

VACUUM INFUSION OF NATURAL FIBRE COMPOSITES FOR STRUCTURAL APPLICATIONS

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ABSTRACT

Experimentation was carried out with various forms of vacuum infusion with the intention of producing natural fibre composites. It was found that high volume fractions of materials were difficult to obtain without the use of a compressive element, and therefore a custom vacuum infusion rig was designed. The purpose of this rig was to produce consistent materials for researching processing variables, and it was found that the vacuum infusion rig improved the quality of materials to an adequate level. It was also found that improvements can be made to the design when using loose natural fibre for unidirectional composites, however when pre-formed mats are used the vacuum infusion rig performs exceedingly well in producing composite plates.

1. INTRODUCTION

Numerous methods of manufacturing natural fibre composites have been reported in the literature, including compression moulding, often in conjunction with a hot press. Other forms of composite manufacture include *Vacuum Assisted Resin Transfer Moulding* (VATRM) and the *Seemann Composite Resin Infusion Moulding Process* (SCRIMP). These methods have been reported to produce natural fibre composites with reasonable mechanical properties [1-2]. In this paper, a vacuum infusion rig is described, that has been developed to produce consistent quality composite plates for studies into optimising the quality of natural fibre composites. The process aims to harness the benefits of vacuum infusion and compression moulding, where vacuum infusion encourages the removal of trapped air in the system and hence void reduction, and additional compression moulding can help to achieve high volume fractions that are otherwise difficult in other processes.

2. PROBLEMS

In many fibre composites, high volume fractions are desirable, but can be hard to achieve, depending on the process. The high compaction of the natural fibre is achieved in this study by the development of a vacuum infusion process to allow the production of unidirectional composite plates, which in turn can cut into testing samples as required. In experimentation with vacuum bagging techniques to gain feeling for the process, a few problems were noted that required an implementation of solutions to provide a base process for further materials' research. Some of the key problems can be viewed in Table 1 on the following page with two of the major issues of uniform resin fill as well as resin escape as shown in Figure 1.

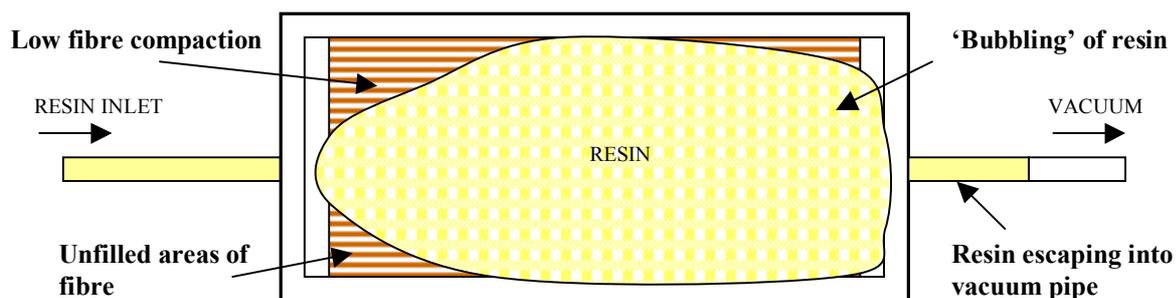


Figure 1: Diagram of main problems experienced with vacuum infusion experimentation

Table 1: Problems initially experienced with vacuum infusion

Problem	Description
(1) Uneven resin dispersal	Even dispersion of the resin flow was problematic in materials, creating unfilled sections of the samples and therefore wastage. A device to promote uniform flow is essential. Experimentation with a 'closed' metal mould made viewing of resin fill very difficult, therefore a solution to address this problem was essential.
(2) Resin flowing into pressure pot	During the fill process, any resin that escapes from the mould has to be replaced or it creates voids. It is essential that resin is only allowed to fill the desired material location. This requires thought as to how to apply a vacuum whilst not removing the resin from the system through the vacuum point.
(3) Void reduction	Voids can be observed in the initial composites samples produced. These are often spherical. This indicates that it may be trapped air bubbles as well as lack of appropriate filling of resin. When voids are left, the resin can wick through the unwetted fibre before fully curing ultimately degrading the quality of the whole composite, not just the unfilled corners.
(4) Poor compaction and alignment of fibre	Caused by unprocessed fibre that retains a twist. Alignment of fibres at this time needs to be addressed to ensure the material is representing a unidirectional composite. If alignment is not achieved large variation in results and trends are likely to be observed from the testing of the materials.
(5) Volume fraction consistency	It is appropriate to improve parts of materials that have little or no fibre through the resin. Proper fibre alignment may aid in evening out fibre concentration. However, particular attention has to be paid to ensuring volume fraction is consistent throughout the material. Again, a process that allows high fibre compaction may help this.
(6) Manufacture consistency	For iterative research studies it is desired that the manufacturing process is consistent otherwise any derived meaning will be lost in quality variation. Implementation of solutions for the problems outlined aim to help manufacturing quality. However, the process itself has to be performed consistently and effectively also by the operator to ensure quality consistency.
(7) Poor finish of composite surfaces	From experimentation with a simple vacuum bagging and other techniques, it was found that due to the lack of a rigid surface in conjunction with reasonable compression the surface finishes tended towards a ripples effect. This therefore produced non-uniform samples. A process that combines compression with void reduction is desired whilst also producing good surface finishes.
(8) Wastage of materials	With vacuum bagging, much plastic and sealant tape that encompassed the samples is wasted. For manufacture of multiple composite plates a more permanent and reusable method was desired.

3. VACUUM INFUSION PROCESS & RIG DESIGN

The vacuum infusion process is shown in Figure 2 along with an exploded model of the designed vacuum infusion rig. The aim of this design is to try to produce materials of reasonable quality for the research study by addressing as many of the indicated problems outlined in Table 1. The natural fibres that are being used in the research are largely loose and often retain a twist, adding to the problem of achieving fibre alignment and uniformity in the samples. Care was taken to achieve as close to unidirectional alignment in the fibre mats as possible under the given situation. The process itself encourages fill of the entire mould and helps to reduce any voids and promote wetting in the composite material.

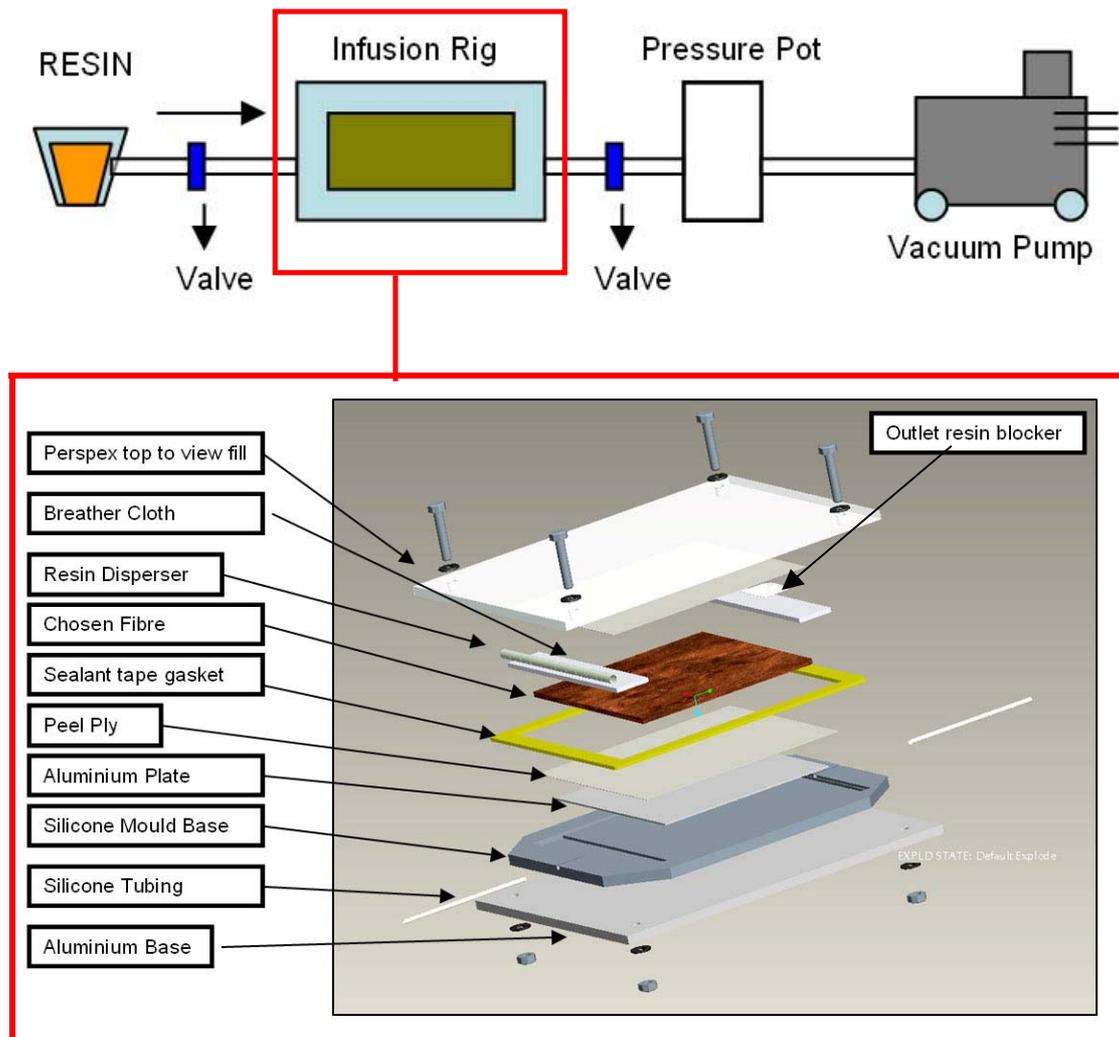


Figure 2: Vacuum Infusion rig - Much experimentation alongside trial and error went into developing the process and reasonable quality of materials.

To avoid excessive use of process materials, the infusion rig has been built with reusability in mind. It is often found that processes such as vacuum bagging lead to excessive wastage of material including plastic sheeting and sealant tape. The vacuum infusion rig has a reusable and washable silicone mould that is sandwiched between a thick aluminium plate and a heavy clear acrylic top face. The clear face allows inspection of the resin progress during fill, which is exceptionally helpful to the operator when controlling the infusion rate using the resin and vacuum control valves. This feature is beneficial as it is observed that very low vacuums can have undesirable effects on the resin, even after extensive degassing. The resin inlet and air outlet are fed into the silicone mould through a channel at each end, and a configuration of peel ply, breather cloth and resin diffuser has been found to produce best fill characteristics.

Vacuum to the rig is provided by a vacuum pump via a pressure pot, buffering pressure perturbations, allowing smooth fill of resin through the highly compacted fibre. The high compaction of the natural fibre is achieved through the sandwiching of aluminium and acrylic outer plates using a configuration of bolt fixings and clamping points, thus compressing the mould and its content. The silicone mould is firm enough to allow high fibre compaction without significant deformation, ultimately producing composites with high fibre content.

With this compression of the mould and its content, high volume fractions are achieved, which can be up to 70% with the adoption of additional clamping force if desired. The materials in this example study were manufactured at 55% volume fraction +/- 5%, with care being taken to evenly spread the pre-weighed fibre as best as possible. The resin infusion of the sample can be viewed in Figure 3. The clear acrylic top face allows viewing of resin



Figure 3: Left to right. The vacuum infusion rig, mould during infusion, and rig just after fill

during infusion, with the resin inlet being controlled by a valve, and the vacuum level being controlled on the pump side of the mould. 703Pa resin for vacuum infusion from Scott Bader was used in the manufacture of the composites materials. The materials were left to cure at room temperature in the mould for 12 hours and then post cured at 80°C for 3 hours as instructed in the resin data sheet from the supplier. In the design of the resin infusion mould, the two critical areas of resin dispersion and escape as outlined in Figure 1 had to be addressed in the infusion process. These particular solutions can be viewed in Figure 4 below.

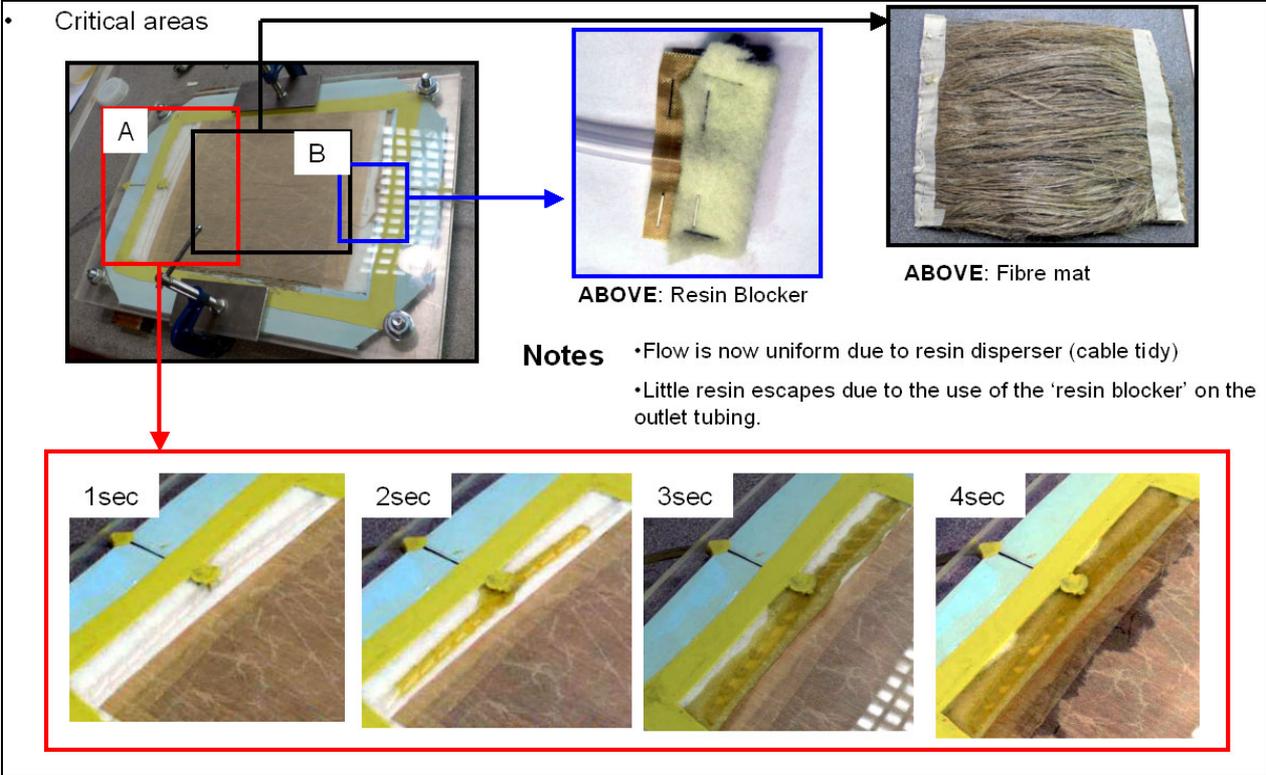


Figure 4: Application of a resin disperser and blocker at the outlet to improve process.

4. RESULTANT MATERIALS

The composite plates produced from the vacuum infusion rig are shown in Figure 5. From recent experimentation, the volume fractions of the composite plates manufactured using the vacuum infusion rig can be up to 70 %. The process thus gives significant scope for increasing fibre levels during research studies. The natural fibre composite plates manufactured from loose fibre are greatly improved in quality over previously manufactured



Figure 5: Composite materials manufactured in plates by vacuum infusion (approx 60% V_f) materials and many of the problems outlined in Table 1 are also less significant. It has also been found that the process is particularly easy to apply to preformed fibre mats, which lend themselves to easier handling and configuration in the mould over the loose natural fibres. An example of other materials produced in the vacuum infusion rig can be viewed in Figure 6. Multiple layers of the Flax short fibre mat can easily be compressed and infused into a thin composite plate. This ability also allows combinations of material layers to be configured for infusion with resin into desired composite materials for investigation.

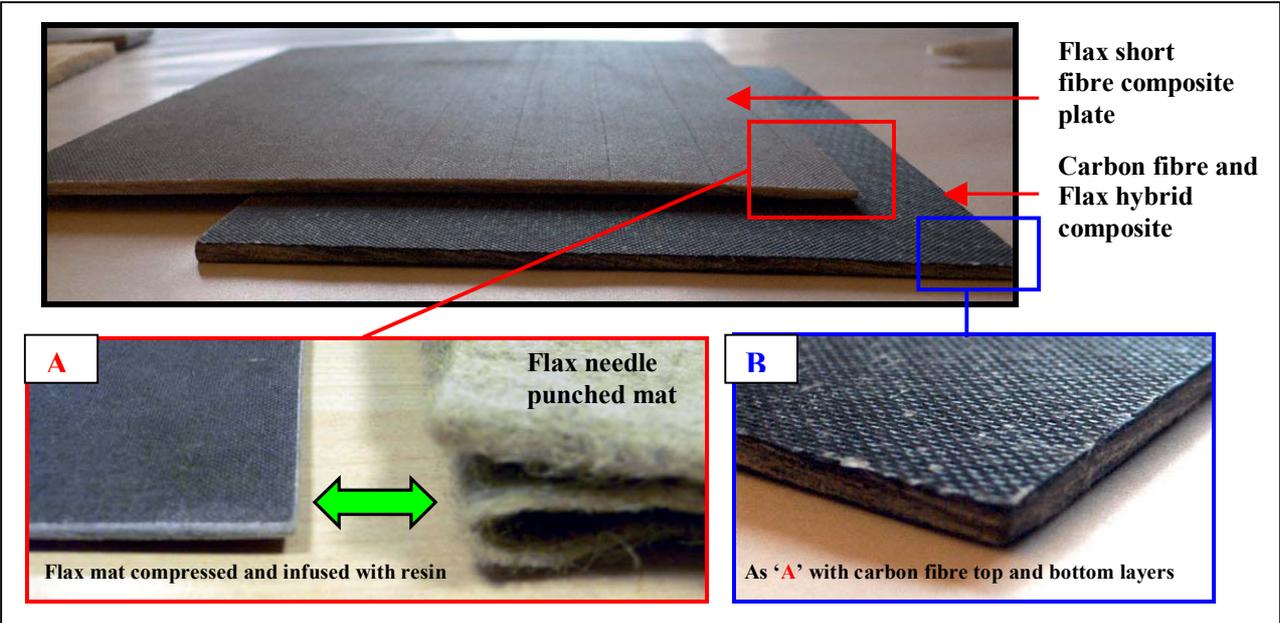


Figure 6: Other examples of materials produced in the vacuum infusion rig

For the sample study of unidirectional natural fibre composites, some macro photographs are shown in Figure 7 with higher magnification photomicrographs of the cross sections given in Figure 8. It is observed that between Abaca, Sisal, Kenaf, Flax and Hemp the variation in cross sectional shape of the fibres is significant. The shape and size between fibres of the same type also varies greatly, which has been reported to add to complexities in measuring base fibre properties and obtaining predictable materials under loading conditions [4]. A brief overview on mechanical properties of the manufactured natural fibre composites is given in the following section.

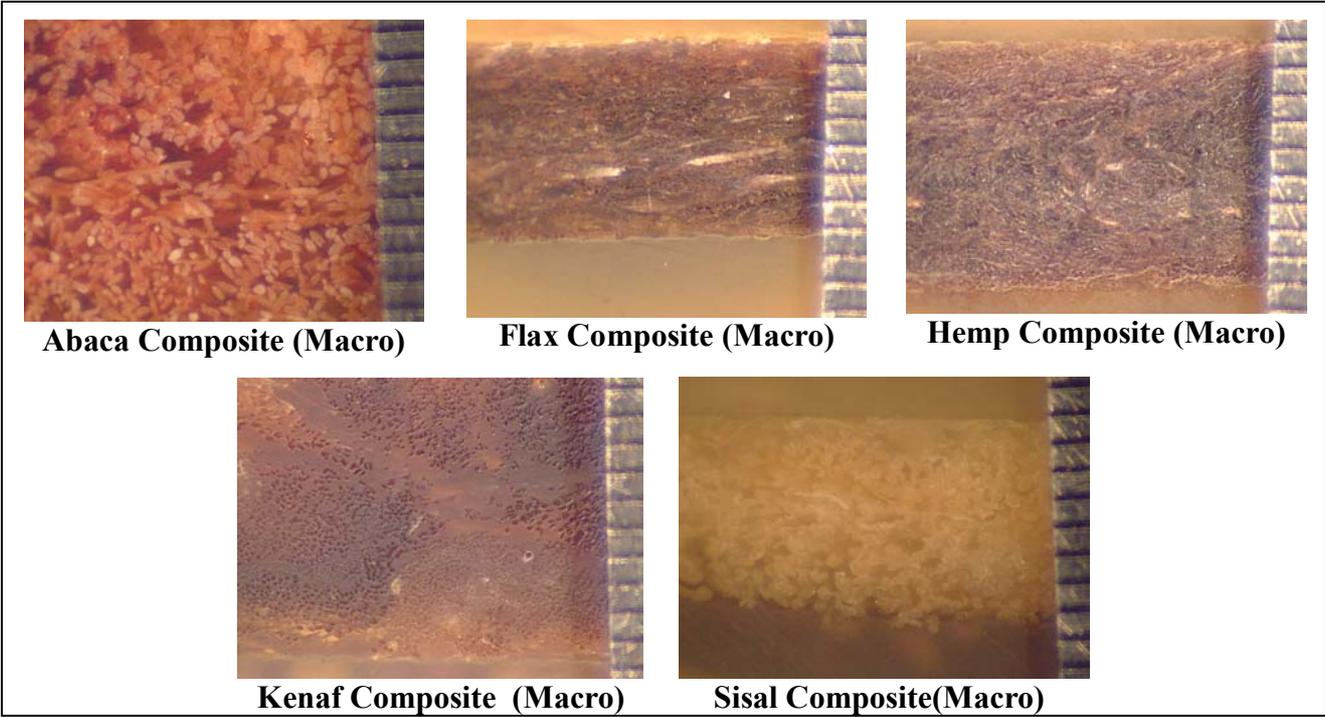


Figure 7: Sample macro photographs of cross section areas of manufactured composites

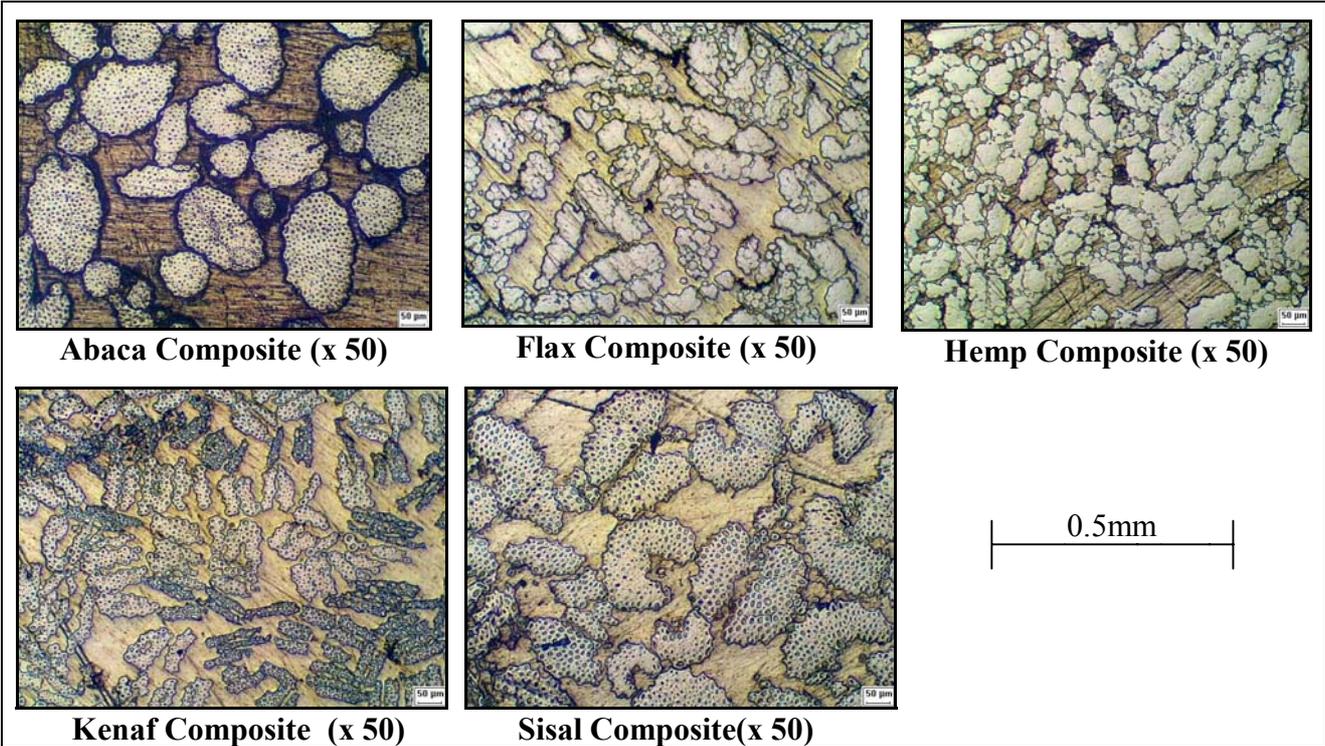


Figure 8: Sample photomicrographs of cross section areas of manufactured composites

5. MATERIAL PROPERTIES

Tensile testing of manufactured composites was carried out to ASTM 638-02a and some of the results are shown in Figure 9. The volume fractions for the tested composite materials are 55% +/- 5%. Testing shows Abaca, Flax and Kenaf to have similar failure strengths in the region of 70 MPa, whilst Sisal is higher at 80 MPa and Hemp slightly lower at 60 MPa. All of the composites show significant improvement of failure strength over the base resin. The improvement of properties over the base resin is however more significant when Young's modulus is considered. Hemp and Kenaf composites show encouraging modulus values at 13.7 and 11.9 GPa respectively, with Flax slightly lower at 10.1 GPa. The composites of

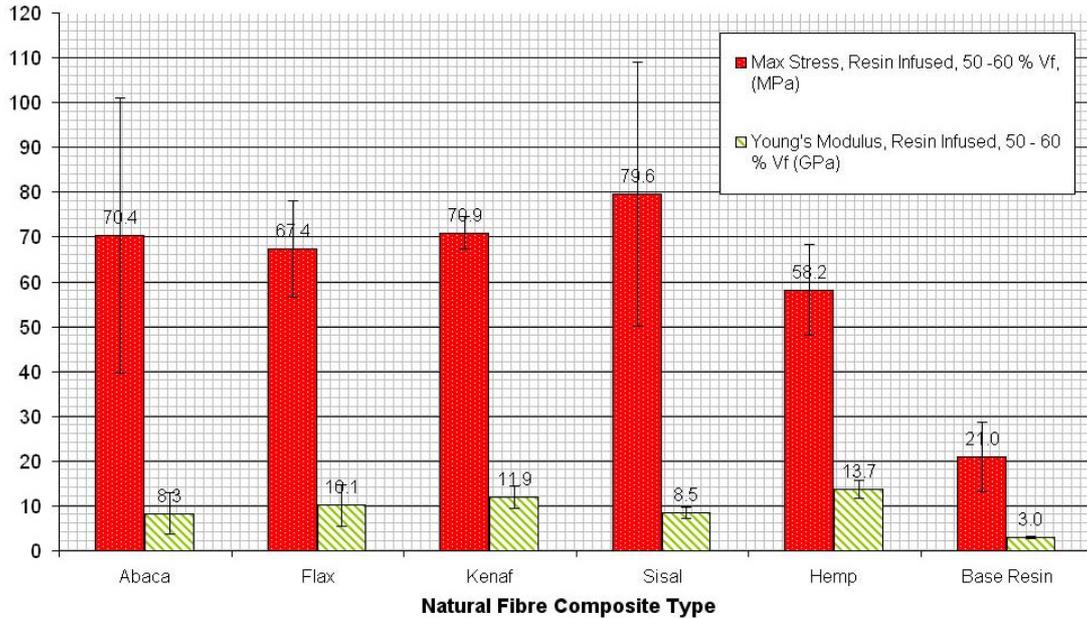


Figure 9: Young's modulus/ failure strength for vacuum infused biocomposites, 50-60% Vf

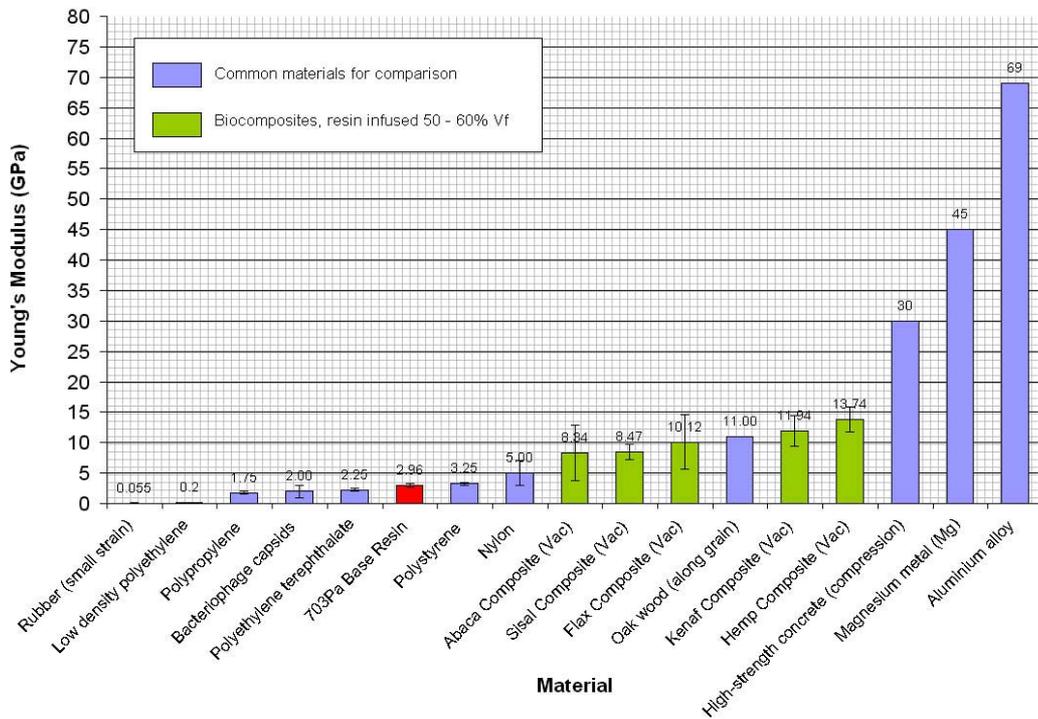


Figure 10: Young's modulus comparison between manufactured composites and other common materials.

Abaca and Sisal exhibit similar properties to each other in the region of 8 GPa. When comparing Young’s modulus of these composites to other materials in Figure 10, it can be observed that performance of Hemp and Kenaf composite is slightly higher than oak, a quality wood and a cellulose-based composite in its own right. This is reasonably encouraging, as it is apparent that the materials may be breaching the property boundaries of glass fibre composites when specific modulus is considered. It is also interesting to note that the composite materials are not showing the same order of mechanical properties in composite form as to the base fibres. This indicates much potential for material development through pre-processing techniques to increase interfacial shear strength between the fibres and matrix. This work is also currently being conducted, and through this it is hoped material properties might improve further. The materials were manufactured from natural fibres from the supplier with no pre-treatment or surface modifications.

6. DISCUSSION

The aim of developing the vacuum infusion rig was to produce composite plates for research into natural fibre composites and to provide high fibre volume fractions whilst reducing void content. From time invested in experimentation and in the design of the vacuum infusion rig it is clear that for the purposes of producing composite plates for research consistently, the initial remit is met. The vacuum infusion rig has improved fibre volume fractions, surface finish of materials whilst also reducing void content in the materials. However, there are still some process areas as displayed in Table 2 that require refinement, and whilst most of these areas are much improved there is clearly room for further development.

Table 2 – Further areas for improvement in the vacuum infusion rig design

Design Improvement Area	Comment
(1) Further improvement of fibre alignment	Whilst fibre alignment can be controlled through investing time in the manufacture of the base fibre matting, when compressing large volumes of fibre there is inevitably some degree of misalignment of the fibres. Work into producing very high quality mats that can be easily layered would be worthwhile.
(2) Control of composite plate thickness	The vacuum infusion rig can produce plates of an approximate thickness through compression of the inserted materials. As the silicone mould allows a degree of deformation, a ‘spacer’ system allowing for exact widths of plate to be produced would be very useful and could possibly be merged into the design.
(3) Consistent dispersal of fibre	As shown in Figure 6, it is apparent the vacuum infusion rig works well for pre-woven matting. It is however harder to exactly align the loose fibres used in the unidirectional composites, and therefore concentrations of fibres are likely in certain areas. If high quality technical mats were available for natural fibre composites the quality of materials would be much greater.

7. CONCLUSION

For the production of natural fibre composite plates for research purposes, the designed vacuum infusion rig allows scope for high volume fractions whilst reducing void content in the vacuum infused composite materials. There is still scope for implementation of a system into the design to improve the alignment of the fibres for unidirectional composites, however if pre-formed mats are used the process works exceedingly well, with additional scope for layering and compressing contents to desired levels. Although many natural fibre composites are being produced by other methods in the academic community it is thought that enclosed vacuum infusion rig presents a viable option for the production of materials.

ACKNOWLEDGEMENTS

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REFERENCES

1. Various contributors, edited by Caroline Bailey "Green Composites – Polymer Composites and the Environment" *CRC & Woodhead Publishing Limited*, ISBN 1 85573739 62. (2004)
2. S.J. Eichhorn, C.A. Baillie L.Y Mwaikambo, M.P. Ansell, "Current International Research into Cellulostic Fibres and Composites" *Journals of Materials Science* 36 (2001) 2107 – 2131
3. P.O.Olesen and D.V. Plackett "Perspectives on the Performance of Natural Plant Fibres" *Plant Fibre Laboratory*, Royal Veterinary and Agricultural University, Copenhagen, Denmark. Essentials for the Future, 27-28 May 1999.
4. Mark C. Symington, W. M. Banks, R. A. Pethrick and Opukuro David West 'Tensile Testing of Cellulose Based Natural Fibre for Structural Composite Applications' Accepted for *The Journal of Composite Materials*. In press.
5. A.K. Bledzki, J. Gassan "Composites Reinforced with Cellulose Based Fibres" *Prog. Polymer Science* (241999) 221-274
6. F. L. Mathews and R.D Rawlings 'Composite Materials: Engineering and Science' *Woodhead Publishing Limited WP0621*, ISBN 185573 473 7