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Case study

Bond characteristics of CFRP strengthened concrete members bonded using Modified Engineered Cementitious Composite

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ABSTRACT

This study focuses on the development of an insulating cementitious adhesive for bonding Carbon Fibre Reinforced Polymer (CFRP) fabrics to a concrete surface. The epoxy adhesive which is the generally used adhesive for CFRP shows a low thermal performance. As a potential solution, Engineered Cementitious Composite (ECC) mortar was modified as a cementitious adhesive with improved thermal insulation. The ECC adhesive was developed using locally available class F fly ash, silica sand and Polyethylene terephthalate (PET) fibres other than the generally used cement and water (PET-ECC). The selected mix proportion for PET-ECC achieved a low thermal conductivity of 0.145–0.180 W/mK which limited the heat transfer through the adhesive layer. The effective bond length of the developed PET-ECC adhesive was 125 mm and the corresponding bond strength was 224.9 MPa. The respective bond strength was further enhanced up to 570.28 MPa by sticking river sand on top of CFRP fabric using epoxy adhesive before bonding it to the concrete surface using the PET-ECC adhesive. The use of PET-ECC as the bonding agent to strengthen compression members with CFRP confinement yielded an average strength enhancement of 34%.

1. Introduction

The strength of reinforced concrete (RC) structures can deteriorate with time due to different external factors. Under those circumstances, the introductory of new retrofitting techniques and further development of existing techniques for RC structures have become a major concern. The use of Carbon Fibre Reinforced Polymer (CFRP) is such a new approach which is already been used in retrofitting purposes both in the construction industry as well as in other industries [1,2]. Effective bonding of CFRP on concrete is an essential requirement when it comes to proper retrofit. Generally, epoxy (organic) adhesives are used as the bonding agent for fibre composites. However, epoxy shows several disadvantages despite the fact that it has a better bonding ability. The strength of epoxy adhesive deteriorates rapidly with an elevated temperature that is beyond the glass transition temperature (T_g) (60–70 °C) [3]. Polymeric adhesives such as the epoxy change from a relatively stiff material to a viscous material at the T_g that causes a sudden drop in properties of the adhesive [4]. Apart from that, epoxy adhesive possesses other disadvantages such as the high cost of materials [5], toxic fumes [6] and flammability [6]. Therefore, insulations are applied over epoxy/CFRP bond [7,8] which is not economically feasible because of the cost spent on both epoxy adhesive and insulation. The research work of Longo et al. [9,10] showed that the use of mortar based bonding agent could provide both structural and thermal retrofitting characteristics to the Fibre Reinforced Polymer

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(FRP) bond system. Cementitious adhesives show better performance under elevated temperatures and they also show a good consistency with concrete [5]. Hence, a cementitious adhesive may perform as a bonding agent and an insulation, simultaneously. Badanoiu and Holmgren [11] found that the load capacity of the cementitious carbon fibre composite is influenced by the amount of fibres in the tow. Loading capacity can be increased if the cementitious matrix can penetrate the interior of the carbon fibre tow [11]. Because of these reasons the use of cementitious adhesives over epoxy adhesives can be suggested as a better solution.

Engineered Cementitious Composite (ECC) is a cementitious composite material reinforced with multidirectional fibres which are engineered to behave in a ductile manner under tensile and flexural loading [12]. ECC shows improved ductile behaviour as it has a strain capacity of 3–7%, whereas OPC shows only 0.1% of strain capacity [13]. Even though other cementitious adhesives perform well under elevated temperatures, they show low ductility. This creates a negative effect on the load transferring from the concrete substrate to CFRP [14,15]. ECC achieves the desired ductility due to the formation of micro cracks in the strain hardening stage [16]. As per the findings of Yang and Li [17], the higher fly ash content in ECC reduces its compressive strength and increases its tensile ductility. Experimental results on the thermal insulation properties of ECC depict that the higher amount of fly ash in ECC resists thermal conductivity [17,18]. Most prominently used fibres in ECC are polymeric fibres such as Poly Vinyl Alcohol (PVA), Polyethylene terephthalate (PET), Polyethylene (PE) and Polypropylene (PP). Sathishkumar et al. [13] conducted experiments on ECC developed using different fibre types (PVA, PET, PE and PP) and fibre contents to analyze the deviation in mechanical properties. The results depict that the ECC developed using PVA and PET fibres show higher mechanical strengths [13]. Wu and Li [15] conducted the direct pull-out test to determine the effective bond length for the CFRP-ECC strengthening system and it was observed that the peak pull out stress is directly proportional to the CFRP embedded length.

In this research work, authors used locally available recycled PET fibres, class F fly ash and silica sand to develop ECC as an adhesive for CFRP. The selection of mix proportion to develop ECC as a cementitious adhesive is documented in the authors' previous publication [19]. As a further extension for the previous work, the developed ECC adhesive is tested for the deviation in its mechanical properties with the increase of the curing period. Then the bond characteristics of the developed ECC adhesive was evaluated by testing for the effective bond length and the bond strength. The respective results were compared with the performance of a commercially available epoxy adhesive. Finally, the developed ECC adhesive was used as the bonding agent in strengthening compression members using CFRP confinement in order to evaluate its feasibility in the application.

2. Development of modified ECC thermo resisting adhesive

The two-part epoxy adhesive used to create the bond between CFRP and concrete is sensitive to elevated temperature [3,20]. This sensitivity leads to the requirement of a fireproofing coat to ensure a sufficient fire rating to the strengthened members in the application of buildings [3]. The replacement of epoxy adhesive bond using a cementitious adhesive may ensure the required fire rating without insulation [21] or it may reduce the insulation required to provide sufficient fire resistance.

However, the cementitious mortar behaves in a brittle manner. This restricts the development of such mortar as an adhesive due to the poor bonding ability. However, the polymer-based adhesives possess sufficient ductility which holds the bond with the concrete substrate without detaching. This ductile nature of polymeric adhesives can be introduced to the cementitious adhesives to some extent by blending fibres which enable to minimise cracking of cementitious mortar when exposed to a fire and to improve the ductility. This is the key principle behind the development of Engineered Cementitious Composite (ECC) in the current research.

Materials used to develop the ECC adhesive are ordinary Portland cement (OPC), silica sand, class F fly ash, water and Polyethylene Terephthalate (PET) fibres (Fig. 1). The silica sand used in this research work was collected from Naththandiya area in Sri Lanka and it contains a silicon dioxide content of more than 95%. The presence of high silicon dioxide level and less amount of other impurities makes silica sand chemically inert, compared to river sand. Further, the fineness in this silica sand type could enhance the workability of the cementitious adhesive. An atomic absorption spectrometer was used to analyze the chemical composition of fly ash (Table 1). Wu and Li [15] had done a similar approach on developing an ECC for the CFRP/concrete bond using Poly Vinyl Alcohol (PVA) fibres instead of PET fibres used in this study. This adhesive system had shown a good thermal performance when compared to CFRP/epoxy/concrete bond.

The development of ECC is not confined to a particular fibre type [22]. However, the ECC developed with any fibre type attains tensile strain hardening properties at a lower volume fraction [22]. ECC developed using PVA fibres (PVA-ECC) has a bigger database of test results compared to ECC developed with other fibres [15,23–25]. However, the data on PVA-ECC had shown that about 75% of the cost of PVA-ECC preparation is spent on PVA fibres [26]. Therefore, the use of PVA fibres in developing ECC is not economically

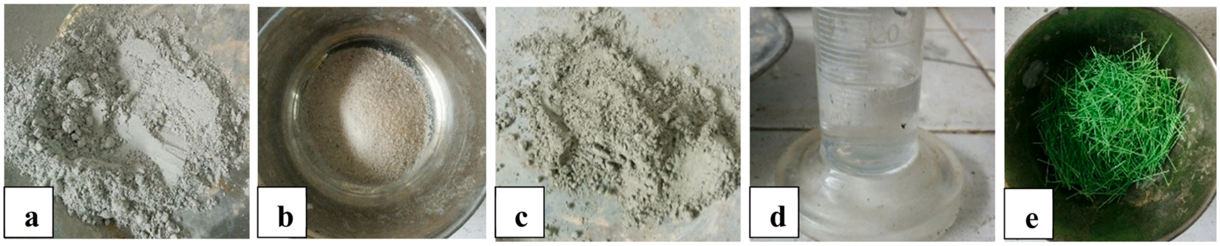

Fig. 1. (a) Cement (b) Silica sand (c) Fly ash (d) Water (e) PET fibres.

Table 1
Chemical composition of fly ash.

Component	Norochcholai Lakvijaya power plant, Sri Lanka	DTE Monroe Power Plant, State of Michigan, USA[15]	Component	Norochcholai Lakvijaya power plant, Sri Lanka	DTE Monroe Power Plant, State of Michigan, USA[15]
SiO_2 (%)	46.89	42.20	K_2O (%)	0.64	1.53
Al_2O_3 (%)	30.69	22.51	P_2O_5 (%)	2.67	–
MgO (%)	1.56	3.20	Fe_2O_3 (%)	1.88	9.20
CaO (%)	7.56	15.66	SO_3	–	1.85
Na_2O (%)	0.23	0.98	Loss on ignition	5.59	1.34

feasible. PET solid waste is a serious environmental issue. Therefore, to minimise the disposal of PET to the environment, the use of recycled PET fibres in the process of preparation of ECC is a sustainable approach. The PET fibres used in the current research are 10 mm in length and 0.4 mm in diameter. The properties of the normal modulus CFRP fabric used for the test programme are mentioned in Table 2 [27].

The details on the initial development of ECC adhesive using PET fibres as the fibre component (PET-ECC) which includes the selection of raw material mix proportions is documented in the previous publication by the authors [19]. Cement: fly ash: silica sand: water mix proportion ratio of PET-ECC by weight is 1:1.2:0.8:0.85 [19].

The application process of developed cementitious adhesive for the CFRP/concrete composite is in two steps; (i) a 5 mm thick PET-ECC adhesive layer on the bondline to adhere CFRP fabric on the concrete substrate, (ii) a 5 mm thick layer of ECC adhesive on top of the CFRP to insulate the bond and enhance the bond performance allowing maximum penetration of adhesive between carbon fibres (Fig. 2(a)). Unlike in epoxy adhesives, a cementitious adhesive includes a considerable dead load to the structure. Hence, the use of a higher PET-ECC layer thickness increases the overall dead load on the structure and the cost for materials. Therefore, the thickness of each PET-ECC layer was selected as 5 mm. This approach sets the overall PET-ECC/CFRP bond system thickness to 10 mm which is comparatively a lower thickness when compared with the dimensions of structural elements. Since this additional PET-ECC layer can always protect the bond from elevated temperature and restrict the penetration of aqueous solution and humidity to the bondline result in more stable service performance. Since the top layer insulates the bond, the thermal conductivity of this newly developed adhesive does a major role when the system is exposed to fire. In this regard, the thermal conductivity of the PET-ECC adhesive was measured by changing the fibre content in order to find the optimum fibre content which enhances the insulating properties. Circular shaped samples with a diameter of 60 mm and a thickness of 5 mm were cast to determine the thermal conductivity using the Lee's disc method (Fig. 2(b,c)). The procedure used to measure the thermal conductivity, the test results and the conclusions made out of the experimental results are documented in the previous publication by the authors [19]. Authors' previous research work concluded that the optimum PET fibre content to develop PET-ECC as 2% of the volume of cement [19]. The thermal conductivity of PET-ECC for the corresponding optimum PET fibre content is in the range between 0.145 W/mK and 0.180 W/mK [19].

3. Material properties of PET-ECC adhesive

The PET-ECC adhesive was tested for its mechanical properties; compressive (Fig. 3(a)), tensile (Fig. 3(b)) and flexural (Fig. 3(c)) strengths in accordance with ASTM C109 [28], ASTM C190-85 [29] and EN 1015-11 [30], respectively. The samples which were cast in the respective moulds were demoulded after 24 h and left to cure in water at ambient temperature (28 ± 3 °C). A total of 9 samples were cast to determine the respective strengths at 3 different curing periods; 7, 14 and 28 days.

Fig. 3(d) shows the typical tensile stress versus strain graph of the PET-ECC adhesive. According to Fig. 3(e), this developed PET-ECC adhesive possesses sufficient strengths even after 7 days of casting. The compressive strength achieved by PET-ECC at room temperature is 3–75% higher than that of ECC developed using PVA (PVA-ECC) in several other studies [15,23,31]. Further, it is 5.8% higher than the compressive strength of ECC mortar developed using PET fibres by Sathishkumar et al. [13]. However, the previous studies indicated that the tensile strength of PVA-ECC varied from 3 MPa to 5 MPa and this PET-ECC mortar shows a tensile strength closer to this range [15,23,31] (Fig. 3(e)). The calculated density of PET-ECC was 1895.04 kg/m^3.

The above comparison provides further evidence on the successful approach of replacing PVA with PET to develop ECC mortar with good material properties. The next step was to verify the adherence properties of PET-ECC in CFRP/concrete composites.

(d) Typical tensile stress versus strain curve of PET-ECC adhesive (e) Measured material properties of PET-ECC adhesive.

Table 2
Manufacturer-provided material properties of CFRP fabric [27].

Parameter	Value	Parameter	Value
Sheet weight	300 g/m^3	Modulus of elasticity	240 GPa
Carbon content	95%	Tensile strength	4000 MPa
Net effective thickness	0.166 mm	Elongation at break	2%

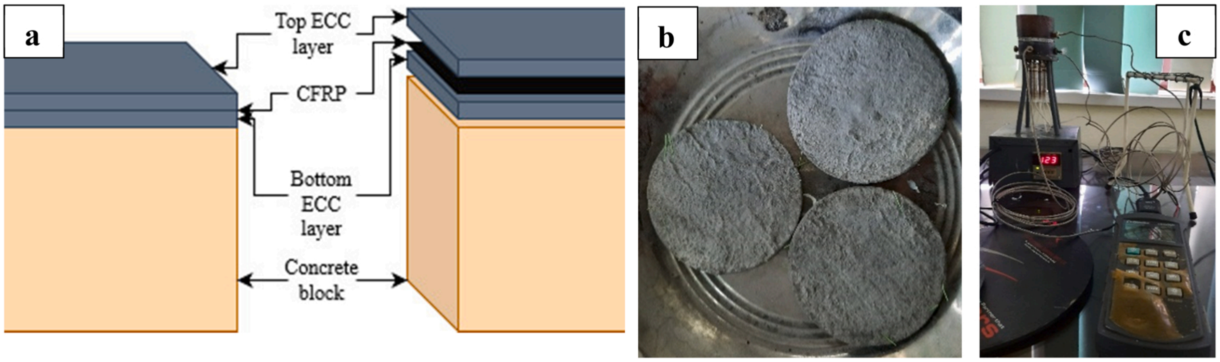

Fig. 2. (a) Application of ECC (b) Samples prepared to test thermal conductivity (c) Thermal conductivity test apparatus.

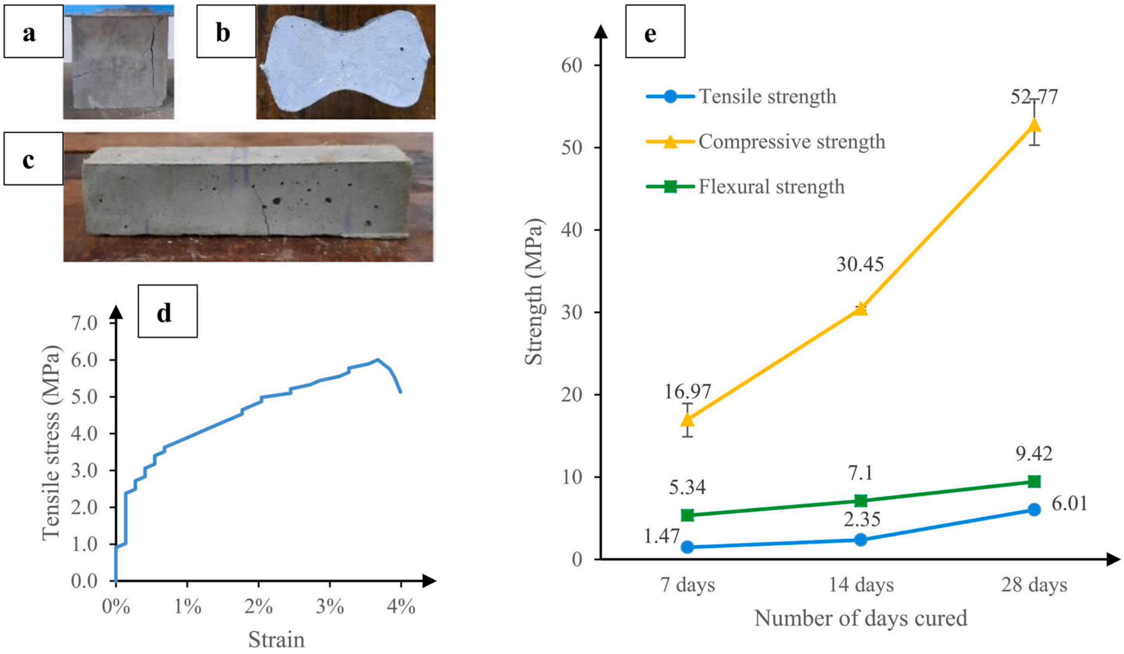

Fig. 3. (a) Compressive strength test sample (b) Tensile strength test sample (c) Flexural strength test sample (d) Typical tensile stress versus strain curve of PET-ECC adhesive (e) Measured material properties of PET-ECC adhesive

4. The bond characteristics of PET-ECC adhesive

The bond characteristics of the developed PET-ECC adhesive was analyzed by conducting a series of single-lap shear tests at ambient temperature. Further improvements were introduced to the bond system in order to enhance the bond strength. Subsequently, the PET-ECC adhesive system was used in the process of strengthening compression members using CFRP confinement.

4.1. Bond performance of CFRP/ECC/concrete bond at ambient condition

A series of single-lap shear tests were conducted in accordance with ASTM – D8337/D8337M-21 [32] to determine the effective bond length of PET-ECC adhesive (Fig. 4(a)). Grade 25 concrete blocks with the dimensions, 100 mm × 100 mm x 200 mm were used to bond the CFRP fabric using developed PET-ECC adhesive (Fig. 4(b)). The bonding surfaces of the concrete blocks were ground and cleaned prior to bonding the CFRP using the adhesive. A 75 mm wide CFRP fabric was adhered to the concrete substrate after applying a 5 mm thick PET-ECC layer. After applying light pressure onto the CFRP fabric in the fibre direction, another 5 mm thick PET-ECC layer was applied on top of the CFRP fabric to enhance the bond strength and insulation properties. In addition, a series of single-lap shear tests were conducted for the epoxy bond for the comparison purpose (Fig. 4(c)). A total of 12 samples were fabricated for a single adhesive type with two samples per bond length. The prepared samples were loaded at a rate of 2 mm/min.

The pull out strength in Fig. 5(a) is calculated by dividing the applied load by the cross sectional area of the CFRP [15]. The results

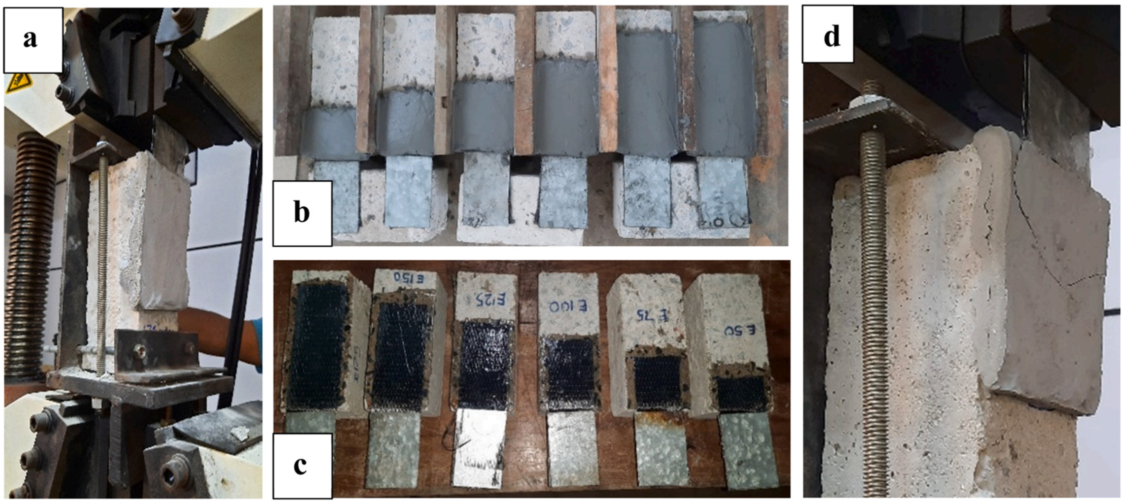

Fig. 4. (a) Conducting single lap shear test (b) PET-ECC bonded samples (c) Epoxy bonded samples (d) PET-ECC/CFRP bond interface failure.

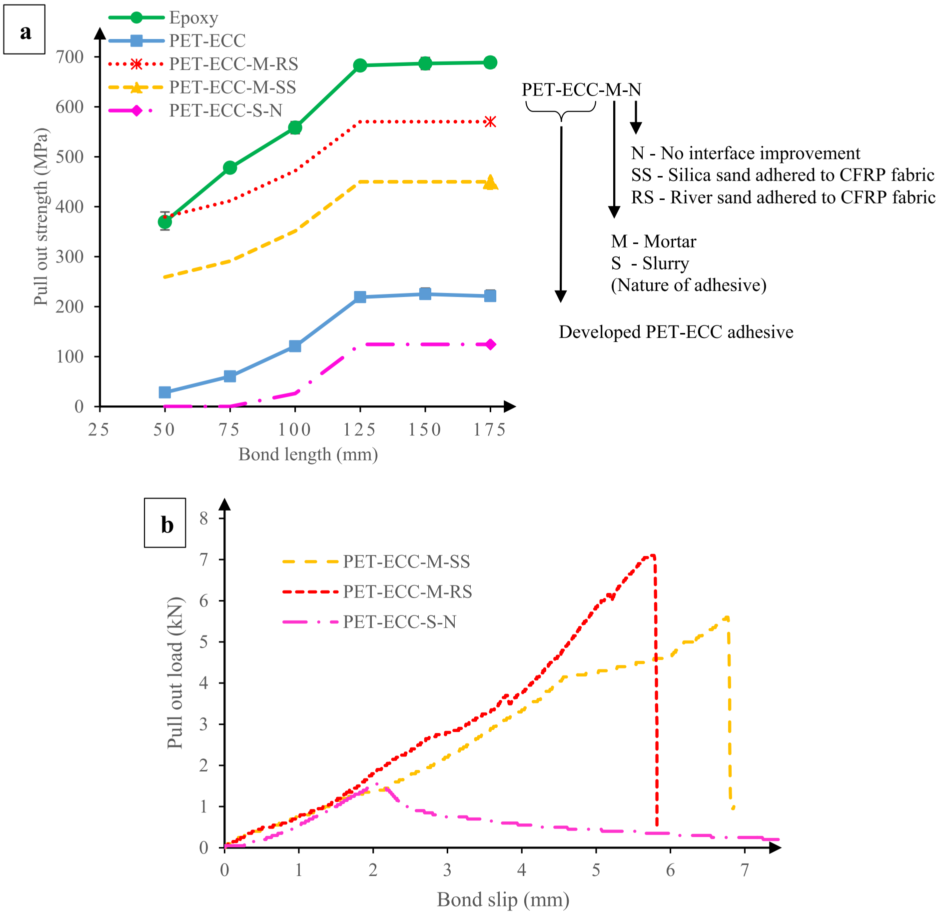

Fig. 5. (a) Bond strength versus Bond length graph for ECC adhesive (b) Pull out load versus Bond slip graph for ECC adhesive.

depict that the effective bond length for the adhesive system is 125 mm where the corresponding average bond strength was 224.9 MPa (PET-ECC-M-N) (Fig. 5(a)). Meanwhile, the epoxy adhesive-bonded setup (Epoxy) with a CFRP bond length of 125 mm showed a bond strength of 670.7 MPa (Fig. 5(a)). The bond strength reduction (66%) in PET-ECC-M-N was due to the interface failure between CFRP and PET-ECC (Fig. 4(d)). Considering this failure phenomenon, it was identified the requirement of increasing interface energy for proper attachment.

One way of enhancing the surface energies can be achieved by improving the surface friction between two surfaces. Therefore, three different attempts were taken to improve the CFRP-ECC bond. As the first attempt, river sand was adhered on both sides of CFRP fabric using epoxy adhesive before adhering it to the concrete block using the developed cementitious adhesive (PET-ECC-M-RS) (Fig. 6(a)). The river sand used to stick on CFRP fabric was taken after sieving through a 1.7 mm sieve. In the next option, the river sand was replaced with silica sand (PET-ECC-M-SS) (Fig. 6(b)). The third option was to use the ECC adhesive slurry (PET-ECC-S-N) instead of ECC adhesive mortar. To develop the ECC slurry, silica sand content was removed from the adhesive mix. No attempt was taken to enhance the surface friction along with this option rather than facilitating easy penetration of ECC slurry into the CFRP fabric layer. In this series of experiments, a total of 6 samples were fabricated with 2 samples from each case and the CFRP bond length was maintained as 175 mm in all the cases. The typical pull out load versus bond slip graphs obtained for all 3 approaches are shown in Fig. 5(b).

As shown in Fig. 6(c-e), all the improved samples except PET-ECC-M-RS showed the interface failure between CFRP fabric and PET-ECC. The sample PET-ECC-M-RS showed a relatively higher strength at ambient conditions compared with other improved samples (Fig. 5(a)). Meanwhile, the respective modification method has improved the interface bond between CFRP and PET-ECC, resulting in the concrete/PET-ECC bond failure. Hence, the application technique of adhering river sand on both sides of CFRP fabric before the application was selected for the development of PET-ECC adhesive system (PET-ECC-M-RS) and the product was further used to analyze its performance in strengthening concrete compression members using CFRP confinement. Henceforth, the combination of PET-ECC with the selected application technique (PET-ECC-M-RS) is referred to as PET-ECC.

4.2. Comparative performance between epoxy and PET-ECC in the application of CFRP for axial confinement of columns

Increased population and accelerated development in cities lead to the addition of few floors to existing multi-storey buildings if the foundation is capable of bearing the structural load. Due to the high strength to weight ratio, ease of application without the use of machinery and high strength enhancement, the CFRP technology is widely gaining appeal in retrofitting of infrastructure. In many cases, the traditional techniques cannot be applied for the columns in lower floors due to the reinforcement congestion and FRP application might be only the solution for restoration in such cases without adding an additional dead load to the substructure. However, a considerable amount of project cost should be allocated for insulation materials to ensure the required fire rating due to the sensitivity of the epoxy bond to the elevated temperature. Therefore, the successful application of the PET-ECC adhesive system in CFRP confinement of columns will show a considerable cost saving in such strengthening projects. Hence, the applicability of this material to enhance axial confinement of compression members using CFRP was assessed. Similar specimens strengthened by CFRP using epoxy as the bonding agent was also tested under the same conditions for comparison purposes.

A total of 9 columns were tested. Three of them were non-strengthened columns (Fig. 7(b)) and the rest were equally strengthened using PET-ECC adhesive (Fig. 7(c)) and epoxy adhesive (Fig. 7(d)). The non-strengthened concrete sample failed due to the crushing of concrete (Fig. 7(e)), while PET-ECC adhesive-bonded samples indicated concrete/CFRP interface failure (Fig. 7(f)). The samples which used epoxy adhesive failed in both CFRP rupture and debonding (Fig. 7(g)). However, the average strength enhancement observed from epoxy and PET-ECC bonded samples were 147% and 34%, respectively (Fig. 7(a)). Depending on the requirement of strength enhancement and possible use without insulation, PET-ECC may be an ideal solution for strengthening columns. For better performance, the authors recommend implementing a technique to enhance PET-ECC/concrete bond interface.

5. Conclusions and recommendations

In this study, an experimental approach was taken to develop an insulating adhesive to be used in CFRP strengthening of concrete members. Further experiments were carried out to evaluate the performance of the developed adhesive comparative to the conventional epoxy adhesive. Therefore, based on the results obtained, the following conclusions were made.

- The ECC mortar can be developed as a cementitious adhesive for CFRP/concrete bond. The PET fibres were used as the fibre component in the developed cementitious adhesive (PET-ECC). Cement: fly ash: silica sand: water mix proportion ratio of PET-ECC by weight is 1: 1.2: 0.8: 0.85.
- The developed PET-ECC adhesive showed a thermal conductivity in the range of 0.145–0.180 W/mK where the PET fibre proportion was used as 2% of the volume of cement. This is relatively a lower thermal conductivity when compared with the ECC mortar developed in previous research projects.
- The PET-ECC adhesive achieved 7 days compressive, tensile and flexural strengths of 16.97 MPa, 1.47 MPa and 5.34 MPa, respectively. The respective strengths gradually increased with the increase of curing period.
- The effective bond length of PET-ECC was 125 mm and the corresponding bond strength was 224.9 MPa. The bond strength can be further enhanced to 570.28 MPa by sticking river sand on top of CFRP fabric using epoxy adhesive before bonding it to a concrete substrate using PET-ECC adhesive. Hence, the percentage bond strength enhancement achieved through the mentioned modification when compared with the bond strength without modification is 158%. Moreover, the bond strength achieved by PET-ECC adhesive system is 85% of the bond strength of epoxy.
- The concrete compression members strengthened with the PET-ECC/CFRP bond system showed a strength enhancement of 34%. However, the respective strength enhancement is lower than that of the strength enhancement acquired by the Epoxy/CFRP bond system. Therefore, the authors recommend enhancing the PET-ECC/concrete interface bond by implementing an anchoring technique.

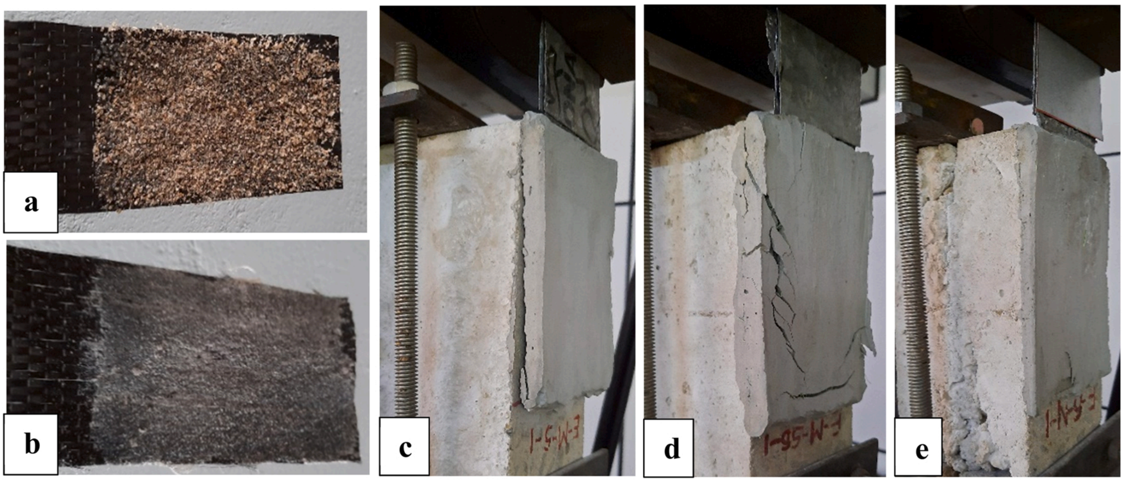

Fig. 6. (a) Sticking river sand on CFRP (b) Sticking silica sand on CFRP (c) Failure mode of PET-ECC-M-RS. (d) Failure mode of PET-ECC-M-SS (e) Failure mode of PET-ECC-S-N.

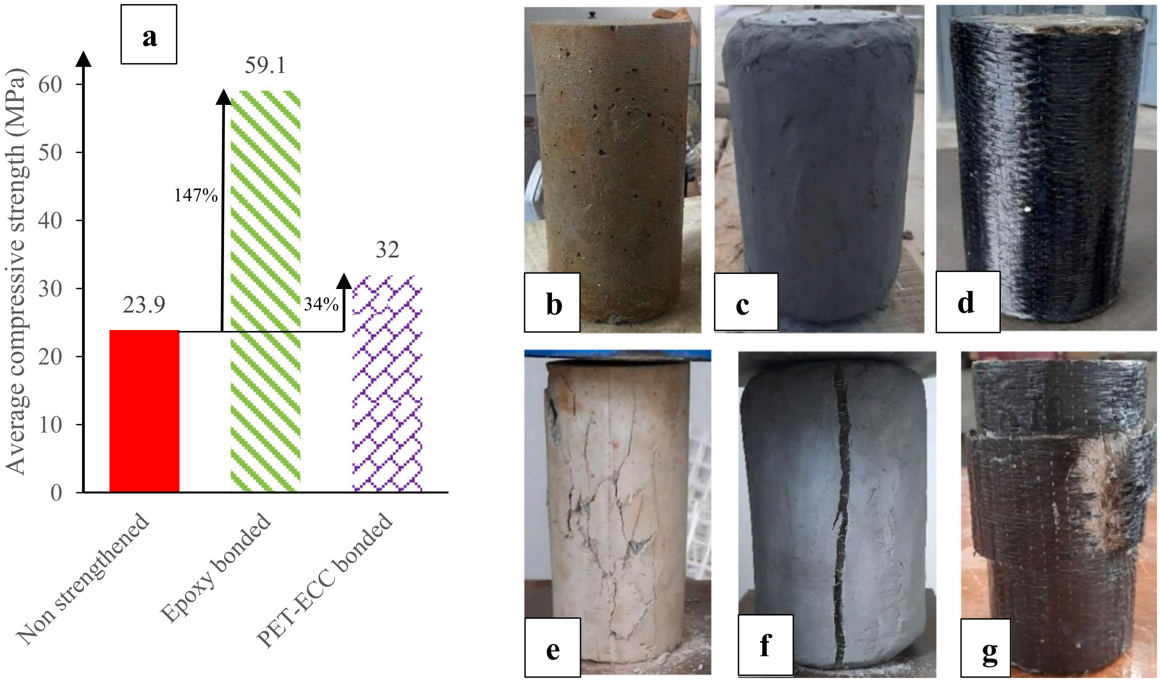

Fig. 7. (a) Comparison of strength enhancement, (b) Non-strengthened (c) PET-ECC bonded (d) Epoxy bonded samples, Failure modes of (e) the non-strengthened (f) PET-ECC bonded (g) Epoxy bonded samples.

CRediT authorship contribution statement

C. Widanage: Methodology, Testing, Analysis, Development and preparation of paper. **J.C.P.H. Gamage**: Research Supervision, Guidance, Planning and Monitoring. **G.I.P. De Silva**: Research Supervision, Guidance, Planning.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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