University of Southern Queensland Faculty of Engineering and Surveying

BEHAVIOUR OF POLYMER CONCRETE FOR INFILLING FIBRE COMPOSITE TUBES

A dissertation submitted by

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In the fulfillment of the requirements of

Courses ENG4111 and ENG4112 Research Project

towards the degree of

Bachelor of Engineering (Civil)

Submitted: October, 2011

ABSTRACT

Timber piles often require rehabilitation and a more recent method of rehabilitation includes the use of a Fibre Reinforced Polymer (FRP) encasement which essentially confines the deteriorated or damaged pile. A suitable filler material is required to infill the area between the FRP and timber pile and is required to transfer all vertical and lateral loads through axial compression and bending.

This paper presents the mechanical properties and behaviours of both epoxy and vinylester polymer concrete as a filler material. Different proportions of polymer resin and fly ash were mixed with 57% sand by volume and tested under an extensive experimental testing program. At current there is no literature evident of a polymer concrete mix design of polymer resin, fly ash and sand. The results from testing were analysed and then used to determine a trend of mechanical properties and behaviours of the two concrete types.

Compression tests were undertaken at 7, 21 and 28 days to determine the compressive strength gain over a period of time. The compression tests at 7 days involved a stress-strain analysis using the platen to platen method. Split tensile and three point bending flexural tests were undertaken at 7 days to determine split tensile strength and flexural modulus respectively.

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ACKNOWLEDGEMENTS

This research was carried out under the principal supervision of Professor Thiru Aravinthan and Dr. Weena Lokuge. I want to thank and honour them very much for their support, time, understanding, expertise and most of all the opportunity to work under their guidance.

I want to thank and honour God for his grace and opportunity to undertake this journey which would not have happened without him.

I want to thank and honour most of all, my beautiful and gorgeous wife Kate who has been by my side throughout this whole journey and been such a blessing to my life. She has loved and supported me more than I could ever have imagined and I could not have completed this journey without her.

I want to thank and honour my two precious children for their love and understanding throughout this journey. It wouldn't have been as enjoyable without them in my life.

I want to thank and honour anyone else who has been a part of this journey.

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NOMENCLATURE

 A_{av} = average cross-sectional area of concrete cylinder

b = width of specimen [m]

d = depth of specimen [m]

E = elastic modulus, modulus of elasticity or Young's modulus

E_f = flexural modulus

f'c = compressive strength of a concrete cylinder

f'c.max = maximum compressive strength of a concrete cylinder

f_{ct.sp} = tensile strength obtained from a cylinder splitting test

L = span length[m]

 L_o = original length

 ΔL = change in length

m = a gradient on a curve

n_c = number of cylinder specimens

n_f = number of flexural specimens

 N_{max} = maximum axial load from compression test

 $P_{lat.max}$ = maximum lateral load acting on tensile cylinder specimen

V = a volume

V_c = volume of cylinder specimen

V_f = volume of flexural specimen

V_m = volume ratio in mix design

W_m = weight of a material of interest

W_t = total weight of batch [kg]

W_% = material percentage weight of concrete batch [kg]

ε = strain

- $\rho_m = \text{density of a material of interest}$
- ρ_{ec} = density of epoxy polymer concrete
- ρ_{vc} = density of vinylester polymer concrete

1 INTRODUCTION

Timber piles are a common component of a structure subject to deterioration, particularly due to marine borers, fungal attack, termite attack, shrinkage, splitting, weathering and lateral impact loads causing structural damage (DMR, 2004). The purpose of a timber pile is to transfer all axial and lateral loads to its foundation through axial compression and bending and is thus a crucial component of a complete structure. Rehabilitation methods using traditional materials such as steel, concrete and timber have proved to be an effective solution in alleviating deteriorated and structurally damaged timber piles to some extent, however each attribute their own drawbacks.

A more recent method of rehabilitation which has been implemented in the construction industry, uses Fiber Reinforced Polymer (FRP) shell technology to confine the deteriorated or damaged timber pile, where the area between the FRP and timber pile is in-filled with a filler material (refer figure 1.1 - "grouting material"). The FRP shell technology has provided to be a very effective solution against environmental attack, however the filler material lacks structural strength (Lopez-Anido *et al*, 2005).



Figure 1.1 Typical design of FRP composite (Lopez-Anido et al, 2005)

This project aims to determine the behaviours and mechanical properties of filler materials such as epoxy and polymer concrete. This dissertation firstly presents a literature review and background information relating to polymer concrete and timber pile rehabilitation methods. Secondly, the experimental program undertaken for compressive, tensile and flexural testing as part of the project is outlined. The dissertation then goes on to define how to interpret the data to achieve the required mechanical properties of polymer concrete such as compressive strength, tensile strength, modulus of elasticity and flexural modulus. The results are then presented followed by a summary and discussion of the results. A conclusion then finalises the dissertation.

2 LITERATURE REVIEW / BACKGROUND

An extensive literature review has been undertaken to evaluate and gain knowledge of the research that has already been completed in relation to polymer based filling materials and timber pile rehabilitation methods and techniques. The review in particular, covers the classifications of concretepolymer composites, properties, behaviour and applications of polyester, vinylester and epoxy polymer concrete, chemistry of polymer types used in polymer concrete and timber pile rehabilitation methods.

2.1 CONCRETE-POLYMER COMPOSITES

Arnold (2003) describes that traditional concrete such as Portland cement concrete (cement concrete) typically consists of a composition of coarse and fine aggregates, water and Portland cement, where the purpose of the cement is to hydrate and bind the aggregates. Ohama (2011) explains that concrete-polymer composites are materials that are made by replacing part of or all the cement component of cement concrete with a polymer. Ohama (2011) then goes on to define that concrete-polymer composites are therefore classified into three types based on their production technique:

- Ø Polymer modified concrete
- Ø Polymer impregnated concrete
- Ø Polymer concrete

Contrary to the concrete-polymer composite classifications given by Ohama (2011), Blagga & Beaudoin (1985b) define that concrete-polymer composites are broken into two groups, namely polymer cement concrete and polymer impregnated concrete. Sirivivatnanon (2003) states that concrete-polymer composites are broken into three groups, namely polymer cement concrete, polymer impregnated concrete and polymer concrete.

Obviously, there is a lack of terminology for concrete-polymer composites, thus to set aside confusion, a set of terminology is to be adopted as such and as shown in figure 2.1 (Note that concrete mortar is the same as PPCC with the use of fine aggregates only) -:

- Ø Polymer cement concrete
- Ø Polymer impregnated concrete
- Ø Polymer concrete



Figure 2.1 Classification of concrete-polymer composites (Guneri, 2005)

2.1.1 POLYMER CEMENT CONCRETE

Blagga & Beaudoin (1985b) explain that polymer cement concrete is produced by replacing part of the cement component of a cement concrete with a polymer (often in a latex form). Sirivivatnanon (2003) states that there are two types of polymer cement concrete, which are defined by when the polymer is added to the concrete mix. The first involves the addition of a monomer system to the cement and aggregate components of a cement concrete before the initiation of the hydration process (i.e. addition of water to hydrate the cement and cure the concrete), and is commonly referred to as premix polymer cement concrete. Following hydration of the cement, the monomer system remains within the structure. The second type involves the addition of a dispersed polymer into the wet cement concrete (i.e. the hydration process has initiated) and is commonly referred to as polymermodified cement concrete. Polymer cement concrete displays a drying shrinkage which is generally lower than cement concrete, however, largely depends on the water-cement ratio, cement content, polymer content and curing conditions (Sirivivatnanon 2003).



Figure 2.2 Polymer cement concrete bridge deck overlay (Gomaco, 2011)

2.1.2 POLYMER IMPREGNATED CONCRETE

Miller (2005) desribes that one of the primary problems in cement concrete is the void content which potentially induces points of weakness and subsequently fracture propagation when the member subject to load. Blagga & Beaudoin (1985b) explain that polymer impregnated concrete is produced by impregnating a low viscous monomer into a pre-cast cement concrete, where the monomer which can either be applied by surface application or full immersion of the concrete (Sirivivatnanon 2003) polymerizes to form a network in the pores and voids of the member.

Mason (1981) and Blagga & Beaudoin (1985b) both mention that the impregnation process reduces the void percentage to almost nil, but also hugely improves the concretes tensile, compressive and impact strength. Mason (1981) also describes an improvement in the mechanical and durability properties of polymer concrete which are primarily due to the polymer filling the pores. They suggest that the interaction between the cement matrix in the cast concrete and the polymer matrix could possibly be responsible for superior strength and durability. Compared to cement concrete, polymer impregnated concrete has a notably improved resistance against freeze-thaw damage and chemical attack (Blagga & Beaudoin, 1985b). At higher temperatures, polymer impregnated concrete as described by Sirivivatnanon (2003) exhibits a higher resistance against creep than that for cement concrete, however possesses a decrease in flexural strength, flexural modulus and elastic modulus.



Figure 2.3 Polymer impregnated concrete specimens (NWES, 2006)

2.1.3 POLYMER CONCRETE

Polymer concrete, also known as synthetic resin concrete and plastic resin concrete is described by Blagga & Beaudoin (1985) as a composite material of fine and coarse aggregate mineral filler and polymer binder, containing no cement. Due to its high strength properties, rapid setting times, better mechanical properties, lower water absorption and ability to withstand corrosive environments, polymer concrete is being used as a worthy alternative for cement concrete (Tegethoff *et al*, 2001) in a range of civil and structural applications such as construction, bridge decking, concrete crack repair, pavement overlays, waste water pipes and structural panels (Garas & Vipulanandan, n.d). Compared to cement concrete, polymer concrete is three to five times lighter and three to five times stronger (Zijlstra 2007) which is a major advantage, particularly in structural applications.



Figure 2.4 Polymer concrete after compressive testing

2.2 GENERAL PROPERTIES OF POLYMER CONCRETE

2.2.1 FILLERS

Miller (2005) describes that the filler component of polymer concrete should possess a solid form, be non-absorbent and have negligible moisture content. Blagga & Beaudoin (1985) describe that the filler can generally be any dry, non-absorbent, solid material. Coarse aggregates such as crushed stone, granite, gravel, limestone, chalk, quartz, slate, sandstone and clay are common types of mineral fillers used in polymer concrete. Fine aggregates such as sand are also used as a mineral filler material in the concrete, however when used without coarse aggregates, the material is referred to as a polymer mortar (Blagga & Beaudoin, 1985a).

Fillers used in polymer concrete extend beyond only mineral materials. Condensed silica fume and metallic fillers have been incorporated as a substitute filler material for coarse mineral aggregates. Waste materials such as glass from recycled bottles and fly ash are also being utilized as a filler material in polymer concrete (Miller 2005).

2.2.1.1 Fly ash

Fly ash (figure 3.6) which is commonly used as a filler material in polymer concretes (Roberto & Tarun, 2000) is a by-product of burning coal in energy production and is obtained as a finely divided residue resulting from the flue gases of combustion boilers (Wegian *et al*, 2011). Roberto & Tarun (2000) explain that the purpose of using a waste material such as fly ash in polymer concrete is not only to alleviate environmental problems, but also to provide a cost effective engineering solution without compromising the concretes performance and structural integrity. Fly ash enhances the surface aesthetics and mechanical properties, especially compressive and flexural strength (Rebeiz & Craft, 2002; Wegian *et al*, 2011).

2.2.2 POLYMERS

Blagga & Beaudoin (1985) describe that there are two types of polymer binders used in polymer concrete, namely thermoplastic and more frequently, thermosetting plastic (thermoset). Literature from Miller (2005) mentions that thermosets should be used as the polymer component in polymer concretes. Blagga (1974) confirms that thermosets are the preferred polymers used in polymer concrete due to its enhanced strength and higher resistance to creep, thus enabling a more suitable material for civil engineering structures. Literature from ENG8803 (2008) describes that thermoplastics see a very minimal usage in structural applications due not only to performance drawbacks, but high processing and material costs. Askeland & Phule (2008) describe that thermoplastics and thermosets are defined by how their molecules are synthesized and their molecular structure.

2.3 THERMOPLASTIC POLYMERS

Thermoplastics are composed of long polymer chains produced by joining together monomers and behave in a ductile manner (ENG8803, 2008). The bonding of the polymer chains in thermoplastics are strong, meaning that rotation and sliding of the chains is difficult. This leads to high strength, stiffness and melting points (Askeland & Phule, 2008) which as mentioned above, largely increases production costs. At room temperature thermoplastics behave as a solid material due to the entanglement of the polymer chains, however, under heat and pressure the chains slip thus allowing the material to be modified into a new shape (ENG8803, 2008; AMCA, 2004).

The behaviour of thermoplastics is non-Newtonian but rather viscoelastic, meaning that the stress and strain of the material is non-linear for most part of loading, giving rise to extremely large elastic and plastic deformation. During loading, entire segments of polymer chains become distorted and on removal of loading, the chains start to move back to their original position over a period of time. Due to this viscoelastic behaviour, thermoplastics display large creep and stress relaxation characteristics (Askeland & Phule, 2008), a major drawback for structural engineering applications.

2.4 THERMOSETTING POLYMERS

Thermosets begin as linear polymer chains in the form of a liquid resin or a low melting point solid (AMCA, 2004) and are cured into a permanent form by the use of low heat, low pressure, radiation, catalysts or a combination of these. This activates the cross-linking process, thereby forming a three-dimensional network structure (Askeland & Phule 2008) as seen in figure 2.2. The formation of cross-linking in a thermoset network results in a stiffer and stronger matrix than that of a thermoplastic network (ENG8803, 2008). Once cured, a thermoset cannot be remelted or reshaped because the polymer has undergone an irreversible chemical change (Askeland & Phule 2008).



Figure 2.5 Formation of 3-dimensional thermoset network in Phenolic Resin (ENG8803, 2008)

The tightly cross-linked structure of thermosets prevents the molecules rotating or sliding, which provides hardness, strength at relatively high temperatures, insolubility, good rigidity, good heat and chemical resistance, and higher resistance to creep (Blagga, 1974; AMCA, 2004) which are advantages over thermoplastics for structural engineering applications. Thermosets also exhibit a superb resistance against a variety of chemical attacks such as acids, solvents and bases (ENG 8803, 2008).

Guneri (2005) mentions that a major advantage over thermoplastics is that many thermosets can be formulated at ambient temperatures, thereby reducing processing costs and the overall cost towards a particular application. Blagga (1974) mentions that when thermosets are heated they will not melt and flow like thermoplastics, but rather soften and retain their original shape and strength. In fact, literature from ENG 8803 (2008) states that the heating of a thermoset composite material can promote further cross-linking and hence a more rigid material.

2.5 CLASSES OF THERMOSETTING POLYMERS

The most common thermosetting polymers used in the composites industry are unsaturated polyesters, epoxies, vinyl esters and phenolics (AMCA 2004). ENG8803 (2008) defines that there are four primary classes for thermosetting matrix polymers which are:

- Ø Unsaturated Polyester resins
- Ø Vinylester resins
- Ø Epoxy resins
- Ø Other resins

The first three classes of materials are of primary interest due to their current viability for civil engineering structures. It should be noted however that 'other resins' such as phenolics and polyurethanes are of interest as a future possibility to civil engineering composites as they possess characteristics such as excellent fire resistance and toughness respectively (ENG 8803 2008).

2.5.1 UNSATURATED POLYESTER RESINS

Polyester covers the lower end of the performance spectrum, however, due to relatively low cost, polyester is the most widely used thermoset (Blagga & Beaudoin, 1985a; ENG8803, 2008) and is supplied in the form of unsaturated pre-polymer (Miller, 2005). Due to ongoing development, polyesters have seen an increased usage in civil engineering structures (ENG8803, 2008).

ENG8803 (2008) defines polyesters as polymers containing multiple ester groups along their molecular chain. Polyester is formed by the reaction of a saturated dicarboxylic acid and unsaturated dicarboxylic acid with a difunctional alcohol such as ethylene glycol or propylene glycol (Encyclopedia Britannica, 2011), which is then co-reacted with an unsaturated vinyl crosslinking monomer to form the final thermoset network. The glycol, saturated acid, unsaturated acid and crosslinking monomer together form the four major components in creating polyester. A variation of one of these components largely modifies the resulting performance in the polyester (ENG8803, 2008).

2.5.2 VINYLESTER RESINS

Vinylester in comparison to polyester and epoxy resins hold the middle of the performance spectrum and although not as cheap as polyester, vinylester still provides a lower cost than epoxy resin (ENG8803, 2008). Peters (1998) mentions that vinylester resin combines inherit toughness with outstanding heat and chemical resistance and unlike other thermosets, vinylester does not have to sacrifice heat and chemical resistance to achieve a high resiliency and toughness. Because vinylester possesses a low ester content and low saturation in comparison to polyester (Miller, 2005), vinylester exhibits a greater resistance to hydrolysis, low peak exotherms during cure and less shrinkage during cure (Peters, 1998).

The formation of vinylester occurs from a reaction between epoxy resins with acrylic or methacrylic acid, whereby the resulting polymer chain network contains terminal unsaturation points which are able to cross-link with an unsaturated monomer such as styrene (ENG8803, 2008).

2.5.3 EPOXY RESINS

Epoxy resin is typically used in applications such as the aerospace industry (Ingenia, 2008), motor racing and racing yachts and takes the higher end of the performance spectrum. Depending on the desired performance of a particular epoxy resin, prices range between \$7/kg to \$500/kg (ENG8803, 2008). Note that the aerospace industry uses the highest performance epoxy resin, where curing temperatures of the resin are at approximately 180°C. Some epoxies are cured at ambient temperatures, thus giving a reduction in production costs (ENG8803, 2008). Such epoxy resins are of particular interest in structural engineering applications, due to their structural performance and durability (ENG8803, 2008).

Epoxy resin has a molecular structure (figure 2.6) containing epoxide groups where the groups are in the form of a three element ring structure consisting of two carbon atoms and one oxygen atom (Peters, 1998).



Figure 2.6 Molecular structure of epoxy resin (DOW, 2010)

The reactivity and final properties of the system are influenced by the location of the epoxide ring which can be located either terminally, cyclically or internally (Sirivivatnanon, 2003). For the purposes of structural engineering applications, epoxies are reacted with catalysts to form a final structure which is rigid (ENG8803, 2008). The most popular catalysts used in epoxy based polymer concrete are polyamines followed by pollyamides and polysulfides (Miller, 2005).

2.6 BEHAVIOURS OF POLYMER CONCRETES

An important behaviour in polymer concrete is workability which as stated in Cement & Concrete (2002), is the concretes ability to flow when in a plastic state. Miller (2005) describes that enough resin should be added into the polymer concrete to produce the minimum workability required for its specific application. This is due to the expensive cost of the polymer binder compared to the other components of polymer concrete. Miller (2005) also describes that limiting the proportion of polymer binder in the concrete to that mentioned above, prevents any noticeable shrinkage during curing and reduces the amount of expansion and contraction in the hardened concrete when subject to a range of temperatures. Blagga & Beaudoin (1985a) state that the amount of binder used is generally small, but depends on the size of the filler. If coarse filler is used, typically 5 to 15 percent of binder is required

however if fine filler is used, up to but not limited to 30 percent of binder can be needed.

Blagga & Beaudoin (1985a) report that polyester polymer concrete has good mechanical strength, relatively good adhesion to other materials and good chemical and freeze-thaw resistance. Some setbacks of polyester polymer concrete are however, its large setting and post-setting shrinkage (up to ten times greater than Portland cement concrete) (Blagga & Beaudoin, 1985a). Miller (2005) mentions that post-shrinkage values of between 0.3 - 0.5% in length have been quoted. Ohama (2011) reports that a particular polyester polymer concrete under outdoor conditions in Japan endured a 10% decrease in compressive strength in the first year, followed by a constant strength retention for approximately eight years under outdoor exposure.

Sirivivatnanon (2003) states that vinylester polymer concretes have a better chemical resistance, are tougher and more resilient that most polyesters. Additionally, a higher full cure time of seven days is typically required compared to four to seven days for polyesters. Sirivivatnanon (2003) also states that with respect to polyester and epoxy polymer concretes, the compressive strength range and coefficient of thermal expansion of vinylester is lower.

Miller (2005) explains that epoxy polymer concrete has superior chemical resistance, excellent structural ability, good adhesion to a variety of surfaces and exhibits a minimal degree of shrinkage during curing. Blagga & Beaudoin (1985a) state that in addition to the abovementioned properties, epoxy based polymer concrete also inherits good creep and fatigue resistance and low water absorption. Blagga & Beaudoin (1985a) and Miller (2005) both agree that a high degree of chemical resistance is achieved in epoxy polymer concrete when a polyamine catalyst is used. Blagga & Beaudoin (1985a) also mention that polyamide cured epoxies have better

heat resistance, reduced chalking tendency in outdoor exposure and greater flexibility. The use of polysulfide cured epoxies produces a polymer concrete with even greater flexibility. Miller (2005) also states that epoxy polymer concrete showcases a flexural strength up to ten times greater than that in cement concrete, superb for structural engineering applications.

Table 2.1 shows a comparison of the mechanical properties of polyester, vinylester and epoxy polymer concrete, with a range of typical values shown for polyester and epoxy. Due to the lack of literature relating to mechanical properties for vinylester polymer concrete, values have been sourced on a particular type of vinylester concrete, namely Novolak Vinylester Polymer Concrete No. 465 (Sauereisen, 1996).

Binder	Density (t/m³)	Compressive Strength (MPa)	Tensile Strength (MPa)	Flexural Modulus (GPa)	Modulus of Elasticity (GPa)
Polyester	2-4	50-150	8-25	15-45	20-40
Vinylester	2.3	83.4	7	15.3	36.8
Ероху	2-4	50-150	8-25	15-50	20-40

 Table 2.1
 Mechanical properties of polymer concretes (Miller, 2005; Sauereisen, 1996).

2.7 CIVIL ENGINEERING APPLICATIONS OF POLYMER CONCRETE

Blagga & Beaudoin (1985a) state that polyester polymer concrete due to its relatively low cost is commonly used in various pre-cast and in-situ applications in construction works, public and commercial buildings, floor tiles, sewer pipes and stairs. A report sponsored by the Nevada Department of Transportation and prepared by O'Connor (1991) outlines that polyester polymer concrete provides a good material for pavement overlays over cement concrete bridge decks due to its durability, high wear resistance, bonding between the bridge deck and low water and chloride permeability's. The report also states that polyester polymer concrete provides effective protection for cement concrete bridge decks, particularly against corrosion of the steel reinforcing bars.

A report by Milosheva (n.d) outlines that polyester polymer concrete is ideal for heavy exploited applications such as new runways and runway repairs, highways, bridge decks and tunnels because of its high strength gain properties. The polyester matrix systems can cure within 15 - 20 minutes, even at temperatures as low as -12° , thus allowing the polymer concrete to be fully trafficable or used according to its purpose in a short period of time, making polyester very attractive in civil engineering.

Vinylester polymer concrete is also used as an overlay on concrete bridge decks as mentioned by Raina (1996), however compared to polyester overlays, the vinylester polymer concrete is more costly, harder to handle, exhibits deterioration due to thermally-induced cracks and bond failure between the concrete and overlay. Note that there seems to be a lack of literature relating to civil engineering applications of vinylester polymer concrete. Blagga & Beaudoin (1985a) state that epoxy polymer concretes are mainly used in special applications, including skid-resistant overlays in highways, use in mortar for industrial flooring, resurfacing of deteriorated structures and epoxy plaster for exterior walls. Further investigation of the behaviour of epoxy polymer concrete will determine more viable structural engineering applications, in particular timber pile rehabilitation.

2.8 TIMBER PILE REHABILITATION

The Timber Bridge Maintenance Manual (DRM, 2005) describes that bridge rehabilitation is the process of restoring a bridge structure to 'as new' condition, excluding the strengthening of a bridge to withstand loads greater than originally designed for. This description of rehabilitation and rehabilitation methods outlined by DRM (2005) may also be employed for jetties, wharves, piers and other timber structures. The manual describes that a timber pile is a substructure member that transfers all vertical and lateral loads into its foundation through shear and bending, and therefore serves as an extremely important component of a complete structure. Figure 2.7 shows a group of severely deteriorated timber piles supporting a harbor pier.



Figure 2.7 Severely deteriorated timber piles (FHWA, 2006)

Timber piles typically fail in compression when the piles cross-section reduces and cannot withstand the axial forces and in bending where lateral loads such as flood debris act on the pile. Due to the age of some timber structures, many piles have become severely deteriorated and require rehabilitation.

Steel and concrete are typical materials used for rehabilitating timber piles and have effectively provided sufficient load carrying abilities, however both attribute drawbacks such as high installation and maintenance costs. The use of timber also provides an effective solution in some cases, however comes under the environmental attack of marine borers in oxygenated zones (DMR, 2005). Fiber Reinforced Polymer (FRP) shells are a more recent material used for rehabilitating timber piles and have provided a very effective solution against environmental attack, however also have drawbacks such as a lack of load transfer between the shell and filler material and lack of structural strength of the filler material (Lopez-Anido *et al*, 2005).

2.8.1 STEEL

Section 11.2 of the Timber Bridge Maintenance Manual (DMR, 2005) outlines the use of either unpainted or galvanised steel piles (UB or UC) as an option for replacing timber piles (refer to figure 2.8) and is used in situations where deterioration is evident over the length of the pile. The typical layout and headstock connection details of figure 2.8 show that the steel piles can either fully replace the timber pile or butt up against the existing timber pile. In both cases, the new steel pile is connected to the headstock and effectively withstands the axial and lateral loading, thus reducing or eliminating the stress on the timber pile. The downside to using steel, whether corrosion protected or not is that steel will electrochemically corrode with time and reduce in strength (Askeland & Phule, 2008; Lopez-Anido *et al*, 2005). The Bridge Inspection Manual (DMR, 2004) describes
other defects that they have found to have commonly occurred on steel sections-:

- Ø Corrosion
- Ø Permanent Deformations
- Ø Cracking
- Ø Loose connections



Figure 2.8 Typical design of steel sections used for rehabilitating timber piles (DMR, 2005)

2.8.2 CONCRETE

Section 11.3 of the Timber Bridge Maintenance Manual (DMR, 2005) outlines the use of concrete piles as an option for rehabilitation of deteriorated existing concrete piles and timber piles and is used in situations where deterioration is localised on the pile. In particular, the method is to encase the deteriorated section of the pile with reinforced concrete (see figure 2.9), whereby the axial and lateral loads at this point are transferred through the concrete. The report by FWHA (2006) mentions that concrete encasement is only moderately useful for reducing the rate of deterioration. Spalling is common in concrete members which in more severe cases, exposes the internal steel reinforcing to corrosion and subsequently a reduction in strength (DMR, 2005; Lopez-Anido *et al*, 2005). The Bridge

Inspection Manual (DMR, 2004) describes other defects that they have found to have commonly occurred on concrete sections-:

- Ø Carbonation
- Ø Alkali-Silica Reaction (ASR)
- Ø Cracking
- Ø Surface Defects
- Ø Delamination



Figure 2.9 Typical design of concrete encasement to rehabilitate timber piles (DMR, 2005)

2.8.3 TIMBER

Lopez-Anido *et al* (2005) outlines the rehabilitation method of timber splicing with steel bolts. This involves cutting an S shape (splice) below the deteriorated section of the timber pile and connecting a new timber pile with the steel bolts (see figure 2.10). Note that there are other methods not discussed. The Bridge Inspection Manual (DMR, 2004) describes defects that they have found to have commonly occurred on timber sections-:

- Ø Fungal attack (rotting)
- Ø Termites
- Ø Marine organisms (marine borers)
- Ø Corrosion of fasteners
- Ø Shrinkage and splitting
- Ø Fire damage
- Ø Weathering



Figure 2.10 Typical design of timber splicing (Lopez-Anido et al, 2005)

2.8.4 FIBER REINFORCED POLYMER

Lopez-Anido *et al* (2004) outlines the use of a prefabricated FRP composite shell which encases the timber pile and is filled with a structural cement mortar or polymer mortar (see figure 1.1). The cement mortar had spalling issues similar to that of normal concrete and thus potentially lost shear strength between the interface of the mortar, pile and shell. The polymer mortar was made out of expanding polyurethane which had excellent workability, pumpability and below water application properties, however had no structural capacity.

3 EXPERIMENTAL PROGRAMME

An extensive experimental program as outlined in this section was undertaken to determine the behaviour and mechanical properties of epoxy and vinylester polymer concretes such as-:

- Ø Compressive Strength
- Ø Modulus of Elasticity
- Ø Tensile Strength
- Ø Flexural Modulus



Figure 3.1 Typical failure after tensile testing

These properties are extremely important factors in determining the suitability of polymer concrete for the infilling of fibre composite shells. Compressive strength is a property which exhibits the axial compressive load a material can withstand before failing and for the purposes of timber pile rehabilitation, the polymer concrete must be able to transfer the load from the timber pile through to the foundation. Modulus of elasticity is a property which exhibits the stress-strain relationship of the concrete and how

the concrete deforms under load. Tensile strength is a property which exhibits the polymer concretes tensile strength and hence whether or not the concrete can resist the tensile forces in the structure. Flexural modulus is a property which exhibits the ability of the concrete to resist bending forces imposed laterally.

In order to analyse these properties, a set of experimental tests were established as shown in table 3.1:

Test	Behaviour analysed	Standard	
Compressive	Compressive Strength, f'c	ASTM D 695 M-91	
Compressive platen to platen method	Modulus of Elasticity, E	ASTM D 695 M-91	
Tensile	Tensile Strength, f _{ct.sp}	ASTM 496	
Flexural	Flexural Modulus, E _f	ISO 178:1993	

Table 3.1 Testing summary

3.1 PREPARATION WORK

3.1.1 MATERIALS

There were six materials used for the mix designs of polymer concrete as shown in table 3.2 and further discussed in section 3.2:

Material	Description
Epoxy Resin	Kinetix R246TX
Epoxy Catalyst	Kinetix H160 Hardener
Vinylester Resin	FGI Vinylester SPV6003 Promthix F01302
Vinylester Catalyst	Norox MEKP-925H
Sand	Wagners CFT
Fly Ash	Wagners CFT

Table 3.2Material types used for mix designs

3.1.1.1 Resin & catalyst

The resin as shown in figure 3.2 was the main binding material for the polymer concrete and was required to be mixed with a catalyst. The purpose of incorporating the catalyst (figure 3.3) was to chemically start the curing process of the resin and hence harden the mix into a polymer concrete. It was important that the catalyst and resin were fully mixed together to ensure that the molecular structure of the mixture was uniform and that the resin would cure.



Figure 3.2 Binding materials: Vinylester resin



Figure 3.3 Binding materials: Vinylester catalyst

For epoxy polymer concrete, a volume percentage of 20% (1:5 parts) catalyst to resin was used. For vinylester polymer concrete, a volume percentage of 1.73% (1.73:100 parts) catalyst to resin was used. The volume percentages were based on the manufacturers specifications as printed on the containers.

3.1.1.2 Sand

The sand stockpile contained a lot of impurities such as coarse aggregate, sticks, etc and contained moisture. It was vital that all impurities and moisture were removed from the sand. The sand was therefore baked in an oven at 110° for approximately 24 hours (see figure 3.4) in accordance with standard ASTM C128 to remove all moisture and was then passed through a 430 micron sieve to remove any impurities (see figure 3.5). Referring to figure 3.5, it can be seen that the sand is fine and without and impurities. Passing the sand through the sieve also ensured that the mix was uniform for each batch.



Figure 3.4 Preparation of sand for sieving



Figure 3.5 430 micron sieved sand (LHS)

3.1.1.3 Fly ash

Preparation work of the fly ash supplied by Wagners CFT included breaking down large clumps into a fine powder and ensuring that there were no impurities in the storage drum. Figure 3.6 shows a typical sample of fly ash.



Figure 3.6 Fly ash (AAERC, 2011)

3.1.2 MOULDS

There were two types of moulds used, namely cylinder moulds for the compressive and tensile specimens (figure 3.7) and flat rectangular shaped moulds for the flexural specimens (figure 3.8). All moulds were waxed to ensure that the cured concrete could be removed from the mould easily and without impurities. Each mould was individually labeled to ensure that the correct batch mix design could be identified after the curing process when required for testing.



Figure 3.7 Cylinder moulds for compressive and tensile specimens



Figure 3.8 Rectangular moulds for tensile specimens

The size of the specimens required for testing in accordance with the specification outlined in table 3.1 are outlined in table 3.3:

Test specimen	Length (mm)	Depth (mm)	Width (mm)	Diameter (mm)
Compressive	100	-	-	50
Tensile	100	-	-	50
Flexural	144 span	9	16	-

 Table 3.3
 Geometric dimensions of test specimens

3.1.3 MIX DESIGNS

The mix designs for the polymer concrete specimens were determined based on different proportions of resin and fly ash with a constant of 57% sand. Figure 3.9 shows the concrete mixing bowl in which each mix design batch was mixed.



Figure 3.9 Concrete mixing bowl

Previous experimental work by Sirimanna *et al* (2010) determined that the sand supplied by Wagners CFT contained a volume void ratio of 43%. The proportions of resin, sand and fly ash also determined by Sirimanna *et al* (2010) are represented in table 3.4 as volume percentage/ratio-:

Resin	Sample	Volume	e percentage/ratio (V _m)		
Туре	(Batch)	Sand	Resin + Catalyst	Fly ash	
	S57E43	57	43	0	
	S57E40F3	57	40	3	
Ероху	S57E30F13	57	30	13	
	S57E22F21	57	22	21	
	S57E20F23	57	20	23	
	S57V43	57	43	0	
Vinylester	S57V40F3	57	40	3	
	S57V30F13	57	30	13	
	S57V22F21	57	22	21	
	S57V20F23	57	20	23	

Table 3.4Mix design batches by percentage volume

Referring to table 3.4, the sample identification represents the volume percentages of sand, resin + catalyst and fly ash. For example, S₅₇E₄₀F₃ represents a batch mix design of 57% sand, 40% epoxy resin and 3% fly ash.

The densities for each of the materials in table 3.2 were required to be evaluated so that the weight of the materials in each mix design batch could be calculated. A cylinder mould measuring a volume of $1.9635 \times 10^{-4} \text{ m}^3$ was filled with each material individually and the weight measured. The weight of the mould was first measured and subtracted from the total measured weight. The densities for each material were calculated using (3.1).

 $\rho_{\rm m} = \frac{w_m}{v_c} \tag{3.1}$

where

 ho_m is density [kg/m³] W_m is weight [kg] V_c is volume [m³]

which may be simplified to:

$$\rho_{\rm m} = \frac{W_m}{1.9635 * 10^{-4}} \tag{3.2}$$

The densities for each material are shown in table 3.5.

Material	Volume (m ³)	Weight (kg)	Density (kg/m ³)
Vinylester Resin	1.9635 x 10 ⁻⁴	0.2525	1286
Vinylester Catalyst	1.9635 x 10 ⁻⁴	0.2656	1353
Epoxy Resin	1.9635 x 10 ⁻⁴	0.2695	1373
Epoxy Catalyst	1.9635 x 10 ⁻⁴	0.2310	1176
Sand	1.9635 x 10 ⁻⁴	0.3525	1795
Fly Ash	1.9635 x 10 ⁻⁴	0.2065	1052

Table 3.5 Density of materials



Figure 3.10 Preparing batches of polymer concrete

For ease of preparing the different mix design batches in the laboratory (figure 3.10), the volume percentages for the total amount of specimens as presented in table 2.7 were converted to weight using (3.3) and incorporated a 30% contingency:

$$W = (V_c n_c + V_f n_f) \frac{v_m}{100} \rho_m 1.3$$
(3.3)

which may be simplified to:

$$W = 0.013 V_m \rho_m \left(V_c n_c + V_f n_f \right) \tag{3.4}$$

whereW is weight [kg] V_c is volume of cylinder specimen [m³] V_f is volume of flexural specimen [m³] V_m is volume ratio in mix design [m³] n_c is number of cylinder specimens n_f is number of flexural specimens ρ_m is density of material of interest [kg/m³]

and results shown in table 3.6:

	Weight per batch (g)				
Batch ID	Sand (g)	Resin (g)	Catalyst (g)	Fly Ash (g)	Total (g)
S57E43	3026	1396	299	0	4722
S57E40F3	3026	1299	278	93	4697
S57E30F13	3026	974	209	404	4614
S57E22F21	3026	714	153	653	4547
S57E20F23	3026	650	139	715	4531
	15132	5034	1079	1866	23111
S57V43	3026	1608	29	0	4663
S57V40F3	3026	1495	27	93	4642
S57V30F13	3026	1122	20	404	4573
S57V22F21	3026	823	15	653	4517
S57V20F23	3026	748	14	715	4503
	15132	5795	105	1866	22899
SUBTOTAL	30265	10829	1184	3733	46010

Table 3.6 Mix design batches by weight

The weight (W_m) values from table 2.6 were then converted to weight percentages of the batch ($W_{\%}$) using (3.5):

$$W_{\%} = \frac{100W_m}{W_t} \tag{3.5}$$

where $W_{\%}$ is material percentage weight of concrete batch [kg] W_m is weight of material of interest [kg] W_t is total weight of batch [kg]

and results shown in table 3.7:

	Actual % by weight					
Batch ID	Sand	Resin	Catalyst	Fly Ash		
S57E43	64.09	29.57	6.34	0.00		
S57E40F3	64.43	27.66	5.93	1.99		
S57E30F13	65.60	21.12	4.52	8.76		
S57E22F21	66.56	15.71	3.37	14.36		
S57E20F23	66.80	14.34	3.07	15.79		
S57V43	64.90	34.47	0.63	0.00		
S57V40F3	65.19	32.21	0.59	2.01		
S57V30F13	66.18	24.53	0.45	8.84		
S57V22F21	67.00	18.21	0.33	14.46		
S57V20F23	67.21	16.60	0.30	15.89		

Table 3.7 Mix design batches by weight percentage

3.1.4 BATCH MIXING

Using the calculated weight values from table 3.6, the batches were then mixed together and casted into their corresponding moulds. The process for mixing the batches was undertaken as outlined below:

- 1. Measure weight of all materials
- 2. Mix together the dry materials in mixing bowl (i.e. sand and fly ash)
- 3. Mix together wet materials in container (i.e. resin and catalyst)
- 4. Add wet materials to dry materials in mixing bowl
- 5. Incorporate all materials well until the mix looked uniform
- 6. Cast into moulds

3.1.5 CASTING AND CURING

The mix design batches were cast into the correctly labeled mould and allowed to cure in a temperature controlled room of 24°C (figure 3.11).



Figure 3.11 Curing room controlled at 24°C

The specimens were then left in their moulds until required for testing (figure 3.12 and 3.13 shows cylinder specimens).



Figure 3.12 Initial curing of cylinder specimens



Figure 3.13 Curing of cylinder specimens after period of time

The flexural moulds were a large rectangular shape of 16mm thick and approximately 180mm square, larger than the required size as shown in table 3.3. This allowed the sample to be clamped in order to cut at least five (5) specimens per sample with a diamond cutting machine. Figure 3.14 shows the cured polymer concrete specimens ready for cutting.



Figure 3.14 Flexural samples cured and ready for cutting into specimens

3.1.6 POST CURING

On completion of the required curing period for the specimens, the final preparation work was undertaken. Figures 3.15 and 3.16 show the finally prepared specimens ready for testing.

3.1.6.1 Tensile & Compressive specimens (cylinders)

The cylinders upon required the following preparation upon curing:

- Ø Removal of concrete specimens from moulds
- Ø Sanding of specimen due to shrinkage. This was done on a sanding machine and it was ensured that the ends be perpendicular to the cylinders length. For compressive testing, this ensured that the load would be evenly distributed against its cross-sectional area. For tensile testing, sanding was not as important but was still done to ensure a smooth end surface.
- Ø Labeling of specimen according to its batch identification
- Ø Measurement of diameter at both ends
- Ø Measurement of length



Figure 3.15 Cylinder specimens ready for testing

3.1.6.2 Flexural specimens

The cylinders required the following preparation upon curing:

- Ø Removal of concrete specimens from moulds
- Ø Cutting of specimens 9mm thick with diamond cutting wheel
- Ø Sanding of specimens to remove any sharp edges or hanging material
- Ø Labeling of specimen according to its batch identification
- Ø Measurement of thickness at one location
- Ø Measurement of width at both ends



Figure 3.16 Flexural specimen ready for testing

3.2 TESTING

On completion of the preparation work outlined in section 3.1, it was then necessary to determine a testing plan. Based on a review of literature, it was determined that polymer concrete gains approximately 90% of its strength at an age of seven (7) days (Sirimanna *et al*, 2010). The concrete then gains its almost full strength over a period of greater than 28 days. It was therefore decided that testing was undertaken in accordance with the plan presented in table 3.8:

Tost	Specimen Age (days)				
1631	7 days	21 days	≥ 28 days	Total	
Compressive	5	2	3	10	
Tensile	3	0	0	3	
Flexural	5	0	0	5	

Table 3.8 Testing samples required for different specimen ages

In total there were ten (10) batches casted and based on the test requirements shown in table 3.8, a total number of tests as shown in table 3.9 were required. Note that flexural testing was undertaken at 21 days due to lack of time on seven (7) days with tensile and compressive testing.

Tost	Specimen Age (days)				
1030	7 days	21 days	≥ 28 days	Total	
Compressive	50	20	30	100	
Tensile	30	0	0	30	
Flexural	0	50	0	50	

 Table 3.9
 Total testing samples required for different specimen ages

3.2.1 MACHINE SETUP AND OPERATION

Due to the workplace health and safety requirements of University of Southern Queensland (USQ), Toowoomba, it was required that trained technical staff set up and operate the testing equipment. A 500kN capacity AVERY testing machine (figure 3.17) was used for compressive and tensile testing and a 100kN capacity MTS testing machine (figure 3.18) was used for flexural testing.



Figure 3.17 500kN AVERY machine for compressive and tensile testing



Figure 3.18 100kN MTS machine for flexural testing

The set up of the MTS machine was more tedious in that a two (2) point bending cell was required (figure 3.19). The span as seen in figure 3.19 was spaced to 144mm as per the requirements in table 3.3.



Figure 3.19 Two (2) point loading cell for three (3) point flexural testing

The set up of both machines required computer input of constraints such as loading rate, test type, standard and data output. Figure 3.20 shows a visual output of the data during testing.



Figure 3.20 Data output from testing

3.2.2 LOADING RATE

A loading rate (cross-head speed rate) of 2mm/min was used for compressive testing which allowed the specimen to deform under loading without a dynamic loading effect, thus giving more accurate results. A loading rate of 1mm/min was used for flexural testing as it was estimated that the loading capacity of the specimens would be a maximum of 1kN and that deflection would be between maximum of 2.5mm.

3.2.3 DATA OUTPUT

Data was output for the entire testing time and consisted of the following:

- Ø Load (kN)
- Ø Deformation (mm)
- Ø Time (secs)

The data was then evaluated as presented in section 4.

3.2.4 COMPRESSIVE TESTING

Compressive testing was undertaken in accordance with the technical requirements outlined in standard ASTM D 695 M-91. Specimens were tested for compressive strength at 7, 21 and 28 days and modulus of elasticity at 7 and 28 days using the uni-axial platen to platen compression method. The methodology for compressive testing consisted of the following steps:

- 7. Initial machine setup as per section 3.2.1
- 8. Specimen was placed centrally in platen (figure 3.21)

- 9. The bottom platen was raised until the top platen just touched the top of the specimen
- 10. The safety Perspex panel was lowered
- 11. The specimen was loaded as per section 3.2.2 until failure (figure 3.22)
- 12. The specimen was removed from the machine
- 13. The machine was then wiped down with a rag to remove all debris
- 14. Repeat steps 2 to 7 until all specimens were tested



Figure 3.21 Compressive testing of specimen



Figure 3.22 Compressive specimen after failure

3.2.5 TENSILE TESTING

Tensile testing was undertaken in accordance with the technical requirements outlined in standard ASTM 496. Specimens were tested for tensile strength at 7 the split tensile method. The methodology for tensile testing consisted of the following steps:

- 1. Initial machine setup as per section 3.2.1
- 2. Specimen was placed centrally in platen (figure 3.23)
- 3. The bottom platen was raised until the top platen just touched the top of the specimen
- 4. The safety Perspex panel was lowered
- 5. The specimen was loaded as per section 3.2.2 until failure (figure 3.24)
- 6. The specimen was removed from the machine
- 7. The machine was then wiped down with a rag to remove all debris
- 8. Repeat steps 2 to 7 until all specimens were tested



Figure 3.23 Tensile testing of specimen



Figure 3.24 Tensile specimen after failure

3.2.6 FLEXURAL TESTING

Tensile testing was undertaken in accordance with the technical requirements outlined in standard ISO 178:1993. Specimens were tested for flexural modulus at 21 days using the three (3) point bending method. The methodology for flexural testing consisted of the following steps:

- 1. Initial machine setup as per section 3.2.1
- 2. The specimen was placed centrally over the two point spanning cell (figure 3.23)
- 3. The top loading cell was lowered until it touched top of specimen
- 4. The specimen was loaded as per section 3.2.2 until failure (figure 3.24)
- 5. The specimen was removed from the machine
- 6. The machine was then wiped down with a rag to remove all debris

7. Repeat steps 2 to 6 until all specimens were tested



Figure 3.25 Flexural testing of specimen



Figure 3.26 Flexural specimen mid test

4 DATA ANALYSIS

Subsequent to the testing program presented in section 3.2, the data output presented in section 3.2.3 was then collaborated and used to determine the mechanical properties and behaviours of the two polymer concrete types. Section 4.1 through 4.4 presents the methods used to convert the data output.

4.1 COMPRESSIVE STRENGTH

The compressive strength for each specimen was determined based on the data output from compressive testing and required that the maximum axial load be converted to a stress (compressive strength) which was calculated using (4.1).

$$f'_{c.max} = \frac{N_{max}}{A_{av}}$$
(4.1)

where *f'_{c.max}* is maximum compressive strength of concrete cylinder [MPa] *N_{max}* is maximum axial load from compression test [kN] *A_{av}* is average cross-sectional area of concrete cylinder [m²]

Tables 10.1 to 10.8 show the geometrical dimensions of the vinylester and epoxy polymer concrete compressive specimens respectively. The compressive strength results are shown in section 5.1 to 5.4.

4.2 MODULUS OF ELASTICITY

The modulus of elasticity (Young's modulus) for each specimen was determined based on the data output from the same compressive tests used for compressive strength (section 4.1) and is the gradient of the linear portion of the stress-strain curve (4.2):

$$E = \frac{f'_{c1} - f'_{c2}}{\varepsilon_1 - \varepsilon_2} \tag{4.2}$$

where E is Young's modulus [GPa] ε is strain [m/m]

and can be seen in figure 4.1.



Figure 4.1 Young's modulus analysis

To achieve the gradient, compressive strength values using (4.1) were plotted against strain values which were calculated using (4.3):

$$\varepsilon = \frac{\Delta L}{L_0} \tag{4.3}$$

where L_o is original length [m] ΔL is change in length [m]

The linear portion of the stress-strain curves for all cylinder tests were not exactly 'linear', but contained a linear trend. Therefore a linear regression analysis in Microsoft Excel[®] was used which analysed all data points within the chosen data region and essentially found a line of best fit within the set of data. The theory of (4.2) still applied in that two points (ϵ_1 ,f'_{c.1}) and (ϵ_2 ,f'_{c.2}) were extruded from the linear regression line (figure 4.1) to calculate Young's modulus.

Stress-strain curves were translated to the left when machine adjusting at initial loading was evident as shown in figure 4.1. The curve has a constant compressive stress of 2MPa up to 0.4% strain and was thus translated 0.4% strain to the left. The stress at the origin was then taken as zero. Young's modulus results are shown in sections 5.5 and 5.6.

4.3 TENSILE STRENGTH

The split tensile strength for each specimen was determined based on the data output from the split tensile tests and required that the maximum load acting laterally against the specimen be converted to a stress (tensile strength) which was calculated using (4.4):

$$f_{ct.sp} = \frac{2^{P}}{1000\pi LD} 10^{3} \tag{4.4}$$

where $f_{ct.sp}$ is the split tensile strength [MPa] $P = P_{lat.max}$ is the maximum transverse load [kN] L is length [m] D is diameter [m]

and may be simplified to

$$f_{ct.sp} = \frac{2P}{1000\pi LD} \, 10^3 \tag{4.5}$$

Table 10.9 and 10.10 show the geometrical dimensions of the vinylester and epoxy polymer concrete tensile specimens respectively. Split tensile strength results are shown in sections 5.7 and 5.8.

4.4 FLEXURAL MODULUS

The flexural modulus for each specimen was determined based on the data output from the three point bending tests and required that the maximum load acting midspan against the specimen be converted to a modulus which was calculated using (4.6):

$$E_f = \frac{L^3 m}{4bd^3} \tag{4.6}$$

where *E_f* is flexural modulus [MPa] *m* is gradient of linear portion of the load-deflection curve [N/mm] *L* is span length[m] *d* is depth of specimen [m] *b* is width of specimen [m]

Split tensile strength results are shown in section 5.9.

5 **RESULTS**

This section presents the final results as determined from the data output analysis outlined in section 4. For bar graphs, blue represents the specimens tested, green represents an average value of the specimens tested and red represents specimens that were considered outliers and were thus not taken into account for the average. For each mechanical property, the values for each batch of each polymer concrete type are plotted against %resin by volume and %fly ash by weight, both on the x-axis to show a trend of the analysed results.

5.1 7 DAY COMPRESSIVE STRENGTH

The results show the 7 day compressive strengths for all batches of polymer concrete.



5.1.1 VINYLESTER PC



(b)



(c)







(e)


(f)

Figure 5.1 7 Day Compressive Strengths (Vinylester PC): (a)S57V43, (b)S57V40F3, (c)S57V30F13, (d)S57V22F21, (e)S57V20F23, (f)Comparison all vinylester PC batches



5.1.2 EPOXY PC



(b)



(c)







(e)



(f)

Figure 5.2 7 Day Compressive Strengths (Epoxy PC): (a)S57E43, (b)S57E40F3, (c)S57E30F13, (d)S57E22F21, (e)S57E20F23, (f)Comparison all epoxy PC batches



Figure 5.3 7 Day Compressive Strengths (comparison)

5.2 21 DAY COMPRESSIVE STRENGTH

The results show the 21 day compressive strengths for all batches of polymer concrete.



5.2.1 VINYLESTER PC



(b)











⁽f)

Figure 5.4 21 Day Compressive Strengths (Vinylester PC): (a)S57V43, (b)S57V40F3, (c)S57V30F13, (d)S57V22F21, (e)S57V20F23, (f)Comparison all vinylester PC batches

5.2.2 EPOXY PC





(b)



(c)





(e)



(f)

Figure 5.5 21 Day Compressive Strengths (Epoxy PC): (a)S57E43, (b)S57E40F3, (c)S57E30F13, (d)S57E22F21, (e)S57E20F23, (f)Comparison all epoxy PC batches



Figure 5.6 21 Day Compressive Strengths (comparison)

5.3 28 DAY COMPRESSIVE STRENGTH

The results show the 28 day compressive strengths for all batches of polymer concrete.



5.3.1 VINYLESTER PC

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⁽f)

Figure 5.7 28 Day Compressive Strengths (Vinylester PC): (a)S57V43, (b)S57V40F3, (c)S57V30F13, (d)S57V22F21, (e)S57V20F23, (f)Comparison all vinylester PC batches

5.3.2 EPOXY PC





(b)



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•		







⁽f)

Figure 5.8 28 Day Compressive Strengths (Epoxy PC): (a)S57E43, (b)S57E40F3, (c)S57E30F13, (d)S57E22F21, (e)S57E20F23, (f)Comparison all epoxy PC batch es

5.4 COMPRESSIVE STRENGTH COMPARISON



Figure 5.9 28 Day Compressive Strengths (comparison)



Figure 5.10 Compressive strength comparisons for all batches



Figure 5.11 Compressive Strength vs Age (Vinylester PC)



Figure 5.12 Compressive Strength vs Age (Epoxy PC)

5.5 MODULUS OF ELASTICITY

The results show the modulus of elasticity for all batches of polymer concrete.











(c)



Figure 5.13 Stress-Strain Curves (S57V43)



Figure 5.14 Modulus of Elasticity (S57V43)

5.5.2 S57V40F3

Due to inconsistencies with data output, the modulus of elasticity could not be determined. The data output recorded for analysis was not saved properly after each test and hence did not record the data properly.



5.5.3 S57V30F13







(d)

Figure 5.15 Stress-Strain Curves (S57V30F13)



Figure 5.16 Modulus of Elasticity (S57V30F13)

5.5.4 S57V22F21



(a)



99







(d)

Figure 5.17 Stress-Strain Curves (S57V22F21)



Figure 5.18 Modulus of Elasticity (S57V22F21)

5.5.5 S57V20F23





(b)



(c)



Figure 5.19 Stress-Strain Curves (S57V20F23)



Figure 5.20 Modulus of Elasticity (S57V20F23)

5.5.6 S57E43





(b)



(c)



Figure 5.21 Stress-Strain Curves (S57E43)



Figure 5.22 Modulus of Elasticity (S57E43)



5.5.7 S57E40F3



(b)



(C)



Figure 5.23 Stress-Strain Curves (S57E40F3)



Figure 5.24 Modulus of Elasticity (S57E40F3)
5.5.8 S57E30F13



(a)



(b)



(C)



(d)



(e)

Figure 5.25 Stress-Strain Curves (S57E30F13)



Figure 5.26 Modulus of Elasticity (S57E30F13)

5.5.9 S57E22F21





(b)



(c)



(d)

Figure 5.27 Stress-Strain Curves (S57E22F21)



Figure 5.28 Modulus of Elasticity (S57E22F21)



5.5.10 S57E20F23



(b)



(c)





(e)

Figure 5.29 Stress-Strain Curves (S57E20F23)



Figure 5.30 Modulus of Elasticity (S57E20F23)

5.6 MODULUS OF ELASTICITY COMPARISON

Figure 5.31 shows the averaged modulus of elasticity results plotted against a combination of % fly ash and % resin on the x-axis. Figure 5.32 and 5.33 shows optimized stress strain curves of each batch of polymer concrete which correspond to the average of all specimens tested for each batch.



Figure 5.31 Modulus of Elasticity versus fly ash and resin



Figure 5.32 Stress-Strain Curves (Vinylester PC)



Figure 5.33 Stress-Strain Curves (Epoxy PC)



Figure 5.34 Comparison of Stress-Strain Curves (Vinylester and Epoxy PC)

5.7 TENSILE STRENGTH

The results show the split tensile strengths for all batches of polymer concrete.

5.7.1 VINYLESTER PC



Figure 5.35 Tensile Strength (S57V43)



Figure 5.36 Tensile Strength (S57V40F3)



Figure 5.37 Tensile Strength (S57V30F13)



Figure 5.38 Tensile Strength (S57V22F21)



Figure 5.39 Tensile Strength (S57V20F23)

5.7.2 EPOXY PC



Figure 5.40 Tensile Strength (S57E43)



Figure 5.41 Tensile Strength (S57E40F3)



Figure 5.42 Tensile Strength (S57E30F13)



Figure 5.43 Tensile Strength (S57E22F21)



Figure 5.44 Tensile Strength (S57E20F23)

5.8 TENSILE STRENGTH COMPARISON



Figure 5.45 Tensile Strength Comparison

5.9 FLEXURAL MODULUS

Due to inconsistencies with data output from the testing machine, the flexural modulus could not be determined.

6 DEVELOPING AN EQUATION FOR MODULUS OF ELASTICITY

The development of an equation for the modulus of elasticity is presented for both vinylester and epoxy polymer concrete. It was required that mathematical models be developed to separately fit both trends of data represented in figure 5.31. It was decided that a polynomial curve fitting technique be employed to achieve this (James, 2007).

Polynomial curve fitting involves finding *n* roots of polynomial of order *j*. A second order polynomial was chosen for vinylester and epoxy data and thus required finding 3 roots, represented thus-:

$$E_{pc} = AF^2 + BF + C \tag{6.1}$$

where
$$A$$
, B and C are roots
 F is volume percentage of fly ash $\leq 23\%$

where

$$F = (100 - 57 - R)\% \tag{6.2}$$

$$F = (43 - R)\% \tag{6.3}$$

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However due to workability issues,

$$R \geq 20\%$$

thus,

$$F = (23 - R)\% \tag{6.4}$$

Using the data points from figure 5.31 and Microsoft $Excel^{
entropy}$ software, roots A, B and C were determined as shown in table 6.1:

Root	Vinylester	Ероху		
А	-0.0247	0.0188		
В	1.5781	-0.0219		
С	28.6000	45.6640		

Table 6.1 Polynomial roots for equation 6.1

Inputting the values from table 6.1 into (6.1), the following equations were derived:

For vinylester polymer concrete:

$$E_{wc} = -0.0247F^2 + 1.5781F + 28.6 \tag{6.5}$$

For epoxy polymer concrete:

$$E_{ec} = 0.0188F^2 - 0.0219F + 45.6640 \tag{6.6}$$

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Using (6.5) and (6.6) where fly ash volume percentage is within the limits of $0\% \le F \le 23\%$, the elastic modulii were plotted against the experimental data as shown in figure 6.1.



Figure 6.1 Experimental versus analytical (Modulus of elasticity)

% Resin	% FA	Vinylester PC			Ероху РС		
		Experimental	Analytical	% Diff.	Experimental	Analytical	% Diff.
43	0	45.66	45.34	-0.71	28.50	28.60	0.35
40	3	45.77	47.27	3.18	33.30	33.11	-0.57
30	13	48.56	52.55	7.60	44.70	44.94	0.54
22	21	53.49	55.51	3.63	51.30	50.85	-0.89
20	23	55.11	56.07	1.72	51.50	51.83	0.64

 Table 6.2
 Experimental versus analytical variation

7 SUMMARY

7.1 COMPRESSIVE STRENGTH

Tables 7.1, 7.2 and 7.3 summarise the compressive strength results presented in section 5 for all batches at 7, 21 and 28 days respectively.

7 day	Resin	FA	Vinylester PC	% Difference (V & E)	Ероху РС
7	43	0	105.84	-33%	71.37
7	40	3	105.34	-31%	72.85
7	30	13	83.61	-13%	72.81
7	22	21	84.19	-9%	76.31
7	20	23	75.01	7%	80.48

Table 7.1 Summary of 7 day compressive results

For 7 day, the results show that there is a decrease in compressive strength for mix designs where fly ash content is less than 21% when comparing a corresponding batch for vinylester and epoxy polymer concrete.

A difference of 33% decrease from vinylester to epoxy polymer concrete is evident when fly ash content is zero, whereas an increase of 7% compressive strength is evident at maximum fly ash content of 23%.

This trend shows that vinylester polymer concrete at 7 days exhibits greater compressive strength than epoxy polymer concrete when the resin content is increased and fly ash decreased.

21 day	Resin	FA	Vinylester PC	% Difference (V & E)	Ероху РС
21	43	0	109.07	-29%	77.60
21	40	3	97.76	-14%	83.88
21	30	13	95.70	-9%	87.31
21	22	21	95.76	-8%	87.85
21	20	23	82.25	13%	93.22

Table 7.2Summary of 14 day compressive results

Similarly for 21 days, the results show that there is a decrease in compressive strength for mix designs where fly ash content is less than 21% when comparing a corresponding batch for vinylester and epoxy polymer concrete.

A difference of 29% decrease from vinylester to epoxy polymer concrete is evident when fly ash content is zero, whereas an increase of 13% compressive strength is evident at maximum fly ash content of 23%. This equates to an increase of approximately 3.5MPa and 7.5MPa at F=0. An increase of approximately 7.2MPa and 13MPa is evident at F=23 for vinylester and epoxy polymer concrete respectively.

This trend also shows that vinylester polymer concrete at 21 days exhibits greater compressive strength than epoxy polymer concrete when the resin content is increased and fly ash decreased.

These results also show that when the age of the concrete increases, the percentage increase in strength for epoxy polymer concrete is greater than that for vinylester polymer concrete. For example, the increase in strength

over a 14 day period for vinylester and epoxy polymer concrete is 2.96% and 8.03% respectively when fly ash content equals zero.

Its also interesting to note that there is a 7.58 MPa decrease for vinylester polymer concrete S57V40F3 between 7 days and 21 days. This may be due to an inconsistency of testing data of this batch which was tested separately to all other batches.

28 day	Resin	FA	Vinylester PC	% Difference (V & E)	Ероху РС
28	43	0	113.84	-19%	91.97
28	40	3	100.85	-8%	92.92
28	30	13	98.22	-5%	92.85
28	22	21	94.98	8%	102.91
28	20	23	93.48	10%	102.95

Table 7.3 Summary of 28 day compressive results

For 28 days, the results show that there is a decrease in compressive strength for mix designs where fly ash content is less than approximately 15% when comparing a corresponding batch for vinylester and epoxy polymer concrete.

A difference of 19% decrease from vinylester to epoxy polymer concrete is evident when fly ash content is zero, whereas an increase of 8% and 10% compressive strength is evident at fly ash contents of 21% and 23% respectively. This equates to an increase of approximately 4MPa and 13MPa at F=0. An increase of approximately 11MPa and 10MPa is evident at F=23 for vinylester and epoxy polymer concrete respectively. This trend shows that vinylester polymer concrete at 28 days exhibits greater compressive strength than epoxy polymer concrete when the resin content is increased and fly ash decreased.

These results also show that when the age of the concrete increases, the percentage increase in strength for epoxy polymer concrete is greater than that for vinylester polymer concrete. For example, the increase in strength over a 7 day period for vinylester and epoxy polymer concrete is 15.62% and 4.19% respectively when fly ash content equals zero.

PC	7 days			21 days			28 days		
	F=0	F=23	% Diff	F=0	F=23	% Diff	F=0	F=23	% Diff
Vinyl	105	75	-29	109	82	-25	114	93	-18
Ероху	71	80	13	79	83	5	92	103	12

Table 7.4 Summary of compressive results between F=0 and F=23

Table 7.4 shows the percentage differences of compressive strengths of vinylester and epoxy polymer concrete between minimum and maximum fly ash contents.

In summary, a maximum compressive strength of 114 MPa was showcased for vinylester polymer concrete which was at F=0. A maximum compressive strength of 103 MPa was showcased for epoxy polymer concrete which was at F=23. The 28 day compressive strength point of intersection as shown on figure 5.10 for vinylester and epoxy polymer concrete is at a mix design of

approximately S57R27F16, where the compressive strength is approximately 97MPa.

7.2 MODULUS OF ELASTICITY

For vinylester polymer concrete, the results show that there is a slight increase in elastic modulus between 0 - 13% fly ash, then a sudden increase from approximately 47GPa to 57GPa up to 21% fly ash and finally reduces to approximately 55GPa at maximum fly ash content.

For epoxy polymer concrete, the results show that there is a curvilinear increase in elastic modulus between 0 - 23% fly ash, corresponding to an increase from approximately 29GPa up to 51GPa.

Both polymer concrete types show an increase in elastic modulus when increasing the fly ash content and reducing the resin content. In comparison, vinylester showcases a higher elastic modulus for all mix designs, however shows a smaller total increase between 0 - 23% fly ash.

Vinylester exhibits a 17.54% total increase in elastic modulus whilst epoxy exhibits a 43.13% total increase which in comparison is 2.46 times greater than vinylester.

The stress strain curves in figures 5.32 and 5.33 highlight the fact that as the fly ash content decreases and subsequently resin content increases, the elastic moduli decreases. This suggests that the mechanical properties of the resin in both polymer concrete types allows the concrete to deform in a ductile manner without sudden failure, hence the more resin the more ductile the concrete.

This is also evident in that the strain rate is greater when the resin content is increased. The curves for both polymer concrete types also show that the stress strain ratio decreases as the resin content increases meaning that the concrete can better withstand load over larger deformations. This again reinforces the fact that an increase in resin content allows the concrete to act in a more ductile manner. Batches S57E40F3 and S57E43 (low fly ash content) in particular showcase a very low stress strain ratio and during testing did not fail, but rather showed typical 45° shear planes.

7.3 TENSILE STRENGTH

The split tensile strengths for vinylester and epoxy polymer concretes are very similar. Referring to figure 5.45, both concrete types show a decrease in split tensile strength when fly ash is increased and subsequently resin is decreased.

The maximum tensile strength for vinylester polymer concrete is approximately 15.2MPa and decreases to approximately 10.8MPa, equating to a decrease of 28.95%. The maximum tensile strength for epoxy polymer concrete is approximately 14.8MPa and decreases to approximately 12.5MPa, equating to a decrease of 15.54%.

Resin	FA	Vinylester PC	% Difference (V & E)	Ероху РС
43	0	15.20	-3%	14.80
40	3	15.20	-7%	14.10
30	13	14.00	-4%	13.50
22	21	11.95	4%	12.40
20	23	10.80	16%	12.50

Table 7.5 Summary of tensile strength results between F=0 and F=23

Similar to the behaviour of the compressive strength for both concrete types, epoxy polymer concrete shows a greater tensile strength than that for vinylester polymer concrete with an increase in fly ash as can be seen in table 7.5. The split tensile strength point of intersection as shown on figure 5.45 for vinylester and epoxy polymer concrete is at a mix design of approximately S57R26.5F16.5, where the split tensile strength is approximately 12.8MPa.

Table 7.6 shows a comparison of the tensile and compressive strengths for all batches of polymer concrete at 7 days. The results show for vinylester polymer concrete that the tensile strength is constant at approximately 14.5% of its corresponding compressive strength. The 16.75% for batch S57V30F13 is high due to the low corresponding compressive strength value. The tensile strength of 14MPa at S57V30F13 appears to be consistent with respect to other batches of concrete. The results show for epoxy polymer concrete that the tensile strength relative to its corresponding compressive strength gradually increases as the fly ash content decreases. Values of between 15% - 21% are evident for epoxy polymer concrete.

Resin F	EA		Vinylester PC		Epoxy PC			
	FA	f'c (MPa)	f'ct.sp (MPa)	f'ct.sp/f'c (%)	f'c (MPa)	f'ct.sp (MPa)	f'ct.sp/f'c (%)	
43	0	105.84	15.20	14.36%	71.37	14.80	20.74%	
40	3	105.34	15.20	14.43%	72.85	14.10	19.36%	
30	13	83.61	14.00	16.75%	72.81	13.50	18.54%	
22	21	84.19	11.95	14.19%	76.31	12.40	16.25%	
20	23	75.01	10.80	14.40%	80.48	12.50	15.53%	

Table 7.6 Summary of tensile strength results between F=0 and F=23

8 CONCLUSION

In conclusion, the behaviour and mechanical properties of filler materials including vinylester and epoxy polymer concrete have been determined and found to be excellent. Both vinylester and epoxy polymer concretes exhibited excellent mechanical properties with respect to traditional cement based concrete, where compressive strengths up around 100MPa were Typically, traditional cement based concrete exhibits showcased. compressive strengths of around 30-40MPa, less than half that of strengths offered by polymer concrete. The modulus of elasticity for vinylester and epoxy polymer concrete exhibited values of up to between 50 - 57GPa, almost twice that of traditional cement based concrete. Tensile strengths between 10-15MPa were commonly seen for both polymer concrete types, 3-5 times that of traditional cement based concrete. Unfortunately, the flexural modulus was unable to be determined due to problems with data output.

With a combination of excellent mechanical properties, low water absorption, ability to withstand environmental conditions, chemical attack and freezethaw degradation and ability to adhere to other materials, polymer concrete with a mix designs of sand, fly ash and resin provides an excellent material for many structural engineering applications including timber pile rehabilitation.

Further work required to determine the materials' suitability for infilling fibre composite tubes includes the following:

- ü Bonding strength between the interface of FRP and pile
- ü Underwater application
- ü Shrinkage

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10 APPENDIX A – PROJECT SPECIFICATION

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project PROJECT SPECIFICATION

- FOR: **ANDREW O'KEEFFE**
- TOPIC: BEHAVIOUR OF POLYMER BASED FILLERS FOR INFILLING FIBRE COMPOSITE TUBES
- SUPERVISORS: DR. WEENA LOKUGE ASSOCIATE PROFESSOR THIRU ARAVINTHAN
- ENROLEMENT: ENG 4111 SEM 1, 2011

ENG 4112 – SEM 2, 2011

PROJECT AIM: This project aims to study the behaviour of epoxy and vinylester resin based filler material suitable for infilling fibre composite tubes.

PROGRAMME: Issue B, 27 July 2011

1. Research the background information related to epoxy, vinylester and polyester polymer concrete, including:

- Ø Properties
- Ø Behaviours
- Ø Applications
- 2. Research current and traditional methods of timber bridge pile rehabilitation
- Test epoxy and vinylester polymer concrete with different proportions of resin, fly ash and sand at different ratios for compressive strengths at 7, 21 and 28 days
- 4. Test epoxy and vinylester polymer concrete with different proportions of resin, fly ash and sand at different ratios for tensile strengths at 7 days
- 5. Test epoxy and vinylester polymer concrete with different proportions of resin, fly ash and sand at different ratios for flexural modulus at 7 days
- Undertake a 7 day modulus of elasticity analysis on all composite mix design ratios and propose an equation for the modulus of elasticity of epoxy and vinylester polymer concrete
- Compare compressive strength, tensile strength, flexural modulus and modulus of elasticity results of epoxy, vinylester and polyester polymer concrete

AGREED:

Andrew O'Keeffe	Date:	//2011
Dr. Weena Lokuge	_Date:/	//2011
Associate Professor Thiru Aravinthan	Date:	//2011

11 APPENDIX B - GEOMETRICAL SPECIMEN DATA

ID	Batch	L (mm)	D ₁ (mm)	D ₂ (mm)	D _{av} (mm)	Area (mm2)	Load (kN)	Age (days)
1	S57V43	104.40	51.88	51.90	51.89	2114.74	230.28	7
2	S57V43	100.81	51.96	51.89	51.93	2117.59	220.98	7
3	S57V43	100.62	52.03	52.01	52.02	2125.35	221.58	7
4	S57V40F3	91.53	52.25	52.70	52.48	2162.69	226.06	7
5	S57V40F3	92.71	52.26	52.76	52.51	2165.58	229.62	7
6	S57V40F3	91.35	52.28	52.26	52.27	2145.83	233.93	7
7	S57V40F3	92.37	52.33	52.35	52.34	2151.58	215.37	7
8	S57V40F3	89.48	52.19	52.23	52.21	2140.90	229.13	7
9	S57V30F13	52.16	52.26	52.21	52.24	2140.90	176.97	7
10	S57V30F13	52.44	51.77	52.11	51.94	2132.30	173.98	7
11	S57V30F13	101.45	52.42	52.10	52.26	2145.01	182.78	7
12	S57V30F13	102.80	52.36	52.61	52.49	2163.52	181.37	7
13	S57V30F13	99.96	52.63	52.09	52.36	2153.22	182.46	7
14	S57V22F21	108.64	52.53	52.12	52.33	2150.35	187.33	7
15	S57V22F21	104.21	52.91	52.18	52.55	2168.47	189.71	7
16	S57V22F21	102.62	52.35	52.15	52.25	2144.19	177.04	7
17	S57V22F21	99.69	52.77	52.07	52.42	2158.16	171.80	7
18	S57V22F21	100.30	52.08	51.82	51.95	2119.63	209.50	7
19	S57V20F23	100.27	52.26	52.60	52.43	2158.98	119.63	7

20	S57V20F23	104.02	52.90	52.21	52.56	2169.29	158.79	7
21	S57V20F23	102.89	52.94	52.31	52.63	2175.07	160.42	7
22	S57V20F23	100.87	52.27	51.90	52.09	2130.67	164.18	7
23	S57V20F23	101.11	52.34	51.92	52.13	2134.35	162.31	7

Table 10.1 7 day Compressive specimen data (Vinylester PC)

ID	Batch	L (mm)	D ₁ (mm)	D ₂ (mm)	D _{av} (mm)	Area (mm2)	Load (kN)	Age (days)
15	S57E43	104.80	52.71	52.59	52.65	2177.14 159.79		7
16	S57E43	102.90	52.73	52.57	52.65	2177.14	151.40	7
17	S57E43	103.80	53.08	52.53	52.81	2189.98	155.85	7
18	S57E40F3	102.67	52.83	52.43	52.63	2175.49	162.57	7
19	S57E40F3	98.28	53.11	52.53	52.82	2191.22	160.25	7
20	S57E40F3	103.93	52.60	52.81	52.71	2181.69	154.19	7
21	S57E30F13	103.21	52.84	52.47	52.66	2177.55	101.33	7
22	S57E30F13	103.41	52.85	52.46	52.66	2177.55	159.48	7
23	S57E30F13	103.33	52.95	52.47	52.71	2182.11	156.02	7
24	S57E30F13	102.44	53.10	52.50	52.80	2189.56	161.34	7
25	S57E22F21	102.35	53.18	52.44	52.81	2190.39	174.22	7
26	S57E22F21	102.49	52.63	52.47	52.55	2168.88	160.85	7
27	S57E22F21	104.81	52.75	52.49	52.62	2174.66	163.58	7
28	S57E20F23	108.79	52.42	53.19	52.81	2189.98	170.22	7
29	S57E20F23	97.01	53.10	52.53	52.82	2190.81	182.36	7

30	S57E20F23	104.30	52.71	52.56	52.64	2175.90	126.17	7
31	S57E20F23	103.02	52.93	52.50	52.72	2182.52	148.33	7

Table 10.2 7 day Compressive specimen data (Epoxy PC)

ID	Batch	L (mm)	D ₁ (mm)	D₂ (mm)	D _{av} (mm)	Area (mm2)	Load (kN)	Age (days)
32	S57V43	97.69	52.60	52.16	52.38	2154.87	237.00	21
33	S57V43	91.35	52.40	52.30	52.61	2173.83	235.13	21
34	S57V40F3	98.61	52.23	52.24	52.24	2142.96	211.56	21
35	S57V40F3	97.50	52.54	52.37	52.46	2161.04	209.20	21
36	S57V30F13	94.51	52.53	52.19	52.36	2153.22	202.84	21
37	S57V30F13	99.39	52.15	52.62	52.39	2155.28	209.50	21
38	S57V22F21	102.75	52.79	52.17	52.48	2163.10	212.41	21
39	S57V22F21	102.63	52.37	52.22	52.30	2147.88	200.45	21
40	S57V20F23	97.16	52.88	52.28	52.58	2171.36	185.12	21
41	S57V20F23	99.77	52.85	52.33	52.59	2172.18	172.15	21

Table 10.3 21 day Compressive specimen data (Vinylester PC)

ID	Batch	L (mm)	D ₁ (mm)	D ₂ (mm)	D _{av} (mm)	Area (mm2)	Load (kN)	Age (days)
42	S57E43	105.74	52.86	52.55	52.71	2181.69	165.28	21
43	S57E43	105.01	52.96	52.63	52.80	2189.15	173.89	21
44	S57E40F3	105.01	52.91	52.45	52.68	2179.62	182.62	21

45	S57E40F3	105.16	52.57	53.10	52.84	2192.47	184.09	21
46	S57E30F13	108.30	52.41	52.92	52.67	2178.38	190.20	21
47	S57E22F21	102.43	52.47	52.96	52.72	2182.52	182.60	21
48	S57E22F21	102.78	52.53	52.08	52.31	2148.70	197.75	21
49	S57E20F23	102.70	53.13	52.57	52.85	2193.71	204.49	21

Table 10.4 21 day Compressive specimen data (Epoxy PC)

ID	Batch	L (mm)	D ₁ (mm)	D ₂ (mm)	D _{av} (mm)	Area (mm2)	Load (kN)	Age (days)
50	S57V43	99.93	52.36	52.13	52.25	2143.78	244.25	28
51	S57V43	103.24	52.73	52.09	52.41	2157.34	242.41	28
52	S57V43	101.01	52.48	52.09	52.29	2147.06	247.37	28
53	S57V40F3	94.27	52.12	52.15	52.14	2134.76	216.63	28
54	S57V40F3	96.84	52.02	52.13	52.08	2129.85	212.99	28
55	S57V40F3	96.63	52.1	52.31	52.21	2140.49	216.36	28
56	S57V30F13	106.35	52.69	52.3	52.50	2164.34	216.40	28
57	S57V30F13	105.87	52.13	52.63	52.38	2154.87	214.47	28
58	S57V30F13	106.02	52.71	52.18	52.45	2160.22	205.55	28
59	S57V22F21	107.34	52.79	52.26	52.53	2166.82	212.77	28
60	S57V22F21	107.90	52.87	52.17	52.52	2166.40	197.69	28
61	S57V22F21	107.62	52.88	52.17	52.53	2166.82	206.91	28
62	S57V20F23	106.35	52.31	52.67	52.49	2163.93	204.35	28
63	S57V20F23	107.12	52.79	52.22	52.51	2165.17	201.83	28

64	S57V20F23	107.34	53.06	52.17	52.62	2174.25	201.77	28
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Table 10.5 28 day Compressive specimen data (Vinylester PC)

ID	Batch	L (mm)	D ₁ (mm)	D₂ (mm)	D _{av} (mm)	Area (mm2)	Load (kN)	Age (days)
65	S57E43	104.77	53.14	52.58	52.86	2194.54	199.63	28
66	S57E43	105.07	52.56	52.69	52.63	2175.07	200.40	28
67	S57E43	104.79	52.46	52.13	52.30	2147.88	199.31	28
68	S57E40F3	105.73	52.93	52.49	52.71	2182.11	199.23	28
69	S57E40F3	105.62	52.59	52.93	52.76	2186.25	197.89	28
70	S57E40F3	105.08	52.52	52.89	52.71	2181.69	211.49	28
71	S57E30F13	107.42	53.00	52.41	52.71	2181.69	204.35	28
72	S57E30F13	106.51	52.86	52.42	52.64	2176.31	201.83	28
73	S57E30F13	106.19	53.15	52.45	52.80	2189.56	201.77	28
74	S57E22F21	107.93	52.80	52.46	52.63	2175.49	217.12	28
75	S57E22F21	102.25	53.11	52.51	52.81	2190.39	228.58	28
76	S57E22F21	107.26	52.69	52.47	52.81	2190.39	229.02	28
77	S57E20F23	106.99	52.44	53.08	52.76	2186.25	228.20	28
78	S57E20F23	107.34	52.51	52.97	52.74	2184.59	223.47	28
79	S57E20F23	107.24	52.43	53.06	52.75	2185.01	223.28	28

Table 10.6 28 day Compressive specimen data (Epoxy PC)

Batch	L (mm)	D1 (mm)	D2 (mm)	D _{av} (mm)	Load (kN)	Age (Days)
S57V43	94.45	52.43	52.15	52.29	112.8	7
S57V43	88.99	52.31	52.12	52.22	113.8	7
S57V43	99.20	52.09	52.37	52.23	129.1	7
V40F3	98.86	52.23	52.31	52.27	124.0	7
V40F3	97.13	52.09	52.12	52.11	137.8	7
V40F3	98.77	52.18	52.04	52.11	124.4	7
S57V30F13	98.47	52.46	52.07	52.27	56.2	7
S57V30F13	103.01	52.09	52.51	52.30	122.1	7
S57V30F13	102.97	52.67	52.07	52.37	115.1	7
S57V22F21	108.37	52.68	52.15	52.42	113.7	7
S57V22F21	108.82	52.72	52.21	52.47	110.1	7
S57V22F21	104.44	52.74	52.17	52.46	91.5	7
S57V20F23	103.00	52.29	53.38	52.84	49.1	7
S57V20F23	100.29	52.68	52.19	52.44	86.8	7
S57V20F23	101.69	52.30	52.76	52.53	91.0	7

Table 10.7 Tensile specimen data (Vinylester PC)

Batch	L (mm)	D1 (mm)	D2 (mm)	D _{av} (mm)	Load (kN)	Age (Days)
S57E43	97.69	53.34	52.58	52.96	123.8	7
S57E43	94.35	52.79	52.55	52.67	111.5	7
S57E43	102.57	53.09	52.57	52.83	123.2	7
S57E40F3	101.85	53.13	52.56	52.85	128.7	7
S57E40F3	96.40	52.77	52.43	52.60	117.1	7
S57E40F3	103.18	52.86	52.46	52.66	110.5	7
S57E30F13	104.02	53.13	52.48	52.81	108.9	7
S57E30F13	103.40	52.80	52.46	52.63	123.0	7
S57E30F13	104.10	53.09	52.46	52.78	85.1	7
S57E22F21	102.33	52.77	52.42	52.60	101.7	7
S57E22F21	102.65	53.13	52.22	52.68	107.5	7
S57E22F21	104.34	52.49	53.01	52.75	85.9	7
S57E20F23	103.91	52.77	52.45	52.61	98.9	7
S57E20F23	104.00	52.79	52.42	52.61	100.5	7
S57E20F23	109.42	52.99	52.51	52.75	128.6	7

Table 10.8 Tensile specimen data (Epoxy PC)