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Review

A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties

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ABSTRACT

The paper discusses the development of the advanced polymer composite material applications in the building and civil/structural infrastructure over the past three to four decades. It endeavours to identify and prioritise the important in-service research areas which are necessary to improve the understanding of the behaviour of FRP materials and FRP structural components. The paper demonstrates the types of structures which have been developed from the FRP composite material and the most advantageous way to employ composites in civil engineering. The material has extraordinary mechanical and important in-service properties which when combined with other materials are utilised to improve the stiffness/strength, durability, the whole-life cost benefit and the environmental impact. The paper concludes by summarising key successes of the advanced polymer composite in the civil infrastructure and suggests areas in which, if they are employed innovatively, FRP composites could be used with great advantage.

1. Introduction

For more than 30 years following the Second World War the construction industry showed a lack of investment in research and development and consequently potential material investors, in the technological revolution in materials and in their processing techniques, were being explored in other sectors of the manufacturing industry and inevitably the construction industry was bypassed, Latham [134] and Egan [61]. Nevertheless, notwithstanding the criticisms by these authors there is evidence in the late 1970s and into the 1980s of an interest by the research departments of universities, research institutes and a few civil engineering consultants in advanced polymer composite (APC) materials; these materials consist of high-strength and stiffness fibres protected by a high-performance thermosetting polymer. The early research and development and the innovations in structural and civil engineering APC systems was instrumental in the current interest, throughout the world, in the use of APC in the civil engineering industry.

The polymer composite derives its mechanical characteristics wholly from those of the fibre and the quality of the fibre/matrix interface, therefore the most important properties required of the polymer is its physical and in-service characteristics. High-performance thermosetting resins are required to provide specific properties in highly demanding environments. These matrices must possess high dimensional stability at elevated temperatures and thermal resistance, low water absorption, good chemical resistance, high mechanical strength, excellent stiffness and high compressive strength. This combination of properties is essential for advanced composites to be utilised in the construction industry, but due to the increase in cross-linking density observed during polymerisation, conventional thermosetting matrices are considered to be brittle and this limits the damage tolerance of the composite, O'Brien [176], Hollaway [98].

Before discussing the current and future composite structural systems used in the civil infrastructure it is important to discuss the characteristics of the material which make them attractive in some areas of construction and other characteristics which require to be improved before full confidence in the material is achieved. This paper, therefore, will be divided into two parts.

Part A will examine the in-service and physical properties of polymers and composites for utilisation in civil engineering. These characteristics are fundamental for a successful structural system to be used in the civil infrastructure.

Part B will demonstrate how these unique characteristics of APCs can be used to form,

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- 'All-FRP-composite' structures.
- Combined with other engineering materials to improve the stiffness, strength and durability of the overall composite structural member.
- Future generations of FRP structural members associated with the construction industry.

The mechanical properties of the component parts of the composite are clearly important but this area has been well documented, Hollaway and Head [90], Hull and Clyne [107], Kim [125] and only a brief discussion will be included in Part A as (a) mechanical properties will be affected by the in-service properties over time and (b) for completeness. Likewise, a brief discussion will be given of the mechanical properties of the FRP composite; typical mechanical values are given in Appendix A.

In civil engineering the APC is generally referred to as the fibre-reinforced polymer (FRP) composite; this description will be used throughout this paper.

2. Part A: the important physical and in-service properties of thermosetting polymers used in the civil infrastructure

2.1. Introduction

The FRP engineering structural composites must possess not only sufficient strength and stiffness properties to resist the full superimposed and self-weight loads to which the structure is exposed but also the relevant in-service and physical characteristics required to function in the aggressive and sometimes hostile environments encountered in the construction industry; these latter characteristics are clearly just as important as the mechanical properties. The greater the degradation of structures over time the lower will be their load carrying capacity. Consequently, the most important properties of the matrix (the polymer), which protects the load carrying fibre component of the composite, are its physical and in-service characteristics.

The vinyl-esters, the epoxies and the polyesters are the thermosetting matrices which are utilised for composite structural members in the civil infrastructure; all are crossed linked. A wide range of amorphous and crystalline polymer materials (an amorphous and a crystalline polymer are those in which there is a random order of their atoms and those in which there is an orderly repeating pattern of their atoms, respectively) can be used to form fibres. In the construction industry the three fibres which are invariably used are the glass, the aramid and the carbon fibres. The basic mechanical properties of the component parts of the composites, their interaction and the techniques for the manufacture of the fibres and the composite materials have been discussed many times in a number of publications, Kim [125], Hollaway and Head [90], Karbhari [118], Hollaway [98] and will not be dealt with here. However, the physical and in-service characteristics of the component parts of the FRP composite will be discussed in the subsequent sections. These characteristics are of primary importance in relation to the durability of the polymer and hence of the FRP composite.

2.2. Polymerisation

It is essential that polymers are manufactured correctly for them to perform their in-service functions efficiently. Polymerisation is a process of bonding together repeating molecular building blocks, known as monomers, through a variety of reaction mechanisms to form large chainlike or network molecule of relatively high molecular mass known as a polymer. At least one hundred and often thousands of monomer molecules must be combined to form a product that has certain physical properties such as high-modulus of elasticity and high tensile strength values or has the ability to form fibres. There are two classes of polymerisation, these are:

- *Addition polymerisation* is a process in which monomers react to form a polymer without the formation of by-products. Addition polymerisation is usually undertaken in the presence of a catalyst, which in certain cases controls the structural properties of the polymer. In this process monomers are dissolved in a solvent that is later removed. The monomers quickly combine by an addition reaction without losing any atoms, so that the polymer has the same basic formula as the monomer.
- *Condensation polymerisation* is a slower stepwise reaction. It results in the loss of atoms or groups of atom as by-products of the linking monomers. Most condensation polymerizations are of a kind of copolymerization, usually consisting of two or more types of monomers. The number of monomers in a polymer determines the degree of polymerization of the polymer. When the number of monomers is high, the compound is said to have a high degree of polymerization and is called a high polymer.

As mentioned earlier thermosetting resins are crossed linked polymers, in which their molecular structure is a network. These resins are formed under the influence of heat and once formed they do not melt or soften upon reheating, and do not dissolve in solvents; they can be made by either addition or condensation polymerisation. It is essential that the correct mix ratio is obtained between the epoxy resin and the curing agent to ensure that a complete reaction does take place as the curing agent molecules 'co-react' with the thermosetting resin molecules in a fixed ratio. If the mix is not in the correct proportions, un-reacted resin or curing agent will remain within the matrix, and this will affect the final properties of the polymer after cure.

There are two procedures which are used to polymerise a thermosetting polymer for the civil engineering industry, these are:

- *The cold cured systems* where the polymer is cured (polymerised) at ambient temperature on site, generally in the region of 10–30 °C; the lower the curing temperature the longer is the cure time. It is advisable with cold cure resins to provide a post cure with a higher temperature over an extended period of time. This regrettably is not generally done on civil engineering site.
- *The hot cured system* where the polymerisation is performed in a factory environment at elevated temperatures of the order of 130 °C; this is generally an automated production procedure.

The cold and hot cured resins have different formulations, consequently, a hot cured system cannot be polymerised using a cold curing agent and vice versa. Attention must be given to the site temperature when using the cold cure polymers; the environmental temperature under working conditions should be some 20° C below the *glass transition temperature* (T_g).

2.3. Temperature

The influence of temperature on polymers can be separated into two effects:

- short-term and
- long-term.

The short-term effect is generally physical and is reversible when the temperature returns to its original state, whereas the