Effects of Processing Conditions on the Mechanical and Water Absorption Properties of Resin Transfer Moulded Kenaf Fibre Reinforced Polyester Composite Laminates

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ABSTRACT

This paper focuses on the mechanical and water absorption properties of kenaf fibre reinforced polyester laminates manufactured by resin transfer moulding. Varying production conditions were considered as alternatives to fibre treatments, thereby potentially avoiding additional cost and complexity in the manufacturing process. Laminates were produced by altering fibre moisture content, mould temperature and mould pressure following injection. Tensile, flexural, impact and water absorption tests were conducted. Production conditions were found to have little effect on properties except for pressurisation which increased tensile and flexural strength and decreased water absorption at low fibre volume fractions. Examinations using a scanning electron microscope showed that all the laminates failed by fibre pull-out.

Keywords: Kenaf fibre; Fibre/matrix bond; Mechanical testing; Resin transfer moulding (RTM)

1 Introduction

Concerns about global warming and that fossil fuels will eventually run out has lead to renewed interest in natural fibres. Reliance on fossil fuels can be decreased through the use of natural fibres in composite materials. When natural fibre reinforced plastics are decomposed or combusted at the end of their life cycle, the carbon dioxide released by the fibres is the same as that absorbed during their growth [1]. Furthermore, natural fibres are easily combustible materials whereas man-made fibres have low energy values and high ash content when burnt [2].

Some of the most common natural fibres being used as reinforcement in composite materials include flax, hemp, jute, sisal and kenaf. There is currently only one company in South Africa producing non-woven natural fibre mats which are suitable for manufacturing composites. The fibre used in these mats is locally grown kenaf and for this reason, this fibre was selected for this investigation.

The major drawback in using natural fibres in composites is that the fibres are hydrophilic meaning that they attract water, whilst the matrix materials are usually hydrophobic, meaning that they repel it [1]. This difference in hydrophility makes good wetting of fibres by the polymer matrix during production difficult to achieve. Poor interphase properties between fibres and matrix consequently result. Fibre surface treatments [1, 3] offer one means by which fibre-matrix interaction can be improved. In some cases, however, the use of fibre surface treatments can make fibres expensive enough that they become unattractive materials [3]. Another approach which potentially avoids the cost and complexity of fibre treatments is to control production conditions.

It is common practise when manufacturing natural fibre reinforced laminates that the fibres are first dried or conditioned before use. This is done to remove or control moisture which can result in voids and poor fibre-matrix adhesion. Bledzki and Gassan [1] reported a 10 % increase in tensile strength and 20 % increase in Young's modulus for jute-epoxy laminates made using dried fibres but did not mention the fibre loading, fibre weave or the manufacturing method used. de Deus *et al.* [4] dried piassava fibres in an oven at 60°C for 30 minutes before producing unidirectional laminates by compression moulding. An increase in flexural strength of around 30-40 % was reportedly achieved by drying the fibres.

Rouison *et al.* [5, 6] used resin transfer moulding (RTM) to produce hemp / kenaf polyester laminates. The fibres were vacuum dried in the mould at 55°C for 2 hours before resin injection. Aziz *et al.* [7, 8] produced kenaf fibre laminates with various polyesters and cashew nut shell liquid matrix by compression moulding and dried the fibres before fabrication in an oven at 110°C for 5 hours. Sèbe *et al.* [9] conditioned hemp fibres at 23°C and 50 % relative humidity before producing laminates by RTM. In these works [5-9], no laminates were produced with undried fibres for comparison of mechanical properties.

Processing temperature can also potentially contribute to fibre-matrix interaction. It is possible that due to differing coefficients of thermal expansion between fibres and resin, the resin could either squeeze or relax around the fibres [10]. In addition, it is also possible that applying heat during production could be sufficient to drive off moisture. Rouison *et al.* [5, 6], Sèbe *et al.* [9], Sreekumar *et al.* [11] and O'Dell [12] produced laminates by RTM and used mould temperatures of 15-20°C, 30°C, 23°C and 55°C respectively but none determined the effects that the mould temperature had on the properties of laminates.

In addition to fibre drying and altering processing temperature, pressurisation of laminates during cure could also potentially improve the fibre-matrix interaction. However, this has not been previously explored in the production of natural fibre reinforced composites.

Resin transfer moulding (RTM) and vacuum infusion have recently gained much popularity due to a low labour requirement, acceptable cycle times, good surface finish, good dimensional tolerances, good process control, reduction of material handling, low cost when compared to other processes, minimal waste, high fibre loading and low void content [13]. Sreekumar *et al.* [11] showed that laminates made by RTM were superior to those made by compression moulding in terms of mechanical performance, water absorption and void content. In addition, RTM offers the opportunity to alter many production parameters such as pressure and temperature before, during, and after injection and thus potentially control laminate quality and cycle times to a greater degree. RTM was consequently selected as the manufacturing process used in this study.

Work regarding the use of kenaf fibres as reinforcement in thermosetting matrices has been conducted by Aziz *et al.* [7, 8, 14] using compression moulding. Further works have examined other non-woven natural fibre reinforced laminates produced by RTM [5, 6, 9, 11, 12]. There have been no previous works in which kenaf fibres have been used as the reinforcement in laminates manufactured by RTM. The objective of this work is to present a systematic comparison of processing conditions and their efficacy in improving the material properties of kenaf fibre reinforced polyester composite laminates.

2 Experimental

2.1 Materials

Non-woven kenaf fibre mats used for this investigation were donated by Sustainable Fibre Solutions, South Africa. The fibre mat had an areal density of 450 g/m^2. The polyester resin used was Scott Bader Crystic 1141. It is an orthophthalic unsaturated polyester resin of low viscosity. The resin was supplied with Crystic Accelerator E and Andonox KP-9 catalyst (M-200 catalyst). Accelerator and catalyst were mixed into the resin in a ratio of 1.5 % by mass each. The mechanical properties of the fibres and the resin can be found in Table 1. Properties of the resin were taken from the manufacturer because specimens made of unreinforced resin were too brittle to be machined and tested. Flexural properties were not available from the manufacturer; hence values for a similar product from another manufacturer are used.

2.2 Production of laminates

An RTM machine designed and built by the principal investigator was used to inject resin. The design of the pneumatically powered machine was based on a schematic in Zhang and Richardson [18] Resin and catalyst are injected separately by two pistons connected to an arm on which the ratio of catalyst to resin can be set between 1 % and 2.5 % using a slider mechanism. The resin and catalyst are mixed just before entering the mould in a static mixer. The machine also has a cleaning head allowing for the lines to be purged with air and then flushed with acetone.

The mould used consists of an upper mould plate, lower mould plate and a spacer plate into which the mould cavity and an o-ring groove are machined. The plates are made of mild steel. The cavity of the mould is sized to produce laminates measuring 280 × 260 × 4 mm. Resin is injected into the mould through a single inlet port located in

the centre of the lower mould plate and exhausted via four ports located in the corners of the mould cavity in the upper mould plate. Rectangular fibre mats were always cut with the lengthwise direction aligned parallel to the lengthwise direction of the fibre roll because the mat was assumed to be directional as found by O'Dell [12] for jute fibre non-wovens. Laminates were produced with fibre volume fractions of 15 %, 22.5 % and 30 %. The maximum fibre volume fraction that could be attained without a complicated closing mechanism or excessive mould deflection was 30%. Fibre volume fractions, V_f, were determined from the laminate mass, M_c, the dry mass of fibres, M_f , the matrix density, ρ_m, and the estimated density of the fibre, ρ_f, using the following equation:

$$V_f = \frac{\frac{M_f}{\rho_f}}{\frac{M_f}{\rho_f} + \frac{M_c - M_f}{\rho_m}} \tag{1}$$

For all fibre volume fractions, the thickness of the uncompressed fibre mat was larger than that of the mould and therefore it was necessary to compress the mat to fit it into the mould. Fibres were packed tightly inside the mould and this prevented any clustering or uneven distribution of fibres in the cured laminates.

For fibre volume fractions of 15 % and 22.5 % an injection pressure of 250 kPa (gauge pressure) was used with a vacuum assist pressure of 40 kPa (absolute pressure). For the 30 % fibre volume fraction, injection pressure was increased to 350 kPa and the vacuum assist pressure remained unchanged. Following complete mould filling, resin was allowed to run until no air bubbles were observed in the exhaust lines. In laminates where the mould was pressurised after filling, a pressure of 600 kPa was applied using a

compressed air line. After demoulding of laminates, all were post-cured for 3 hours at 80°C according to the resin manufacturer's data sheet.

Five different combinations of processing conditions were used to produce kenaf fibre laminates. Three parameters, namely fibre moisture content, mould temperature and post-injection-pressure, were varied to produce these five combinations. These combinations are listed in Table 2.

When required, the mould was heated to between 50°C and 55°C by placing it in an oven for three to four hours prior to use. This amount of time was found to be sufficient for the mould to reach the desired temperature which was verified using an infrared thermometer. Considering the large mass of the mould it was unlikely there were any significant quenching effects caused by the injection of room temperature resin.

2.3 Drying of fibres

Vacuum drying of fibres inside the mould as in the work of Rouison *et al.* [5, 6] was experimented with but the reduction in fibre moisture content was found to be low. It is well known that there are three ways in which heat can be transferred; convection, conduction and radiation. Vacuum drying eliminates convective heat transfer because there is no air through which heat can be transferred. Natural fibres are hollow in structure and are thus good insulators making conductive heat transfer between fibres poor as well. This means that vacuum drying of natural fibres relies mainly on radiation for heat transfer. Only fibres near the mould surface are therefore dried as radiation is unable to penetrate to the centre of the fibre mats and this was hypothesised as the cause of the low reduction in moisture. In order to verify this, three layers of fibres were vacuum-dried in the mould and the fibre mass was recorded periodically. One layer of

fibres was then vacuum dried in the mould and the fibre mass was once again recorded periodically. As expected, one layer of fibres lost a higher percentage of moisture than three layers because the radiation could penetrate proportionally deeper into the single layer of fibres. Results are shown in Fig. 1. For comparative purposes values obtained for drying of fibres at atmospheric pressure, 83 kPa, in the oven have also been included. In all cases, fibres were taken from ambient room conditions where temperature ranged from 20-23°C and relative humidity ranged from 45-55 %. Tests were postponed when these conditions were not met during adverse weather, .

The investigation into the efficacy of vacuum drying prompted a further investigation regarding the drying method of Rouison *et al.* [5, 6]. The mould used by these authors was made of aluminium. According to Gray and Mueller [19] and Harrison [20], steel has a higher emissivity than aluminium. This implies that using an aluminium mould for vacuum drying should result in poorer drying of fibres than if steel is used. To investigate this, one layer of fibres was placed between two sealed aluminium plates and then heated under vacuum. As expected, the fibres lost a lower mass percentage than when the steel mould was used. These results are also included in Fig. 1. Smooth surfaces such as those required in a mould for good surface finish emit less radiation than rough or black surfaces. Rouison *et al.* [5, 6] did not provide any data to show the efficacy of their method of vacuum drying. However, the results shown in Fig. 1 indicate that due to the low emissivity of smooth surfaces, drying of fibres under vacuum in moulds such as those used for RTM is ineffective.

It is clear that in order to adequately dry the fibres, they need to be dried in air. It was found that acceptable drying of the fibres could be achieved by loading the fibres into a preheated mould, placing the mould in the oven and drawing warm air through it. This method prevented the fibres from reabsorbing moisture while being loaded into the

mould after drying. Air was drawn through the mould using a venturi connected to the inlet port. The results obtained using this method are also presented in Fig. 1. Not all fibres could be dried in this way. Laminates made using dried fibres in a room temperature mould had to be produced by drying the fibres in an oven and then placing them inside the mould quickly enough to avoid the fibres absorbing moisture from the atmosphere. Tests were conducted and it was determined that if the fibres were removed from the oven and sealed inside the mould within two minutes, they did not absorb a significant amount of moisture.

As a result of these tests, all fibres were dried for at least three hours. When fibres were dried in the oven and subsequently sealed inside the mould, this process was completed within two minutes of their removal from the oven.

2.4 Testing

Tensile and flexural tests were conducted in accordance with ASTM D638 and ASTM D790 respectively on a JJ Lloyd tensile testing machine. Tensile specimens were of type M-I with a test section of 10 mm width and 4 mm thickness. Flexural test specimens were 16 mm wide and 4 mm thick. A support span of 64mm was used for flexural tests. ASTM D638 and D790 allow for testing of materials which exhibit linear or non-linear behaviour. The linear region of the kenaf laminates tested was very small. Both the linear and secant moduli for tensile and flexural tests were consequently calculated and reported. An example of a typical stress-strain curve for a tensile test is shown in Fig. 2. In the figure, the linear region has been highlighted. The linear modulus is determined by calculating the slope of the linear region of the stress-strain curve and the secant modulus is determined by dividing the failure stress by the failure strain.

Impact tests were conducted in accordance with ASTM D256 for in-plane Izod impact tests using an instrumented impact machine. Impact specimens were 12.7 mm wide, 10.16 mm wide at the notch, 4 mm thick and 62 mm long. The moment arm between the point of impact and the notch was 31.75 mm. Total impact energy, initial impact energy (energy absorbed at the onset of failure), propagative impact energy (energy absorbed between the onset of failure and ultimate failure) and impact strength were determined. Examination of impact specimen failure surfaces was conducted using a JEOL 840 scanning electron microscope (SEM). Specimens were coated with carbon and gold-palladium to increase their conductivity.

Water absorption tests were conducted in accordance with ISO R62. Water absorption specimens measured approximately 50 mm × 50 mm × 4 mm. The standard requires specimens to be immersed in water for 24 hours and measurements of mass and dimension then taken. The standard was modified so that the first measurements were taken after 1 hour and then again after a further 23 hours. Specimens were subsequently measured at various time intervals for four weeks.

3 Results and discussion

Results have been presented using a laminate coding system. Each laminate type was coded using either three or four sets of characters. The first set indicates the resin system: UP (unsaturated polyester). The second set indicates whether or not the fibres were dried: AD (air dried) and ND (not dried). The third set indicates the temperature of the mould: H (heated) and NH (not heated). The fourth set is used only where applicable and indicates if the mould was pressurised following injection: P (pressurised). As an example, UP-ND-H stands for: unsaturated polyester resin, fibres not dried and mould heated.

3.1 Tensile tests

Results of the tensile tests show no significant difference in tensile strength (Fig. 3), secant modulus (Fig. 4) or linear modulus (Fig. 5) for laminates made with either dried or undried fibres for any fibre volume fraction. For the 22.5 % and 30 % fibre volume fraction laminates made using dried fibres (UP-AD-H, UP-AD-NH & UP-AD-H-P) it appears as though a cold mould might produce laminates with slightly lower tensile properties than those where the mould is heated. When the error bars, which correspond to one standard deviation are taken into account however, the difference is not clear enough to be considered significant. Laminates where the mould is pressurised after injection (UP-AD-H-P) produce the highest strength for all fibre volume fractions but once again the difference is not significant. Contrary to the findings of Bledzki and Gassan [1], laminates made using dried fibres performed no better than those made using undried fibres.

It is interesting to note that the tensile strength of all the laminates is lower than that of the unreinforced polyester resin which, according to the manufacturer, is equal to 63 MPa. This is contrary to normal expectation. The reduction in tensile strength is probably due to the inclusion of voids which can be seen in Fig. 6. In addition, weak interfaces between the fibres and matrix may also have played a role. The increase in elastic modulus after the addition of fibres and the non-linear behaviour of the stress curve are indications that the interface is failing at a low stress level. The addition of fibres to the resin has slightly improved the tensile secant moduli for all fibre volume fractions. Tensile linear moduli are also higher than the modulus of the unreinforced polyester resin for all fibre volume fractions and increase with fibre volume fraction.

3.2 Flexural tests

Results of the flexural tests show no significant difference in flexural strength (Fig. 7), secant modulus (Fig. 8) or linear modulus (Fig. 9) between the five laminate types tested except for the case of the 15 % fibre volume fraction. In this case, the laminates made using the pressurised mould (UP-AD-H-P) have the highest flexural strength which is around 15-20 % greater than that of the other laminates. Secant and linear moduli are also higher but not by a significant amount. The reason for the increase could be attributed to the size of the voids reducing as a result of the pressure applied after injection. However, at higher fibre volume fractions, pressurisation of the mould has little effect on the flexural properties. This is especially true at 30 % fibre volume fraction where all five laminates have almost identical values of flexural strength. Contrary to the findings of de Deus *et al.* [4] the flexural properties of laminates made using dried fibres are no better than those made using undried fibres.

The flexural properties of the resin were not available from the manufacturer and so the flexural strength and flexural modulus of a similar resin from another manufacturer are used here. These values are quoted as 84 MPa and 3.93 GPa respectively [17]. At 15 % fibre volume fraction, all laminates have a flexural strength lower than that of the resin. At 22.5 % the flexural strength of the laminates are approximately equal to that of the resin and at 30 % are higher at just under 100 MPa. Flexural secant moduli are lower than that of the unreinforced resin at 15 % and 22.5 % fibre volume fractions but are slightly larger at 30 % fibre volume fraction. The flexural linear moduli of the laminates are approximately equal to that of the unreinforced resin at 15 % fibre volume fraction but are higher at 22.5 % and 30 %. At 30 % fibre volume fraction, the flexural linear moduli are approximately 25-30 % higher than that of unreinforced resin. Both flexural secant and linear moduli increase with increasing fibre

volume fraction and there is a larger increase from 22.5 % to 30 % than from 15 % to 22.5 % fibre volume fraction.

3.2.1 Impact tests

Fig. 10 shows the results obtained for impact energy. In this figure, the division in each bar indicates the division between initial and propagative impact energies and the sum of the two represents the total energy absorbed.

For all fibre volume fractions, laminates made using undried fibres absorb slightly more total energy than laminates made using dried fibres except at 30 % fibre volume fraction where the UP-ND-H laminate absorbs the least energy. The reduced impact energy of this laminate can probably be attributed to variability between specimens.

Low impact energy is normally an indication of less fibre pull-out and more fibre breakage during failure [22] which, in turn, is an indication of improved fibre-matrix adhesion. At 15% fibre volume fraction the UP-AD-NH laminate absorbs by far the least total energy. This is probably an anomaly since, if the UP-AD-NH laminate at 15% fibre volume fraction has noticeably better fibre-matrix adhesion than the other laminates, it should also exhibit noticeably better tensile and flexural properties. This is not the case, however. In fact, a rescan of Figs. 3, 4, 7 and 8 shows that the tensile and flexural properties of the UP-AD-NH laminate at 15% fibre volume fraction are lower than those of the UP-AD-H-P laminate. Therefore the lowest impact energy of the UP-AD-NH laminate at this fibre volume fraction is attributed once more to variability between specimens.

At each fibre volume fraction, the initial impact energy is approximately equal indicating that the mode of failure is similar for all production conditions because the initial impact energy shows how much energy is absorbed prior to failure.

Impact strength (Fig. 11) at each fibre volume fraction is also found to be similar for all laminates. The UP-AD-NH laminate has the lowest strength at 15 % fibre volume fraction. As discussed previously, it is believed that this is likely to be the result of variability between specimens and not of production conditions.

The initial impact energy and strength are not significantly affected at any fibre volume fraction by the production conditions. This leads to the conclusion that the production conditions have little influence on fibre-matrix adhesion.

3.3 SEM studies of impact failure surfaces

Fig. 12 shows SEM micrographs of the failure surfaces of the 22.5 % fibre volume fraction laminates after impact testing. All laminates failed by fibre pull-out, confirming why the results of the mechanical testing are very similar. It is evident that the variation of production conditions does not alter the failure mechanism. SEM examinations were also conducted for 15 % and 30 % fibre volume fractions. These images are not presented because they are very similar to those of Fig. 12.

3.4 Water absorption tests

Fig. 13 shows the water absorption for the 22.5 % fibre volume fraction laminates over a four week period. The trends observed in this figure are similar for all fibre volume fractions. The rate of mass increase due to water absorption is first seen to be high and then diminishes with time. Due to practical considerations, water absorption tests could not be carried out for longer than four weeks so equilibrium was not reached. The results however, suggest that equilibrium would eventually be obtained.

Fig. 14 shows that water absorption increases as expected with fibre volume fraction due to the increasing numbers of hydrophilic fibres. At 15 % and 22.5 % fibre volume fractions the UP-AD-H-P laminate absorbs the least water. This trend suggests

that pressurising the mould after injection helps reduce water absorption at lower fibre volume fractions, probably as a result of the reduction in void size. Evidence of such voids was presented in Fig. 6. There is, however, no benefit from pressurisation at 30 % fibre volume fraction. At this fibre volume fraction, the UP-AD-NH laminate absorbs the least amount of water. The UP-AD-NH laminates also absorb less water than most of the other laminates at 15 % and 22.5 % fibre volume fractions. Thus, it is not possible to suggest a single combination of production conditions that will reduce water absorption. Depending on fibre volume fraction, using dried fibres in a cold mould or pressurising the mould after resin injection can result in reduced water absorption.

Fig. 15 presents the increase in thickness of the samples after four weeks of water immersion. It can be seen that the thickness increases with fibre volume fraction. The effect of production conditions on the thickness does not show any consistent trend. At 15 % fibre volume fraction, the increase in thickness is almost identical for all laminates. At 22.5 % fibre volume fraction, all laminates made using dried fibres show an almost identical increase in thickness. This is also true for the laminates made using undried fibres. These, however, absorbed slightly less water than those made from dried fibres.

A comparison of Figs. 14 and 15 reveals that both the amount of water absorbed and thickness increase with fibre volume fraction. However, the rate of increase is different in each case. Further comparison of these figures at 15 % and 22.5 % fibre volume fractions shows no similarity between changes in thickness and in mass for the various production conditions. For example, at 15 % fibre volume fraction, the UP-AD-H-P laminate absorbs the least water but shows the largest increase in thickness. At 30 % fibre volume fraction, there is some similarity in the results for the various production conditions. At this fibre volume fraction, the UP-AD-NH and UP-ND-H

laminates absorb the least water and show the lowest increases in thickness while the mass and thickness increases in the other laminates are approximately equal.

Figures 16 and 17 present the increase in length and width of the samples after four weeks of water absorption. It can be seen that they exhibit different trends. At 15 % fibre volume fraction for example, the UP-AD-H-P laminate shows the second lowest increase in length but the highest increase in width.

It is interesting to note that the increase in length of every laminate is more than that of the width. This indicates that the non-woven fibre mats are directional and that more fibres are orientated along the width of the specimens i.e. in the direction of the length of the non-woven roll. Thus, because the hygroscopic strain of the fibres is greater across their diameter than along their length [23], the widths of the specimens increase less than their lengths.

As fibre volume fraction increases, the increase in both length and width decreases and this is most prominent for the width. The reason for this could be that as the fibre volume fraction is increased, the fibre mats are compressed between the mould faces and so the three-dimensional structure of the non-woven fibre mats is flattened into a quasi two-dimensional structure. Thus, at low fibre volume fractions, the radial swelling of the fibres during water absorption contributes more to the in-plane hygroscopic strain of the specimens than at high fibre volume fractions.

When comparing the thickness, length and width increases in figures 15 to 17, it is evident that the increase in thickness is much larger than those of length and width. This indicates that the coefficient of hygroscopic expansion is greatest in the through-thickness direction. This is believed to be due to the greater swelling of the fibres in their radial direction than along their length and the fact that the preferentially in-plane

alignment of the fibres prevents strains in the through-thickness direction from being constrained.

4 Conclusions

A number of interesting conclusions can be drawn from the above.

- Neither drying of fibres nor altering of the mould temperature has any significant effect on mechanical properties of non-woven kenaf fibre reinforced polyester laminates.
- At low fibre volume fraction, pressurising the mould improves tensile and flexural strengths.
- Addition of kenaf fibres to polyester resin results in laminates with lower tensile strength than that of the resin but higher tensile modulus.
- SEM examinations show no change in failure mode from fibre pull-out for any production conditions.
- Water absorption is not significantly altered by any production condition except by pressurisation at low fibre volume fraction.
- Water absorption increases with fibre volume fraction.
- Water absorption causes all three dimensions of the laminates to increase. However, the increase in length and width is very small in comparison to the increase in thickness.

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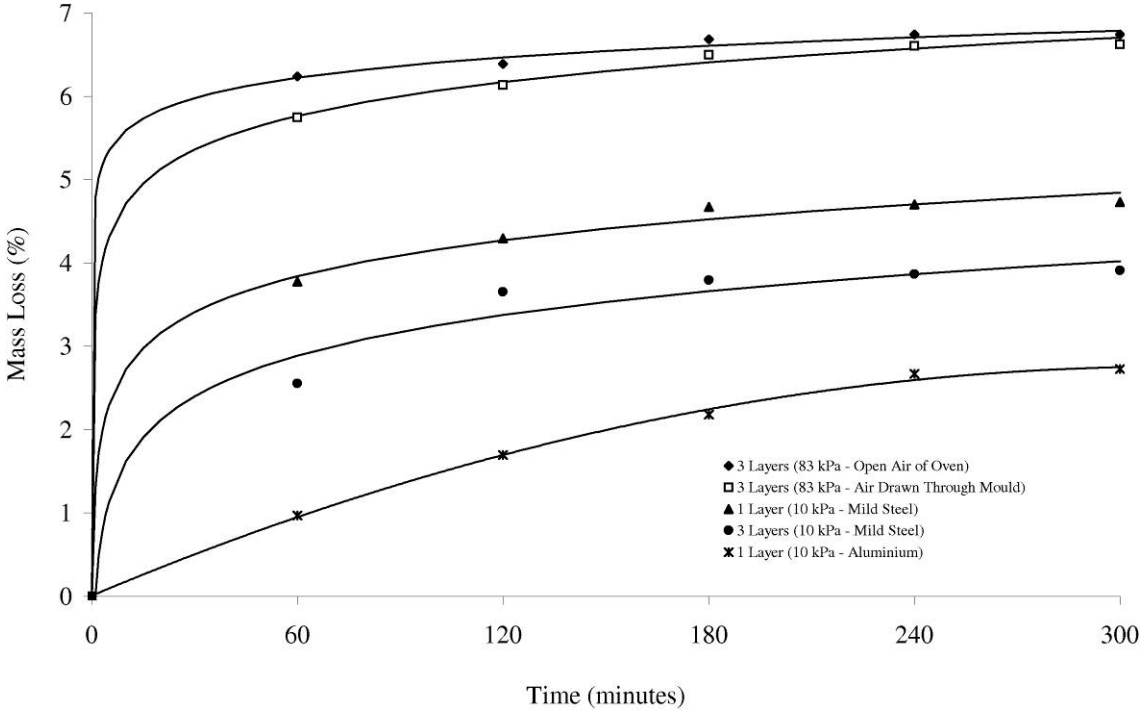

Fig. 1 Effect of various drying methods on fibre moisture loss at 55°C

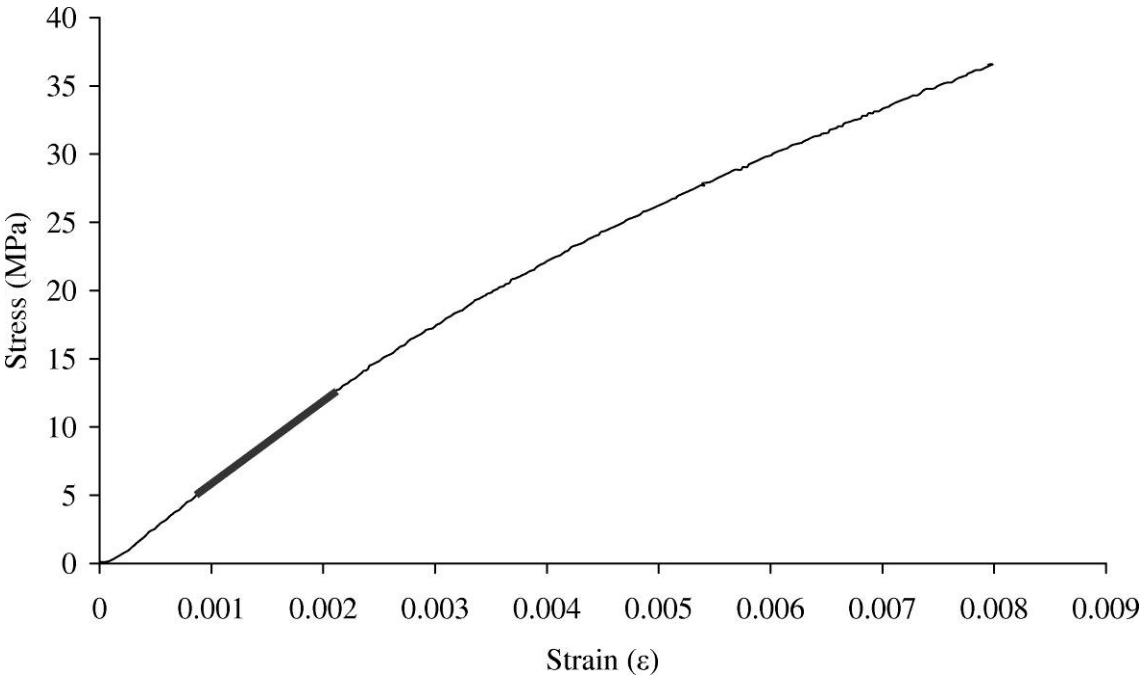

Fig. 2 Tensile test stress-strain curve showing linear region

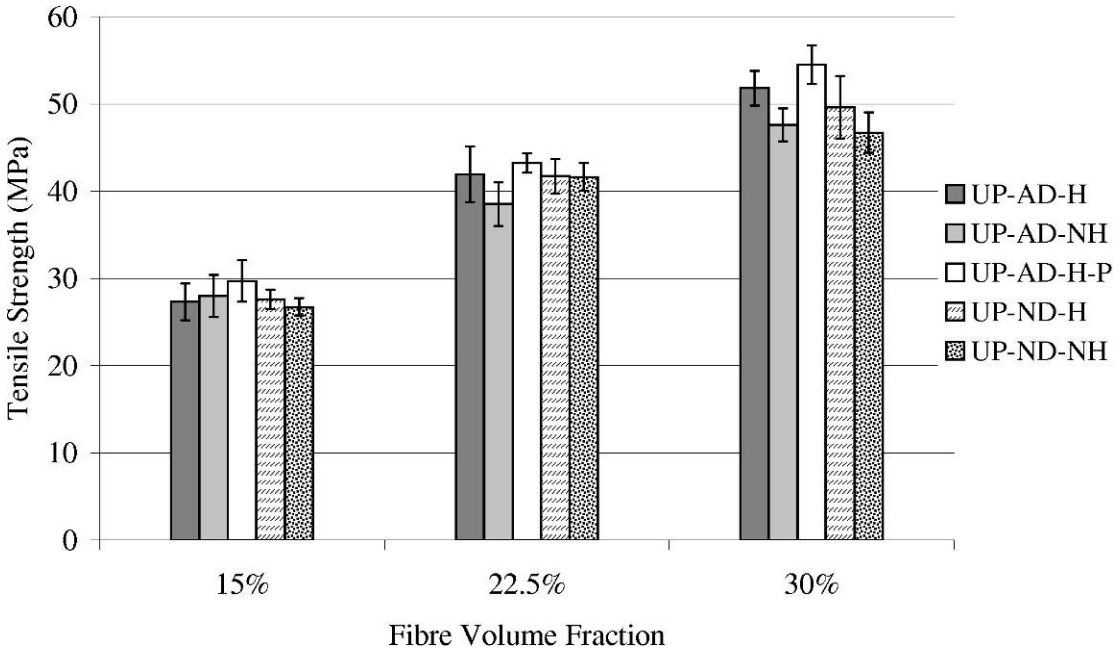

Fig. 3 Tensile strength

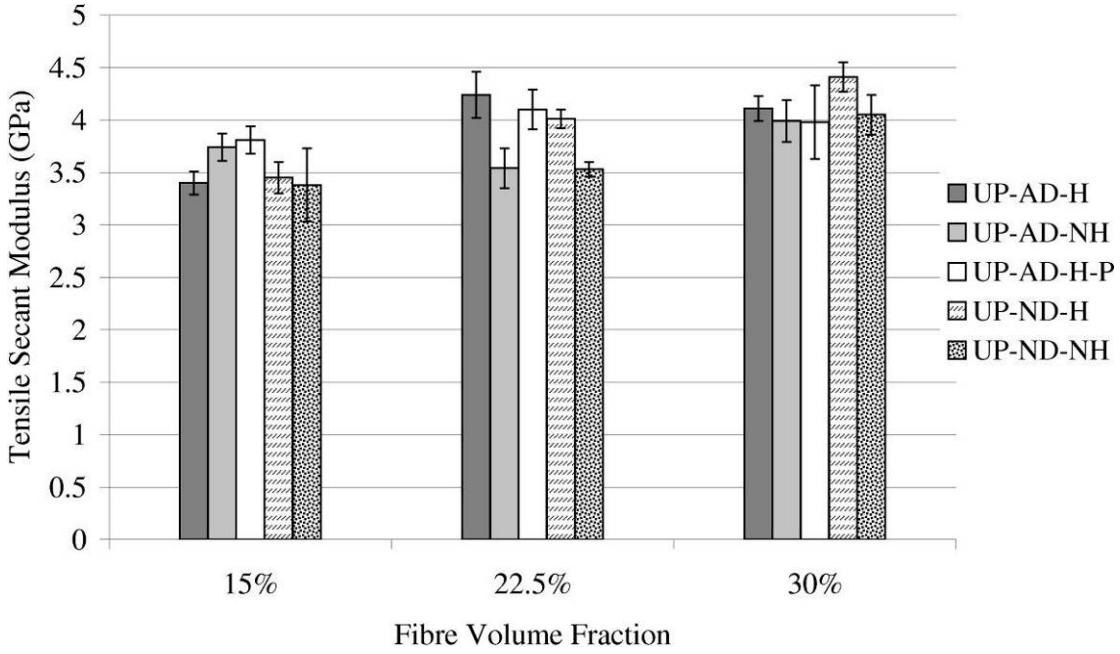

Fig. 4 Tensile secant modulus

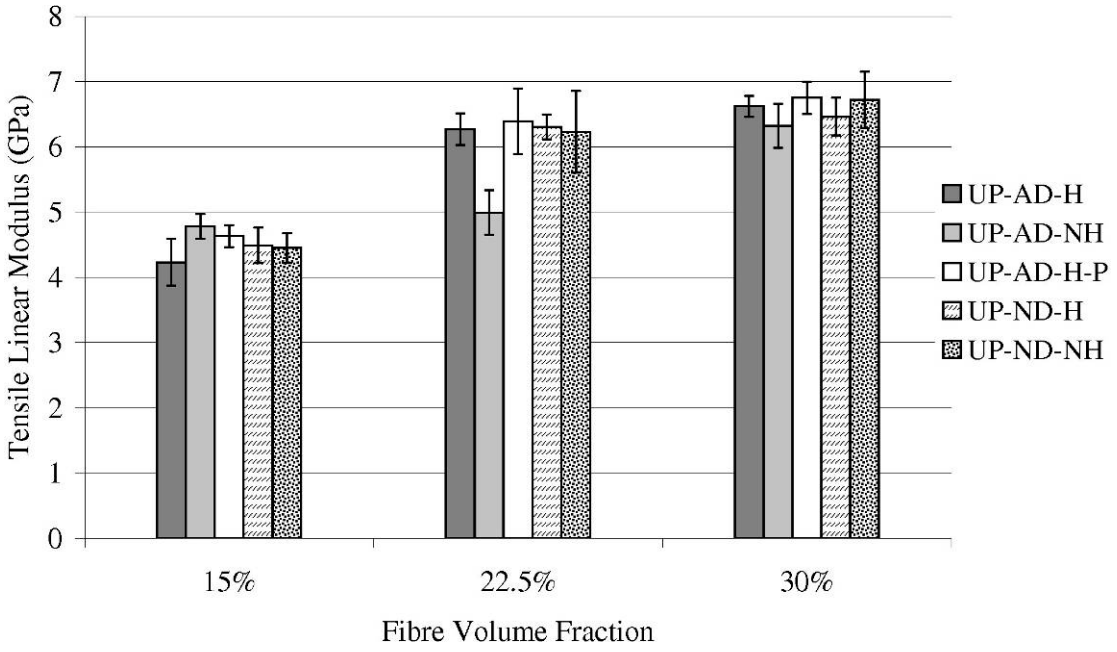

Fig. 5 Tensile linear modulus

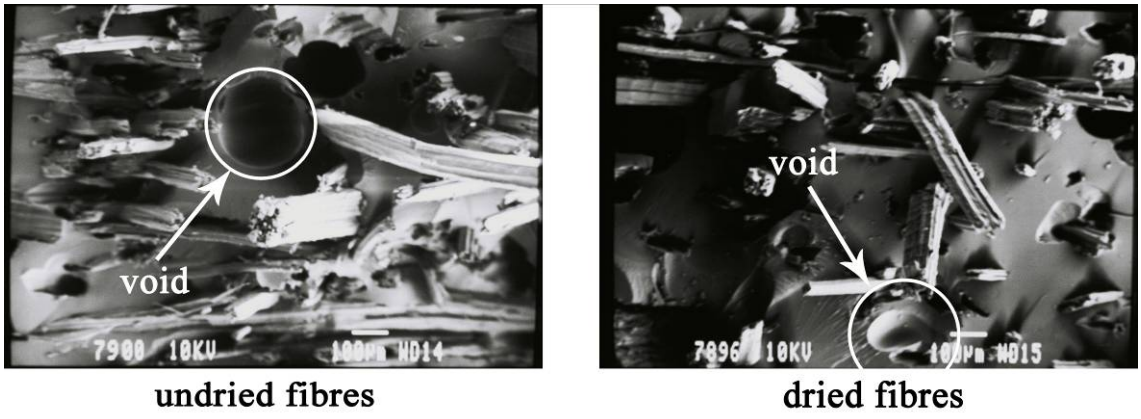

Fig. 6 Voids in 15 % fibre volume fraction laminates

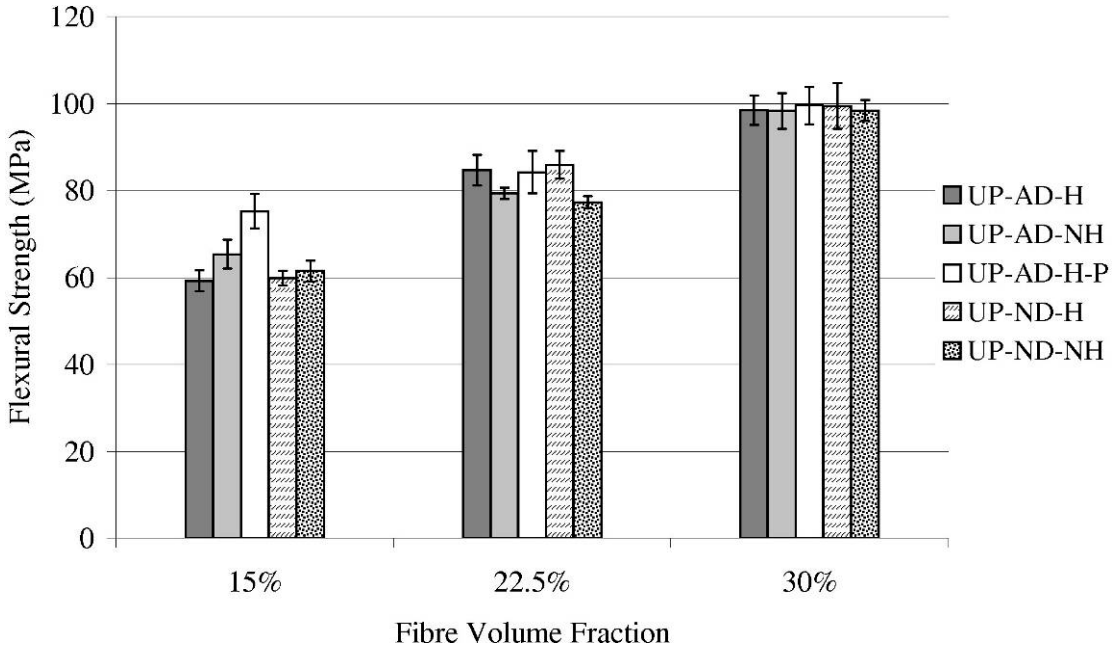

Fig. 7 Flexural strength

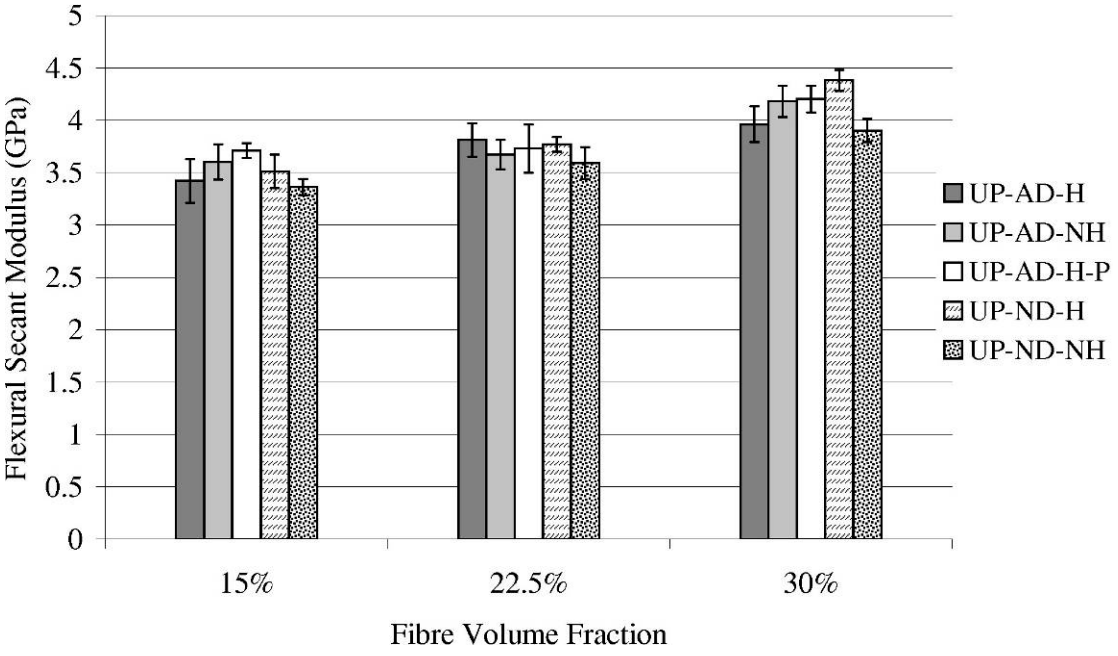

Fig. 8 Flexural secant modulus

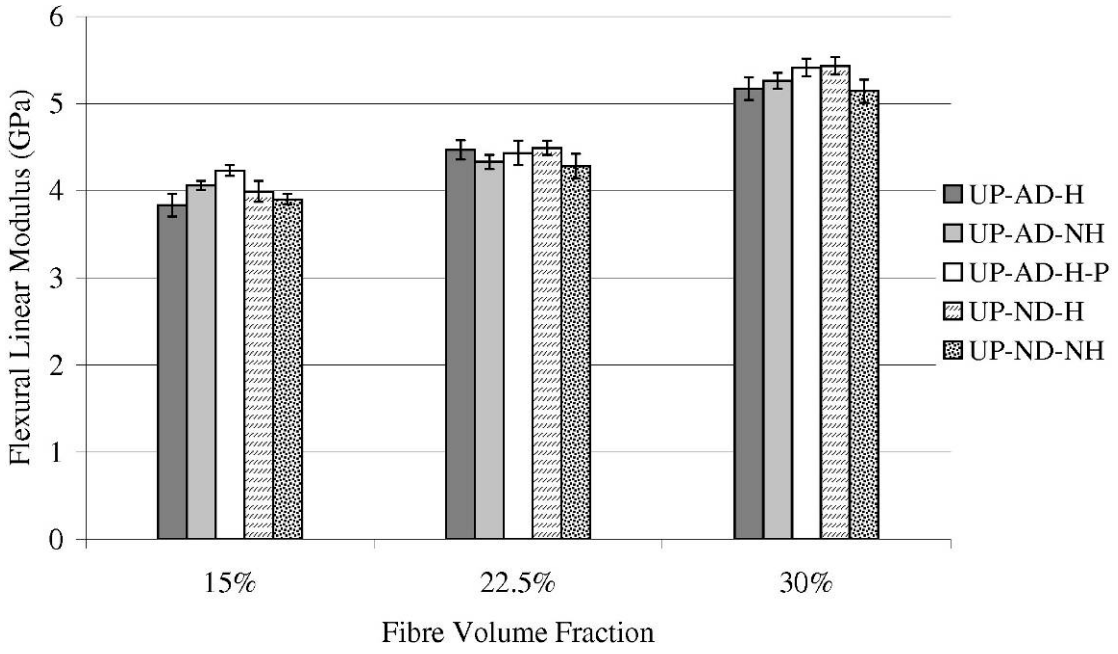

Fig. 9 Flexural linear modulus

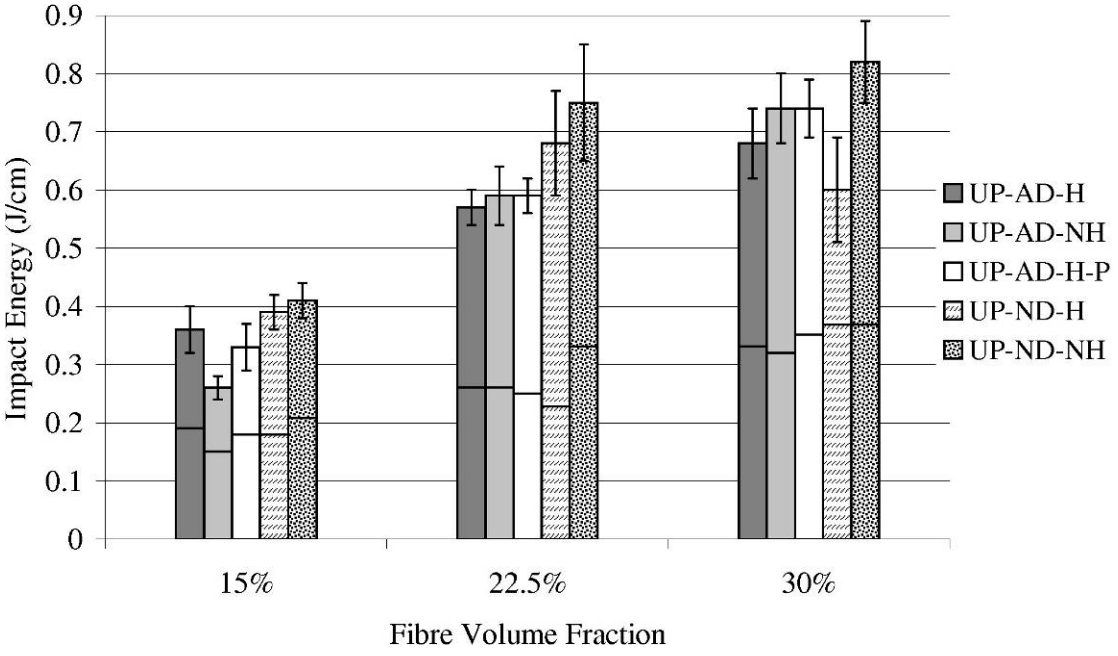

Fig. 10 Impact energy

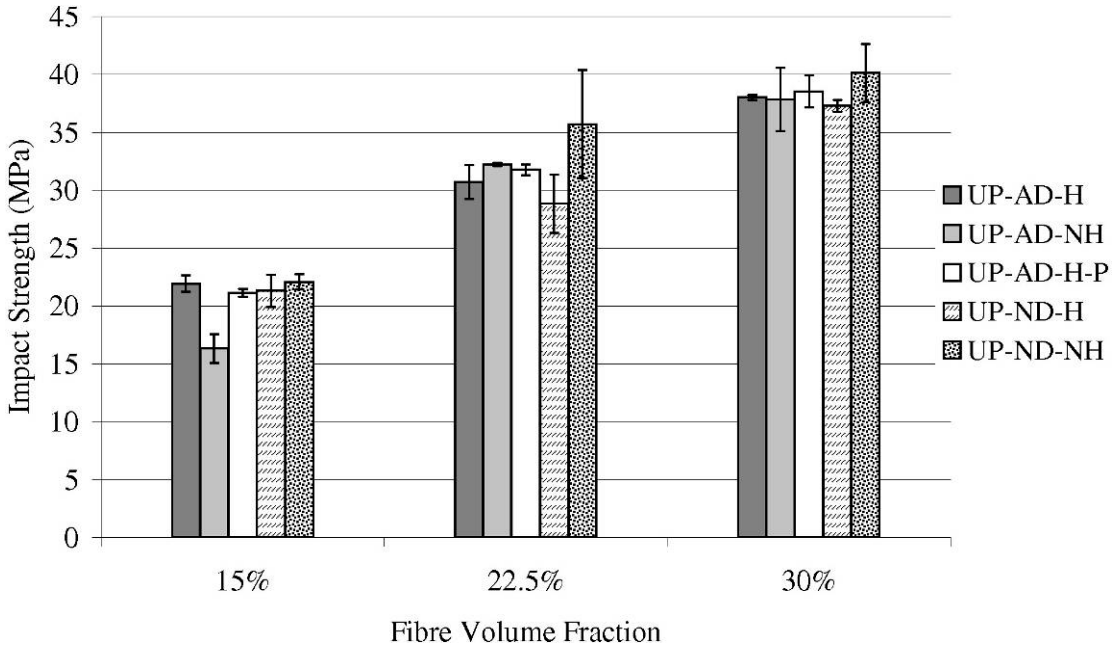

Fig. 11 Impact strength

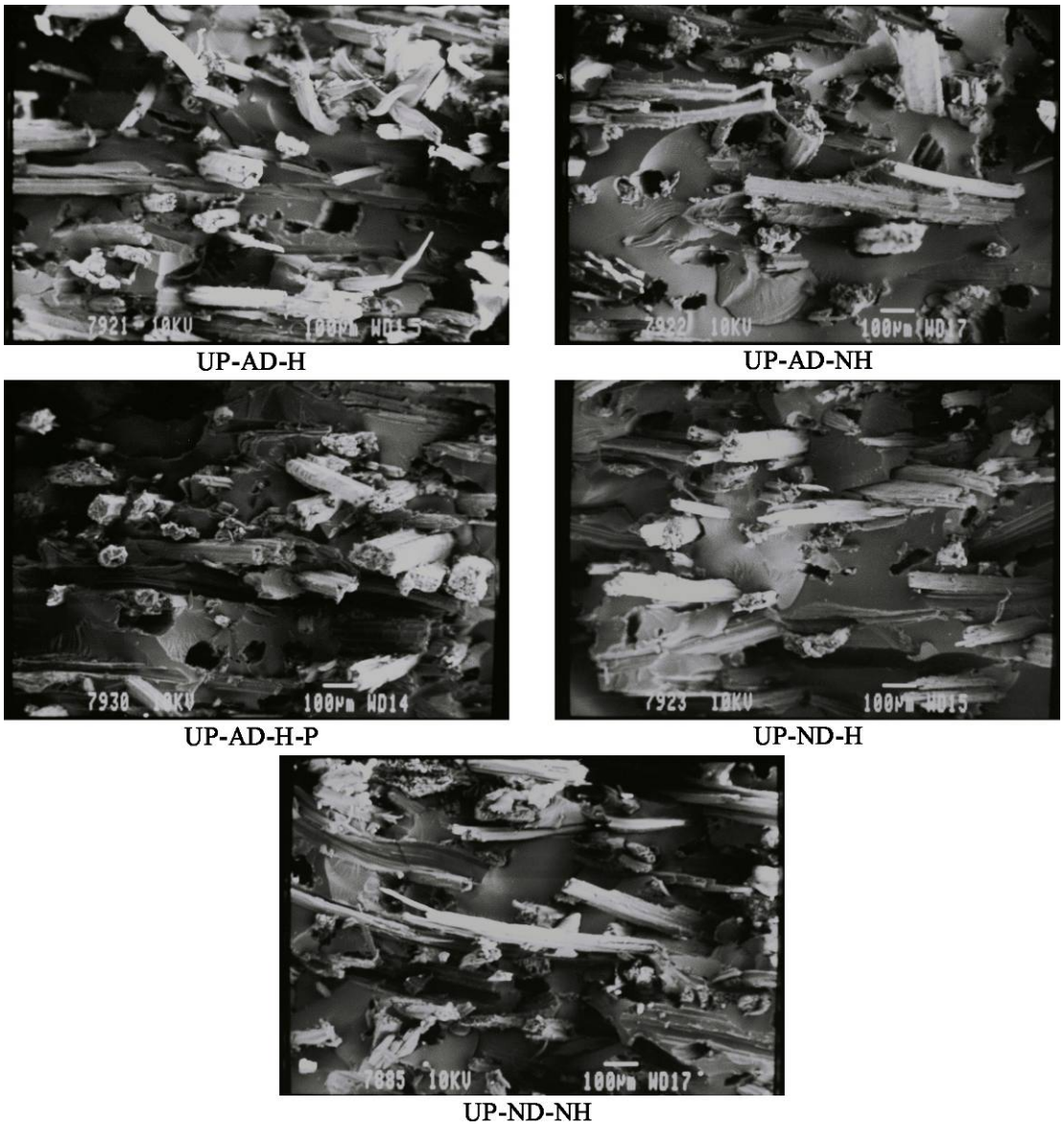

Fig. 12 SEM micrographs of impact failure surfaces of laminates for 22.5 % fibre volume fraction

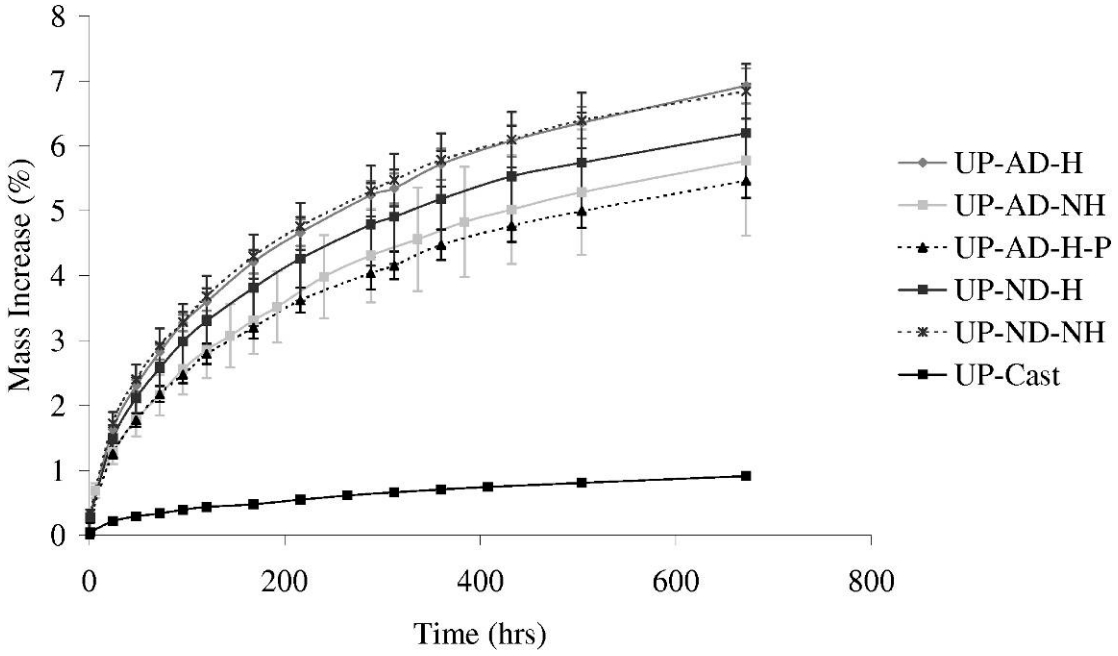

Fig. 13 Mass increase over 4 weeks of water absorption for 22.5 % fibre volume fraction

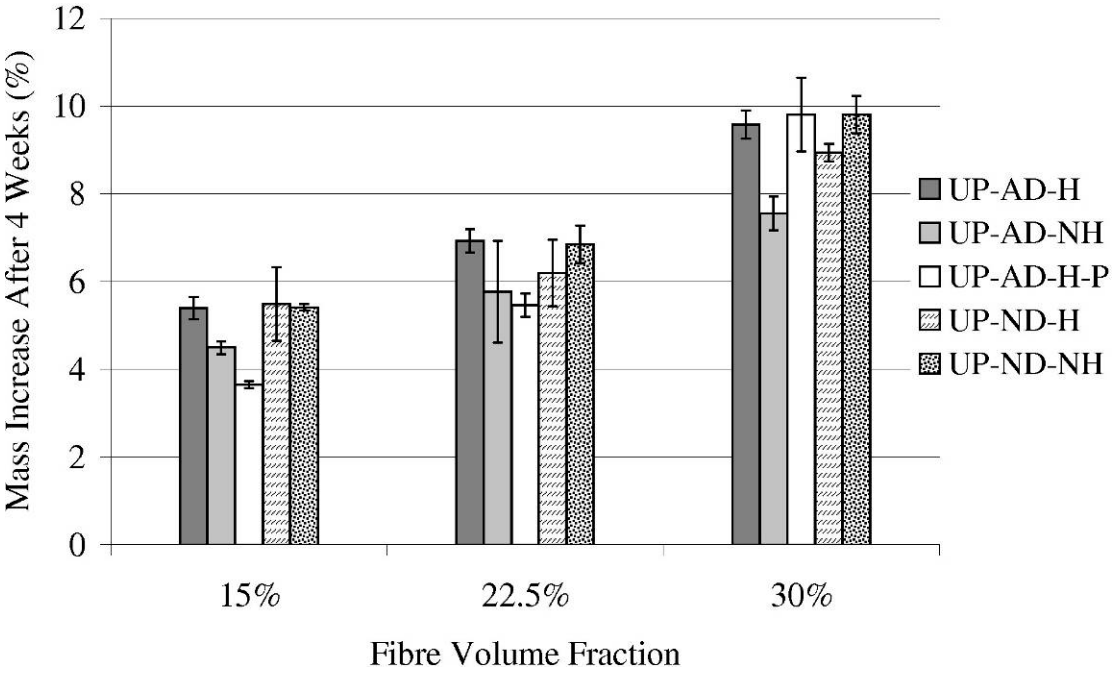

Fig. 14 Mass increase after 4 weeks of water absorption

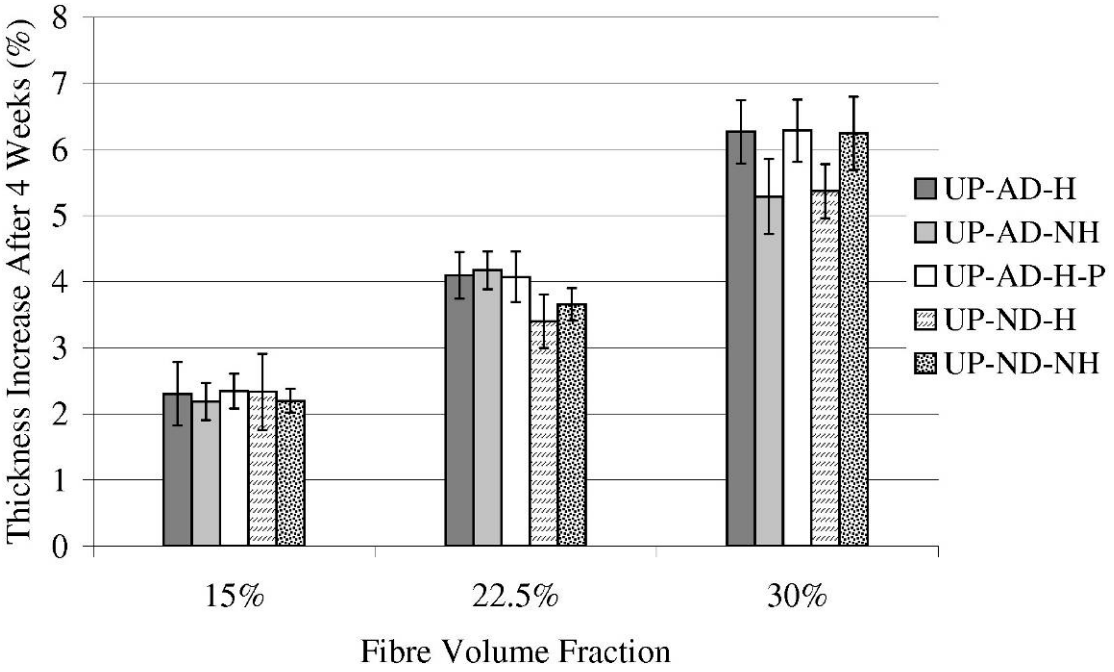

Fig. 15 Thickness increase after 4 weeks of water absorption

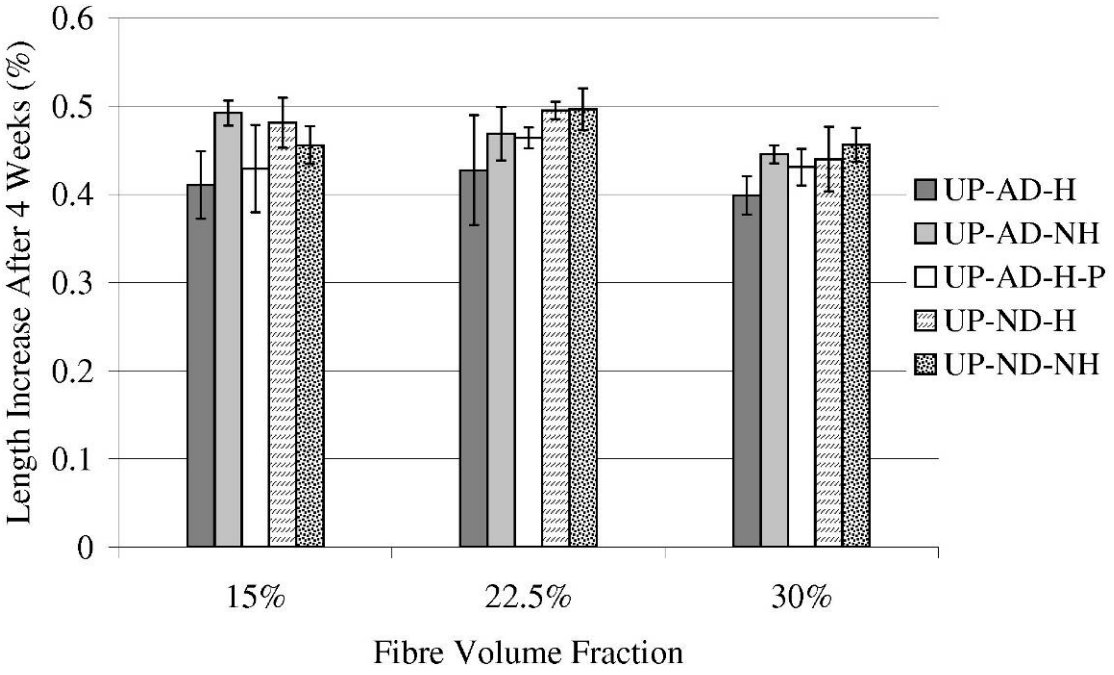

Fig. 16 Length increase after 4 weeks of water absorption

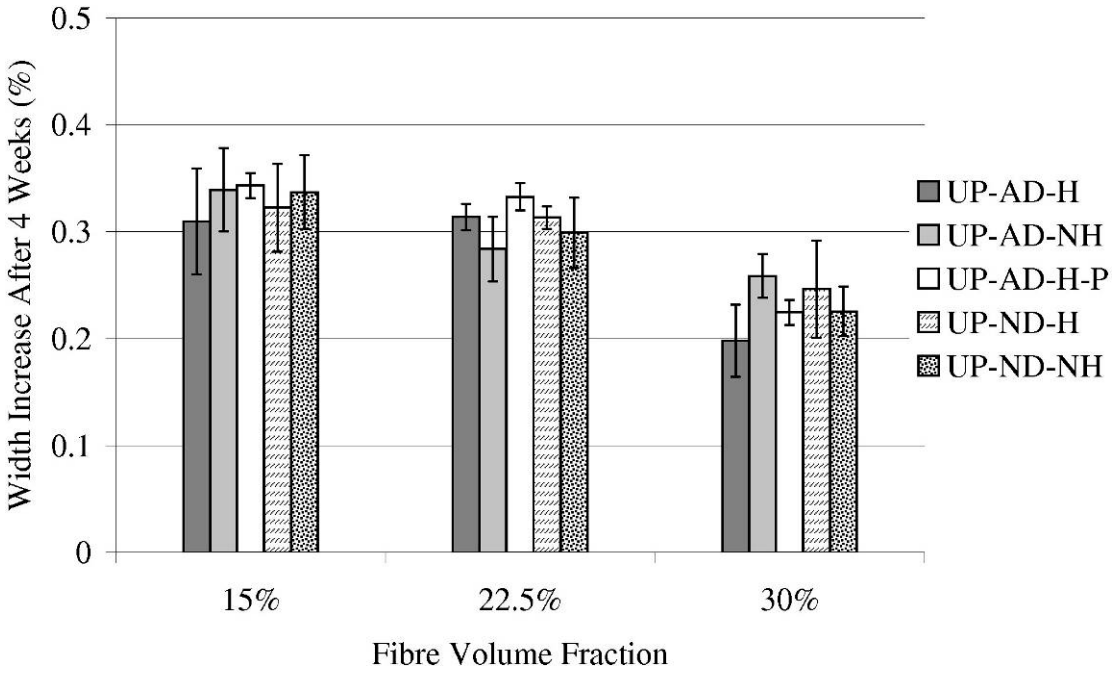

Fig. 17 Width increase after 4 weeks of water absorption

Table 1 Properties of kenaf fibre and polyester resin

Property	Unit	Kenaf Fibre	Polyester Resin
Tensile Strength	MPa	350-600 [15]	69 [16]
Elastic Modulus	MPa	40000 [15]	3800 [16]
Elongation at Break	%	2.5-3.5 [15]	2.3 [16]
Flexural Strength	MPa	N/A	84 [17]
Flexural Modulus	MPa	N/A	3930 [17]
Density	kg/m^3	1500 [15]	1140 [16]

Table 2 Production conditions for laminates

Fibre Vol. Fraction	Room Temperature Mould	Heated Mould (50-55°C)
15, 22.5 & 30 %	Kenaf Fibres Undried	Kenaf Fibres Undried
15, 22.5 & 30 %	Kenaf Fibres Dried	Kenaf Fibres Dried
15, 22.5 & 30 %		Kenaf Fibres Dried and Mould Pressurised (600 kPa)