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A new fire resistant FRP for externally bonded concrete repair

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HIGHLIGHTS

- ▶ A nanoclay reinforced FRP was prepared for fire tolerance.
- ▶ A combination of nanocomposite with fire resistant coating was investigated.
- ▶ Nanocomposite shows improvement in fire tolerance.
- ▶ Fire resistance coating further enhances fire tolerance of nanocomposite.
- ▶ It may be a potential technology for resisting fire hazard in FRP repaired RC structures.

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ABSTRACT

Fiber reinforced polymer (FRP) composites, as a mature technology, have been widely used to repair/retrofit/reinforce damaged/degraded concrete structures such as steel reinforced concrete (RC) beams or columns by externally bonding FRP sheet(s) onto the surface of substrate concrete structures. However, the performance of FRP systems exposed to fire is a serious concern due to the combustibility of FRPs. The objective of this study is to understand and develop a new fire resistant technology with nanoclay reinforced intumescent coating. RC beams were prepared, damaged, and repaired by FRP with the new coating. The repaired RC beams were subjected to fire hazard again, and re-evaluated for its residual structural capacity. The effectiveness of the developed new coating for fire resistance was evaluated based on the test results. It is believed that this coating system would enhance fire resistance of the FRP, and safety and reliability of FRP repaired concrete structures.

1. Introduction

The infrastructure in United States and around the world is deteriorating or degrading at an unprecedented rate due to steel reinforcement corrosion, freeze–thaw, deicing salt, hygrothermal attacks, seawater immersion, vehicular impact, overload, initial design or construction deficiency, and natural disasters such as fires, earthquakes and hurricanes. To solve this pressing problem, fiber reinforced polymer (FRP) composite materials have been extensively studied and widely used in repairing/retrofitting/reinforcing damaged steel reinforced concrete (RC) beams or columns. There is an ample supply of research papers, design codes, and demonstration projects all over the world [1,2].

However, FRP repairing systems are limited due to the poor fire resistance and higher flammability of FRPs [3]. During burning, FRPs release smoke, heat, and toxic fumes. Additionally, the polymer matrix is burnt and evaporated at high temperature. It further causes decomposition of the fiber. As a result, the FRPs lose their reinforcement effect and the concrete beams or columns lose their structural capacity. Therefore, FRPs cannot reach their full market potential until the behavior under fire is fully understood and rational fire safety guidelines are established [4,5].

For example, bridge fires are typically petrol fires, or liquid pool fires and hydrocarbon fires. Usually, bridge fires are characterized as reaching extremely high temperature within the first few minutes of fire exposure [6,7]. Some standard hydrocarbon fire curves for design exist but have limitations for application to bridges. According to the American and Eurocode standards, hydrocarbon fires [8,9] exceed 1000 °C within the first few minutes and continue to increase throughout the fire duration. Most materials degrade when exposed to high temperature conditions. For FRPs, the fire burning is not like a regular load. The polymer resin become rubbery and viscous, if the temperature ranges from 65 to 150 °C [3,10,11]. At temperatures above 400 °C, FRPs are susceptible to combustion of polymer matrix, even evaporate. Although there

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are several methods which can increase the fire resistance of FRP repairing system, the most easy and cost effective way is to spray intumescent coating on the surface of FRP repairs. Some intumescent coatings can withstand extreme temperature (up to 1093 °C for 1 h) [12]. However, most FRP repairs are decomposed around 400 °C. Because the fire resistant coating cannot prevent the heat from transferring into the FRP substrates, FRP decomposition cannot be avoided even with coating protection. Therefore, a new fire and thermal resistant coating system needs to be developed in order to solve this problem. The key is to further reduce the heat transfer by increasing insulated layers between the intumescent coating and FRP repairing patch.

There is an increased interest in the polymer based nanocomposites reinforced with organically modified montmorillonite (MMT) due to their high modulus, large surface area, and high aspect ratio. From previous research, when the nanoclay morphology changed from discontinued intercalated status to well dispersed and continued exfoliated status, it formed insulated layers. During fire exposure, these insulated layers form thick charring layers that could partially prevent the chemical reaction between oxygen and polymer, reduce the speed of chemical reaction, and also reduce the thermal diffusivity of the FRP composite [13]. Therefore, it is believed that new nanoclay enhanced FRP layer can improve the fire resistance and increase the FRP's residual strength after exposed to high temperature.

Although there are many existing models for fire exposure of FRP repaired concrete structures, there are very few experimental studies for hydrocarbon fire exposure. The objective of this study is to (1) investigate the feasibility of using nanoclay enhanced FRP repairing layer in enhancing the residual loading carrying capacity of FRP repaired RC beams after exposure to hydrocarbon fire; (2) investigate the thermo- and physical properties of nanoclay enhanced FRP repairing system; and (3) provide valuable experimental data for developing fire resistant FRP repairing design code.

2. Experiments

2.1. Methodology

It is well known that nanoclay morphology has a significant effect on its physical/mechanical properties. In fact, poorly dispersed nanocomposites may have degraded mechanical properties. Depending on the mixing technique used, conventional nanoclay reinforced composites can take the form of phase-separated microcomposite, intercalated nanocomposites, or exfoliated nanocomposites [14]. Phase-separated microcomposites offer little improvement in material properties while exfoliated nanocomposites show the greatest interfacial interaction and phase homogeneity [14]. Therefore, the degree of exfoliation is the most important parameter to evaluate the physical properties of polymer based nanocomposites [15,16].

In this study, nanoclay particles are mixed with the most commonly used epoxy resin, separately, by using the ultrasonic generator and three-roll mill. Our previous study proved that combination of these two equipments can obtain the exfoliated nanocomposites. Once the exfoliated nanoclay reinforced epoxy is prepared, the hand lay-up technology is used to prepare the FRP sheet and is bonded to the surface of damaged concrete structures. After FRP repair is fully cured, intumescent coating is brushed on its surface and forms the new fire resistant FRP, as shown in Fig. 1. It is expected that the intumescent coating would insulate most heat flow and the exfoliated nanoclay would form lots of insulate layers. This insulation layer can not only increase the mechanical properties, but also reduce the thermal conductivity of FRP when it is exposed to the fire condition. Furthermore, exfoliated nanoclay would prevent the FRP layer from peeling off during the long fire exposure by increasing the interfacial bonding between the FRP layer and the concrete beam.

2.2. Raw materials and preparation

2.2.1. Fire resistant coating layer preparation

There are many fire retardant additives in the market. In this study, Firefree 88 was used which is a water-based intumescent coating. It can withstand extreme temperature (up to 1093 °C for an extended period of time of up to 1 h). The fire resistance coating needs to be stirred 5 min by using drill mixer before brushing to the surface.

2.2.2. Fire resistant FRP preparation

MBrace EG 900 fabrics, as one of the most commonly used fabric for concrete structure repairing, was used to fabricate the new fire resistant FRP system.

DER 332 epoxy resin and DEH24 curing agent were used to prepare the epoxy matrix. From the manufacturers' data sheets, the Young's modulus and Poisson's ratio are, respectively, 1.8 GPa and 0.37 for the cured epoxy.

Nanoclay used was *Cloisite 30B nanoclay*. The silicate platelets are 1 nm in thickness and 70–150 nm across. In order to get full exfoliation in nanoclay reinforced polymer, four-step mixing efforts were used in this study. Step 1: 1.0 wt.% nanoclay was mixed with the epoxy resin by using the stirring machine for 30 min; Step 2: the mixture was followed by 1 h of ultrasound mixing; Step 3: the mixture was further followed by three-roll mill shear mixing; and Step 4: the mixture from step 3 was followed by another 1 h of ultrasound mixing. After that, the mixture was mixed with hardener, and ready for FRP preparation.

The two major pieces of equipment used for mixing were ultrasonic generator and three-roll mill, as shown in Fig. 2. The amplitude of the ultrasonic generator was set to 40%, and the pause was set to 5 s every 20 s sonification. It was found that ultrasound can help uniformly distribute the nanoclay in the polymer matrix and also improve nanoclay's exfoliation within the polymer matrix. The MMT/Epoxy mixture obtained after ultrasonic mixing was then pulled into the center roll of the three-roll mill, which was later on transferred to the apron roll by adhesion. Dispersion is achieved through the shear forces generated between adjacent rolls. The milled materials were then removed from the apron roll by a knife that runs against the roll.

2.2.3. Concrete preparation

Type I Portland cement, gravel, natural sand, water, and DARAVAIR 1000 were used to prepare the concrete. Concrete with a 28-day compressive strength of 40 MPa was designed as a control mix. The mix design followed the American Concrete Institute (ACI) Standard 211.1 [17]. The mix ratio by weight for the concrete was cement:water:gravel:sand:admixture = 1:0.51:3.49:1.88:0.001. It was found through concrete experiments that the slump was 20.2 cm, the air-content was 8.1%, and the 28-day compressive strength was 37.6 MPa.

2.3. Morphology

Nanoclay exfoliation was observed for surface morphology using a Scanning Electronic Microscopy (SEM). The SEM images made it easy to understand the microstructure of nanoclay-reinforced FRP. In order to find out the degree of nanoclay exfoliation, Transmission Electron Microscopy (TEM) was also used to evaluate the morphology of nanoclay in the FRP.

2.4. Specimen fabrication

In order to investigate the capability of the FRP for shear reinforcement, the beams were sized as short beams with a dimension of 50.8 cm long, 7.52 cm wide, and 13.97 cm deep, so that shear failure is possible. Using ACI 318-99 code [18], it was determined that the balanced flexural reinforcement needs one #4 rebar (diameter 12.7 mm). A total of 27 beams were prepared, as summarized in Table 1.

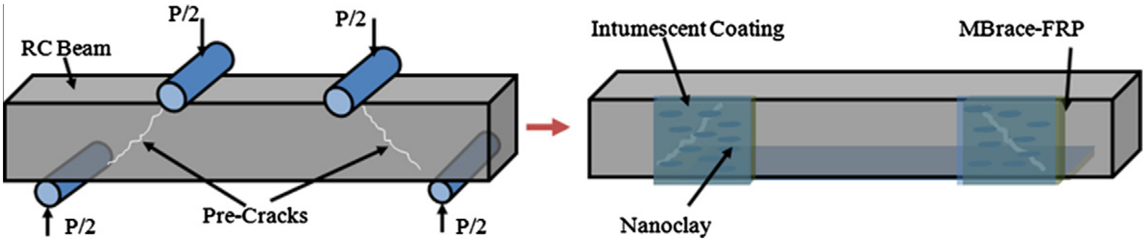

Fig. 1. Schematic of new fire resistant FRP repaired concrete beam.