STUDY REPORT

No. 172 (2007)

Fibre Reinforced Polymer Composites

NJ Marston

FUNDED BY
THE BUILDING
RESEARCH LEVY
BUILDING RESEARCH

The work reported here was funded by the Building Research Levy.

ISSN: 0113–3675

Acknowledgments

This work was funded by the Building Research Levy. The plots containing New Zealand climate data were kindly supplied by NIWA. Many thanks to Dr Toby Mottram for acting as the external reviewer of this report.

External reviewer

Dr Toby Mottram, School of Engineering, University of Warwick, Coventry, UK.

FIBRE REINFORCED POLYMER COMPOSITES

BRANZ Study Report SR 172 (2007) N J Marston

Reference

Marston NJ. 2007. 'Fibre Reinforced Polymer Composites'. BRANZ *Study Report 172*. BRANZ Ltd, Judgeford, New Zealand.

Abstract

Presented in this report are a literature review and an initial study to examine the performance and potential of fibre reinforced polymer (FRP) based composite materials for the building industry. Interest in, and utilisation of, FRPs in engineering products has steadily grown over the last three decades. Their high strength-to-weight ratios and rot and corrosion resistances are advantages for an increasing number of diverse applications from armoury through to yachting and land transportation.

Overseas, FRP products are used in frame buildings for primary load-bearing applications. The use in buildings of these materials is also on the increase in New Zealand, but mainly for secondary structural applications, such as claddings and architectural features. Their potential in residential and commercial buildings for other more demanding applications has not been fully investigated. Moreover, the long-term durability performance of FRPs has not been fully characterised for New Zealand conditions. Given this background, the aim of this project is to examine the use, performance and potential of FRP products within the New Zealand building industry.

Following a comprehensive literature review it is observed that there exists core knowledge regarding FRP mechanical properties and the forms of construction products to be used. The review highlights that, because of the large range in FRP materials (due to reinforcement type(s), reinforcement arrangement, polymer-matrix composition and processing method), the preparation of succinct codes and standards is going to be more difficult than it has been for conventional building materials.

It is promising that local suppliers are well positioned to meet existing and future demands for FRP products. By way of a preliminary experimental study, using FRP materials sourced in this country, it is found that, over short periods, they are durable when exposed to the New Zealand environment. These materials are also shown to behave as expected in fire tests.

BRANZ finds that FRPs do provide a tremendous opportunity to New Zealand's building industry. However, to facilitate their adoption and acceptance, further work is needed to provide the knowledge and understanding to prepare codes and standards. To make this goal deliverable, and in a timely fashion, it is recommended that effort be focused on assessing a limited range of FRP materials and applications that offer the maximum advantages to the country's commitment for long-term sustainable development.

Keywords

Fibre reinforced, polymer, FRP, GRP, composite, construction, infrastructure.

Contents

Page

Figures

Page

Tables Page

1. INTRODUCTION

Composite materials are those composed of two, or more, distinct parts. This project is concerned with fibre reinforced polymer (FRP) composites where high strength reinforcing fibres are combined with a polymer (plastic) matrix. The fibres provide strength and stiffness to the composite. They are typically composed of glass, carbon or aramid. In this report, unless stated otherwise, FRP is used to denote a glass reinforced composite material. The polymer matrix comprises a thermoplastic or a thermosetting resin, as well as functional additives (e.g. filler, colour, release agents, flame retardants). Thermoplastics can be reshaped using heat and pressure, while thermosets do not re-soften. To achieve optimum performance the modulus of the fibres must be higher than that of the matrix and the polymer must adhere well to the fibres. The matrix protects the reinforcement and the fibres are inert within the matrix.

Of the fibre types noted above the most economic, and therefore most commonly used, fibres are made from glass. Depending on the application this glass may be low alkali content “E-glass” or alkali resistant “AR-glass” for use in reinforcing bar for concrete. High strength glass fibres are available and are used in aerospace applications. Carbon fibres, well known from the aircraft and high performance car applications that have used them for many years, offer superior rigidity compared to glass fibres. However, this additional performance commands a higher price. Aramid fibres can be either low modulus, e.g. for energy absorption in body armour, or high modulus for aerospace applications.

The structure of the reinforcement can also be varied depending on application and manufacturing method. Use of chopped glass fibres and chopped stand mats both result in randomly orientated fibres in the final product. This format is cheap, easy to use and is used in large quantities for reinforcement of deck coverings and in translucent corrugated roofing profiles. There it enhances puncture and movement resistance. Woven glass rovings offer greater direction strength and can be used to increase unidirectional or bi-directional strength. Thin glass surface tissue, or scrim, can be used when a resin-rich surface is needed. Continuous fibres, oriented in a single direction, offer the ultimate properties along the axis of the fibres, but the cross-direction of the product inevitably has lower properties. Careful design of the part is, therefore, essential to make best use of this anisotropy.

Matrix resins can be selected from a number of different chemistries. The choice is generally based upon the required performance and, of course, cost. Polyethylene and polypropylene are the cheapest thermoplastic resins. These materials typically find applications in composite cable applications where lightweight and reasonable environmental resistance are attractive attributes. Polyester thermosetting resin materials are also a cost conscious choice. They offer moderate environmental resistance and have been widely used in New Zealand for the production of FRP roof profiles. Epoxy resins are also thermosetting, but cost about twice as much as polyester resins. They are perceived to offer superior environmental resistance. Polyurethane thermoplastic resins offer even better environmental resistance, but also cost about twice as much as polyester-based composites. They find applications in aggressive environments, such as chemical plants, where they are used to substitute for metals. Phenolic-based thermoset systems have cornered the off-shore platform market. Good resistance to fire and the highly saline environment have driven this trend. Phenolic materials are also cost competitive with polyester materials, which implies that they have potential for wider use in construction.

Composite materials can be produced by a range of processes. These vary from the manual lay-up of reinforcement and hand application of resin to fully automated continuous processes. The most common techniques are:

- Hand or spray lamination is the most common process, accounting for over 40% of composite production worldwide. This is due to its flexibility, which allows use of all reinforcement types. The use of polyester resins dominates, but epoxy and vinyl ester resins are also used.
- Compression moulding accounts for about 25% of all composites processing worldwide. It is a highly automated process in which pressure is used to force preheated resin to adopt the shape of the mould and impregnate the reinforcement. The process uses thermosetting resins and heat and pressure are applied until the resin is cured.
- Resin injection production accounts for about 5% of global FRP composite production. It can be a highly automated technique, producing smooth-sided parts and delivering low volatile organic chemical emissions.
- Pultrusion is a highly automated process suited to the production of continuous profiles such as I beams, T sections and tubing. Continuous fibres are impregnated with resin, then pulled through a shaping die and cured. Pultrusion processes are used to produce about 5% of global FRP composites.
- Vacuum infusion reduces emissions, compared to hand lamination, by employing a fully enclosed mould. Components can be exactly reproduced offering higher quality and performance.
- Prepregs, i.e. reinforcement material pre-impregnated with resin, is supplied as a sheet ready for use by the moulder. Most are based on epoxy resin and carbon fibre.
- Continuous sheet production produces flat or corrugated translucent or coloured profile. A layer of resin is deposited onto moving polymer film. Chopped glass fibre is then added and impregnated with resin. The resin is then cured.

Further information concerning the composition and manufacturing of FRP composites can be found at:

- Composites Australia (www.compositesaustralia.com.au)
- Network Group for Composites in Construction (www.ngcc.org.uk)
- American Composite Manufacturers Association (www.acmanet.org).

FRP composites have a history of use in civil infrastructure retrofitting in New Zealand. Applications range from wraps for seismic retrofit of columns, externally bonded reinforcing plates for strengthening of walls, beams and slabs, and low maintenance exterior cladding solutions. Opportunities also exist for their use in strengthening metal and timber structures. FRP composite use in these applications is predicated on performance attributes linked to their high stiffness-to-weight and strength-to-weight ratios, ease of installation in the field, potential lower systems level cost, and potentially high overall durability.

In new build the use of FRP composites is more limited. New Zealand has not had demonstration projects using composite bridge decks, structural systems and FRP reinforcing bars to the same extent as in other countries. The use of FRP composite materials has become accepted in applications such as wind turbine blades and fuel storage tanks. Meanwhile, FRP composite use in new build has mainly been restricted to glazing panels, substitution of metals in harsh (mostly indoor) environments and joint ties for concrete slabs.

An increasing range of composite systems are becoming available that are not reliant on fossil fuels to produce feed materials. These employ recycled resins as well as resins and reinforcements derived from biological sources. As yet, there is no widespread adoption of these materials. However, it is believed that their use will become more widespread as the technology is refined, their properties and durability quantified and oil supplies dwindle.

The types of FRP composites used in construction are dictated by the applications and material costs. AR-glass or carbon fibres in a vinyl ester or epoxy matrix are the materials of choice for concrete reinforcement. These reinforcement and matrix materials are dictated by the aggressive, highly alkaline nature of the concrete pore water that they will be in contact with. Glass unidirectional rovings are favoured for the seismic remediation of columns. These fibres are usually bound in a polyester or vinyl ester matrix to offer fit-for-purpose weathering resistance. For external strengthening applications, carbon fibre reinforcement is favoured because it offers maximal rigidity. In these applications the resin choice is less critical as the reinforcements are usually affixed in sheltered areas where weathering resistance is not critical.

However, since FRP composites are still relatively unknown to the practising civil engineer and infrastructure systems planner, there are heightened concerns related to the overall durability of these materials, especially as related to their capacity for sustained performance under harsh and changing environmental conditions under load. The consistency of the materials is also a critical factor if their adoption is to become widespread.

This project concentrated on producing a snap-shot of the potential for increased use, and the performance of FRP materials, in New Zealand. The aim of the project was to begin the process of generating better knowledge and understanding about polymer-based composites for application within the New Zealand building industry. Important aspects, including the applicability, durability and flammability of composites, were examined.

The project has focused in the areas of FRP composite reinforcing bars for concrete, FRP composite wraps and laminates for structural remediation and FRP composite pultrusion profiles. These were selected as offering the largest potential for use, and resulting benefits, in New Zealand construction.

A search of the literature was performed to gain an understanding of both the guidance available for the construction industry and the level of scientific understanding of the properties and performance of FRP composites.

A short experimental programme was also completed. This examined the effects of exposure in the New Zealand environment on the properties of FRP composite materials. It also investigated the response of FRP composites to fire.

2. LITERATURE REVIEW

Although the literature contains dozens of guides and reports concerning FRP composites for use in construction, the review presented here was targeted to examine recent publications that offer guidance on the use of FRP composites in construction and to identify the gaps requiring future research. This work also targeted review articles that covered specific testing or technologies applicable to the New Zealand building industry. The scientific understanding of FRP composites is the key to the increased use of these materials and this area will be covered in detail.

2.1 Guidance for the construction industry

A number of committees, from professional organisations, are working towards recommendations for use and specification of FRP composites. Those of relevance to the use of FRP composite in New Zealand are discussed below. However, it should be noted that this represents a snap-shot of the guidance available since design guideline documents have a short life. This is because of continued progress in maturing the technologies.

2.1.1 American Concrete Institute (ACI) Committee 440

The ACI Committee 440 has 10 different sub-committees focused on producing engineering guidelines for FRP application areas.

The *State-of-the Art Report on Fiber Reinforced Plastics (FRP) Reinforcement for Concrete Structure* was published in 1996 (ACI 1996) and re-approved in 2002. This report summarised what was known of the properties of the composite constituents and discussed the philosophies for design of reinforced and pre-stressed elements. The report also presented details of actual applications of FRP composites. A revision of this report is currently under development.

The ACI 440H Committee has also published the *Guide for the Design and Construction of Concrete Reinforced with FRP Bars* (ACI 2001) and this has been revised in 2003 (ACI 2003) and 2006 (ACI 2006). This guide covers the history of use of FRP composite reinforcement, describes the unique properties of FRP and offers guidelines for design of concrete structural members using FRP rebars.

The ACI 440F Committee has since produced a guideline for the design and construction of wrapping systems for strengthening of concrete structures (ACI 2002). The document, titled *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, covers requirements including shipping, storage, handling, installation, inspection, acceptance, maintenance and repair. A revised version of the guide is currently under development.

In 2004 the *Guide to Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures* was published (ACI 2004). This document provides model test methods for the short and long-term mechanical, thermo-mechanical and durability of FRP bars and laminates.

Several new documents are also under development by the 440 Committee. These are targeted at defining specifications for carbon and glass FRP composite bars (ACI 2007a), offering guidance on the design and construction of externally bonded FRP composite systems (ACI 2007c) and assessing the durability of FRP composite used with concrete reinforcement for concrete structures (ACI 2007b).

2.1.2 American Society of Civil Engineers (ASCE)

The ASCE established the Structural Composites and Plastics Committee for the purpose of developing standards for the design, fabrication and construction of buildings using FRP composites.

In the early 1980s this committee published a design manual (ASCE 1984). The manual set out to provide assistance and guidelines to structural engineers for design using plastics and structural FRP composite components. Approaches that were believed to result in the most efficient use of plastics for structural applications were described and illustrated with examples. Methods to quantitatively evaluate the effectiveness of designs for fabricated parts were also described.

The design manual was subsequently supplemented by the publication of a plastics selection manual (ASCE 1985). This manual offered further information to allow design calculations for the selection of materials or material combinations. It also contained guidelines on materials selection procedures and examined factors affecting properties during material production and use.

Publication of an update of the design manual is expected soon.

A new ASCE / American Composite Manufacturers Association project is scheduled to begin in June 2007 with the aim of drafting a "Standard for load resistance factor design of pultruded fiber-reinforced structures".

2.1.3 Composites Association of New Zealand (CANZ) Fibre Reinforced Plastic Design Manual

This brief design manual was published in 1989 (CANZ 1989) with the purpose of presenting design data and applications in which FRP composites could be used. Besides background information on fibre types, resins and production processes, the manual tabulated comparative properties of materials. The majority of the manual was dedicated to discussion of specific existing applications in New Zealand.

2.1.4 Composites Institute of Australia Code of Practice

In 2000 the Composites Institute of Australia (CIA), now known as Composites Australia Inc, began a programme to address the lack of appropriate structural design standards for composite materials in civil engineering. A programme to develop an Australian industry code of practice was initiated, beginning with the definition of a national system of grading and certification of composite constituents.

The grading programme for the constituent materials was defined as comprising five parts:

1. General programme guidelines
2. Polymer matrix materials for FRP laminates
3. Fibre reinforcement materials
4. Core materials
5. Adhesives.

Characterisation of each of the constituents forming the GRP material was conceived as a route to simplify the evaluation process. The aim of the code was to evaluate all commercial available systems, and this resulted in a significant programme of experimental work.

No further progress appears to have been made since the publication of a paper concerning work on characterising lamina behaviour in 2004 (Ayers 2004). It appears that further funding to complete the material characterisations has not been obtained (Van Erp 2007).

2.1.5 International Code Council (ICC)

The International Conference of Building Officials, latterly consolidated into the ICC, has developed two criteria documents for the use of FRP composites for strengthening. Acceptance Criteria AC125 is for strengthening of concrete and reinforced and unreinforced masonry with FRP. Acceptance Criteria AC178 is for inspection and verification of such strengthening.

The qualification requirements for AC125 include testing of the structure: columns for flexure and shear; beam/column joints; flexure and shear of beams; in/out-of-plane flexure for walls, wall/floor joints; flexure of slabs. Tests on the FRP include: outdoor exposure; freeze/thaw; aging; soil resistance; fire resistance; finish; fuel resistance; adhesive lap strength; bond strength.

The inspection and quality control requirements are covered in AC178. The requirements include site inspection, material verification, field testing, identification and repair of defects and a review of documentation. The field tests that may be performed at the request of the owner, engineer or inspector include pull-off, resin properties and cured thickness.

2.1.6 International Federation for Structural Concrete (Fédération Internationale du Béton (*fib*))

In 1996 *fib* Task Group 9.3 was established with the aim of producing design guidelines for use of “FRP Reinforcement for Concrete Structures”. The task group is divided into two sub-groups: FRP reinforcement for reinforced concrete and pre-stressed concrete; and externally bonded reinforcement.

The task group’s members are drawn from most European universities, research institutes and industrial companies. There are also members from Canada, Japan and the USA. The main objectives of the group are said to be:

- The elaboration of design guidelines in accordance with the design format of the Comité Euro-International du Béton – Fédération International de la Précontrainte Model Code and Eurocode 2.
- Links with other initiatives regarding material testing and characterisation and development of standard test methods.
- Participation in the international forum in the field of advanced composite reinforcement, stimulating the use of FRP for concrete structures.
- Guidance on practical execution of concrete structures reinforced/pre-stressed/upgraded by FRP.

The work performed is published as *fib* bulletins and to date these include:

- *fib* Bulletin 14: "Externally bonded FRP reinforcement for RC structures – Technical report on the design and use of externally bonded fibre reinforced polymer reinforcement for reinforced concrete structures".
- *fib* Bulletin 35: “Retrofitting of concrete structures by externally bonded continuous composite reinforcement for concrete structures”.

A further bulletin on FRP reinforcement for concrete structures is also under development.

2.1.7 Institution of Structural Engineers (ISE)

To facilitate the adoption of FRP composites in the UK the ISE has published an interim guide on the design of reinforced concrete structures using FRP reinforcement (ISE 1999). The guide is specifically aimed at engineers familiar with the design of conventionally reinforced concrete structures in accordance with the current UK design codes but who have little, or no, experience of the use of FRP rods or grids as embedded reinforcement.

The guidance given is not specific to any particular FRP composite material and pre-stressing and externally bonded reinforcement are not included.

The guide takes the form of suggested changes to the British design codes BS 8110:1997 *Structural use of concrete. Code of practice for design and construction* (Parts 1 & 2) and BS 5400:1990 *Steel, concrete and composite bridges. Code of practice for the design of concrete bridges* (Part 4), which are both derived from publicly available information.

The approaches adopted are in line with similar recommendations under development elsewhere in the world.

2.2 Current scientific understanding

The scientific study of FRP composite materials has progressed in parallel with the commercial development and use of materials. The study of FRP composite materials has always been relatively difficult because they are complex mixtures of numerous constituents, primarily formulated by the manufacturer to deliver an acceptable price/ performance balance to fit the intended application.

The performance of the matrix resin is enhanced by the addition of functional additives, which can include fillers, colours, release agents, flame retardants, thermal and light stabilisers. While these additives may deliver the required primary properties, other properties may be impacted.

The scientific literature contains thousands of individual studies, but the assembly of this information into any structured, systematic understanding is still ongoing.

2.2.1 Civil Engineering Research Foundation (CERF) Gap Analysis for Durability of Fiber Reinforced Polymer Composites in Civil Engineering

This gap analysis was completed by CERF, the research arm of the ASCE, to quantify where research effort should be targeted to facilitate the acceptance of FRP composites by engineers, architects and planners.

Unsurprisingly, the project concluded that the requirements for FRP composite use in civil infrastructure applications are different from those in other sectors, particularly in respect of service environment and durable lifetime. This explains why FRP composites have been successfully used in automotive, marine, industrial and aerospace applications for several decades, but have not penetrated construction and infrastructure applications to a significant degree.

Anecdotal evidence indicated that if appropriately designed and fabricated, these systems can provide longer lifetimes and lower maintenance than equivalent structures fabricated from conventional materials. However, actual data on durability was believed to be sparse, not well documented, and in cases where available not easily accessible to the civil engineer.

In addition, contradictory data was found published in a variety of venues that tended to be confusing. The reasons for the apparent contradictions on durability were identified and related to the reporting of data without sufficient detail of the actual raw materials used and the application of different forms of materials and processing techniques. This includes changes in the materials systems over time, especially resin formulations, which are specified only by generic names.

The study also noted that there was some evidence of rapid degradation of specific types of FRP composites exposed to certain environmental conditions found in civil engineering applications, and that premature degradation of FRP products has been seen in some past projects. This was said to raise concerns related to the applicability of this class of materials for civil infrastructure.

It was concluded that as no easily accessible and comprehensive database on these materials exists, it is difficult for civil engineers and designers to use FRP composites on a routine basis. Additionally, the authors believed that the lack, or inaccessibility, of data related to the durability of these materials was proving to be one of the major challenges that needed to be addressed prior to the widespread acceptance and implementation of FRP composite materials in civil infrastructure.

2.2.1.1 Adoption of the recommendations

Disappointingly, progression of research along the lines recommended by the CERF gap analysis seems to be limited. Indeed, awareness of the existence of the report itself appears to be limited.

A science citation search was performed for literature referring to the gap analysis document itself, or to the extract published in peer reviewed literature (Karbhari 2003). The results indicated only 10 citations in the six years since publication.

2.2.2 Network Group for Composites in Construction (NGCC) Composite IQ Report

This report concluded that due to the ready availability of tested and relatively low cost steel-based, concrete-based and wood-based materials, the breakthrough of FRP composite materials in engineering has been slowed (NGCC 2006a).

FRP composite materials have carved a niche in rehabilitation, reparation and reinforcement of existing structures, but the advantages that make them attractive for innovative structures are not being fully exploited.

The report concluded that the further development of FRP composite use requires new sets of regulations.

2.2.3 NGCC R&D Workshop Report

This meeting was held at the National Physical Laboratory (NPL) in London on 31 May 2006. The aim of meeting was described as "finding out what challenges are facing the construction industry as the use of composites in construction applications increases (NGCC 2006b).

The meeting identified key areas needing work and further research. These were reported as:

- Development of standards for design and rehabilitation using FRP materials
- Demonstration projects
- Inspection and non-destructive testing procedures
- Hybrid use of FRP in conjunction with traditional construction materials
- Joining technology, FRP to FRP, FRP to steel or concrete
- Education and training.

The discussion session also identified the key barriers to adoption of FRP composites in construction. These were reported as:

- Conservative industry
- Codes and standards (there is a lack of these for FRP composites and a need to pull together what already exists)
- Bad experiences, coupled with the fact that material failures get a lot of publicity
- FRP composites still seen as a new material, therefore no 'guarantee' of durability
- Costly when compared to other alternatives
- Education of the workforce, the wider construction industry and training as part of degree course
- Inspection procedures need development or refining.

It was observed that has there been little progress over the last 5-10 years and the causes for this were identified as:

- Funding – the system does not allow funding to perform reviews and disseminate research findings
- Innovation required as design is still influenced by traditional thinking
- Time pressures within industry
- Architects not understanding FRP composites
- No focus point for academia in the field of composites for construction.

2.2.4 National Composites Network (NCN) UK Roadmap

In June 2006, a team from NGCC (Network Group for Composites in Construction), working with NCN (National Composites Network) representatives, formed the first UK roadmap for Composites for the Construction Industry. The methodology which was used to produce the document was said to follow the procedures typically used for other existing roadmaps.

The final outcome of the process was a list of priority items requiring action in order to enable the industry to progress in a more dynamic and competitive manner. These included:

- Identification of product areas where structural FRP composites have a distinct advantage over other materials and where their unique characteristics are exploitable.
- Development standards for material quality assurance and design quality assurance, with provision of codes of practice for composites in construction.
- Research to understand joints and connections, especially durability of joints and characterisation of joint behaviour.
- More focus on composites working in harmony with other materials.
- More R&D effort in the areas of durability, life-cycle assessment (LCA), whole-life costing (WLC), and examination of the environmental footprint.
- Better promotion of composites and training courses for engineers and architects so that FRP composites are routinely treated as part of their toolkit.

2.2.5 Literature database on R&D with pultruded fibre reinforced polymers

An excellent on-line literature database on research and development with pultruded fibre reinforced polymers is maintained by Dr Toby Mottram, School of Engineering, University of Warwick, Coventry, UK (Mottram 2006).

The database is updated monthly and so represents an invaluable resource to find articles of interest and for finding new publications in the area. The database currently contains over 1500 entries drawn from books, conference proceedings, journals, patents, standards, theses and websites.

3. EXPERIMENTAL PROCEDURES

The experimental work undertaken as part of this project was focused upon examining the properties of FRP composite materials available to the New Zealand building industry. The work also examined the performance of these materials in the New Zealand environment.

As already discussed, FRP composites offer a wide range of properties that often represent a step change in performance compared to many incumbent building materials. However, FRP composites are expensive when compared to contemporary materials and so their use only makes sense if the WLC of the project is considered. Then FRPs have a significant advantage over other strengthening materials, and this is the prime motivator for their widespread adoption in retrofitting and repair of structures.

For this reason the choice of materials for study was carefully considered and limited to materials where it was believed that an FRP alternative was realistic substitution for incumbent materials.

3.1 FRP composite materials

FRP composite materials from different manufacturers, produced by different manufacturing processes and made from different classes of matrix resin, were selected for this study. All materials comprised standard glass fibre reinforcement. A summary of the materials used is given in Table 1 . The approximate glass content of the samples has been derived from the sample residue in cone calorimeter tests at 50 kW/m² irradiances.

Table 1. Materials selected for experimental work

Sample name	Generic matrix resin type	Manufacturing process	Thickness / mm	Tests completed	Approx. % glass by mass
Hand-laminated epoxy sheet	Epoxy	Hand-laminated	5.5	Exposure Fire	31
Hand-laminated polyester sheet	Polyester	Hand-laminated	3.0	Exposure Fire	41
Pultruded polyester	Polyester	Pultruded	3.0	Fire	67
Pultruded polyurethane	Polyurethane	Pultruded	3.5	Fire	65

The hand-laminated sheet samples used a chopped strand mat reinforcement. These reinforcements had a random fibre distribution in the plane of the samples. The fibre lengths in the samples were approximately 40 to 80 mm. The samples were finished with a white gel coat on one surface. A gel coat is a resin-rich coating applied to the surface. Its function is to protect the bulk of the material from the environment and to produce a cosmetically appealing surface finish. It is understood that this gel coat was formulated to withstand outdoor exposure in the New Zealand environment.

The pultruded box sections used continuous filament mats as reinforcement. A scrim material was used to cover the underlying glass reinforcement on the outside surfaces. This improves aesthetics and resistance to environmental degradation.

Examples of the box section profiles tested in this work are shown in Figure 1. The scrim used to improve the aesthetics of the outside surface of the profiles can be seen in Figure 2 and the inside surface of the profiles is shown in Figure 3.

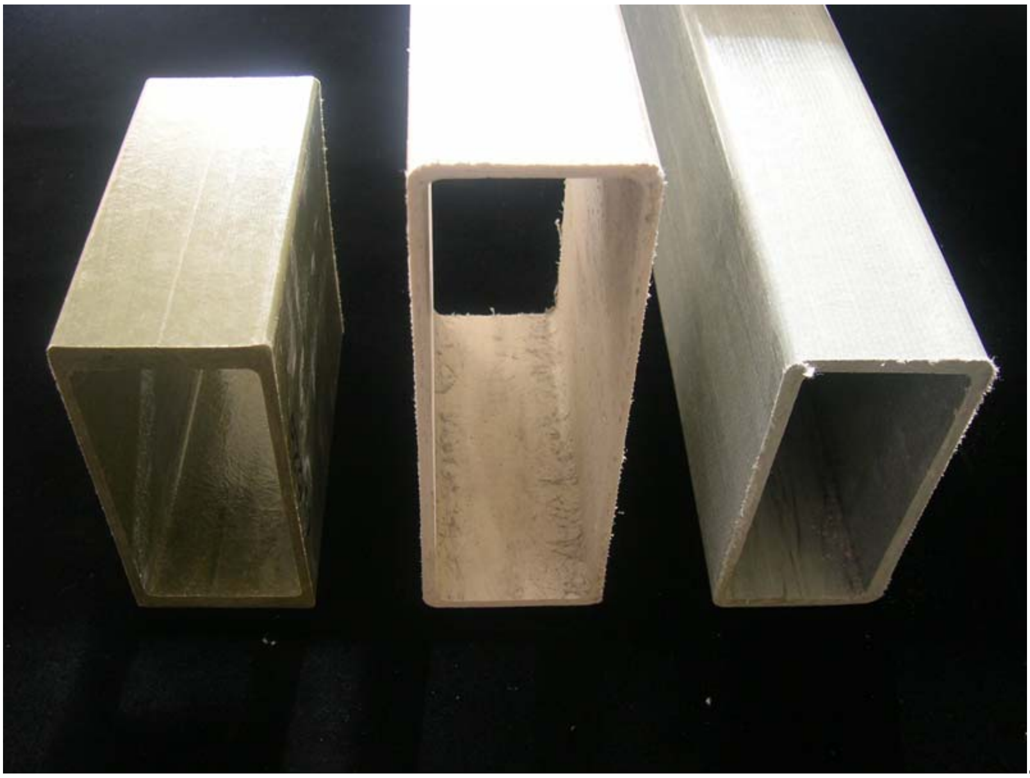
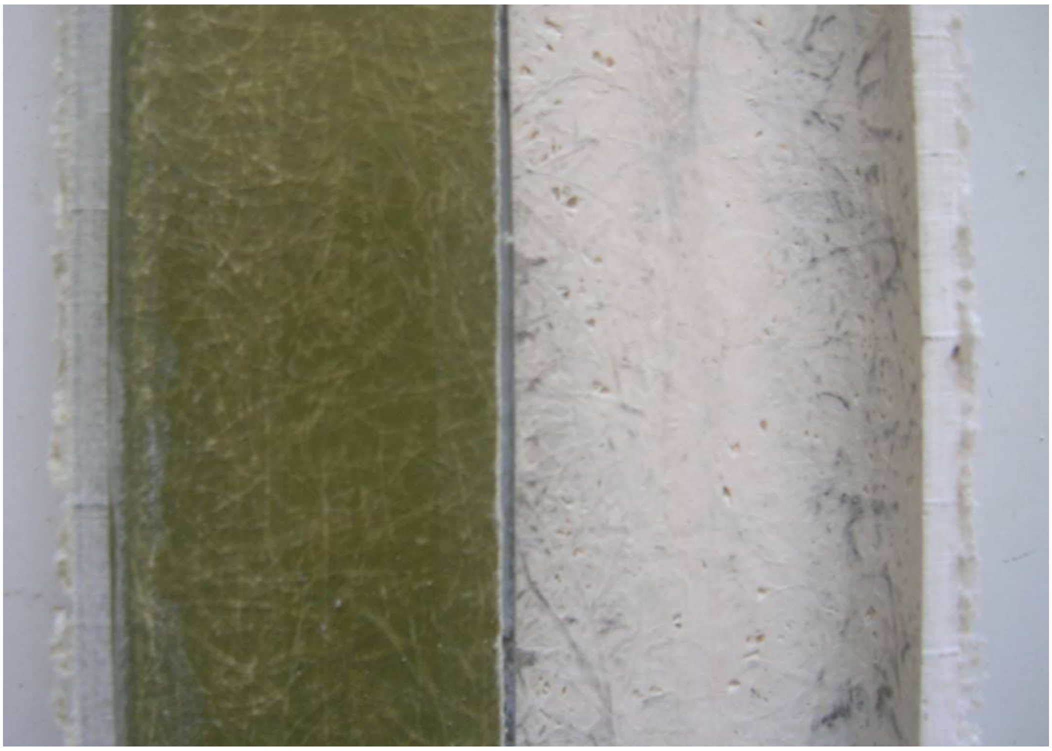


Figure 1. Examples of the pultruded polyurethane profiles used in this project.

(a) (b)

Figure 2. The box profiles contain a scrim on the outside surface: (a) polyester-based profile and (b) polyurethane-based profile.



(a) (b)

Figure 3. The inside surface of the profiles is not finished as well as the external surface: (a) polyester-based profile and (b) polyurethane-based profile.

It can be seen in Figure 3 that the inside surface of the profile is considerably rougher and that there are areas where the resin is voided around the fibres.

3.2 Outdoor exposure

FRP composite materials have previously been exposed on the BRANZ exposure site, at Judgeford near Wellington, for about 20 years. As part of this project the sample records were reviewed to identify the specimens of FRP composites exposed during this period.

Exposed polyester-based glass reinforced roofing profile samples were identified. The records showed the samples bore a label issued under licence by Standards Australia. It is inferred that the samples were certified in accordance with AS 2376.2 *Plastics building sheets – Glass fibre reinforced polyester*.

Additionally, a small section of pultruded profile was identified.

The samples were removed from the exposure site and examined for surface degradation and mechanical properties.

As part of this project, the hand-laminated FRP composites based upon epoxy resin and polyesters (listed in Table 1) were mounted at exposure sites at various locations in New Zealand in 2005. The pultruded profiles listed in Table 1 were not exposed.

The aim of the exposure testing was to provide improved detail on the effect of climatic variation on the durability of FRP composites. Nine sites were chosen at locations spanning the length of the country. The sites were located at Invercargill, Cromwell, Christchurch, Westport, Judgeford, Paraparaumu, Rotorua, Auckland and Kaitaia.

The exposure sites lay at latitudes from 35° South to 47° South. The majority of the sites were located within 15 km of the coast. The exceptions were the Rotorua site, and the Cromwell site in Central Otago. In both cases the coast was over 100 km distant.

The altitudes of all sites are not far removed from sea level, with Rotorua being the highest at about 400 m above sea level.

The exposure sites are positioned across the different zones of temperature, moisture/rainfall and UV radiation that exist throughout the country.

The climate in the most northern sites, in Kaitaia and Auckland, is distinguished from the other sites due to it having a typical annual solar irradiance of over 5.30 GJ/m² per year. The site in Rotorua and those near Wellington (Judgeford and Paraparaumu) have a typical annual solar irradiance closer to 5.10 GJ/m² per year. The trend of decreasing solar radiation intensity continues for the sites further south, with Westport and Christchurch having typical annual solar irradiance of 4.67 and 4.83 GJ/m² per year respectively. Central Otago, due to the clean air, has higher annual solar irradiances. The Cromwell site typical has an annual solar irradiance of about 5 J/m² per year. Finally, at the southern extreme of the exposure sites, Invercargill receives an average annual solar irradiance amounting to roughly 4.4 GJ/m² per year (NIWA 2007a).

The solar irradiance at a given location can also be simply represented in terms of the UV index. The UV index scale is derived from the intensity of the incident sunlight, weighted to the sensitivity of human skin. The approximate locations of the exposure sites and the maximum annual UV index values across New Zealand are shown schematically in Figure 4 (NIWA 2007b).

Rainfall also varies between the different site locations. Most sites receive about 1000 mm of rain per annum. Rainfall at BRANZ's site at Judgeford, near Wellington, varies between about 1000 and 1500 mm per annum. Considerably more rain falls in Westport, approximately 2000 mm per annum, due to its position on the west coast of the South Island. Conversely, both Christchurch and Cromwell have an annual rainfall of less than 750 mm per annum. A map showing details of median annual rainfall is shown in Figure 5 (NIWA 2007c).

Daily average maximum and minimum temperatures vary predominantly in line with the latitude of the exposure sites. The exception is Cromwell, where mountainous surroundings of the site results in maximum temperatures over 30°C and minimum temperatures around -5°C. The daily average maximum and minimum temperatures maps are shown in Figure 6 and Figure 7 (NIWA 2007c). The approximate locations of the exposure sites are also included in these figures.

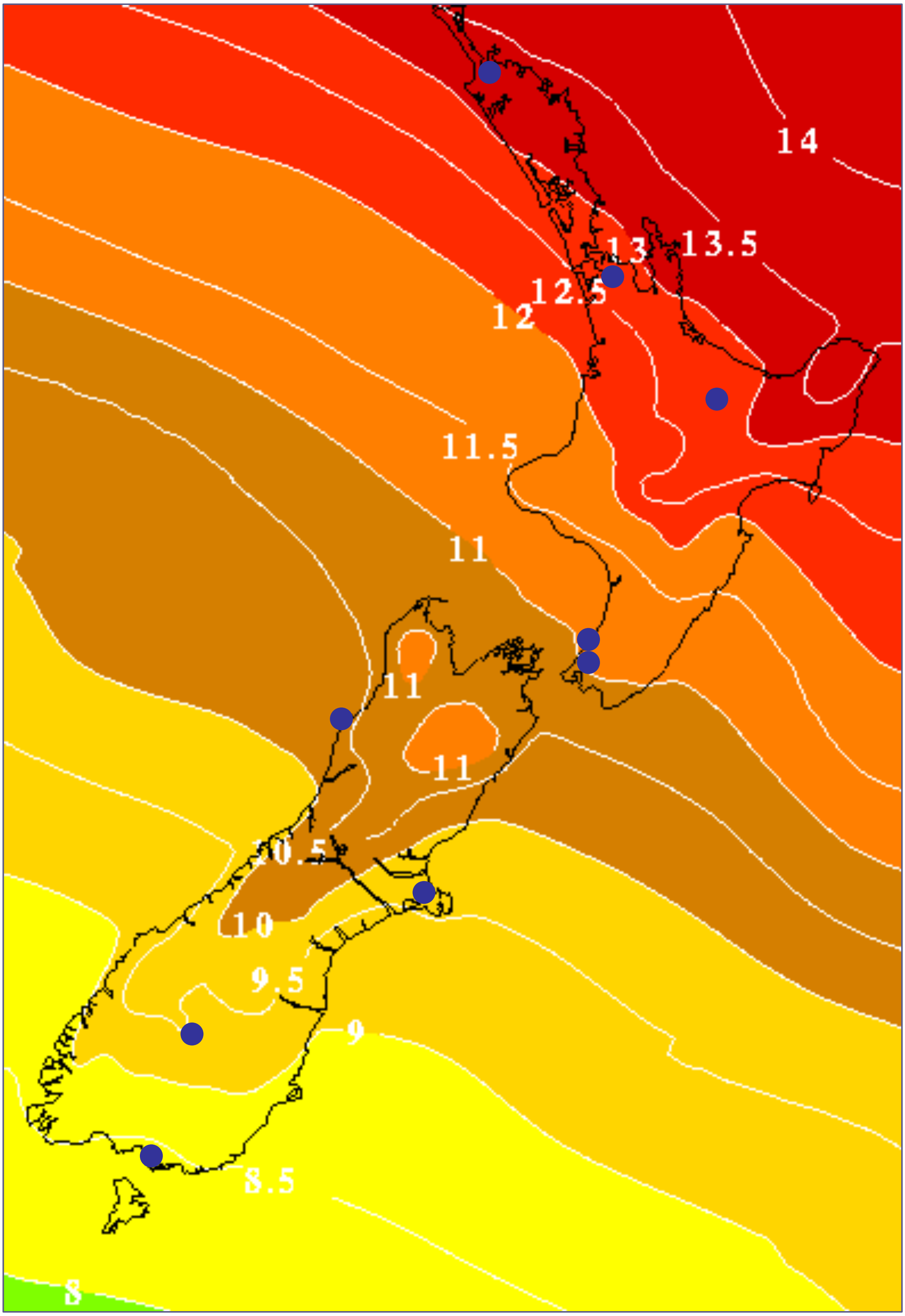


Figure 4. Maximum annual UV index at BRANZ exposure sites (UV index map provided by NIWA).

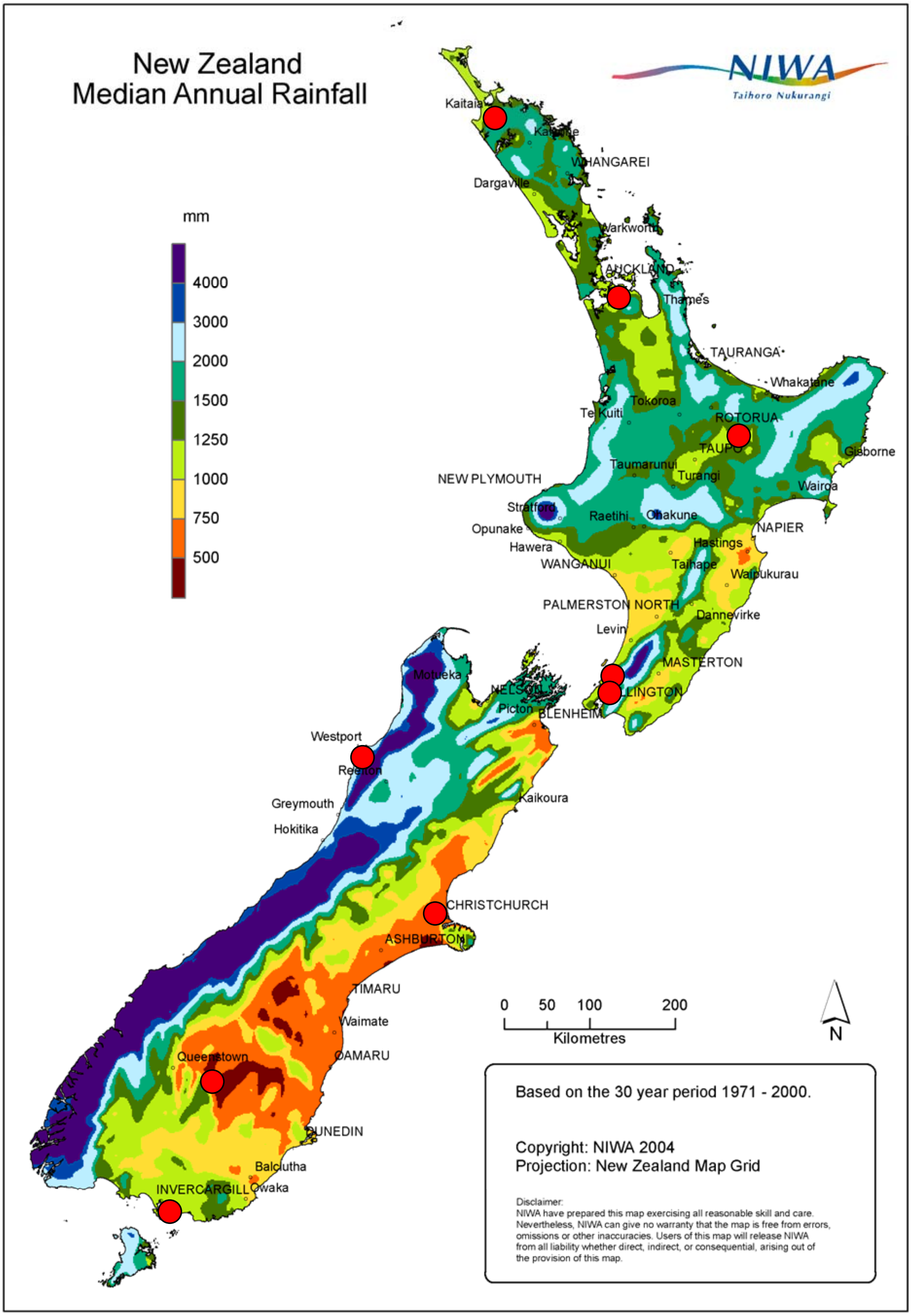


Figure 5. Median annual rainfall map provided by NIWA.

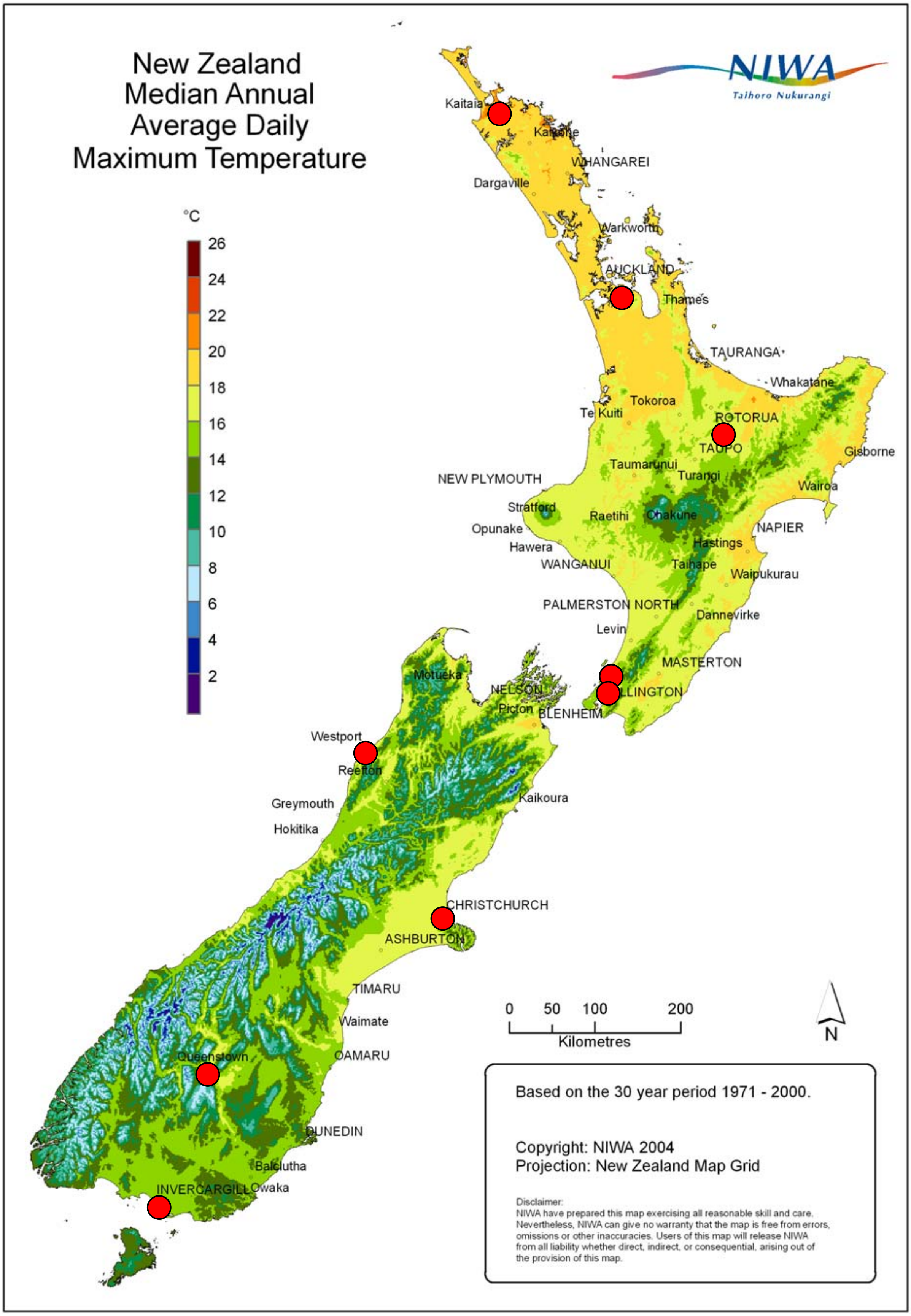


Figure 6. Median annual average daily maximum temperature map provided by NIWA.

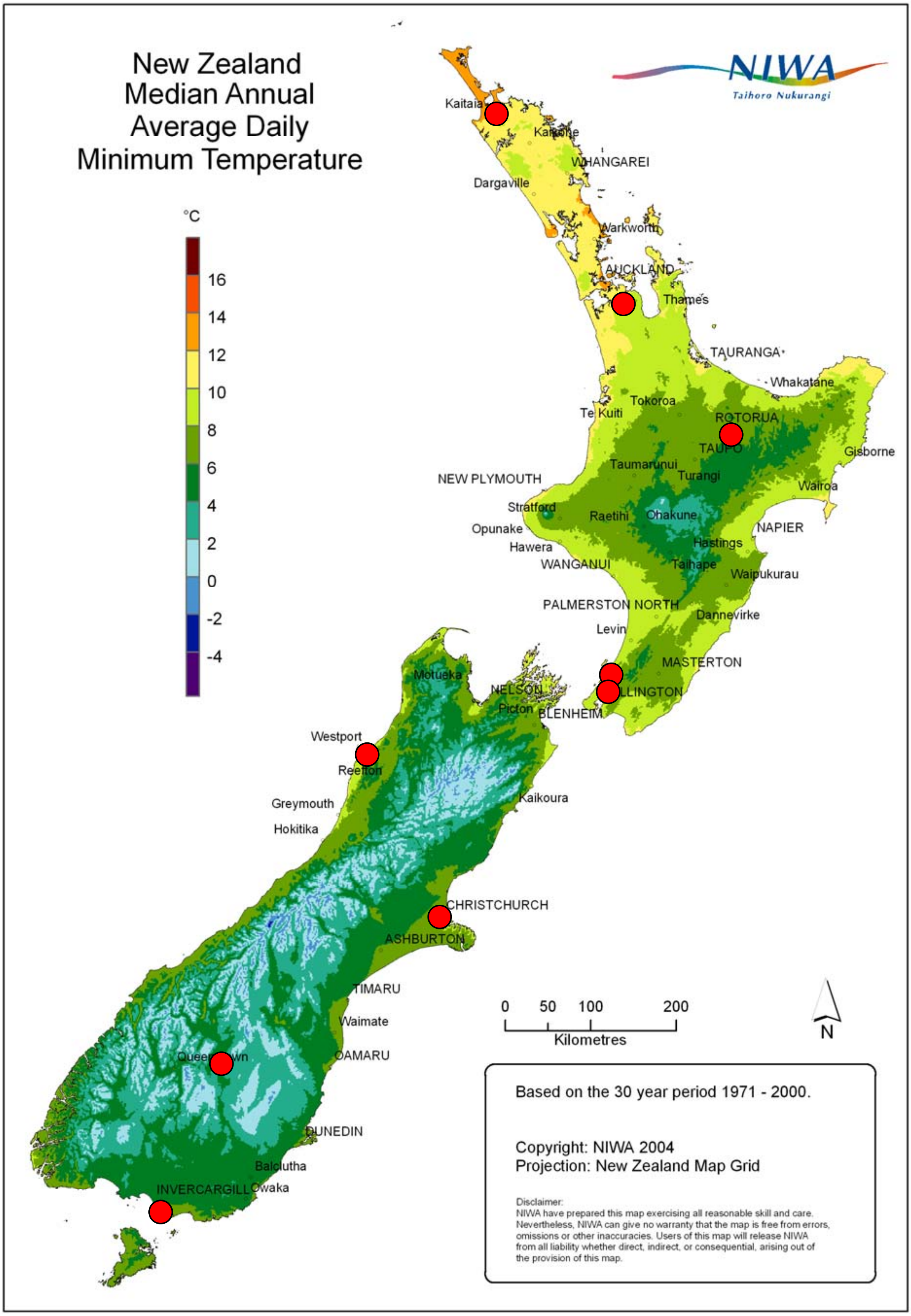


Figure 7. Median annual minimum daily maximum temperature map provided by NIWA.

The epoxy resin and polyester-based hand-laminated glass reinforced sheet products were exposed on the racks with the gel-coated side facing down. This directly exposed the matrix resin and reinforcement to the elements. This was expected to maximise the effects of solar radiation, air borne moisture and thermal cycling. Sample sheets had dimensions 200 mm by 250 mm. A typical arrangement of the samples during exposure is shown in Figure 8.

Figure 8. BRANZ exposure rack configuration (the composite materials are the white and pink/orange sheets on the left hand side of the exposure rack).

It should be noted that control samples were retained and stored in a climate controlled environment at 23°C and 50% RH for the entire duration of the outdoor tests.

3.3 Mechanical testing

The as received mechanical properties of the FRP composite samples were tested for all the samples listed in Table 1. The mechanical properties of the hand-laminated materials were also tested after 12 months and two years of outdoor exposure.

Flexural testing was selected as it was decided that this would most effectively examine the effects of surface degradation on the mechanical properties of the FRP composite materials. Testing was performed with the weathered face of the samples in tension to give maximum sensitivity.

Test coupons (10 mm x 120 mm) were cut from the pultruded polyester and polyurethane profiles. Five coupons were taken from each direction of the polyurethane profile and from the direction of pultrusion only of the polyester profile (due to width of the profile being too small to make 120 mm samples). The samples were then conditioned at 23.0°C and 50% RH for 48 hours.

Six test pieces (20 mm x 140 mm) were cut from each hand-laminated epoxy resin and polyester sheet specimens. Three pieces were cut from each direction of the composite sheets to examine for fibre orientation effects. The samples were then conditioned at 23.0°C and 50% RH for 48 hours.

Post-conditioning, the test pieces were subjected to flexural strength testing. The modulus of rupture (MOR) was determined to ASTM D790 with the following variations:

- the roller/loading nose diameter was 25 mm
- 100 mm span
- cross-head rate of 15.0 mm/min.

The modulus of elasticity (MOE) was also derived from the data collected. MOE reduction was expected to occur if outdoor exposure of the materials degraded the matrix resin or the reinforcing glass filaments.

Testing was carried out on a calibrated Instron Universal Testing Machine with a 10kN load cell. Testing in progress is shown in Figure 9.

Figure 9. Flexural property testing.

3.4 Cone calorimetry

Each of the FRP composites tested in this project were in accordance with AS/NZS 3837 by exposure to radiant heat fluxes of 30, 50 and 70 kW/m² using a cone heater. A cone calorimeter is shown schematically in Figure 10.

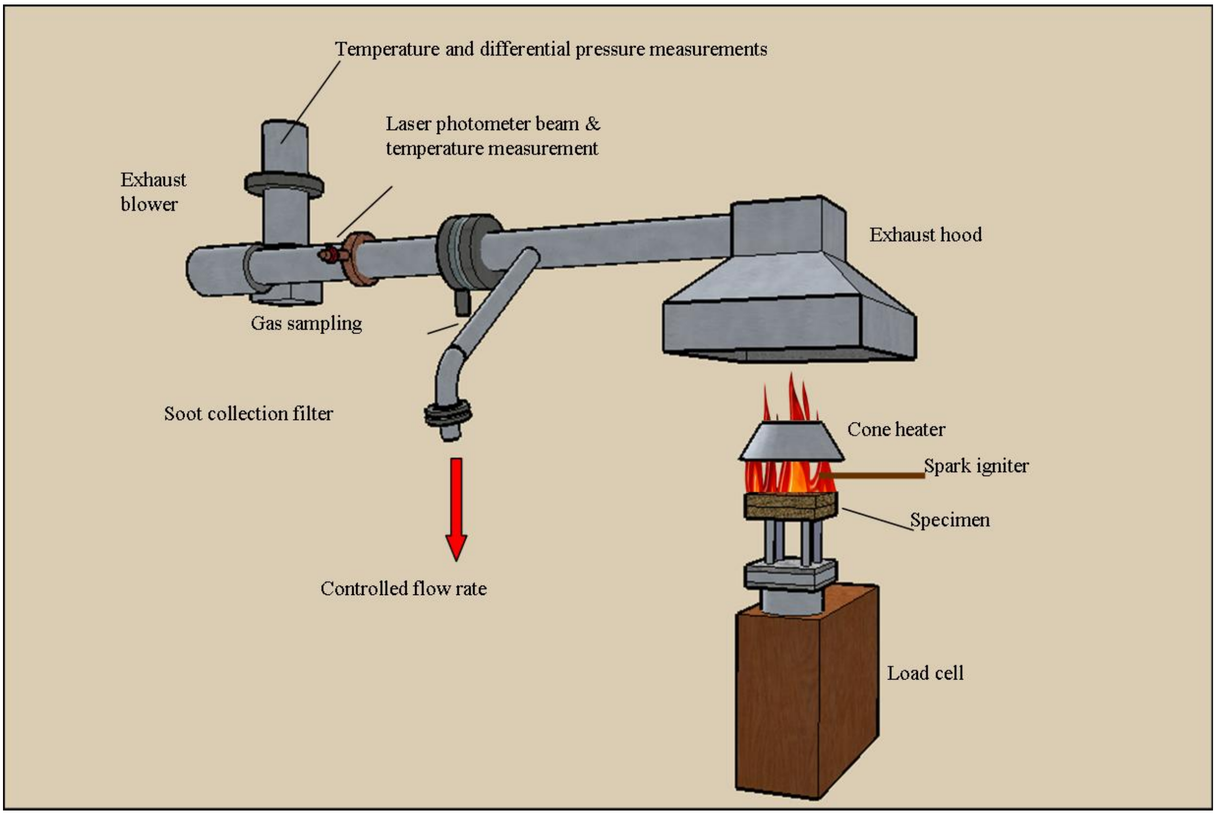


Figure 10. Cone calorimeter.

The cone calorimeter is able to expose samples to levels of incident radiation that are similar to that experienced in fully developed fires. The operator observes the sample to record the time taken for sustained burning to occur. The instrument monitors the level of oxygen in the exhaust, the amount of smoke in the exhaust, and the mass of the specimen during the test. From these measurements the energy released from the sample is calculated and a figure for the heat of combustion for the material is derived by reference to the mass loss rate.

A selection of samples of hand-laminated epoxy resin were conditioned at 90°C for 24 h before testing to examine if the resin was completely cured.

The data recorded included time to sustained burning, heat release rate, total heat release, specific extinction area and effective heat of combustion.

4. RESULTS AND DISCUSSION

4.1 Outdoor exposure

4.1.1 Historical exposed samples

A number of samples were identified from sample records that had been exposed on the BRANZ site for approximately 20 years. However, unexposed control samples were not available.

The majority of these samples were polyester-based roofing profile materials and had been exposed since 1988. These samples were located and removed from the site, as shown in Figure 11.

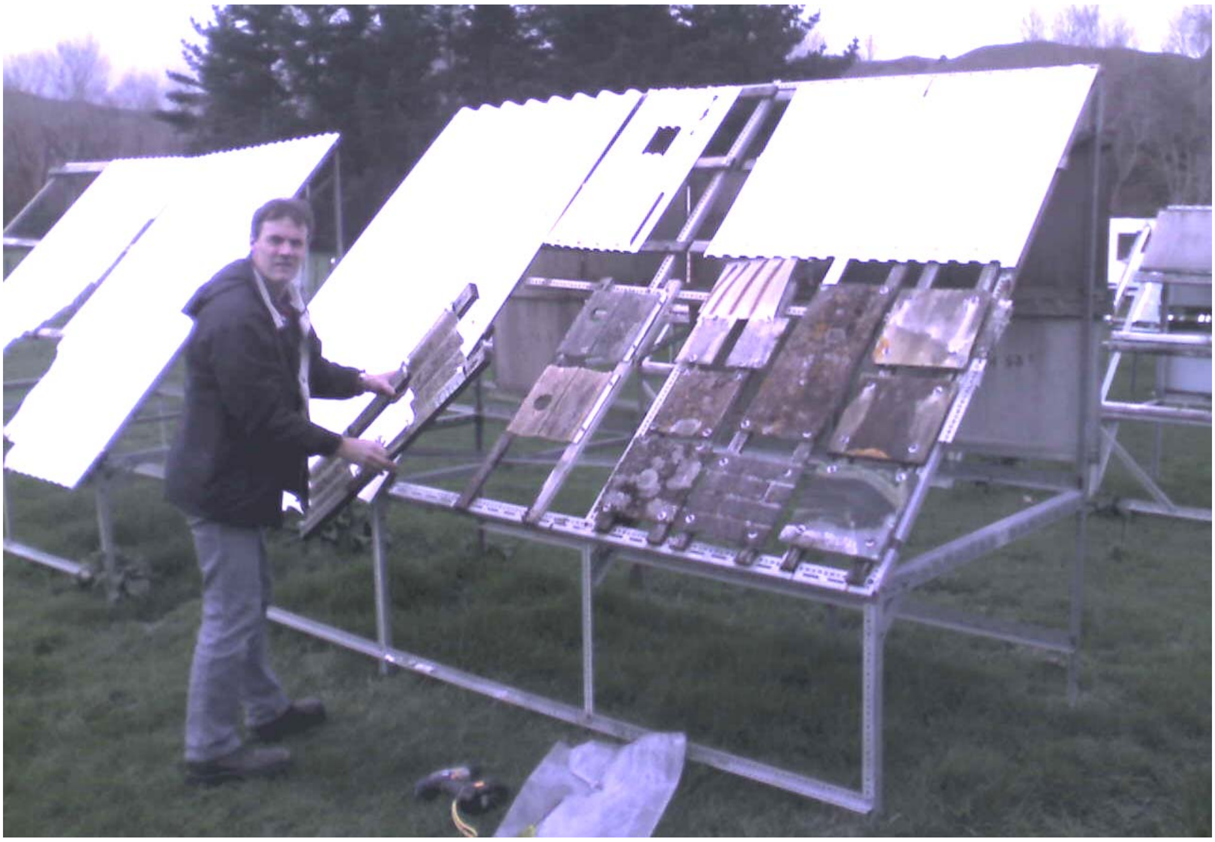


Figure 11. Collection of FRP composite samples from the BRANZ exposure site.

The polyester-based roofing profiles were sourced from a New Zealand producer. Their composition was believed to be optimised for the New Zealand environment, likely including the addition of UV stabilisers.

All samples appeared to have undergone significant surface degradation and loss of the resin from the surface. This result was inferred from the considerable amount of exposed glass reinforcement at the surface as shown in Figure 12, and by comparison with the appearance of the unexposed underside of the samples.

Figure 12. Exposed glass reinforcement at the surface of a polyester-based FRP composite following 19 years of exposure.

Despite us not knowing how the control material would respond under flexure, the exposed material was easily ruptured and had the characteristics of embrittlement with time.

A single thicker polyurethane resin-based FRP composite component was also removed from the BRANZ exposure site, where it had been exposed since 1984. This component was a pultruded C-section, approximately 6 mm thick. The exposed face of the sample had degraded and loss of resin had occurred. Even the sheltered back face of the sample showed some resin loss, believed to be result of reflection and scatter of solar radiation from surrounding objects. The sample is shown in Figure 13 and Figure 14.

Figure 13. Exposed glass reinforcement at the surface of a pultruded FRP composite section after 22 years of exposure.

Figure 14. Evidence of exposure of the reinforcement on the sheltered area on the reverse of the pultruded sample (on the left of the photo) compared to the unexposed area on the right of the sample.

Once again, no unexposed control sample was available and the dimensions of the sample made it impractical to produce specimens for mechanical testing. The performance and composition of this sample aligns well with what is known about the stability of polyurethane resin to exposure to solar radiation.

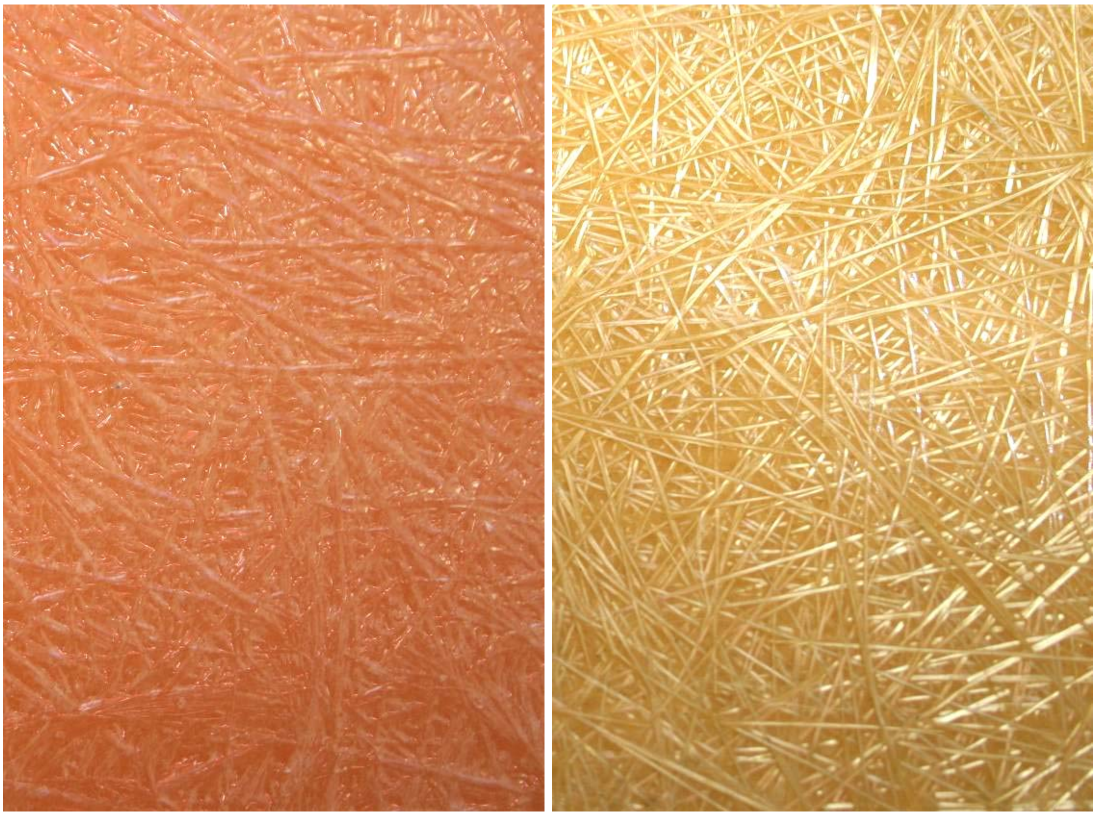
Disappointingly, it was not possible to draw any definite conclusions from the samples exposed long-term on the BRANZ exposure site.

4.1.2 Exposed samples from the exposure site network

After 12 months of exposure it was not possible to comment on the colour change of the hand-laminated epoxy resin samples. This was because the material showed a considerable variability in colour in the as received condition. However, it is reasonable to assume that the colour shift will be influenced by degradation of the resin at the surface, incident radiation, and changes in characteristics of the glass reinforcement due to moisture absorption etc.

The pigmented polyester samples containing titanium dioxide showed no significant colour shift during the 12 months of exposure period.

After two years of exposure, loss of the unpigmented epoxy resin at the surface had revealed the underlying fibre structure. This was clearly evident at every site. These effects are demonstrated in Figure 15 below.

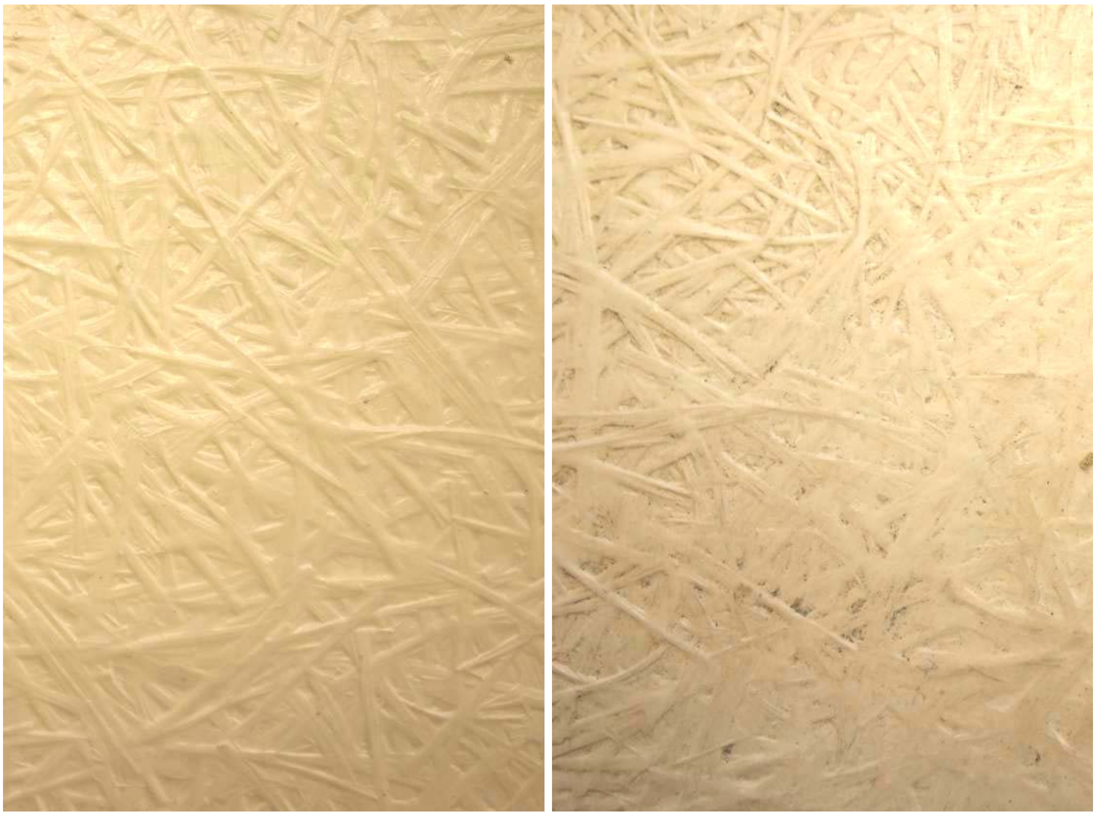


(a) **(b)**

Figure 15. (a) Hand-laminated epoxy resin control and (b) after two years of exposure in Auckland.

The change of colour appeared to be confined to the surface of the specimens and extended only to a depth of 100 μm. Again, it was not possible to accurately interpret the trends in colour change because of the inherent variability of the material.

In contrast, the pigmented polyester samples showed no significant loss of resin at the surface, and minimal colour change after two years of exposure. This is demonstrated in Figure 16. It was clear, however, that at the BRANZ exposure site at Judgeford a significant amount of fungal growth was occurring on these samples when compared to the other sites. At present no clear explanation can be offered for this observation. This should be further investigated in any future work and should be considered in other current exposure projects.



(a) (b)

Figure 16. (a) Hand-laminated polyester resin control and (b) after two years of exposure in Auckland.

4.2 Mechanical testing

4.2.1 Initial properties

The pultruded polyester and polyurethane-based box sections, listed in Table 1, were tested as received. The MOR and MOE results obtained for the polyurethane samples are presented in Figure 17 and Figure 18. The results are separated according to which surface of the box section profile was placed in tension and the direction from which the samples were cut from the profile.

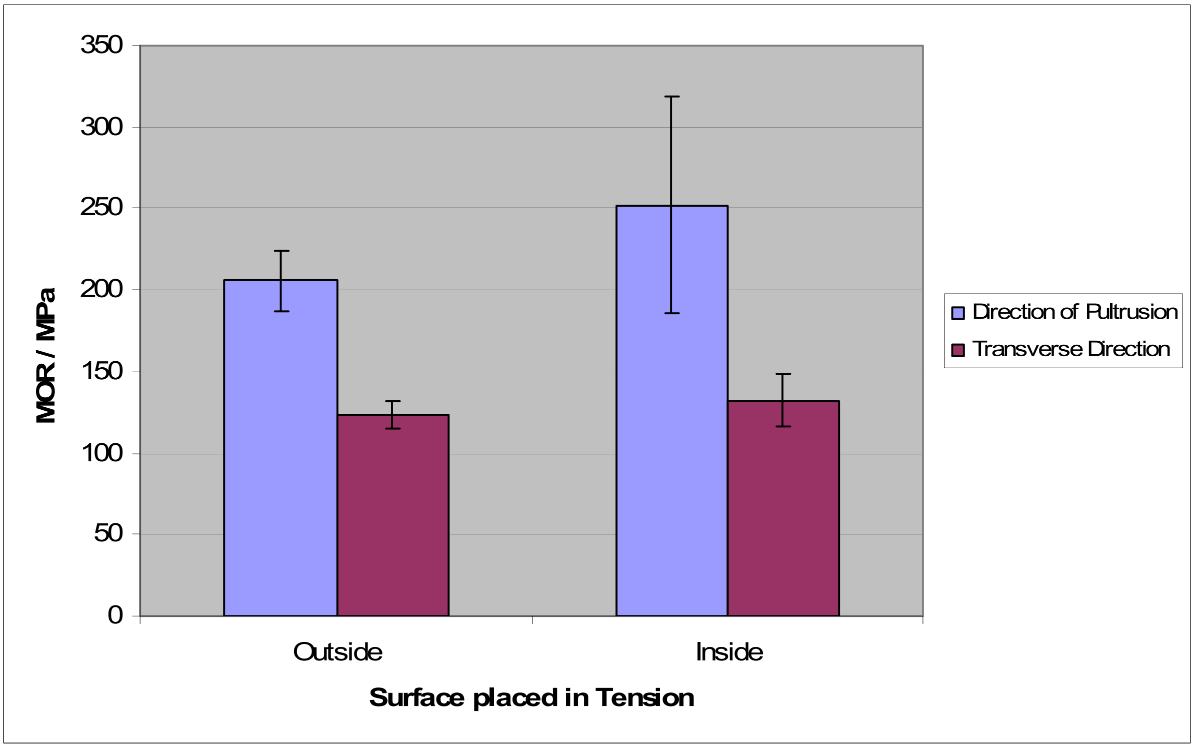


Figure 17. MOR results for the pultruded polyurethane profile.

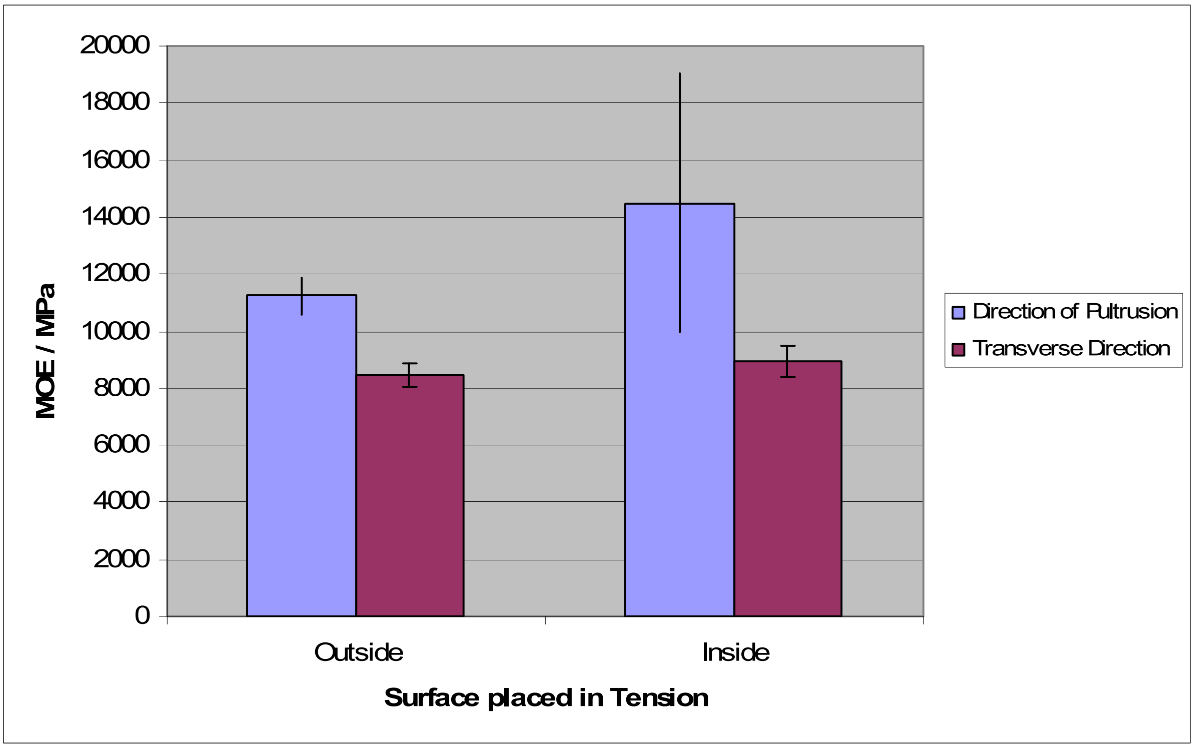


Figure 18. MOE results for the pultruded polyurethane profile.

As expected the polyurethane pultruded box sections showed a marked difference in flexural properties, dependent upon the direction from which the test samples were cut and the direction in which the samples were flexed. The differences in mechanical properties between the direction of pultrusion and transverse directions of the samples containing highly oriented reinforcing fibres are well known (Bader 2000).

The differences in properties when the outside and inside of the profile are placed in tension is slightly unexpected. It is clear from the data that placing the inside face of the profile, which contains more imperfections (compare Figure 2 and Figure 3), in tension results in better strength and higher modulus results. These results imply that the scrim on the outside of these profiles is weaker than glass reinforcement. It appears that the presence of this material is the key determinant and that the imperfections in the structure of the internal face, visible in Figure 2, do not play as significant role. The effect of the imperfections perhaps manifests in the higher variability of both the MOR and MOE values when the inside face of the polyurethane profile is placed in tension, as evident in Figure 17 and Figure 18.

For the pultruded polyester box section, testing in the cross-direction was not possible due to the width of the profile being less than the required length of the test samples. The MOR results obtained are shown in Figure 19, while the MOE results are shown in Figure 20. Again, the results are separated according to which surface of the box section profile was placed in tension.

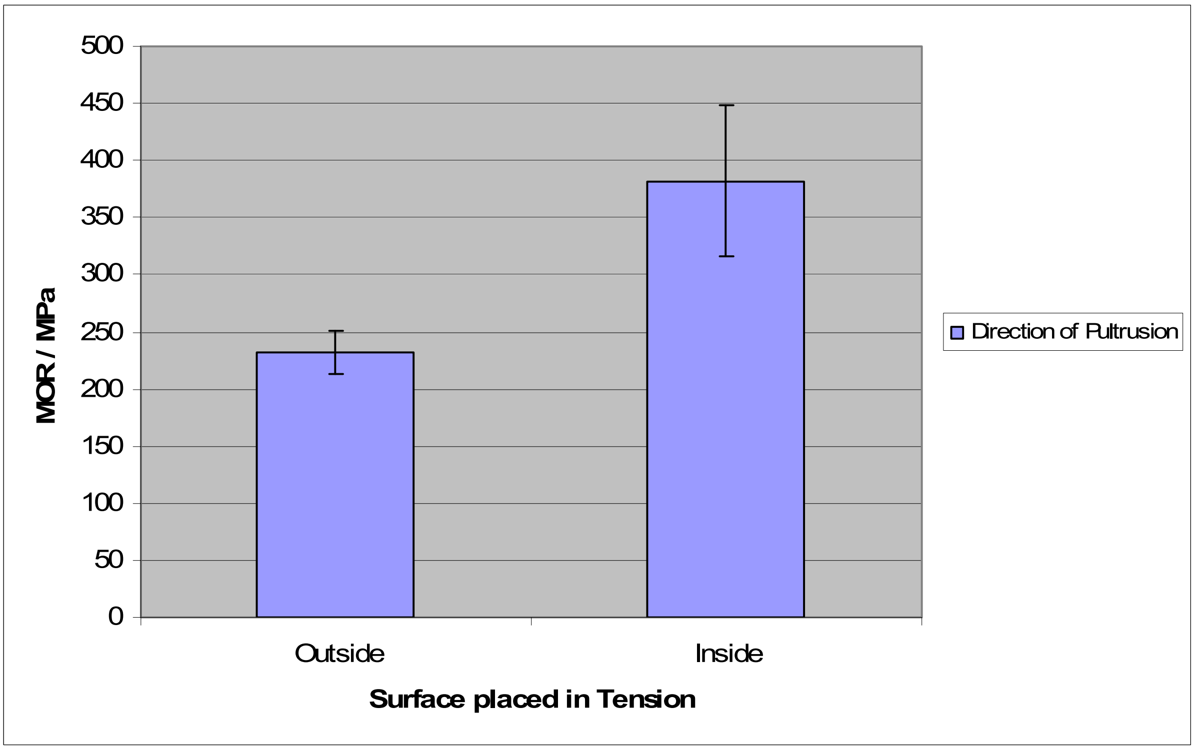


Figure 19. MOR results for the pultruded polyester profile.

.

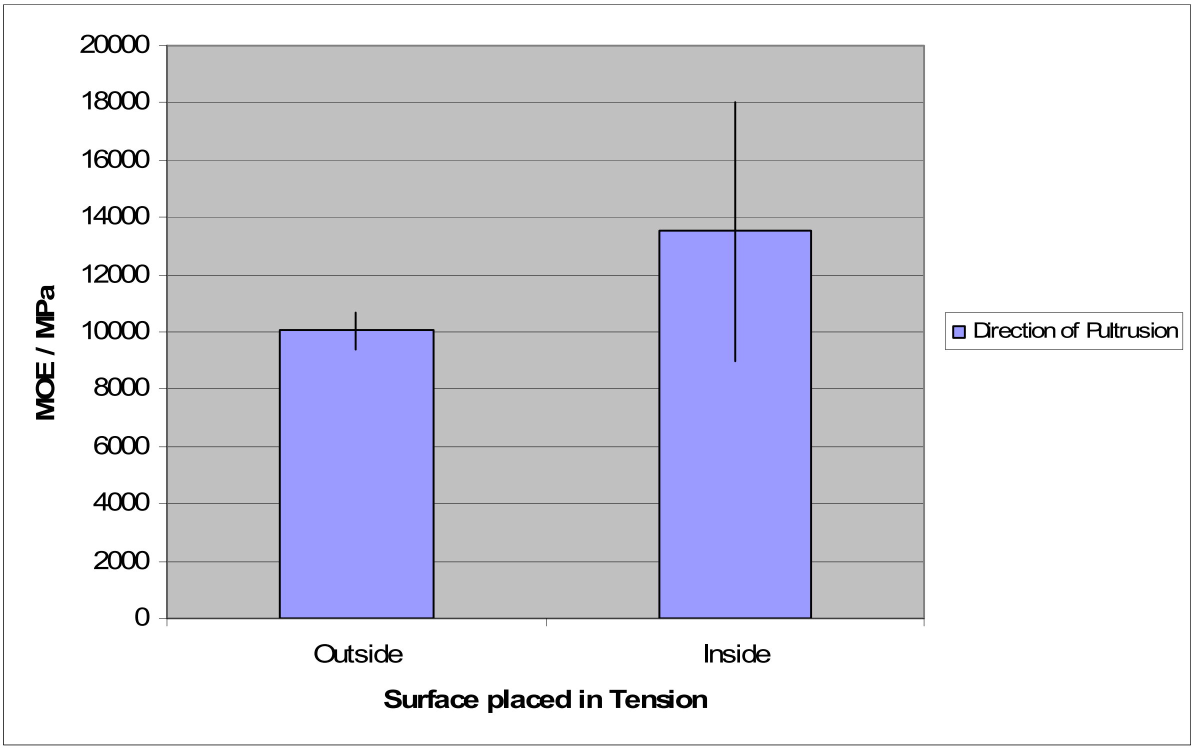


Figure 20. MOE results for the pultruded polyester profile.

Similar results were obtained for the pultruded polyester profile. The inside face of the polyester profile was of generally better uniformity than the polyurethane profile, with few imperfections in the inside surface (see Figure 2). However, it is clear in Figure 19 and Figure 20 that the same trend is evident as found for the polyurethane box profile samples.

The flexural properties of the hand-laminated composites sheets as received and as a function of sampling direction are shown in Figure 21 and Figure 22. The results are separated according to the direction from which the samples were cut from the sheet.

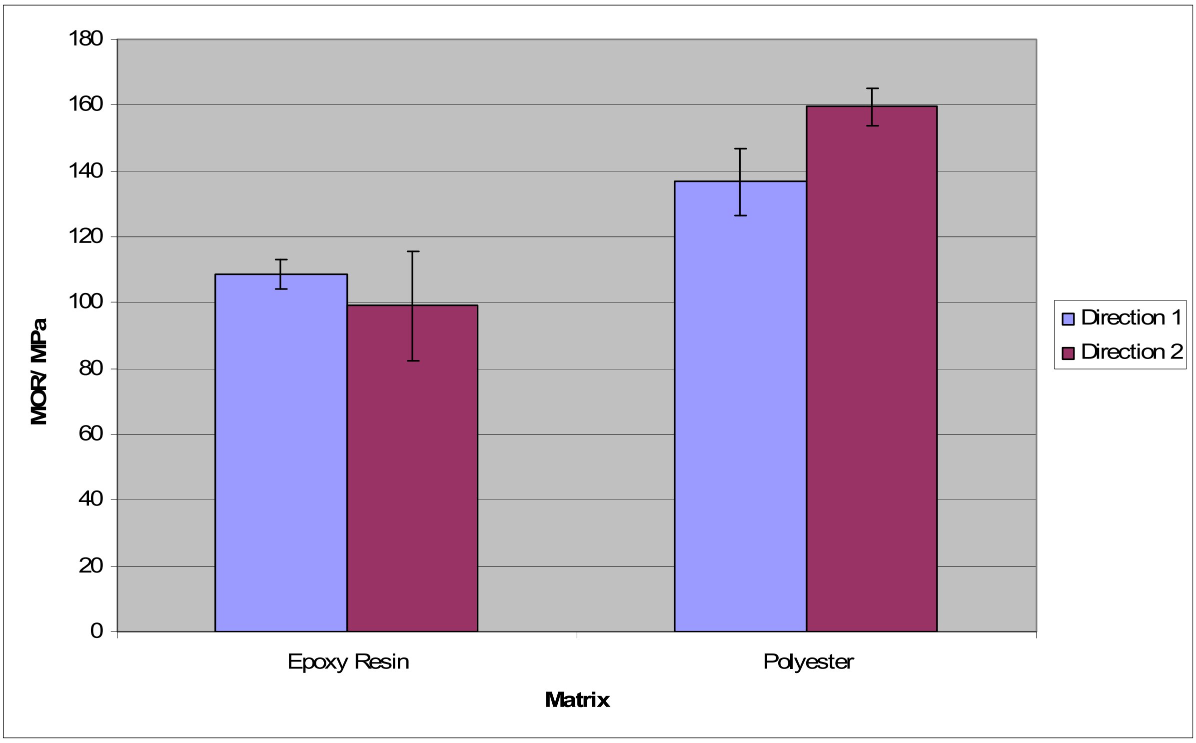


Figure 21. MOR results as a function of sampling direction for the hand-laminated FRP composite sheets.

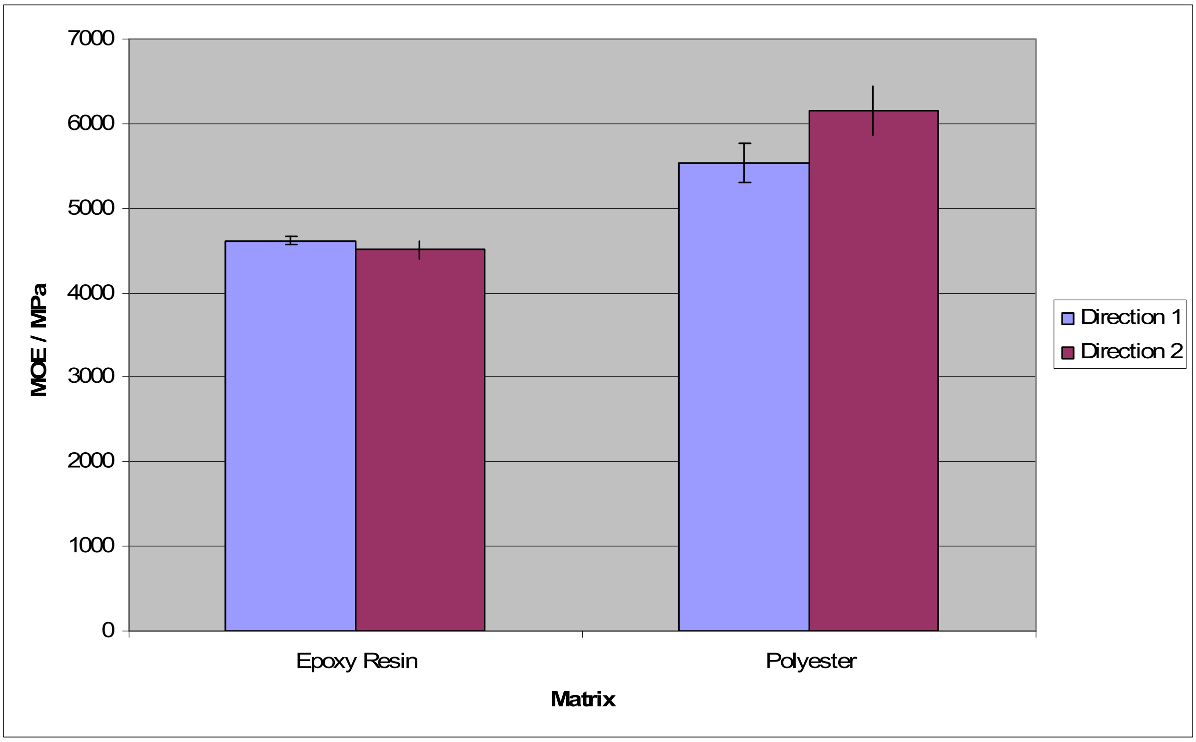


Figure 22. MOE results as a function of sampling direction for the hand-laminated FRP composite sheets.

It is clear from Figure 21 and Figure 22 that the flexural properties of the hand-laminated materials are markedly lower than the pultruded profiles. This is as expected, due to fibres in the hand-laminated materials being arranged at random, while there is a strong directional alignment of the fibres in the pultruded samples.

The results for the hand-laminated samples indicated that the polyester sheets were of considerably higher flexural strength and modulus than the epoxy resin-based sheets. This is believed to be, in part, due to differences in the glass reinforcement used in the sheets. There is more glass reinforcement in the polyester sheet (see Table 1) and it is formed from larger filament bundles (this can be seen by comparing Figure 15 (a) and Figure 16 (a)) which could be expected to offer superior resistance to flexural loads.

The hand-laminated epoxy resin and polyester sheets appeared to be generally of similar flexural properties when tested in both directions. As a result all flexural property data for exposed samples is presented as an average, irrespective of the direction the test pieces were cut from the exposed sheet.

4.2.2 Exposed samples

The flexural properties of both the hand-laminated epoxy resin sheet after 12 months of exposure and an equivalent unexposed control sample are tabulated in Table 2 and shown in Figure 23 and Figure 24. The flexural properties of the hand-laminated epoxy resin sheet after two years of exposure and an unexposed control sample are tabulated in Table 3 and shown in Figure 25 and Figure 26.

Table 2. Flexural properties for hand-laminated epoxy resin-based samples after 12 months of exposure

Area	MOR (MPa)	MOR (S.D)	MOE (MPa)	MOE (S.D)
Kaitaia	144	6.0	6490	171
Auckland	124	0.2	5250	375
Rotorua	108	14.7	5320	462
Paraparaumu	116	31.3	5330	574
BRANZ	129	16.0	6070	115
Westport	130	3.4	5940	113
Christchurch	154	8.3	5980	31
Cromwell	134	7.2	6000	146
Invercargill	128	11.6	5850	958
Control	121	8.3	6800	1130

Table 3. Flexural properties for hand-laminated epoxy resin-based samples after two years of exposure

Area	MOR (MPa)	MOR (S.D)	MOE (MPa)	MOE (S.D)
Kaitaia	137	8.5	5930	223
Auckland	139	3.1	6090	366
Rotorua	142	22.9	5550	723
Paraparaumu	122	5.2	5600	290
BRANZ	123	2.9	5380	388
Westport	133	7.4	5440	179
Christchurch	136	6.0	5530	157
Cromwell	134	4.5	5100	346
Invercargill	132	4.8	5360	67
Control	108	4.4	4610	46

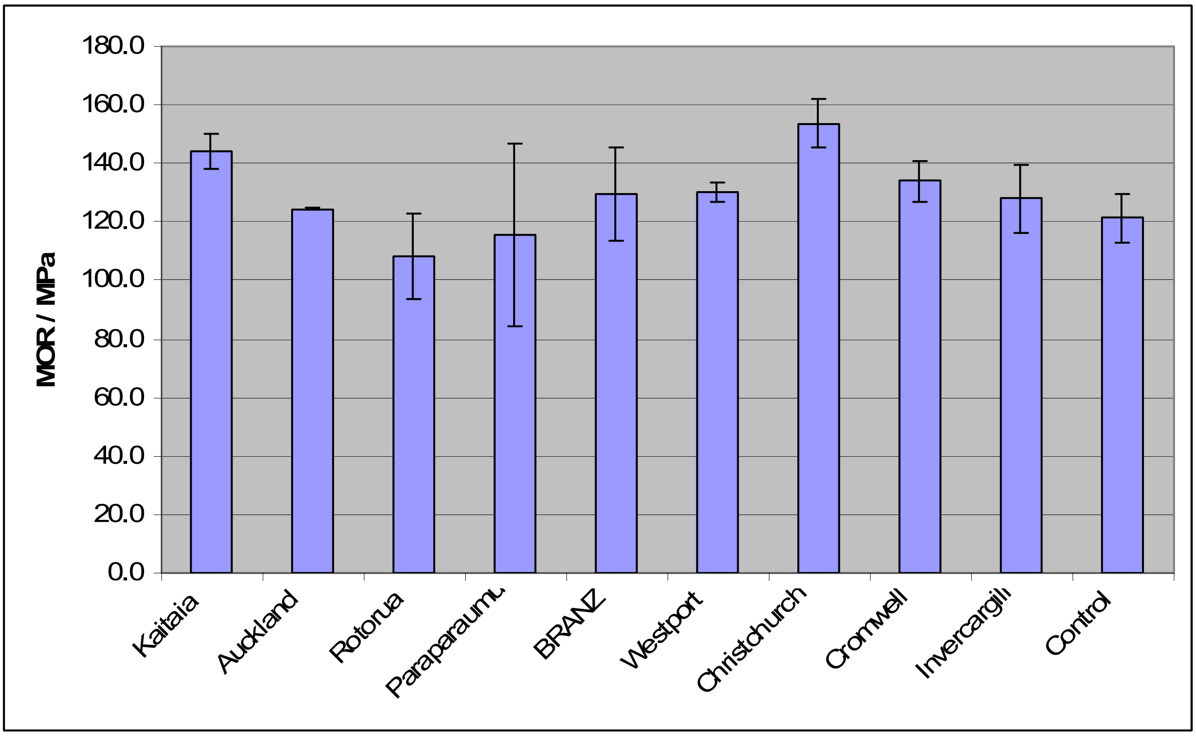


Figure 23. MOR results for hand-laminated epoxy resin-based samples after 12 months of exposure.

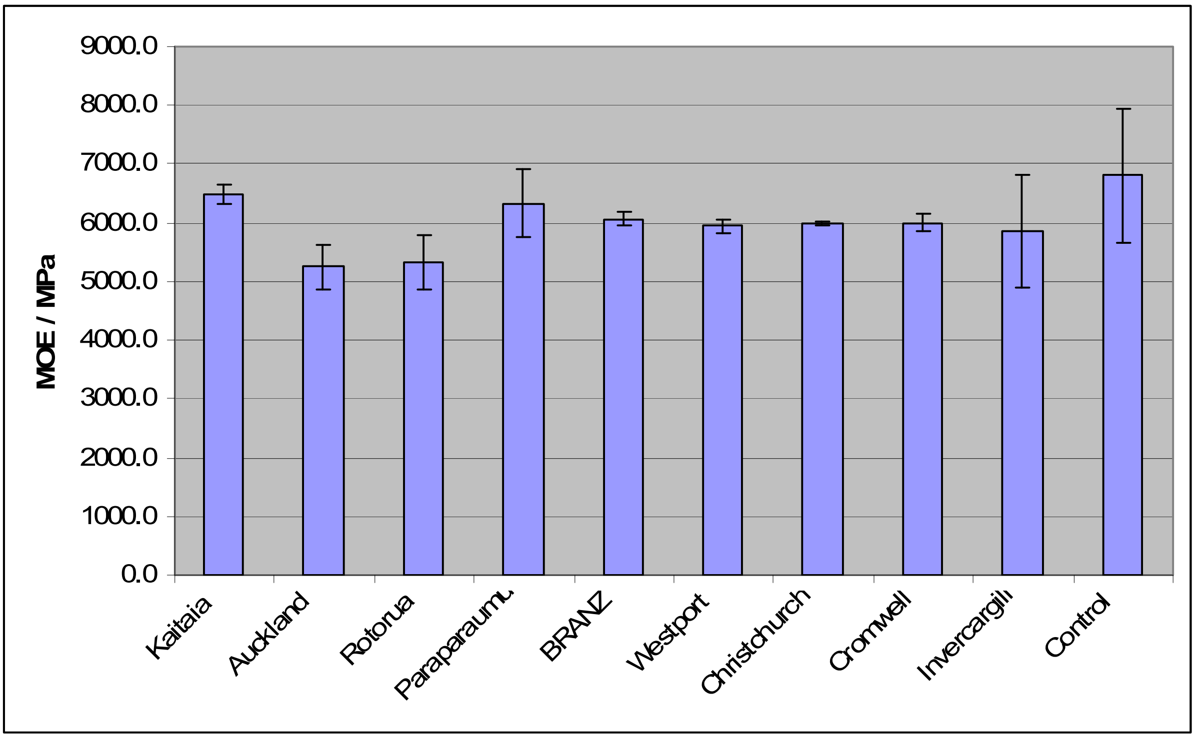


Figure 24. MOE results for hand-laminated epoxy resin-based samples after 12 months of exposure.

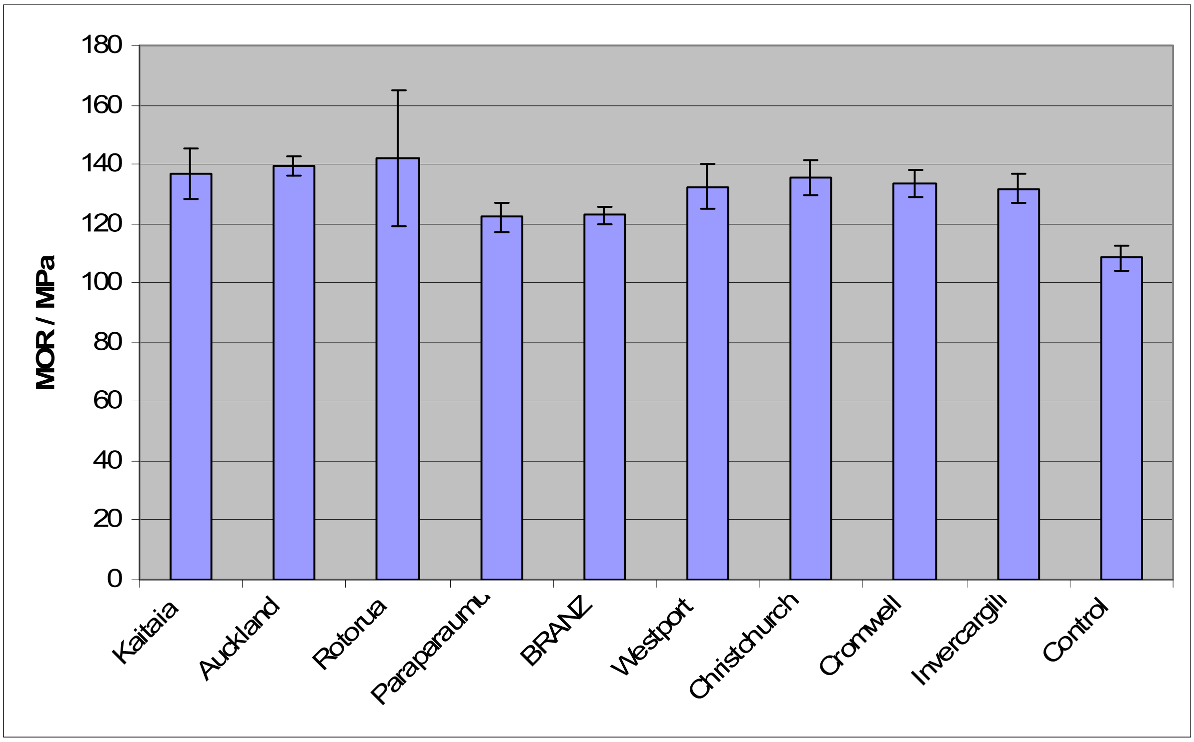


Figure 25. MOR results for hand-laminated epoxy resin-based samples after two years of exposure.

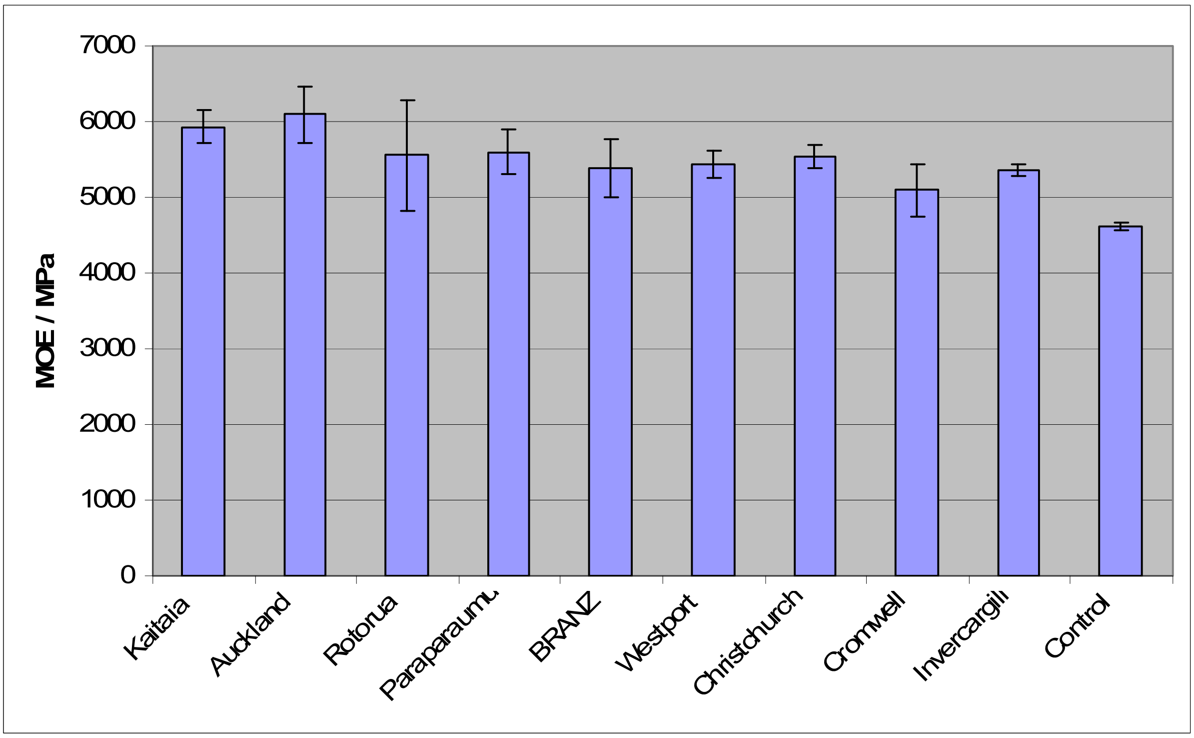


Figure 26. MOE results for hand-laminated epoxy resin-based samples after two years of exposure.

It is clear from the figures that the properties of the unexposed control samples are variable. The variability is believed mainly to be caused by sample thickness inconsistencies resulting from the manufacturing process. This variability means that no clear trends with exposure location can be extracted from the data. However, it is still possible to surmise that no significant loss of mechanical properties has occurred for the hand-laminated epoxy samples at any of the exposure locations after two years of exposure.

The flexural properties of the hand-laminated polyester resin sheet from each exposure site after two years of exposure and an unexposed control sample are tabulated in Table 4 and shown in Figure 27 and Figure 28.

Table 4. Flexural properties for hand-laminated epoxy resin-based samples after two years of exposure

Area	MOR (MPa)	MOR (S.D)	MOE (MPa)	MOE (S.D)
Kaitaia	112	12.7	4770	587
Auckland	132	12.8	5330	445
Rotorua	139	8.2	6070	250
Paraparaumu	134	7.9	5930	336
BRANZ	120	11.5	4770	320
Westport	130	21.1	5260	802
Christchurch	127	17.8	5250	465
Cromwell	121	10.4	4930	241
Invercargill	140	12.0	5250	639
Control	148	14.4	5840	413

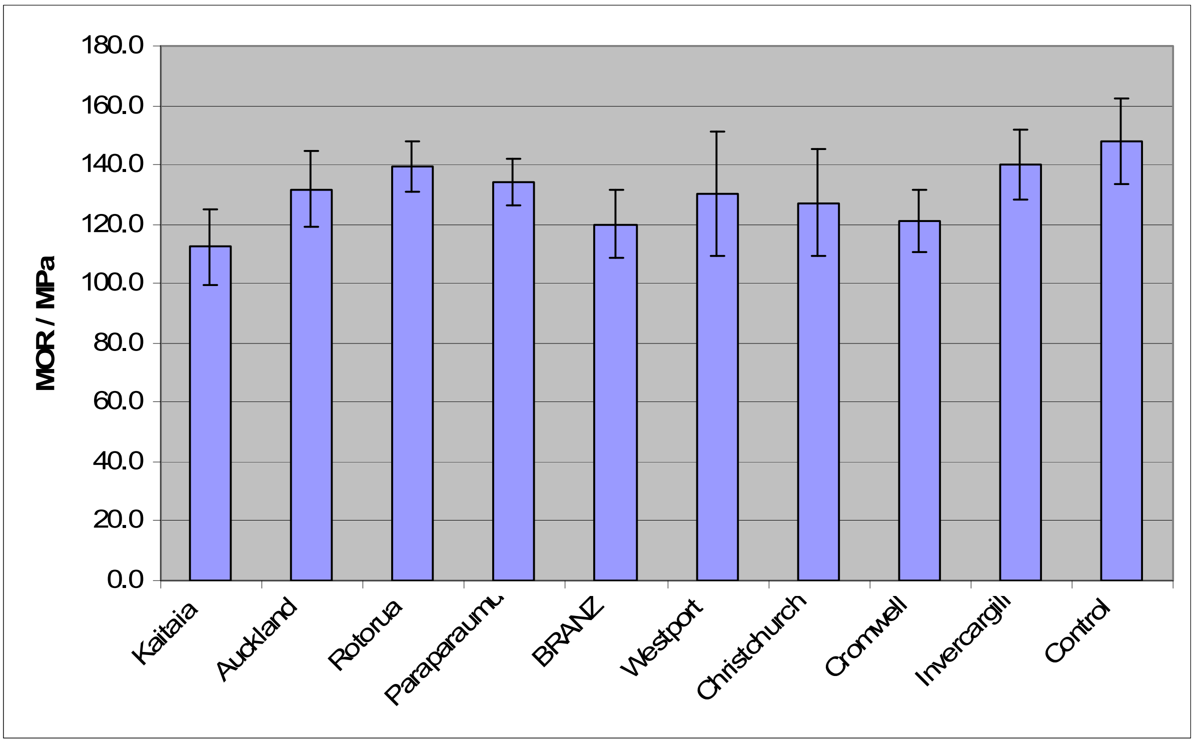


Figure 27. MOR results for hand-laminated polyester-based samples after two years of exposure.

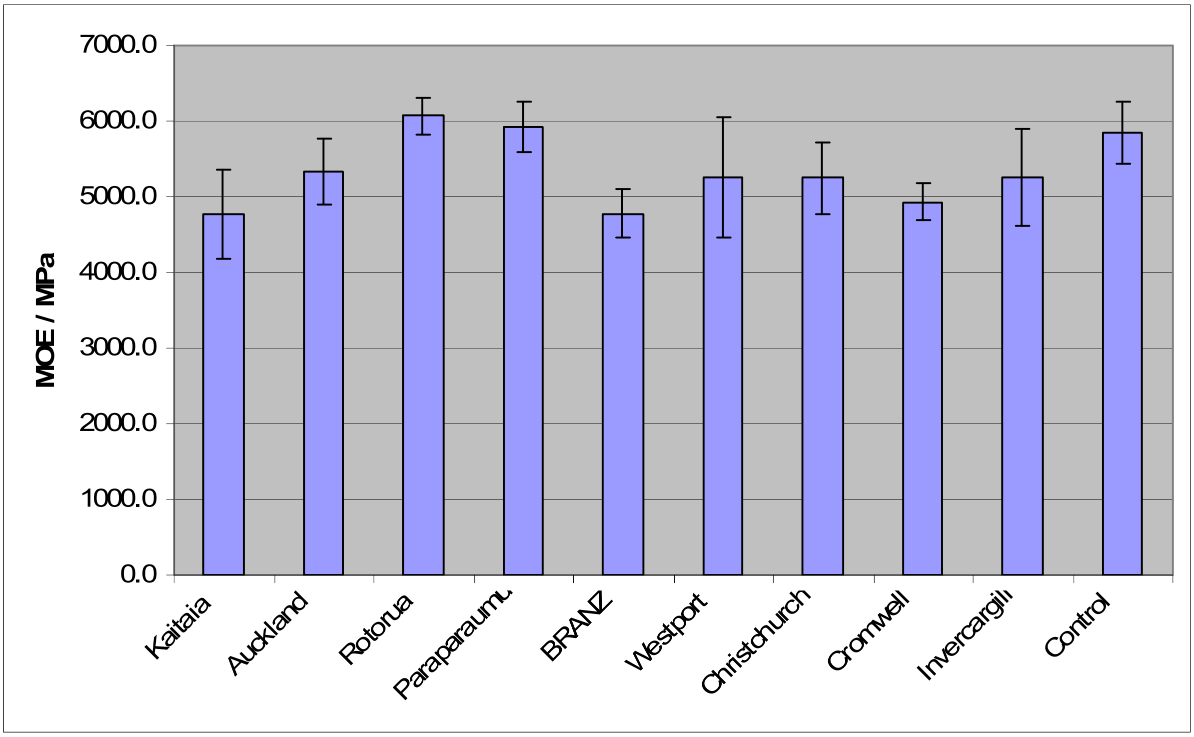


Figure 28. MOE results for hand-laminated polyester-based samples after two years of exposure.

It is clear that the properties of the exposed polyester samples are also variable. Once again, the variability is believed mainly to be a result of sample thickness inconsistencies.

It is not possible to draw any firm conclusions from the data collected from the exposed samples to date. This is because the variability of the sheet materials is significant. This variability is believed to be a result of the hand-lamination manufacturing process, which does not necessarily give consistent control of sheet thickness.

It is recommended that the exposure sites should be maintained, that sample collection should be continued, most preferably on a semi-annual basis, and that monitoring of the flexural properties of the exposed samples should be continued in the expectation that clear trends will become apparent as sample degradation becomes more pronounced.

4.3 Cone calorimetry

A sample undergoing cone calorimeter testing is shown in Figure 29. The radiant heat source can be seen above the flaming sample. The sample itself sits upon the load cell so that sample mass can be recorded throughout the course of the test.

Figure 29. Cone calorimeter testing.

A typical curve of the heat released as the combustion of the composite samples progresses is shown in Figure 30. The plot contains two pairs of curves measured for each surface of the composite box section. The labels indicate the stages of the combustion process.

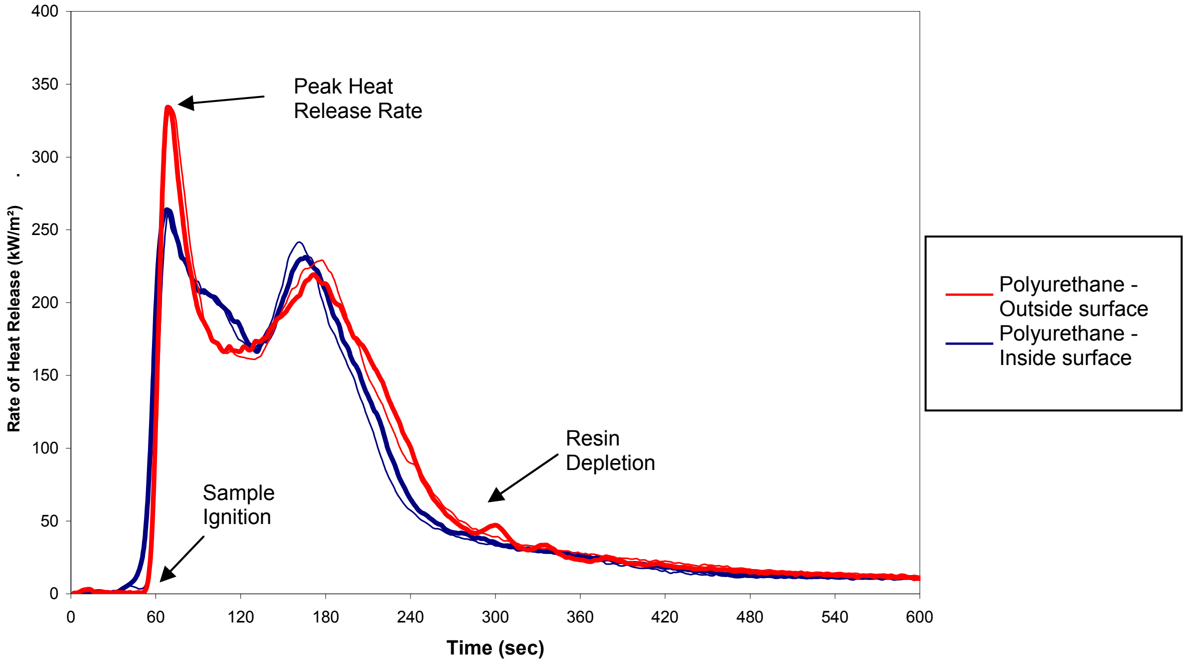


Figure 30. Rate of heat release against time for the pultruded polyurethane samples at an irradiance of 70 kW/m².

The cone calorimeter results are summarised in Table 5 to Table 8. The time to sustained burning was recorded by the operator for each sample tested and was taken to be the time when the sample would continue burning by itself and the ignitor could be withdrawn. The peak heat release rate records the maximum amount of energy released by the combustion of the sample, while the total heat release records the aggregate amount of heat released from the sample during the whole test. The specific extinction area is a measure of the smoke released during the combustion of the sample. The heat of combustion measures the energy released as a function of mass lost from the sample. Clearly this result applies to the matrix material i.e. the resin and any additives it contains. Each result quoted in the tables is an average of two experiments on two separate samples of sheet.

Table 5. Cone calorimeter results for hand-laminated epoxy resin-based samples

Sample	Surface Tested	Sample Thickness / mm	Irradiance Level / kW/m²	Time to Sustained Burning / s	Peak heat Release Rate / kW/m²	Total Heat Release / MJ/m²	Specific Extinction Area / m²/kg	Heat of Combustion / MJ / kg
Hand-laminated Epoxy with Gel Coat	Gel Coat surface	5.7	30	69	539	140	952	25.2
Hand-laminated Epoxy with Gel Coat	Back surface	5.2	30	57	484	116	941	25.0
Hand-laminated Epoxy with Gel Coat	Gel Coat surface	5.8	50	32	602	130	1008	24.4
Hand-laminated Epoxy with Gel Coat	Back surface	5.4	50	22	542	132	1003	24.2
Hand-laminated Epoxy with Gel Coat	Gel Coat surface	5.1	70	19	740	122	1045	25.1
Hand-laminated Epoxy with Gel Coat	Back surface	5.4	70	13	765	131	1006	24.5
Cured Hand-laminated Epoxy with Gel Coat	Gel Coat surface	4.9	50	34	518	112	921	23.9
Cured Hand-laminated Epoxy with Gel Coat	Back surface	4.8	50	24	532	123	910	24.1

Table 6. Cone calorimeter results for pultruded polyurethane-based samples

Sample	Surface Tested	Sample Thickness / mm	Irradiance Level / kW/m²	Time to Sustained Burning / s	Peak Heat Release Rate / kW/m²	Total Heat Release / MJ/m²	Specific Extinction Area / m²/kg	Heat of Combustion / MJ / kg
Pultruded Polyurethane	Outside surface	3.4	30	195	227	27.1	735	17.4
Pultruded Polyurethane	Inside surface	3.4	30	193	189	30.9	700	18.2
Pultruded Polyurethane	Outside surface	3.3	50	83	291	37.3	798	18.9
Pultruded Polyurethane	Inside surface	3.3	50	75	271	39.5	820	19.7
Pultruded Polyurethane	Outside surface	3.4	70	51	330	41.1	788	18.2
Pultruded Polyurethane	Inside surface	3.4	70	48	310	42.8	837	18.4
Pultruded Polyurethane – repeat	Outside surface	3.4	70	50	333	37.9	772	17.4
Pultruded Polyurethane - repeat	Inside surface	3.5	70	49	264	35.1	828	18.5

Table 7. Cone calorimeter results for hand-laminated polyester-based samples

Sample	Surface Tested	Sample Thickness / mm	Irradiance Level / kW/m²	Time to Sustained Burning / s	Peak Heat Release Rate / kW/m²	Total Heat Release / MJ/m²	Specific Extinction Area / m²/kg	Heat of Combustion / MJ / kg
Hand- laminated Polyester with Gel Coat	Gel Coat surface	3.2	50	33	426	63	963	21.5
Hand-laminated Polyester with Gel Coat	Back surface	3.1	50	27	454	58	975	21.3

Table 8. Cone calorimeter results for pultruded polyester-based samples

Sample	Surface Tested	Sample Thickness / mm	Irradiance Level / kW/m²	Time to Sustained Burning / s	Peak Heat Release Rate / kW/m²	Total Heat Release / MJ/m²	Specific Extinction Area / m²/kg	Heat of Combustion / MJ / kg
Pultruded Polyester	Outside surface	3.3	50	59	415	44	568	18.6
Pultruded Polyester	Inside surface	3.4	50	64	364	47	666	19.0

4.3.1 Effect of matrix resin

As expected, it was found that the epoxy resin-based material gave a markedly higher heat of combustion than either the polyester or polyurethane materials. This is demonstrated in Figure 31.

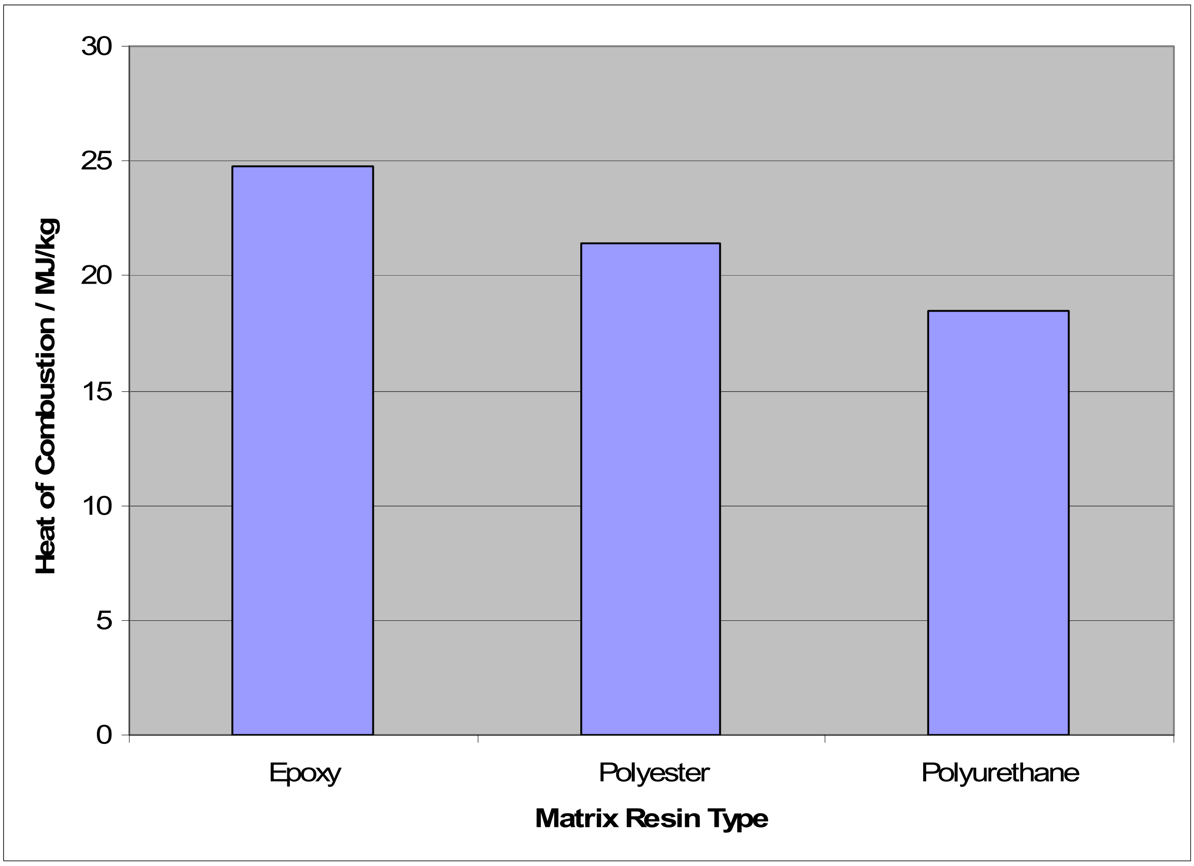


Figure 31. FRP composite heat of combustion as a function of matrix resin type.

The heat of combustion of polymeric materials is known to be a function of the chemical composition of the polymer chains (Walters 2001). The results obtained are in good agreement with those found by other workers (Usman 1998, Scudamore 1994, Nazaré 2006). The results presented in Figure 31 are averages from results of 16, 8 and 16 separate tests for the epoxy, polyester and polyurethane samples respectively.

It is clear that the choice of matrix resin can exert a considerable influence over the energy entrained in a section of FRP composite. This energy can vary by as much as 30% based upon the result reported here and in other studies (Gibson 1995).

These trends are clearly important in the selection of matrix resin for FRP composite materials in the construction industry. The agreement of the results obtained for locally sourced samples with results from the international literature is reassuring. However, the results reported here are for a very limited number of samples and should be regarded as merely indicative. A more complete and systematic examination of results for locally sourced materials should be incorporated into any future work in the area.

4.3.2 Effect of sample surface structure

Some interesting trends are evident in the data collected for the FRP composite samples and these are explored below.

The effect of irradiance level and the surface tested are presented in Figure 32 for the hand-laminated epoxy resin-based sheet.

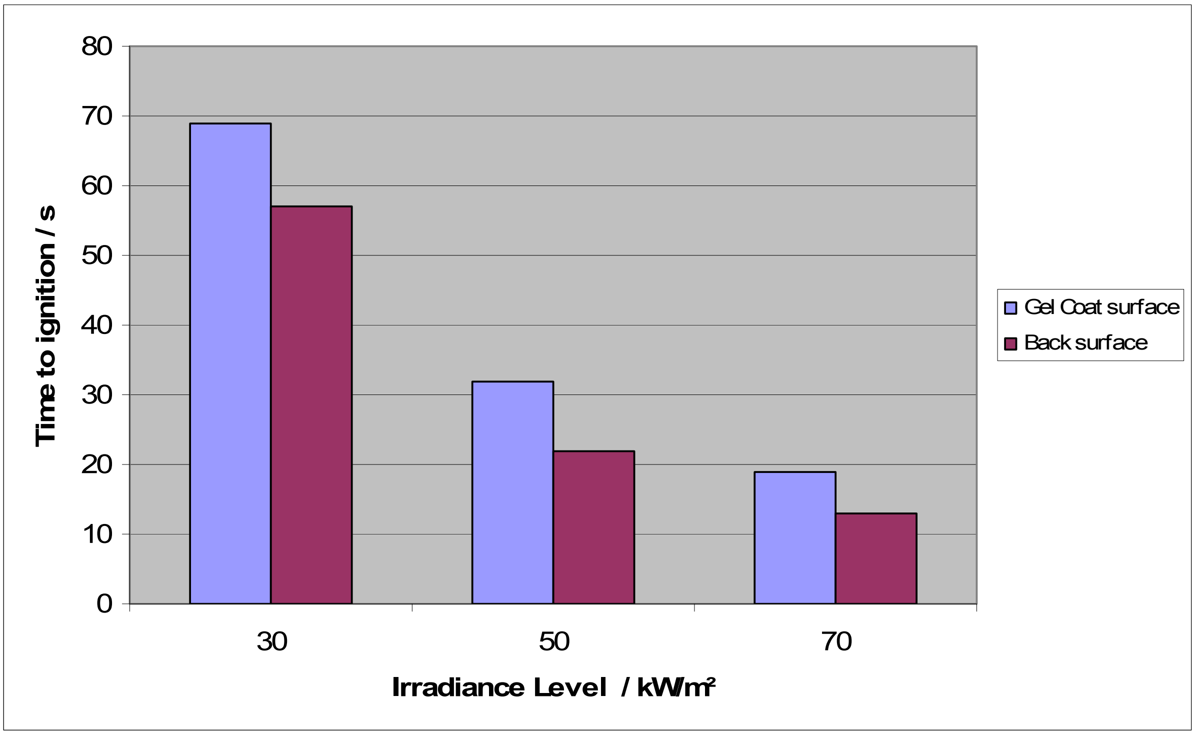


Figure 32. Effect of cone calorimeter heat flux and sample surface tested for hand-laminated epoxy resin-based samples.

As noted by previous workers (Gibson 1995, Scudamore 1994) the time to ignition of the specimens reduces as the applied radiant heat flux is increased. However, the orientation of the sample also consistently exerts an influence over the time taken for the sample to ignite. From the data it appears that the more highly filled and pigmented gel coat resists ignition slightly better than the resin on the back of the samples. Similar effects have been reported previously for polyester-based materials (Scudamore 1994). This may be due to higher filler level in the gel coat dissipating heat more effectively, a reduction of available fuel in the gel coat due to filler content, or retardation of transport of volatiles to the combustion zone

The effect of irradiance level and the surface of the sample tested are presented in Figure 33 for samples cut from pultruded polyurethane-based box section.

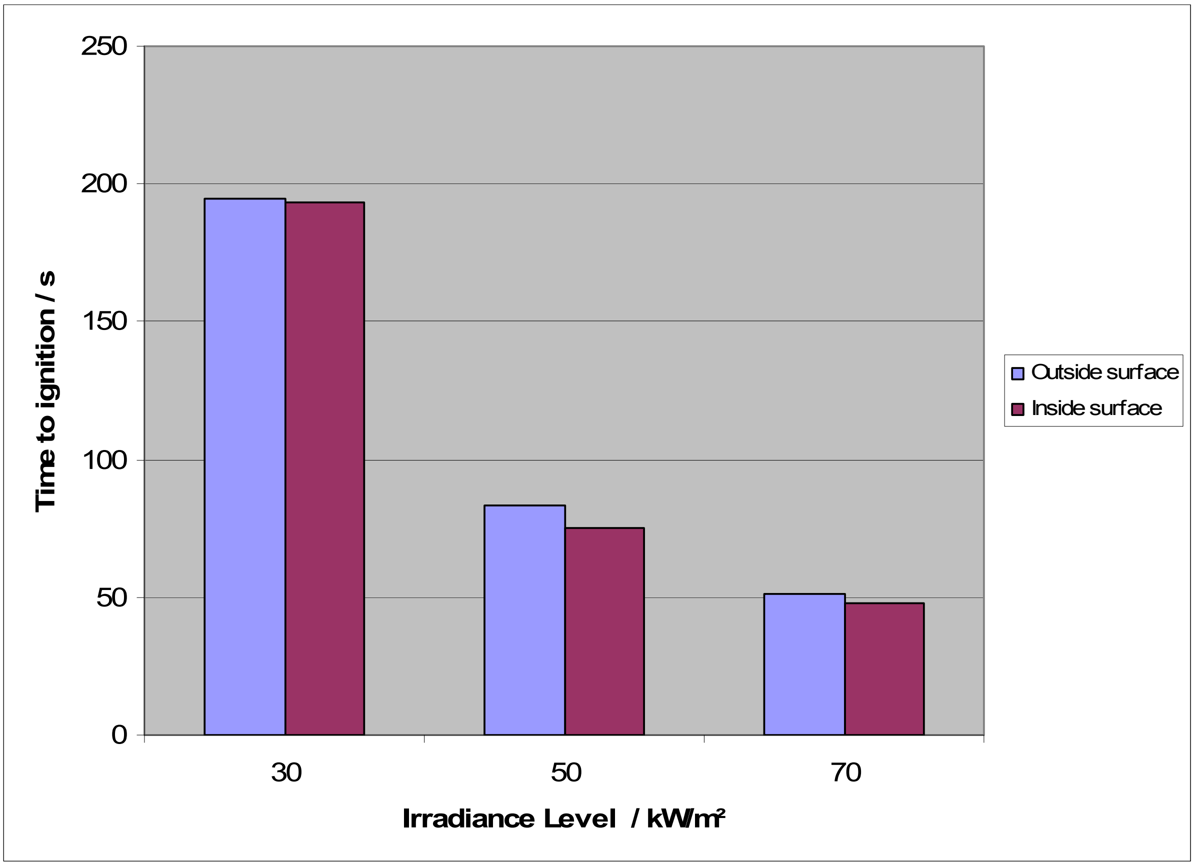


Figure 33. Effect of cone calorimeter heat flux and sample orientation for pultruded polyurethane-based samples.

As with the hand-laminated epoxy samples the time to ignition of the specimens reduces as the applied radiant heat flux is increased. Once again, the surface of the sample tested also consistently exerts an influence over the time taken for the sample to ignite. From the data it appears that the outer surface of the pultruded box section, containing a scrim, resists ignition slightly better than the resin on the inside of the box section. This is likely to be a result of the woven structure of the scrim layer retarding transport of volatiles to the combustion zone. This conclusion is supported by the observation of bubbling of molten resin material through the holes in the scrim layer during testing.

However, once ignited the “finished” faces of the samples were found to release more heat than the other face. This is shown in Figure 34 for the hand-laminated epoxy samples.

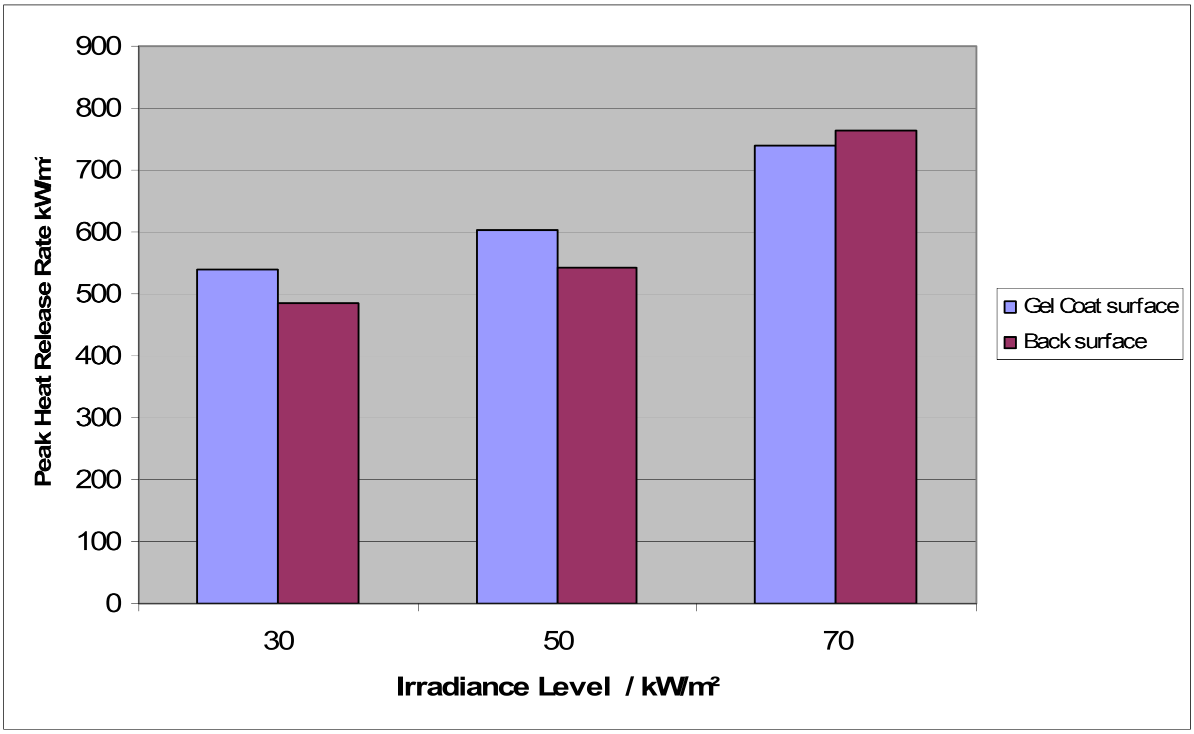


Figure 34. Effect of cone calorimeter heat flux and the sample surface tested for hand-laminated epoxy resin-based samples.

The peak heat release rates results obtained for these samples are considerably higher than those reported by other workers (Mouritz 2007). However, it is likely that this is due to the tests reported being for different sample thicknesses or reinforcement contents (Scudamore 1994, Gibson 1995).

The data presented above show higher peak heat releases, at irradiance levels of 30 and 50 kW/m², from the gel coat surface of the samples than for the back surface. The results obtained at an irradiance of 70 kW/m² are very similar for each surface. It is believed that this is because the samples tested on the gel coat surface were thinner.

This interpretation is supported by the results found for the pultruded polyurethane samples shown in Figure 35.

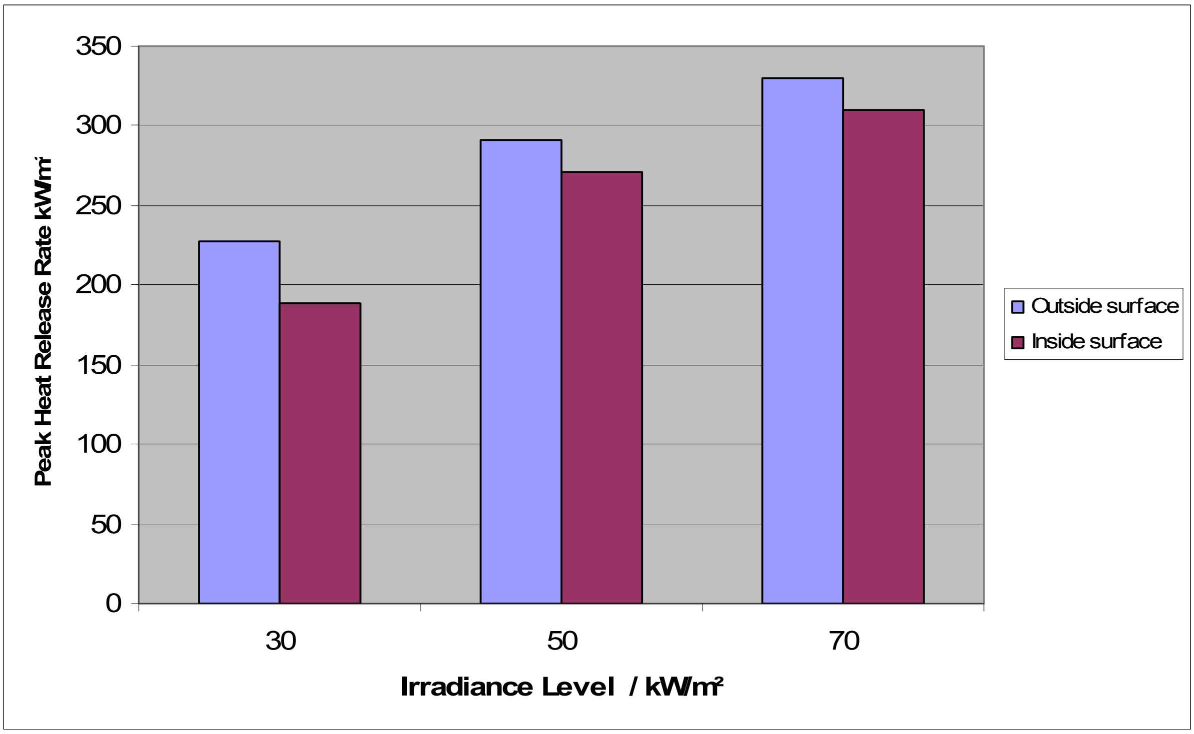


Figure 35. Effect of cone calorimeter heat flux and the sample surface tested for pultruded polyurethane-based samples.

As noted for the epoxy resin-based sample above, the peak heat release rates obtained are high compared with those reported elsewhere (Mouritz 2007). The other authors do not give any details on sample thickness or reinforcement content. It is clear from Figure 35 that the outside scrim-containing surface of the pultruded polyurethane box section consistently gives higher peak heat release rates than the inside surface of the box section. It is believed that this is a result of the outer surface having a higher resin concentration than the inner face of the box section.

When these results are considered in combination with the mechanical property test results for the box section profiles, the efficacy of using a scrim layer on the outside surface appears to be worthy of further consideration. The scrim is employed to give a resin-rich and aesthetically pleasing surface. However, the relatively high percentage of resin at the surface not only degrades the flexural strength of the samples when the outside surface is placed in tension (see Section 4.2.1), but also appears to act as a fuel reservoir under fire conditions. An opportunity would seem to exist to avoid both these negative aspects by not using a scrim (glass surface tissue) in applications where performance outweighs aesthetic considerations e.g. in framing applications. Although this is likely to result in a decrease in the time to ignition of the samples (see previous section) the advantages seem likely to outweigh this.

These potential enhancements to performance are believed worthy of further examination as part of any future work programme.

4.3.3 Effect of curing

The epoxy hand-laminated samples tested by cone calorimetry had been stored for approximately two years at 23°C : 50% RH prior to testing. The epoxy resin, from which the samples were produced, would have been incompletely cured when the sheets samples left the factory, but the curing of the samples would have proceeded while in storage. The post-curing of the samples is designed to drive the cure of the resin to completion and hence give an indication of the completeness of the cure in the remainder of the samples tested.

The post-curing was performed by heating a selection of samples at 90°C for 24 h. These conditions were selected to complete the cure process in a reasonable time and were based upon industry standard practices so as to not overheat the samples and trigger degradation.

The post-curing of the hand-laminated epoxy resin-based samples resulted in a reduction of peak heat release rate. The results obtained are presented in Figure 36.

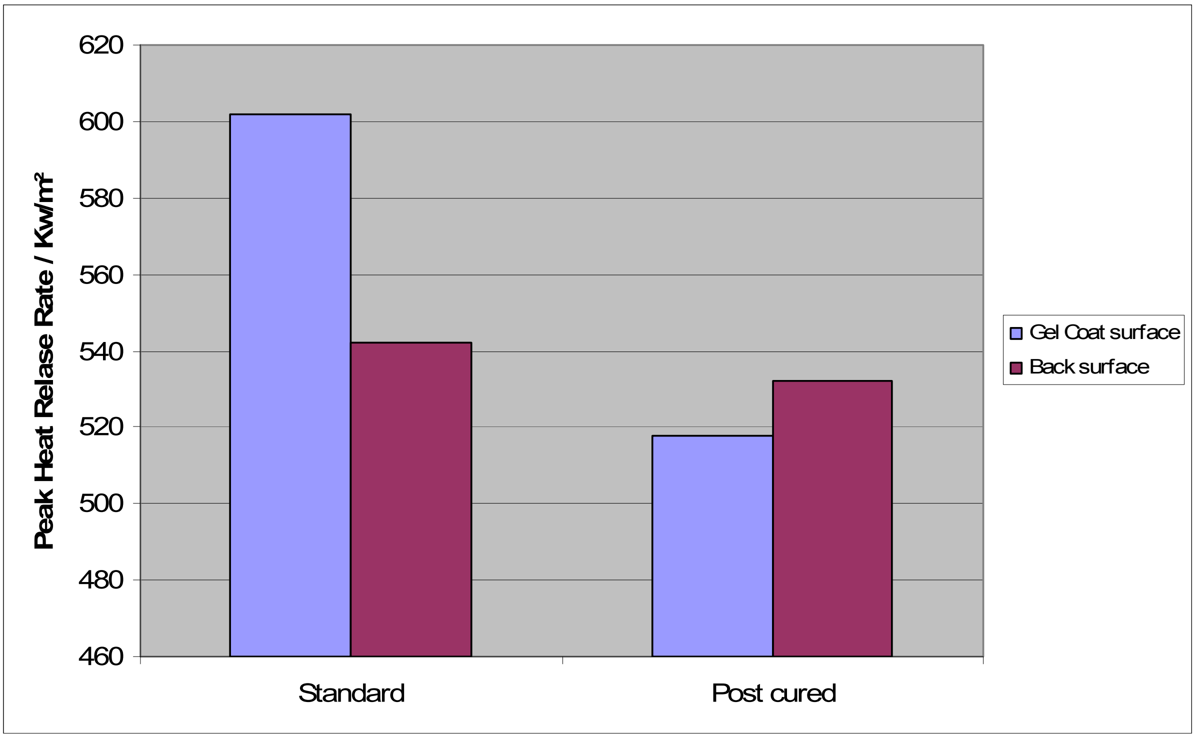


Figure 36. Effect of post-curing of hand-laminated epoxy resin-based samples.

A dramatic effect was observed for the peak heat release rate for the samples when tested with the gel coat surface uppermost. The peak heat release was reduced by almost 15%. These results are the average of two specimens for each test condition. It is believed that the gel coat has a relatively low percentage cure prior to heat treatment. This is expected to be a result of the fillers used to pigment the layer. There is a suggestion that this effect may have been observed by other workers (Hergenrother 2005).

As discussed previously for the scrim on the outer surface of the pultruded samples, the presence of the gel coat (to deliver aesthetic benefits) may be degrading the performance of the materials. These effects should be explored in more detail as part of any future work programme.

5. CONCLUSIONS

5.1 Literature review

Globally the construction industry is in general dependent on codes, standards and regulations when making material choices. In most territories, and in New Zealand, FRP composites are not referenced by these documents. This stands in the way of their widespread use.

This literature review has highlighted that the use of polymer composite reinforcing bars has been researched in great depth. A number of national guidelines for material selection and structural design exist. The development of standards and codes for this field of FRP composite application are also progressing in a number of countries.

Extensive use of polymer composites for remediation of existing concrete, brick and steel structures was also found. Within New Zealand there is a mature market for the remediation of concrete structures within commercial buildings, and a wealth of technical expertise to service the existing market resides with the material suppliers.

There is a global recognition of the need to develop standards for FRP composites. Australia has begun progress along the path of developing an industry code of practice for FRP composites. This is expected to result in the definition of a system of grading and to certify composite constituents. However, progress appears to have stalled for reasons that are not fully understood.

These conclusions have been identified by a number of other authors. It is hoped that the findings of these studies will be heeded by those researching in the FRP composites area, although this does not appear to always be the case (see Section 2.2.1.1. of this report).

5.2 Experimental work

The experimental programme completed as part of this project has confirmed the susceptibility of locally produced FRP composites to some surface degradation in the New Zealand environment.

The degree to which the surface of the hand-laid epoxy resin-based materials degraded is reasonably unexpected, given that the samples have only been exposed for two years. Epoxy is generally regarded as durable to outdoor exposure, at least in the medium term. However, the samples were deliberated exposed in a way that would not be replicated in-service and the loss of resin from the surface of the samples has not, as yet, resulted in any measurable reduction of mechanical properties. These measurements also highlighted the potential for insufficient consistency of FRP composite materials. The hand-laminated samples, used as part of this study, were of inconsistent thickness. This made it difficult to draw any meaningful conclusions since the variation of the mechanical properties of the unexposed control samples did not give a consistent baseline to compare with. This variability is believed to be related to the hand-lamination manufacturing process used to produce the sheets. This manufacturing technique depends critically on the operator to ensure consistent product thickness, and it is clear that the level of control was insufficient when the samples used for this study were produced.

The fire testing found the expected trends of entrained energy tracking with matrix resin type. Effects of surface structure on ignition characteristics were also in agreement with those found by other workers. The results highlight the importance of the choice of composition on fire performance. This performance needs to be balanced with durability and cost considerations in the choice of FRP composite components.

Although the experimental work presented here has found the expected trends, it represents only a very initial look at the performance of FRP composite materials in the New Zealand environment. Some interesting observations concerning the effects of surface finish on material performance have emerged. However, to be confident of the reliability of the preliminary conclusions drawn in this report further testing work will be required.

6. FUTURE WORK

In order to either validate or reduce industry scepticism a diagnostic durability verification methodology is required for the determination of the functional lifetime, in the New Zealand environment, for FRP composite materials for use as building components. Initially, cooperation with the construction industry would be required in order to quantify the perceived issues and to identify research goals.

Development of an improved understanding of durability issues and recommended solutions for the problems involving FRP composites would also feed into code compliance documents.

Work should also incorporate evaluation of FRP composite materials when exposed across New Zealand over multi-year periods.

Ideally, any test methodology would have the capacity to determine property degradation rates as a function of composition and application over short exposure periods. It should also be capable of considering environmental conditions in a flexible manner, which would include both current architectural design and future best practice for optimum durability performance. These goals could be achieved through the development of verification techniques that varied as a function of structural environment.

If warranted, the conclusions of the work would also lead to a development or revision of standards and, with the support of the FRP composite producers, an increase in creative solutions available within the market place.

Any future programme of work in this area should not only examine exiting FRP composite technologies, but should also encompass the increasing range of composite systems that are not derived from fossil fuels. These include recycled resins, bio-polymer resins, and natural fibre reinforcements, such as flax.

7. REFERENCES

ACI. 1996. *440R-96: State-of-the-art Report on Fiber Reinforced Plastic (FRP) Reinforcement for Concrete Structures*. ACI, Farmington Hills, USA.

ACI. 2001. *440.1R-01: Guide for the Design and Construction of Concrete Reinforced with FRP Bars.* ACI, Farmington Hills, USA.

ACI. 2002. *440R.2R-02: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*. ACI, Farmington Hills, USA.

ACI. 2003. *440.1R-03: Guide for the Design and Construction of Concrete Reinforced with FRP Bars*. ACI, Farmington Hills, USA.

ACI. 2004. *Guide to Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures*. ACI, Farmington Hills, USA.

ACI. 2006. *440.1R-06: Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars*. ACI, Farmington Hills, USA.

ACI. 2007a. *440.CR: Specifications for Carbon and Glass Fiber Reinforced Polymer (FRP) Bars for Bonded Concrete Reinforcement* (http://aci-int.org/committees/CommitteeHome.asp?Committee_Code=0000440-00 accessed on 27 March 2007).

ACI. 2007b. *400.DR: Durability of Fiber Reinforced Polymer (FRP) Composites used with Concrete Reinforcement for Concrete Structures* (http://aci-int.org/committees/CommitteeHome.asp?Committee_Code=0000440-00 accessed on 27 March 2007).

ACI. 2007c. *440.MR: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Unreinforced Masonry Structures* (http://aci-int.org/committees/CommitteeHome.asp?Committee_Code=0000440-00 accessed on 27 March 2007).

American Society for Testing and Materials. 2003. *D790-03: Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.* ASTM, West Conshohocken, USA

ASCE. 1984. *Structural Plastics Design Manual (ASCE Manual and Reports on Engineering Practice No. 63).* ASCE, Reston, USA.

ASCE. 1985. *Structural Plastics Selection Manual (ASCE Manual and Reports on Engineering Practice No. 66).* ASCE, Reston, USA.

Ayers SR and Van Erp GM. 2004. 'A Code of Practice for the Structural Design of Fibre Composites'. *Structures & Buildings* 157(SB1): 3–8.

Bader MG. 2000. 'Polymer Composites in 2000: Structure, Performance, Cost and Compromise'. *Journal of Microscopy* 201(2): 110–121.

British Standards Institution. BS 5400:4:1990 *Steel, concrete and composite bridges. Code of practice for design of concrete bridges.* BSI, London, UK.

British Standards Institution. BS 8110:1:1997 *Structural use of concrete. Code of practice for design and construction*. BSI, London, UK.

British Standards Institution. BS 8110:2:1985 *Structural use of concrete. Code of practice for special circumstances*. BSI, London, UK.

CERF. 2001. *Gap Analysis for Durability of Fiber Reinforced Polymer Composites in Civil Engineering*. ASCE, Reston, USA.

Composites Association of New Zealand. 1989. *Fibre Reinforced Plastic Design Manual*. CANZ, Dunedin, New Zealand.

fib Task Group 9.3. *FRP Reinforcement for Concrete Structures*. (www.labomagnel.ugent.be/fibTG9.3/index.html accessed on 22 March 2006).

fib. 2001. Bulletin 14*: "*Externally bonded FRP reinforcement for RC structures – Technical report on the design and use of externally bonded fibre reinforced polymer reinforcement for reinforced concrete structures*".*

fib. 2006. Bulletin 35: "Retrofitting of concrete structures by externally bonded continuous composite reinforcement for concrete structures*".*

Gibson AG and Hume J. 1995. 'Fire Performance of Composite Panels for Large Marine Structures'. *Plastics, Rubber and Composites Processing and Applications* 23: 175–183.

Hergenrother Paul M and Thompson Craig M. 2005. *Flammability of Epoxy Resins Containing Phosphorus: Federal Aviation Authority Report No. DOT/FAA/AR-TN05/44.* Federal Aviation Authority*,* Washington, USA.

ICC. AC125. *Acceptance Criteria for Concrete and Reinforced Masonry Strengthening using Fiber Reinforced Composite Systems*. ICC Evaluation Services Inc, Whittier, USA.

ICC. AC178. *Acceptance Criteria for Inspection and Verification of Concrete and Reinforced Masonry Strengthening Using Fiber-reinforced Polymer (FRP) Composite Systems.* ICC Evaluation Services Inc, Whittier, USA.

ISE. 1999. *Interim Guidance on the Design of Reinforced Concrete Structures Using Fibre Composite Reinforcement*. ISE, London, UK.

Karbhari VM and Chin JW et al. 2003. 'Durability Gap Analysis for Fiber-Reinforced Polymer Composites in Civil Engineering'. *Journal of Composites for Construction* 8(3): 238–247.

Mottram JT. *Literature Database on R&D with Pultruded Fibre Reinforced Polymers* (www2.warwick.ac.uk/fac/sci/eng/staff/jtm/pfrp_latest.pdf accessed on 6 November 2006, pdf file updated every month).

Mouritz AP and Gibson AG. 2007. 'Fire Reaction Properties of Composites'. In *Fire Properties of Polymer Composites* (Springer, The Netherlands).

Nazaré S and Kandola BK et al. 2006. 'Flame-retardant Unsaturated Polyester Resin Incorporating Nanoclays'. *Polymers for Advanced Technologies* 17(4): 294–303.

NCN. 2006. *Technology Roadmap for Composites in the Construction Industry*. NCN, Cambridge, UK.

NGCC. 2006a. *Composites IQ: Overview of Composites in Construction*. NGCC, Chesterfield, UK.

NGCC. 2006b. *NGCC R&D Workshop Report: Meeting Industry Needs Through Research (31 May 2006).* NGCC, Chesterfield, UK.

NIWA. 2007a. *Mean Daily Global Radiation.* NIWA, Omakau, New Zealand.

NIWA. 2007b. *UV Atlas Version 2.1*. NIWA, Omakau, New Zealand.

NIWA. 2007c. *ClimateExplorer*. NIWA, Wellington, New Zealand.

Scudamore M. 1994. 'Fire Performance Studies on Glass-reinforced Plastic Laminates'. *Fire and Materials* 18: 313–325.

Standards Australia. AS2376.2:1981. *Plastics building sheets – Glass fibre reinforced polyester*. Standards Australia, Sydney, Australia.

Standards New Zealand. AS/NZS 3837:1998 *Method of test for heat and smoke release rates for materials and products using an oxygen consumption calorimeter*. SNZ, Wellington, New Zealand.

Usman S and Ness J et al. 1998. *Fire Safety of Composites in the US Navy*. 43rd International SAMPE Symposium, 31 May 1998, Anaheim, CA, USA.

Van Erp GM. 2007. Personal communication.

Walters, Richard N. 2001. *Molar Group Contributions to the Heat of Combustion: Federal Aviation Authority Report No. DOT/FAA/AR-TN01/75*. Federal Aviation Authority*,* Washington, USA.