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MONITORING THE STRENGTH GAIN OF STRUCTURAL ADHESIVES USING THE ELECTROMECHANICAL IMPEDANCE TECHNIQUE: AN EXPERIMENTAL INVESTIGATION

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ABSTRACT
Structural adhesives are employed to externally bond fibre-reinforced polymer (FRP) composites onto concrete structures for repair and strengthening purposes. The strength development of the bond layer is important to ensure the overall performance of the FRP-strengthened system. The non-destructive piezoelectric-based monitoring technique, namely the electromechanical impedance (EMI) technique, is introduced to monitor the strength gain of structural adhesives. In this study, the curing process of the commercially available structural adhesive, Sikadur 330, was monitored using the EMI technique. Throughout the experimental study, the 7-day strength gain of the adhesive was observed from the movement of acquired frequency peaks. The frequency peaks moved noticeably to the right for the first 24 hours. After that, the rate of movement decreased significantly. An empirical equation is established to correlate the tensile strength of the adhesive to the acquired resonance frequency for different curing durations. The current study shows the capability of the EMI technique to monitor the strength gain of structural adhesives, particularly at an early age of curing.

KEYWORDS
Curing process, electromechanical impedance (EMI) technique, lead zirconate titanate (PZT), structural adhesive, tensile strength.

INTRODUCTION
Two-part cold curing structural adhesives are commonly used to externally bond fibre-reinforced (FRP) composites onto concrete structures for strengthening purposes. The bonded interface between the FRP composites and the concrete substrate determines the integrity of the FRP-concrete system. Weak bond formation from poor curing can cause premature failure. Structural adhesives undergo strength gain throughout the curing process. Physically, the adhesives are in a paste form when the resin and hardener are freshly mixed. The mixture progressively develops into a tack-free solid and eventually into a fully-cured solid after a certain period of curing. The fully-cured solid is stronger and possesses good chemical and mechanical resistances over the fresh mixture (Corcione et al., 2014).

There are a few monitoring techniques that have been used to monitor the structural adhesives under curing, such as raman spectroscopy technique, dielectric technique and an acoustic technique (Gupta et al., 2017). These techniques are however time consuming and do not offer real time and continuous monitoring capabilities. The use of non-destructive piezoelectric-based monitoring techniques can potentially overcome the abovementioned shortcomings.

The commonly employed piezoelectric-based monitoring techniques are the electromechanical impedance (EMI) and wave propagation (WP) techniques. The piezoelectric materials used for the two techniques are made from lead zirconate titanate (PZT) and they are available in patch form. Since the focus of the study is to employ the EMI technique for the monitoring purposes, the fundamentals of the WP are herein omitted. Detailed descriptions of the WP technique can be found in Lim et al. (2019) and Tang et al. (2019). For the EMI technique, a PZT patch can be used as a collocated actuator and sensor to monitor the curing process of structural adhesives. Due to the converse piezoelectric effect, the applied alternating voltage across the PZT patch actuates the mechanical vibration forces of the PZT. The interaction between vibrational forces of the PZT and the adhesive modulates an electrical current due to a direct piezoelectric effect. The electrical impedance or the EMI signatures can be then measured by an impedance analyser. The objective of this study is to report a proof-of-concept experimental study that investigates the capability of the EMI technique for monitoring the curing process of structural adhesives.

RESEARCH METHODOLOGY

Sample Preparation

In order to study the curing process of structural adhesives, two-part structural adhesive, Sikadur-330, was employed in the experimental study. The adhesives sample was prepared based on the recommendation of the manufacturer, by mixing a resin/hardener ratio of 4:1 by weight. Two types of samples were prepared, namely rectangular prism beams and dog-bone specimens. A rectangular prism beam with dimensions of 15 mm in width, 15 mm in height and 160 mm in length was prepared for monitoring purposes whereas 12 dog-bone specimens were prepared in accordance with BS EN ISO 527-1 (1996) to determine tensile strength. A detailed description of sample preparation can be found in Lim et al. (2019).

The EMI Technique

The experimental set-up for the EMI technique consists of an impedance analyser (Hioki IM3570) and a personal computer as shown in Figure 1. Two PZT patches, with dimensions 10 mm in width, 10 mm in length and 0.3 mm in thickness, were attached onto the surface of freshly-mixed adhesive paste. The EMI signature was acquired immediately after the PZT patches were attached onto the samples. A 5V alternating voltage was then applied across the PZT patches using the impedance analyser. Frequency ranges of 5 – 100 kHz were utilised. The EMI signatures were sequentially acquired by activating one PZT patch at a time. For this study, the EMI signatures were recorded for curing durations of 9, 10, 12, 15, 24 hours as well as 3, 5 and 7 days.

Tensile Tests

A universal test machine (MTS Criterion Model 43 of 10 kN load capacity) was utilised to determine the tensile strength of the dog-bone specimens. Due to the fluidic properties of the dog-bone specimens at a young age, tensile tests commenced after 9 hours of curing when a minimal hardening was achieved in order to grip the specimens. The physical states of the structural adhesives at different curing durations are reported in (Lim et al., 2019). The dog-bone specimens with curing durations of 9, 12, 24 hours and 3, 5 and 7 days were tested at a displaced rate of 1 mm/min until rupture occurred. Two dog-bone samples were tested for each of the abovementioned curing durations.

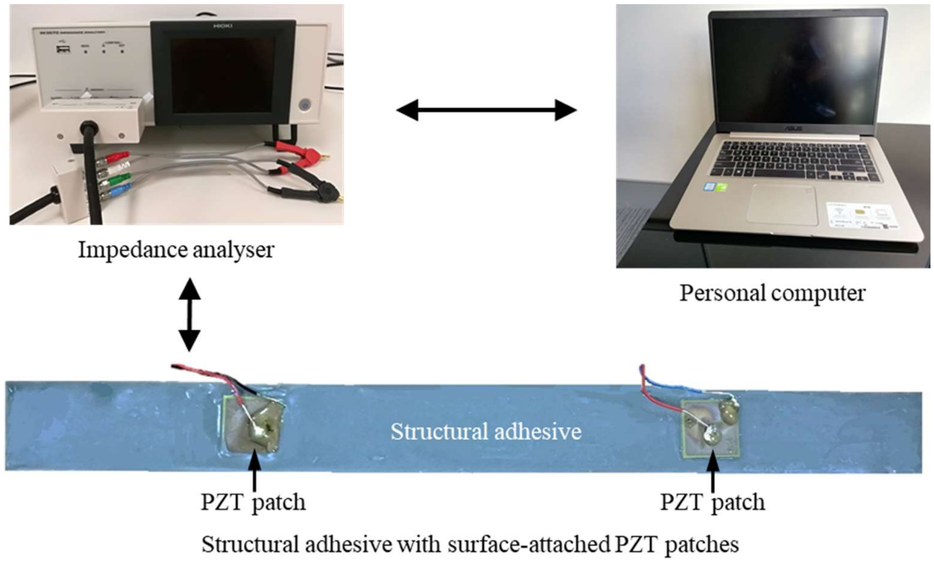

Figure 1. The EMI technique set-up for acquiring signatures from structural adhesive under curing.

RESULTS AND DISCUSSION

The acquired EMI signatures for structural adhesives under curing are graphically summarised and presented in Figure 2. Since the acquired EMI signatures from both of the PZTs are similar, only one of the results is presented here. Generally, the resonance peaks show rightward movement from 9 hours to 7 days of curing. Rapid rightward movement of the resonance peak (i.e. 4.08 kHz) for the first 24 hours of curing indicates the rapid strength development of the structural adhesives (Lu et al., 2019). This observation is similar with the physical changes, where the adhesives transformed from high-viscous liquid to solid, as reported by (Lim et al., 2019). For 1-7 days, the rightward movement of the resonance peaks is relatively slower (i.e. showing an increment of 0.6 kHz) as compared to the first 24 hours.

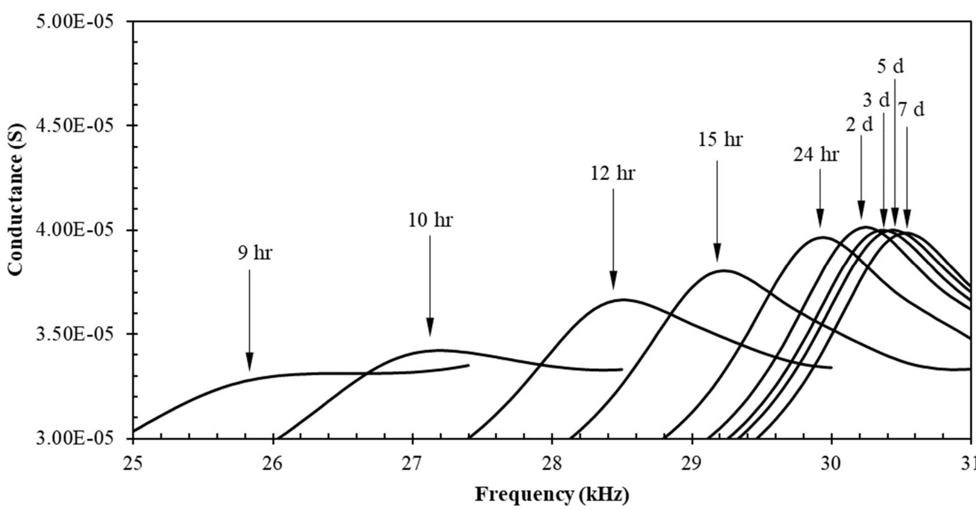

Figure 2. Rightward movement of resonance peak showing increase of strength for different curing durations.

Both the resonance frequency and tensile strength increases with curing duration. A correlation between the increasing tensile strength to the rightward movement of the resonance frequency throughout the curing durations can be developed. A reliable (R^2=0.999) exponential relationship, as illustrated in Figure 3, is established to correlate the tensile strength from the acquired resonance frequency. The relationship is expressed mathematically in Equation (1).

$$\sigma(t) = 7.041 \times 10^{-8} e^{0.650 f(t)} \quad (1)$$

where $\sigma(t)$ is the tensile strength of structural adhesives in MPa at different curing durations while $f(t)$ is the resonance frequency in kHz of a selected peak from the EMI technique. Both parameters are a function of curing duration, t.

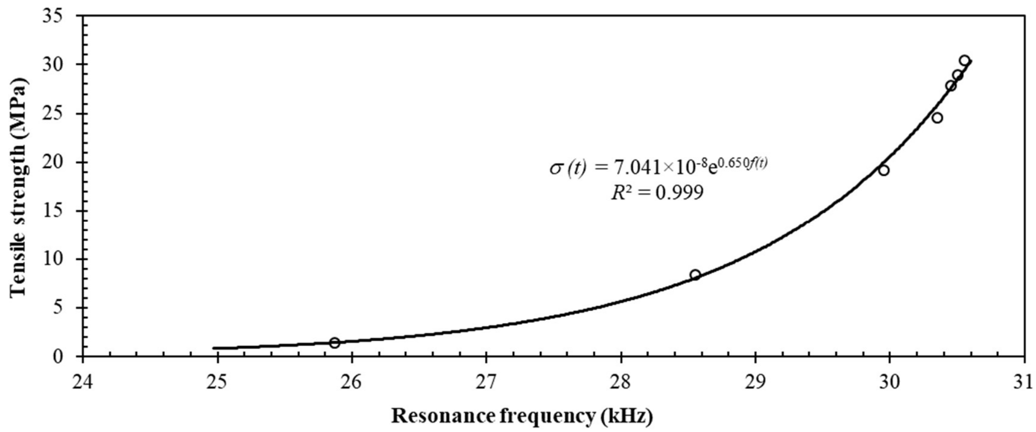

Figure 3. Correlation between tensile strength and resonance frequency (circle marker = experimental result; solid line = exponential curve fitting)

CONCLUSIONS

This paper has discussed the capabilities of the EMI technique for monitoring the curing process of structural adhesives. Based on the experimental study, the strength gain of adhesives can be observed from the rightward movement of the resonance peaks acquired from the EMI technique. Rapid rightward movement of the resonance peak in the first 24 hours indicated rapid strength gain. Peak movement and strength gain then continues to develop for 1-7 days. An empirical equation was developed to correlate the adhesive tensile strength based on the acquired resonance frequency with different curing durations. The study can be extended to investigate the consistency of the EMI technique for monitoring the curing process of adhesives, as well as different environmental conditions such as temperature and humidity.

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