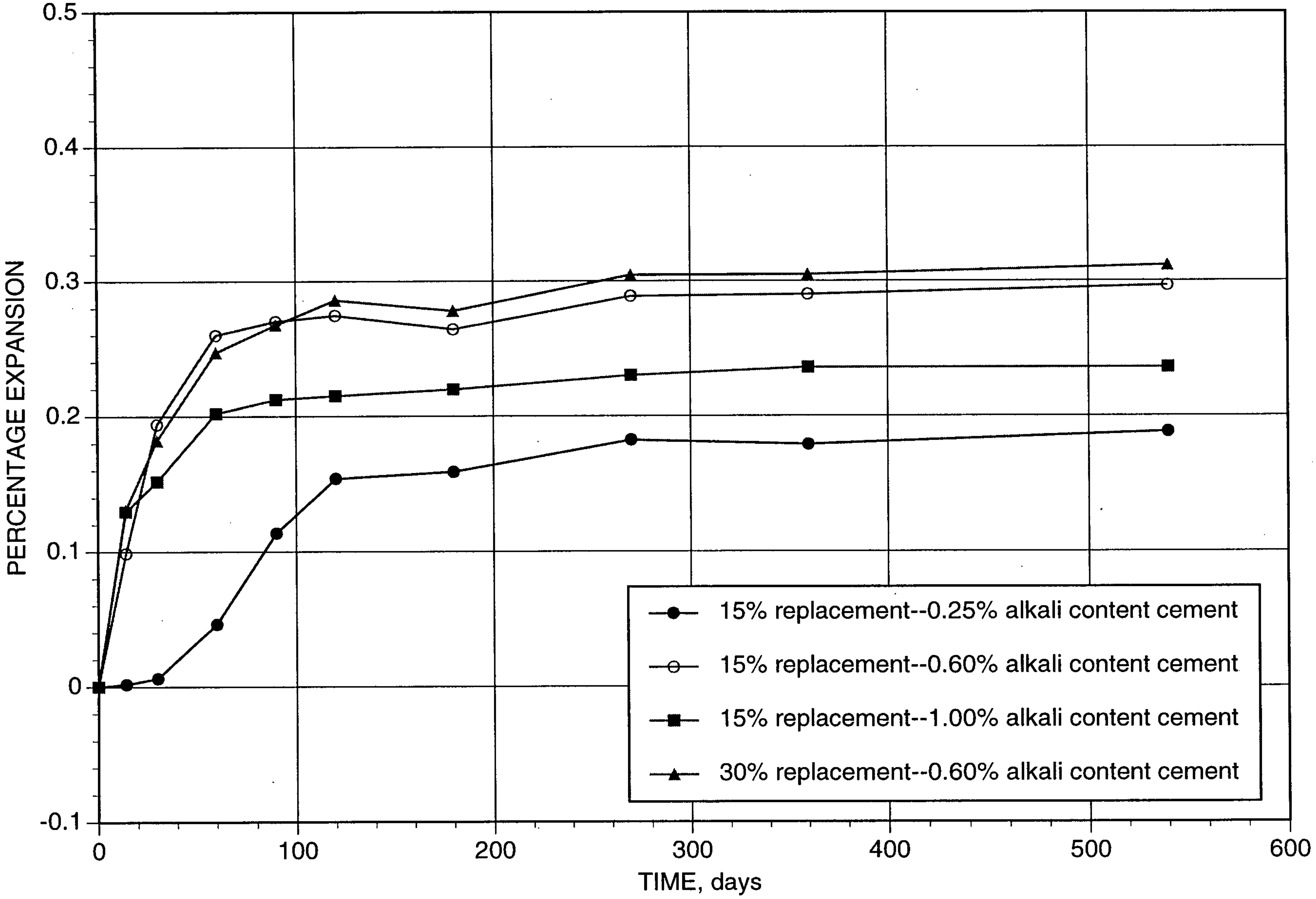


FIGURE 5.9 : STRAIN-TIME CURVE



SET 2

4TH STREET ROCK FLYASH -- Class C

FIGURE 2.4 : EXPANSION VS. TIME