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Thermal Shock and Thermal Fatigue on Delamination of Glass Fiber Reinforced Polymeric Composites

B. C. RAY
Department of Metallurgical and Materials Engineering, National Institute of Technology, Rourkela-769008, India
bcray@nitrkl.ac.in

ABSTRACT

Glass fiber reinforced unsaturated polyester and epoxy resins composites were exposed to 75°C temperature gradient thermal shock for ten times in different stage of conditioning times. The other lot of short beam shear specimens were conditioned with a thermal shock of again 75°C temperature gradient for the different cycles. The three-point bend test was performed on the conditioned specimens to evaluate the value of interlaminar shear strength. These conditionings may induce matrix cracking because of large misfit strain. The present experiments aim to study the fiber/matrix debonding effect of thermal shock/thermal fatigue, post curing hardening phenomena of thermal conditioning and also the mechanical keying factor of sub-zero conditioning.

KEY WORDS: glass fiber, polymer, thermal shock, thermal fatigue, interface, mechanical behavior

INTRODUCTION

Delamination is one of the most common life-limiting crack growth modes in laminate composites. It may be introduced in cyclic fatigue and in service or even during fabrication [1]. The characteristics of interface/interphase depend on the fiber and as well as on the polymer matrix. The optimization of the mechanical properties of composites is influenced by the behavior of interface/interphase [2-4]. A great deal of research has, therefore, been focussed on the analysis of interfacial phenomena in composite materials [5-7]. It may be reasonable to assume that the weak interface of fiber reinforced polymeric composite is susceptible to repeated applications of thermal shock of a lower magnitude. The present experiment has been carried out to evaluate the interlaminar shear strength (ILSS) of glass/epoxy and glass/polyester composites of woven fabrics and chopped fibers by changing the holding time at the holding temperature during the thermal fatigue. It is important to experimentally assess the degree of degradative effect of thermal fatigue on conditioning times during exposure to above-zero and sub-zero temperatures. The predominant failure mechanisms in a composite laminates are a very complex combination of energy absorption mechanisms such as delamination mainly caused by mode II shear, matrix cracking due to transverse shear, and translaminar fracture in terms of fiber fracture and kinking[1, 8]. The interlaminar shear strength (ILSS) has been used for the assessment of bond strength between fiber and matrix resin in a laminated composite.The differences in the thermal expansion coefficients of the fiber and matrix, cure shrinkage in thermosetting matrices result in the development of residual stresses at the fiber/matrix interface [9,10]. The situation may become more complex during thermal fatigue condition. Glass fiber reinforced polymer composites are exposed to varied temperature cycles during their applications in many areas. It is important to experimentally evaluate the extent of degradative effects of thermal fatigue on interfacial properties of such composite materials. One of the disadvantages of glass fiber is poor adhesion to matrix polymer. The nature and degree of degradation due to thermal shock cycles need to be more investigated to expand the applications of polymeric composites. The affected interfacial zones between the fiber and matrix are likely to control the overall mechanical behavior of a fiber reinforced composite. The interfacial area is dependent on the processing conditions, which are generally chemical, mechanical and thermo-mechanical in nature. These may introduce spatial non-uniformity of properties at the fiber/matrix interface [11].

EXPERIMENTAL

Unsaturated polyester and epoxy resins were used with chopped and woven roving glass fibers to fabricate the laminates. The short beam shear (SBS) specimens from these laminates were exposed to 60^{o}C temperature for 5 minutes and then they were immediately put in a freezer at -15^{o}C temperature for the same time. The thermal shock was repeated ten times for the same situation. The treatment was carried out for 10, 15, 20, 25 and 30 minutes of holding time at these temperatures. The three-point bend test was performed on the conditioned specimens, with a small span length, which promotes failure, by interlaminar shear. The ILSS values were measured from the test and they were plotted against the holding times. The SBB test is used as a quality control test of the composite materials. The present experiment has also been carried out to evaluate the ILSS value of glass/epoxy and glass/polyester composite after exposing them to different numbers of thermal shock cycles. The fiber/matrix interfacial degradation may be reflected in such short beam shear (SBS) tests [12].

RESULTS AND DISCUSSION

Figure 1 is drawn to show the effect of ten thermal shock cycles on ILSS value of the thermally (at above and below the room temperature) conditioned woven fabric glass/epoxy and glass/polyester composites for different conditioning times. There is an improvement in shear strength for the less conditioning times. Thereafter, the fall in ILSS is observed for both types of composites. The post-curing strengthening phenomena could be the cause of for the initial exception. The different thermal coefficients of glass and resins may lead to greater degree of residual stress at the interface for the longer conditioning time. That possibly results in higher order of debonding at the interfaces and the fall in ILSS values is reflected in the figure. Fatigue damage by the debonding mechanism depends on the interfacial bond strength between the fiber and the matrix. Low bond strength may promote a large fiber/matrix interfacial debonding. Interfacial debonding is expected to introduce the intralaminar crack initiation for composite that contains weak fiber/matrix interface bonds[13]. The sign of improvement in the shear value for the 30 minutes conditioning is probably due to the development of greater cryogenic compressive stress due to the more available time. It may help in more keying factor at the interface between the fiber and the matrix.

Figure 2 shows the effect of thermal fatigue on the ILSS values of the thermally conditioned specimens for the random glass fibers reinforced epoxy and polyester based composites. Here also it is evident that there is a rise in shear strength for the less conditioning time. The conditioning at 60^{o}C temperature may improve fiber/matrix interfacial strength by a surface chemistry principle. This could be dominating over the de-adhesion effect of thermal fatigue for the less conditioning time. The more conditioning time may develop a greater thermal stress because of larger extent of mismatch between the fiber and resin. The debonding phenomena are more degradative for glass/polyester system due to the weaker interface. It may also be attributed to the very high curing shrinkage of polyester resin. The laminates with low bond strength exhibits large areas of interfacial debonding that intensifies other damage mechanisms to promote laminate failure. It should be noted that unmodified epoxy and polyester resins could undergo a limited extent of deformation prior to failure. Matrix cracking becomes a macroscopic form of damage that could subsequently lead to delamination failure. The interfacial bonding in the epoxy laminates is believed to be too high to induce extensive delamination[13].

Figure 3 shows the effect of thermal shock cycles on the ILSS value of woven glass/epoxy and woven glass/polyester composites. It is evident that the improvement in shear value is indicated at a lesser number of thermal shock cycles. The reduction in ILSS value is observed with the increase of cycles. The conditioning at 60^{o}C temperature may impart better adhesion at the fiber/matrix interface by a surface chemistry mechanism and/or by a post-curing effect. The sub-zero conditioning at –15^{o}C temperature may similarly improve the adhesion by mechanical keying mechanisms as a results of shrinkage compressive stress at the interface. The debonding phenomena of thermal fatigue because of different thermal expansion/contraction coefficients is being introduced with those of strengthening phenomena (further polymerization and more interlocking principles) during such type of complex and active environmental conditionings. The initial rise in ILSS value may be attributed to the dominating effect of strengthening by thermal and sub-zero conditionings. The fall in ILSS value at a higher number of cycles is possibly due to the greater misfit strain effect. That leads to more debonding at fiber/matrix interfaces.

The variation of ILSS value of chopped glass fiber/epoxy and chopped glass fiber polyester laminates are plotted against the number of thermal shock cycles in Figure 4. The more phenomenal rise in ILSS value in glass/epoxy composites as compared to glass/polyester system may probably due the more cross-linking phenomena in epoxy resin. The better adhesion is possibly incorporated at the fiber/matrix interface by a greater surface chemistry mechanism in the epoxy system. The reduction in shear strength is more evident in glass/polyester system for higher cycles of exposure to thermal shock in compared to the glass/epoxy system. Thermal and sub-zero conditionings result in much improved interfacial strength in epoxy resin not only by more mechanical interlocking but by also chemical principles at the interface.

The presence of more interfacial area in chopped glass fibre may lead to more improved adhesion chemistry by the thermal conditioning in compared to the woven roving glass fiber. Differential coefficients of thermal expansion would modify the local stress threshold required for interfacial debonding which may eventually lead to nucleation of delamination. The failure mechanisms commonly attributed to fatigue are matrix cracking, fiber/matrix debonding and delamination [13]. Thermal fatigue may be assumed to accelerate deterioration in polymer matrix either by de-polymerization and/or by weak-link degradation of polymers [14].

CONCLUSIONS

Thus, in conclusion the fiber/matrix debonding effect of thermal fatigue, post-curing phenomena for thermal conditioning and mechanical interlocking effect of sub-zero temperature conditioning are shown here. It may be stated that polyester matrix is more susceptible to debonding by this type of severe environmental exposure compared to the epoxy matrix. The extent of degradative effect of thermal fatigue may differ for the orientations of fibers in the composites. The reason could be for the cause is the area of interfaces in a composite. That depends on the orientation of reinforcements of a composite.

It may also be reasonable to conclude that the debonding effect of thermal fatigue is more evident in glass/polyester system. The degradative effect of such exposure is not so dominating in epoxy matrix because of greater adhesive properties. The orientations of glass fibers are to be taken into consideration to assess the degree of susceptibility to degradation by this type of thermal fatigue. The magnitude of crack multiplication because of thermal fatigue may depend on the stress distribution and differences in coefficients of mutual influence between ply layers. Thermal fatigue may induce gross matrix cracking because of large misfit strain. The subsequent damage could usually be weaker interface and/or delamination.

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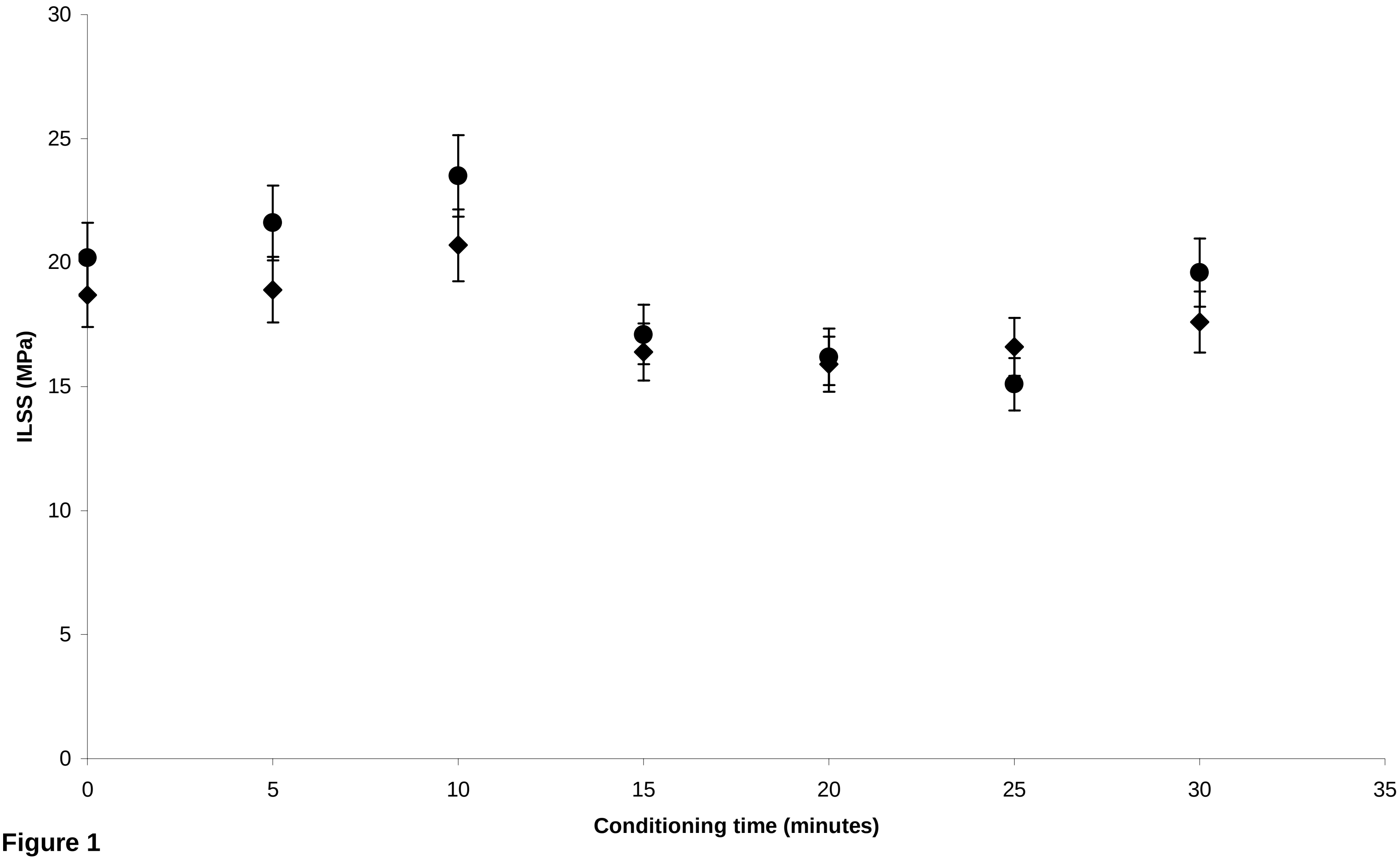
Figure Captions

Figure 1 Effect of repeated thermal shock on ILSS value of woven fabrics glass fiber reinforced epoxy (•) and polyester (♦) matrices composites.

Figure 2 Effect of repeated thermal shock on ILSS value of random orientation glass fiber reinforced epoxy (•) and polyester (♦) matrices composites.

Figure 3 Effect of thermal fatigue on ILSS value of woven glass fiber reinforced epoxy (•) and polyester (♦) matrices composites.

Figure 4 Effect of thermal fatigue on ILSS value of chopped glass fiber reinforced epoxy (•) and polyester (♦) matrices composites.



30
25
20
15
10
5
0
ILSS (MPa)
0
5
10
15
20
25
30
35
Conditioning time (minutes)

Figure 1

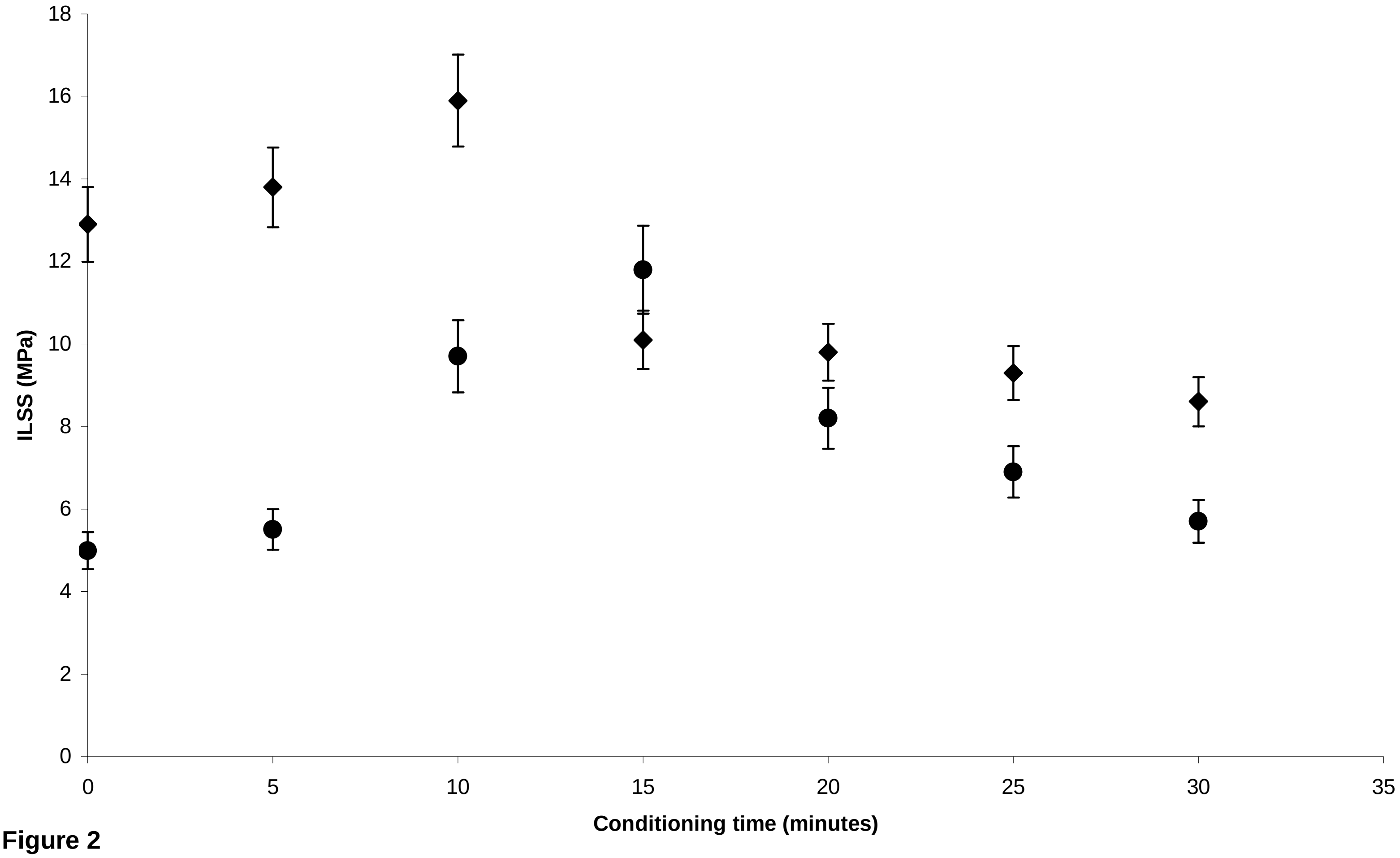

18
16
14
12
10
8
6
4
2
0
ILSS (MPa)
0
5
10
15
20
25
30
35
Conditioning time (minutes)

Figure 2

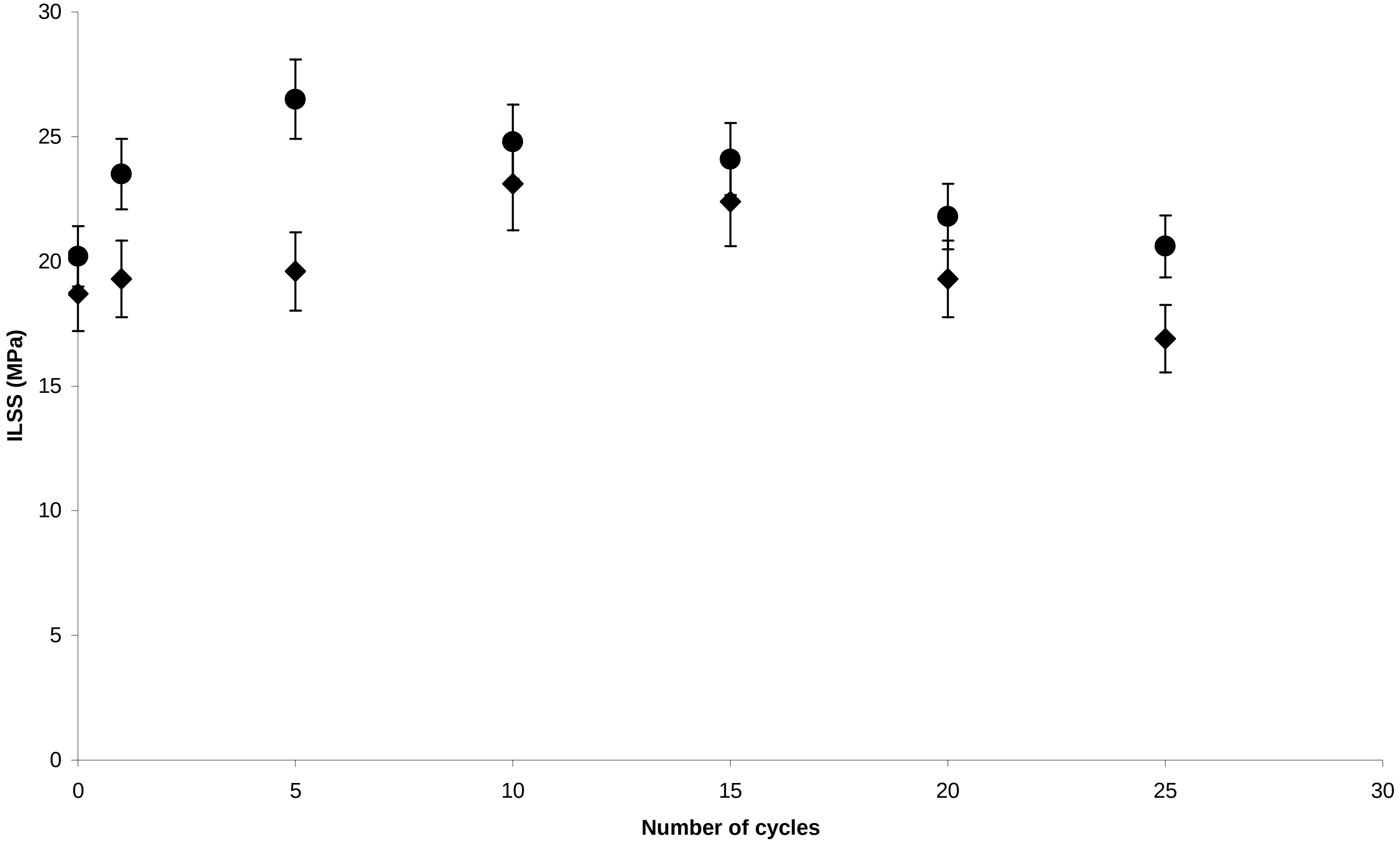
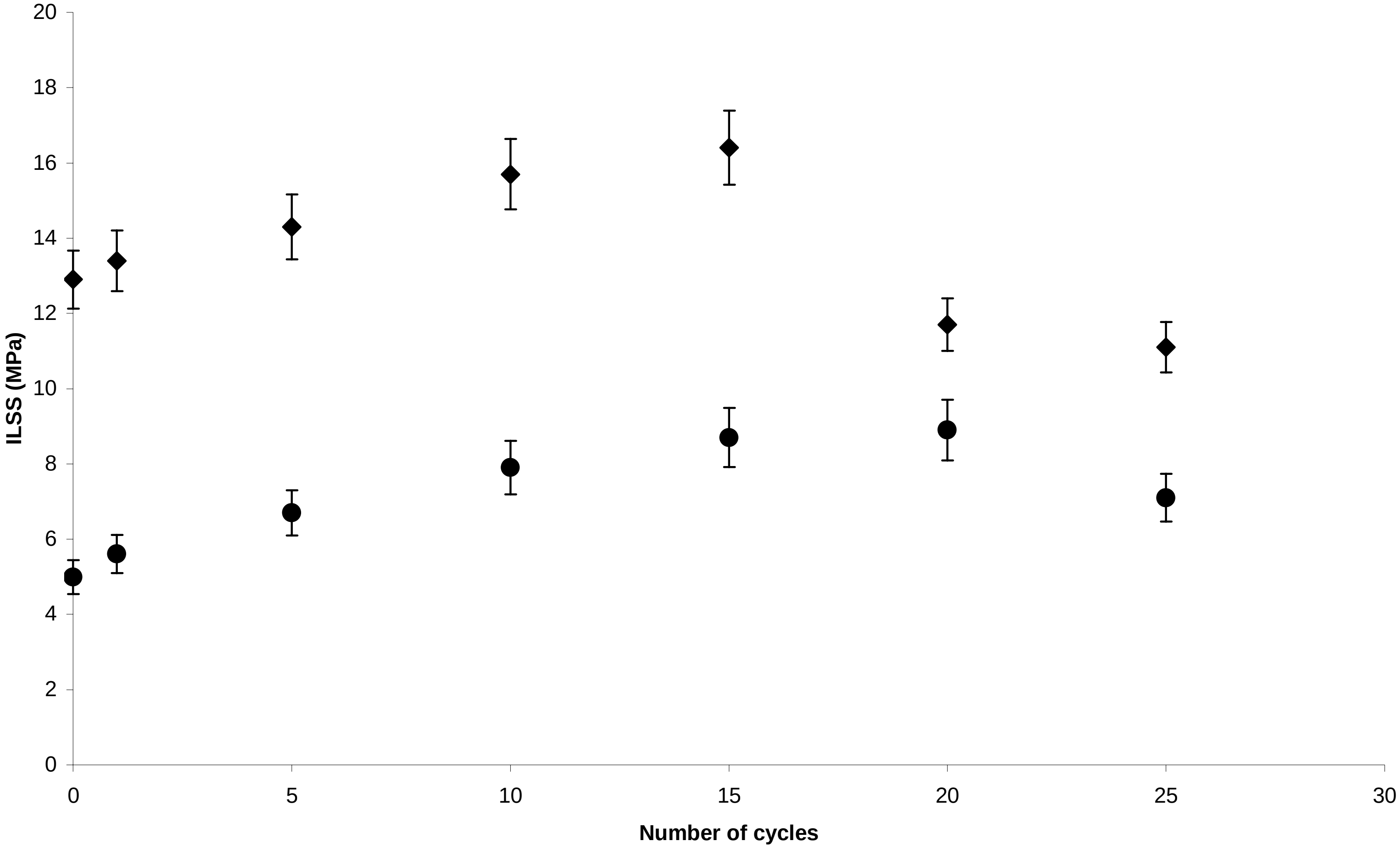


Figure 3



20
18
16
14
12
10
8
6
4
2
0
ILSS (MPa)
0
5
10
15
20
25
30
Number of cycles

Figure 4