BOND PERFORMANCE OF CFRP STRENGTHENING OF CONCRETE MEMBERS USING NANOCLAY MODIFIED ADHESIVE

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ABSTACT

FRP composites are externally glued to concrete structures using epoxy adhesives. However, these adhesives are sensitive to temperatures beyond their glass transition temperature. Once this temperature is reached, the mechanical behaviour of the whole strengthened member rapidly deteriorates. In order to improve the performance of the whole strengthened system, epoxy adhesive properties need to be enhanced. Nanomaterials have previously been used for modified epoxy matrix in the aerospace and materials applications. In these applications, improvements in both mechanical and thermal performance have been found by adding small amounts of nanosize fillers to the polymer matrix. In this study, the performance of CFRP externally strengthened concrete members using nanoclay-modified epoxy adhesives was investigated. The effect of the degree of adhesive cure was explored by post-curing the adhesives. Single–lap shear tests at room and elevated temperatures were adopted to evaluate the bond efficiency of the whole strengthened system. The glass transition temperature of the epoxy adhesive with and without modification was also investigated.

Keywords: CFRP, Concrete, Adhesive, Nanoclay, Glass transition temperature, Bond

INTRODUCTION

Structural repair and strengthening of existing concrete structures have received great attention globally because many old structures show deterioration of material properties, exposure to extreme environmental conditions, increase in traffic load, poor quality construction and a need to meet current design requirements[1,2,3,4]. Among many materials, fiber reinforced polymer (FRP) have been widely used for strengthening concrete structures. This can be attributed to their excellent properties such as lightweight, high tensile strength, high stiffness, good chemical resistance, corrosion resistance and ease of application. For external strengthening, FRP sheets or plates are bonded to the concrete surface using epoxy resin.

However, the performance of the FRP/concrete system, dramatically deteriorates when the service temperatures are close to, or exceed the glass transition temperature of the adhesive. As reported by numerous researchers, when the epoxy resin reaches this temperature, it starts to soften and change from a glassy state to a rubbery state and leads to a loss in bonding between the FRP and the concrete member[5,6] To improve polymer properties, additives can be added to the epoxy matrix to modify its mechanical and thermal performance. One such additive is nanoparticles which have previously been reported to lead to significant enhancement in the polymer properties[7,8].

Evidence from literature has shown that clay-epoxy nanocomposites demonstrate a favourable combination of mechanical and thermal properties, even at very low filler weight fractions. The addition of small amounts (typically less than 5 %) of nanometer-thin layered inorganic fillers results in mechanical and thermal improvements[9]. Enhancement in the adhesives properties, such as the glass transition temperature and density was also achieved by post-curing the adhesives [10]. However, it is not known how well this can be applied to epoxy adhesives typically used in CFRP-concrete applications. Thus, the objective of this study was to investigate and provide an experimental evidence for the bond behaviour of CFRF-concrete substrates using different percentages of nanoclay to modify the adhesive as a bonding agent. Additionally, the effect of the post-curing was studied since it is part of the requirement to determine whether materials are mixed in a stoichiometric ratio's, by observing the effect of the ratio dependence of the reactants, on the glass transition temperature of the fully-cured samples.

MATERIAL PROPERTIES

Normal strength concrete with an average 28-day compressive strength of 35 MPa was used in this study.

The carbon fiber fabrics used are commericially available CF 130. The tensile elastic modulus, tensile strength and ultimate tensile strain of the fibers are 240 GPa, 3800 MPa and .1.5%, respectively.

One type of a commercially available epoxy resin,compartiable to use with the carbon fiber fabrics, was used. It was modified with the addition of nanoclay. The epoxy adhesive is a two-

part system. Part A of this resin consists of more than 60 % Bisphenol-A epoxy resin. Additionally, around 10-30 % of Part A are Alkyl glycidyl ether, and solid components. Part B is the curing agent (hardener), which consists of more than 60 % Isophoronediamine. Part B contains less than 10 % Salicyclic acid.

The nanoclay used in this work is layered silicate of clays with platelets of 1 nm and aspect ratio of 400 – 1000. The clay mineral is a natural montmorillonite modified with an octadeyl amine. The physical properties of the nanoclay are summarized in Table 1.

Table 1: Physical Properties of the nanoclay

Appearance	***White Powder***
Mean Dry Particle Size (microns)	8-10
+325 Mesh Residue (%)	0.1
Specific Gravity	1.71
Bulk Density (gm/ cc)	0.41
Moisture (%)	3 max
Mineral Purity (% min)	98.5

MIXING METHOD

A mechanical stirrer was used for mixing nanoclay with part A of the epoxy adhesive. Different percentages of nanoclay (1 %, 2.5 %, 5 %, 7.5 % and 10 %) by weight were used. Since nanoclay absorb moisture from air very easily, the nanoclay was dried in a vacuum oven for 24 hr at 70 °C before mixing. The whole procedure for mixing was carried out in a fume hood. The desired amount of Part A was placed in a 250 ml beaker and heated up to 80 °C using a hot plate. In order to control the temperature, the beaker was placed inside a water bath.

The desired amount of the nanoclay was dispersed in Part A of the adhesive using a stirrer at 500 rpm. After stirring for 1 hr, the nanoclay/Part A mixture was removed from the hot plate and allowed to cool to room temperature. The curing agent, Part B, was then added and mixed manually to get a homogenous mixture. Figure 1 shows a schematic of the mixing process.

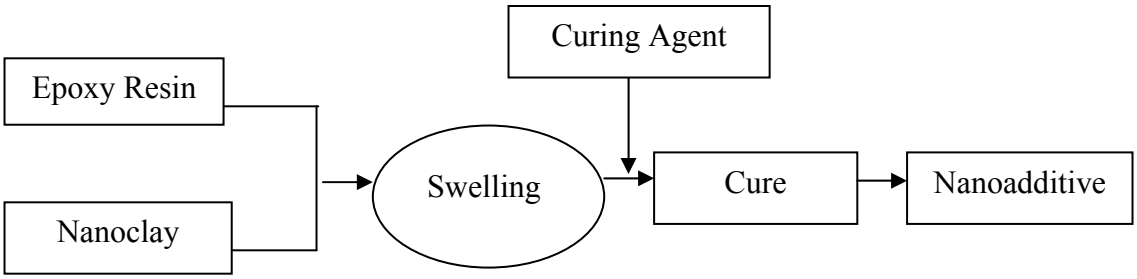


Fig.1: Flowchart of the Nanocomposite Preparation

CURING REGIME

Epoxy adhesive samples with or without modification with nanoclay were post-cured after the initial room temperature cure (more than 7 days). A cure cycle of 4 hrs, consisting of 2 hrs at 100 °C followed by 2 hrs at 140 °C in an oven, was adopted to study the effect of post-curing on the glass transition temperature of the epoxy adhesive.

CONCRETE- CF FABRIC SAMPLES PREPARATION

The concrete surface was prepared using high-pressure water jet method to remove the paste and expose the coarse aggregates as shown in Figure 2. The surface was then cleaned from any dust particles or any loose materials by using a brush.

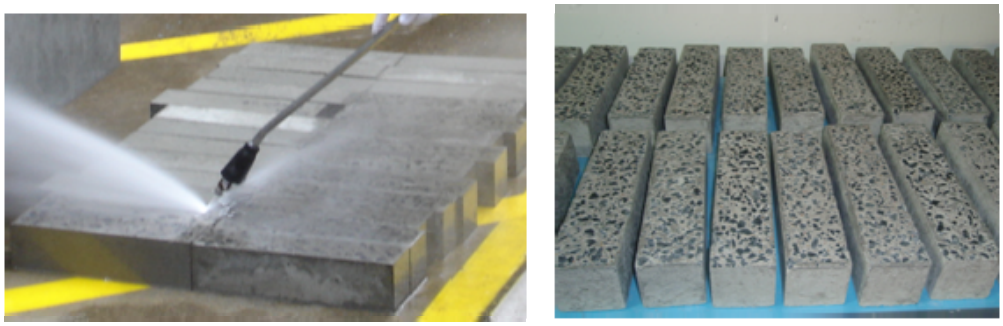


Fig. 2: Surface preparation by high pressure water jetting

Prior to the adhesive application, a primer of two part system was applied. It was mixed with its hardener at (3A:1B) mixing ratio to get a homogenous mixture. A thin layer of the primer was applied to the concrete surface using a brush. The specimens were then kept for 45 minutes cure as recommended by the manufacturer. A thin layer of the adhesive with or without modification was placed uniformly over the area on which the CF fabric was to be placed.

A wet lay-up method was used to apply CF fabric as shown in Figure 3. In this method, unidirectional CF fabric was saturated with the epoxy and pressed onto the concrete surface using a ribbed roller. The curing regime described above was used. This was followed by placing aluminium plate grips on both sides of the free end of the CF fabric. Epoxy adhesive Araldite 420 was used to fix the grips and the specimens were then left to cure 7 days.

Fig.3: CF fabrics application by wet lay-up method

In the tests involving elevated temperature exposure, type K- thermocouples were used to obtain the temperature within the adhesive layer. One thermocouple was placed in a central position on the concrete surface before the application of the epoxy layer as shown in Figure 4.

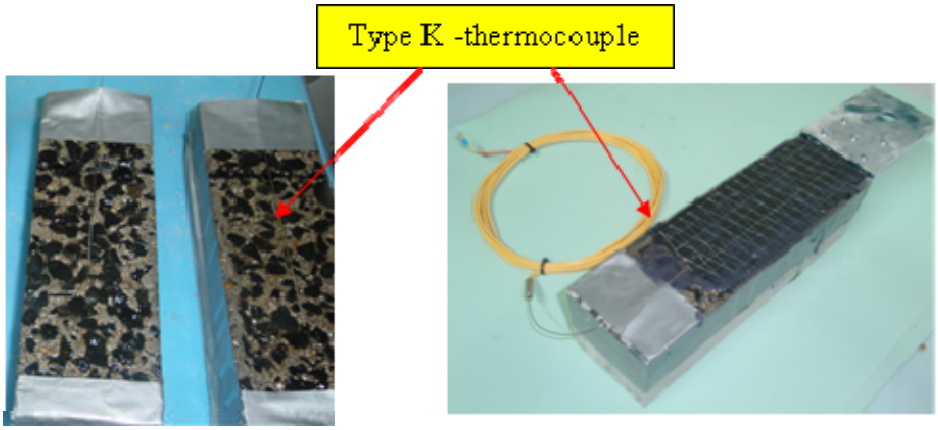
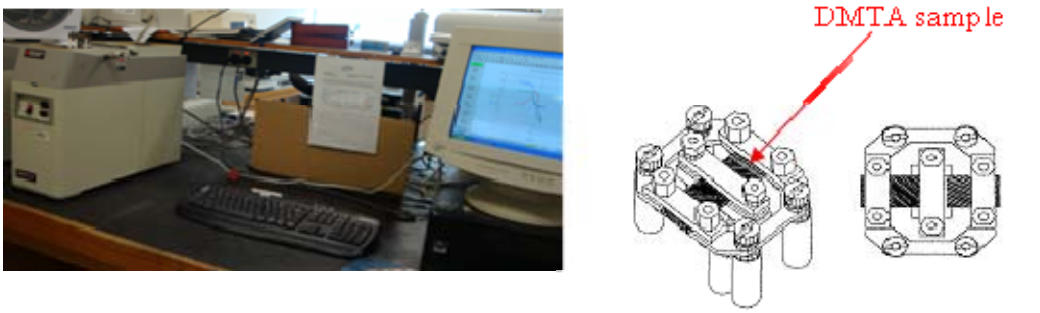


Fig. 4: Sample preparation for elevated temperature testing

MEASURENTS OF THE GLASS TRANSITION TEMPERATURE (T_g)

The Dynamic Mechanical Thermal Analysis (DMTA) technique, Figure 5a, was adopted to measure the glass transition temperature of the unmodified and modified epoxy adhesives. The modified samples were nanoclay-modified adhesive. The samples length,

width and thickness were 40, 5, 2 mm, respectively. They were placed in a medium DMTA fixture as illustrated in Figure 5b. The strain amplitude was set at 0.05 % with 1 Hz frequency. The temperature was scanned from 25 °C to 150 °C with at a heating ramp rate of 2 °C/minute.



(a) (b)

Fig. 5: Dynamic Mechanical Thermal Analysis (DMTA) technique: (a) the device, and (b) clamping arrangement

SINGLE-LAP SHEAR TESTS

Concrete specimens having the dimensions of 75×75×250 mm were tested at room temperature. A specimen was placed in a special test set up as shown in Figure 6. Two rollers were placed on the upper plate to eliminate peeling effects that may result from the eccentirc loading. The set up was installed into an Instron testing machine. All samples were tested under displacement control, with a displacement rate of 0.5 mm/ min until failure.

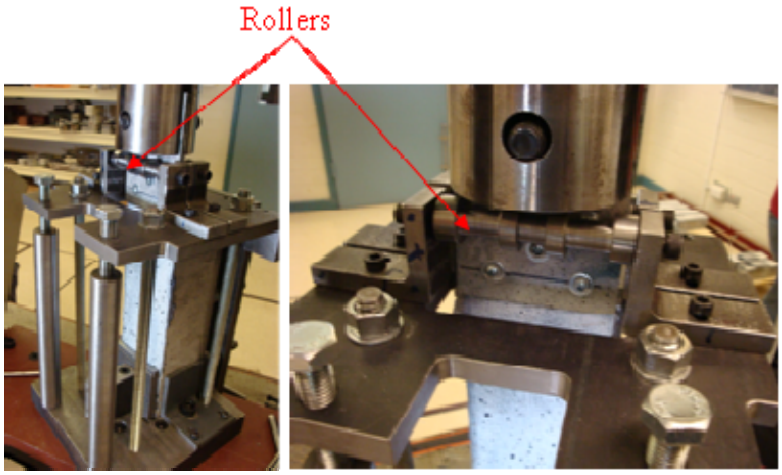


Fig. 6: Single –lap shear set up for room temperature tests

Another set of 18 concrete specimens were tested at elevated temperatures. A specimen was placed in a special test set up as shown in Figure 7. This set up was designed in a similar way used at room temperature testing. The set up was then placed inside an Instron oven as shown in Figure 8. The loading was implemented using an Instron actuator with clamping rods and jaws assembled as shown in Figure 8. All samples were tested under a constant service load taken as 40% of the ultimate load. The oven temperature was gradually ramped up at a rate of 2°C/ min.

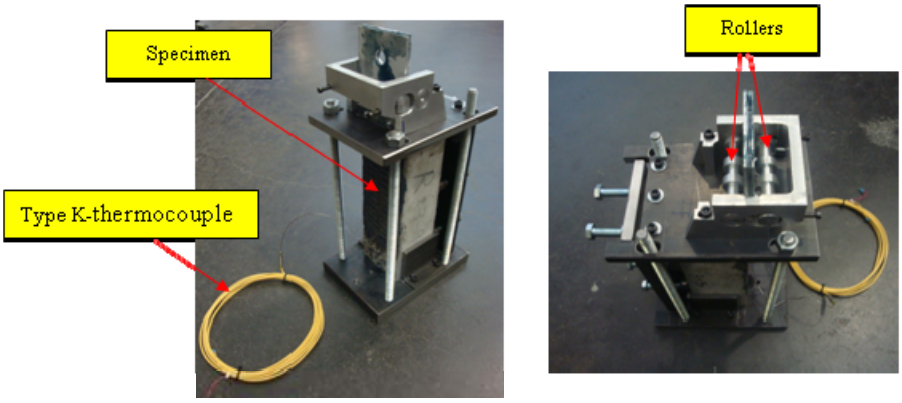


Fig. 7: Single-lap shear set up for elevated temperature testing

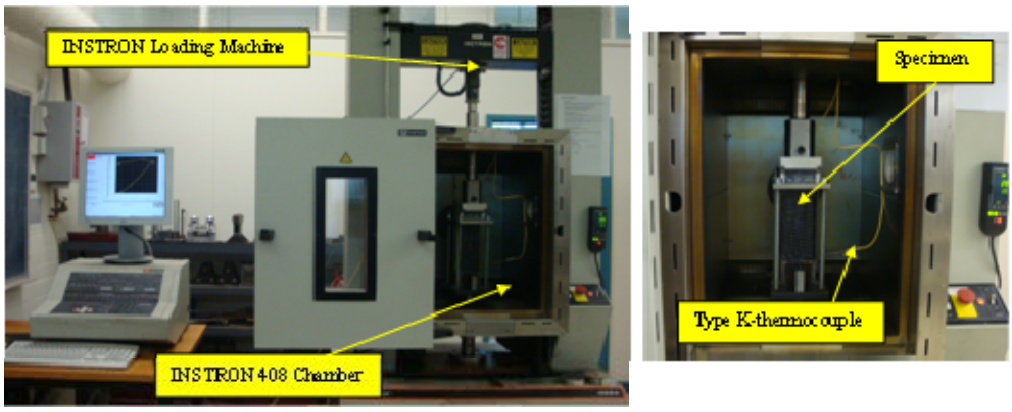


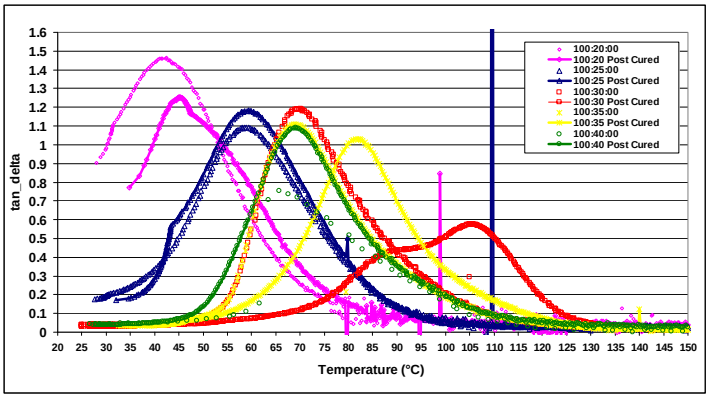
Fig.8: Arrangements for the single-lap shear test at elevated temperatures

RESULTS AND DISCUSSION

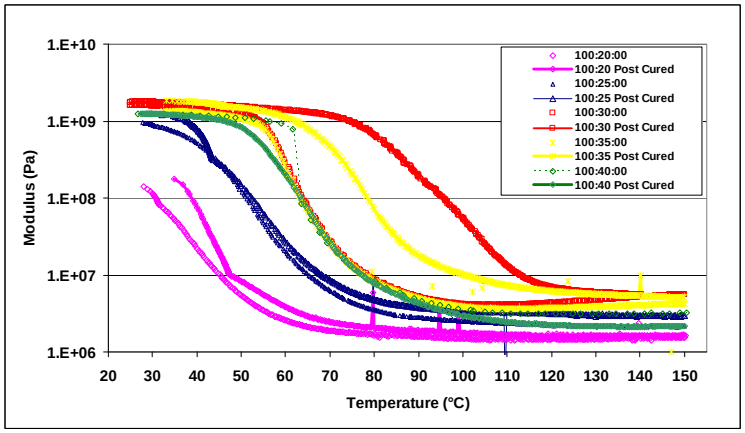
GLASS TRANSITION TEMPERATURE

The glass transition temperatures of different mixes of the adhesive cured at room temperature and post-cured were measured using the DMTA technique. The T_g of a material is determined from the temperature location of the tan δ peak in the DMTA traces, where δ is the ratio of the loss modulus (E'') to the storage modulus (E'). The goal

is to find the mixing ratio that leads to a higher T_g. As shown in Figure 9, reduction in T_g was observed for all mixing ratios at room temperature curing except 100:30 which gives the highest T_g. When post-curing regime was used, the sample with 100:30 mixing ratio showed a noticeable increase in T_g in comparison with other mixes. Table 2 summaries the results from the DMTA traces.



(a)



(b)

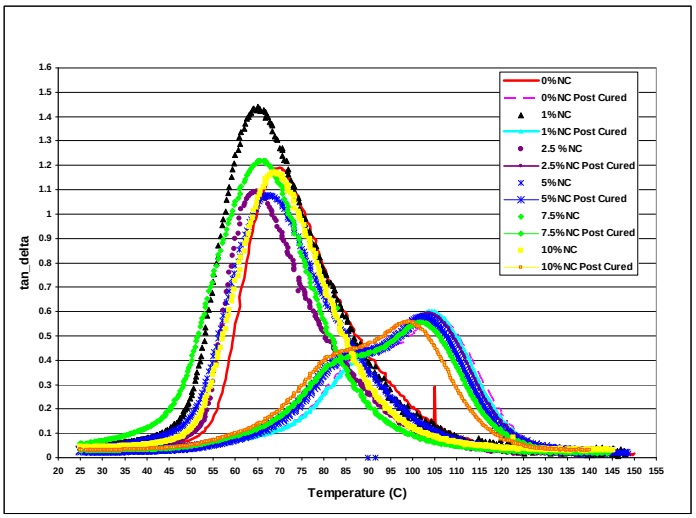
Fig. 9: DMTA measurements for (Part A: Part B) Mixes: (a) tan delta vs. temperature and (b) modulus vs. temperature.

Table 2: Glass transition temperature (T_g) from DMTA measurements for different (Part A: Part B) mixes

Mixing ratio (by weight)	T_g (°C) (Room temperature curing)	T_g (°C) (Post-curing)
100:20	42	46
100:25	59	60
100:30	70	110
100:35	69	82
100:40	65	69

The glass transition temperatures of different mixtures of nanoclay modified adhesive cured at room temperature and post cured were also measured using the DMTA technique. The mixing ratio 100:30 was adopted to be modified with different percentages of nanoclay. As shown in Figure 8a, a reduction in T_g was noted for all samples modified with nanoclay. Table 3 shows a summary of the T_g for nanoclay modified adhesive. This reduction was assumed to be due to combined factors such as lower crosslink density. However, a strong increase in the glass transition temperatures was observed for all the samples by post-curing them after the initial room temperature cure stage (more than 7 days). From DMTA traces, epoxy modulus can also be obtained as shown in Figure 8b It is evident from this figure that the modulus decreased with the increase in the nanoclay percentage.

However, the post-cured nanoclay-adhesive samples shows less variation in the modulus in comparison with the samples reacted at the room temperature. Additionally, post-curing increased the modulus of 1 % NC at temperatures above the T_g, as shown in Figure 8b. The modulus increased only for 0 % NC at the temperatures in the region where the modulus is equal to the T_g.



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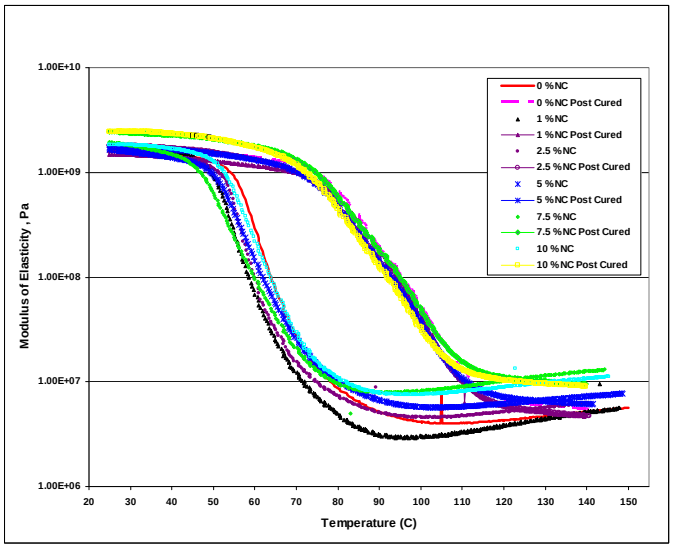

(b)

Fig.8: DMTA measurements for nanoclay modified Part A of the adhesive: (a) tan delta vs. temperature and (b) modulus vs. temperature

Table 3: Glass transition temperature (T_g) from DMTA measurements for different nanoclay/epoxy adhesive mixes

Nanoclay modified Part A of the adhesive		
NC (%)	T_g (°C) (Room temperature curing)	T_g (°C) (Post-curing)
0	70	110
1	65	111
2.5	68	110
5	69	110
7.5	65	108
10	68	106

SINGLE-LAP SHEAR TESTS

Experimental test results of single-lap shear samples are listed in Table 5. As shown in Figure 9, concrete rupture was identified as the common failure mode for all concrete samples strengthened with CF fabrics and tested at room temperature. The effect of adding different percentages of nanoclay to Part A of the epoxy adhesive is irrelevant to the single-lap shear test results at room temperature since the failure is governed by the concrete rupture.

Table 5: Single-lap shear results at room temperature

Specimens	***Failure load (KN)***	***Failure mode***
0 %NC (control)	23.54	Concrete Rupture
0 %NC Post Cured	19.79	
1 % NC	19.87	
2.5 % NC	23.0	
5 % NC	24.49	
7.5 % NC	21.67	

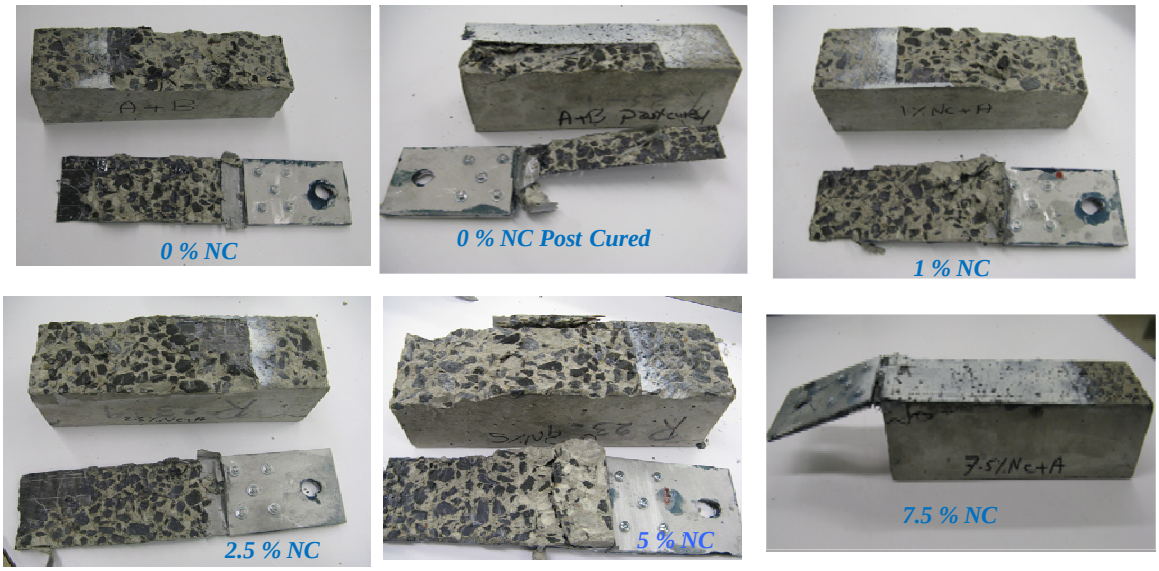

Fig.9: Failure modes of the single-lap shear test at room temperature

The peeling- off of the CF fabric was observed as the common failure mode for all the samples tested at elevated temperatures as shown in Figure 10. In the case of the modified adhesive samples, the bond of the CFRP-concrete systems started to soften at temperatures less than that for the control one (0 % NC) as shown in Figure 1. However, a slight improvement in the bond loss temperature was observed for the adhesive samples modified with 5 % NC and 7.5 % NC. Additionally, the post-cured samples showed the highest improvement of approximately 9 °C in comparison with the control sample.

Fig. 10: Failure mode of testing single-lap shear samples at elevated temperature

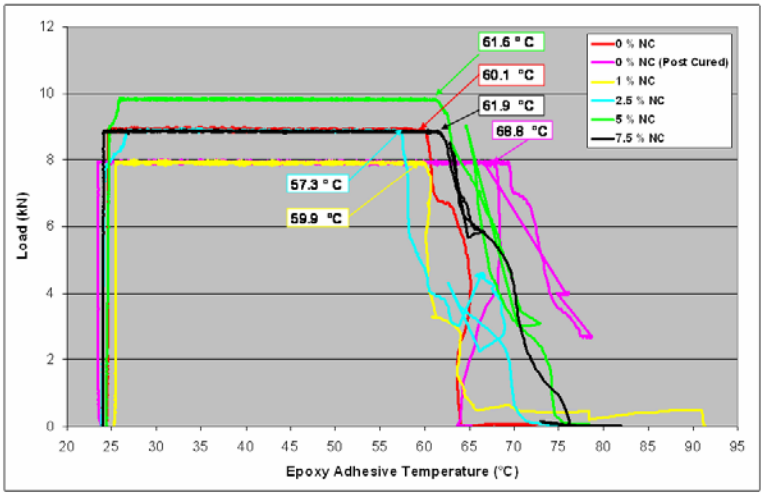

Fig.11: Single-lap shear test results at elevated temperatures

CONCLUSIONS

The objective of this study was to investigate the bond behaviour of the CFRP-concrete system subjected to elevated temperatures using adhesives modified with nanoclay, in addition to investigating the effect of post-curing on the bond behaviour. The following conclusions are drawn from the investigation:

1. The glass transition temperature (T_g) of the modified adhesives decreases slightly with the addition of nanoclay to the epoxy adhesive. The combination of factors can cause such a reduction in (T_g) could be a decrease in lower crosslink density and the presence of unreacted resin which causes plasticisation.

2. A strong improvement in the glass transition temperature (T_g) was found following post-curing the adhesives with or without modification. This enhancement in T_g is attributed to the increase in cross-link density resulting from the additional curing reaction occurring by due to post-curing.

3. The bond of the CFRP-concrete samples modified with (1% NC and 2.5 % NC) was lost at temperatures slightly lower than that for the control one (similar to changes observed for the glass transition). However, a slight improvement in the bond loss temperature of the CFRP-concrete samples was observed when the adhesive modified with 5 % NC and 7.5 % NC.

4. Post-curing improves the bond between the CFRP and the concrete members. The bond loss temperature of the CFRP-concrete system showed a strong improvement (approximately 9°C) in comparison with the control sample.

5. The adhesives started to reduce their modulus and lose their adhesive properties when subjected to temperatures which approach or exceed their $_{Tg}$. Therefore, peeling off of the CF fabric was the common failure mode for the samples tested at elevated temperatures (60- 68°C) using both the modified and unmodified adhesives.

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