Flexible Polymer-Cement Repair Materials and Their Applications

Ivan Razl, Ph.D., P.Eng.
Gemite Products Inc., Mississauga, Ontario, Canada

ABSTRACT: Polymer modification of cement paste increases the tensile and flexural strength of mortars and concrete and reduces their brittle nature. Since the polymer-modified cement is a composite of two entirely different types of materials, the characteristics of the key components, cement and polymer, will be briefly described. Classification of the polymers used in modification is followed by a description of the main characteristics of flexible polymer-modified cement composites and their applications in concrete repair.

1 INRODUCTION

Portland cement based concrete and mortar are among the most widely used construction materials. Low cost, high stiffness, high compressive strength, non-flammability and ease of fabrication are the most obvious advantages of concrete, whilst low tensile strength, brittleness and, to some extent, long term durability represent its most serious limitations. Reinforcing the concrete with steel provides the necessary tensile strength and the incorporation of fibres increases its toughness (resistance to crack propagation). Polymer modification of cement paste increases its tensile and flexural strength and reduces its brittle nature by increasing toughness of mortars and concrete. In this presentation we will briefly review the field of polymer modified concrete and mortars. Since the polymer modified cement is a composite of two entirely different types of materials, the characteristics of the key components, cement and polymer, will be briefly described. Classification of the polymers used in modification is followed by a description of the main characteristics of polymer-modified cements and their applications in concrete repair. The presentation will then describe performance characteristic and applications of novel highly flexible, polymer modified cement composites. We will conclude by showing that future use of polymer modified cement composites will likely be in the area of durability and performance improvements of cement materials applied in thin sections.

2 BRIEF HISTORY

The ancient history of using natural polymers including asphalt to modify lime and clay mortars goes back to the Babylonians, Egyptians and ancient India. Europeans in the Middle Ages knew how to use ox blood and egg white to increase the toughness and durability of lime mortars. The modern history of man-made modifiers starts in the late fifties with the development of butadiene styrene, polychloroprene and acrylic latex and their use in modifying mortars and concrete. The main application of latex polymer modified cements at that time was in concrete repair. The use of polymers in the fabrication of bridge and parking garage overlays was developed in the USA and Canada in the early seventies. The function of the polymer was mainly to reduce concrete permeability and to increase resistance to chloride penetration, toughness and adhesion. Dry polymer modifiers, so called redispersable powders, based on ethyl-vinyl acetate (EVA), polyvinyl acetate-vinyl carboxylate, (VA/VeovVa), acrylics, styrene-acrylics and others were introduced in the early eighties. Dry polymer modifiers allow the formulation of one-component systems. Initially dry polymer modifiers were inferior in many aspects to polymer emulsion (latex) but more recently the dry polymers are becoming as effective as their chemical equivalents in the latex form.

3 CLASSIFICATION

Polymer modified Portland cement paste is a composite material consisting of an inorganic cement paste and polymer. Each material is different and it is beyond the scope of this presentation to discuss the individual characteristics of these two components. We will only define Portland Cement, Polymer and Composite Material (Encyclopedia Britannica).

"Portland cement is a binding material in the form of a finely ground powder, usually gray, that is manufactured by burning and grinding a mixture of limestone and clay or limestone and shale. When mixed with water, the anhydrous calcium silicates and other constituents in the Portland cement react chemically with the water, combining with it (hydration) and decomposing in it (hydrolysis), hardening and developing strength".

"Polymer is any of class of natural or synthetic substances composed of very large molecules, called macro-molecules, that are multiples of chemical units called monomers".

"Composite Material is a solid material that results when two or more different substances, each with its own characteristics, are combined to create a new substance whose properties are superior to those of the original"

For the purpose of this paper we are using the word "cement" to describe "mortars" based on Portland cement binder, but the word "cement" does not exclude other cement binders and pozzolanic or other inorganic admixtures, that can be used as part of the mortar composition. The performance characteristics of polymer-modified cement are controlled by the characteristics of its individual components. The main characteristics of hydrated Portland cement paste and polymer are summarized in Table 1.

Table 1. The basic characteristics of polymer and hydrated Portland cement paste.

Polymer	Hydrated Cement Paste
Organic	Inorganic
Low modulus of elasticity	High modulus of elasticity
High tensile strength	Low tensile strength
High elongation	Low elongation
High fracture toughness	Low fracture toughness
Temperature sensitive	Temperature insensitive

The type of cement, the type of polymer and their respective quantities mainly control the properties of polymer-cement composites. Other influences controlling the final properties of the composite include the type of surface-active agents used, mixing, curing, etc. There are a large

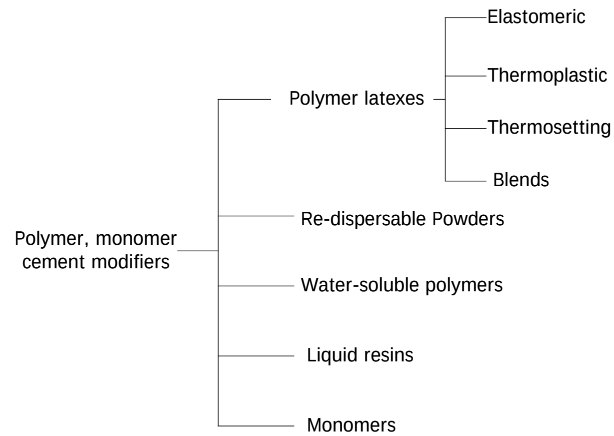

Figure 1. Classification of polymer (monomer) modifiers of cement paste.

number of polymer (monomer) types that are used in modification of Portland cement paste. Figure 1, (Chandra & Ohama 1994), shows the main classes of materials available. For the purpose of this presentation we will direct our attention primarily to polymer latexes. These types of polymers can be further classified by their chemical nature. Since we are mainly interested in flexibility of polymer cement composites, we need to introduce the term "glass transition temperature "T_g" of a polymer. Below the T_g temperature, polymers exhibit "glassy" behavior and are relatively brittle with limited flexibility. At temperatures above T_g, the polymer is more flexible and tough and exhibits a larger elongation in tension. At T_g properties such as specific volume, specific heat, dielectric coefficient, rates of gas/liquid diffusion through the polymer and conductivity change as shown in Figure 2.

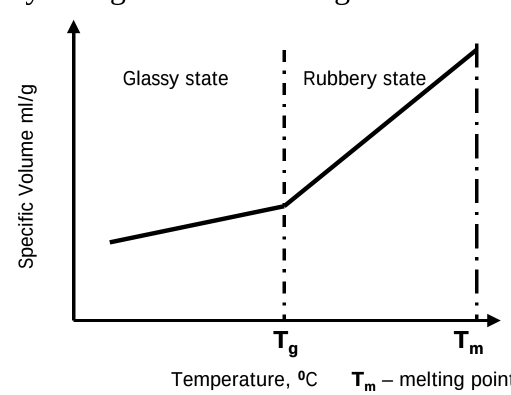

Figure 2. Glass Transition Temperature (T_g) of an amorphous (non-crystalline) polymer.

4 POLYMER MODIFICATION MECHANISM

The mechanism of polymer modification of Portland cement paste is complex but can be schematically described in three separate steps:

1. Immediately after mixing with water, the cement paste particles start to hydrate and cement gel begins to form on the surface of the cement particles.
2. The mixture of cement gel covered unhydrated cement particles is enveloped with a close-packed layer of polymer particles.
3. In the third step, the removal of water by hydration and evaporation, the closely packed polymer particles start forming polymer films (membranes).

5 PROPERTIES OF FLEXIBLE POLYMER MODIFIED CEMENT (FPMC)

Polymer modification of cement paste changes the properties of mortar and concrete. These effects depend mainly on the polymer content, expressed as polymer/cement ratio, the type of polymer and also the design of the mortar or concrete. Typical effects are summarized in Table 2.

Table 2. Typical effects of polymer modification on performance of Portland cement mortars and concrete.

Property	Effect
Compressive strength	Decreased or increased
Tensile strength	Increased
Fracture Toughness	Increased
Adhesion	Increased
Modulus of Elasticity	Decreased or increased
Drying shrinkage	Decreased or increased
Water vapor permeability	Decreased
Hydraulic permeability	Decreased
Creep	Decreased of increased
CO_2 permeability	Decreased
Chloride penetration resistance	Decreased
Chemical resistance	Increased in some chemicals

The first commercially available latex modifiers for Portland cement exhibited T_g in the range of 10-20 ^oC. This relatively high T_g of the modifier results in an increase in the compressive, tensile and bending strengths as well as increase adhesion and impact strength of Portland cement based mortars and concrete up to a certain level of polymer cement ratio. The tensile elongation is also increased, but the ultimate tensile strain does not increase much over 1%. The typical relationship between the polymer content, expressed as polymer/cement ratio (meaning the weight of polymer solids divided by the weight of cement solids), is shown in Figure 3. The T_g of the acrylic polymer used in the study presented in Figure 3, was +13 ^oC.

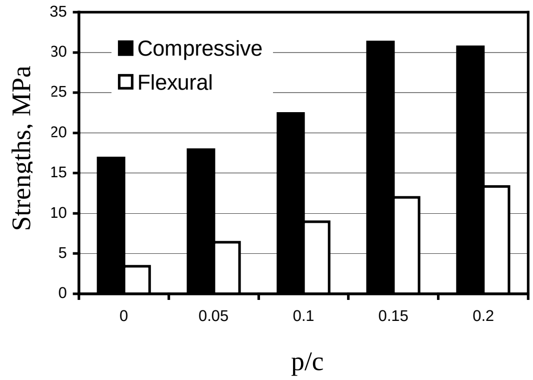

Figure 3. Compressive and flexural strengths of polymer modified mortars vs polymer cement ratio (p/c).

5.1.1 *Tensile Properties*

Decreasing the T_g of polymer modifier and increasing the polymer content in the mortar increases the tensile elongation. The ultimate tensile elongation may vary anywhere from 5% to 100% depending on the level of polymer modification, the type of the polymer used (even for a given T_g), and the type of mortar used. The ultimate tensile stress may vary from 1 MPa to 6-7 MPa and more, but typically with increasing tensile strength the tensile elongation decreases and vice versa. The addition of fibres or use of reinforcing fabric affects the tensile stress/strain behaviour of flexible polymer cement composite. Figure 4 shows the stress/strain relationship of a non-reinforced and a polypropylene fabric reinforced, proprietary FPMC. The addition of short fibre reinforcement generally increases the tensile strength but may reduce the tensile elongation. The

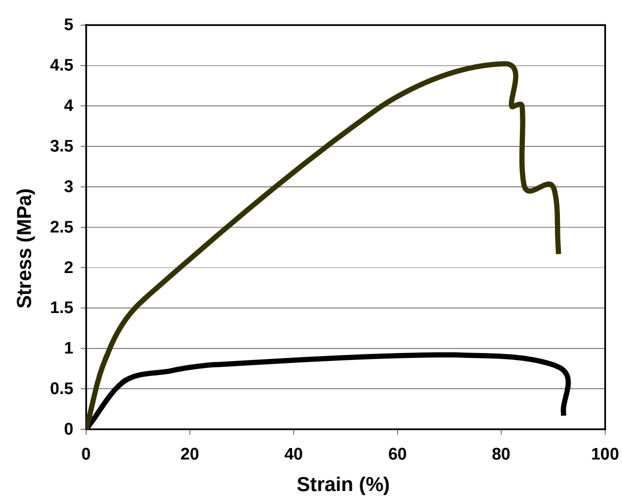

Figure 4. Tensile stress/strain curves of non-reinforced and reinforced FPMC.

reinforcing fabric increases the tensile strength properties without significantly reducing the tensile elongation. The type of fibre or fabric, their moduli of elasticity, fabric design and volume fractions will affect the tensile stress/strain behaviour of such a composite, but it is beyond the scope of this presentation to cover this area. The tensile stress/strain properties and other mechanical properties of FPMC composite are affected by temperature. With decreasing temperature the flexibility of the FPMC composite decreases and this decrease becomes critical around temperatures below the T_g of the polymer used. The tensile stress/strain behaviour is also affected by the wet or dry state of the composite material. A non-reinforced composite will exhibit lower ultimate tensile stress and ultimate elongation in a wet (water saturated) state than those of dry material. Tensile properties of flexible polymer modified cements may decrease with time but this decrease is also dependent on the type of exposure such as continuous "wet", continuous "dry" or "wet and dry". The decrease in tensile elongation is usually accompanied by an increase in tensile strength but it can be to some extent controlled by the formulation of the cement mortar.

5.1.2 *Compression properties*

The compressive strength of polymer-modified mortar is also affected by polymer modification. Figure 5 shows the ultimate compressive strength values of mortars modified with polymers of varying T_g temperature.

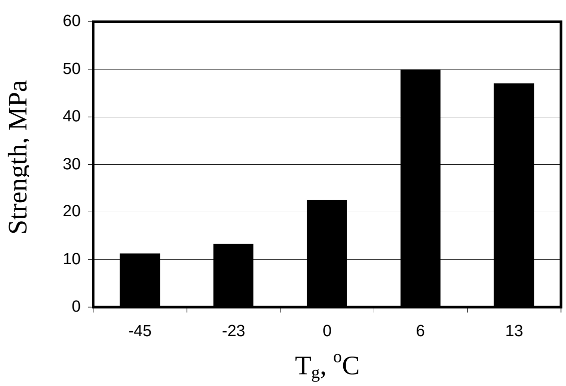

Figure 5. Compressive strength of mortars modified with polymer latexes of varying T_g. (w/c=0.6, p/c=0.3, sand/cement ratio =2, the control compressive strength of unmodified mortar 41.6 MPa, test temperature 18^0C).

5.1.3 *Modulus of elasticity in tension*

The tensile modulus of elasticity of flexible polymer cement will vary considerably depending on the polymer content, T_g of the polymer and the composition of the cement matrix. Thus the moduli of elasticity may reach values as low as 300-500 MPa for highly flexible composites.

5.1.4 *Crack Spanning*

One of the reasons for using FPMC is their flexibility, allowing waterproofing of concrete structures with "moving cracks". The crack bridging capacity of a non-reinforced and fabric reinforced proprietary product in a thickness of 2.5 mm at different levels of polymer modification is shown in Figure 6.

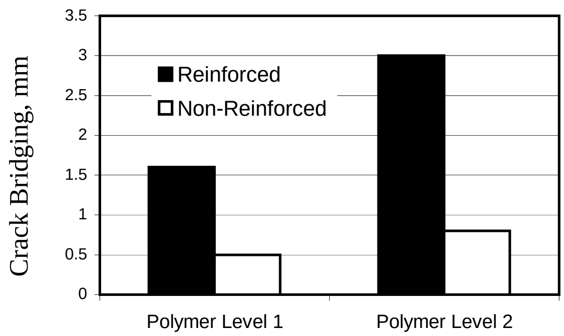

Figure 6. Crack-bridging capability of reinforced and non-reinforced proprietary FPMC as a function of polymer content.

5.1.5 *Hydraulic Permeability*

FPMC exhibit very good hydraulic impermeability. A relatively thin layer, 1.6-2.00 mm thick, applied to concrete will resist water head pressure in excess of 30-40 meters on both negative and positive sides.

5.1.6 *Water vapor transmission*

Depending on the polymer/cement ratio, type of polymer and formulation of the modified mortar, the FPMC will exhibit a wide range of water vapour transmission. When expressed in terms of permeance, a thin 2 mm layer may act as a very efficient vapour retarder with permeance around 50-60 ng/Pa.s.m^2 (or approximately 1 perm). On the other hand, flexible polymer modified cements can be formulated at the same thickness of 2 mm to exhibit permeances, in excess of 500-600 ng/Pa.s.m^2, (or 10 Perms), thus providing a highly "breathable" waterproofing and protective layer.

5.1.7 *Carbon dioxide and chloride penetration resistance*

Data available from technical information on commercial products show that polymer modified cements, including flexible cements, exhibit excellent resistance to carbon dioxide penetration and are very effective protection for reinforced concrete structures against carbonation and consequent corrosion of the reinforcing steel. Similarly the resistance to chloride penetration of these materials is also very good (Coppola et al. 1997).

5.1.8 *Abrasion resistance*

Properly formulated FPMCs exhibit very good abrasion resistance mainly because of their toughness. Figure 7 shows “wet” abrasion resistance of several materials: conventional sand cement/mortar, high T_g polymer modified mortar, a “dry” polymer modified proprietary repair mortar, a proprietary FPMC and a polyurethane membrane – the type used in protection of balconies. The Taber Abrader was used to determine the abrasion rate and the results show that the polymer-modified cement with low Tg is superior to conventional and polymer modified mortars and has similar abrasion resistance to that of polyurethane membrane. The testing was carried out under both dry and wet conditions. Under wet (water saturated) conditions the abrasion is higher for all the materials tested in very similar proportions.

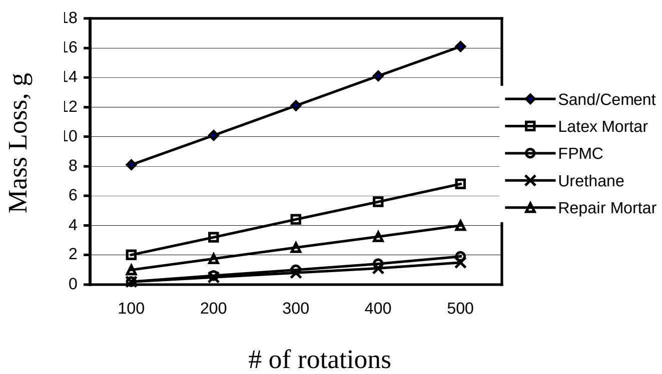

Figure 7. Abrasion resistance of various mortars in wet state – Taber Abrador Model # 503, abrador wheel, Calabrase H-22, mass on each arm =500g.

5.1.9 *Salt Scaling Resistance*

The salt scaling resistance of FPMC is generally very good, most likely due to the flexibility of the materials.

5.1.10 *Chemical Resistance*

Due to their high polymer content, FPMC exhibit a considerably higher chemical resistance, even in acidic environments, than conventional Portland cement mortars or concrete.

6 APPLICATIONS OF FPMC COMPOSITES

6.1.1 *Repair of Concrete Digester Tank, Bedford, Nova Scotia, Canada*

In 1993 the concrete roof of a digester tank in Bedford, Nova Scotia, Canada collapsed. The concrete roof was replaced with a “gas holding” steel roof. Over the years and due to excessive pressure the reinforced concrete tank, which measured 10 m in diameter and 7 m high, had developed vertical and horizontal cracks. The repair required long term sealing of the cracks in the reinforced concrete wall as well as concrete protection. The designer selected two materials for the repair: alkaline resistant glass fibre-reinforced, micro-silica enhanced mortar as the primary waterproofing layer and a FPMC as the secondary waterproofing and protective layer. Tests and practical experience with the fibre-reinforced mortar had shown that if the crack telescoped through the layer it would be only hairline. But since it was difficult to accurately determine the movement of the cracks in the reinforced concrete wall of the tank under the fully loaded condition, it was conceivable that the primary waterproofing layer would develop fine through cracks due to movement of the substrate cracks. Therefore an additional protective coat of FPMC was applied as a secondary waterproofing and protective layer. The high flexibility allowed crack spanning of fine cracks and the high polymer content provided improved chemical resistance. After cleaning the tank by sandblasting the vertical and horizontal cracks were covered using a galvanized welded fabric (1.7 mm wire diameter, 30 cm wide strip with opening 5 cm by 2.5 cm) mechanically fastened to the concrete. After the placement of the welded wire fabric, a 12 mm thick layer of fibre-reinforced mortar was applied to the concrete surface of the tank. The material was mechanically applied using the wet process shotcrete method. The following day the surface of the primary layer was thoroughly cleaned with high-pressure water. Then an approximately 3 mm thick layer of FPMC was rolled on in two coats. The waterproofing, protective system was air cured for approximately one week before the tank was put back into use. The performance of the repair has been excellent. The interior of the tank was inspected in 1997, 4 years after the installation, and no leaks or deterioration of the waterproofing system was found. Further inspections in 2000 and 2003 also revealed no leaking.

6.1.2 *Municipal and Industrial Land-fill sites, Chemical Protection of “Dry” Pre-Cast Manholes, Brantford, Sarnia, Ontario, Canada*

Extensive investigation of concrete manholes and concrete drainage pipes of a municipal land-fill site in Ontario using robotic TV camera investigation showed that after 25 – 30 years of service, there is approximately 12-15 mm deep concrete deterioration in many areas due to chemical attack. Since the specified design life of such structures is presently being changed from 30 to 100 years, the design engineers have been looking for various methods to increase the chemical resistance of wet or dry cast concrete pipes and manholes. The commonly used epoxy coatings exhibit high chemical resistance but in negative side applications where the water is also getting behind the coating the epoxy coatings de-bond. FPMC with a high content of a low T_g polymer provide considerable improvement in chemical resistance to that of Portland cement mortar. This improvement is sufficient to increase the service life of the pre-cast concrete components to presently specified levels and beyond. In addition they do not exhibit the problem of de-bonding as in case of epoxy coatings. They are easier to apply and less expensive than the epoxies. The dry-cast concrete pipes were cleaned using high-pressure water. The FPMC layer was applied by spraying and brushing. A brush was used to provide a pin-hole free coating approximately 1 mm thick. The second coat was applied in the same manner and thickness and air-dry cured.

6.1.3 *Underground, reinforced concrete tanks, Port of St. John's, Newfoundland Canada*

Large volume underground reinforced concrete tanks were built during the Second World War and used for storage of bunker oil. In 1997 it was decided to refurbish the tanks and use them as storage tanks for drilling "mud" used in off shore oil drilling in Newfoundland. The tanks had extensive cracking but. the most serious problem was the contamination with oil residues and an originally applied bituminous protective coating. The surface of the concrete was cleaned using high-pressure water with sand in combination with industrial degreasers. The degreasing of the surface was carried out several times. The cracks were treated with a FPMC layer, reinforced with approximately 15 cm wide polypropylene reinforcing fabric. The remaining areas were coated with a different type of FPMC designed to provide long-term chemical resistance to the drilling mud.

6.1.4 *Cooling tower interior, Bishan, People's Republic of China*

The cooling towers at a thermal power plant in Bishan, China, were built in the mid Eighties. The original coal tar epoxy applied to the interior side of one of the cooling tower wall had failed after approximately 10 years of service. In 2000 the original epoxy coating had been removed and another epoxy coating had been applied to the interior. This application failed completely, by severe delamination of the epoxy, in about three to four years. In 2004 it was decided to use FPMC as waterproofing. There were a number of reasons for changing the widely used very low permeability epoxy system but the main reason was the historically poor performance of epoxy systems in these types of applications throughout northern China and elsewhere. A thorough computer analysis of the moisture content in the concrete wall, the climatic conditions and all modes of moisture and heat transfer, showed that having a very low water vapor transmission coating (vapor barrier) on the interior was not necessary, since its water vapor permeability has relatively little effect on the overall moisture content in the concrete wall of the cooling tower. The lower cost of the polymer-modified cement versus the epoxy coating and the ease of application were also important considerations is selecting the FPMC over the epoxy. The total interior area was approximately 8,000 m^2. The most difficult task was to remove the existing epoxy coating since only some of the epoxy was completely de-bonded and considerable areas of the epoxy remaining well adhered. Rotating, mechanical, hand held grinders were used to remove the epoxy. Due to time and economic constraints, well-adhered epoxy was not removed. The FPMC was brush applied in two coats to a total thickness of 2 mm.

7 CONCLUSIONS

Polymer modification of mortars or concrete increases the toughness and, to some extent, the tensile and bending strengths of these materials. By using a higher level of polymer modification with a polymer exhibiting a low T_g, a high flexibility in such composites can be achieved. The main use of these materials is in thin section applications, in waterproofing and protection of concrete structures. The high flexibility allows the spanning of substrate cracks and provides waterproofing and protection that cannot be achieved using conventional mortars or high T_g polymer modified mortars.

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