STRENGTH DEGRADATION OF GFRP BARS

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic and State University
in a parital fulfillment of the requirements for the degree of

MASTER OF SCIENCE
in
Civil Engineering

APPROVED:

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September 2002
Blacksburg, Virginia

Keywords: Glass Fiber Reinforced Polymer (GFRP) bars, Durability, Arrhenius relationship, Prediction

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(ABSTRACT)

The primary objective of this research was to determine if the strength degradation of Glass Fiber Reinforced Polymer (GFRP) bars with using the Arrhenius type relationship as a means of projecting life. The work done includes a thorough literature review, experiments and development of strength prediction models. The experimental work involves exposure of GFRP bars incased in cement mortar to lime-water solution at 30, 45 and 57^{o}C. Overall 100 specimens were included in the experimental program. The tensile strength and modulus of elasticity retention after 180 days of exposure at 57°C was 57% and 82% respectively.

The secondary objective was to determine the moisture absorption property of GFRP bars. The moisture absorption data available is till 80 days from the immersion of the specimens in the tank.

The collected data was used in the development of strength retention models. Two strength prediction models, Time Shift Method and Fickian Model for moisture absorption are formulated. Using the Fickian Model, strength is predicted for GFRP bars, if used in bridge decks in Roanoke, Virgina. The strength loss predicted was 45% after 50 years of exposure in real life environment. A linear relationship was observed when the moisture content and strength retention were plotted. The study estimates a strength loss higher than the ACI-440H recommended environmental factor of 0.7 to calculate the design ultimate tensile strength.

Dedications

To

My Parents – *Sudhakar and Ujwala Bhise*

Grandmother – *Mandakini Bhise*

Sister *Linal* and her Husband *Mileend*

Nieces *Alisa* and *Karina*

Acknowledgements

I want to thank Dr. Carin L. Roberts-Wollmann and express my sincere gratitude for being my advisor and chairperson on my committee and also for her immense contributions to both my academic and research success. I would also like to thank Dr. John J. Lesko and Dr. Thomas E. Cousins for being on my committee and for their participation in my project. The other individuals whom I would like to thank are Steve Phifer, for his advice and to share with me the knowledge he has on this topic, Brett Farmer and Dennis Huffmann, for there help in the structures lab, Bob Simonds, for lending me hand during my tensile tests, Clark Brown, for getting the controllers ready, David Mokarem, for his help in the concrete mix room and all my other friends who have assisted me during my work.

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Chapter 1
INTRODUCTION

1.1 Background:

In recent times, consideration has been given to the option of replacing steel as the reinforcing bars in structures like bridge decks and parking structures. In such structures, steel reinforcement deteriorates due to its exposure to chloride. As a replacement to steel reinforcement, Fiber Reinforced Polymers (FRP) bars have gained popularity due to their non-corrosive and non-metallic properties. Of all the different types of FRP bars available Glass Fiber Reinforced Polymer (GFRP) bars are the most popular to be used in civil engineering applications, especially due to their low cost as compared to the other fibers.

GFRP bars are made up of continuous glass fibers, which are bound together with a resin and are manufactured using modified pultrusion process. They have high strength to weight ratio and are corrosion resistant. However, they are prone to degradation in certain environments and also are susceptible to alkali attack. So it is necessary to know the rate of degradation of GFRP bars and the mechanism driving the degradation. As the expected service life of the FRP reinforcement is several decades it is impractical to expose these bars to real working conditions. So to predict the strength retention properties of these bars under working conditions, the bars are subjected to aggressive accelerated ageing conditions for shorter time periods.

Extensive research has been done on durability of GFRP bars with different chemical compositions and varying environmental conditions. Results varied from severe degradation for shorter exposure to minimal degradation for a longer exposure. However, the cause for concern is that these bars will be exposed to concrete in civil engineering applications, that possesses pH as high as 13.5 and glass fibers are prone to degrade at high pH (Hartman et al.). In structures like bridge decks, the bars will be embedded in concrete, hence additional data on the rate of degradation in such an environment is required. This study deals with the strength degradation of GFRP bars when exposed to alkalinity, moisture and high temperature and also the moisture absorption property of the bars.

1.2 Objectives:

1.2.1 Primary Goal:

The primary goal of this study is to examine the strength degradation of GFRP bars at high temperature and alkalinity and determine if the Arrhenius relationship can be used as a means of projecting life. In this study No.3 GFRP bars provided by Hughes Brothers were exposed to high temperature and alkalinity. The bars are made up of E-Glass fibers bound together by vinyl ester resin and are slightly sand coated.

1.2.2 Secondary Goals:

The secondary goal of this study is to examine the moisture absorption properties of the GFRP bars. For this study the bars were exposed to saturated $Ca(OH)_2$ solution maintained at 30,45 and 57°C. Specimens were removed and weighed on the prescribed days and then weighed again after oven drying them.

One aim of the project is also to develop methods to predict the service life of GFRP bars when used in concrete bridge decks. Two methods were used to determine the strength prediction of GFRP bars, one Time Shift Method and the other using a Fickian Model for moisture absorption. Both methods assume that there exists an Arrhenius relationship between rate of reaction and temperature. Finally, the strength retention is predicted for GFRP bars after 50 years of exposure, if used in bridge decks in Roanoke, Virginia.

Chapter 2
LITERATURE REVIEW

2.1 General:

A major hindrance in using GFRP reinforcing bars in civil engineering applications is the susceptibility of their behavior to weathering conditions. The research done to date has shown that GFRP is prone to degradation when exposed to different environmental conditions. The scope of this literature review encompasses a brief overview of fibers and matrices used in FRP reinforcing bars and the various environmental conditions that cause the degradation.

2.2 Materials:

Fiber Reinforced Polymers are made up of fibers and matrix, where the fibers provide strength and stiffness while matrix holds the fibers together, protects them from abrasion and corrosion and also transfers stresses to the fibers.

2.2.1 Fibers:

Fiber Reinforced Polymer reinforcing bars are typically made up of one of three types of fibers –glass, carbon and aramid. Glass fibers are the most popular of all the fibers used for reinforcement due to their relatively lower costs. Table 2.1 presents some mechanical properties of the reinforcing bars made up of different fibers as compared to steel

Table 2.1 –Mechanical properties [13,14]

	Tensile Strength		Modulus Of Elasticity		Density	
	MPa	ksi	GPa	10^3 ksi	g/cc	lbs/in^3
GFRP	483-1035	70-150	35-45	5.1-6.5	2.58	161
CFRP *	600-2900	87-420	120-300	17.4- 43.5	1.8	112.3
AFRP **	1000-1400	145-203	60-87	8.7-12.6	1.45	90.5
Steel	483-690	70-100	200	29	7.8	486.7

* CFRP is Carbon Fiber Reinforced Polymers.
** AFRP is Aramid Fiber Reinforced Polymers.

2.2.1.1 Carbon Fibers:

Among all the fibers carbon fibers have the highest strength and stiffness. They are quite popular in the aerospace industry. But the high cost creates a major hindrance to their use in civil engineering applications.

2.2.1.2 Aramid Fibers:

Aramid Fibers are aromatic polyamide called poly paraphenylene terephthalamide (PPD-T). They have high strength and are rigid due to their chain alignment but fracture in a ductile manner.

2.2.1.3 Glass Fibers:

Glass fibers are of different types such as E-Glass, S-2 Glass, AR- Glass, A-Glass, C-Glass, D-glass, R-Glass and ECR-Glass depending on their properties and chemical composition [13]. Of the different types of glass fibers, E-Glass is mostly used for reinforcement due to its high strength and electrical resistivity. Glass fibers have high strength and temperature resistance, but it is the low cost that makes GFRP the most popular FRP reinforcement in civil engineering applications. However, glass fibers corrode in acidic as well as alkali environments and lose a significant percentage of their tensile strength when exposed to high temperature. Below is a brief review of work done by different researchers to study the strength degradation of different types of glass fibers when exposed to aggressive environment.

Hartman et al. (1994) observed that E-Glass fibers lose more strength than S-2 Glass fibers when exposed at 96°C to acidic environment (H_2SO_4 and HCl), alkali environment (Na_2SO_4) and water for a period of 24hrs. and 168 hrs.

Tannous and Saadatmanesh (1999) did a study on the durability of AR glass FRP bars when exposed to aggressive environment. They observed that for No.3 bars (vinyl ester matrix) when exposed to Ca $(OH)_2$ with a pH of 12 and maintained at 25°C and 60°C, experienced strength loss of 13% and 23% respectively.

According to Fuji et al. (1993) there was a reduction of tensile strength to about 28% when E-Glass fibers were exposed to 5% HNO_3 after 100 hrs.

2.2.2 Matrix:

Polymeric matrices are of two types, thermosetting resins and thermoplastic resins. Vinyl ester, polyester and epoxy are all thermosetting resins while polysulfone, polycarbonate and polyphenylene oxide are all thermoplastic resins. The type of matrix used and also its toughness play an important role in the characteristics such as matrix cracking and debonding of the fiber/matrix interface as shown by Fuji et al.(1993)

2.2.2.1Thermoplastic Resins:

The different types of resins mentioned above for thermoplastic resins are more prevalent in the aerospace industry. They have higher viscosity than thermosetting resins and they may be crystalline in nature. These resins are tough, less brittle and are used mostly with discontinuous fibers.

2.2.2.2 Thermosetting resins:

Among all the thermosetting resins mentioned above vinyl ester and polyester are used more in construction industry. Vinyl ester though costlier than polyester resin, has a higher tensile strength. Thermosetting resins are semi-permeable thus allowing water to pass through it but not the alkali ions (Dejke, 2001). However, alkali penetration was detected in the test results on GFRP done by Dejke (2001) after about 6 months of exposure at 60°C in alkaline solution. Below is a brief review of the study performed on the strength properties of vinyl ester and polyester resin after accelerated ageing.

Chin et al. (1997) observed that when vinyl ester and polyester were exposed to water, salt water and cement pore water at temperatures 23°C, 60°C and 90°C there was not much change in the glass transition temperature (Tg) but there was considerable change in their tensile strengths. The change in tensile strength of polyester resin was so much that they could not be tested after 10 weeks at 90°C as they were degraded [16].

Bakis et al. (1998) studied E-Glass fiber reinforced plastic composite reinforcement rods made with different proportions of resins-100% vinyl ester, 50% vinyl ester and 50% iso-polyester, 20% vinyl ester and 80% iso-polyester following accelerated ageing. They observed that rods made up of 100%vinyl ester had the smallest reduction in modulus of elasticity and the least degradation in tensile strength as compared to the rods made with the other proportions [17].

Gangarao and Vijay (1997) did a study on accelerated aging of GFRP bars with five different types of resins and under aging conditions like high pH, sustained stress as well as humidity and temperature variations. It was observed that the bars consisting of vinyl ester resin showed the least degradation of tensile strength.

2.3 Manufacturing Process:

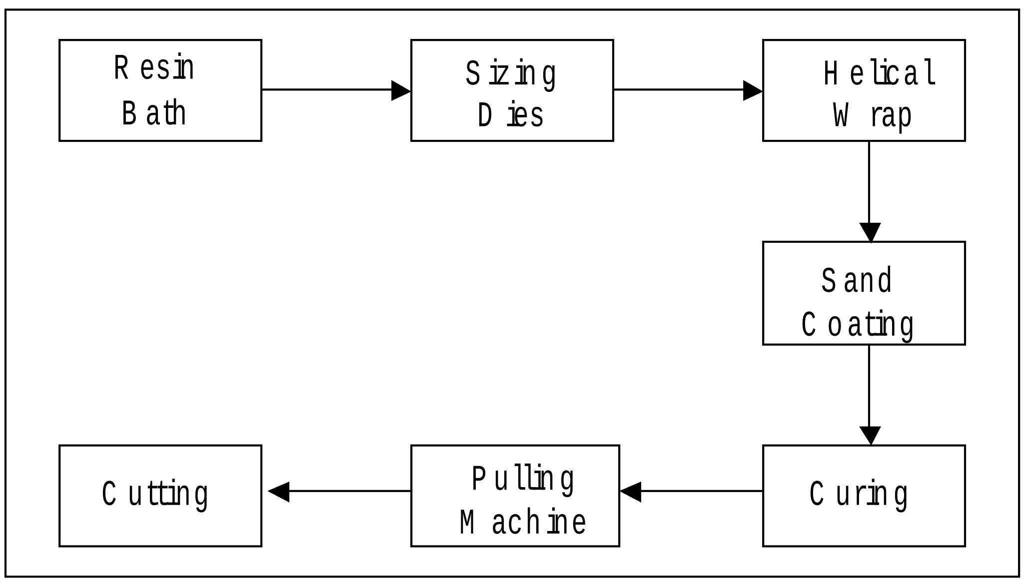


Figure 2.1- Manufacturing process for GFRP reinforcing bars [9]

GFRP Reinforcing bars are manufactured by modified pultrusion process. The molding process used for the fabrication of fibers and thermosetting resins is called a pultrusion process and is used in the fabrication of composites having constant cross-sectional profile. The manufacturing process is as shown in figure 2.3 above, initially the glass fibers are passed through a resin bath containing thermosetting resin, where the fibers are thoroughly coated with the resin. After impregnating the fibers with resins, they are passed through a heated dye where they are given desired shape, after which they are helically wrapped and later sand-coated. The next step is to pass the composite through a curing tunnel, which is maintained at high temperature. After which they are passed through a pulling machine and later cut to desired sizes.

The higher the glass content the better is the end product. According to Gremel (1999) the maximum achievable and ideal ratio is about 75%of glass content and 25% resin.

2.4 Applications:

GFRP bars should be considered in the following cases:

- In a concrete member where the reinforcement is exposed to chloride ion or chemical solution
- In a concrete member exposed to electromagnetic waves
- In secondary load bearing member.

2.5 Environmental factors affecting GFRP products:

The use of any material in structural applications needs a detailed study of the effect of environmental conditions on its properties. The environmental factors that cause the degradation of GFRP reinforcing bars and sheets are temperature, moisture, alkalinity, freeze-thaw, ultraviolet rays and others. Considering the environmental effect on the degradation of FRP, ACI 440 has recommended environmental reduction factors for different fibers depending on their exposure condition. The environmental factors for GFRP are 0.7-0.8 as per their exposure conditions. In this study, the evaluation of GFRP will be done only for conditions of temperature, moisture and alkalinity.

2.5.1 Moisture and Temperature:

A detailed study has been done on the effect of moisture on FRP composites in construction industry. Especially the combination of moisture and temperature is used to accelerate the rate of diffusion and also to see their combined effect on these composites.

According to ACI 440-3.1.3, the use of FRP reinforcement is not recommended for use in structures that are exposed to high temperature, as the modulus is reduced after being exposed to temperature in excess of the glass transition temperature (Tg). In general the value of glass transition temperature ranges from 200 to 300°F. As fibers provide the strength and stiffness in FRP reinforcement, a structural collapse can occur only after the temperature reached is in excess of that the fibers can handle, which for glass is 1800°F.

Shen and Springer (1981) performed tensile tests on Thornel 300/ Fiberite 1034 graphite epoxy composites using 0 °, 45 and 90° lay-ups with temperatures ranging from 200 K to 450 K. They concluded that regardless of moisture content for 0°and 45° there is negligible effect on tensile strength for temperature ranging from 200 K to 380 K while there is less than 20% decrease in tensile strength for 380 K to 450 K. For 90° there is significant decrease in strength as high as 60-90% and it also depends on moisture content for temperature ranging from 200 K to 450 K.

Litherland et al. (1981) did tension tests on Cem-FIL A.R glass fiber in Portland cement in hot water at temperatures ranging from 20°C to 80°C. They concluded that there is just one chemical reaction controlling the rate of degradation of the fibers over that temperature and developed a method to predict long-term behavior of the composite using the accelerated testing. This methodology was validated by Proctor (1985) on the basis of extensive laboratory testing in correlation with the observations of these glass fiber reinforced cements (GRC) behavior in different climatic conditions over several years.

Tannous et al. (1998) examined strength loss on 10mm (3/8 in.) and 19.5mm (3/4 in.) diameter GFRP bars in water at room temperature. Their goal was to determine changes in the moisture content and mechanical properties of GFRP bars when fully submerged in chemical solution that resembles the conditions in the field. They observed that there was more loss in strength for bars having polyester as resin than vinyl ester.

Pantuso et al. (1998) conducted a study on GFRP bars where polyester was used as resin. The bars used in the study were of three different diameters 12,16 and

20mm. The bars were exposed to water cyclically, one full day of immersion and the other day air dried at a temperature of 23.2°C. After 2 months of this type of exposure, they observed that there was small reduction in tensile strength and modulus of elasticity in the order of 1 to7% and 1 to 10% respectively.

Phifer et al. (2002) are studying the moisture absorption and strength reduction curves of pultruded E-glass/ vinyl ester laminates as a function of water immersion temperature ranging from room temperature to 80°C and time. The authors showed that the moisture diffusion process and strength reduction with respect to time require a double exponential solution, thus indicating that there are two mechanisms driving the degradation. The mechanisms may be fiber degradation and resin or fiber interface degradation. And also an Arrhenius model gives a good representation of diffusion and strength reduction with respect to temperature. It was also observed that the activation energies associated with strength loss for various vinyl ester and polyester systems were in the range of 8 to 16kcal/mol.

2.5.3 Alkalinity:

Micelli and Nanni (2001) did a study on the effects of alkaline environment and other factors on GFRP rods. The rods were made up of E glass fibers and polyester resin and exposed to a distilled water solution containing 0.16% $Ca(OH)_2$ + 1% Na (OH) + 1.4% KOH, having a pH of 12.6 and maintained at a temperature of 60°C (140°F). The rods were tested after 21days and 42 days, the strength retention observed was 70% and 59% respectively. Also tests were done on specimens exposed to combined environmental conditioning: freeze thaw, high temperature, high relative humidity and UV indirect exposure in a controlled chamber, the strength retention observed for ¼ in. sand coated GFRP rods was 93%.

In a research program conducted by Eurocrete, Sheard et al. performed durability investigations of GFRP bars subjected to factors like pH of 10 to13.5, solution containing K, Na and Ca, temperature from 21°C to 80°C and stress levels from 5%-75% of ultimate tensile stress. It was observed that for 5% stress level, the maximum strength reduction was 29%.

A detailed study was done on the durability of GFRP bars in concrete by Valter Dejke (2001) a Swedish researcher, which also included developments of service life prediction models. The experimental program included approximately 1400 specimens. Four different types of GFRP bars were exposed to concrete, alkaline solution and water maintained at 20,40,60 and 80°C, but the bars were not subjected to any mechanical stresses. No significant change was observed in the modulus of elasticity. After 1.5 years of exposure the tensile strength retention was 41% for bars supplied by FIBERBAR (E-glass/Vinyl ester), 57% for the bars supplied by Hughes Bros. (E-glass/Vinyl ester), 45% for AR-glass/vinyl ester and 53% for AR-glass/polyester.

Tannous et al. (1998) as mentioned earlier also examined strength loss of GFRP bars in alkaline solution with pH of 12 and in acidic solution and observed that the loss in strength in alkaline solution was more than when GFRP bars were exposed to acidic solution at room temperature. In the case of 10mm diameter bars for 25°C and 60°C, the measured loss in strength was 25 and 28.6 % for bars coated with polyester resin whereas 13 and 20.3 % for vinyl ester resin respectively.

Alsayed et al. (1998) studied the strength degradation of two types of GFRP bars, coated with cement paste (water/cement ratio 0.5) and uncoated specimens. The chemical compositions of the two types of GFRP bars is as given in Table 2.2.

Table 2.2 – Chemical composition of GFRP bars used by Alsayed et al. (1998)

GFRP type 1		GFRP type 2	
Materials	Composition (%)	Materials	Composition (%)
E-Glass	70	E-Glass	76.14
Urethane Modified Vinyl Ester	15	Resin	22.18
Unsaturated polyester	10	Filler	1.26
Corrosion Inhibitor	1.5	Catalysts	0.37
Ceramic Reinforcement	3.5	U.V.	0.05

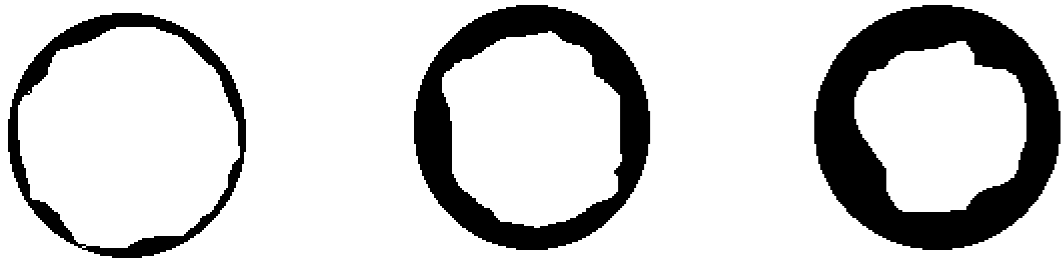
The bars were exposed to drinking water, 5gm/lit. NaOH and 20gm/lit. NaOH solution. From the data available from tension tests on specimens after 1 month and 4 months, they concluded that the strength deterioration of GFRP bars in alkalinity and temperature depends on the chemical composition and manufacturing process of the bars.

Pantuso et al. (1998) performed tension tests on the same bars (explained in 2.5.2) but in alkaline environment. The bars were embedded in concrete and were subjected to same process of immersion in water as explained in 2.5.2 at 23.2°C temperatures. After 60 days of exposure, the strength loss observed was 6 to 21% and loss in modulus of elasticity of 3 to 11%.

Altizer at al. (1991) conducted accelerated tests on No. 4 and No. 6 bars (E-glass fiber) with fiber volume fraction of approximately 45%, manufactured with different thermoset polymer resins to evaluate environmental effects on them. Of the five resins, only two were vinyl ester resins of which one was isocyanurate vinyl ester and the other was urethane vinyl ester. The bars were placed in an unstressed condition in an alkaline solution of pH~13. After 203 days of immersion, the isocyanurate vinyl ester resin bars suffered strength and stiffness losses in a range of 25.4 to 64.3% and 0.4 to 9.3% respectively while the loss in strength and stiffness for urethane vinyl ester resin was in the range of 8.4 to 16.9% and 5.3 to 7.7% respectively. They also did alkaline stressed tests on No. 4 bars with resulting sustained stress approximately 25 to30% of ultimate stress after losses. The loss in strength and stiffness observed for isocyanurate vinyl ester resin bars was 37.1 to 76.5% and 6.1 to 31.6% respectively while there was negligible, about 0.8% loss in strength and 15.2% loss in stiffness after 203 days.

To study the penetration of alkali in FRP rods, Katsuki and Uomoto (1995) performed accelerated tests on AFRP, GFRP and CFRP rods with vinyl ester as resin. GFRP rods were exposed to 1.0 mol/liter NaOH solution at 40°C while the AFRP and CFRP rods to 2.0 mol/liter NaOH solution. After 120 days of exposure the strength loss for GFRP and AFRP rods was 72% and 5% respectively, while there was strength gain of 1% for CFRP rods. They also checked the alkali penetration on sections of FRP rods using Electron Prove Microscope Analyzer (EPMA), and the alkali penetration could be clearly seen in GFRP rods.

Figure 2.1 shows a diagram showing how the section of GFRP will be seen when observed through an EPMA and a rough estimate of the alkali penetration in a GFRP rod after 7, 30 and 120 days.



7 days 30 days 120 days

Figure 2.2: Rough estimate of alkali penetration in GFRP rods
[After Katsuki and Uomoto (1995)]

Manufacturers in Japan have developed new type of hybrid rebar, which is a combination of GFRP and AFRP. This combination was considered as AFRP have better alkali resistant while GFRP are the cheapest among the different FRP bars available. This hybrid bar known as AGFRP contains 23% Aramid fibers and 42% glass fibers. Where the glass fiber is the main reinforcement while aramid fibers are used to protect the glass fibers from alkali attack. Vinyl-ester is used as the matrix. Uomoto and Nishimura (1997) did a study on durability tests on GFRP, AFRP and AGFRP bars. The bars were exposed to 1.0 mol/liter NaOH solution at 40°C temperature. It was observed that even after 120 days of exposure negligible strength reduction was observed for AFRP and AGFRP bars, while for GFRP bars there was as high as 70% strength reduction.

Coomarasamy and Ip (1998) investigated the long tem durability of GFRP bars manufactured by five different manufacturers, but having the same nominal diameter of ½ in. Results discussed in this literature review are only for two manufacturers, as the remaining data was not reported .The specimens were exposed to a solution prepared by mixing sodium hydroxide, potassium hydroxide and calcium hydroxide with a pH of 13.5 maintained at 60°C. After 17 weeks of exposure for bars with vinyl ester resin, specimens from one of the manufacturers showed 17% strength loss while the ones from the other manufacturer showed 26 % loss in strength. The specimens with polyester resin showed substantial loss in strength under the same conditions. The authors also studied the effect of alkaline treatment on tensile properties of pretensioned GFRP specimens. The specimens were pretensioned by applying load of 15% of the failure load using a specially designed steel frame. After 7 weeks of exposure to an alkaline solution of pH 13.5 at 60°C, the strength loss observed was around 46%.

Devalapura et al. of Owens Corning performed durability tests on pultruded GFRP rods. The specimens were exposed to cement extract solution having pH 11 and maintained at 60°C. After 90 days of exposure, the specimens were cooled at room temperature for 48 hrs, towel dried, weighed and individually stored at room temperature in airtight bags in preparation for stress rupture testing. The strength loss after 90 days was 14% for E glass/Polyester resin rods.

Sen et al. performed an experimental study on durability of E-glass/ vinyl ester bars. The bars were exposed to simulated concrete pore solution with a pH ranging from 13.35 to 13.5 for periods of 1,3,6 and 9 months under unstressed and stressed conditions. They observed that specimens under unstressed conditions lost 63% of their strength while the specimen stressed to 10% of their ultimate short-term tensile strength lost 70% of their strength. The specimens exposed to more than 10% of ultimate strength failed by 180 days.

2.6 Moisture Absorption property of GFRP bars:

The test method used in this research to check the moisture absorption property was as per given in ASTM D5229 / D5229M.

Loos and Springer did a study on the moisture absorption property of E–glass/ polyester composite. They concluded that in a range of 23°C to 65°C the maximum moisture content depends strongly on the type of the material and also the environment (type of liquid or air) it is exposed to. Under most conditions Fick's law is applicable in determining diffusivity and moisture content till the maximum moisture content is reached.

Zayed did a study on the moisture absorption of No. 3 E-glass-polyester bars immersed in a saturated $Ca(OH)_2$ solution maintained at 40°C. He observed that the initial weight gain in samples followed Fickian behavior whereas after long time exposure the behavior was non-Fickian.

Alsayed is studying the influence of temperature and alkalinity on the moisture absorption and strength degradation of GFRP bars. The readings available are only for 1 month and 4 months during which period the specimens were immersed in tanks containing drinking water, 5 gm/lit NaOH solution and 20 gm/lit NaOH solution maintained at 22°C to 40°C.Two types of GFRP bars were used during the study, whose chemical compositions are given in 2.5.2. It was observed that for both 22°C and 40°C, there was negligible reduction in weight for a period of 1 and 4 months in drinking water, while on an average there was 1% reduction in weight in 5 gm/lit. NaOH solution. For 20 gm/lit NaOH solution there was a reduction in weight of 1.2% and 1.8% for GFRP type 1 bars after 1 month and 4 months respectively whereas it was1.6 to 2.8% for GFRP type 2 bars. (GFRP types chemical composition as in 2.5.3)

Uomoto and Katsuki (1995) did a study on moisture diffusion of GFRP bars in 1.0 mol/lit. NaOH solution having a pH of 12.The diffusivity recorded was $7.78 \times 10^{-10} cm^2/sec$.

Tannous and Saadatmanesh (1998) did a study on the diffusivity and moisture content at saturation on four types of GFRP samples, which were immersed in seven different solutions. They concluded that under most conditions Ficks law is applicable to predict the changes in the mechanical properties and moisture content with time till the moisture content at saturation is reached. Rapid increase in the moisture content was observed beyond the saturation due to the excessive cracking and fracturing of the matrix materials and fiber damage.

Bank et al. (1998) conducted diffusion tests on E-Glass / Vinyl Ester rods to determine the moisture content of the material. Specimens of sizes 20mm (~ ¾ in.), 60mm (2-3/8 in.) and 100mm (~ 4 in.) were initially dried at 60°C for 28 days and then immersed in deionized water for 90 days at temperatures of 23, 60 and 80°C. The maximum moisture content was observed to be a function of temperature and specimen size, as the end of the specimens were not sealed.

Phifer et al. as mentioned earlier in 2.5.2 also performed a moisture absorption study on pultruded E-glass/ vinyl ester laminates exposed to 25, 35, 45, 55, 65 and 80°C. They observed that the Fickian Model for moisture/time curve showed a poor fit for lower temperature curves (25-55°C) but was adequate for higher temperature and over predicted at the knee in the moisture/time curve. They showed that Langmuirian model, which is a four-parameter diffusion model, gives a better fit even for the lower temperatures.

2.6 Summary:

Major aspects of this literature review are compiled in a tabular form. Table 2.3 gives a summary of the various researches done on GFRP bars under unstressed conditions while Table 2.4 summarizes for the stressed conditions.

An important observation during this literature review was that there exists no **standard test method**, so it is difficult to compare the results available from the work done by different researchers. But from the results it was observed that there is significant degradation of GFRP bars, especially more with polyester resin matrix than the vinyl ester resin matrix. The thin matrix film is not sufficient to prevent the degradation. It can be seen that accelerated aging has significant effect on strength and stiffness of the bars due to the severe environmental conditions. The results obtained from accelerated aging tests can only give indications of the long-term durability of the GFRP composites and not the actual solution

From the research done on strength prediction of GFRP bars, it is shown that the rate of strength degradation exhibits Arrhenius relationship. The study on the moisture absorption property of GFRP bars, showed that the initial weight gain in GFRP bars followed Fickian behavior and after long term exposure follows non-Fickian behavior.

Table 2.3: Summary of literature review for durability of GFRP (E-glass) bars under **unstressed** condition

Author	Resin	Solution	pH	Duration (days)	Temperature (°C)	Strength Reduction (%)
Tannous and Saadatmanesh (1998)	Vinyl Ester	Saturated Ca $(OH)_2$	12	180	25	13
					60	20
	Polyester				25	25
					60	29
Valter Dejke (2001)	Vinyl Ester	NaOH 2g/liter + KOH 19.6g/liter + Ca $(OH)_2$ 3.6g/liter + Water	13.7	100	20	10
					40	25
					60	35
					80	50
				200	20	18
					40	28
					60	45
					80	53
Alsayed and Alhozaimy (1998)	Urethane Modified Vinyl ester (15%) + Unsaturated Polyester (10%)	20 g/liter NaOH solution	No report	30	22	2
					40	15
				120	22	15
					40	30

Uomoto and Katsuki (1995)	Vinyl Ester	1.0 mol/liter NaOH	No report	120	40	60
Altizer et al. (1996)	Isocyanurate Vinyl Ester resin	97.4% Water + 0.2% Ca $(OH)_2$ + 1.4% KOH + 1.0% NaOH	≈13	203	≈23	25.4 to 64.3
	Urethane vinyl ester					8.4 to 16.9
Pantuso et al. (1998)	Polyester	Water	No report	120	23 ± 2°C	6 to21
Coomarasamy and Ip (1998)	Vinyl Ester	0.6M KOH+ 0.2M NaOH +saturated Ca $(OH)_2$	13.5	77	60	8
				175		32
Devalapura et al. (1998)	Polyester	Saturated cement extract	11	90	60	14
Micelli and Nanni (2001)	Polyester	0.16% Ca $(OH)_2$ + 1% Na(OH) + 1.4% KOH	12.6	21	60	30
				42		41

Table 2.4: Summary of literature review for durability of GFRP bars under **stressed** condition

Author	Resin	Load (% of failure load)	Solution	pH	Duration (days)	Temperature (°C)	Strength Reduction (%)
Sen et al.	Vinyl Ester	10	Simulated concrete pore solution	13.35 to 13.5	30	No report	60
					90		72
					180		69
					270		70
Sheard et al.	No report	5	K, Ca and Na	10 to 13.5	No report	21 to 80	29
Altizer et al.	Isocyanurate Vinyl Ester resin	25 to30	97.4% Water + 0.2% Ca $(OH)_2$ + 1.4% KOH + 1.0% NaOH	~13	203	No report	37.1 to 76.5
	Urethane vinyl ester						0.8
Coomarasamy and Ip	Vinyl Ester	15	0.6M KOH+ 0.2M NaOH +saturated Ca $(OH)_2$	13.5	49	60	46

Chapter 3

EXPERIMENTAL METHODOLOGY

3.1 Introduction:

The work on this project started in August 2001. The objective of the project is to investigate the residual strength of GFRP bars as a function of exposure to a simulated concrete environment. This chapter presents details on the test setup, specimen preparations and the testing procedures involved. Initial work to be done was to get the set up ready for the acclerated exposure of the No. 3 Glass Fiber Reinforced Polymer (GFRP) rebars provided by Hughes Brothers. In order to achieve this objective, three tanks were constructed, each containing saturated calcium hydroxide solution and maintained at 86, 113, and 135°F (30, 45 and 57°C) respectively.

The specimen length, anchor size and length for the tensile tests were calculated as per the minimum criteria given in ACI 440 (2000 revision). The specimens used for tensile tests were 35 in. length while the ones for the moisture absorption test were 4 in. length.

Tensile tests were performed on the specimens in a Universal Testing Machine (UTM). Using the ultimate failure load and the linear displacements measured by the Linear Variable Differential Transformers (LVDT's), the reduction in strength and stiffness were determined. The tensile testing procedures were done as explained in ACI 440. The experimental program consists of 100 tensile test specimens and 66 moisture absorption specimens. Also changes in the moisture content for the No. 3 bars were determined using the method explained in ASTM D5229.

3.2 Experimental Setup:

3.2.1 Conditioning Tanks:

Three conditioning tanks were constructed to condition the GFRP bars at 86, 113 and 135 °F (30, 45 and 57°C respectively) in a saturated calcium hydroxide solution. The temperatures selected were well below the glass transition temperature (T_g) for resin, which is 200 to 300°F as per ACI 440, so as not to change the structure of the resin.

Three polypropylene tanks were selected each having a capacity of approximately 35 gallons. The tanks were insulated on all sides with Styrofoam sheet and placed in a ¾ in. thick plywood box. The plywood box was insulated on all sides so as to minimize the heat loss. Each tank contained fully submersible heaters (4-50 watts for 86°F tank, 4-150 watts for 113 °F tank and 1-150 and 4-300 watts for 135 °F tank), manufactured by Aquarium Systems. The heaters were positioned at the corners of the tank and were controlled by a controller (CN77000 Series Omega). To ensure uniform heat distribution and proper circulation of water, aquarium pumps (2 per tank) manufactured by MARINELAND were placed on the either side of the tank. Before putting the specimens in the tanks, each tank was filled with water and checked to ensure it was heated to the required level. Figure 3.1 shows the setup of the tanks along with their controllers.

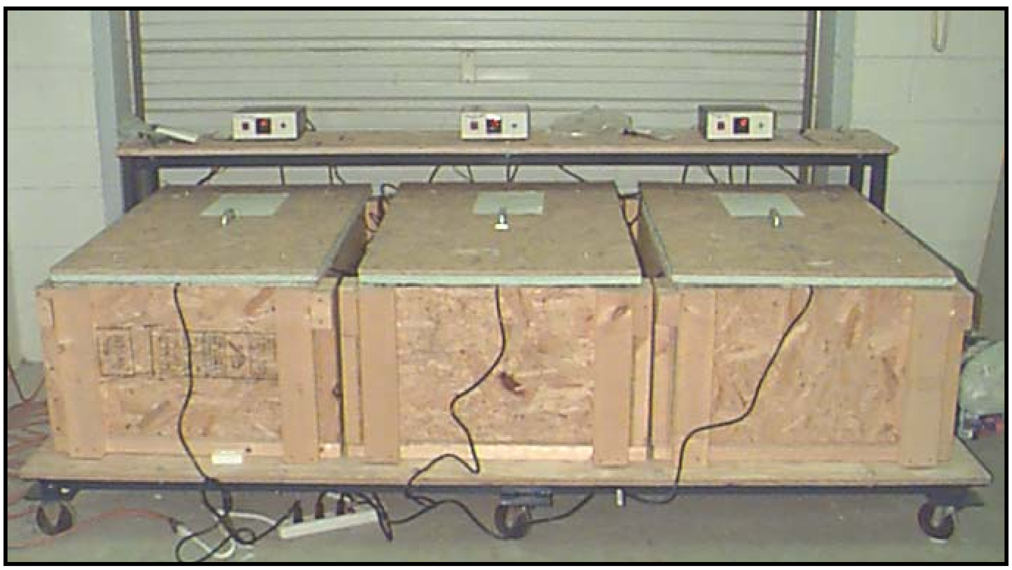


Figure 3 1: Setup of the tanks along with the controllers

A plexi-glass rack per tank was prepared in such a way that five specimens to be tested on the prescribed day could be removed as one layer. Due to the high temperature maintained in the tank, plexi-glass was found be the best material to build the rack for holding the specimens. Figure 3.2 illustrates the side and front view of the tanks along with the specimens, heaters and pumps.

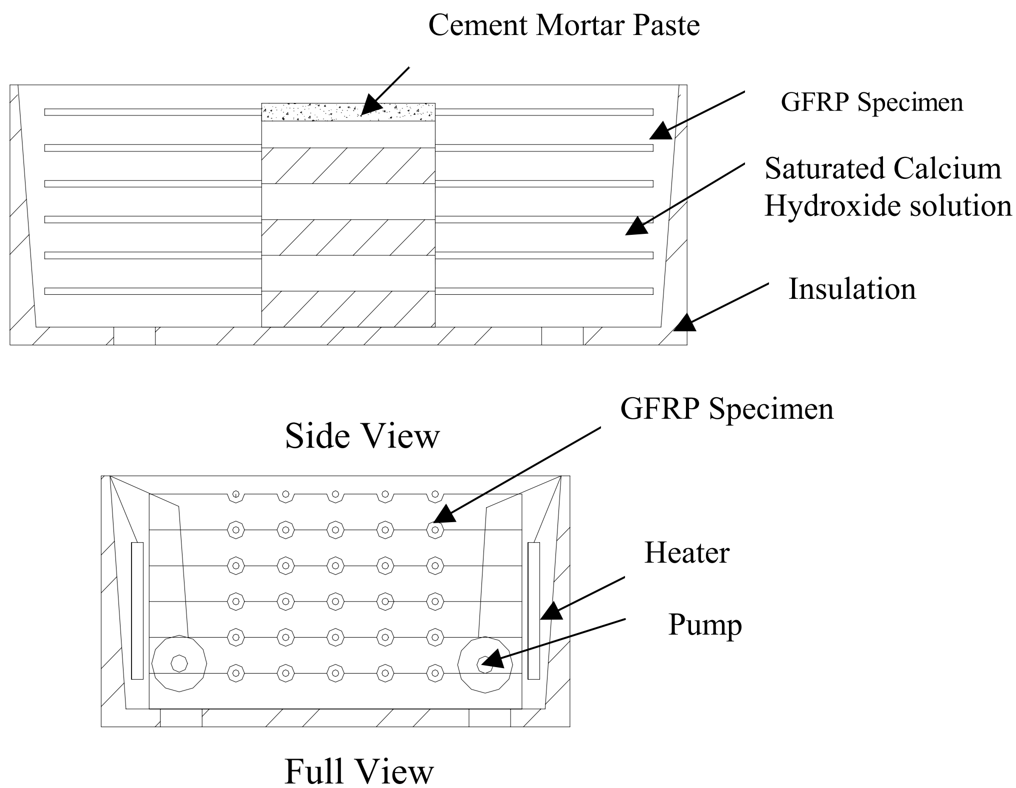


Figure 3.2: Schematic views showing the aging tank with the locations of the heaters, pumps and the racks with the specimens placed on it.

The three controllers were set at 86, 113 or 135 °F respectively and having a dead band of zero i.e. as soon as the temperature of the solution in the tank reaches above the set point of the controller, the flow of electricity to the heaters stops and vice versa. The temperature of the solution was checked using a manual thermometer at different portions of the tank so as to ensure a uniform temperature throughout. After putting the specimens on the rack in the tank, the top of each tank was covered with bubble wrap and later with the lid of the tank, so as to minimize the heat and moisture loss from the top. The pH of the alkaline solution was checked periodically using a pH meter HI8424 manufactured by Hanna Instruments and was found in a range of 8.5 to 9. The water level in each of the tanks was checked periodically.

3.2.2 GFRP Reinforcing Bar Specimens:

GFRP bars (Aslan 100) provided by Hughes Brothers are helically wrapped and slightly sand coated. The bars were manufactured using pultrusion process, where the resin used was Ashland Chemical Helron 922 vinyl ester.

3.2.2.1 Tensile Strength Specimen:

The specimen length of the GFRP specimen as well as the length and the diameter of the anchor to be used for the tensile tests were calculated as per provisions given in ACI 440K (1999). End anchors placed at the ends of the specimen are needed for better gripping of the specimen to the wedges of the UTM and also to distribute the load from the UTM to specimen. For the No.3 GFRP bars used in this study, the specimen length was 35 in. while the anchor length and diameter were 10 in. and ¾ in. respectively. The middle 10 in.of each specimen was encased with a cement mortar paste, so as to exposed the bar to similar conditions when used in a bridge deck. The mortar was prepared by mixing sand, cement and water in 3:2:1 proportion. The cement used was Type 1 Portland cement. The pH of the cement mortar paste was 13.2. The mortar was placed in a 1in. diameter plastic sleeve, which was 10 in. in length. After the mortar cured, the plastic sleeve was removed and the remaining portion of the specimen was coated with a VC Tar Epoxy Barrier paint manufactured by West Marine systems. This was done so as to minimize the degradation occurring at that portion of the specimen. The paint was allowed to dry for the time specified by the manufacturer. Once the coating on the bars dried, they were placed in the tanks, 30 specimens per tank.

The bars were to be removed from the tanks after 10, 30, 60, 90, 180 and 300 days. The 300-day test results are not included in this thesis, as tensile test were not performed on the specimens to date. Five specimens per tank were tested on each of the above-mentioned days as per the minimum requirements of ACI-440 (2000). On the specified day the specimens were removed from the tank and allowed to dry at room temperature. Later the assembly and casting of the anchor to the specimen was done. Each steel anchor used in this project is 10 in. in length. Its external surface was grinded for better gripping during the tension tests. Two PVC anchor caps (each ¾ in. in diameter) per anchor were used; a hole was drilled in the center of one of the anchor caps so the GFRP bar could barely pass through it. The other anchor cap had a slot drilled in the center so that the bar could fit in the center of the cap for better alignment purpose. The anchors were filled with epoxy resin and hardener produced by West System and sand, mixed in proper proportion. Initially the sand was weighed, after which epoxy resin was added to it in proper proportion and mixed thoroughly. Later hardener was added and again the mixture was mixed thoroughly. The epoxy resin and the hardener were in ratio of 5:1 as provided by the manufacturer, whereas for 1 part of hardener, 28.5 grams of sand was mixed. Initially one anchor was cast and allowed to set for 24 hrs, before the other anchor was cast. The setting time for both the anchors for a specimen was 48 hours, after which they were ready for tensile tests. Figure 3.3 illustrates the GFRP specimen used for the tensile tests.

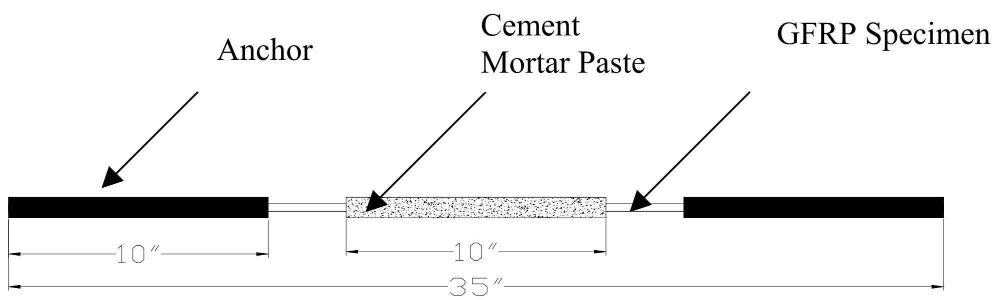


Figure 3.3: Layout of the specimen ready for tensile test.

3.2.2.2 Tensile Tests:

The objective of the tests is to determine the tensile strength and modulus of elasticity for each GFRP bar. The tensile tests were performed in a Universal Testing Machine (UTM); the experimental set up for the tensile tests was as shown in Figure 3.4. For each tensile test, the specimen was mounted on the SATEK UTM machine with the steel pipe anchors gripped by the wedges of the upper and the lower jaw of the machine. To measure the linear displacement, three Linear Variable Differential Transformers (LVDT's) were used in the experiments. Measurements Group Inc. provided calibration information for each LVDT to a full-scale displacement of 10.00 mm. Before the load was applied, gage length was measured.

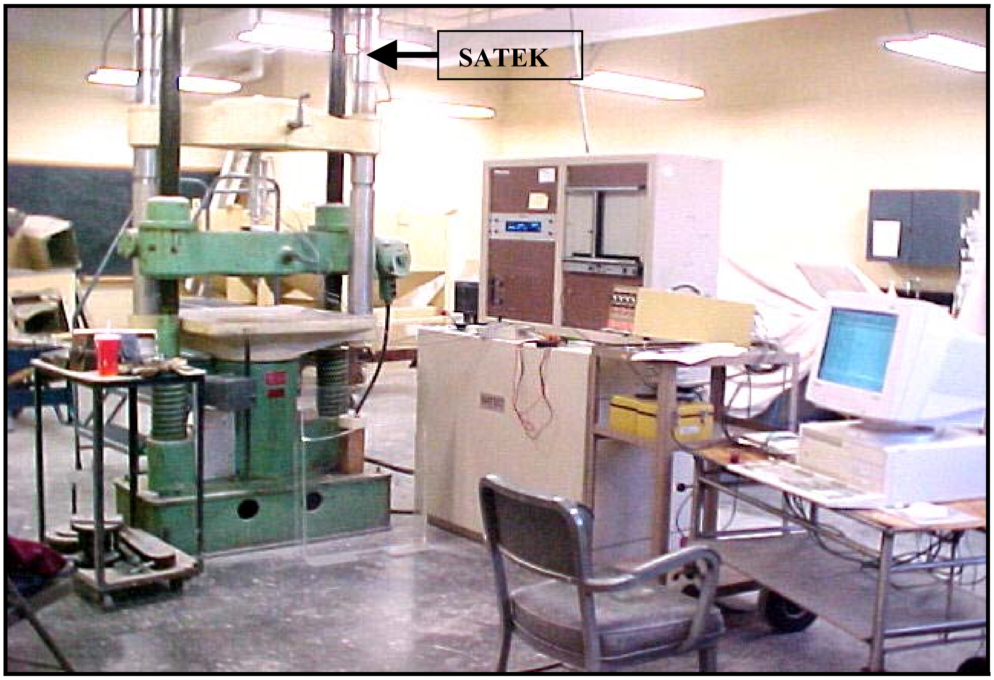


Figure 3.4: Experimental Setup

The rate at which load was applied was such that a tensile strength test typically ended in around three minutes from the start of the load till the specimen failed. This load rate was within the range of 14.5 to 72.5 ksi per minute as per the requirements of ACI 440. The failure load was recorded to calculate the ultimate tensile strength. Due to the brittle nature of GFRP, no yielding occurs, so the stress-strain behavior is linear in nature. The data (load and displacement) received by the computer was in terms of voltage, which was later converted to its proper units. Each LVDT was numbered, as the full scale output used for converting data from voltage to its proper units is different for the three LVDT's. Figure 3.5 shows the LVDT setup just before and after the test.

Before Failure After Failure

Figure 3.5: LVDT setup

Initially 10 plain bars as supplied by the manufacturer were tested. Also testing was done on specimens that were incased in the cement mortar paste but not conditioned in the alkaline solution. After 10 days at room temperature the bars were tested and the results were compared to the ones that were incased and conditioned. Altogether 5 plain specimens, 10 incased but unconditioned specimens and 90 incased and conditioned specimens were tested for tensile strength and modulus.

3.2.2.3 Moisture Absorption study:

The objective of the moisture absorption study was to determine if the weight gain of the GFRP bar is a function of time. Specimens used for the weight gain measurements were 4 in. in length. The ends of the specimens were coated with the VC Tar Epoxy paint, so as to reduce the moisture diffusion through the ends and then immersed in the alkaline solution. Initially the moisture uptake was recorded after hours of immersion. Moisture immersion data is available till 80 days of immersion. At the specified time the specimens were removed from the tank, surface dried and weighed in a Mettler H31AR Balance having resolution of 0.1milligram. Later they were oven treated till no further weight change was observed. The oven temperature used for drying the specimens was 65 °C. The specimens initially were removed after 24 hrs and weighed. The specimens were oven dried again till the weight recorded was constant. The time after which the specimens were removed from the tank was 1, 2, 4 hours and later after 1, 2, 5, 10, 15, 30, 65 and 80 days after immersion. On the specified time, 2 specimens per tank were removed. Altogether 66 specimens were used for the moisture absorption study.

The percent weight gain was measured by:

$$\%M = \frac{W_x - W_d}{W_d} * 100$$

Where, W_x = wet weight at time x

W_d = oven dry weight

Chapter 4

RESULTS

4.1 Introduction:

Tensile tests were performed on the No.3 GFRP bars to obtain the ultimate tensile strength, modulus of elasticity and the stress-strain behavior. Tests were performed on plain specimens, unconditioned but incased in cement mortar paste and conditioned and incased specimens for 30, 45 and 57°C.

4.2 Plain Specimens:

Tensile tests were performed on the plain specimens and tensile strength was calculated using the nominal area and measured area. The nominal area is the area of a No.3 steel reinforcing bar, while the measured area is determined from the average of the diameter measured at the top, bottom and the center of the GFRP specimen using a vernier caliper. Tensile strength and modulus of elasticity published by the manufacturer, which is calculated using the nominal area, is 110 ksi and 5920 ksi respectively. The results are as shown in Table 4.1.

Table 4.1: Tensile Strength and Modulus of Elasticity for Plain Bars

No.	Tensile Strength (ksi)		Modulus of Elasticity (ksi)	
	Nom. Area *	Meas. Area **	Nom. Area *	Meas. Area **
1	100.2	84.3	6470	5450
2	NA	NA	NA	NA
3	100.4	84.5	6550	5520
4	102	85.9	6530	5500
5	104.3	87.8	6680	5630
Average	101.8	85.6	6550	5520
Coefficient of Variation (%)		1.80		1.40

* Strength calculated using the nominal area ($0.11 in^2$)
** Strength calculated using the measured area ($0.13\ in^2$)

4.3 Conditioned and Incased Specimens:

Tensile test were performed on specimens that were incased in cement mortar paste and were conditioned in calcium hydroxide solution. The solution was maintained at 30, 45 and 57°C in three different tanks. The pH of the solution was in the range of 8.5 to 9 for the three tanks and the cement mortar paste had a pH of 13.2. Tensile tests were performed on 10, 30, 60, 90 and 180 days after the bars were first immersed in the solution. On the prescribed days the specimens were removed in a batch of five as per the ACI requirements.

4.3.1 Tensile Strength:

Table 4.2 gives the tensile strength for conditioned and incased specimens. It can be seen that there is variation in data for the specimens of the same batch. The tensile strengths are calculated based on measured area.

Table 4.2 Tensile strength for all the conditioned specimens.

Days	Specimen Nos.	Temperatures (°C)		
		30	45	57
10	1	94.6	88.6	81.5
	2	95.3	78.5	90.3
	3	91.2	91.1	90.7
	4	85.6	81.8	76.5
	5	93.6	79.5	81.2
30	1	72.3	68.5	62.7
	2	86.5	78.1	66.1
	3	72.8	65.5	68.1
	4	90.1	67.8	61.5
	5	69.8	83.3	59.6
60	1	70.3	69.1	52.1
	2	71.1	59.8	65.1
	3	68.6	63.1	74.7
	4	86.1	62.8	51.2
	5	70	71.7	66.4
90	1	66.1	59.7	62.1
	2	60.7	61.7	60.4
	3	63.9	66.9	60.4
	4	73	Anchor Slip	59.8
	5	67.4	69.8	60.2
180	1	Failure*	Anchor Slip	40.0
	2	Anchor Slip	61.2	39.9
	3	59.1	Failure*	48.8
	4	Anchor Slip	Anchor Slip	52.4
	5	Anchor Slip	Anchor Slip	46.8

* Failure between the anchor and the encased cement mortar portion
** Tensile strengths given in ksi.

The average tensile strengths till 180 days are tabulated below for conditioned specimens for 30, 45 and 57°C.

Table 4.3: Average tensile strength for the conditioned specimens.

Days	Temperatures (°C)					
	30		45		57	
	Average	COV (%)	Average	COV (%)	Average	COV (%)
10	92.1	4.2	83.9	6.7	84.1	7.4
30	78.3	11.8	72.6	10.5	63.2	5.4
60	73.2	9.9	65.3	7.5	62	16.2
90	66.2	6.9	64.5	10.9	60.5	1.4
180	59.1	NA	61.2	NA	43.9	12.6

* Tensile strengths calculated using measured area
** Tensile strengths given in ksi.

Figure 4.1 shows the comparison of strength retention with time for the conditioned bars with the conditioned GFRP bars use in Dejke's study. The GFRP bar type used for the comparison of the four different types studied by Dejke, are E-glass/ vinyl ester provided by Hughes Bros. The bars are exposed to alkali solution containing sodium hydroxide (NaOH), calcium hydroxide ($Ca(OH)_2$), potassium hydroxide (KOH) and water. The pH of the alkali solution was 13.7.

Strength loss observed during the initial phase of this project for the 45 and 57°C was less as compared to that observed in Dejke's study for 40 and 60°C. The strength loss observed after 180 days in 57°C was 50% as compared to 45% at 60°C from Dejke's study. For the unconditioned specimens tested after 10 days, strength loss observed was 15%. Only one reading was available from the specimens tested after 180 days of conditioning at 30 and 45°C.

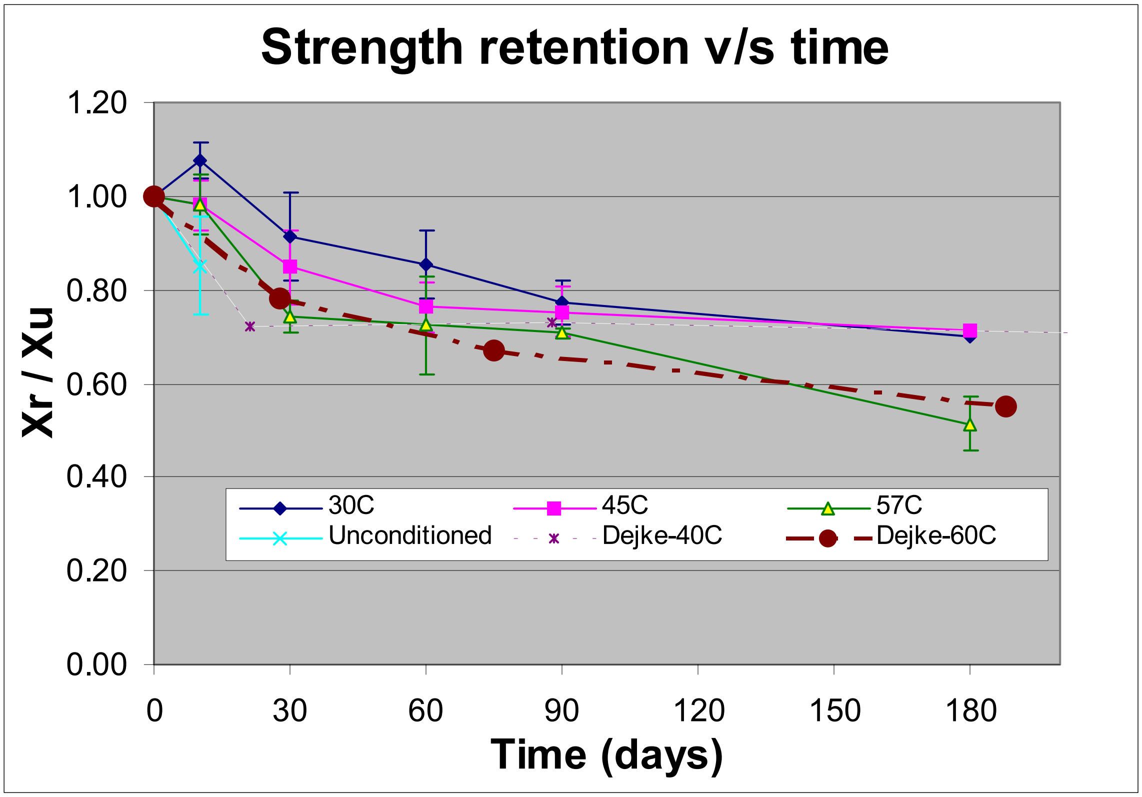


Figure 4.1: Strength retention with time.

4.3.2 Modulus of Elasticity:

The modulus of elasticity was calculated using the average of the strains measured by the three LVDT's. The modulus for each LVDT was calculated from the slope of the largest portion of the line that had no breaks and jumps. This mostly occurred between 5 to 40 percent of the load. As compared to the tensile strength, there is not much variation in the modulus of elasticity. The modulus of elasticity falls in the range of 5000 to 6000 ksi. Table 4.4 gives the values of the modulus of elasticity for conditioned and incased specimens.

Table 4.4: Modulus of Elasticity for all the conditioned specimens.

Days	Specimen Nos.	Temperatures (°C)		
		30	45	57
10	1	5270	5160	5080
	2	NA	5410	5000
	3	5340	5230	5260
	4	5400	5210	5360
	5	5270	5380	5230
30	1	5270	5290	5400
	2	5540	NA	5260
	3	5670	5140	5240
	4	4640	5170	5500
	5	5360	5130	4680
60	1	4470	5640	5270
	2	4130	5380	5420
	3	5310	5370	5330
	4	5420	5320	5230
	5	5170	5190	5480
90	1	5270	5300	5330
	2	5200	5090	5350
	3	5190	5430	5250
	4	5390	5330	5440
	5	5290	5300	5200
180	1	5860	4970	5200
	2	5160	5070	4650
	3	5660	4830	5030
	4	4550	4720	5070
	5	5140	4460	5170

* Modulus of Elasticity calculated using measured area

** Modulus of Elasticity given in ksi.

The average modulus of elasticity and the coefficient of variance till 180 days is tabulated below for conditioned specimens for 30, 45 and 57°C.

Table 4.5: Average and Coefficient of Variation (COV) modulus of elasticity for the conditioned specimens.

Days	Temperatures (°C)					
	30		45		57	
	Average	COV (%)	Average	COV (%)	Average	COV (%)
10	5320	5.8	5270	2.52	5180	1.36
30	5290	4.33	5180	1.68	5210	5.54
60	4900	2.3	5380	0.97	5340	2.6
90	5260	2.32	5290	2.6	5310	2.01
180	5070	6.73	4810	7.2	5020	7.17

* Modulus of Elasticity calculated using measured area.
** Modulus of Elasticity given in ksi.

Figure 4.2 shows the strength retention with time for the conditioned and incased bars for the 30, 45 and 57°C till 180 days. The change in the modulus of elasticity was in the range of 10%.

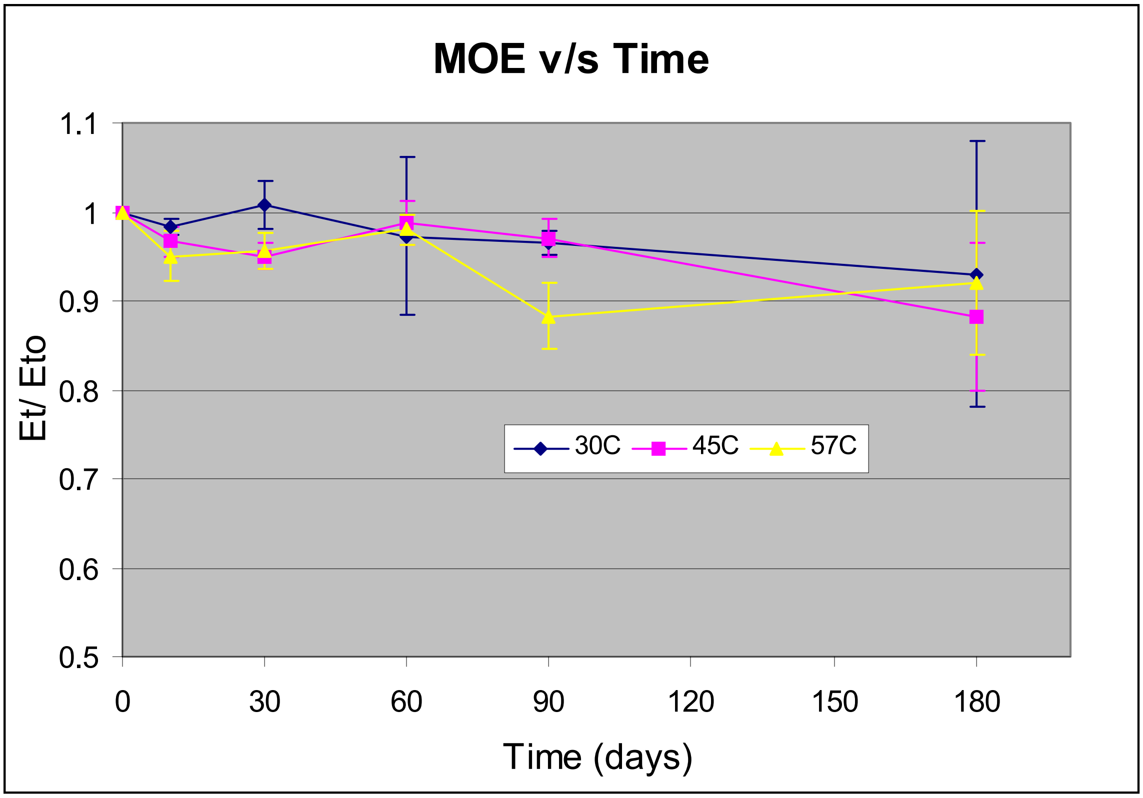


Figure 4.2 Modulus of Elasticity with time.

4.4 Unconditioned but Incased Specimens:

Tensile tests were performed on specimens that were incased in cement mortar paste but were not conditioned in calcium hydroxide solution. Specimens were tested after 10 days and the results are as given in Table 4.6

Table 4.6: Tensile Strength and Modulus of Elasticity for Uncondtioned but encased specimens after 10 days of exposure.

No.	Tensile Strength (ksi)		Modulus of Elasticity (ksi)	
	Nom. Area *	Meas. Area **	Nom. Area *	Meas. Area **
1	81.6	68.7	6290	5300
2	72.9	61.4	6640	5590
3	93.3	78.5	6700	5640
4	81.3	68.5	6200	5220
5	104	87.5	NA	NA
Average	86.6	72.9	6450	5430
Coefficient of Variation (%)		14.0		3.80

* Strength calculated using the nominal area (0.11in^2)
** Strength calculated using the measured area (0.13 in^2)

4.5 Stress–Strain Behavior:

The elongation of each tensile test specimen was measured using three LVDT's. Each LVDT is numbered and had a full-scale reading of 10mm. Strain was calculated using the average elongation divided by the measured initial gage length. A typical stress-strain diagram is shown in Figure 4.3, while the stress-strain diagrams for all the specimens tested during the project are shown in Appendix A.

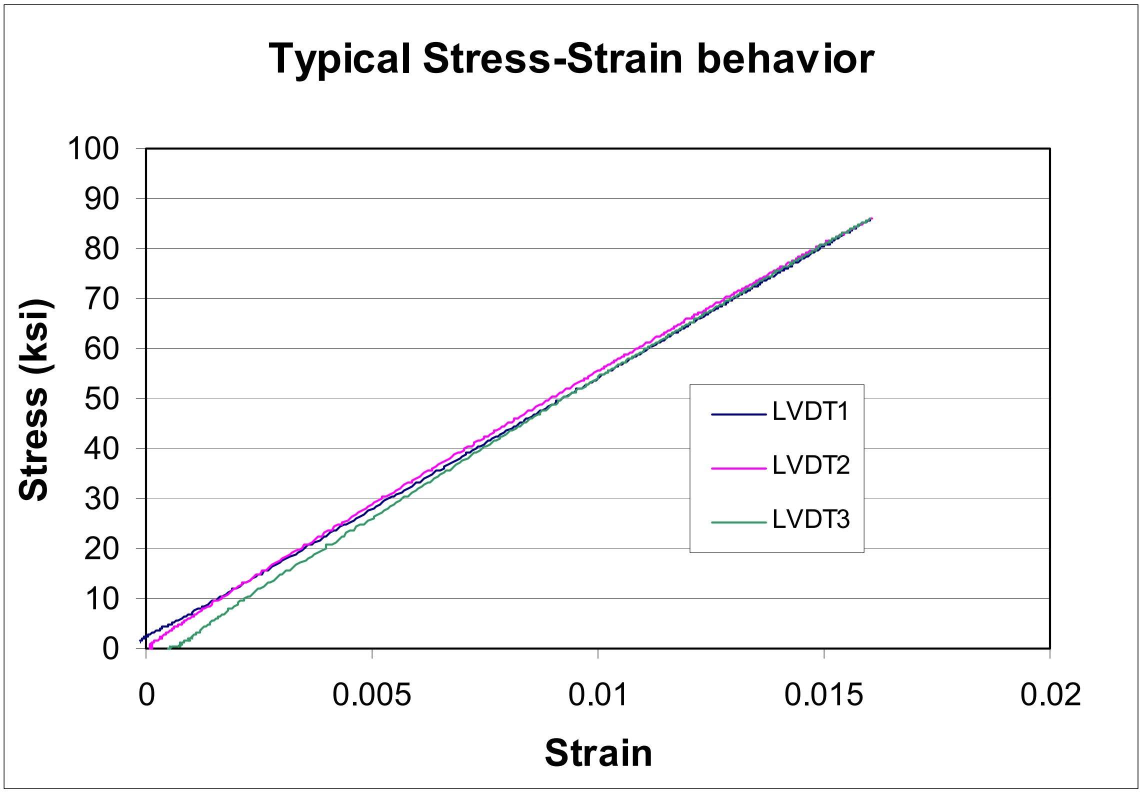


Figure 4.3 Typical Stress – Strain relationship.

Figure 4.3 illustrates that there exists a linear stress-strain behavior, till failure. There is no yielding as in steel, so GFRP bars can be described as brittle in nature. In some of the readings shown in Appendix A, there are variations in the three LVDT readings. This may be due to the slow start of one LVDT to measure the reading as compared to the others. It may be also due to the tilting of the plate that acts as a surface on which the plunger of the LVDT's rest. But overall, due to the use of three LVDT's, the average value gives a fair result.

4.6 Moisture Content:

Table 4.7 presents the moisture absorption data that was recorded till 80 days from the day of immersion of the specimens in the tank.

Table 4.7: Moisture absorption data for specimens immersed in limewater solution.

Time (Days)	30°C	45°C	57°C
0.042	0.12	0.16	0.17
0.084	0.16	0.155	0.19
0.167	0.19	0.19	0.22
1	0.26	0.25	0.43
2	0.32	0.39	0.57
5	0.39	0.61	0.74
10	0.51	0.89	1.33
15	0.7	0.95	1.29
30	0.88	1.41	1.81
65	1.06	1.29	1.87
80	1.02	1.57	1.92

* Above given moisture absorption value is average of two specimens.

Chapter 5
PREDICTION OF STRENGTH RETENTION

5.1 Introduction:

As has been mentioned earlier, one aim of this project is to develop methods to predict the service life of GFRP bars when used in concrete bridge decks. It is practically not feasible to expose the bars in real environmental conditions for its service life of 50-100 years. So the service life is predicted using the data available from accelerated ageing conditions for shorter time periods. In this project the bars were exposed to cement mortar immersed in a saturated solution of $Ca(OH)_2$ maintained at three different temperatures of 30, 45 and 57°C. The moisture absorption data available is for 80 days and the strength retention data available is for 180 days.

According to Phifer and Lesko (2002), using Fickian diffusion for the resin and the pultuded laminates, the moisture – temperature curves were clearly represented by Arrhenius relationship. They also showed that a linear relationship exists when tensile strength versus moisture content was plotted. Therefore, a method is sought to predict moisture uptake with time and temperature for GFRP bars. Then the moisture content can be related to strength degradation.

The moisture diffusion analysis is performed using the Fickian model, which is a two-parameter equation. This was chosen instead of a Langumirian model, which is a four-parameter equation, as only short-term data was available. Moisture diffusion for a cylindrical shape composite (bar) is modeled using a single exponential equation with a constant maximum moisture content at infinite time as given by Crank (1979). It is assumed that there exists an Arrhenius relationship between the maximum moisture content and the diffusion constant and temperature for accelerated ageing conditions.

Also in this chapter, an attempt is made to predict the strength retention using the time shift factor method. Finally, the strength retention is predicted after 50 years of exposure, if used in bridge decks in Roanoke, Virginia. Also a comparison is made between the number of days of exposure required for the bars in 57°C tank for accelerated ageing to yield a degradation predicted after 50 years in a bridge deck. The other questions addressed in this chapter are : Is the degradation process Single Arrhenius or Double Arrhenius? Does there exist a relationship between the moisture content and strength degradation for GFRP bars?

5.2 Fickian Model:

The moisture content of an FRP bar is a function of the Diffusion constant, D, and the maximum moisture content the bar can achieve, M_{∞}. For FRP these attributes have been shown to be a function of temperature as given by the Arrhenius equation which is temperature dependant and is given by equation 1. The higher the temperature, the higher will be the level of moisture saturation, and the higher the diffusion constant.

$$X = X_O . e^{(-Ex/RT)} \qquad [1]$$

Where X is M_{∞} or D, X_o (in our case D_o and $M_{\infty o}$) is a constant, E_x is the activation energy, R is the gas constant (1.99 cal/ deg mole) and T is the absolute temperature (^oK).

The mathematical theory of diffusion as put forward by Fick (1855) is based on the hypothesis that the rate of transfer of a diffusing substance through a unit area of section is proportional to the concentration gradient measured normal to the section (Crank, 1979). But for a cylindrical section, concentration is a function of radius and time. The moisture absorption for a cylindrical solid specimen represented by a Fickian model is given by equation 2.

$$\frac{M_t}{M_\infty} = 1 - \sum_{n=1}^{\infty} \frac{4}{a^2 \alpha_n^{\ 2}} \exp(-D\alpha_n^{\ 2} t) \qquad [2]$$

Where M_t denotes the quantity of diffusing substance, which has entered or left the cylinder in time t, M_{∞} the corresponding quantity after infinite time, D is the diffusion constant, a is the radius of the specimen (which in our case is 0.1875in.), α_ns are roots of equation $J_o = 0$ where J_o (x) is the Bessel function of the first kind of order zero. Bessel functions of the first kind of order zero can be calculated using Mathematica or using the Bessel function tables. In this project, for calculation purpose the first five roots of the Bessel function of the first kind of order zero were used.

Moisture absorption data is available until 80 days for specimens immersed in solution maintained at 30, 45 and 57°C. The specimens were removed initially after 1, 2 and 4 hours and later after 1, 2, 5, 10, 15, 30, 65 and 80 days from each tank. The specimens were removed in a batch of two specimens per tank at each of the above mentioned times, after which they were surface dried and then weighed, to get the weight of the specimen due to moisture absorption. Later they were dried in an oven until a constant weight of the dried specimen was observed. Figure 5.1 shows the plot of moisture absorption (%M) versus time (days). The plot is for both the specimens removed per tank on the prescribed days. The moisture absorption data and the corresponding time were substituted in Origin, a curve fit software, along with the Crank's equation. The two unknowns in the equation, maximum moisture, M_∞ and the diffusion coefficient, D, were determined for the best-fit curve. Table 5.1 gives the values of D and M_∞ for different temperatures.

Table 5.1: Maximum Moisture and Diffusion for different temperatures.

Temperature (°C)	Maximum Moisture (M_∞)	Diffusion Coefficient (D)
30	1.076	0.168
45	1.484	0.205
57	1.93	0.236

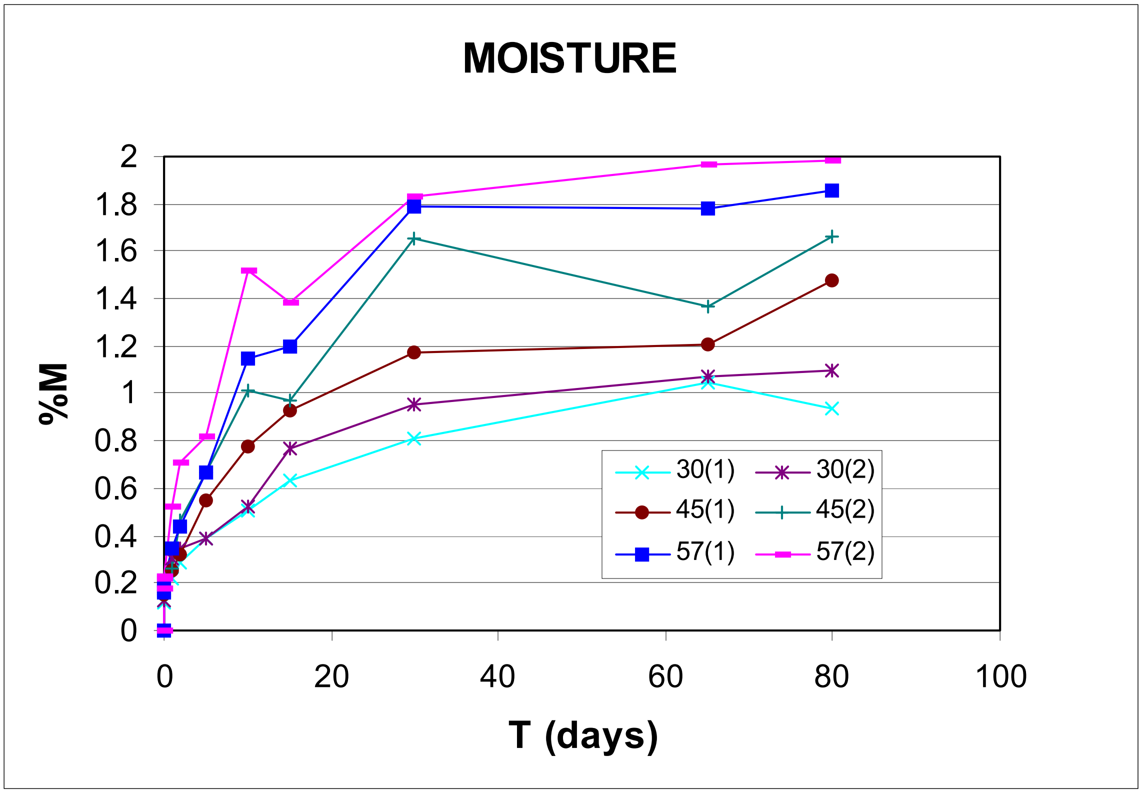


Figure 5.1: Moisture absorption versus Time.

As given earlier the Arrhenius equation, taking Moisture content into consideration, is given by –

$$M_{\infty(T)} = M_{\infty O}.e^{(-E_m / RT)}$$

Taking natural log on both sides

$$\ln(M_{\infty(T)}) = \ln(M_{\infty 0}) + (\frac{-E_m}{RT})$$

Multiplying both sides by –1 we get

$$\ln(\frac{1}{M_{\infty(T)}}) = \ln(\frac{1}{M_{\infty 0}}) + (\frac{E_m}{R})(\frac{1}{T})$$

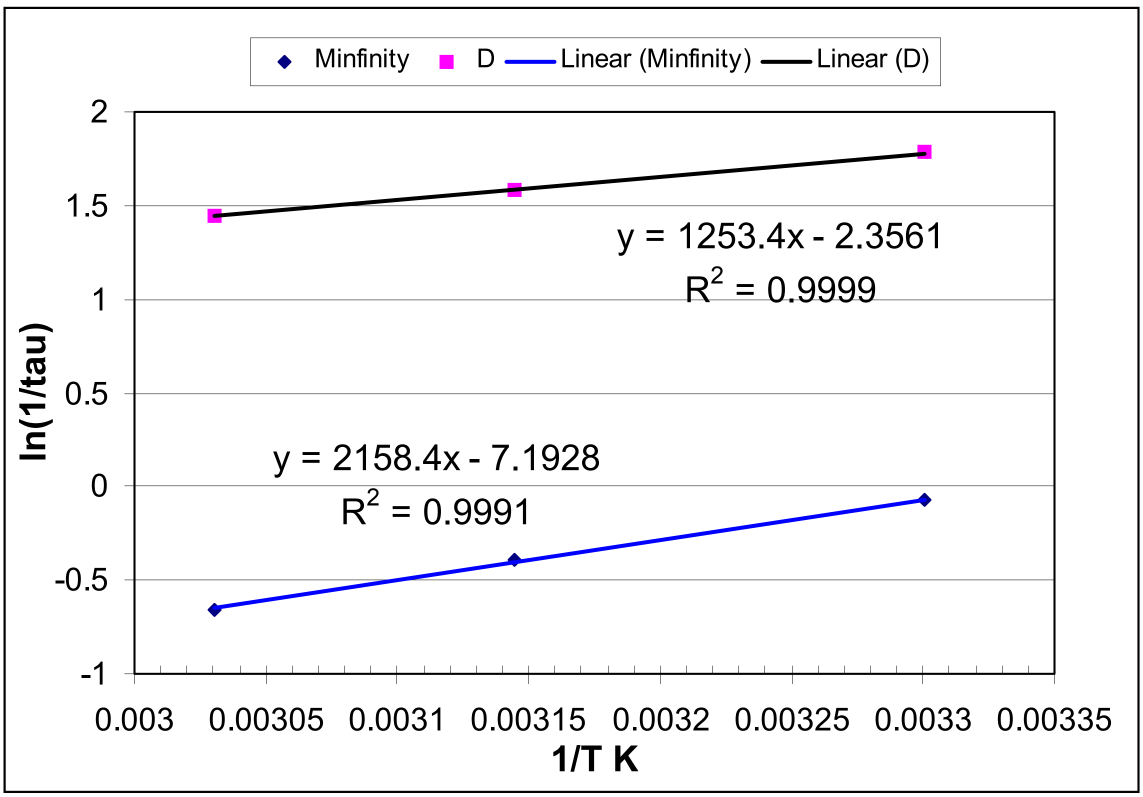
which is a straight-line equation.

The plot of 1/T (°K) versus ln(1/D) and 1/T (°K) versus ln(1/ M_∞) gives a straight line equation (as shown in Figure 5.2). The activation energies E_D and $E_{M\infty}$ can be calculated from the slope and the intercept gives the value of D_o and $M_{\infty o}$ as shown in Table 5.2.

Table 5.2: Arrhenius analysis based upon Fickian curve fit with respect to immersion temperature.

Type	Temp (°C)	$E_{M\infty}$ (kcal/mol)	$M_{\infty 0}$ (%MC)	R^2	E_D (kcal/mol)	D_o (mm^2/s)	R^2
#3 GFRP	30-57	4.28	13.394	0.9991	2.49	1.22E-04	0.9999

Substituting the above values in the Arrhenius equation, we get D, rate of diffusion and M_∞, maximum moisture content. The trend lines is drawn using a least square fit represented by a straight-line equation.



* tau is a notation given to $M_{\infty(T)}$ and D.

Figure 5.2: Arrhenius analysis for Moisture absorption and Diffusion versus inverse of temperature

The R-square value given in Figure 5.2 is also known as coefficient of determination, and reveals how closely the estimated data for the trendline corresponds to the actual data. It is given in the range form 0 to1, and is most reliable if the R-square value is at or near 1. The R-square value from Figure 5.2 illustrates that the estimated data for trendline is very close to the actual data for both M_∞ and D.

As mentioned earlier, the aim is to predict the strength degradation of these bars when used in bridge decks in Virginia. According to the Comparative climatic data for United States for 1998, (US Department of Commerce, National Oceanic and Atmospheric administration) the mean annual temperature for Roanoke, Virginia is 55.8°F. Substituting this temperature in Kelvin, D and M_∞ values calculated earlier in the Cranks equation, the moisture content for time, t can be calculated. For a period of 50 years, the moisture content calculated is used to determine the tensile strength of these bars, by using the plot of the tensile strength and moisture content. As shown in Figure 5.3, there appears to be a linear relationship between the moisture absorption and tensile strength. The calculations for strength prediction are shown in Appendix B.

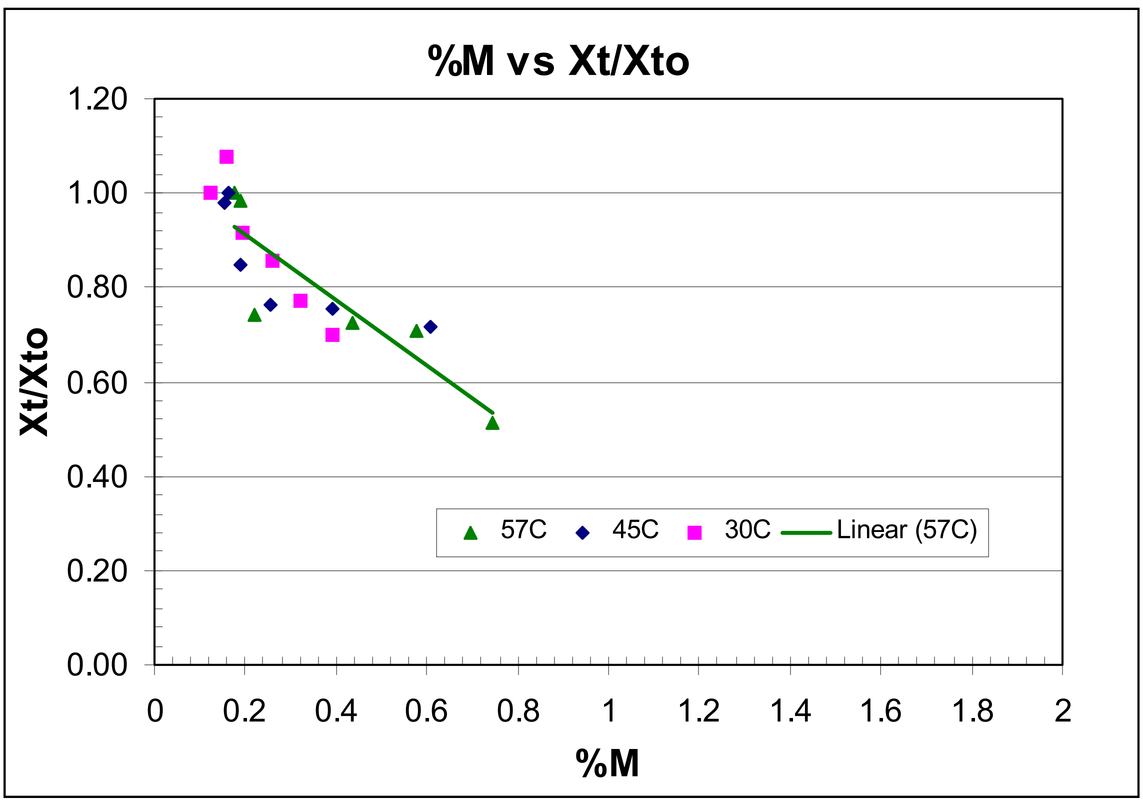


Figure 5.3: Moisture Absorption versus Strength retention for GFRP bars.

Figure 5.4 shows the plot of moisture absorption versus strength retention plot for GFRP sheets for all the temperatures as shown by Phifer et al.(2002). The purpose of their research was to predict the strength degradation over long-term aging of GFRP sheets in a finite difference diffusion / finite element stress code. They showed that for untoughened pultruded E-glass laminates, the tensile strength - moisture content curve reveals a linear relationship for all the immersion temperatures, which appears to hold true for GFRP bars as shown earlier.

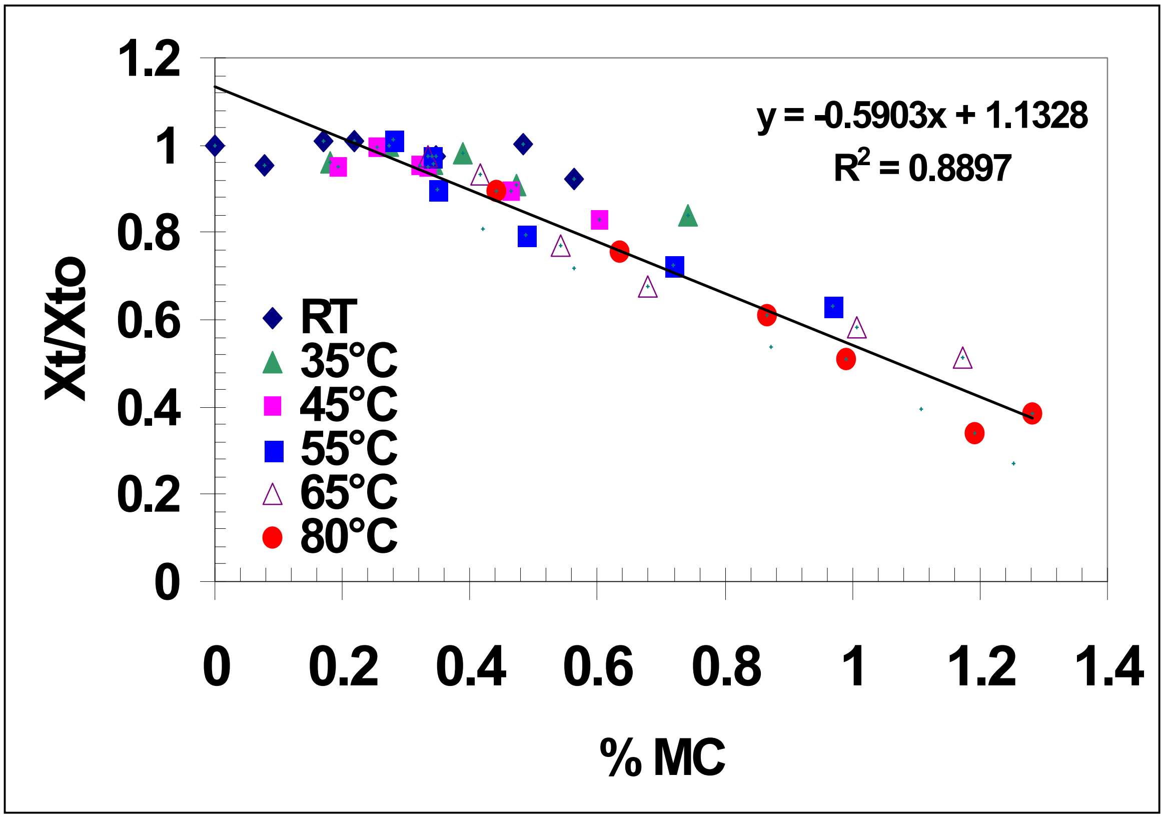


Figure 5.4: Moisture Absorption versus Strength retention for GFRP sheets as shown by Phifer et al.

5.2.1 Conclusion:

After 50 years of exposure of GFRP bars in bridge decks in Roanoke, Virginia, this model predicts a 45% strength loss. To get a degradation of 45% in real weather conditions, the exposure time for the bars in 57°C is about 135 days. The degradation process is a two-step process. For GFRP bars, the tensile strength versus moisture content plot shows that there exists a linear relationship between them, and that if the moisture content can be predicted, it can be related to the tensile strength. However, this model must be used with caution as all strength versus moisture content data are for exposure time of less than three years. An extrapolation to a 50 year service life may not be valid.

5.3 Time Shift Method:

It was proposed to project the strength retention using the time shift method. The time shift method is based on the assumption that the rate of strength retention at different temperatures can be described by the Arrhenius equation. Figure 5.5, shows the plot of strength retention and log of time for different temperatures, from the plot it can be seen that the curves are not of the same slope. This means that there is no Arrhenius type time–temperature relationship and there is not a single process that controls the kinetics of degradation. Thus it is possible that there exists a double Arrhenius relationship, where the degradation might be due to fiber, matrix or the fiber-matrix interface effects.

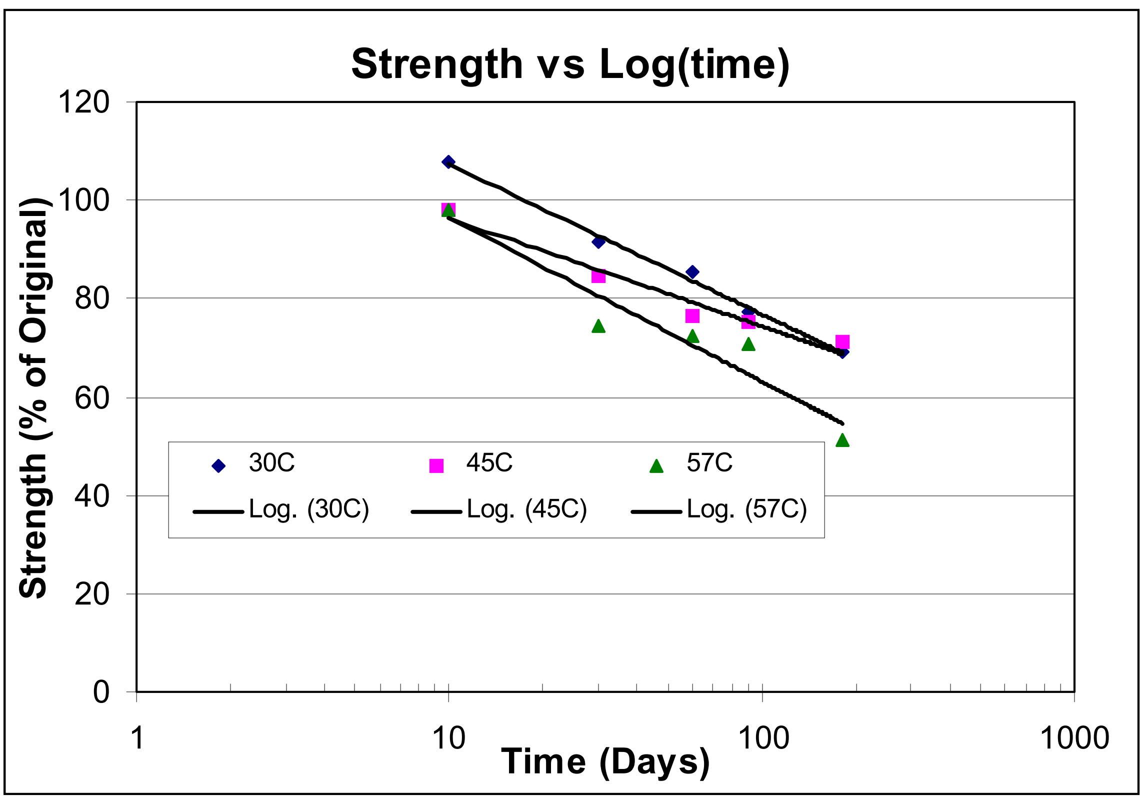


Figure 5.5: Percent Strength retention versus Log (time).

5.3.1 Conclusion:

Figure 5.5, shows that the curves from the plot of strength retention and log of time for different temperatures are not of the same shape. Thus there is no Arrhenius type time –temperature relationship which is the basic assumption to use this method.

Chapter 6
CONCLUSION AND RECOMMENDATIONS

6.1 Introduction:

The primary objective of this project is to determine the strength degradation of GFRP bars in accelerated ageing conditions and to examine whether the strength degradation exhibits an Arrhenius relationship. The secondary objective was to determine the moisture absorption property of these bars. The work done includes a thorough literature review, experiments and development of strength prediction models for the GFRP bars.

6.2 Conclusion:

From the work done in this project, the following conclusions were made:

- From the literature review chapter it can be clearly seen that there exist no standard test method, so it is difficult to compare the results available from the work done by different researchers. Also, it was seen that vinyl ester as compared to polyester is a better resin to prevent strength degradation.

- The results show that there is considerable strength degradation when GFRP bars are exposed to high temperature and alkalinity, while there is very little change in the modulus of elasticity of these bars. Strength loss of as high as 50% was observed for the specimens exposed to 57^{o}C after 180 days.

- The strength loss observed after 10 days for the specimens incased in the cement mortar paste at room temperature was 15%.

- Two methods were used to determine the strength prediction of GFRP bars. One using the Time Shift factors and other using the Fickian Model for moisture absorption. Both methods assume that there exists an Arrhenius relationship between rate of reaction and temperature.

- From the plot of strength retention and log of time for different temperatures, it could be seen that the curves are not of the same slope. Hence there is no single Arrhenius time-temperature relationship, which is the basic assumption of the Time Shift method. But the results available for this work were only for short term data, so this method needs to be reviewed for long term data.

- Using the Fickian Model for moisture diffusion, it was seen that the moisture – temperature curves were represented by Arrhenius relationship for maximum moisture content and diffusion coefficient for the GFRP bars. A linear relationship was observed when moisture content and tensile strength were plotted. So if the moisture content is predicted, then it can be related to the tensile strength.

- Finally strength retention is predicted for GFRP bars after 50 years of exposure, if used in bridge decks in Roanoke, Virginia. From the data available the strength loss predicted was 45% after 50 years of exposure in real life environment. To get a degradation of 45% in real life environment, the bars need to be exposed for 165 days of accelerated ageing in the 57^{o}C tank.

- The long term strength degradation predicted for GFRP reinforcement is greater than the ACI 440K recommendation of using 0.7 as the environmental reduction factor to calculate the design ultimate strength for glass fibers in unexposed and unconditioned space.

6.3 Recommendations:

The following recommendations are made for future research:

- Experiments need to be performed in stress conditions along with been to different environmental conditions. In real life conditions, the bars would be exposed to stresses especially if used as primary reinforcement.

- Long term data is required to predict the strength degradation of these bars along with different seasonal climatic conditions, to which the bars will be exposed in real life conditions if used in structures like bridge decks.

- A standardized test method is recommended to determine the strength degradation of GFRP bars.

- Long term data to determine if moisture absorption behavior is Fickian or Langmuirian for GFRP bars, should be collected.

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APPENDIX A

STRESS-STRAIN DIAGRAM FOR TENSILE TESTS

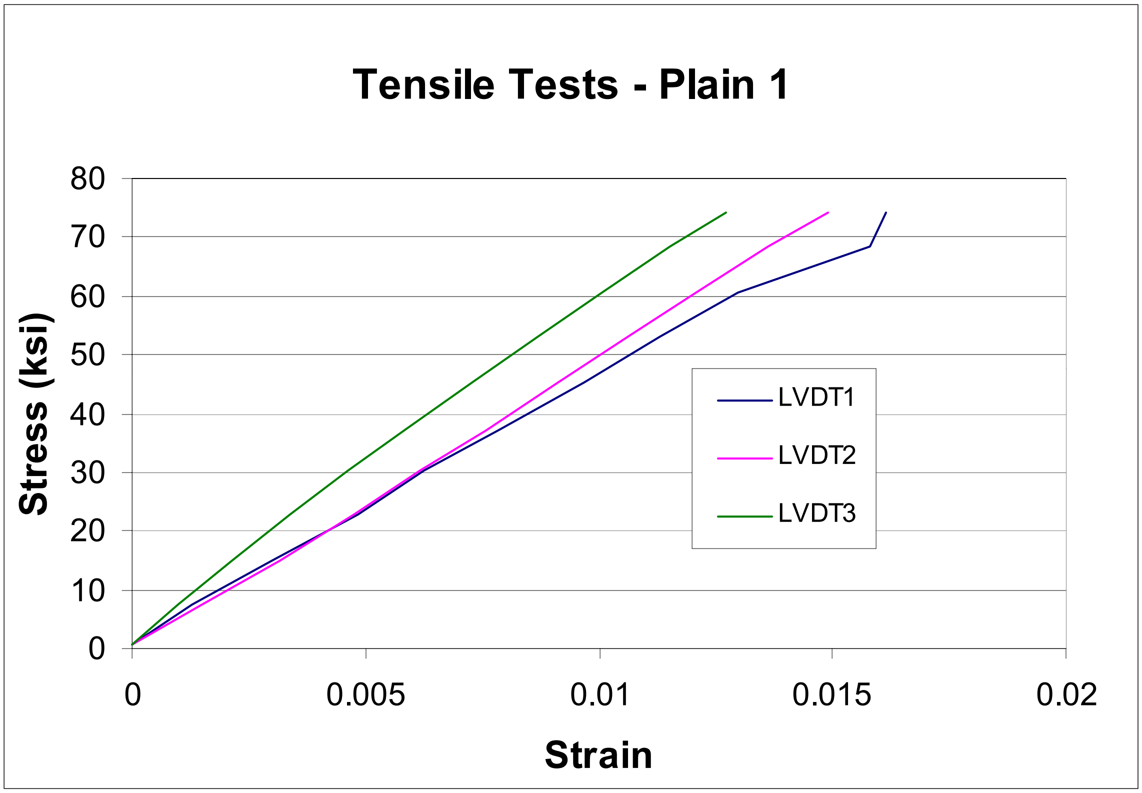
Tensile Tests:

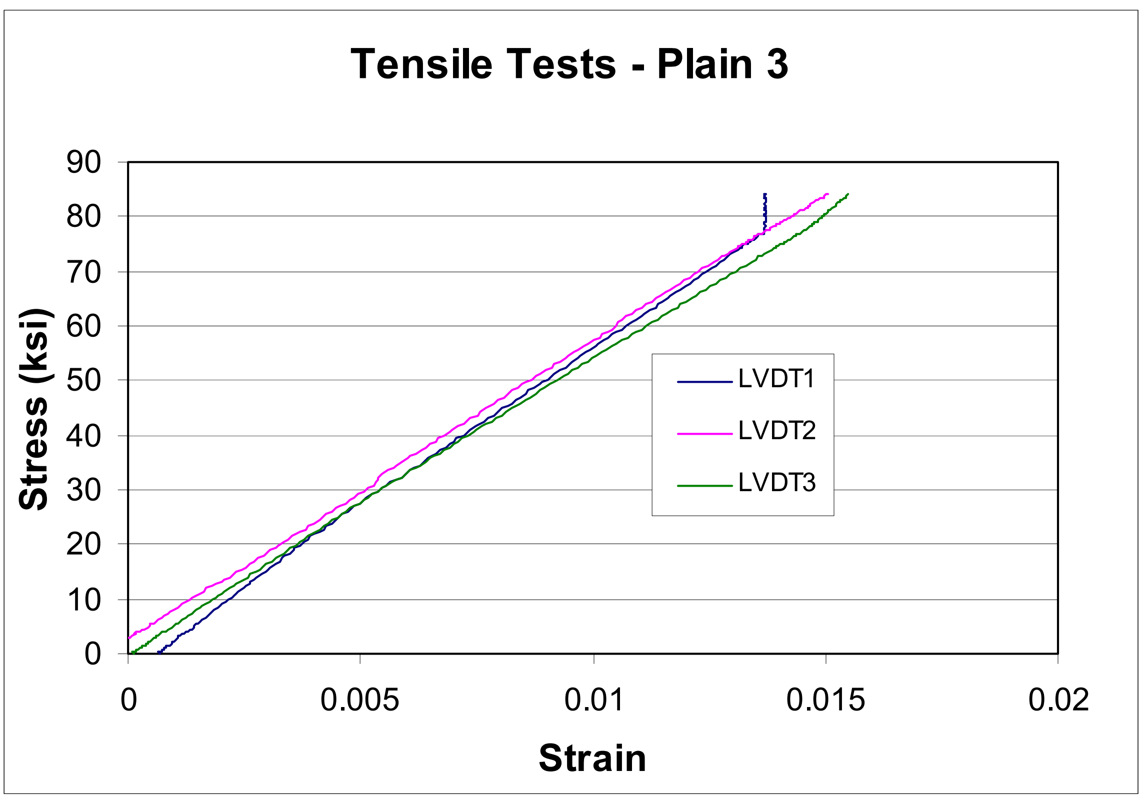
Legend entries are as follows:

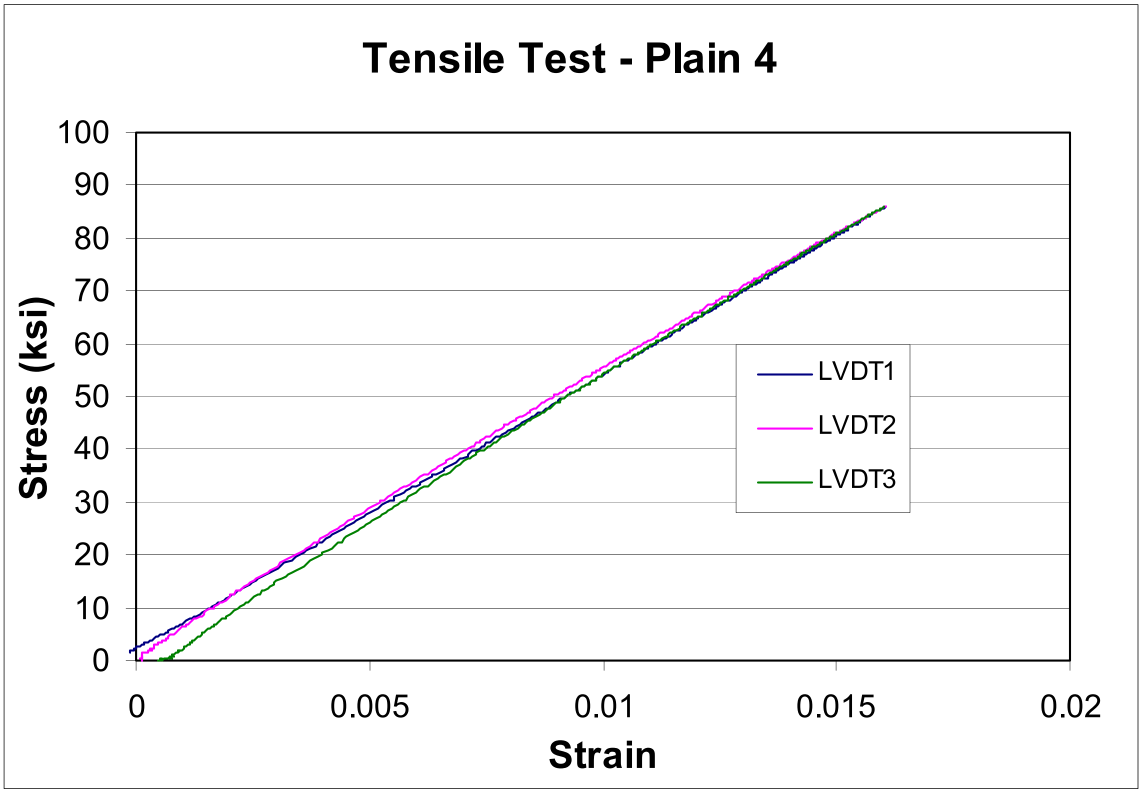
LVDT1 – Linear Variable Differential Transformers - 1

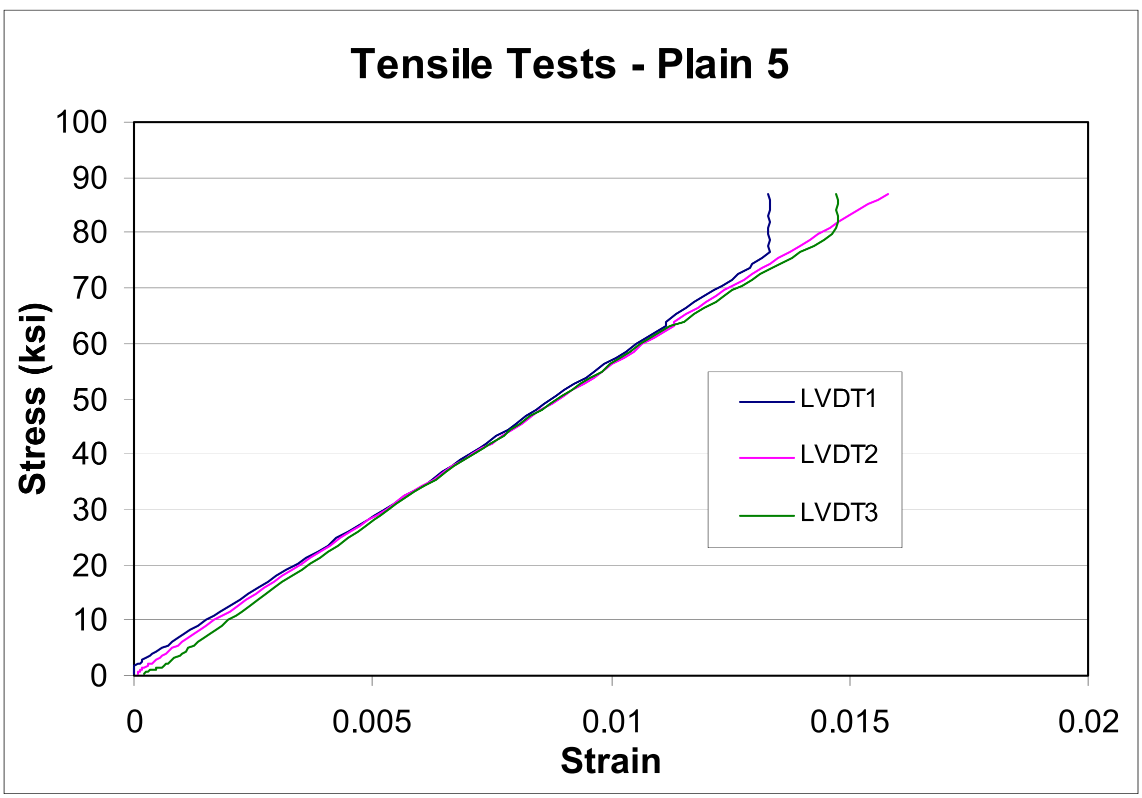
LVDT2 – Linear Variable Differential Transformers - 2

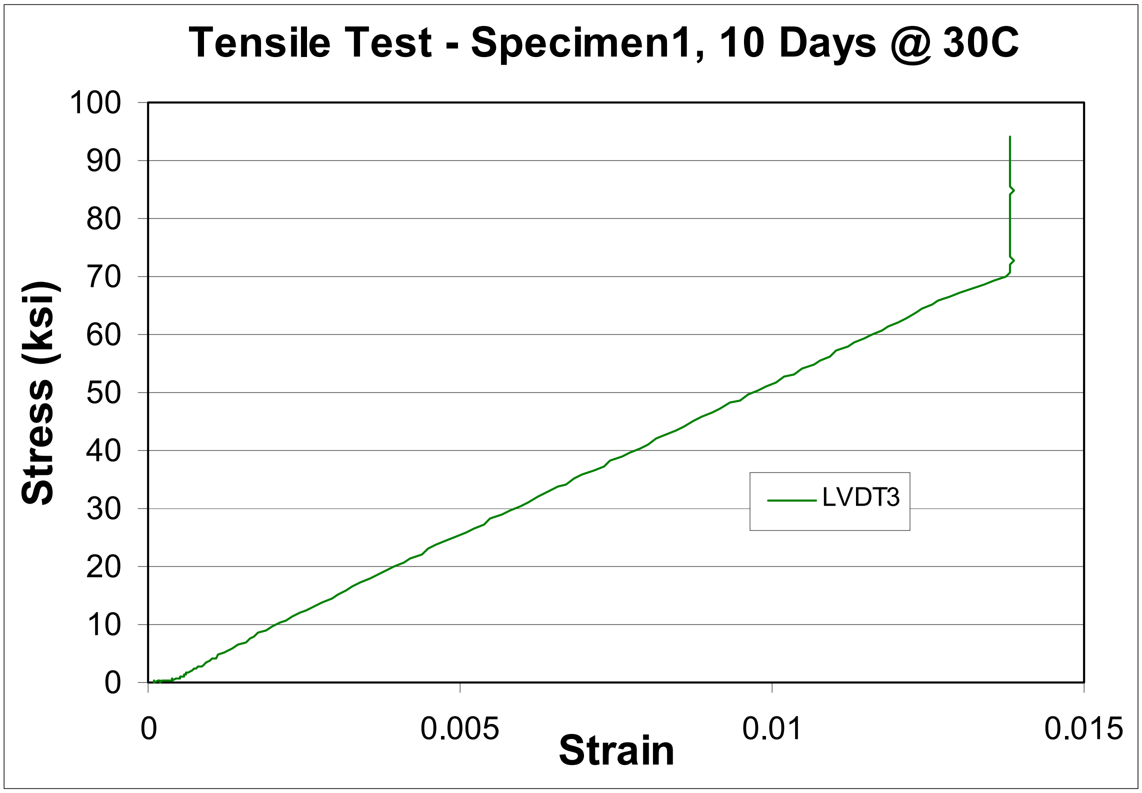
LVDT3 – Linear Variable Differential Transformers - 3

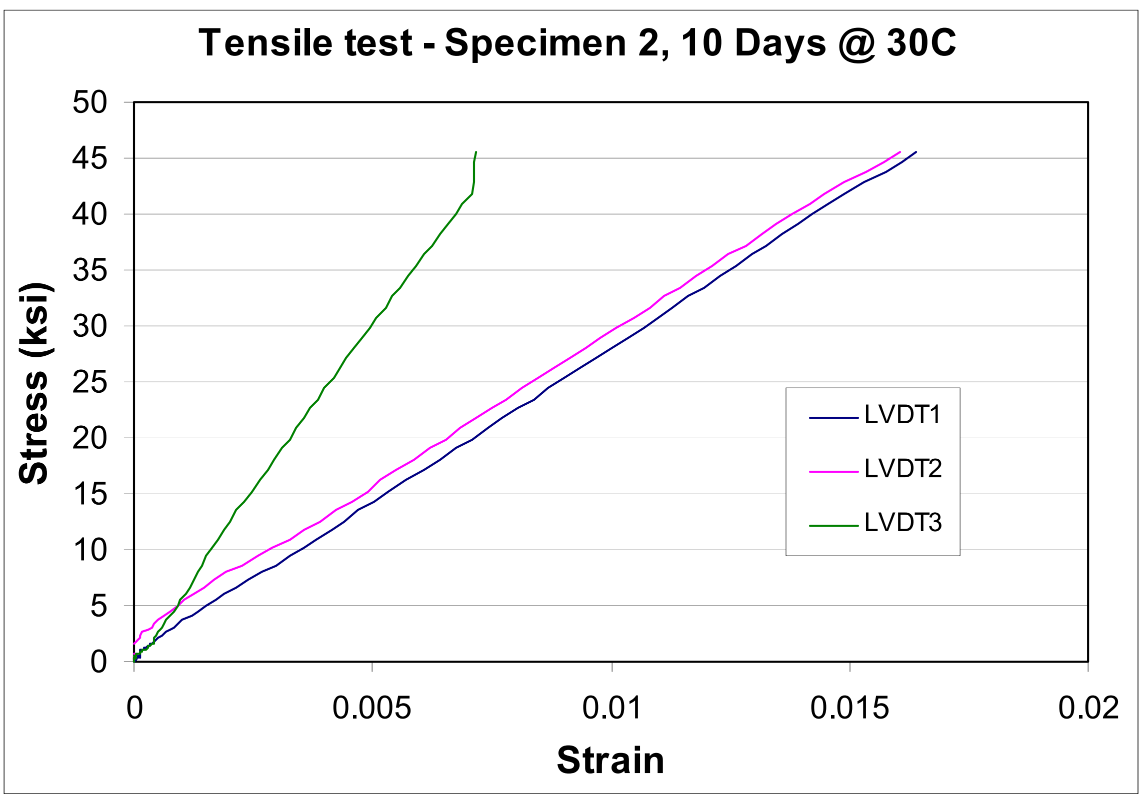

Tensile Tests - Plain 1
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
0
10
20
30
40
50
60
70
80
0
0.005
0.01
0.015
0.02

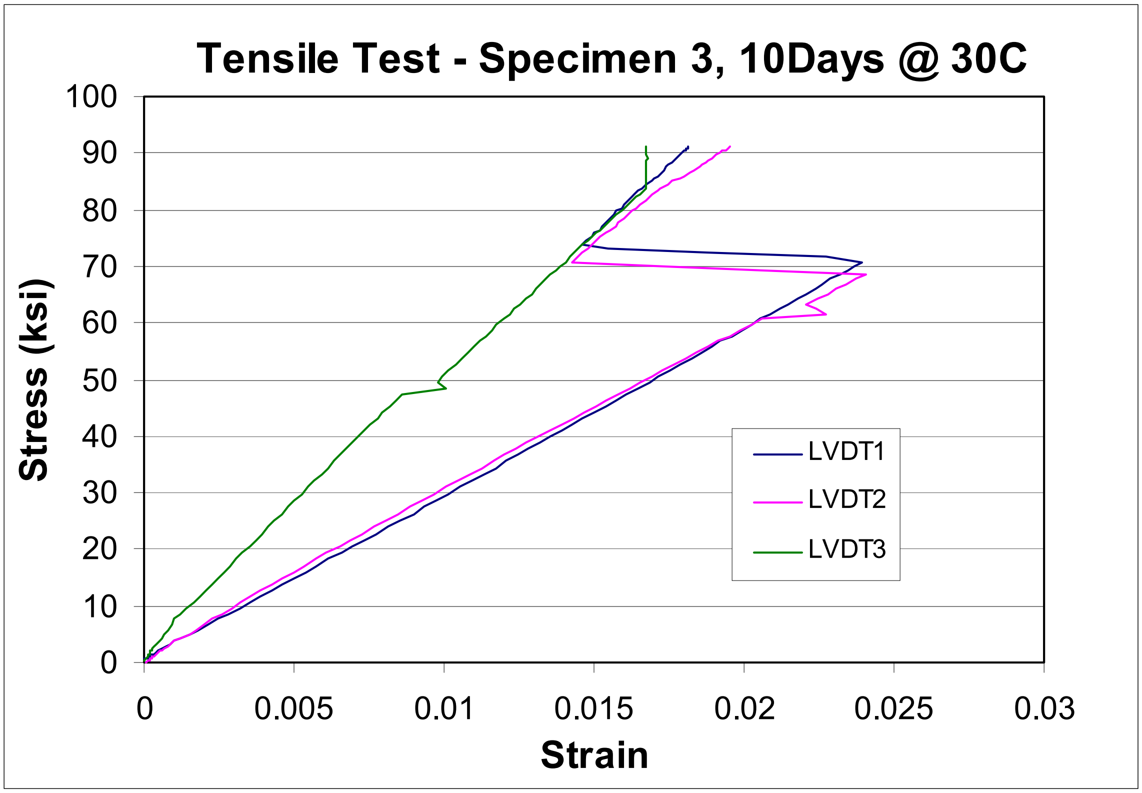

Tensile Tests - Plain 3
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
0
10
20
30
40
50
60
70
80
90
0
0.005
0.01
0.015
0.02


Tensile Test - Plain 4
Stress (ksi)
100
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3


Tensile Tests - Plain 5
Stress (ksi)
100
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3


Tensile Test - Specimen1, 10 Days @ 30C
Stress (ksi)
100
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
Strain
LVDT3


Tensile test - Specimen 2, 10 Days @ 30C
Stress (ksi)
50
45
40
35
30
25
20
15
10
5
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3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100
90
80
70
60
50
40
30
20
10
0
Stress (ksi)
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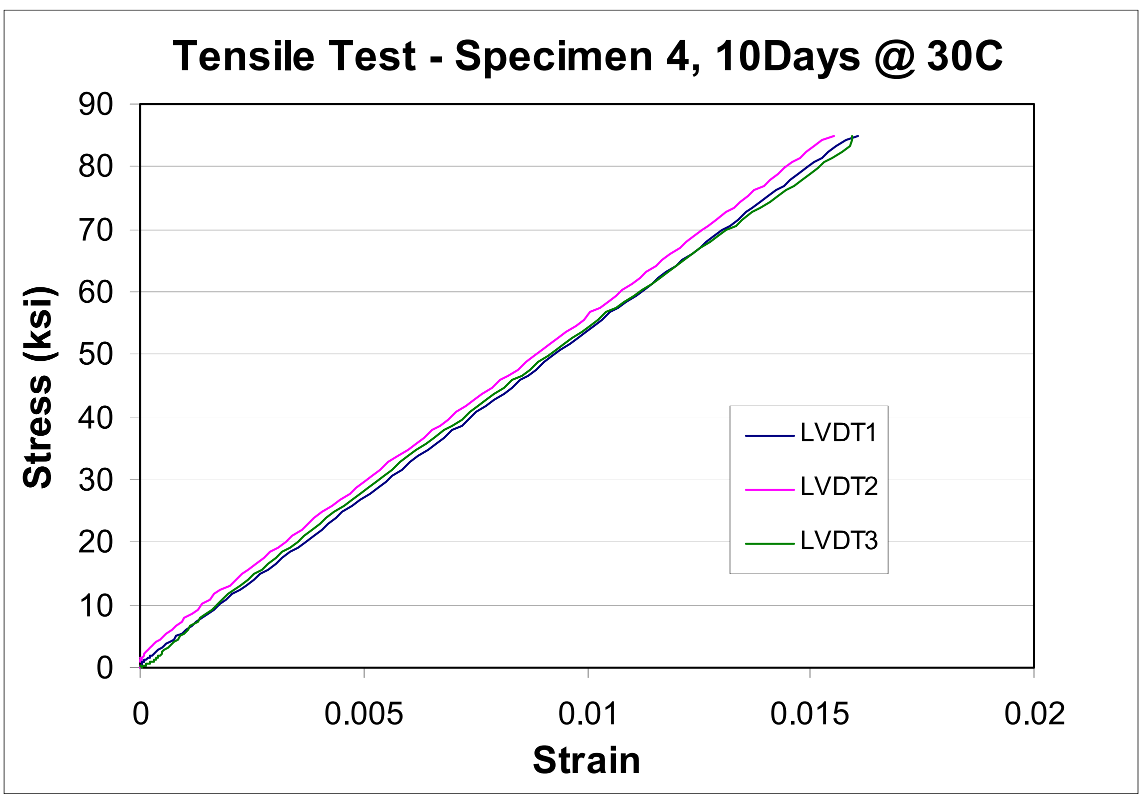
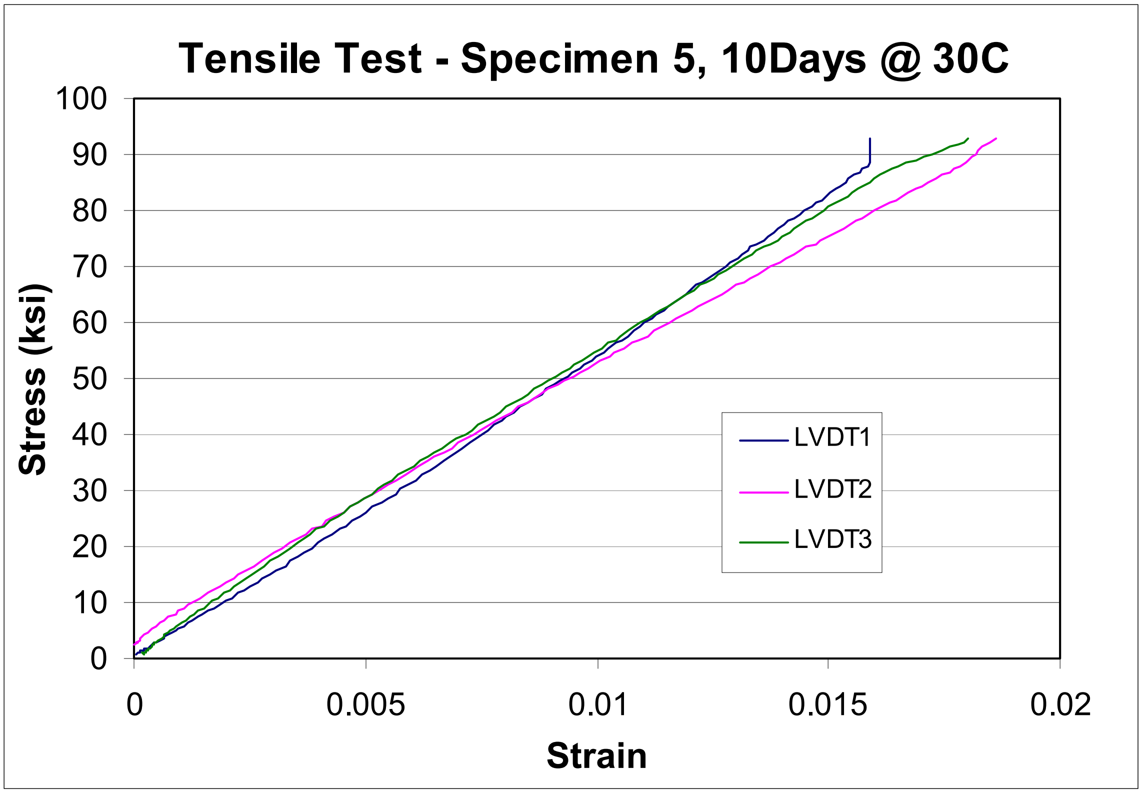
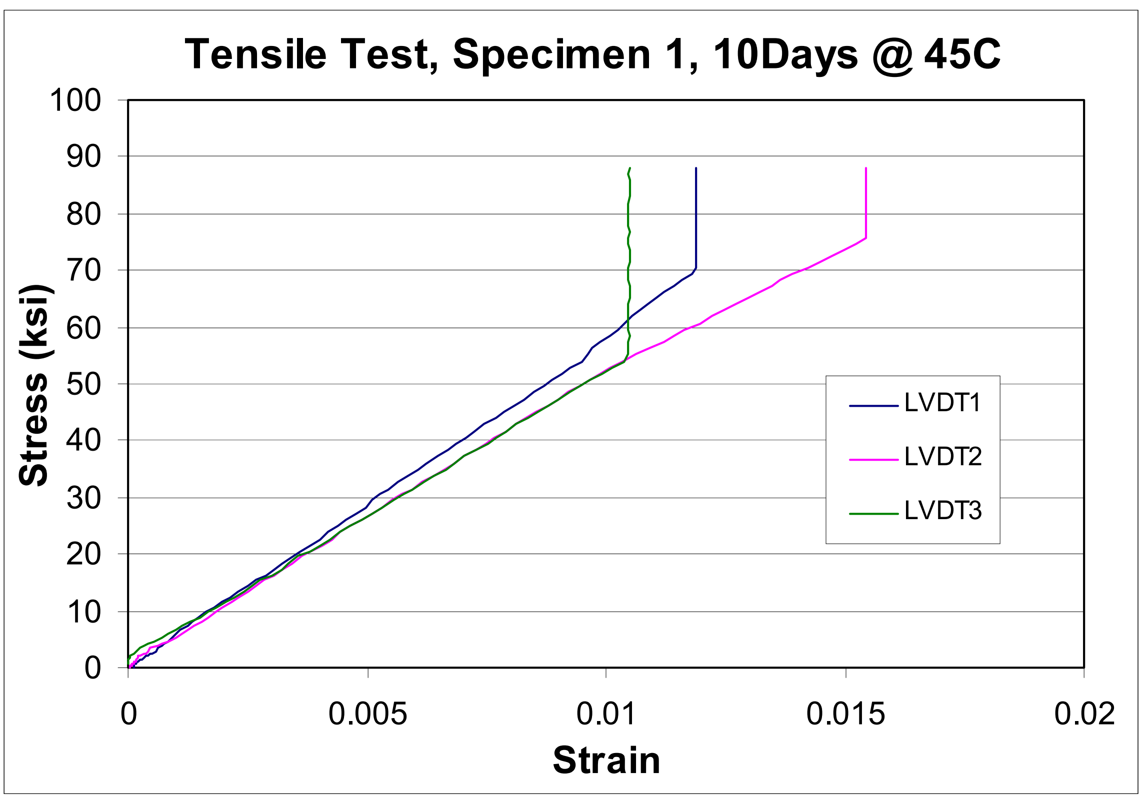
0.01
0.015
0.02
0.025
0.03
Strain
LVDT1
LVDT2
LVDT3

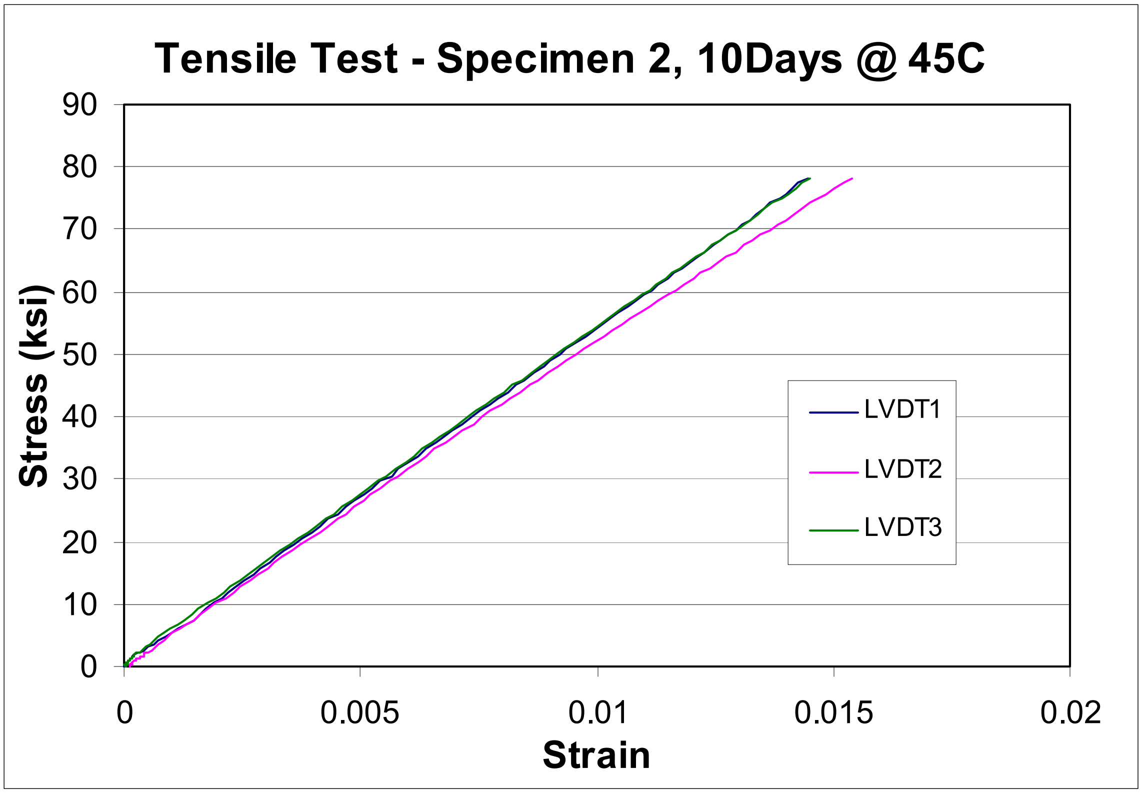

Tensile Test - Specimen 4, 10Days @ 30C
90
80
70
60
50
40
30
20
10
0
Stress (ksi)
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3

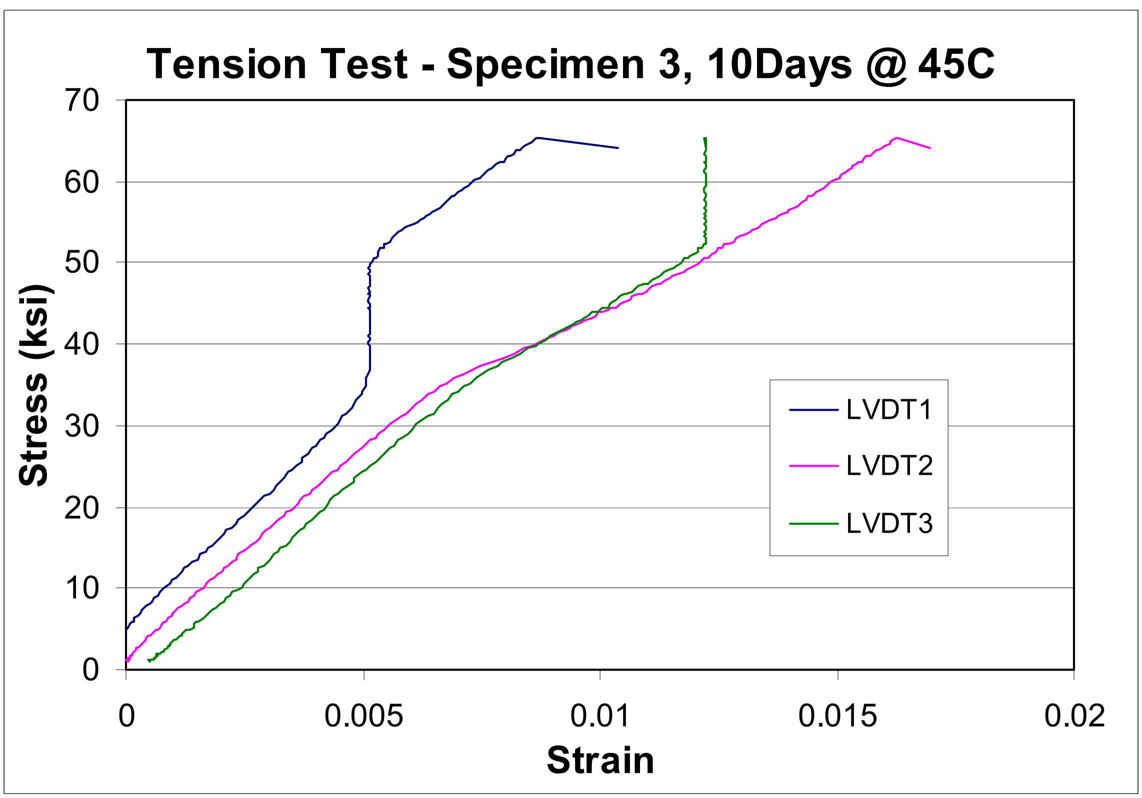


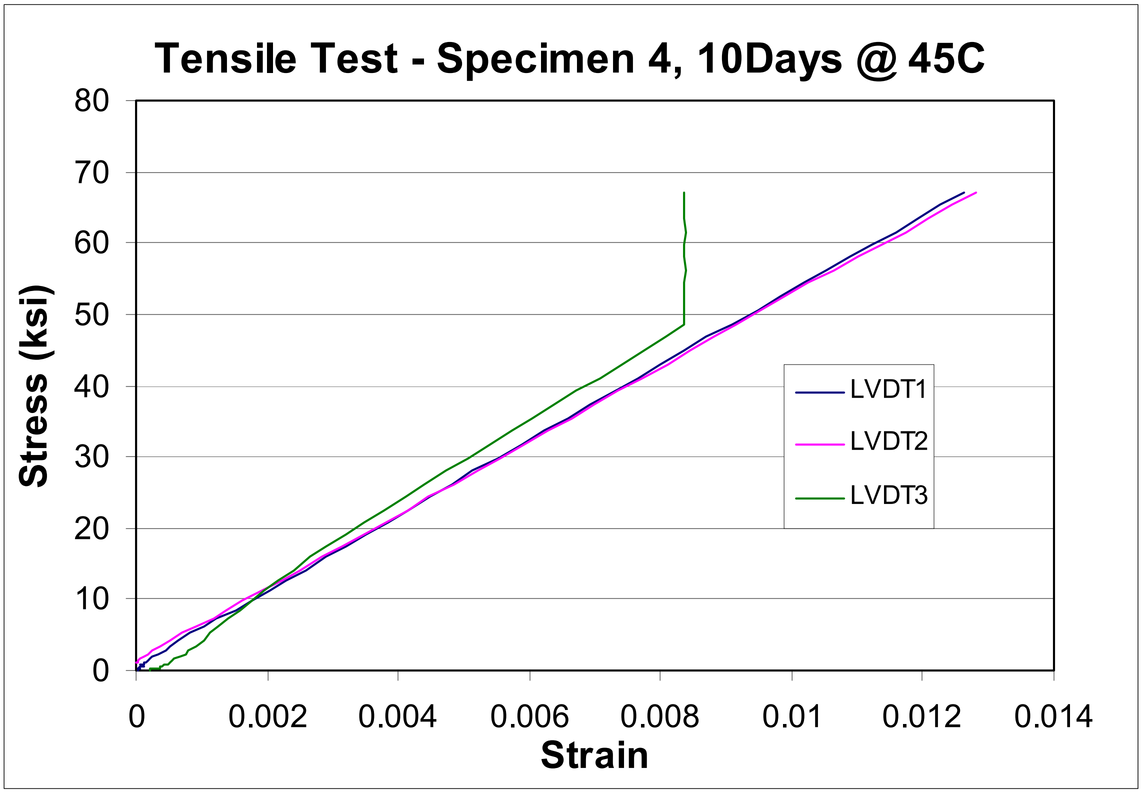
Tensile Test - Specimen 5, 10Days @ 30C
Stress (ksi)
100
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3



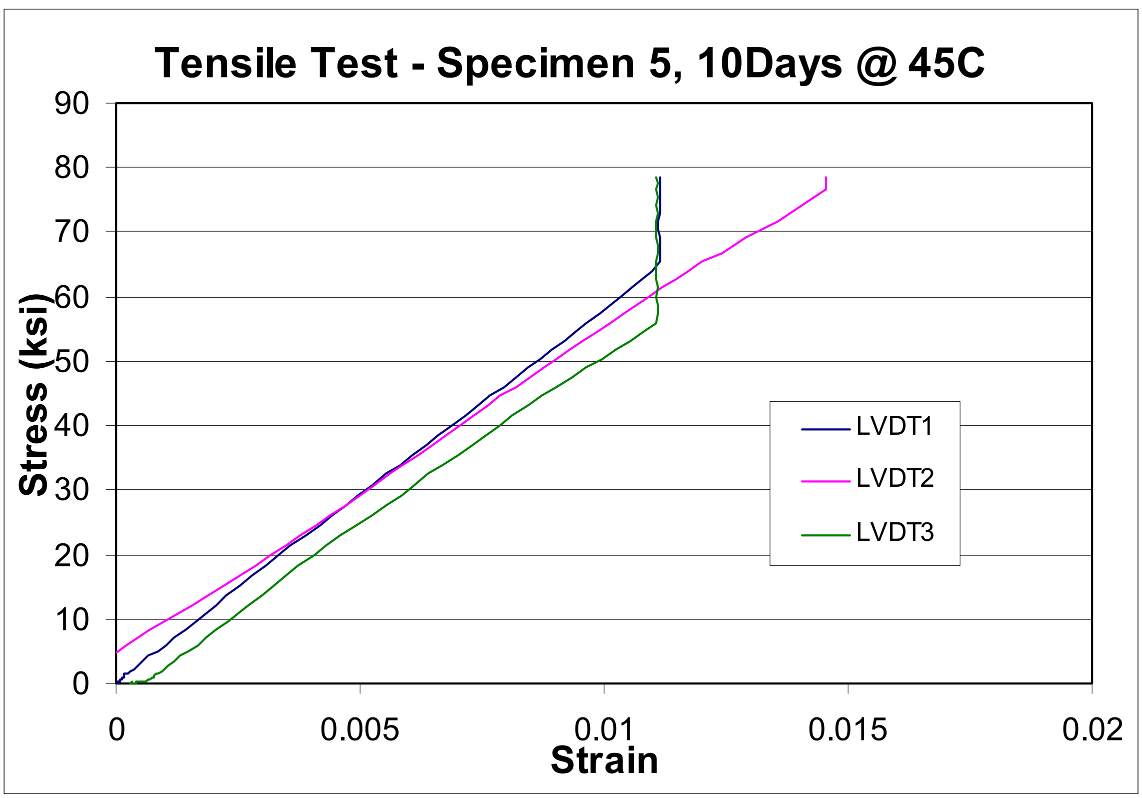
Tensile Test, Specimen 1, 10Days @ 45C
Stress (ksi)
100
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3


Tensile Test - Specimen 2, 10Days @ 45C
Stress (ksi)
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3


Tension Test - Specimen 3, 10Days @ 45C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3



Tensile Test - Specimen 4, 10Days @ 45C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
0
10
20
30
40
50
60
70
80
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014



Tensile Test - Specimen 5, 10Days @ 45C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
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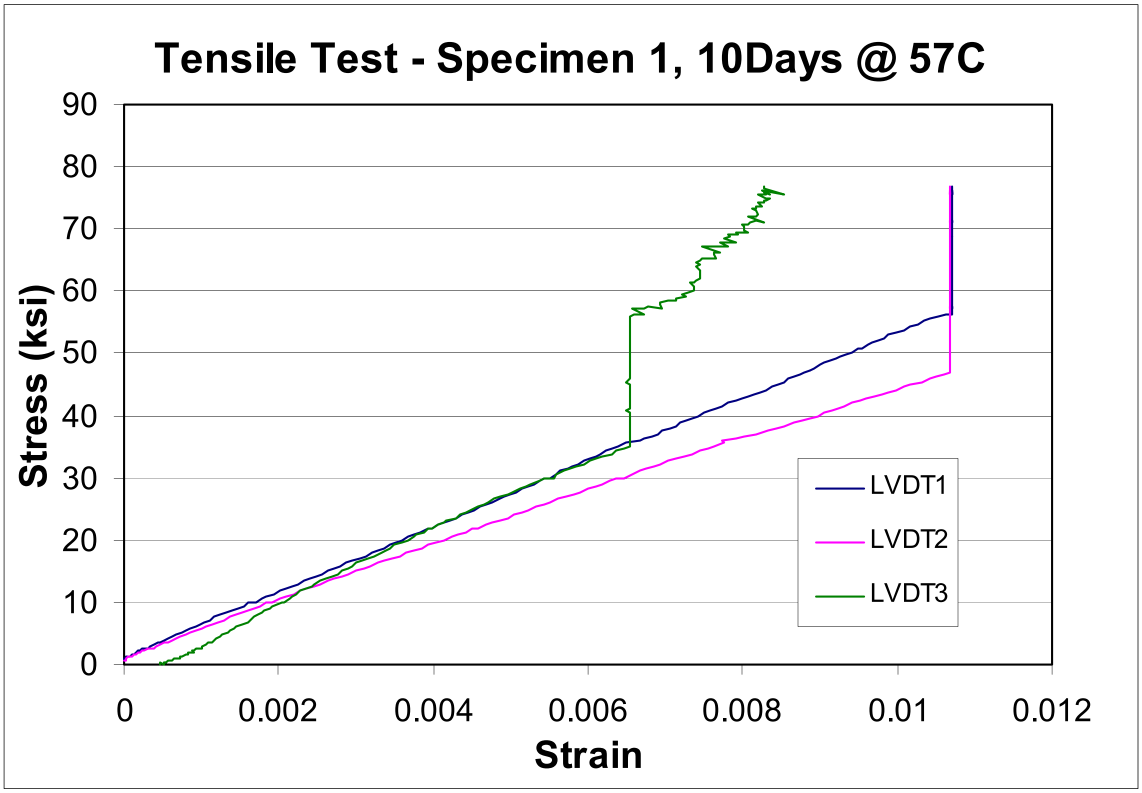
10
20
30
40
50
60
70
80
90
0
0.005
0.01
0.015
0.02


Tensile Test - Specimen 1, 10Days @ 57C
Stress (ksi)
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80
70
60
50
40
30
20
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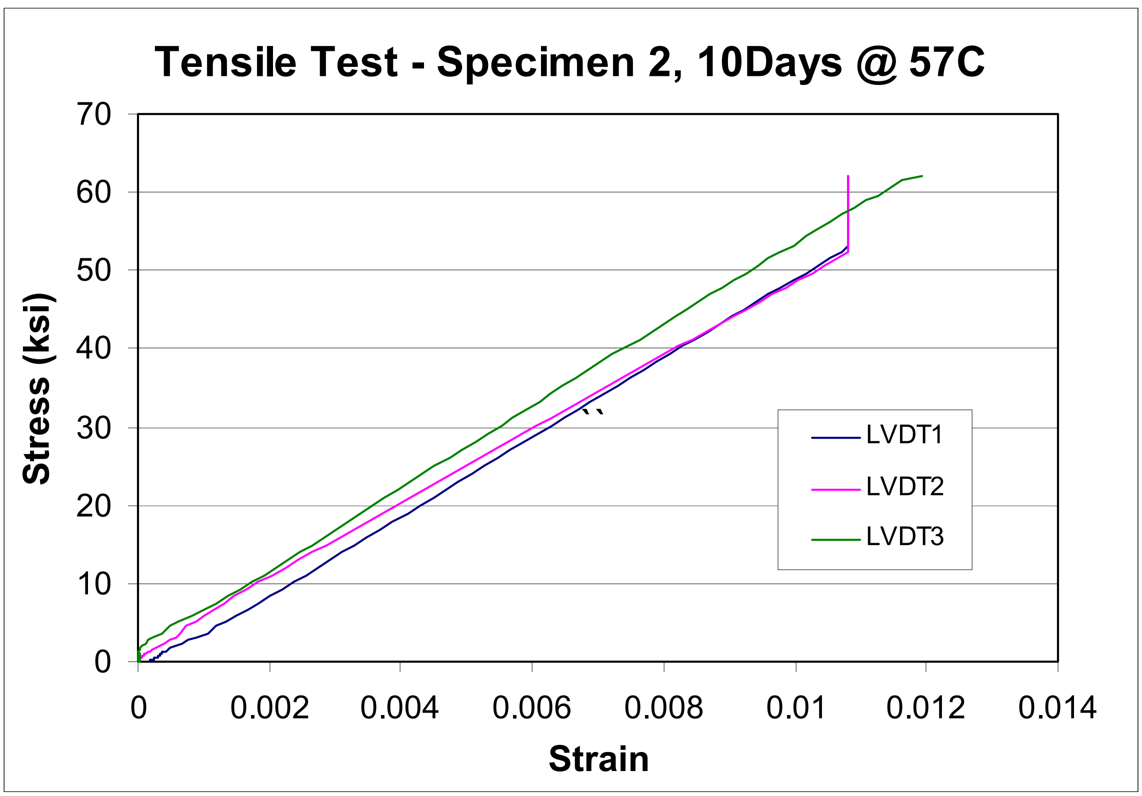
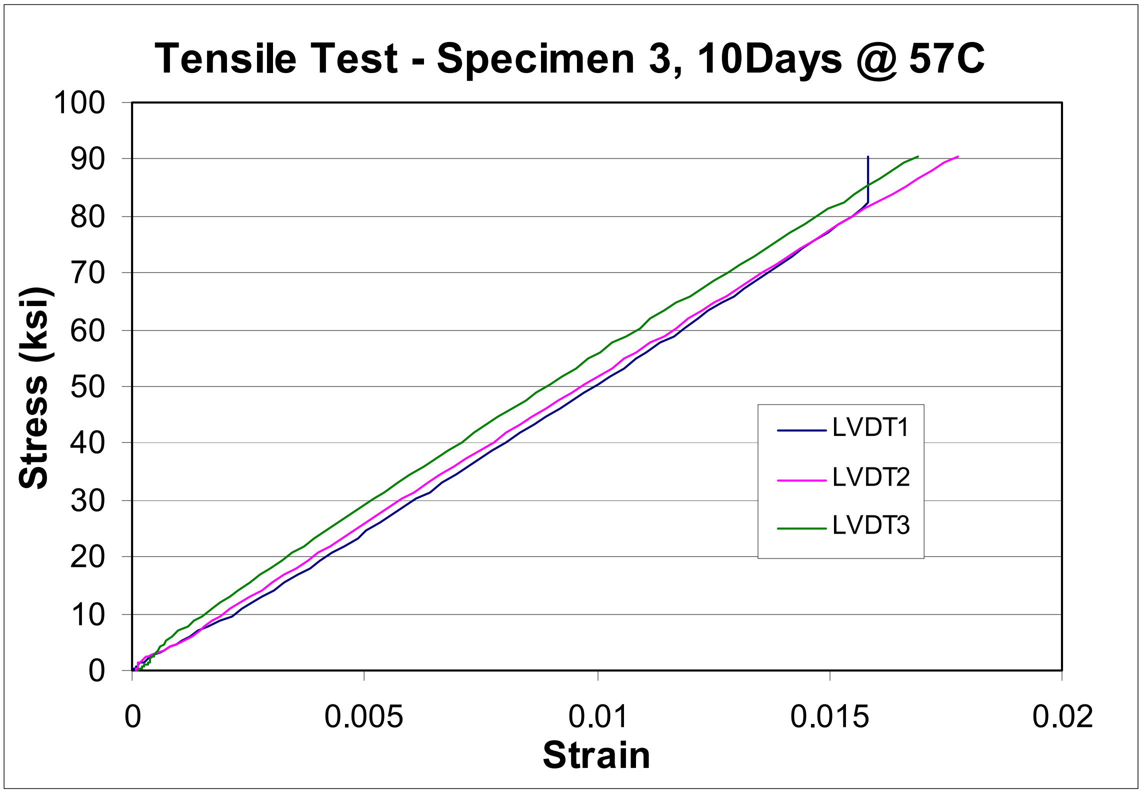
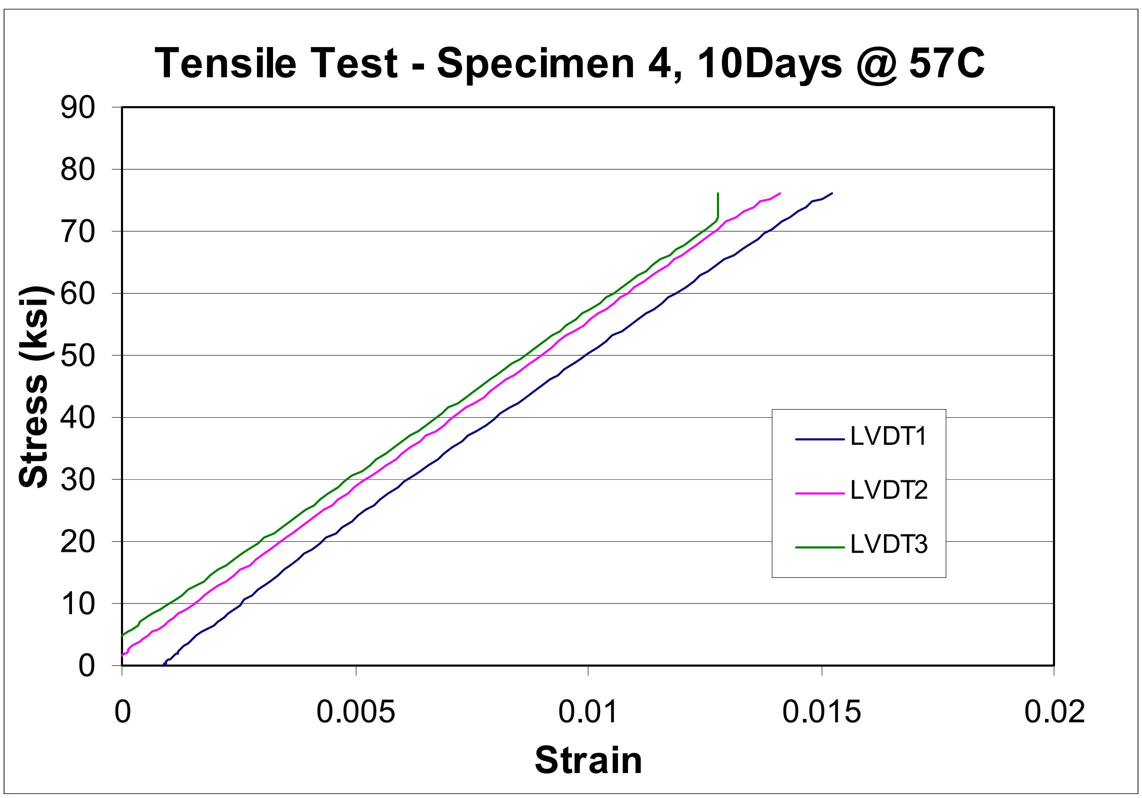
0.004
0.006
0.008
0.01
0.012
Strain
LVDT1
LVDT2
LVDT3

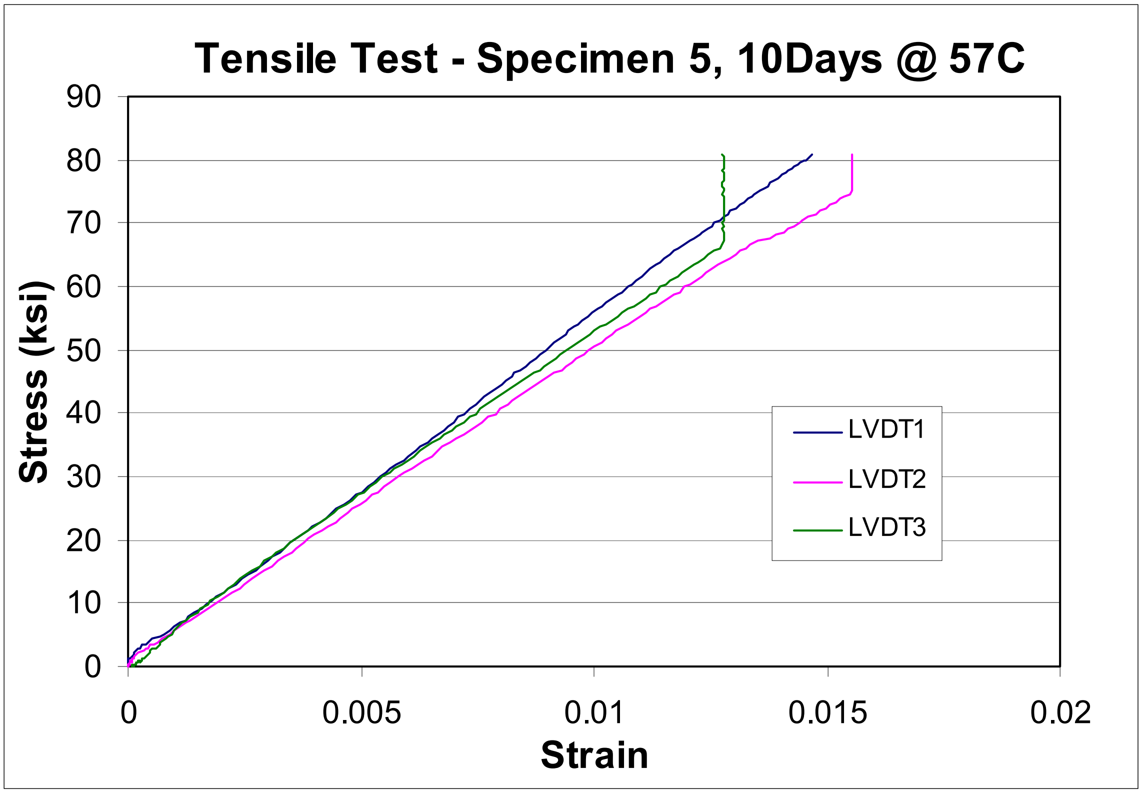

Tensile Test - Specimen 2, 10Days @ 57C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3



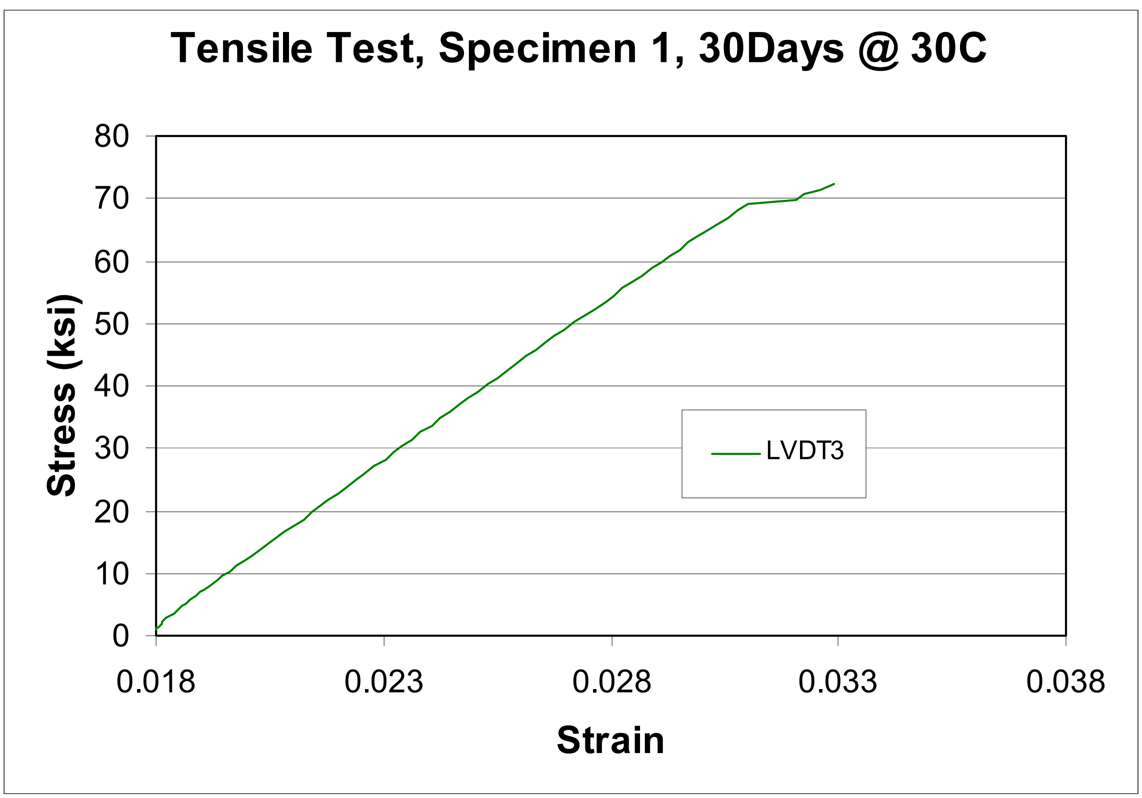
Tensile Test - Specimen 3, 10Days @ 57C
Stress (ksi)
100
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3



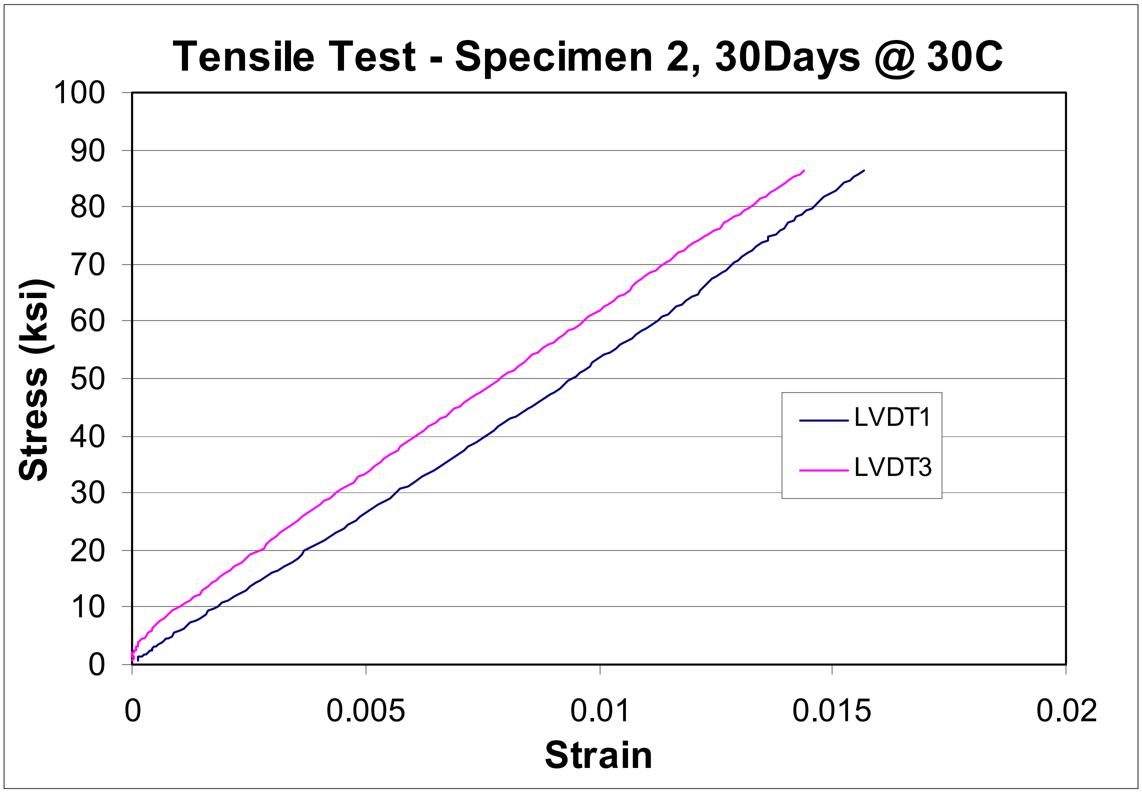
Tensile Test - Specimen 4, 10Days @ 57C
Stress (ksi)
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3

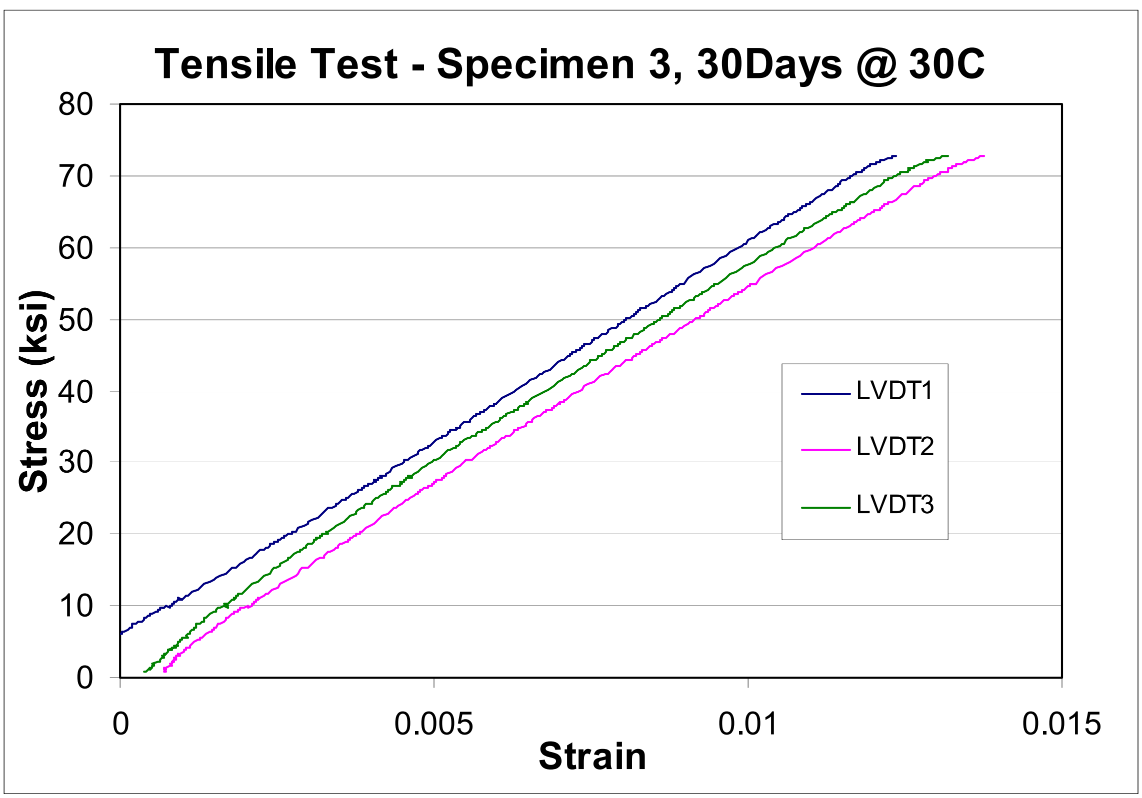


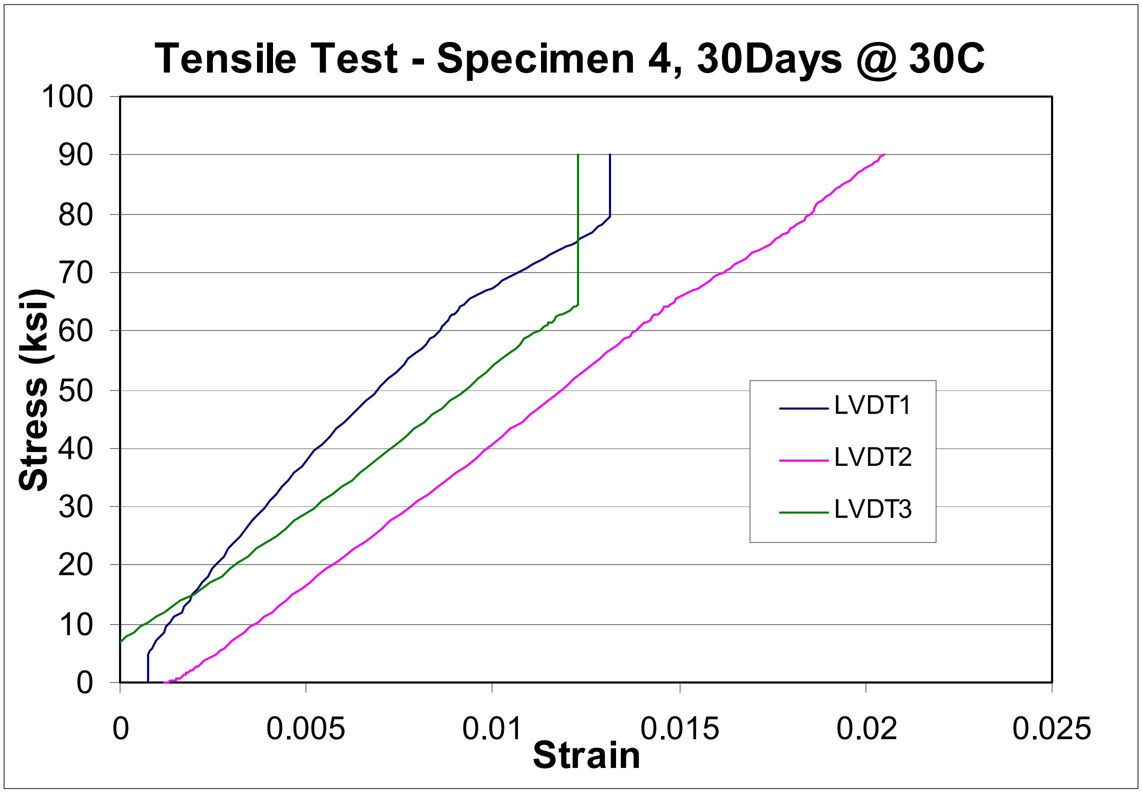
Tensile Test - Specimen 5, 10Days @ 57C
Stress (ksi)
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3

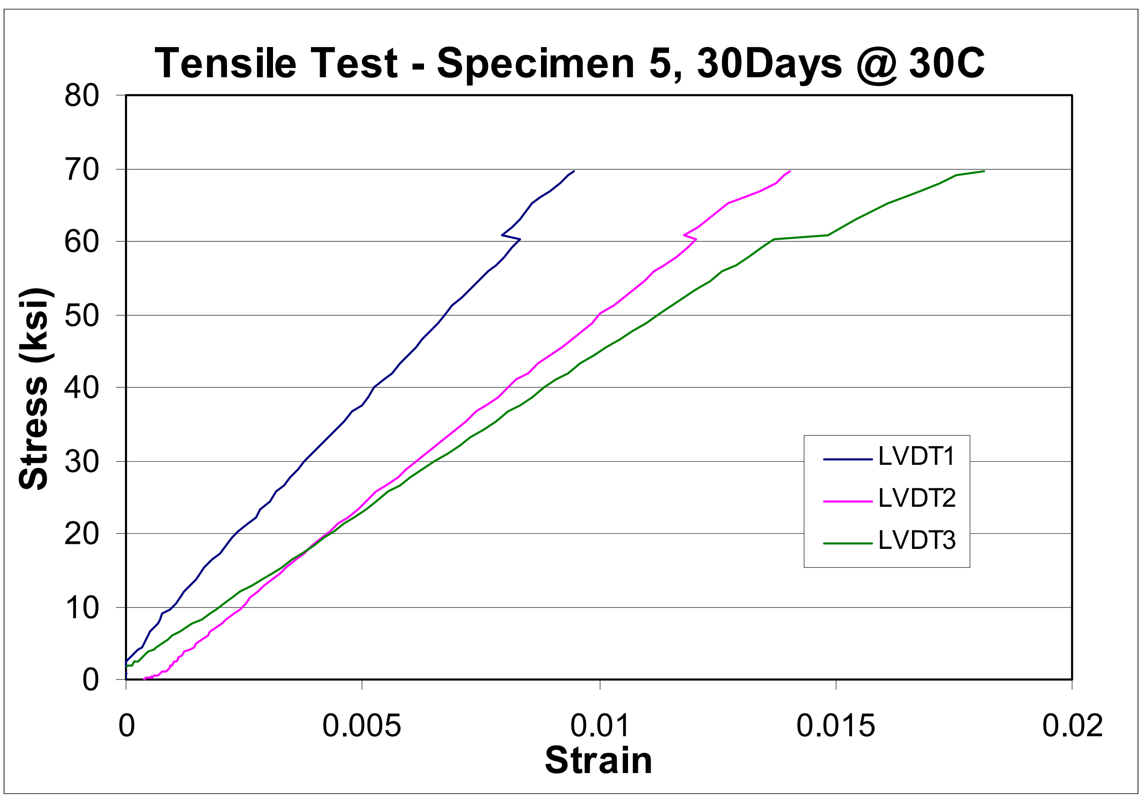


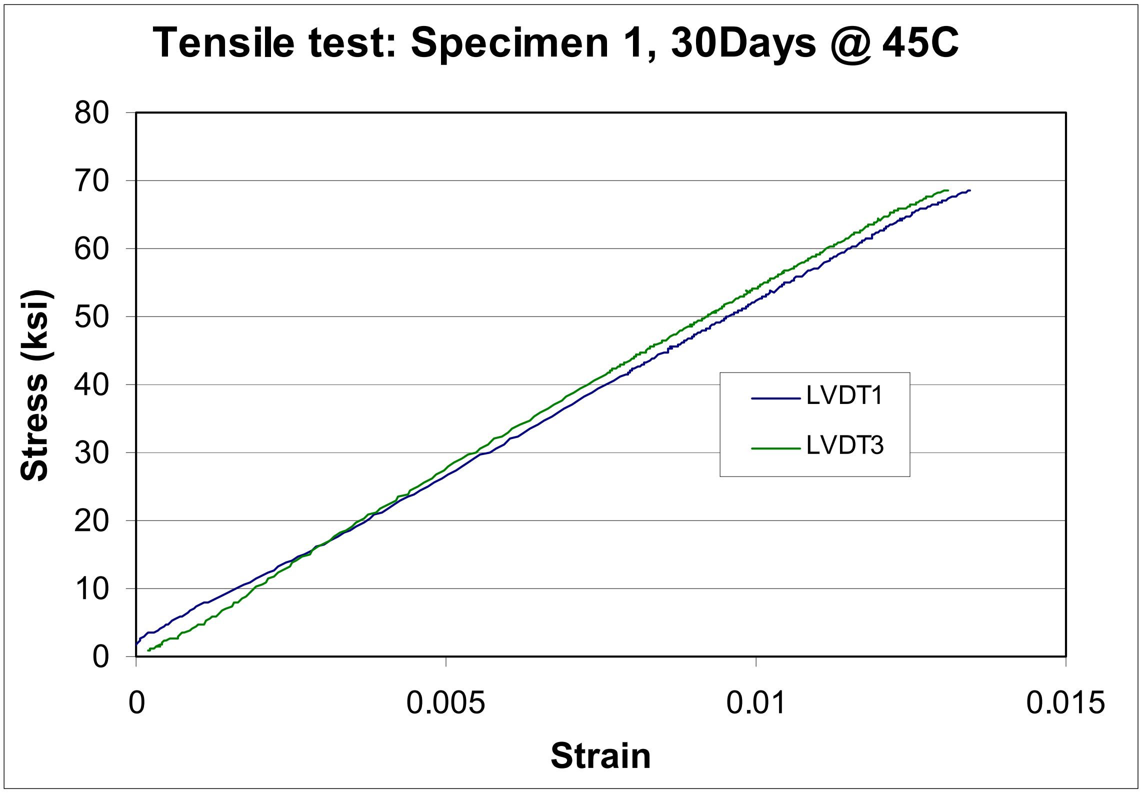
Tensile Test, Specimen 1, 30Days @ 30C
Stress (ksi)
80
70
60
50
40
30
20
10
0
0.018
0.023
0.028
0.033
0.038
Strain
LVDT3

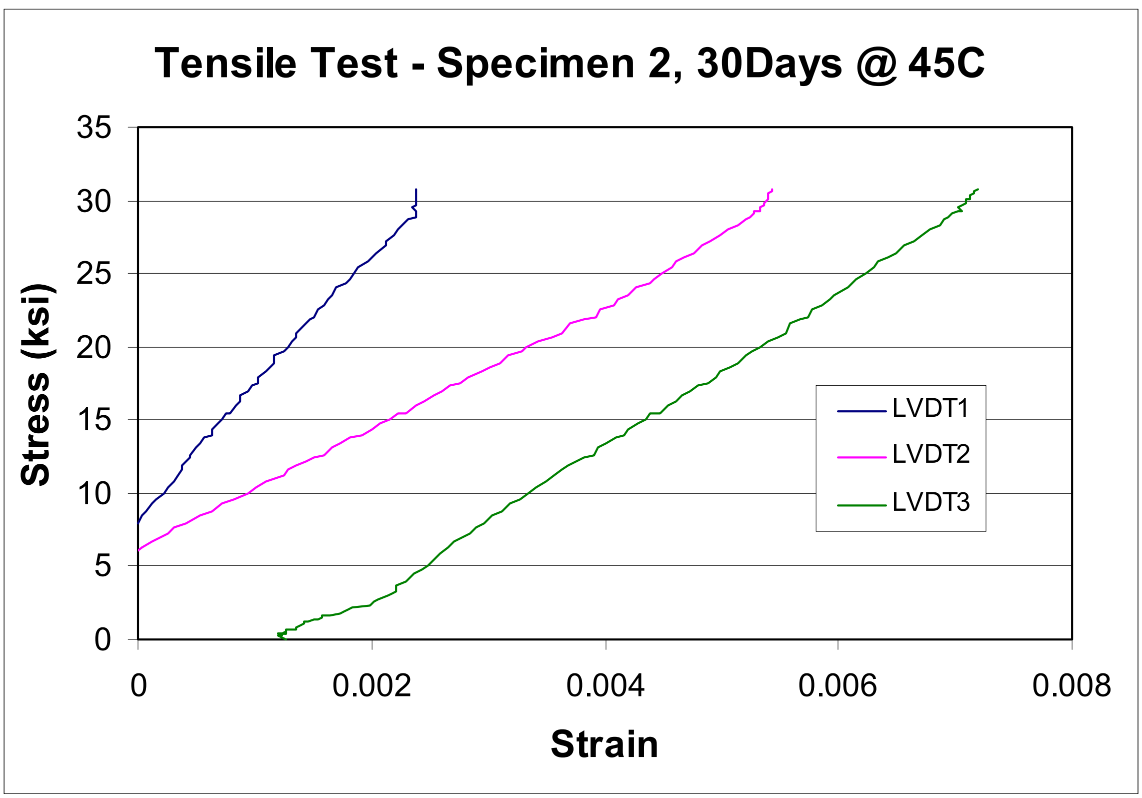

Tensile Test - Specimen 2, 30Days @ 30C
Stress (ksi)
100
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT3

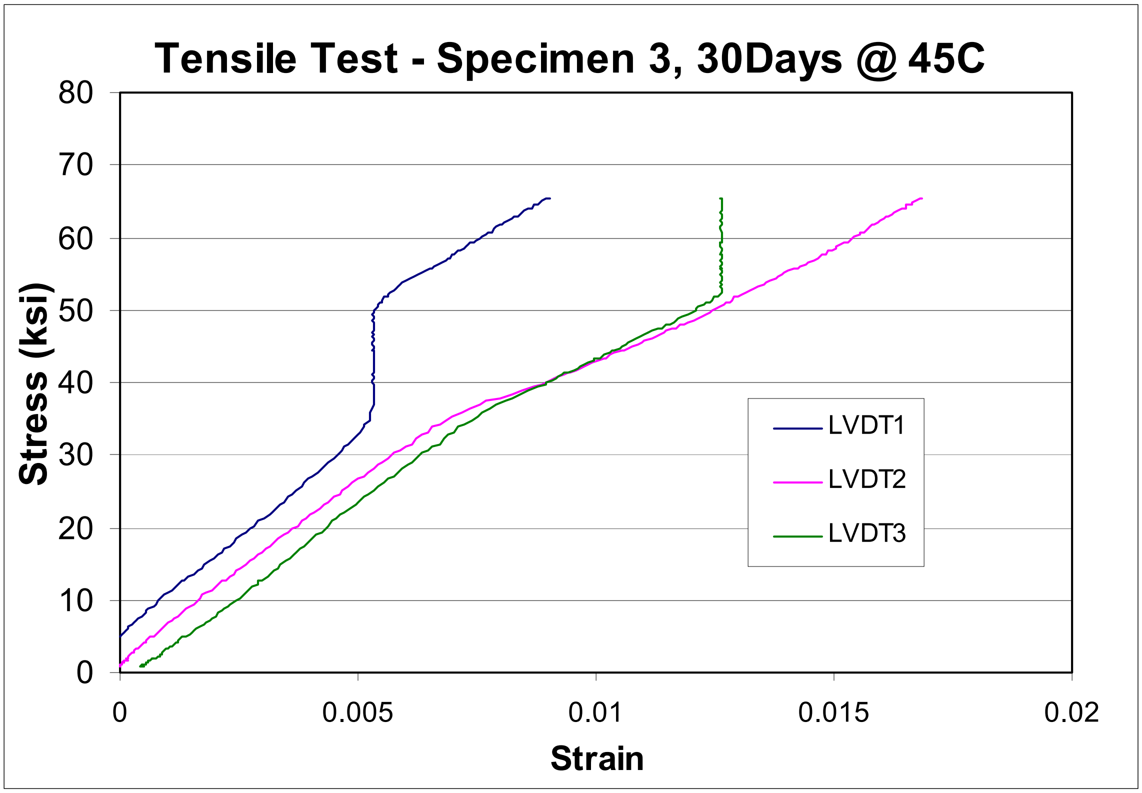

Tensile Test - Specimen 3, 30Days @ 30C
Stress (ksi)
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
Strain
LVDT1
LVDT2
LVDT3

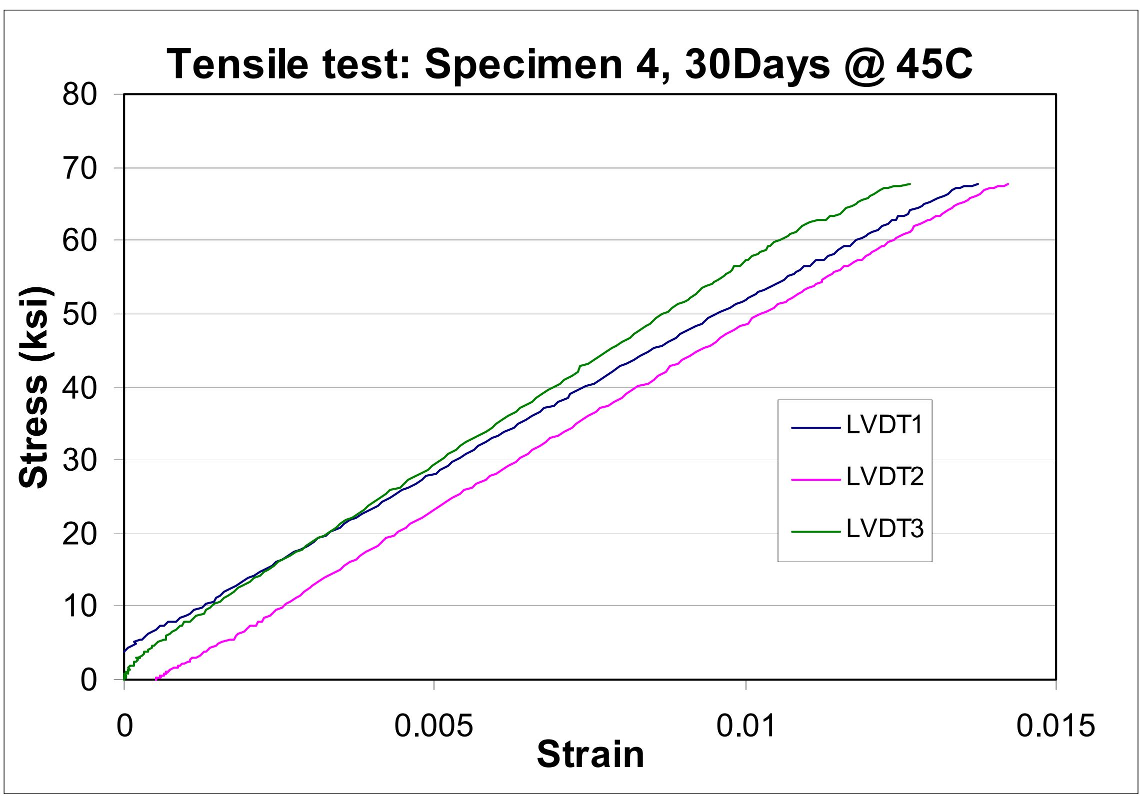

Tensile Test - Specimen 4, 30Days @ 30C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
0
10
20
30
40
50
60
70
80
90
100
0
0.005
0.01
0.015
0.02
0.025

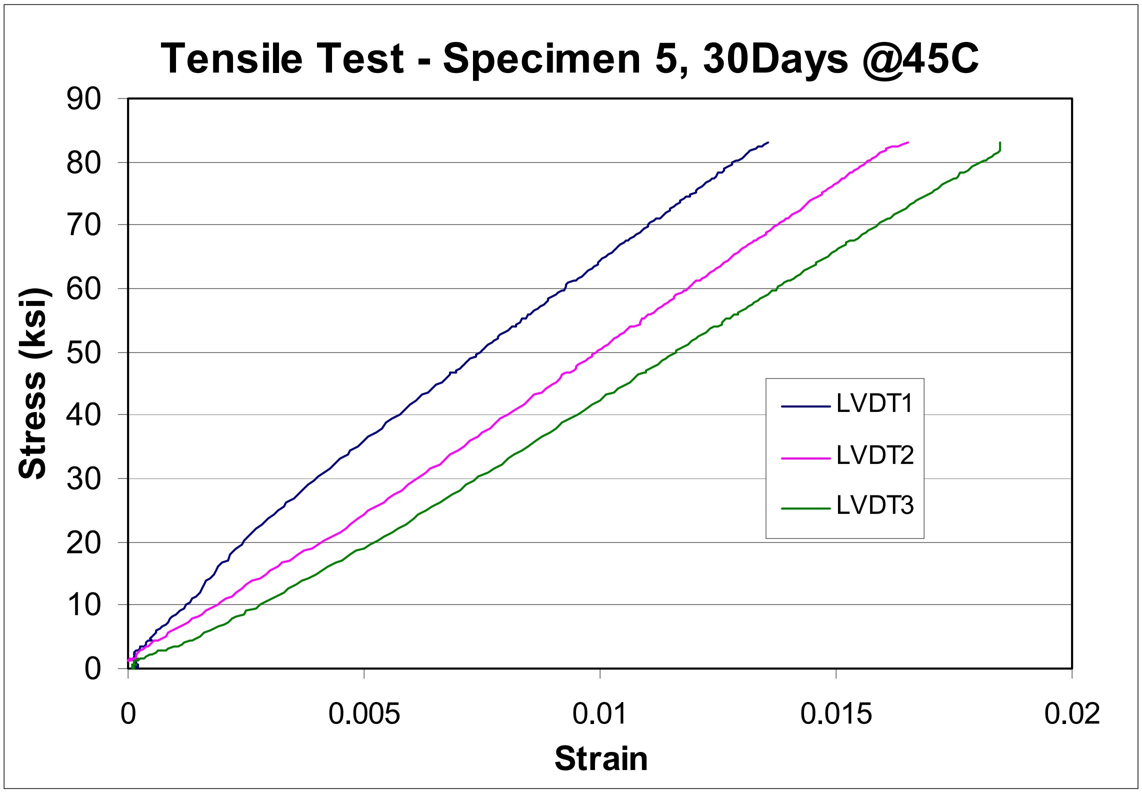

Tensile Test - Specimen 5, 30Days @ 30C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
0
10
20
30
40
50
60
70
80
0
0.005
0.01
0.015
0.02


Tensile test: Specimen 1, 30Days @ 45C
Stress (ksi)
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
Strain
LVDT1
LVDT3

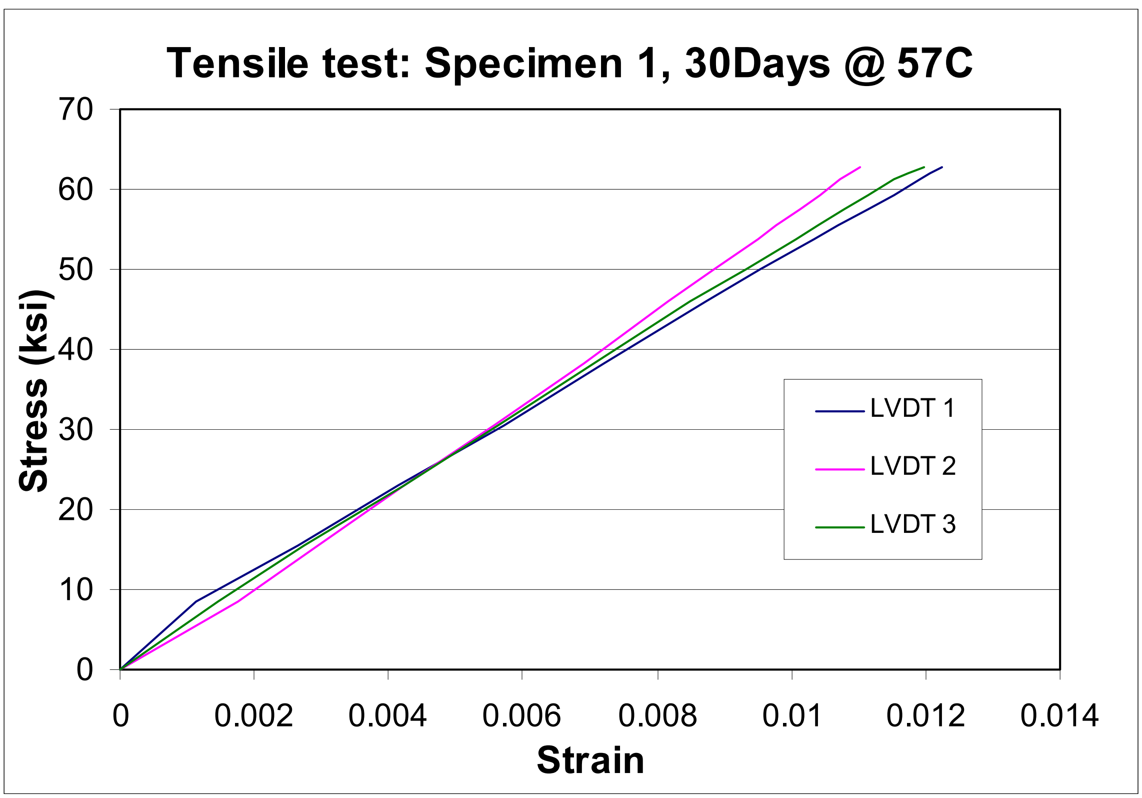

Tensile Test - Specimen 2, 30Days @ 45C
Stress (ksi)
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
Strain
LVDT1
LVDT2
LVDT3


Tensile Test - Specimen 3, 30Days @ 45C
Stress (ksi)
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3

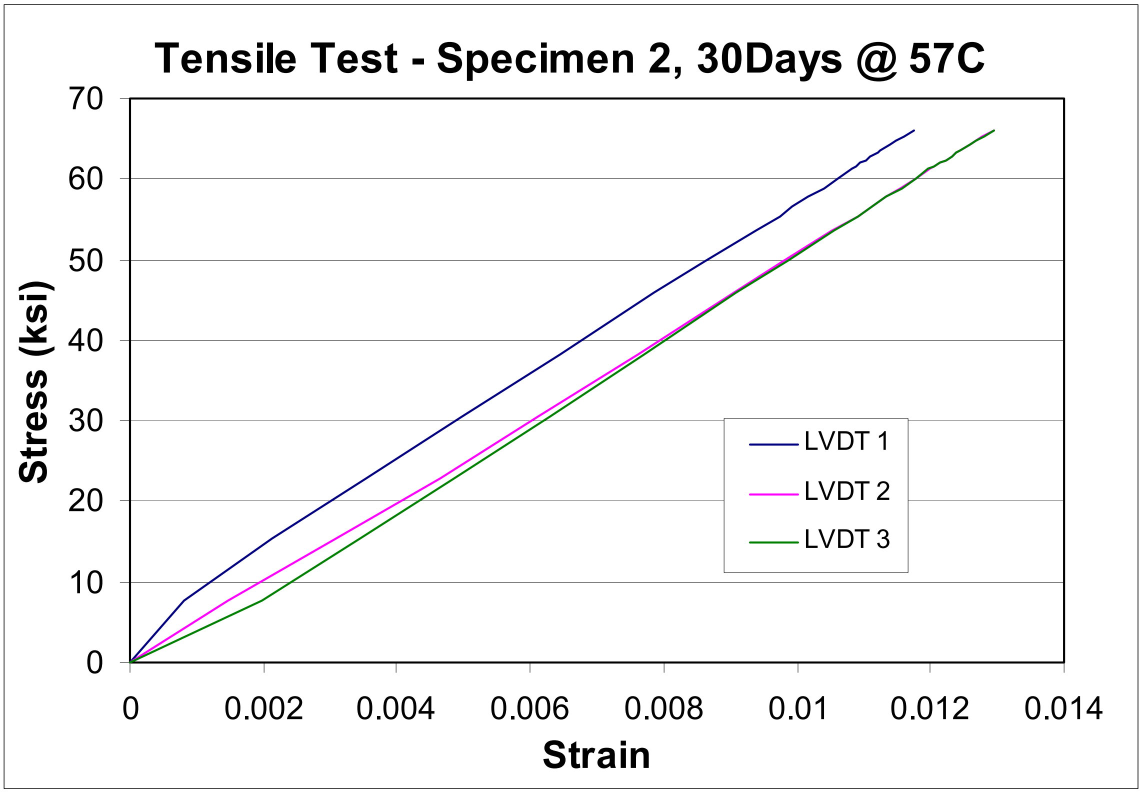

Tensile test: Specimen 4, 30Days @ 45C
Stress (ksi)
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
Strain
LVDT1
LVDT2
LVDT3

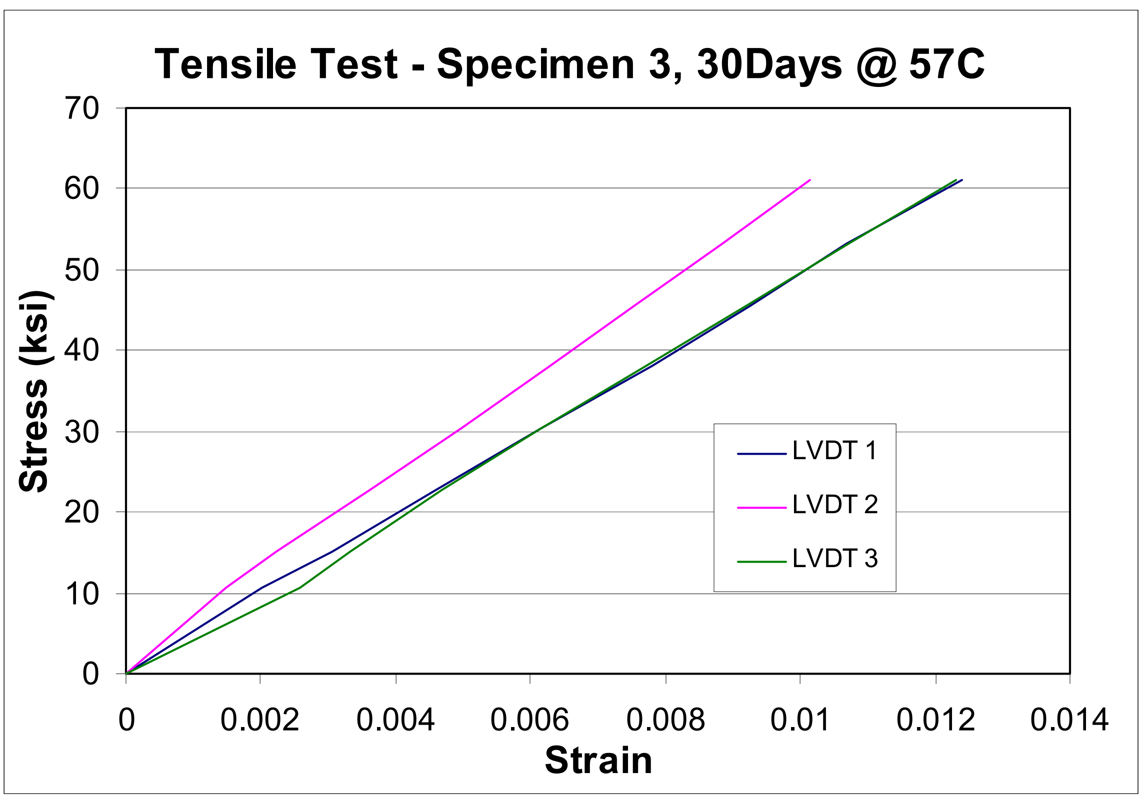


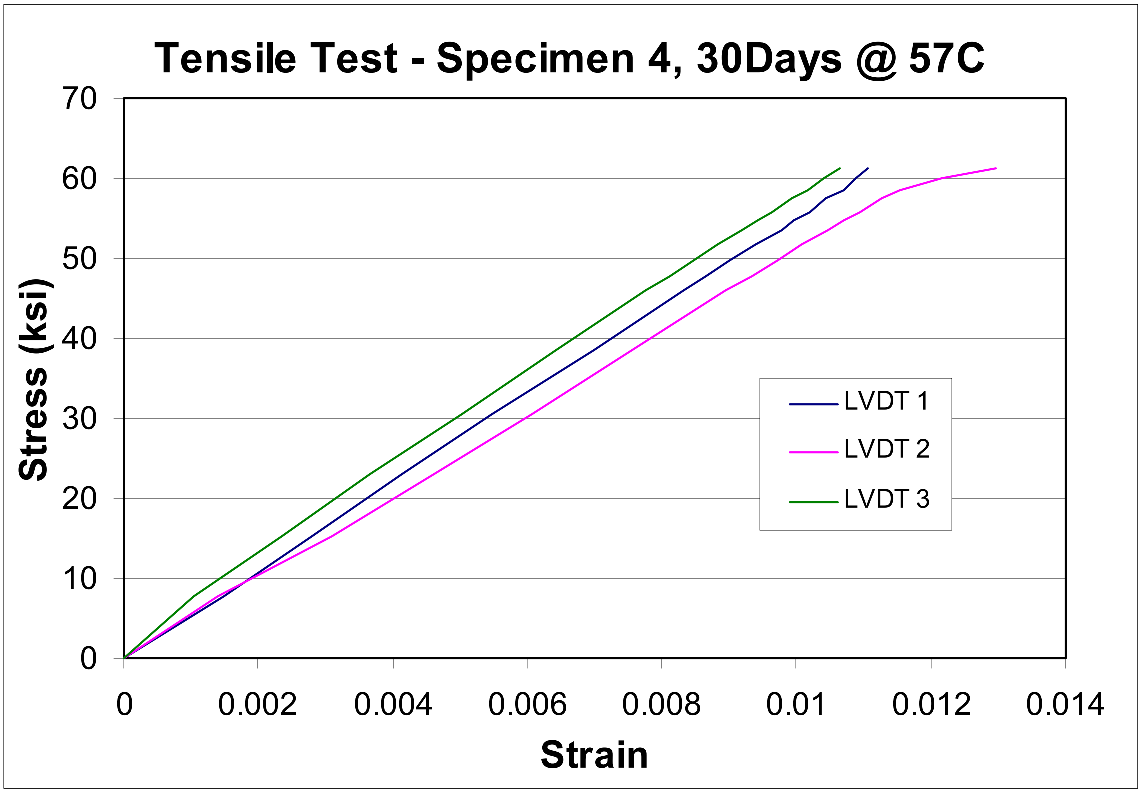
Tensile Test - Specimen 5, 30Days @45C
Stress (ksi)
Strain
0
10
20
30
40
50
60
70
80
90
0
0.005
0.01
0.015
0.02
LVDT1
LVDT2
LVDT3

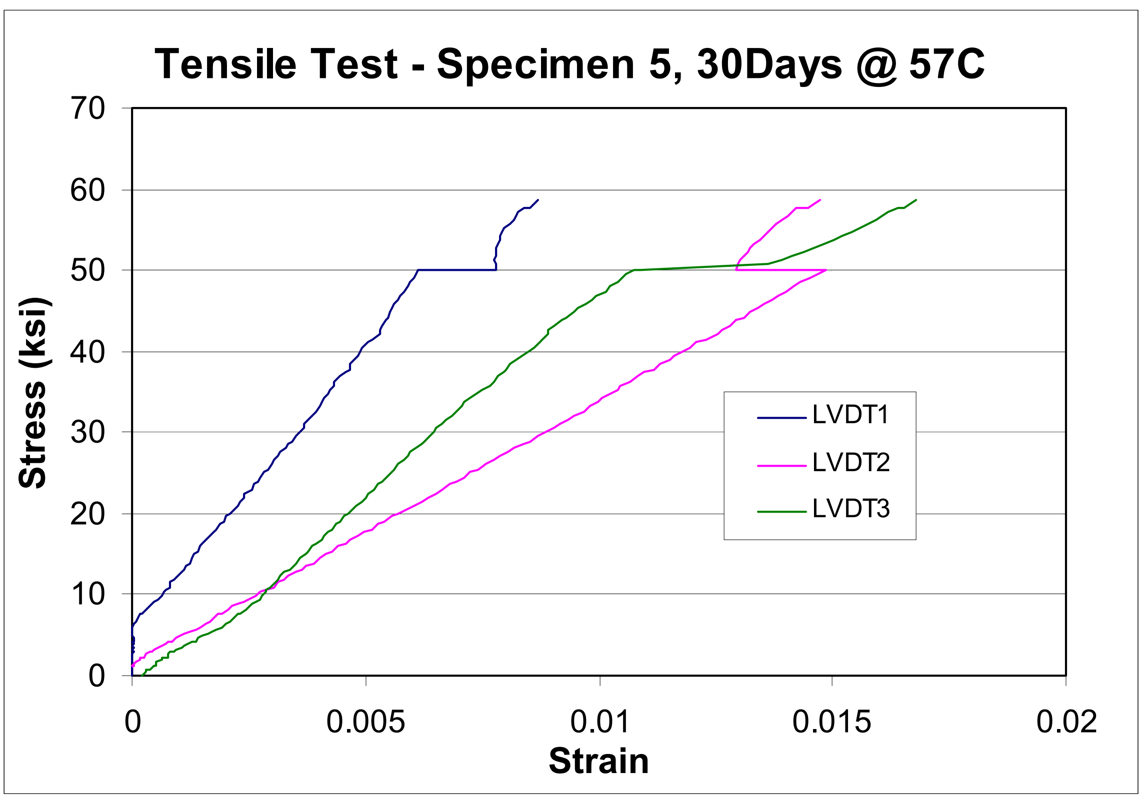


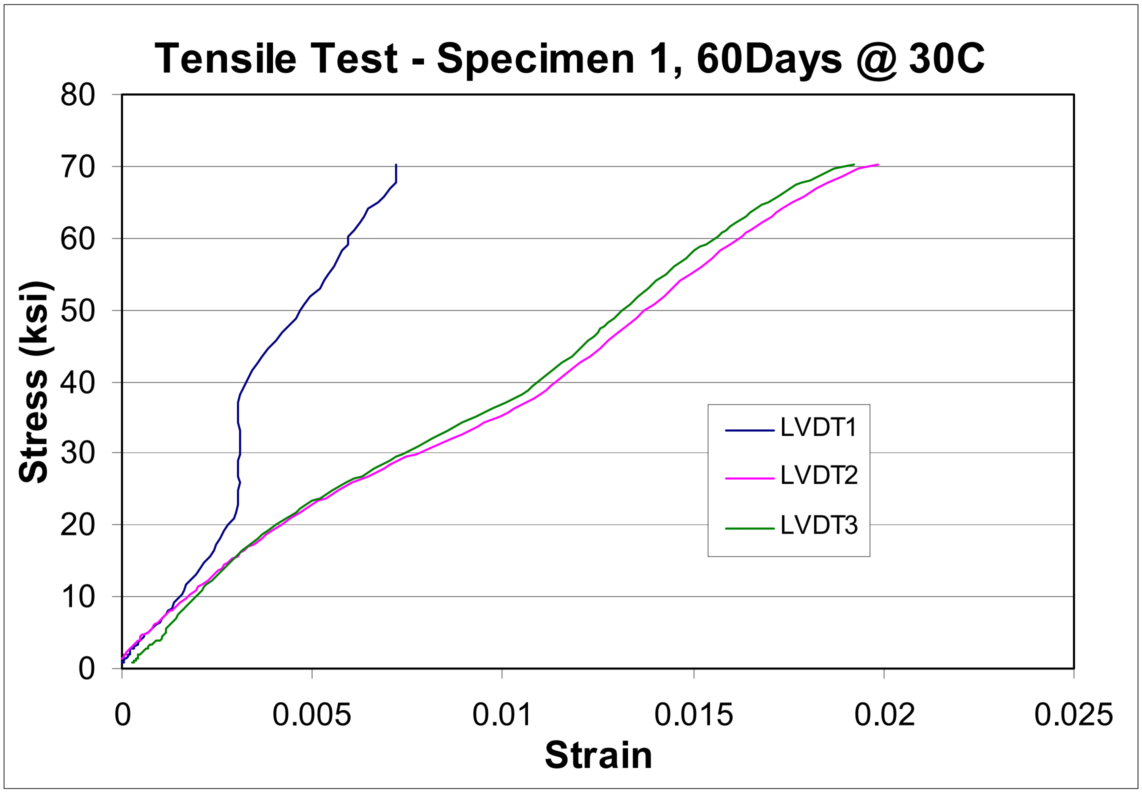
Tensile test: Specimen 1, 30Days @ 57C
Stress (ksi)
Strain
0
10
20
30
40
50
60
70
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
LVDT 1
LVDT 2
LVDT 3

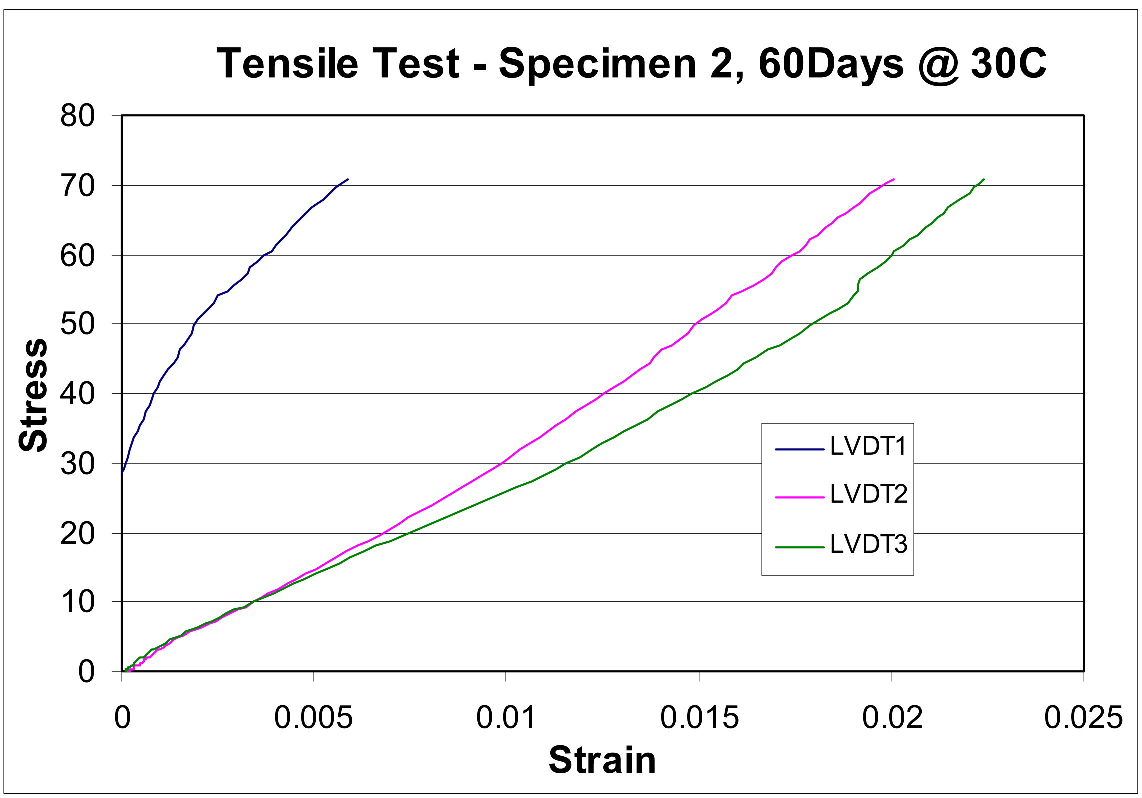

Tensile Test - Specimen 2, 30Days @ 57C
Stress (ksi)
Strain
0
10
20
30
40
50
60
70
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
LVDT 1
LVDT 2
LVDT 3

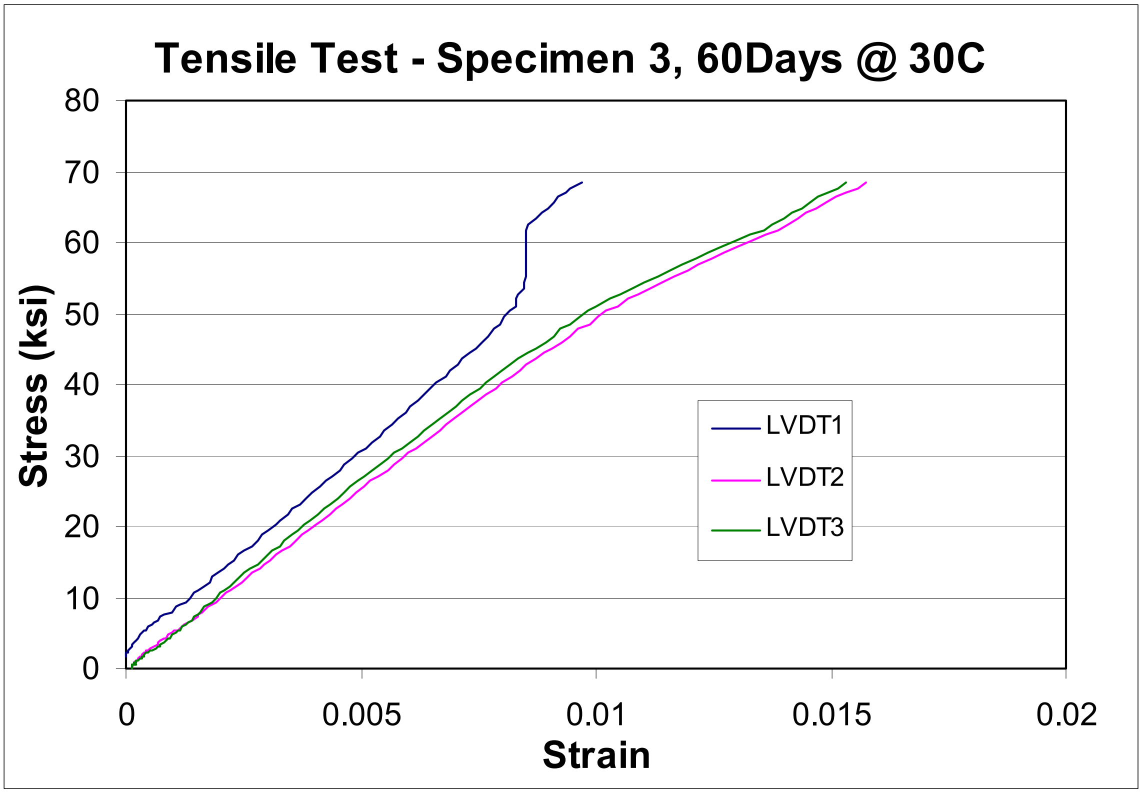

Tensile Test - Specimen 3, 30Days @ 57C
Stress (ksi)
Strain
0
10
20
30
40
50
60
70
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
LVDT 1
LVDT 2
LVDT 3

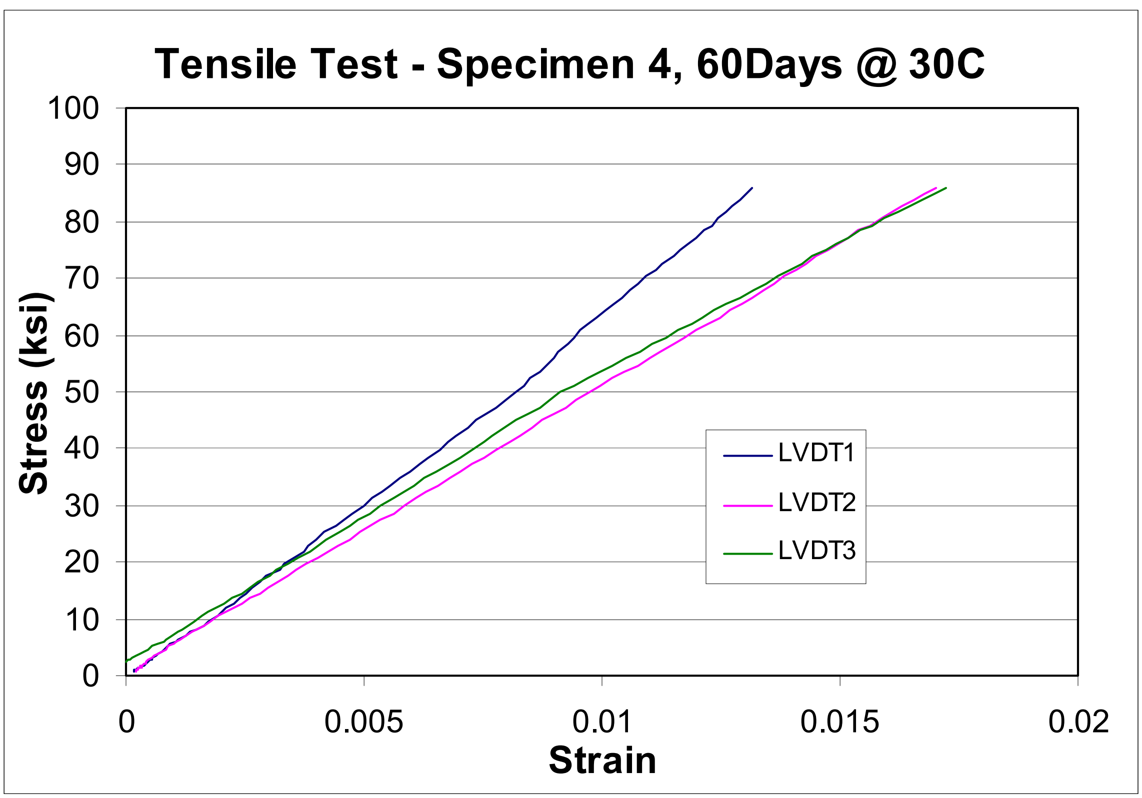

Tensile Test - Specimen 4, 30Days @ 57C
Stress (ksi)
Strain
LVDT 1
LVDT 2
LVDT 3
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014

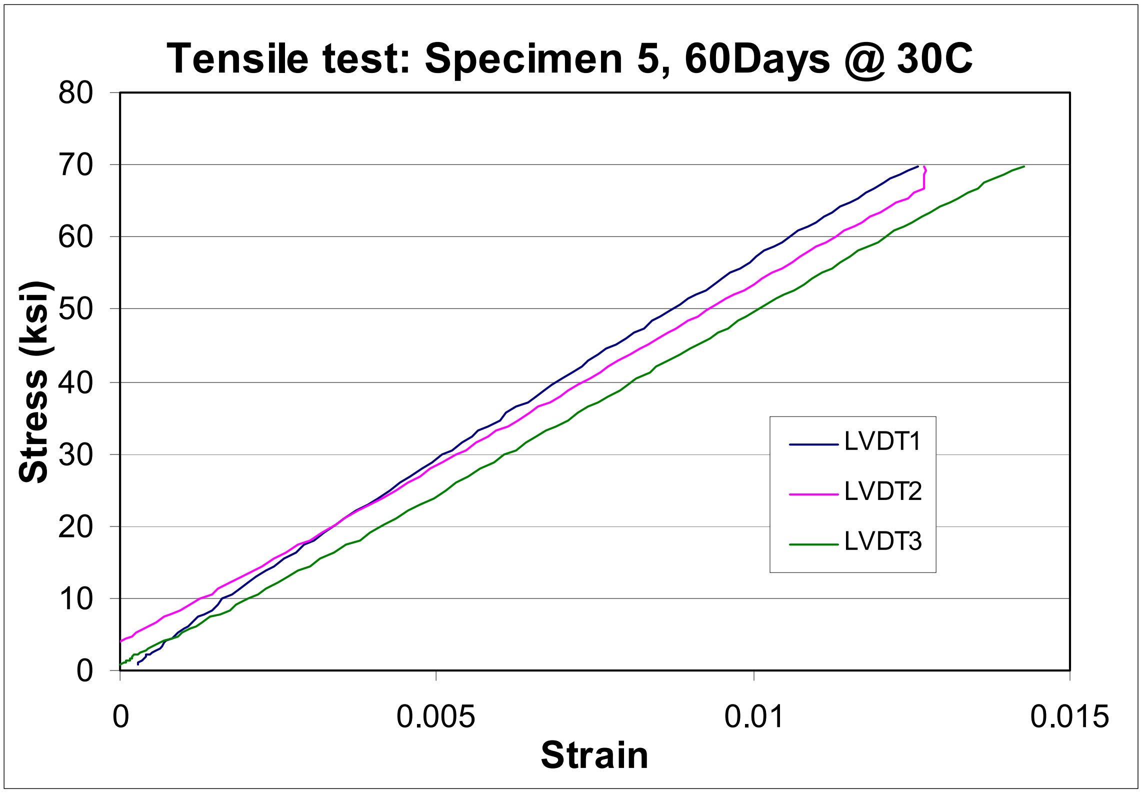

Tensile Test - Specimen 5, 30Days @ 57C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02

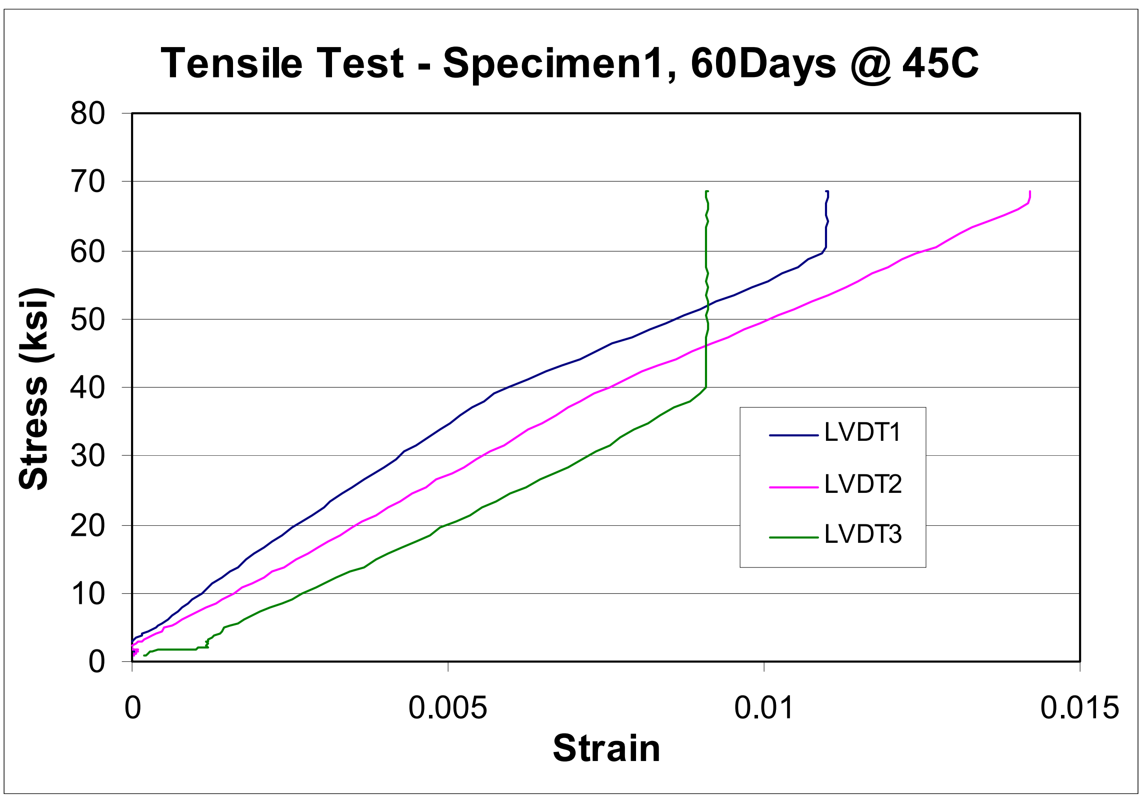

Tensile Test - Specimen 1, 60Days @ 30C
Stress (ksi)
Strain
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
0.025
LVDT1
LVDT2
LVDT3

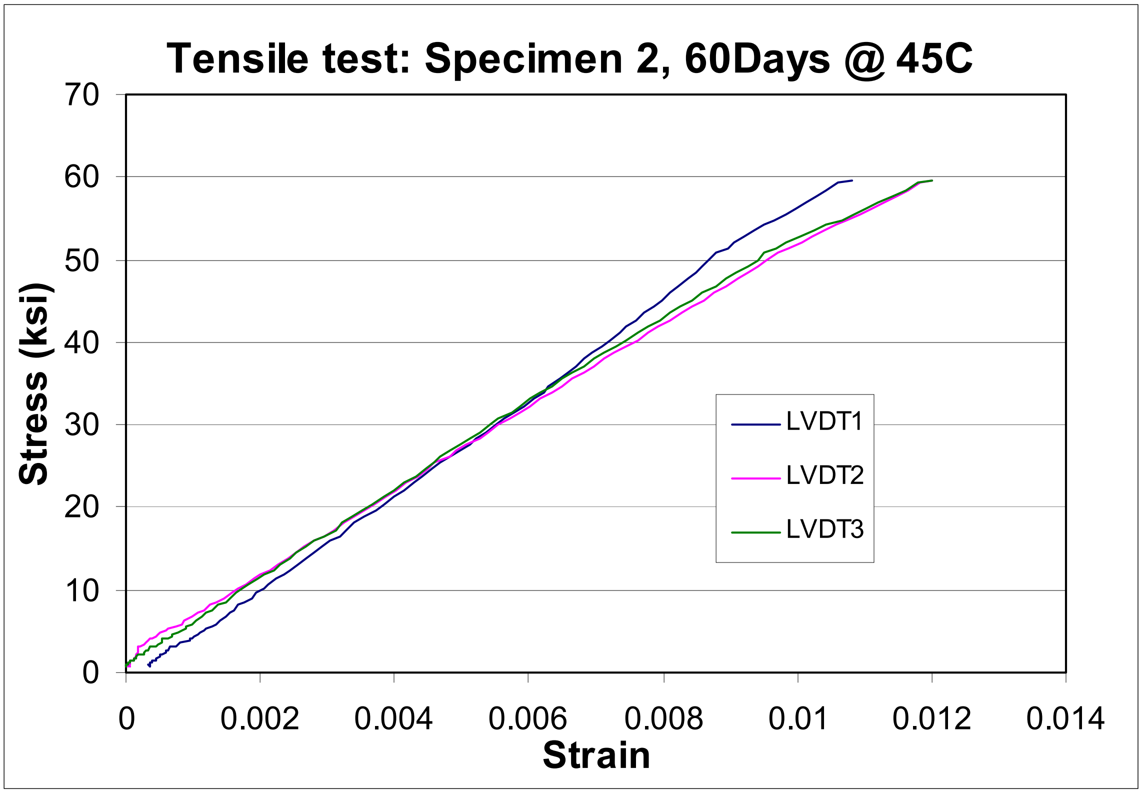

Tensile Test - Specimen 2, 60Days @ 30C
Stress
Strain
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
0.025
LVDT1
LVDT2
LVDT3

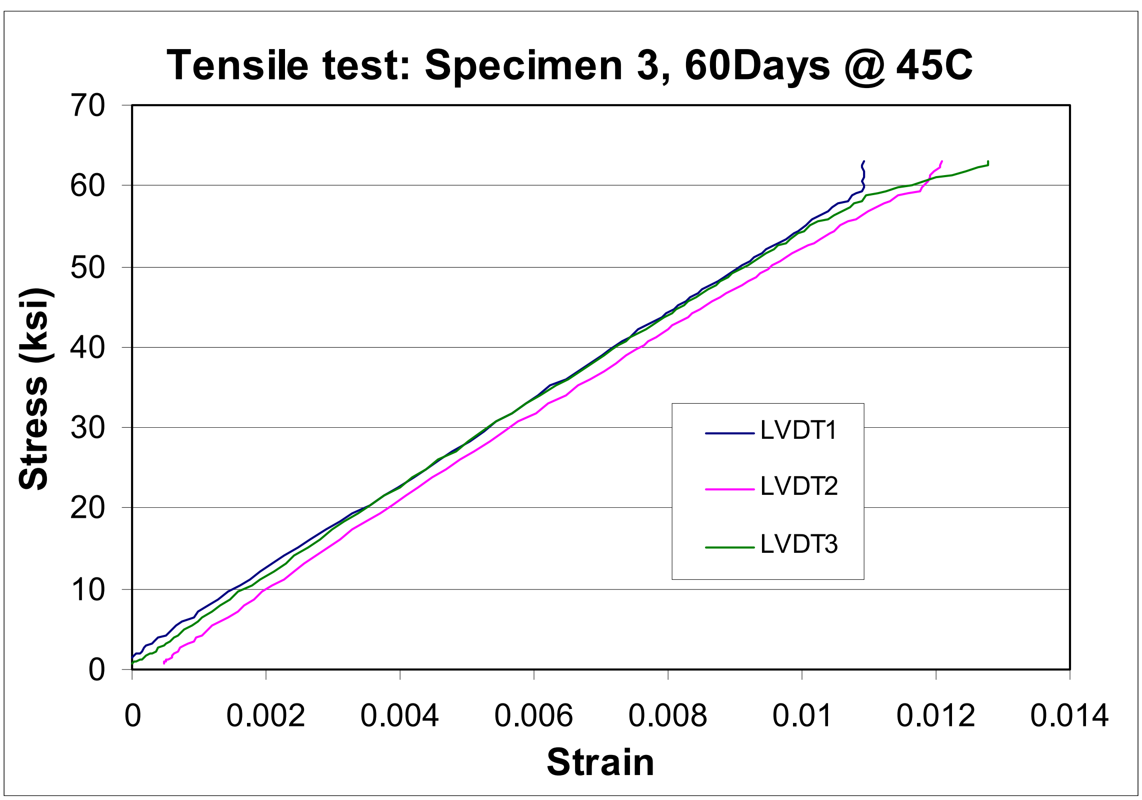

Tensile Test - Specimen 3, 60Days @ 30C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
0
10
20
30
40
50
60
70
80
0
0.005
0.01
0.015
0.02

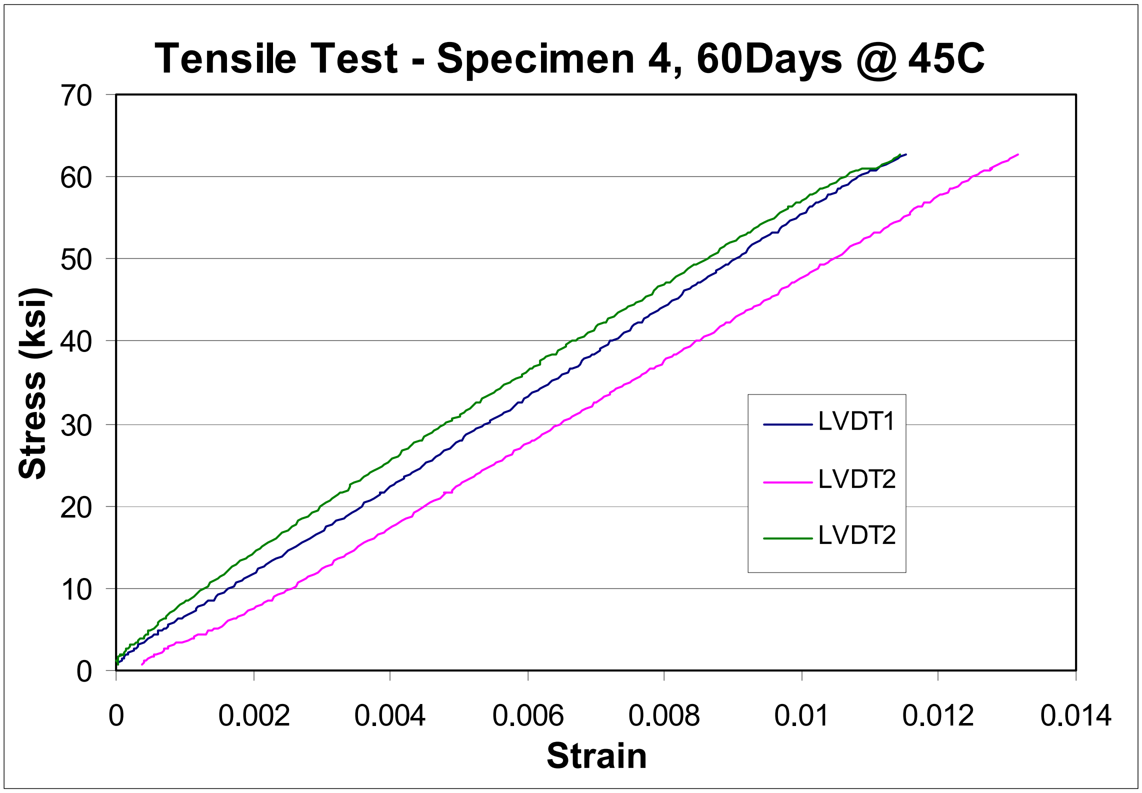

Tensile Test - Specimen 4, 60Days @ 30C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
0
10
20
30
40
50
60
70
80
90
100
0
0.005
0.01
0.015
0.02

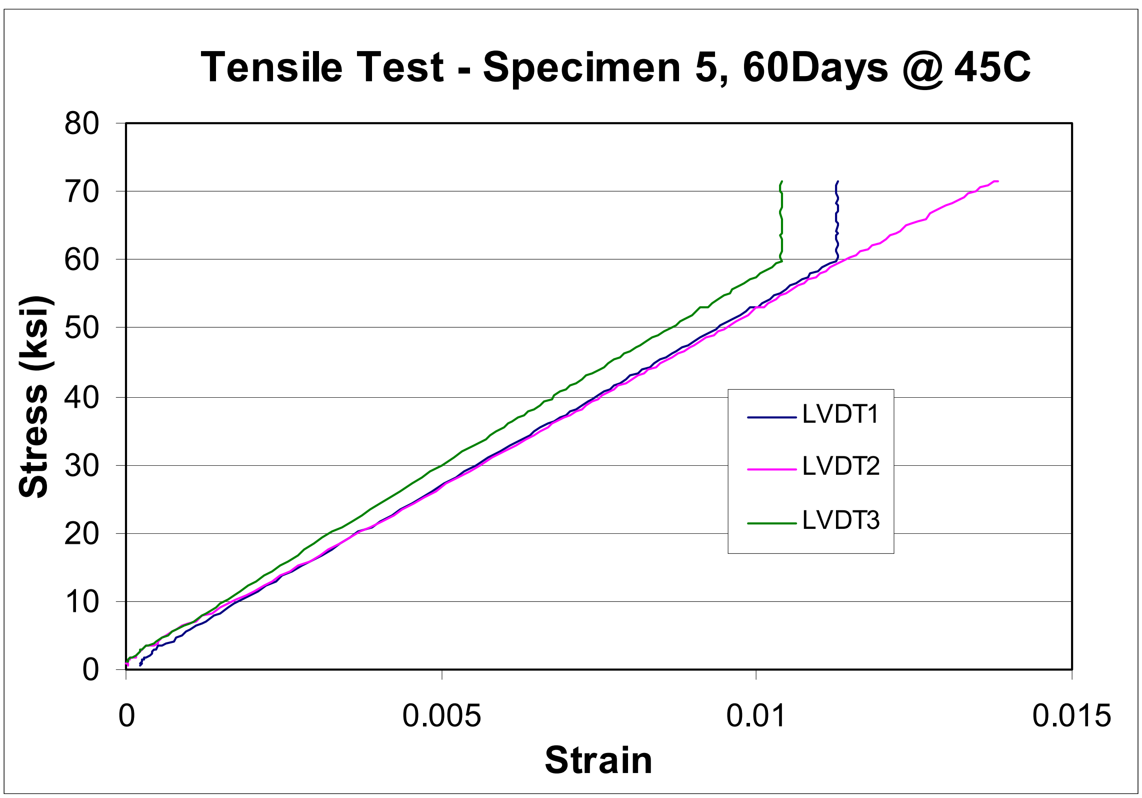

Tensile test: Specimen 5, 60Days @ 30C
Stress (ksi)
Strain
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
LVDT1
LVDT2
LVDT3

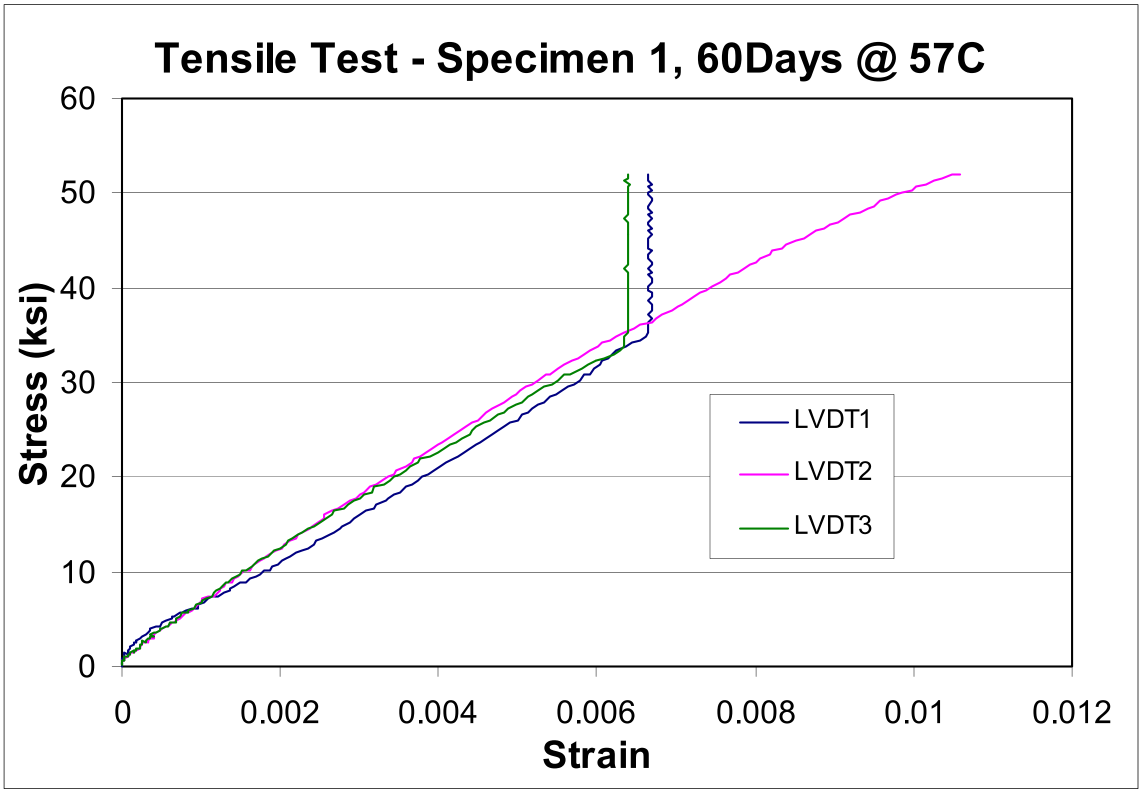

Tensile Test - Specimen1, 60Days @ 45C
Stress (ksi)
Strain
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
LVDT1
LVDT2
LVDT3

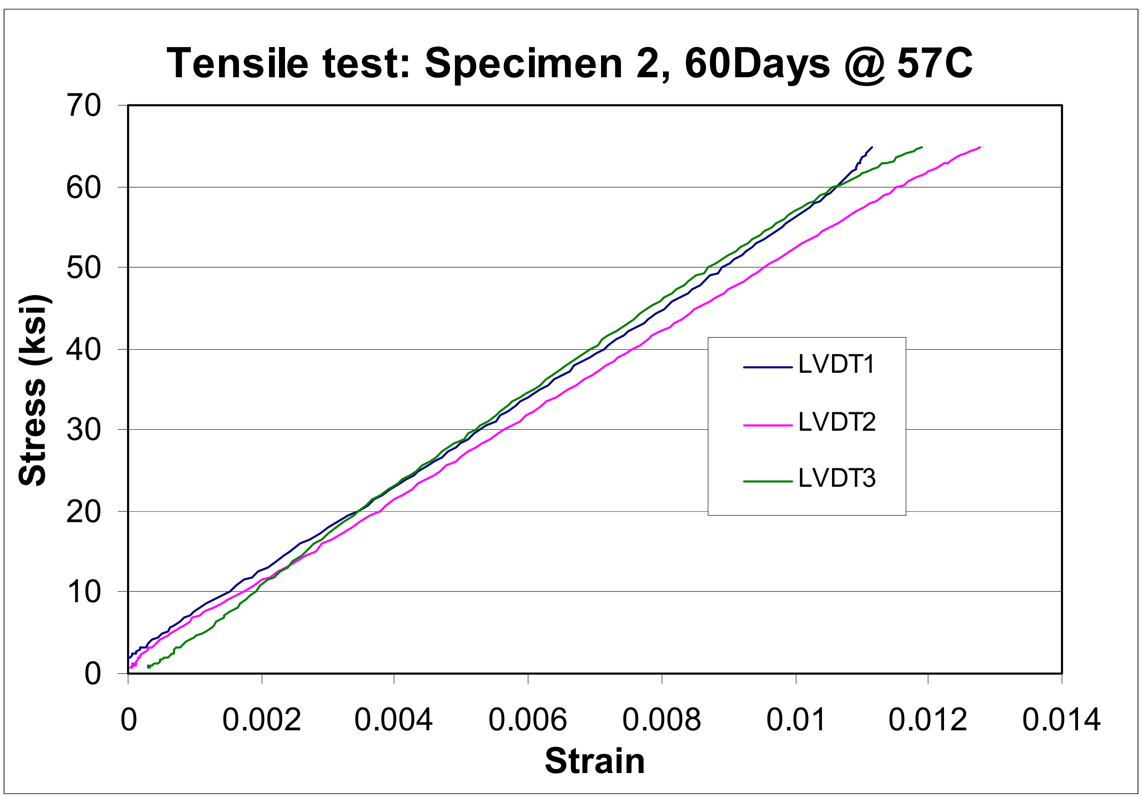

Tensile test: Specimen 2, 60Days @ 45C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3

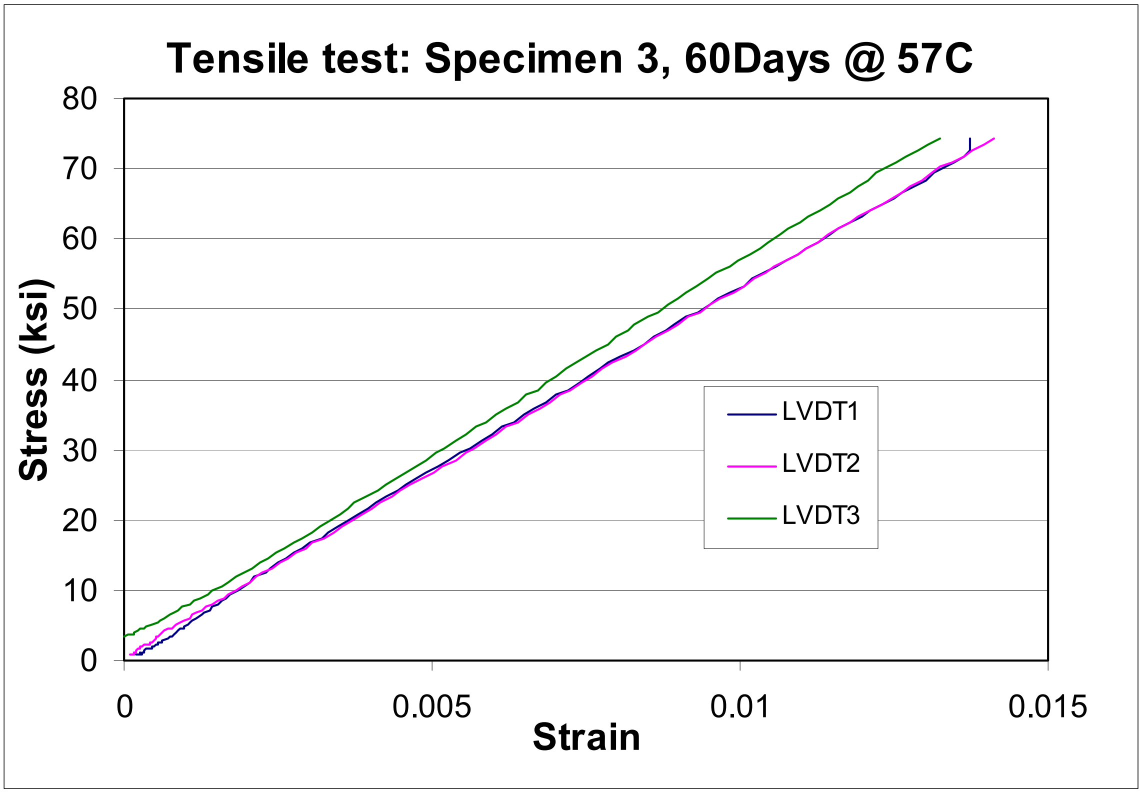

Tensile test: Specimen 3, 60Days @ 45C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3


Tensile Test - Specimen 4, 60Days @ 45C
70
60
50
40
30
20
10
0
Stress (ksi)
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT2

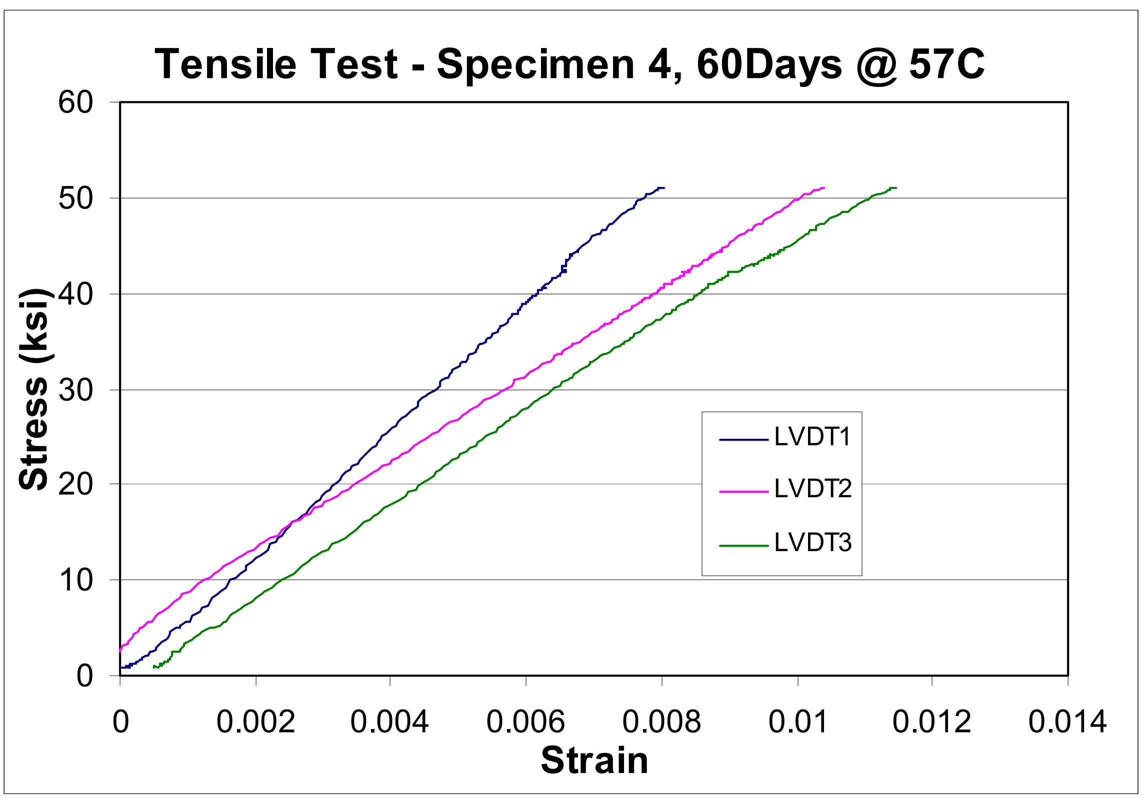

Tensile Test - Specimen 5, 60Days @ 45C
80
70
60
50
40
30
20
10
0
Stress (ksi)
0
0.005
0.01
0.015
Strain
LVDT1
LVDT2
LVDT3


Tensile Test - Specimen 1, 60Days @ 57C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012

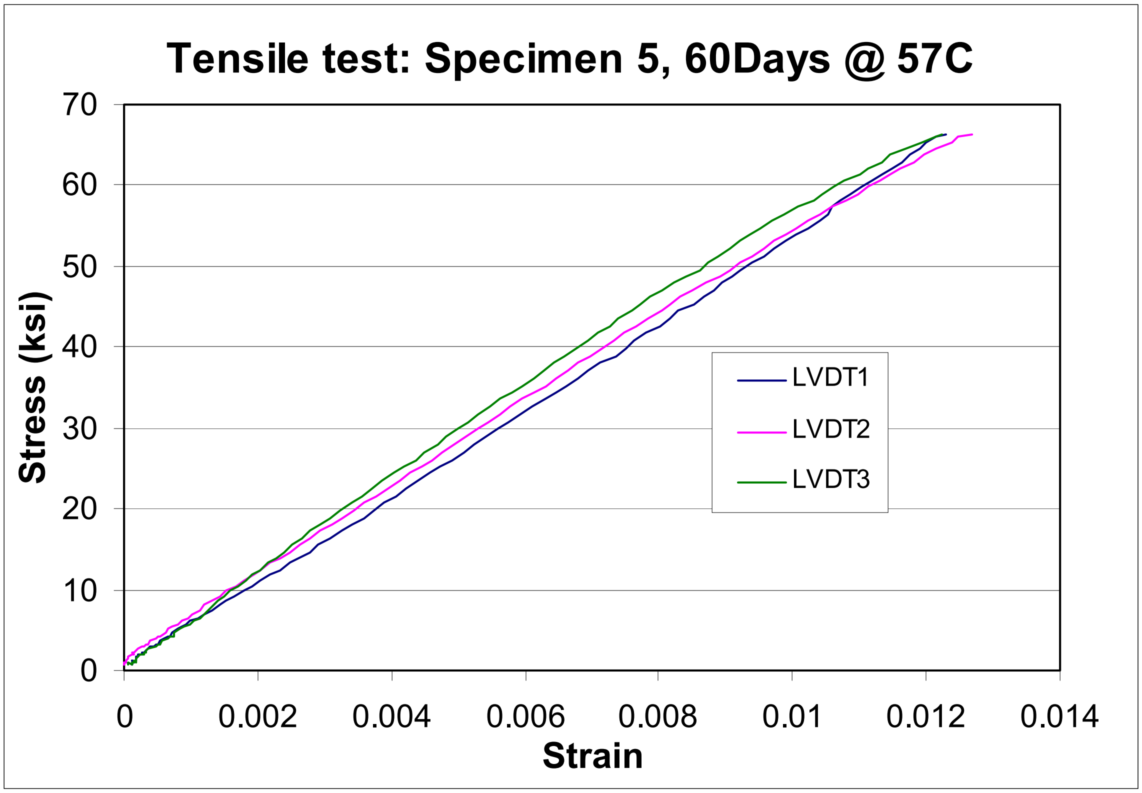

Tensile test: Specimen 2, 60Days @ 57C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014



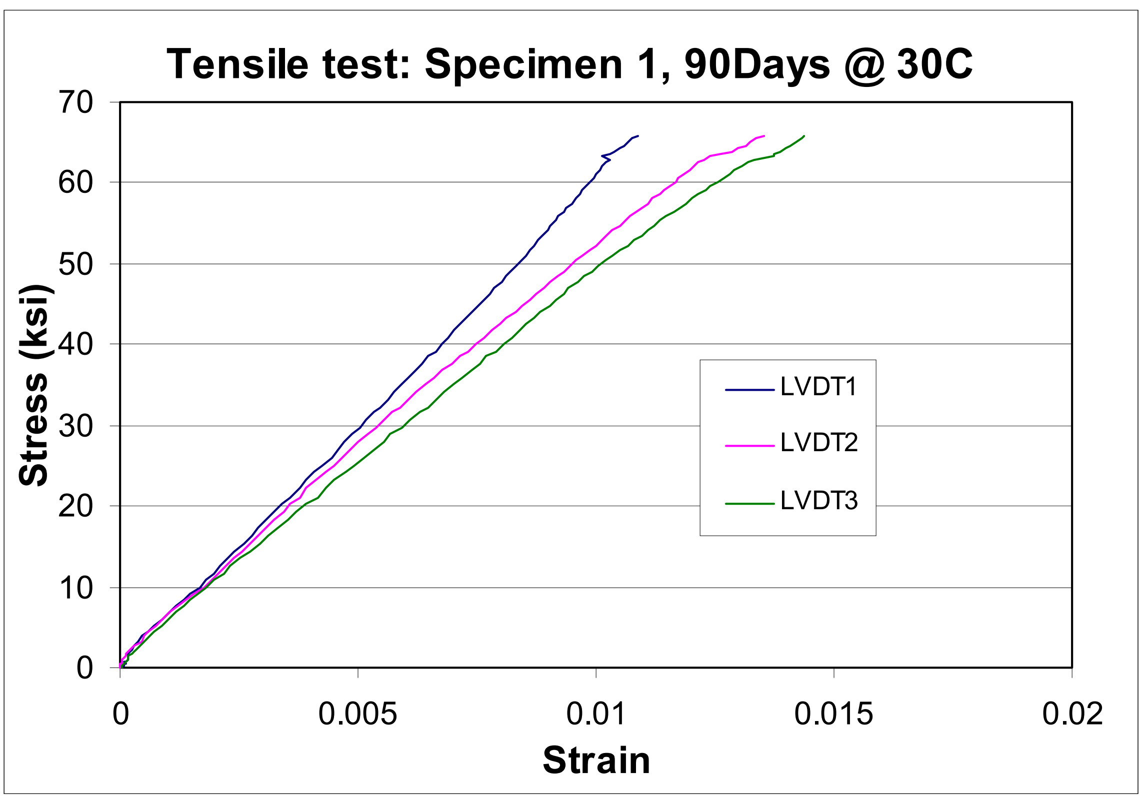
Tensile test: Specimen 3, 60Days @ 57C
Stress (ksi)
Strain
0
10
20
30
40
50
60
70
80
0
0.005
0.01
0.015
LVDT1
LVDT2
LVDT3



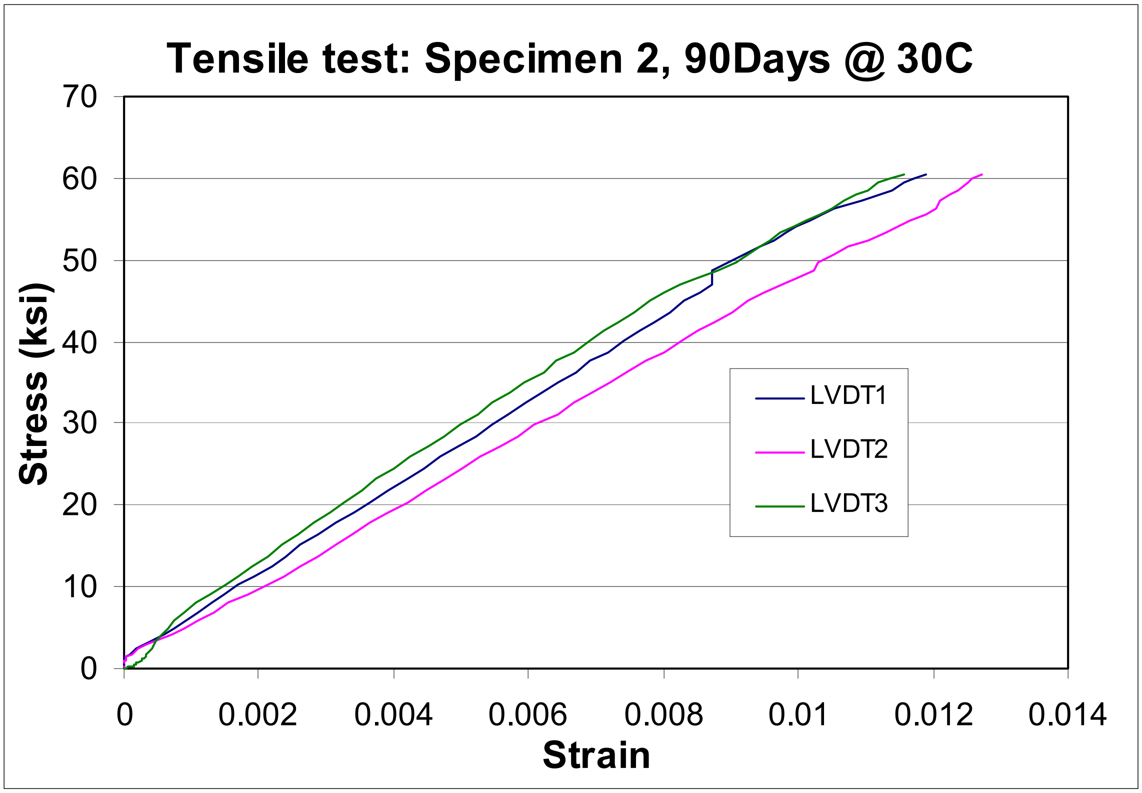
Tensile Test - Specimen 4, 60Days @ 57C
Stress (ksi)
Strain
0
10
20
30
40
50
60
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
LVDT1
LVDT2
LVDT3



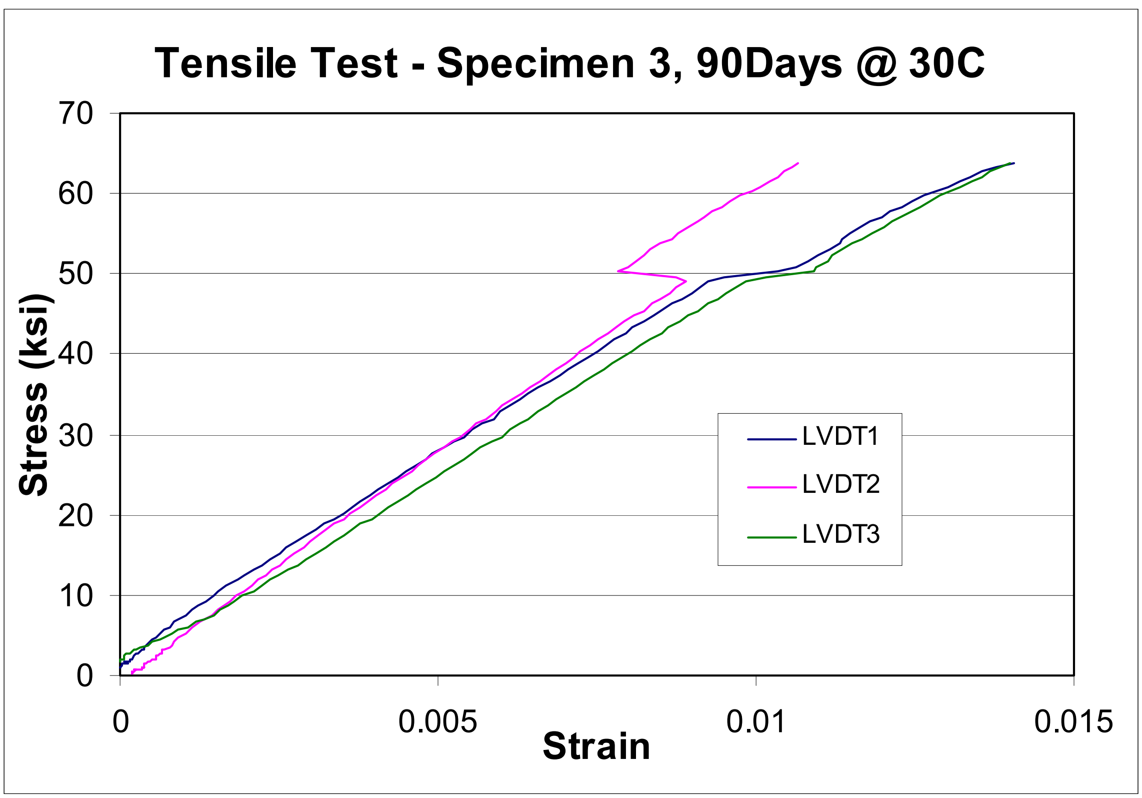
Tensile test: Specimen 5, 60Days @ 57C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3



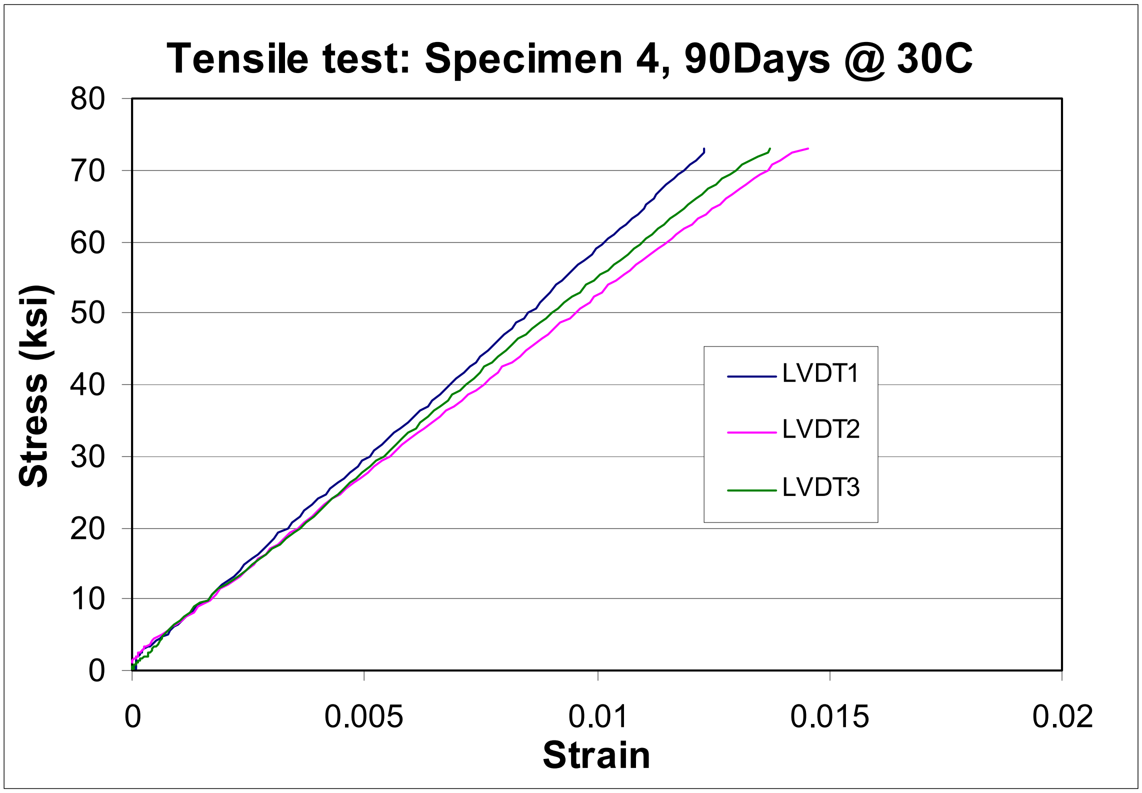
Tensile test: Specimen 1, 90Days @ 30C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3



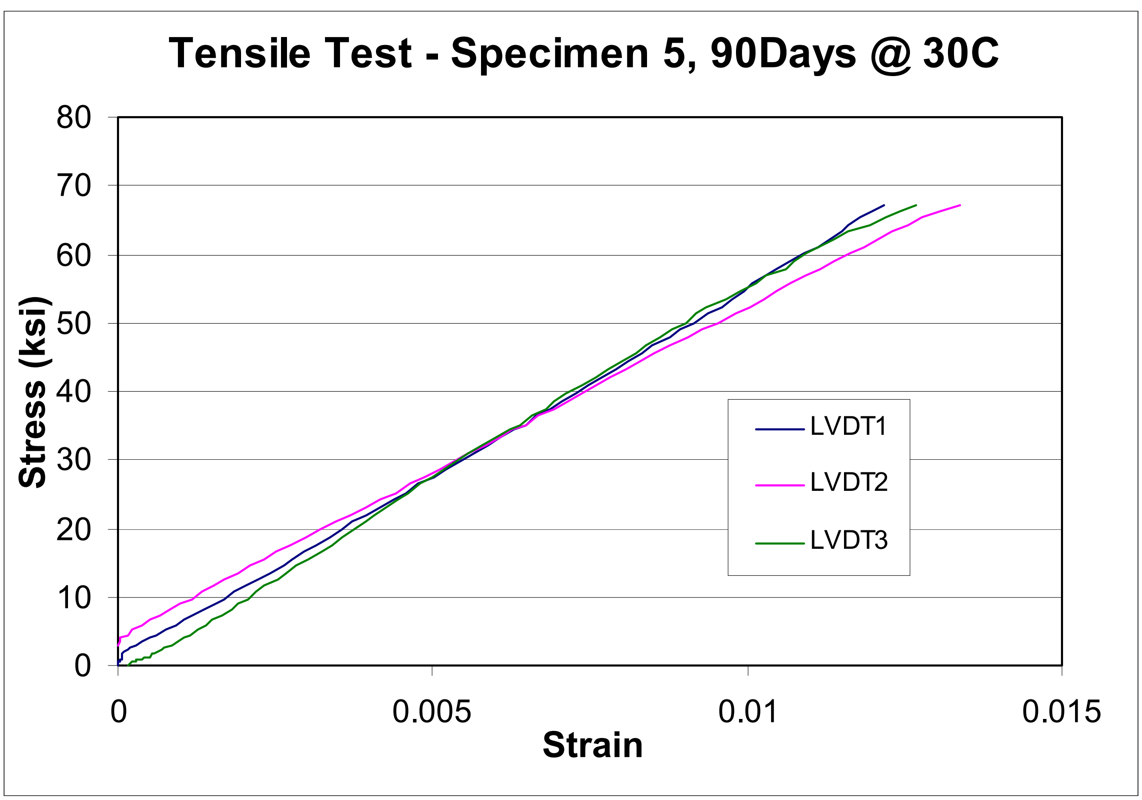
Tensile test: Specimen 2, 90Days @ 30C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3



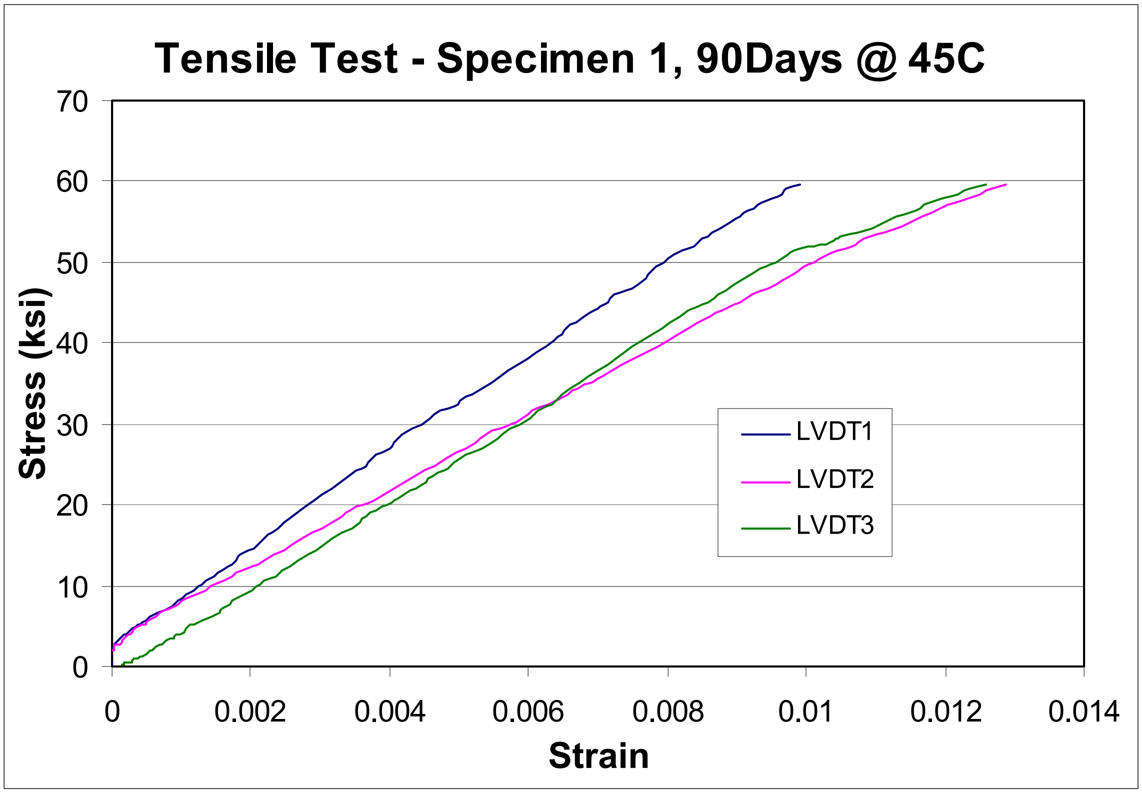
Tensile Test - Specimen 3, 90Days @ 30C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
Strain
LVDT1
LVDT2
LVDT3



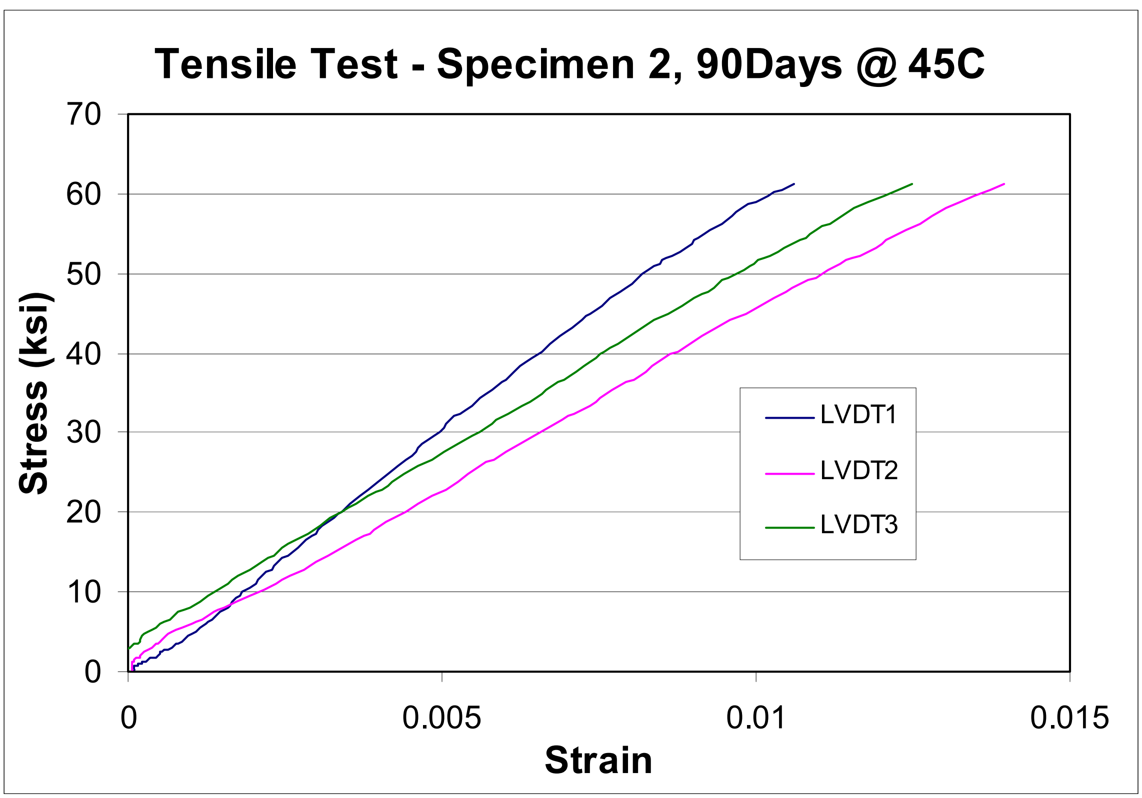
Tensile test: Specimen 4, 90Days @ 30C
Stress (ksi)
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3



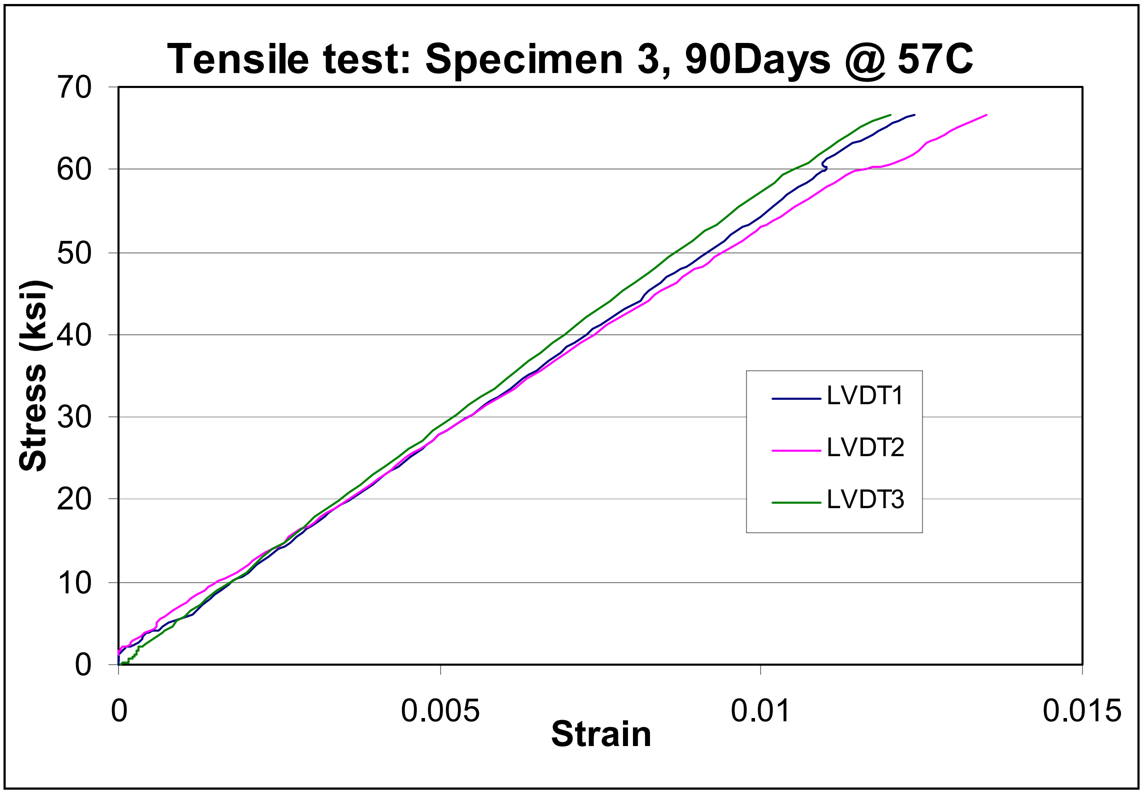
Tensile Test - Specimen 5, 90Days @ 30C
Stress (ksi)
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
Strain
LVDT1
LVDT2
LVDT3

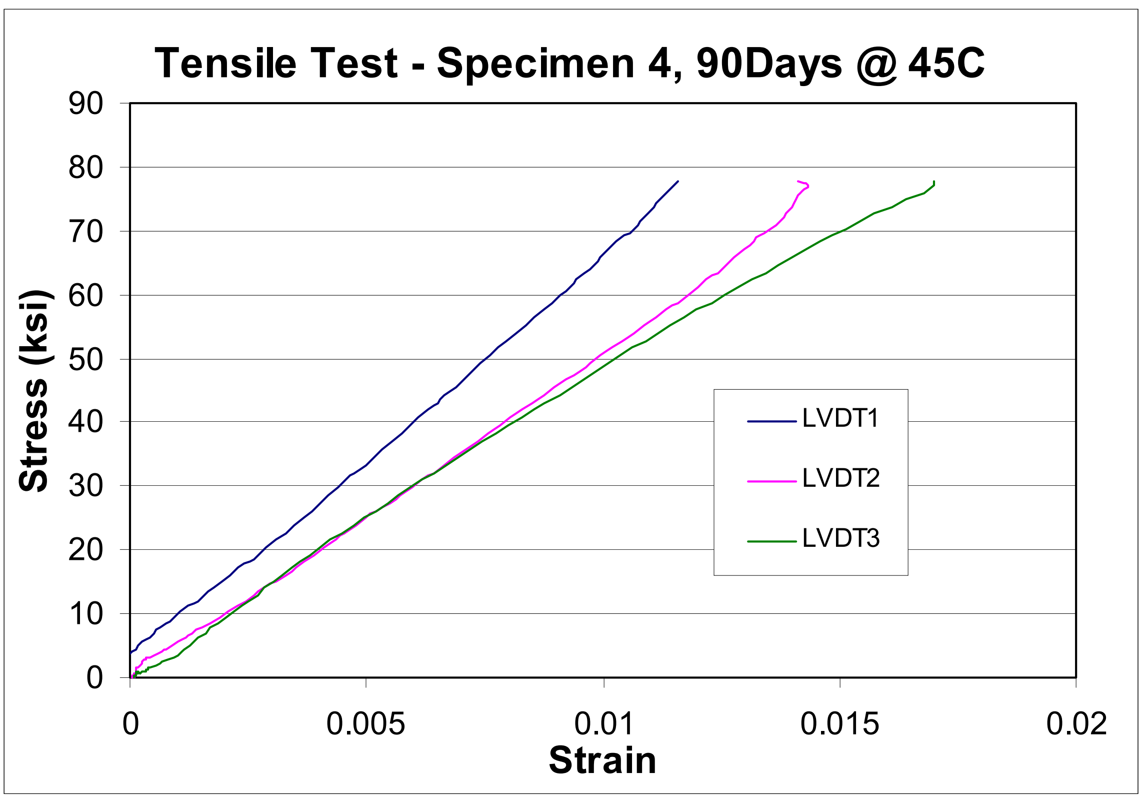


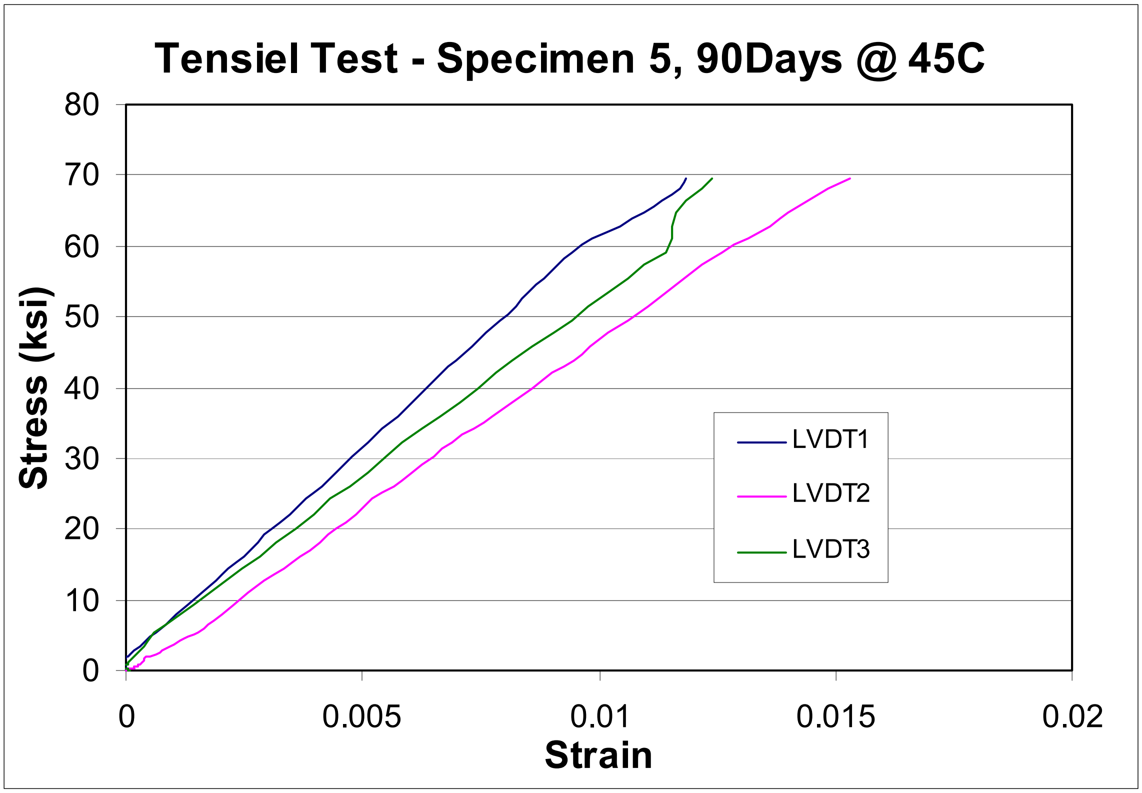
Tensile Test - Specimen 1, 90Days @ 45C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3

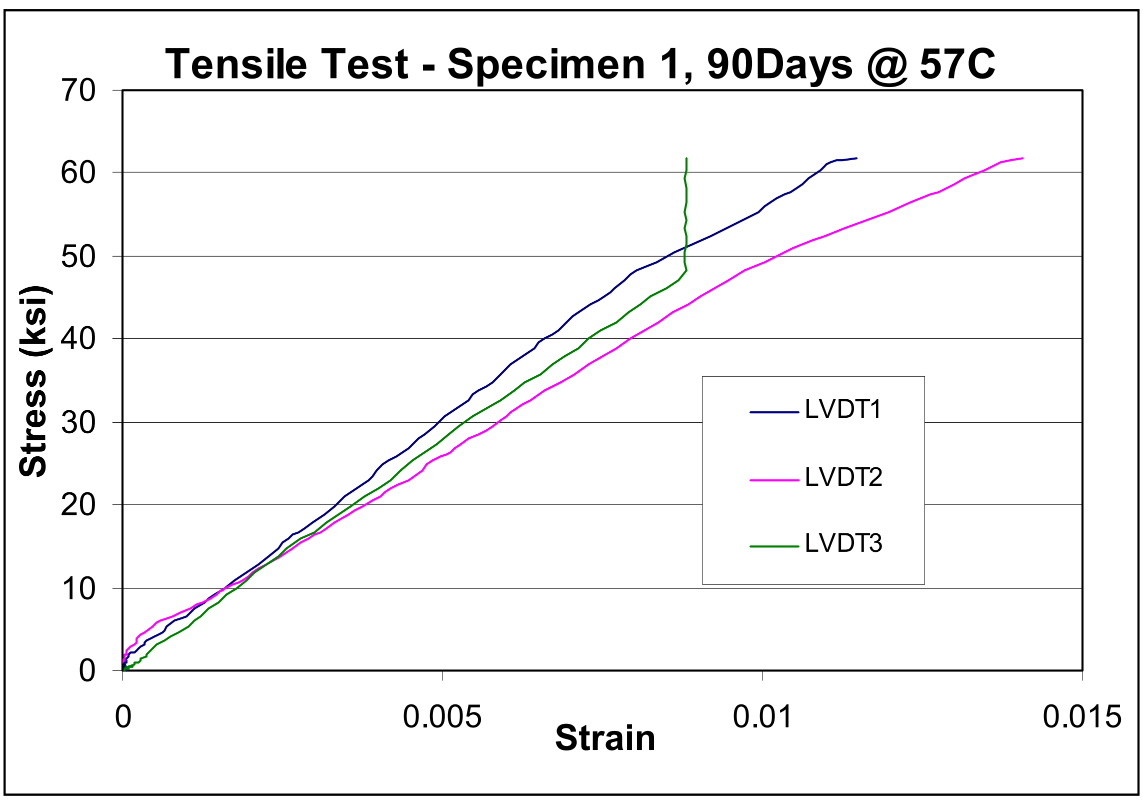


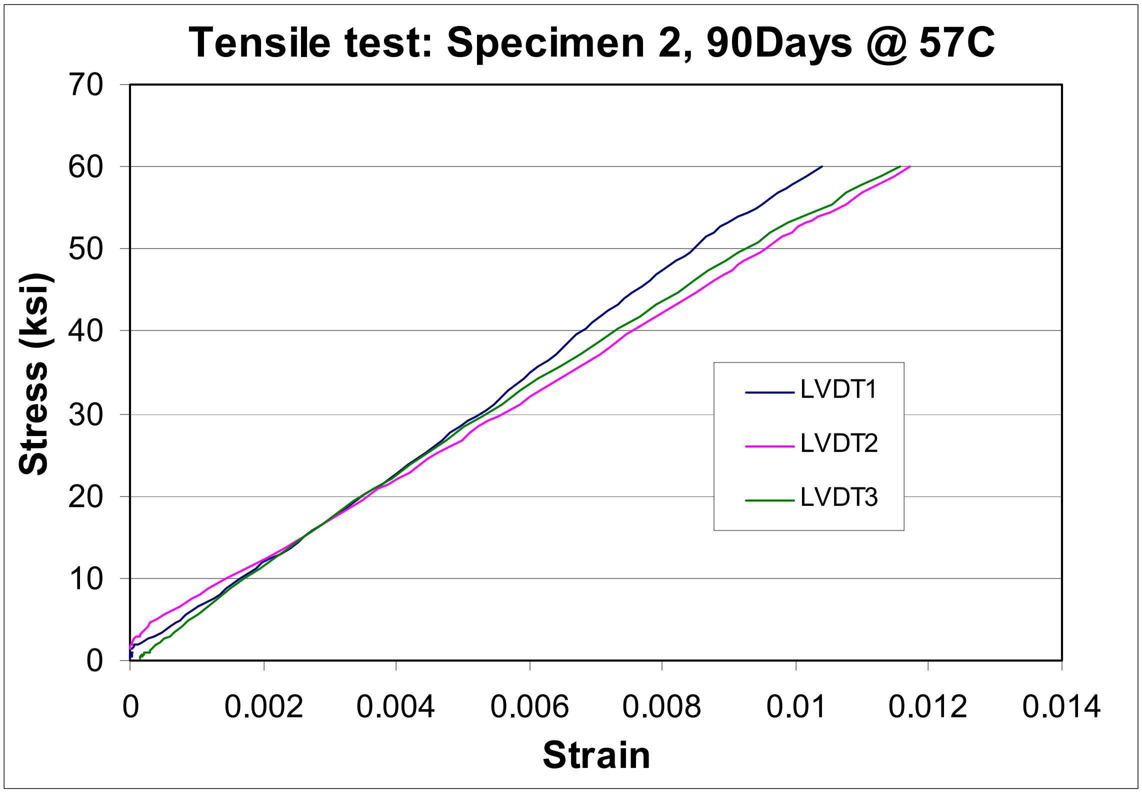
Tensile Test - Specimen 2, 90Days @ 45C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
Strain
LVDT1
LVDT2
LVDT3

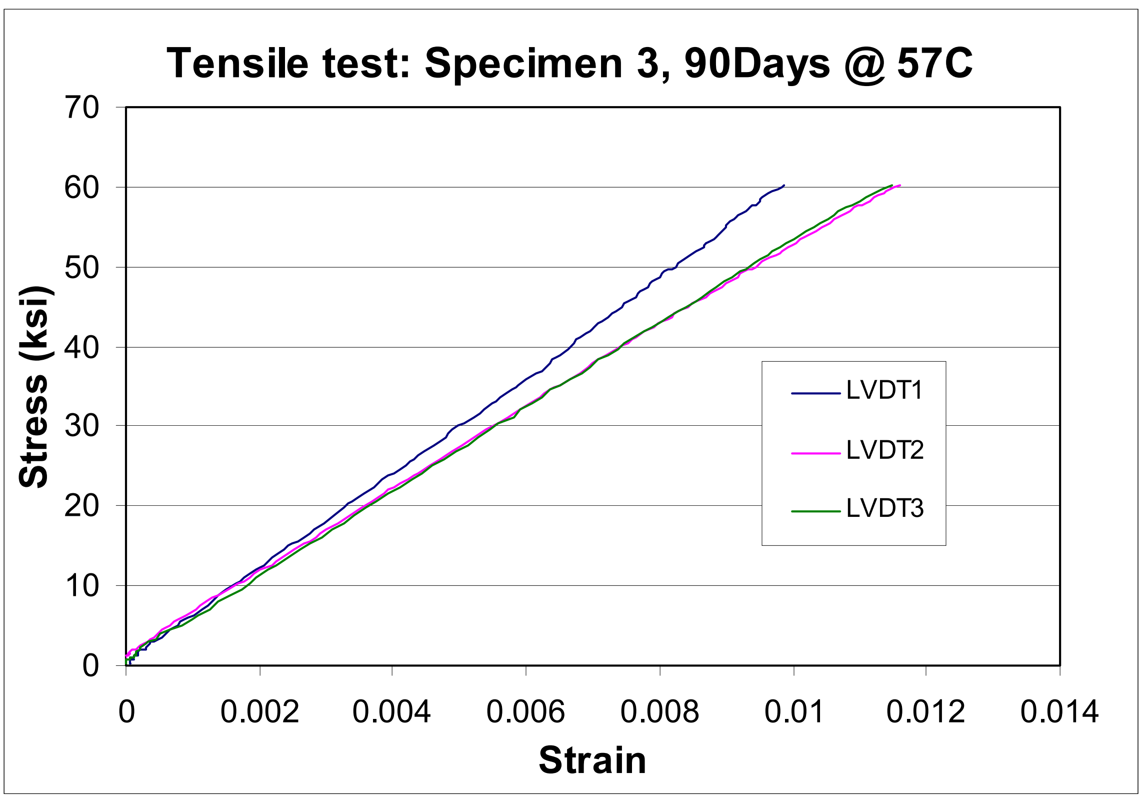

Tensile test: Specimen 3, 90Days @ 57C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
Strain
LVDT1
LVDT2
LVDT3

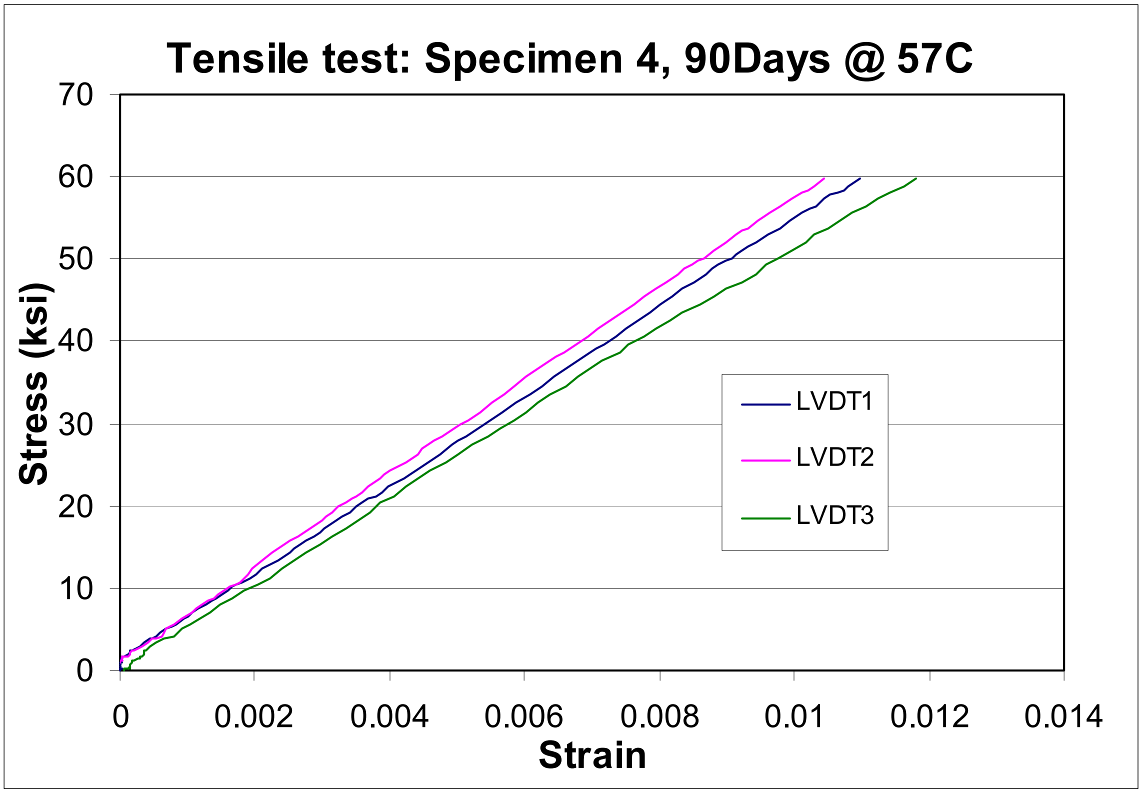

Tensile Test - Specimen 4, 90Days @ 45C
Stress (ksi)
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
Strain
LVDT1
LVDT2
LVDT3

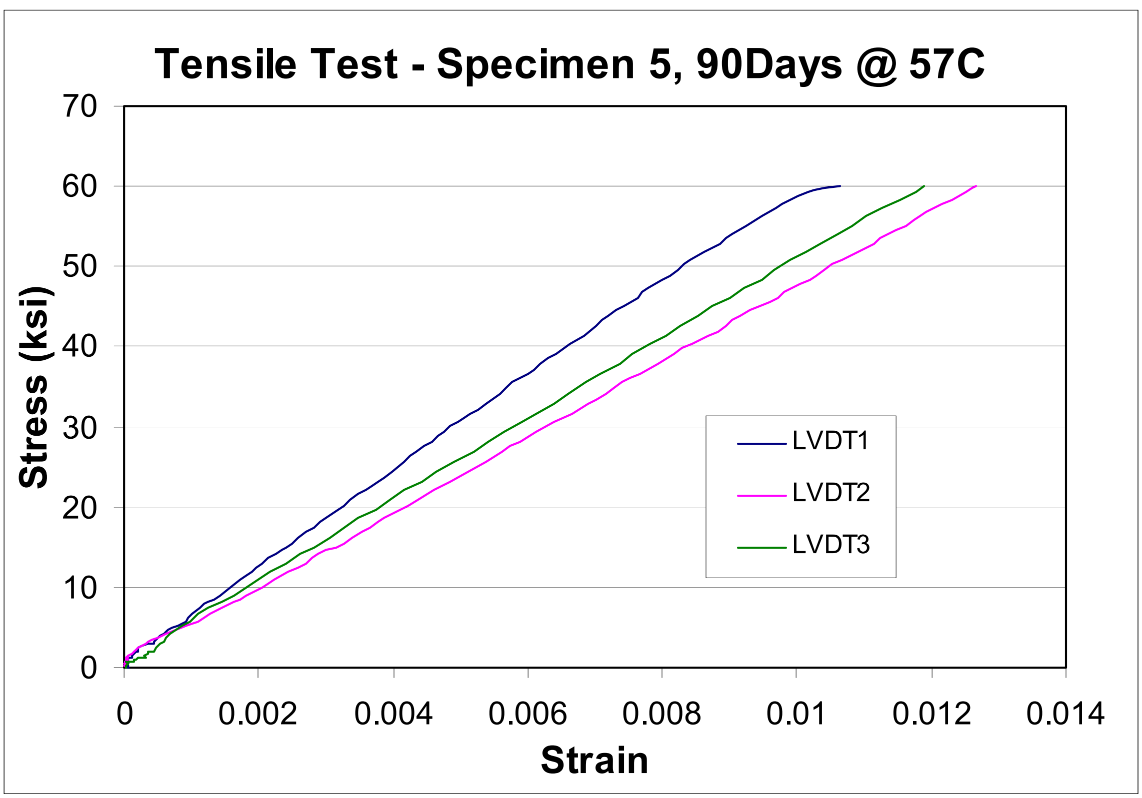

Tensiel Test - Specimen 5, 90Days @ 45C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3

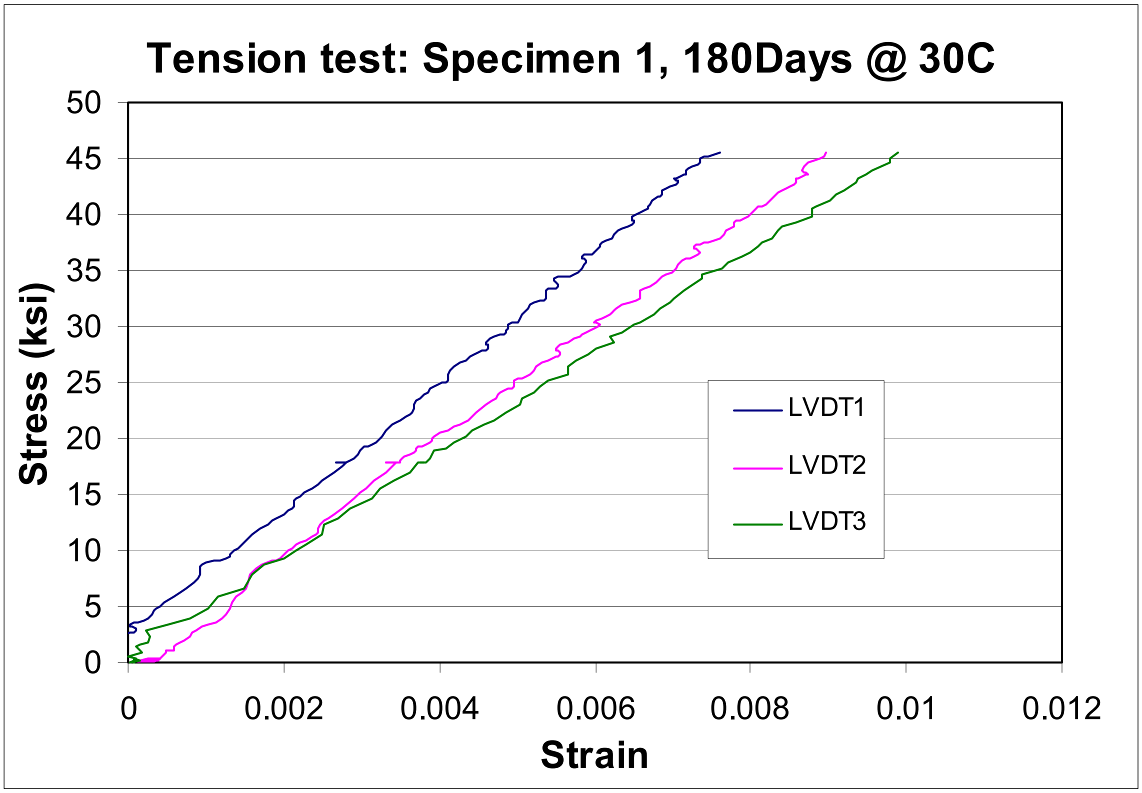

Tensile Test - Specimen 1, 90Days @ 57C
Stress (ksi)
Strain
LVDT1
LVDT2
LVDT3

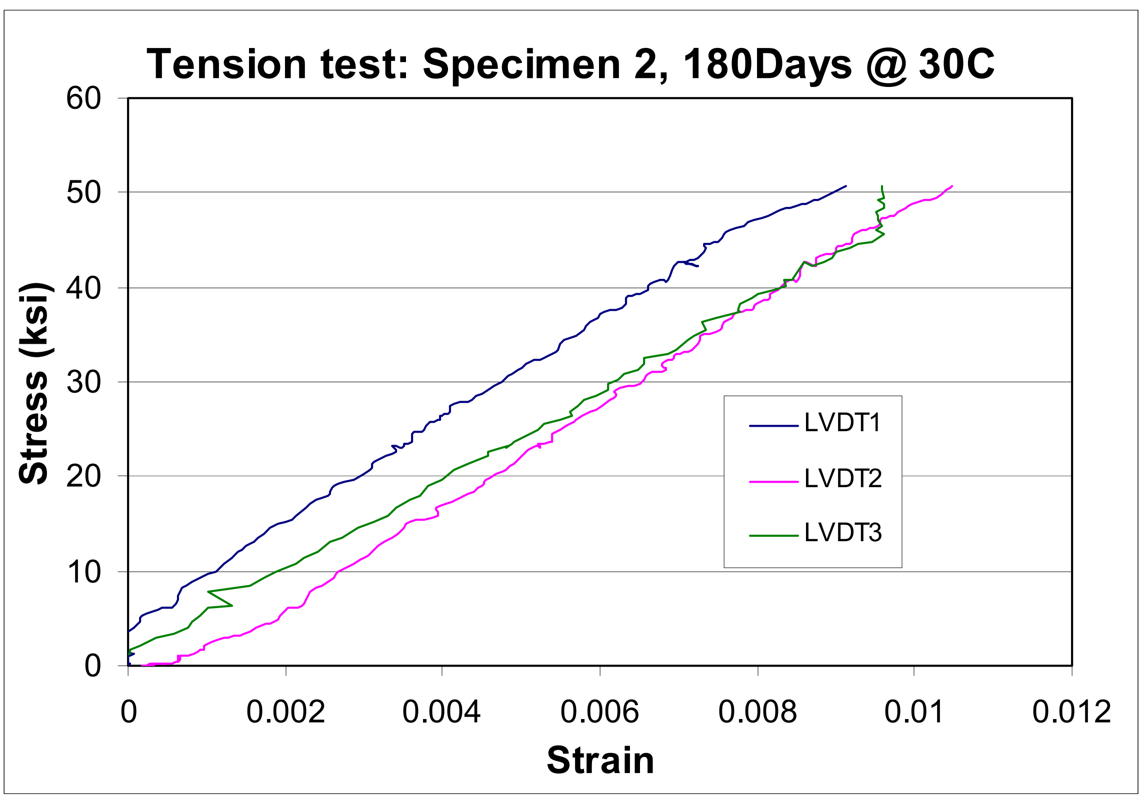

Tensile test: Specimen 2, 90Days @ 57C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3

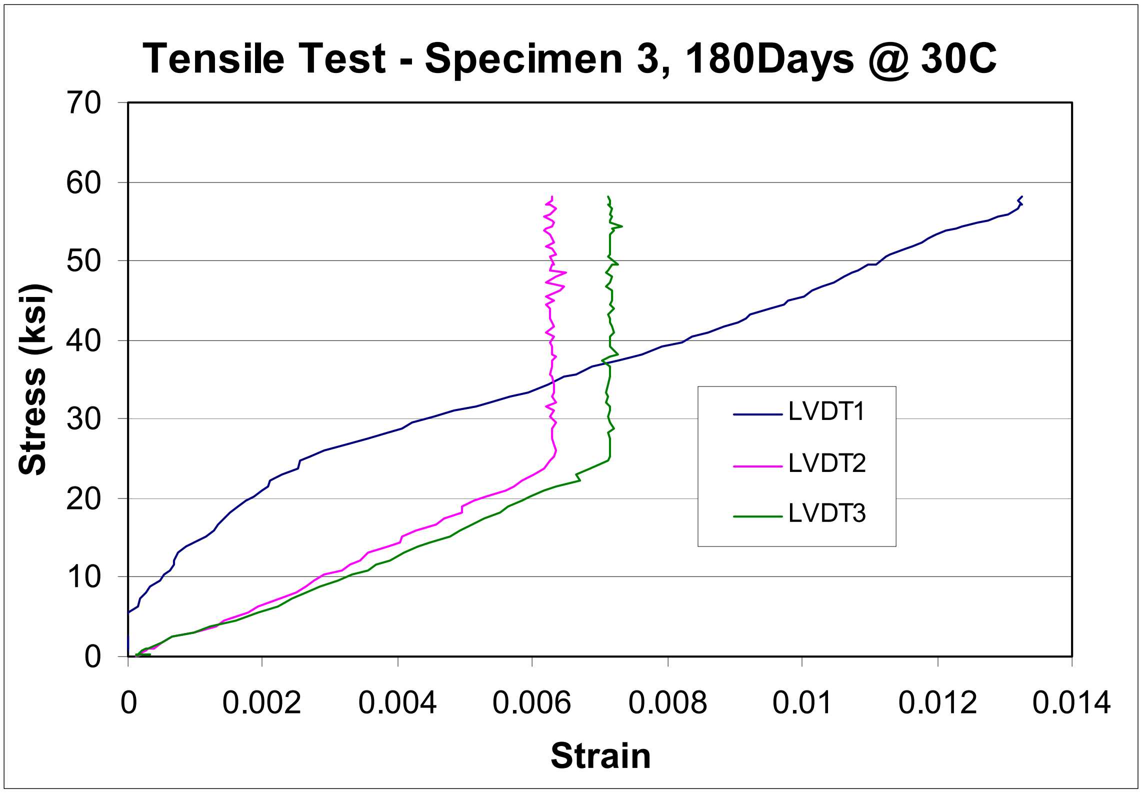

Tensile test: Specimen 3, 90Days @ 57C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3


Tensile test: Specimen 4, 90Days @ 57C
Stress (ksi)
Strain
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
LVDT1
LVDT2
LVDT3

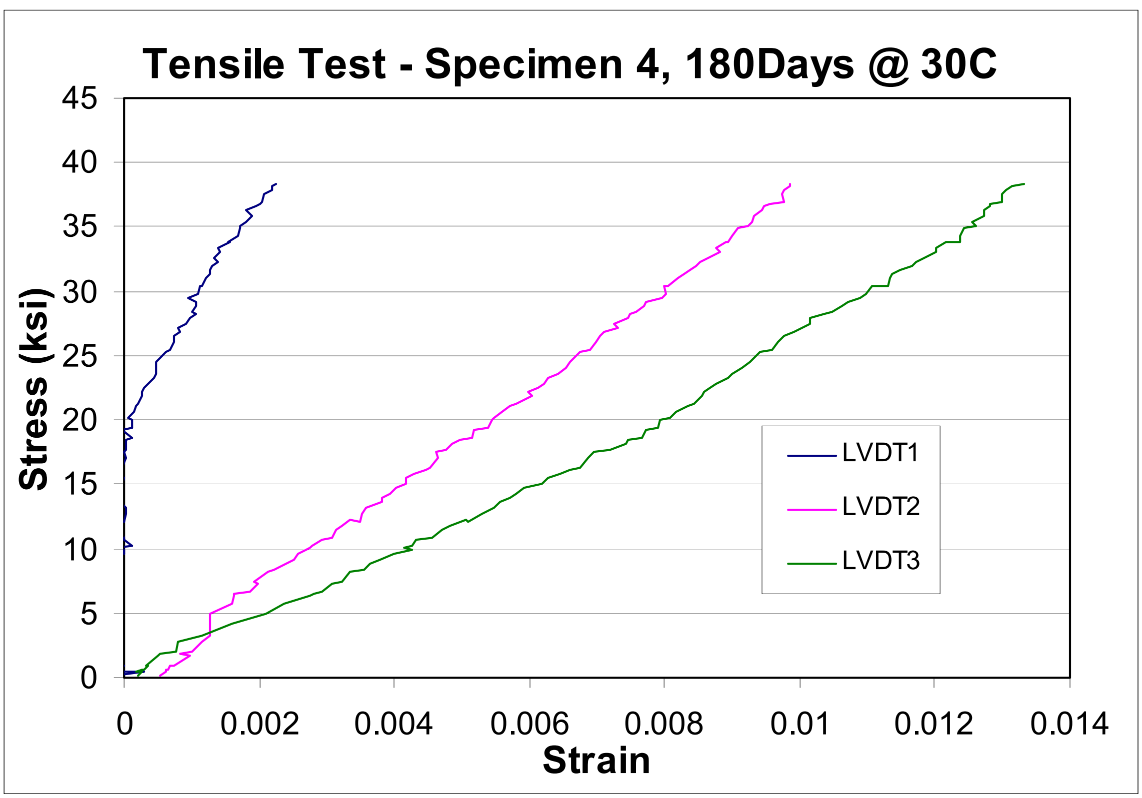

Tensile Test - Specimen 5, 90Days @ 57C
Stress (ksi)
Strain
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
LVDT1
LVDT2
LVDT3


Tension test: Specimen 1, 180Days @ 30C
Stress (ksi)
50
45
40
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
0.012
Strain
LVDT1
LVDT2
LVDT3

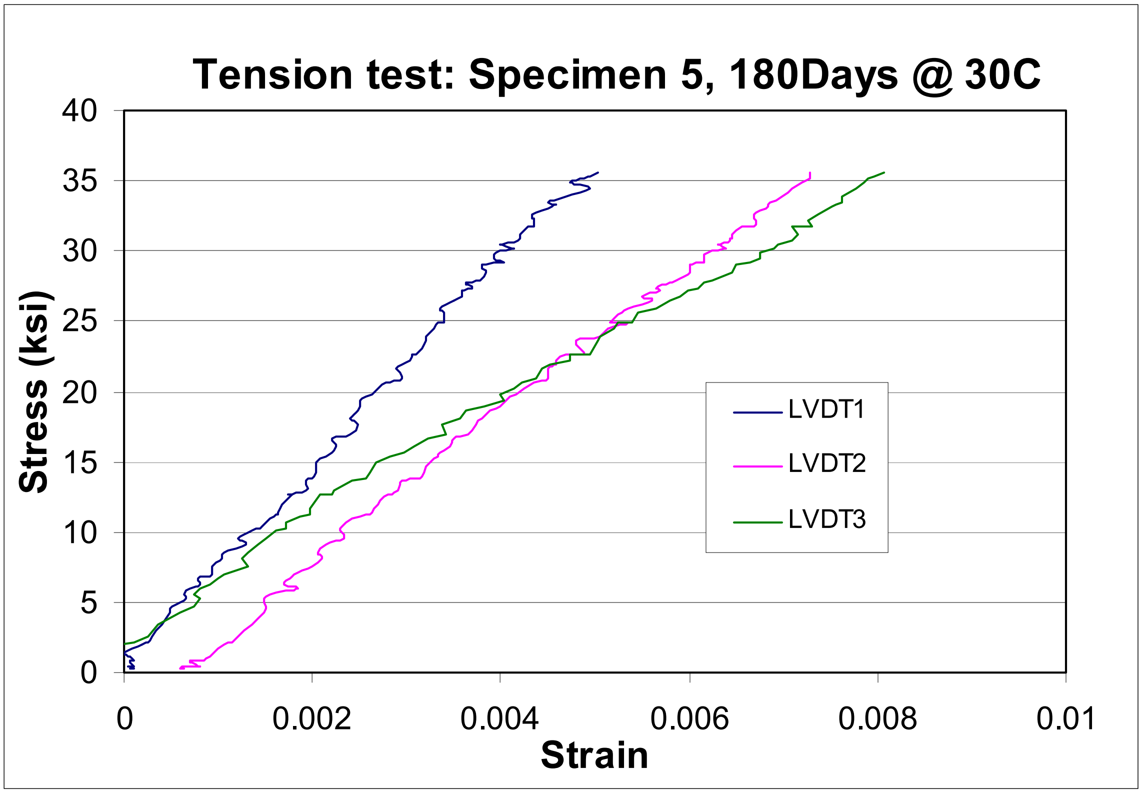

Tension test: Specimen 2, 180Days @ 30C
Stress (ksi)
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
Strain
LVDT1
LVDT2
LVDT3

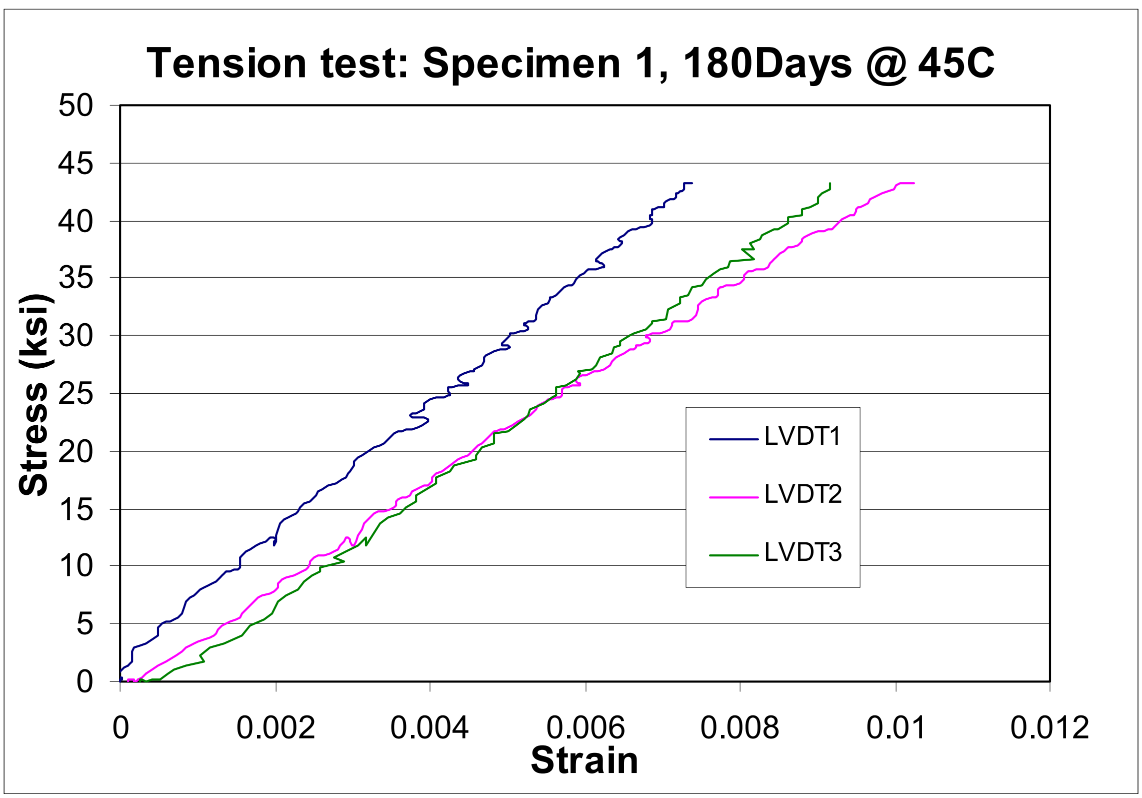


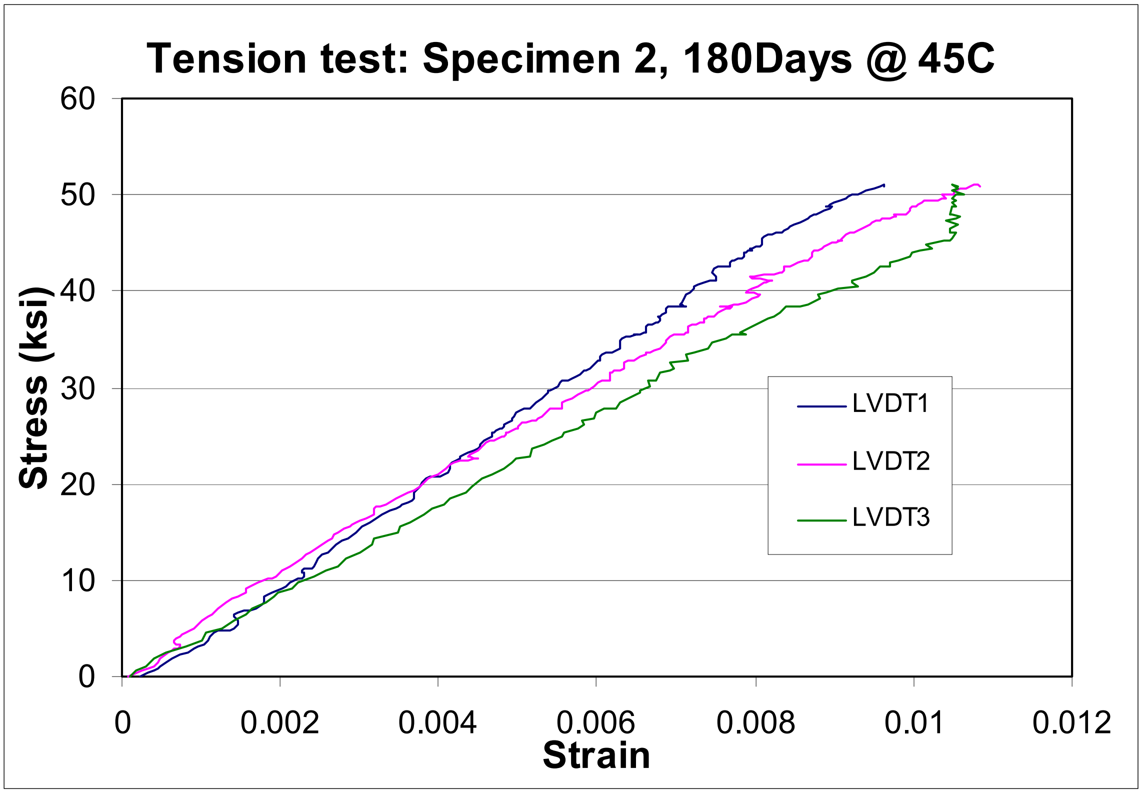
Tensile Test - Specimen 3, 180Days @ 30C
Stress (ksi)
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3



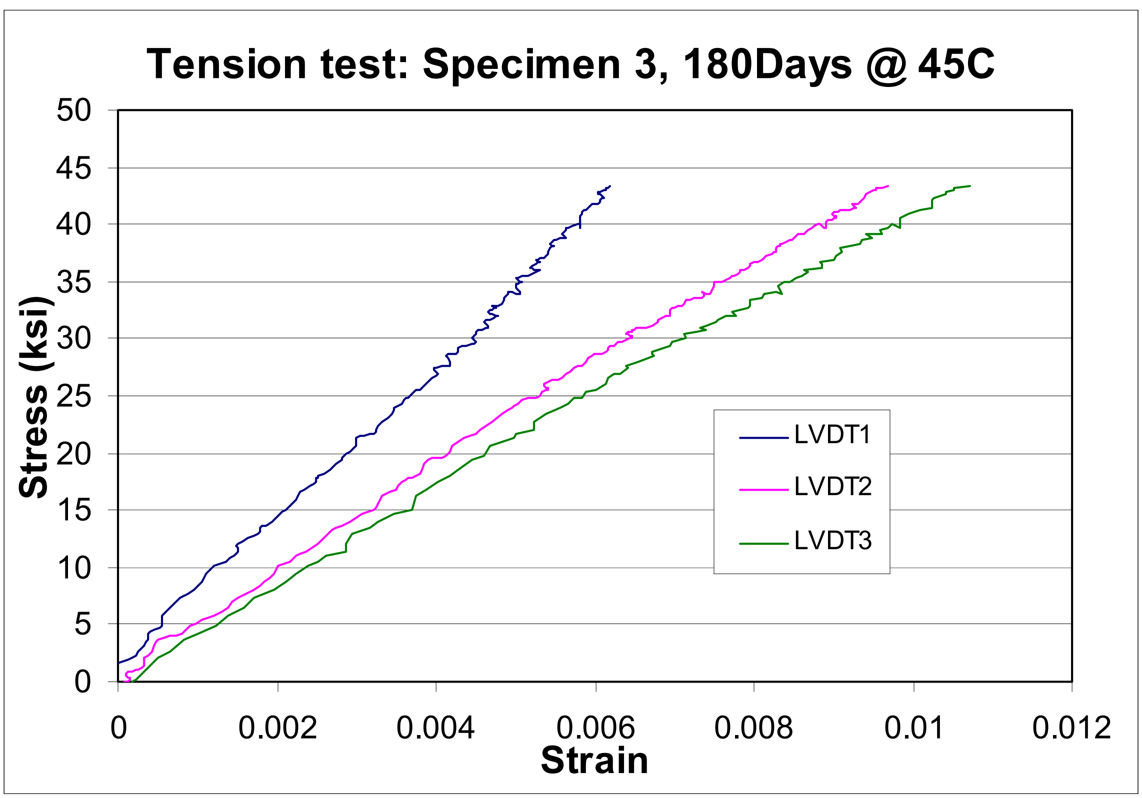
Tensile Test - Specimen 4, 180Days @ 30C
Stress (ksi)
45
40
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3


Tension test: Specimen 5, 180Days @ 30C
Stress (ksi)
Strain
0
5
10
15
20
25
30
35
40
0
0.002
0.004
0.006
0.008
0.01
LVDT1
LVDT2
LVDT3

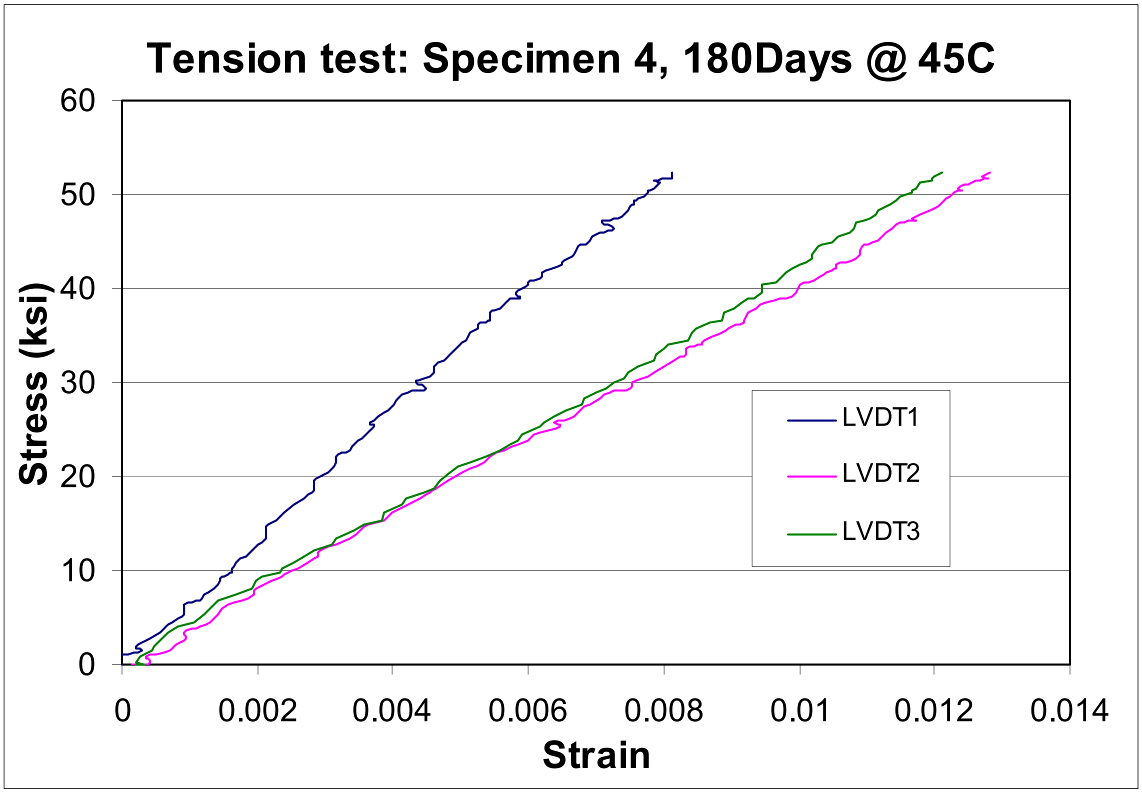

Tension test: Specimen 1, 180Days @ 45C
Stress (ksi)
Strain
0
5
10
15
20
25
30
35
40
45
50
0
0.002
0.004
0.006
0.008
0.01
0.012
LVDT1
LVDT2
LVDT3

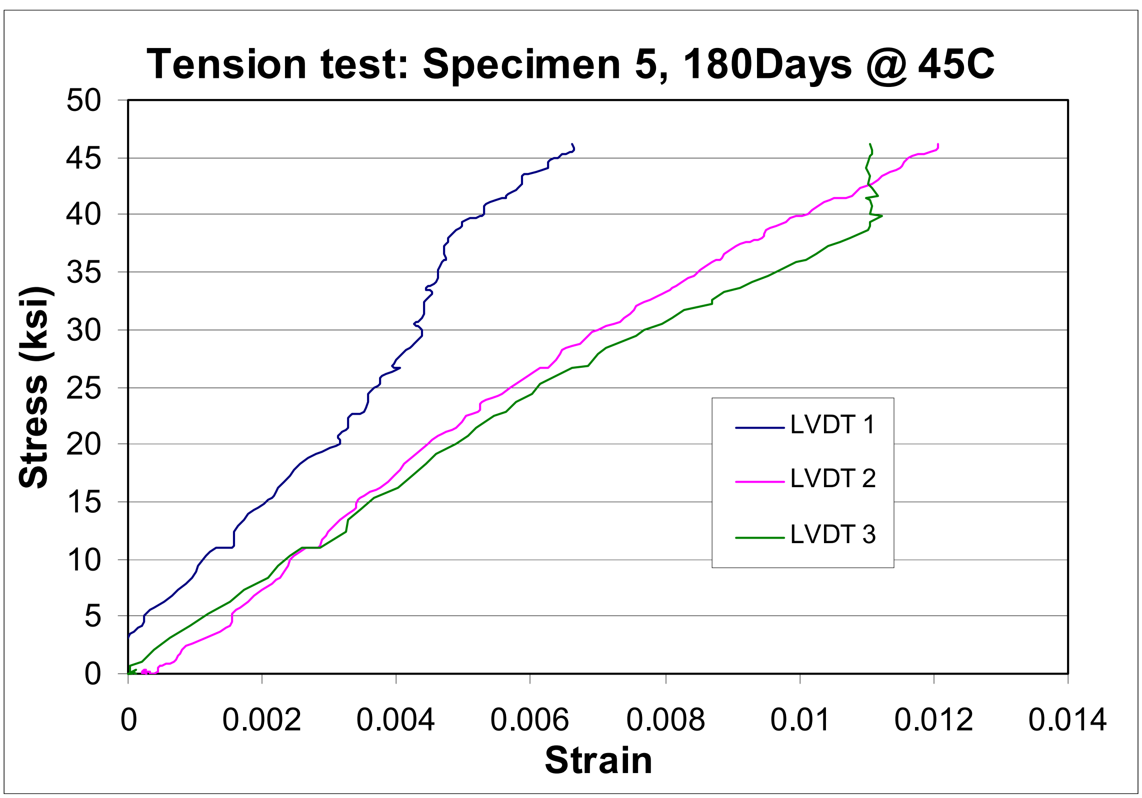


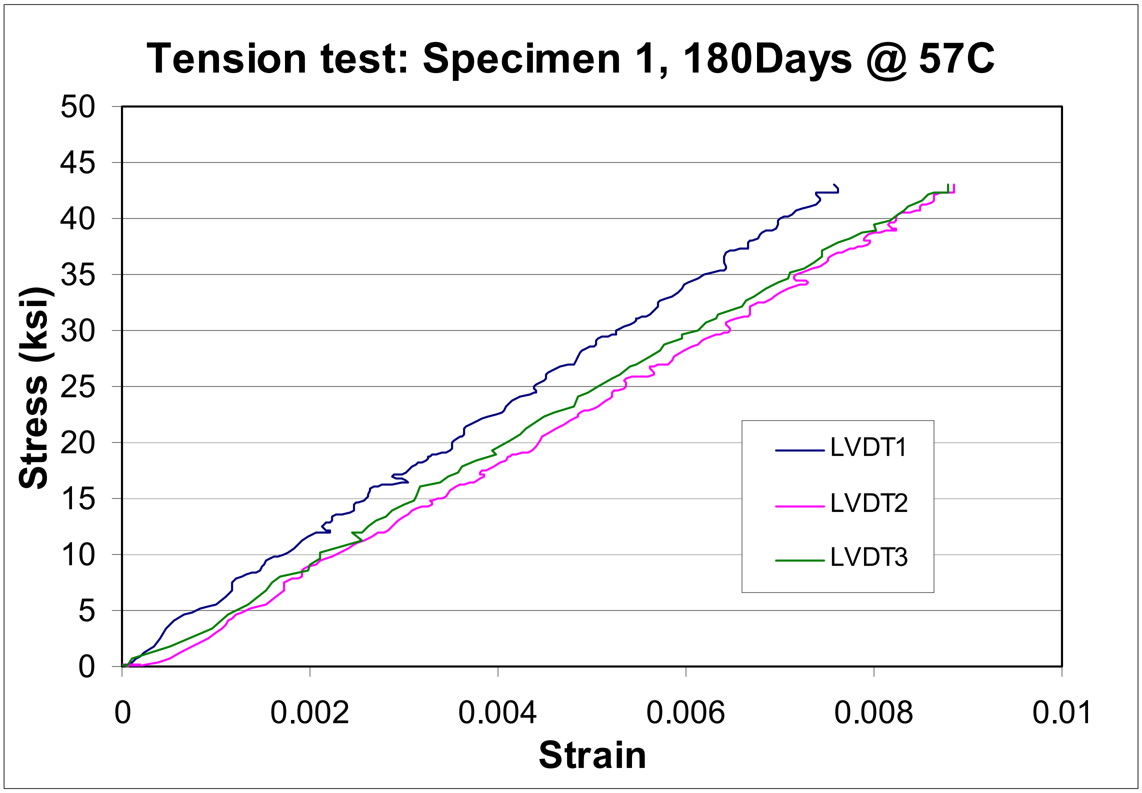
Tension test: Specimen 2, 180Days @ 45C
Stress (ksi)
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
Strain
LVDT1
LVDT2
LVDT3

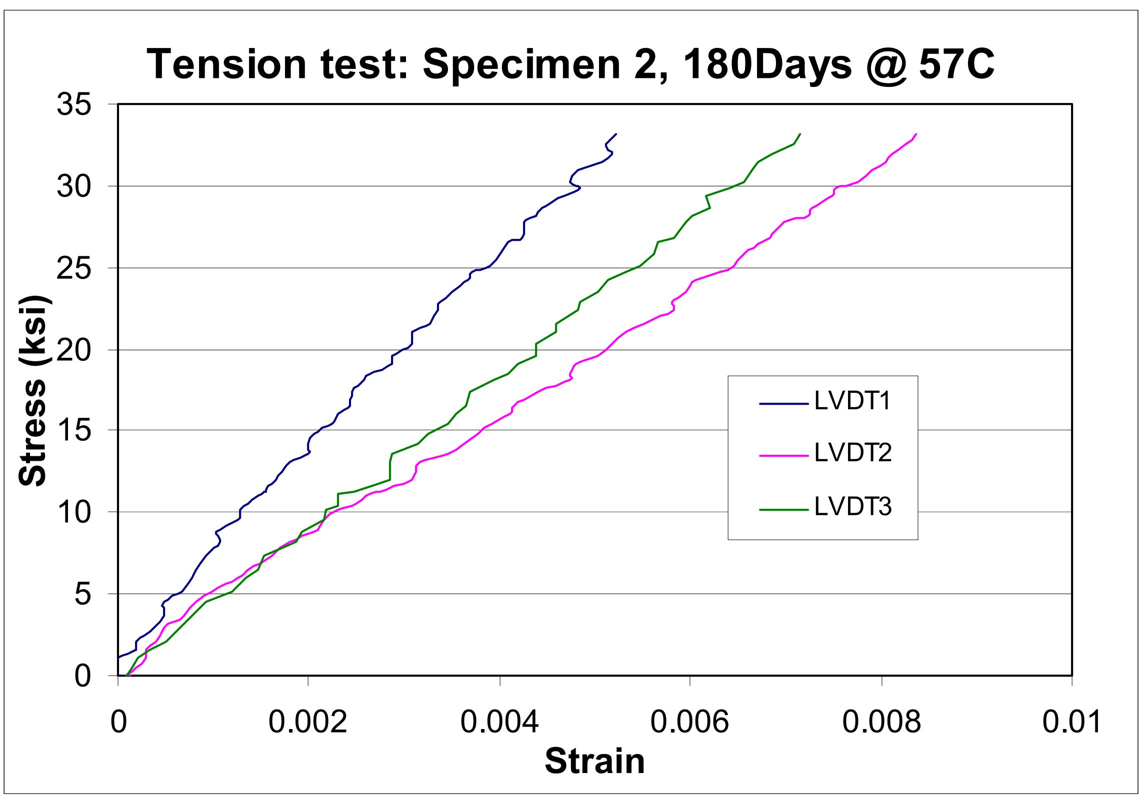


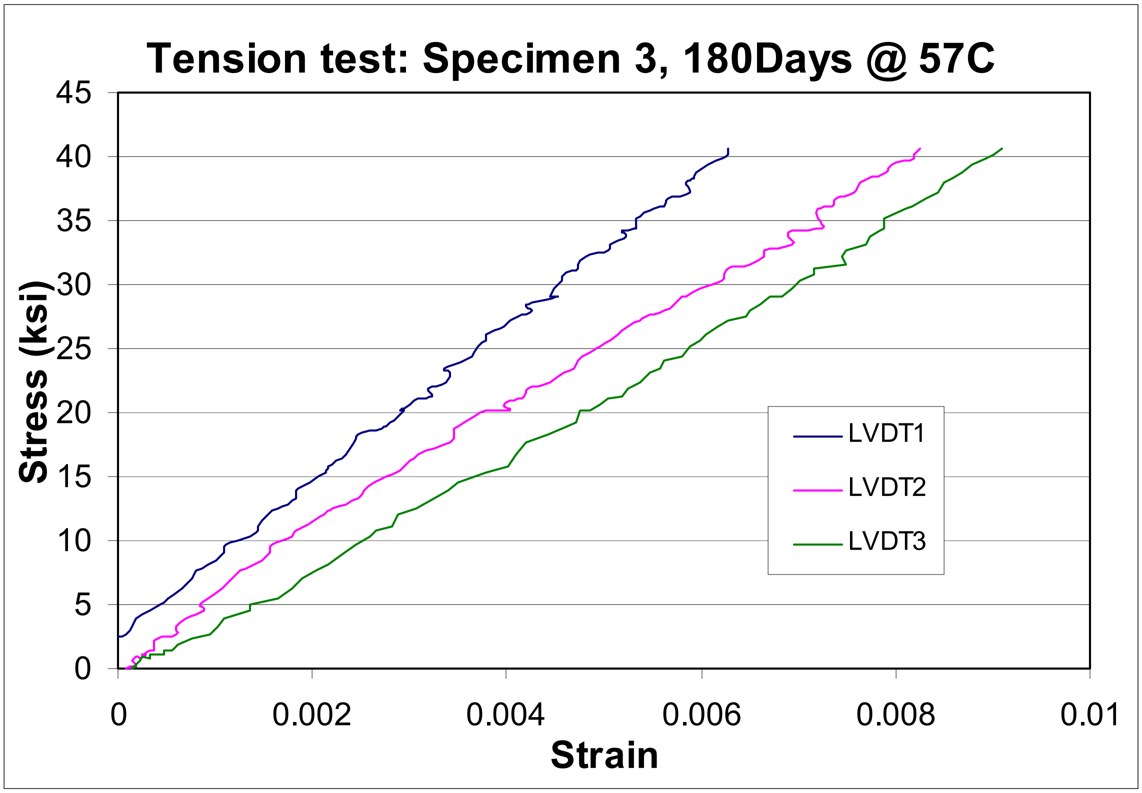
Tension test: Specimen 3, 180Days @ 45C
Stress (ksi)
50
45
40
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
0.012
Strain
LVDT1
LVDT2
LVDT3

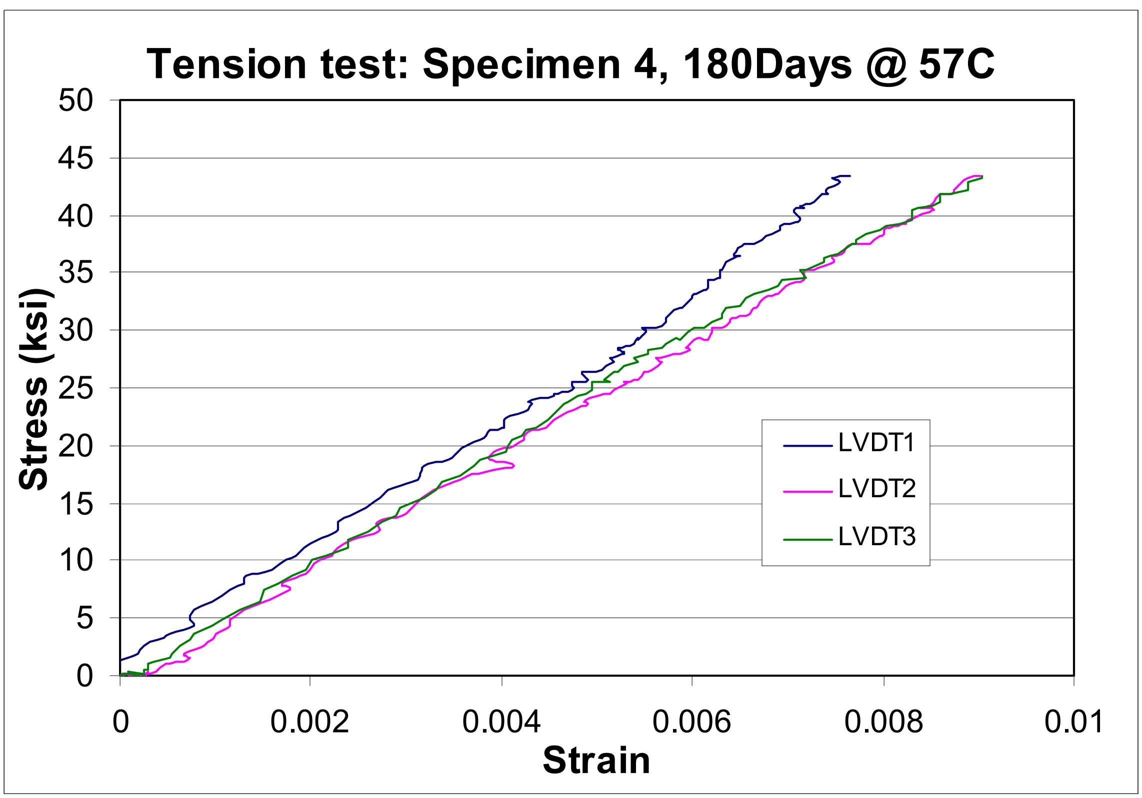

Tension test: Specimen 4, 180Days @ 45C
Stress (ksi)
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT1
LVDT2
LVDT3

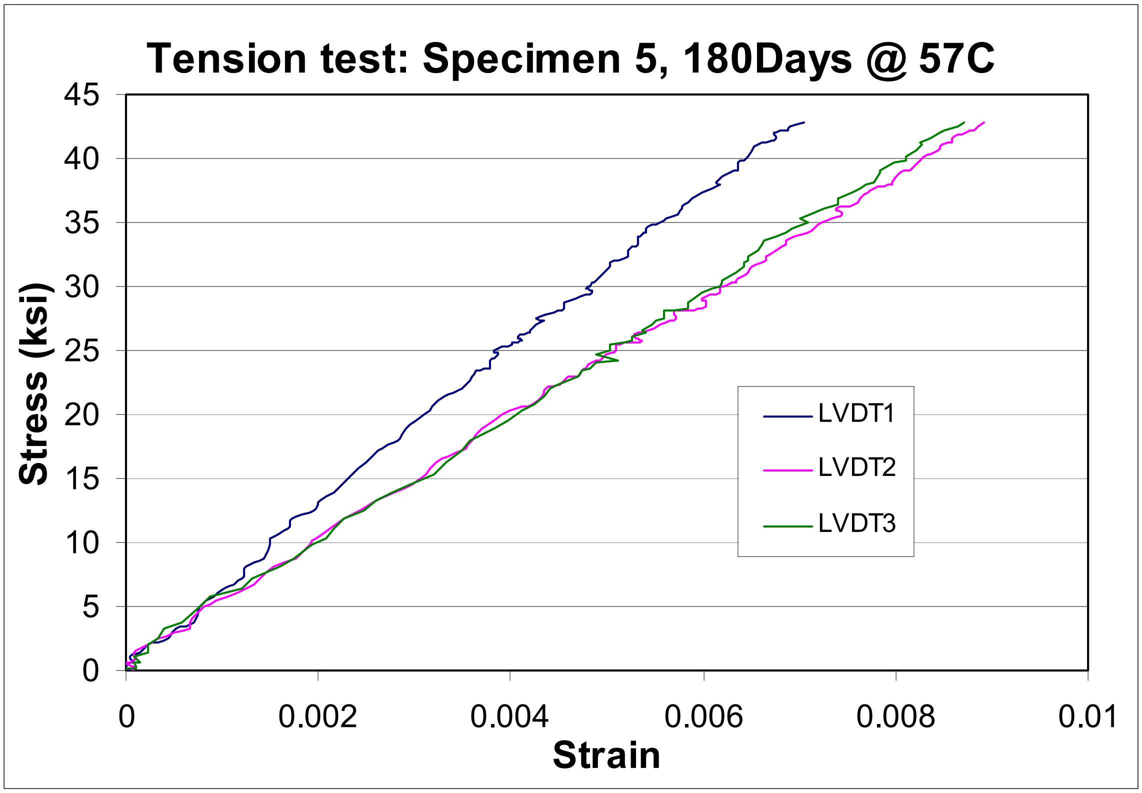

Tension test: Specimen 5, 180Days @ 45C
Stress (ksi)
50
45
40
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Strain
LVDT 1
LVDT 2
LVDT 3

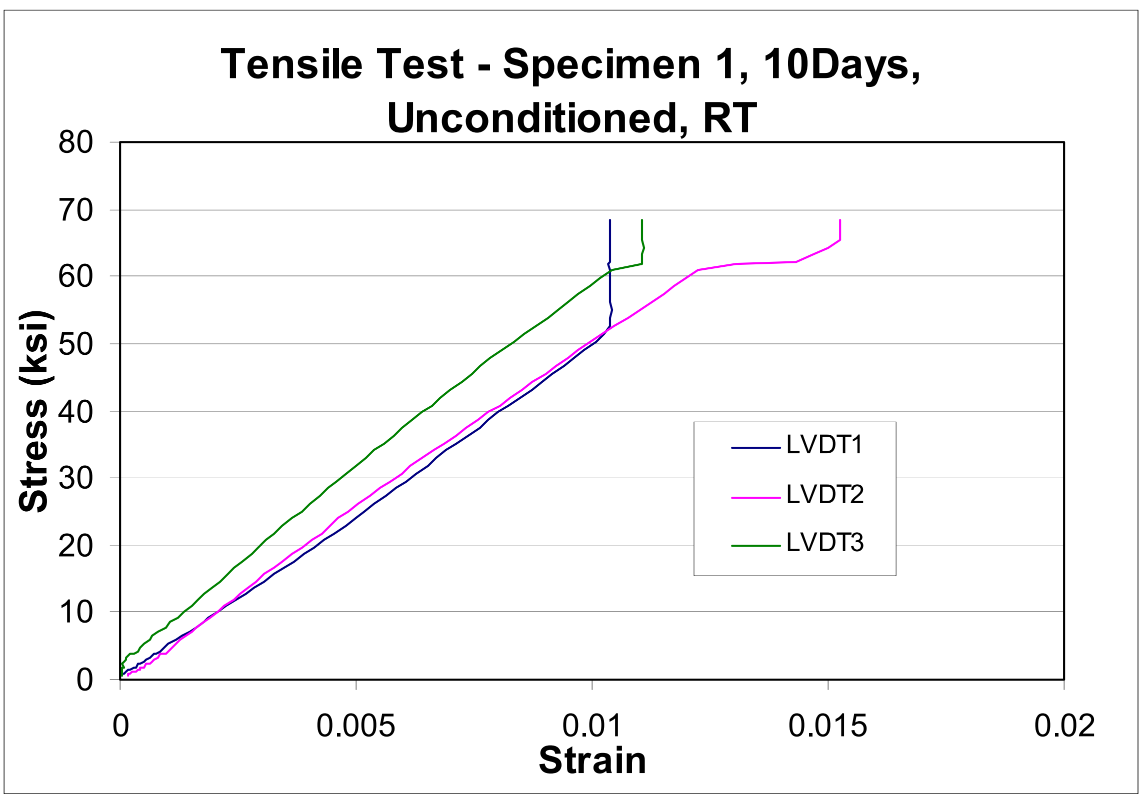

Tension test: Specimen 1, 180Days @ 57C
Stress (ksi)
50
45
40
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
Strain
LVDT1
LVDT2
LVDT3

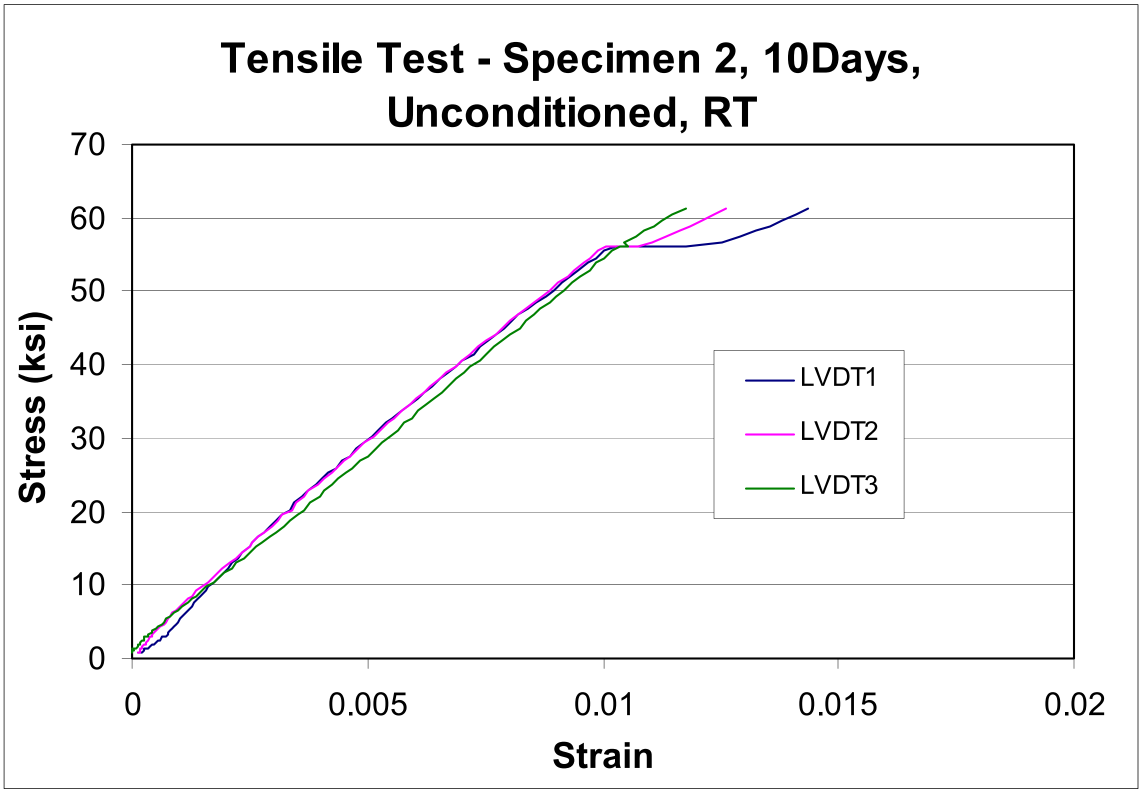

Tension test: Specimen 2, 180Days @ 57C
Stress (ksi)
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
Strain
LVDT1
LVDT2
LVDT3

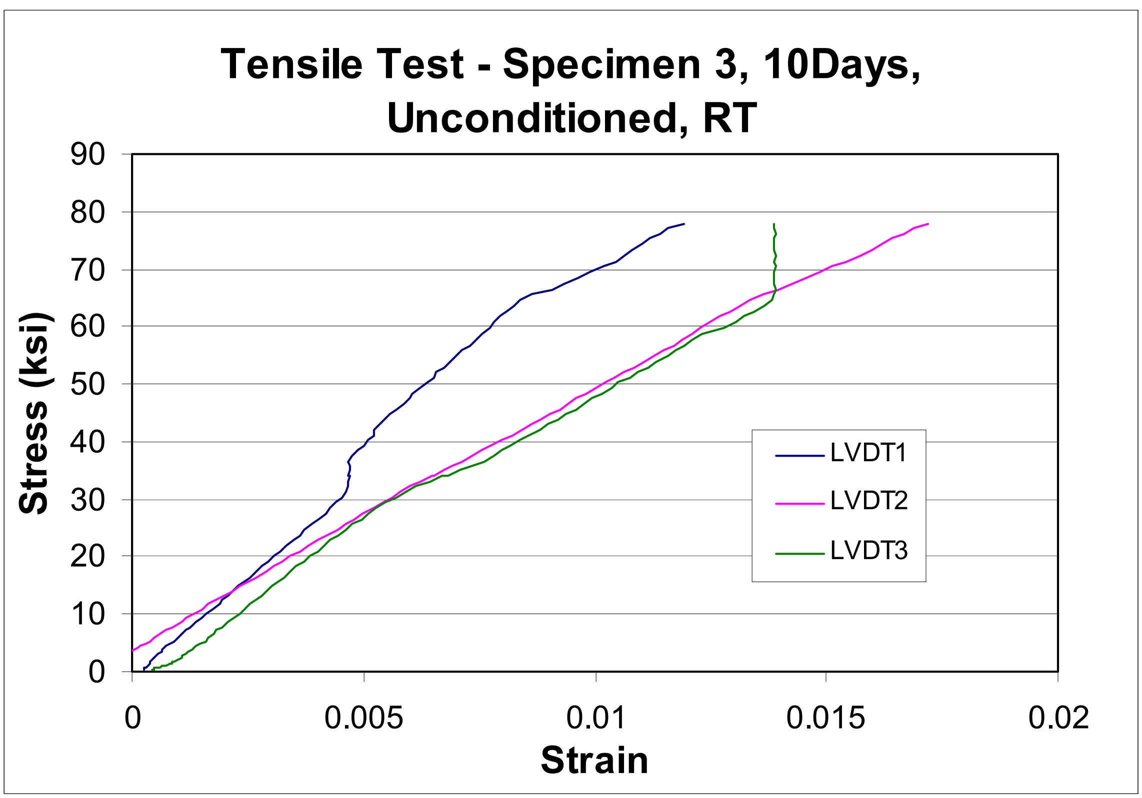

Tension test: Specimen 3, 180Days @ 57C
Stress (ksi)
Strain
0
5
10
15
20
25
30
35
40
45
0
0.002
0.004
0.006
0.008
0.01
LVDT1
LVDT2
LVDT3

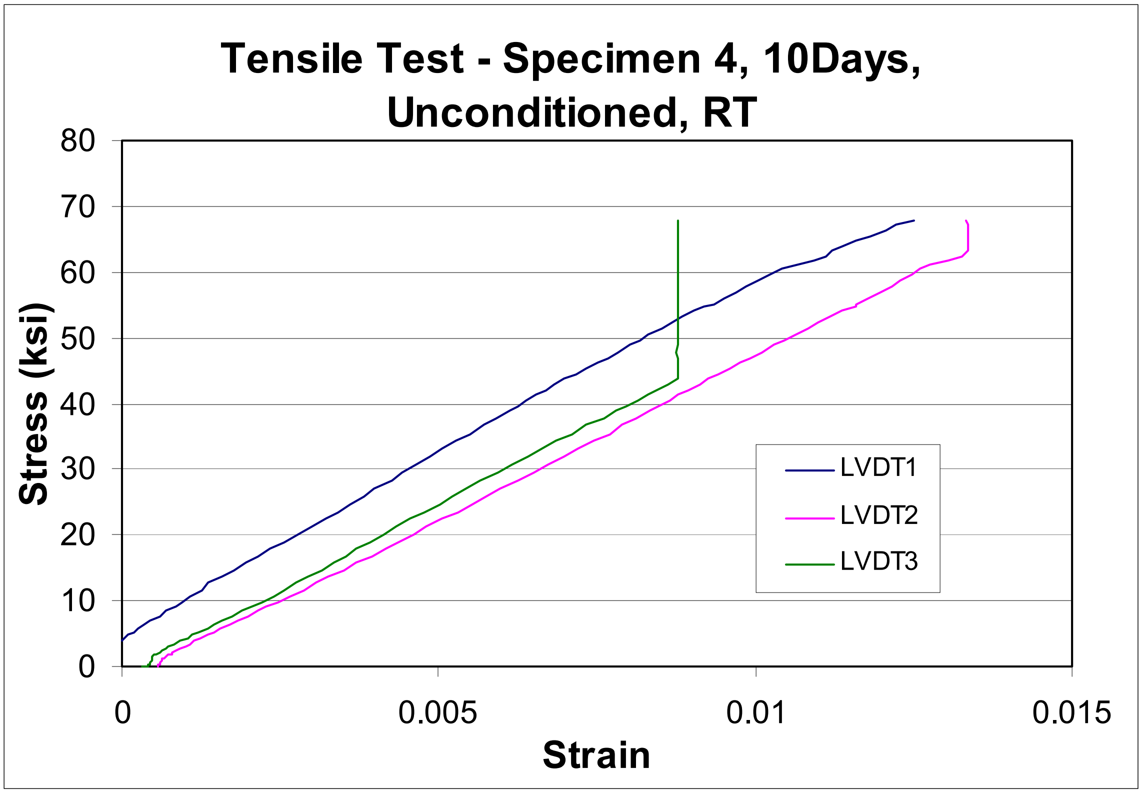

Tension test: Specimen 4, 180Days @ 57C
Stress (ksi)
Strain
0
5
10
15
20
25
30
35
40
45
50
0
0.002
0.004
0.006
0.008
0.01
LVDT1
LVDT2
LVDT3


Tension test: Specimen 5, 180Days @ 57C
Stress (ksi)
Strain
0
5
10
15
20
25
30
35
40
45
0
0.002
0.004
0.006
0.008
0.01
LVDT1
LVDT2
LVDT3


Tensile Test - Specimen 1, 10Days, Unconditioned, RT
Stress (ksi)
Strain
0
10
20
30
40
50
60
70
80
0
0.005
0.01
0.015
0.02
LVDT1
LVDT2
LVDT3


Tensile Test - Specimen 2, 10Days, Unconditioned, RT
Stress (ksi)
Strain
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
LVDT1
LVDT2
LVDT3


Tensile Test - Specimen 3, 10Days, Unconditioned, RT
Stress (ksi)
Strain
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
LVDT1
LVDT2
LVDT3


Tensile Test - Specimen 4, 10Days, Unconditioned, RT
Stress (ksi)
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
Strain
LVDT1
LVDT2
LVDT3

APPENDIX B

Determine the strength prediction using moisture content and diffusivity.

From Table 5.2 we get the activation energies, maximum moisture content and diffusion constant. Substituting it in the Arrhenius equation we get two equations

.
$$M_{\infty(T)} = 1339.43\, e^{\left(\frac{-4280}{1.99.T}\right)} \qquad [1]$$

$$D_{(T)} = 10.55\, e^{\left(\frac{-2490}{1.99.T}\right)} \qquad [2]$$

For Roanoke the Mean annual Temperature is 55.8°F ie 286.2 °K, we get $M_{\infty\,(T)} = 0.73\%$ and $D_T = 0.133$ mm^2/day.

Substituting this values in Cranks equation,

$$M_t = 0.73(1 - \sum_{1}^{5} \frac{4}{(0.1875 * 25.4)^2 \alpha_n^{\;2}} e^{-0.133(\alpha_n^{\;2} t)})$$

where t is the time in days.

For 50 years = 18250 Days, we get $M_{50} = 0.73\%$

VITA

Vikrant Bhise was born in Bombay, India on 19th November, 1975. He graduated from University of Bombay in January 1999 with a bachelor in Civil Engineering. Later he worked in a consulting firm as a structural engineer. He came to graduate school in Virginia Polytechnic and State University in August 2000. He received his M.S. in Civil Engineering from Virginia Tech in September 2002. Now he is working in a consulting firm in Richmond, VA.