


Research Article

Strengthening of Damaged Masonry Walls Using Engineered Cementitious Composites: Experimental and Numerical Analysis

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Engineered cementitious composites (ECC) are special types of high-tensile and high-ductility concrete that are designed using a micromechanics approach, with a tensile strain capability of more than 3%. Due to their higher strain hardening capacity, ECC can be applied as a strengthening material on structural walls, which improves the structural strength and inelastic deformation capacity. This study presents an experimental and numerical analysis of brick masonry wall strengthened by traditional mortar, ECC, and ECC with 40% fly ash (FAECC) subjected to uniaxial compression. The tests, such as compressive strength, indirect tensile strength, and bond strength, were conducted. Based on the experimental results, a numerical model is developed, and a failure prediction for the existing masonry structure is made. The compressive strength of ECC is observed to be higher than normal mortar and FAECC whereas the indirect tensile strength of both ECC and FAECC was almost similar, which is higher than that of normal mortar. The bond strength of ECC and FAECC is found to be 70% higher than that of normal mortar. It is evident that brick masonry units strengthened by ECC have a higher compressive strength than masonry units strengthened by conventional mortar and FAECC. It also controls crack development and spalling of masonry units. Then, a micromodelling along with CDP model is made in Abaqus/CAE software and an excellent correlation between experimental and numerical results was noted. The suggested models were shown to be capable of predicting the common behaviour of masonry units.

1. Introduction

Unreinforced masonry construction is a popular construction method preferred all around the world. Most of the ancient and historical buildings constructed were load bearing structures and hence reconstruction is not an appropriate approach due to the vast number of buildings constructed with URM brick walls [1]. This emphasises the need for evaluating relevant structural strengthening measures for these structures. In order to strengthen the masonry structures, the strengthening material should have adequate tensile capacity to withstand heavy loads. Hence, engineered cementitious composites (ECC) would be a better option as a strengthening material on masonry wall as the application of ECC over the wall is similar to mortar

plastering and also the ability to withstand high temperature compared to other retrofitting materials, like FRP [2].

ECC is a highly ductile cementitious material having a tensile strain hardening capacity of more than 3%. This comes under the class of high-performance cementitious composites having high ductility and the ability to bend rather than fracture under severe loading conditions [3]. ECC is a combination of cement, sand, fibre, water, and some recurrent chemical additives. Coarse aggregates are not used in the mixture as they adversely affect the ductile property of the composite. ECC does not utilize a large amount of fibre unlike other types of fibre-reinforced concrete. Generally, the volume of discontinuous fibre less than 2% is appropriate, even though the composite is designed for structural applications [3–5]. Unlike high-

performance fibre-reinforced concrete, ECC reveals self-controlled crack width under increased loading conditions. These microcracks are formed within the material and then begin to spread once the load is applied. Due to the presence of fibres within the mixture, the cement matrix widens to a mean width of about $60\ \mu\text{m}$ [6, 7]. Normally the cement content of ECC is more than $1000\ \text{kg/m}^3$. This will lead to the generation of large amount of carbon dioxide, responsible for 5% emission of greenhouse gas created by human activities [8]. Therefore, it is imperative that green ECC be developed by adding mineral admixtures to partially replace cement to comply with global sustainable development. Fly ash has been an obligatory ingredient for ECC to improve its mechanical strength and reduce drying shrinkage [9].

Since ECC possess excellent crack control capability, researchers have been working on ways to reduce the crack widths that occur on structural elements using ECC. Zheng et al. [10] used a combination of ECC and basalt fibres to strengthen RC beams externally at the soffit, which functioned together as a composite reinforcement layer, and thereafter the flexural behaviour of the beam is examined through four-point loading and an increase in strength and stiffness is observed. Some studies were also made on fire-damaged RC beams strengthened by steel-reinforced ECC to determine its shear behavior [11]. Al-Gemeel and Zhuge [12] investigated the confinement effectiveness of different confining systems made using ECC and basalt fibre-reinforced ECC on square column through which the compressive strength of column confined using ECC has been proved to be higher compared to other columns. ECC has also been used for strengthening RC beam-column joints to determine its effectiveness under seismic conditions [13].

Though ECC has been widely used on RC structural elements, research on masonry walls strengthened by ECC is very less comparatively. So far, focus has been more on strengthening of RC structures compared to strengthening of masonry structures. Moreover, the development of masonry strengthening techniques has also taken place at a discrete level. Masonry strengthening is often necessary if damage is caused by earthquakes, poor construction, or deterioration of the structure [14]. Chourasia et al. [15] conducted an experimental investigation of seismic strengthening technique for confined masonry buildings in which masonry walls are strengthened using chicken mesh, welded wire mesh, industrial geogrid mesh, polypropylene band mesh, nylon mesh, and plastic cement bag mesh and their response under uniaxial and lateral loading is examined. Shabdin et al. [16] investigated the effectiveness of textile-reinforced mortars (TRM) in strengthening unreinforced masonry (URM) walls through which the strength enhancement potential of TRMs was determined by conducting diagonal tension (shear) tests on ten masonry walls. The results confirmed that the masonry units strengthened on both the faces show better performance compared to that strengthened on only one face. Though alternate materials are available for strengthening masonry walls, ECC possess better thermal property compared to other materials [2]. Soleimani-Dashtaki et al. [17] performed a shake table test on unreinforced masonry walls strengthened by sprayable

eco-friendly ECC thorough which the lateral load carrying capacity of the masonry walls strengthened on single and double faces was examined. The results confirmed that the single-sided retrofitting is sufficient enough for a low-rise building to withstand major earthquake whereas double-sided retrofitting can be preferred for high-rise buildings carrying heavy loads on walls. Pourfalah et al. [18] conducted a flexural road test on masonry walls partially and fully bonded by ECC through which the out-of-plane behaviour was examined. The deflection that occurred on masonry walls fully bonded by ECC was found to be less compared to the walls with partially bonded ECC. The propagation of cracks can also be controlled by providing ECC overlays on masonry walls [19]. Previous research demonstrates that the ductility of the masonry walls can be improved by applying ECC on both the faces of the masonry walls [18, 20]. Prior studies have also shown that the tensile characteristics of ECC possess a substantial impact on the in-plane behaviour of the modified walls [21].

Along with masonry strengthening, numerous studies were also made on bond strength of brick and mortar. The capacity of mortar or any binding material used in masonry units to remain bonded during the application of severe axial and lateral loads is referred to as bond strength. This is a critical parameter of masonry unit to produce appropriate tensile strength, as well as the ability to endure wind and seismic stresses, as well as slight displacement. Deficient bond strength will result in cracking and dislocation of bricks in masonry construction [22]. Since cracking is a brittle mode of failure, redistribution of stresses would occur and hence there is a possibility of widespread damage if bond strength is insufficient. The weakness might be conspicuous only when the masonry is subjected to supreme loading condition, such as a high wind or an earthquake, when it might lead to collapse [23]. According to Sarangapani et al. [24], the bond strength of ordinary brick mortar interface coated with epoxy as an enhancing material increases by 4 times. Also, bricks with rough surface possess higher bond strength compared to bricks having plane surface [25]. Curing is another important factor to be considered for the development of bond strength. In comparison to dry curing, wet curing of masonry units is preferred to gain better bond strength and elastic modulus [26]. Overall, the factors that impact the bond strength between brick and mortar include the mortar type, surface properties, water absorptions of the brick, frog dimension, and curing process [27–29].

Although previous studies provided necessary information on ECC and various masonry strengthening techniques, some parameters such as effect of bond strength on strengthened masonry walls and amount of fly ash required in ECC to strengthen masonry walls have not been found. More importantly, most of the studies were undertaken on strengthening of undamaged masonry walls rather than weak and damaged walls. With an emphasis on the development of structural behaviour of historic masonry buildings, this study involves the strengthening of damaged masonry units by ECC. It is also concentrated to prepare an eco-friendly ECC by adding fly ash to the mixture. Hence, in this research, weak masonry units were developed,

TABLE 1: Properties of fibres.

Fibres	Length (mm)	Diameter (mm)	Aspect ratio	Type of fibre	Tensile strength (MPa)	Modulus of elasticity (GPa)
Steel	26	0.7	37.1	Hooked end	1000	200
Polypropylene	30–40	0.3–0.35	100–115	Monofilament	551–658	3.5–7.5

TABLE 2: Properties of superplasticizer.

Type	Appearance	pH	Chloride	Sodium sulphate
Polycarboxylic	Yellowish viscous fluid	8.4	≤0.01	≥0.2

strengthened by ECC and thereafter the strengthening effect of ECC is studied through experimental and numerical analysis.

2. Experimental Program

This study investigates the efficacy of using ECC in strengthening masonry walls. Initially the compressive strength and indirect tensile strength of mortar, ECC, and ECC with fly ash were tested. Following that, the shear bond strength of these samples on masonry units was determined through triplet test [22–26]. Then, the major investigation was performed on three sets of double-layered weak masonry units strengthened by normal mortar, ECC, and ECC with 40% fly ash. All the elastic and plastic properties were collected from the above tests and are further used for numerical analysis.

2.1. Materials. Ordinary Portland Cement (OPC 53 grade) having a specific gravity of 3.15 is utilized. Manufactured or M sand that has been passed through 300-micron sieve is used as fine aggregate [30]. For both mixing and curing purpose, ordinary portable water is used. To ensure acceptable workability, a high-range water-reducing admixture was utilized. Two types of fibres were used in this study; they are polypropylene fibre and steel fibre. The conventional mortar is prepared according to IS:2250 (1981) [31] and the ECC mixture is made using the micromechanics design concept. Class I clay bricks of size (10 × 7.5 × 20.5) were used for masonry purpose. The bricks were brought from NRA Traders, Chennai, and it is confirmed that the properties satisfy IS-1077 [32]. The properties of fibres and superplasticizer were mentioned in Tables 1 and 2.

2.2. Mix Design. The mix design of ECC is completely based on the micromechanics design principle [30, 33]. The micromechanics of ECC is a body of knowledge that defines the interaction between fibres and cement matrix synergized to form multiple cracks under tension. The mixing procedures of ECC with and FAECC were similar [34]. The dry cement and fly ash mixtures were thoroughly blended together for few minutes. The polycarboxylate superplasticizer was added with water and mixed effectively before combining it with cement and fine aggregate. While mixing the wet cement and fine aggregate mixture, the steel and polypropylene fibres were included. The polypropylene

fibres were dipped in water before combining them with wet mixture as the dry fibre has the ability to absorb water from the wet mixture. Since fibre distribution has a significant impact on mechanical qualities, it is critical to ensure that the fibres are evenly dispersed within the mortar. The mix proportions for normal mortar, ECC, and ECC with fly ash are mentioned in Table 3.

2.3. Test Specimen. The samples were prepared for mortar, ECC, and ECC with 40% fly ash to test the mechanical properties. The compressive strength test was carried out on 50 mm × 50 mm × 50 mm cubes in accordance with ASTM C109/109M-21 [35] whereas the indirect tensile strength was performed on 200 mm × 100 mm concrete cylinder based on ASTM C496/C 496M-04 [36]. Three sets of double-layered masonry units of size 190 mm × 220 mm × 420 mm were prepared for strengthening and are tested for compression based on BS EN772-1-2000 [37]. To determine the shear bond strength of masonry units with normal mortar, ECC, and ECC with 40% fly ash as bed joints, a triplet test was conducted based on EN1052-1 [38]. Figures 1(a) and 1(b) show the dimension of the specimens used for compressive strength and triplet tests. The experimental setup of triplet test and compressive strength test is shown in Figures 2(a) and 2(b).

2.4. Strengthening Procedure. The double-layered masonry units prepared for the compressive strength test are intentionally damaged by applying initial cracking load. Once the cracks are formed, the loading is stopped, and the specimens are shifted for the strengthening process. Three sets of specimens were taken, and the strengthening is made using mortar, ECC, and FAECC for each set of specimens. The strengthening is made by filling the cracks and plastering both faces of the masonry units. The thickness of the strengthening layer is 10 mm. A thickness of about 3 to 30 mm has been proved to be preferable in a study conducted by Arslan and Celebi [14]. Once the strengthening is done, the specimens were tested for compression after 28 and 90 days of curing.

2.5. Compressive Strength of Mortar and ECC. The compressive strength of mortar and ECC was conducted based on ASTM C109/109M-21 [35]. Fresh mortar and ECC were prepared and were poured into 50 mm × 50 mm × 50 mm

TABLE 3: Mix proportions.

Mix	Cement	Fly ash	M sand	W/C	Steel fibre	PP fibre	SP
Mortar	1	—	3	0.4	—	—	—
ECC	1	—	0.6	0.36	0.01	0.01	0.005
FAECC	0.6	0.4	0.6	0.36	0.01	0.01	0.005

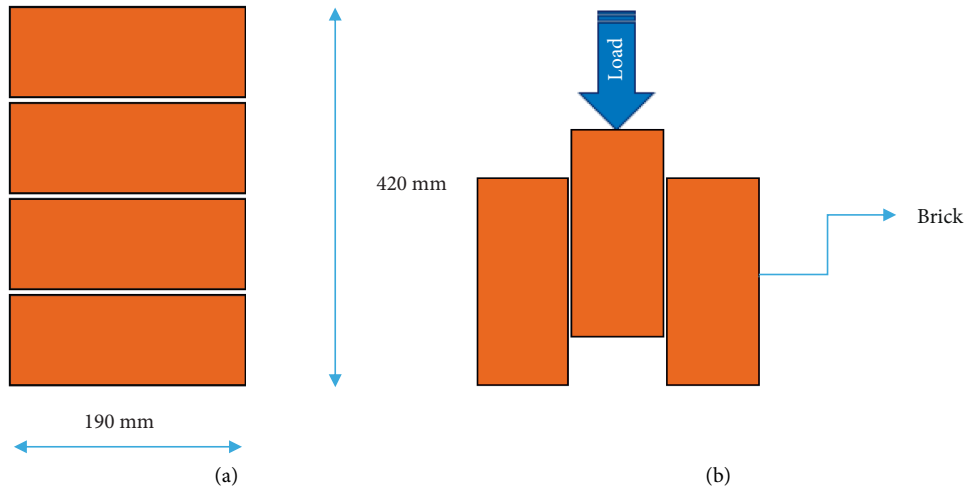


FIGURE 1: (a) Specimen for compressive strength test. (b) Triplet test setup.



FIGURE 2: (a) Triplet test setup. (b) Specimen for compressive strength test.

mould. The mortar was poured in 3 layers and each layer was compacted. Necessary precautions have been made for even distribution of ECC fibres through proper mixing. After casting, the samples were kept under room temperature for about 24 hours and then they were demoulded. After demoulding, the cubes were dipped into water for curing. After curing the cubes for 7, 28, 56, and 90 days, it is tested for compression. The compressive strength of normal

mortar, ECC, and FAECC at 7, 28, 56, and 90 days is mentioned in Figure 3. The strength attained by mortar, ECC, and FAECC was 23.4 MPa, 38.2 MPa, and 30.4 MPa on 7 days and 49.45 MPa, 59.3 MPa, and 50.6 MPa on 90 days, respectively. The compressive strength of ECC without fly ash exhibited 12% and 20% increase in strength at 28 and 90 days compared to conventional mortar. The compressive strength of ECC with fly ash is found to be less compared to

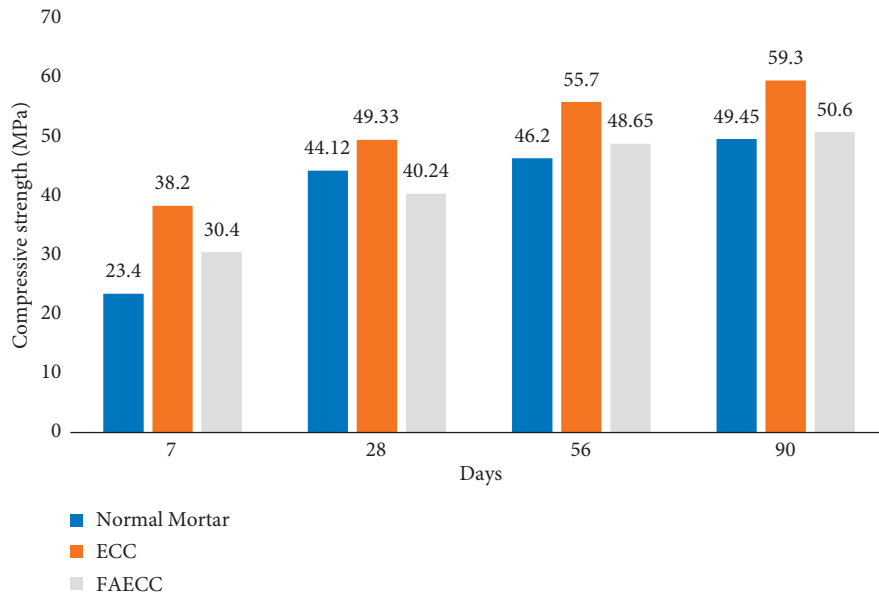


FIGURE 3: Compressive strength.

ECC without fly ash but comparatively similar to normal mortar. But ECC with fly ash has a greater rate of increase in strength compared to traditional mortar after 90 days. This increase in strength of ECC is due to the high load carrying capacity of the composites and also the bridging of cement matrix by fibres resulting in formation of microcracks. This microcrack behaviour was also observed in ECC with 40% addition of fly ash. The tested samples were shown in Figure 4.

2.6. Indirect Tensile Strength. Splitting tensile strength test is an indirect method of determining the tensile strength of concrete or any cementitious material [39]. In this study, the indirect tensile strength tests of mortar and ECC were conducted based on ASTM C496/C496M-04 [36]. This codal practice was chosen since Qudoos et al. [39] clearly state that conducting indirect tensile strength test for mortar using concrete testing methods does not affect the experimental results of mortar specimen.

Fresh mortar and ECC were prepared, and they were poured into 200 mm × 100 mm cylinder. Then, each layer was tamped properly to prevent segregation and to improve the distribution of fibres in ECC. Once the specimens were cast, they were kept under room temperature for about 24 hours. Then, the specimens were demoulded and they were dipped into water for curing. After curing the cylinders for 28 and 90 days, they were tested for tensile strength. The cylindrical specimen is placed in such a way that the longitudinal axis is perpendicular to the load. The load was progressively increased at a nominal rate without creating any shock. The maximum applied load as reported by the testing equipment and the mode of fracture was recorded. Figure 5 shows the indirect tensile strength of mortar, ECC, and FAECC. At 28 days, ECC attains 88% increase in strength and FAECC attains 56% increase in strength

compared to normal mortar. After 90 days of curing, the indirect tensile strength of both ECC and ECC with fly ash were nearly found to be similar. The tested samples were shown in Figure 6.

2.7. Bond Strength. To find out bond strength, the specimens were made in the form of stack bonded triplets by standard bricklaying procedures using masonry mortar and ECC as bed joints. The area of the masonry units where the load is to be applied should be plane and perpendicular to the bearing surface. Once the specimens were cast, it was kept under curing for 28 and 90 days. The specimen after curing was placed into the Universal Testing Machine (UTM) and the load was applied parallel to the mortar joints. To reduce the bending moment, it is better to relocate the point of load application as close to the joint as feasible. The load is applied in a way that creates a peak load within 1 to 2 minutes of completion of the test. Using tangential force and area of application of mortar, the shear bond strength is determined. The test was carried out in clay bricks with normal mortar, ECC, and ECC with fly ash as bed joints, and the results are shown in Figure 7.

The bond strength of brick with conventional mortar, ECC, and FAECC is found to be 0.45 MPa, 0.8 MPa, and 0.81 MPa at 28 days. The bond strength is almost the same for ECC and FAECC when further curing is made. The use of polypropylene fibres and higher cement content in ECC and FAECC improved the shear capacity of bed joints, resulting in higher bond strength. Ronald Lumantarna and Biggs [28] investigated the shear bond strength of masonry walls constructed between 1880s and 1940s in New Zealand using lime mortar through which a bond strength ranging from 0.02 MPa to 0.6 MPa was achieved for distinct loading levels. Also, for general kinds of masonry units, an implicit bond strength of 0.2 MPa was achieved using mortar with mix

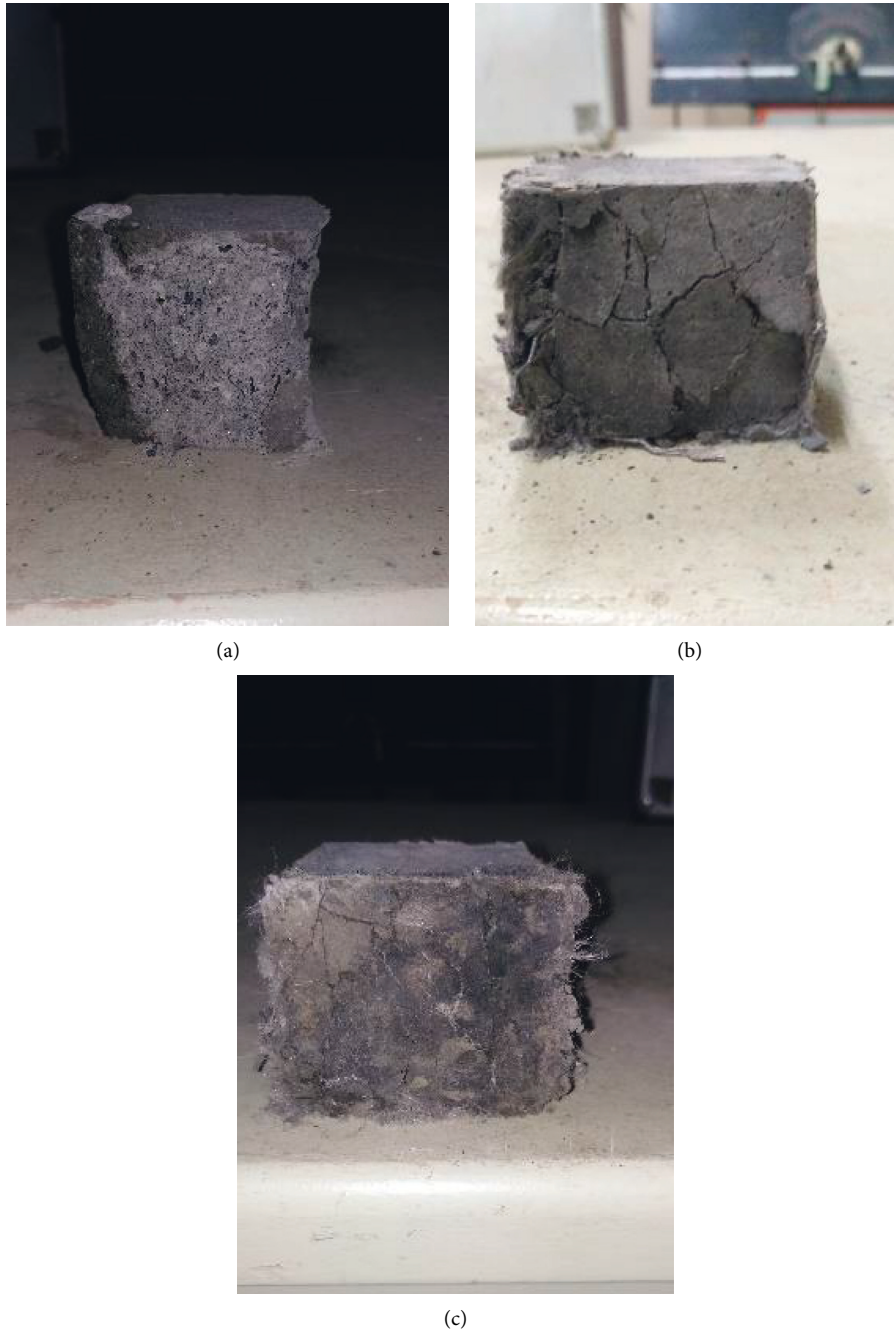


FIGURE 4: Cubes after testing: (a) mortar, (b) ECC, and (c) FAECC.

proportions specified in AS3700:2018 [40]. Thus, in comparison to other mortar mixes used in prior testing, ECC achieved a 20 percent improvement in bonding strength.

2.8. Compressive Strength of Strengthened Masonry Prism.

The compressive strength test was conducted on three sets of double-layered stack bond masonry prism. First, the masonry prisms were weakened by applying the initial cracking load and then the strengthening process is done. The strengthening was made by mortar, ECC, and ECC with fly ash on both the faces of the prism respectively. After casting,

the specimens were kept under curing for 28 and 90 days. The curing is made using wet sack and is made sure that there is no evaporation of water. After 28 and 90 days of curing, they were tested for compression using UTM. The deformations and the crack patterns were noted and thereby all the elastic and plastic properties were collected from the experimental data.

The compressive strength of weak masonry units strengthened by normal mortar, ECC, and ECC with 40% fly ash was tested for 28 and 90 days as per BS EN772-1-2000 [37]. In Table 4, the test results are shown. It is observed that the compressive strength of the masonry units strengthened

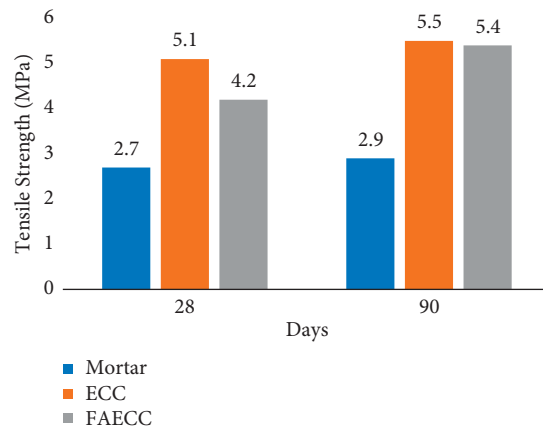


FIGURE 5: Indirect tensile strength.



(a)

(b)



(c)

FIGURE 6: Specimens after testing: (a) mortar, (b) ECC, and (c) FAECC.

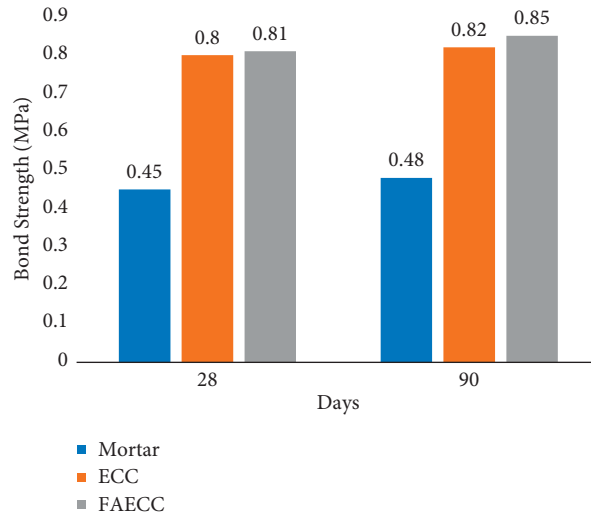


FIGURE 7: Bond strength.

TABLE 4: Masonry compression results.

Masonry units strengthened by	Compressive strength (MPa)		Modulus of elasticity (GPa)	Poisson's ratio
	28 days	90 days		
Mortar	3.7	4	2.8	0.08
ECC	6.2	7.1	3.2	0.1
FAECC	5.85	6.9	3.12	0.1

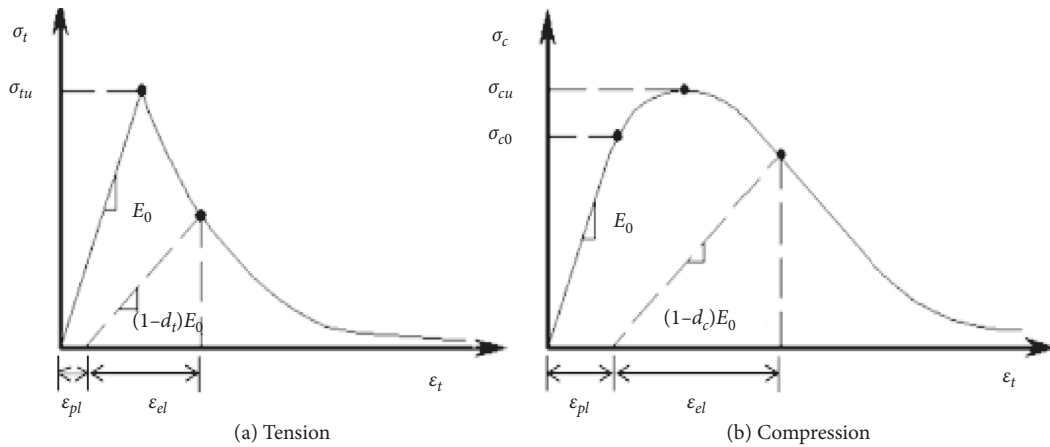


FIGURE 8: The compressive and tensile response of concrete to uniaxial loading described by Duval [44]. (a) Tension. (b) Compression.

TABLE 5: Mechanical properties of masonry assemblage.

Samples	Mass density (Kg/m ³)	Young's modulus (GPa)	μ	ψ	Eccentricity	f_{bo}/f_{co}	K
Masonry prism	2672	2.8	0.08	34	0.1	1.16	0.67
ECC	1848	15	0.1	36	0.1	1.16	0.67
FAECC	1826	15	0.1	36	0.1	1.16	0.67

by ECC is 67% higher than normal mortar strengthening and 6% higher than masonry units strengthened by ECC with fly ash (FAECC) at a curing period of 28 days. After 90 days, the compressive strength of masonry units

strengthened by FAECC is just 3% less than masonry units strengthened by ECC.

The spalling of the masonry prism is clearly observed at failure load for normal mortar strengthening but in case of

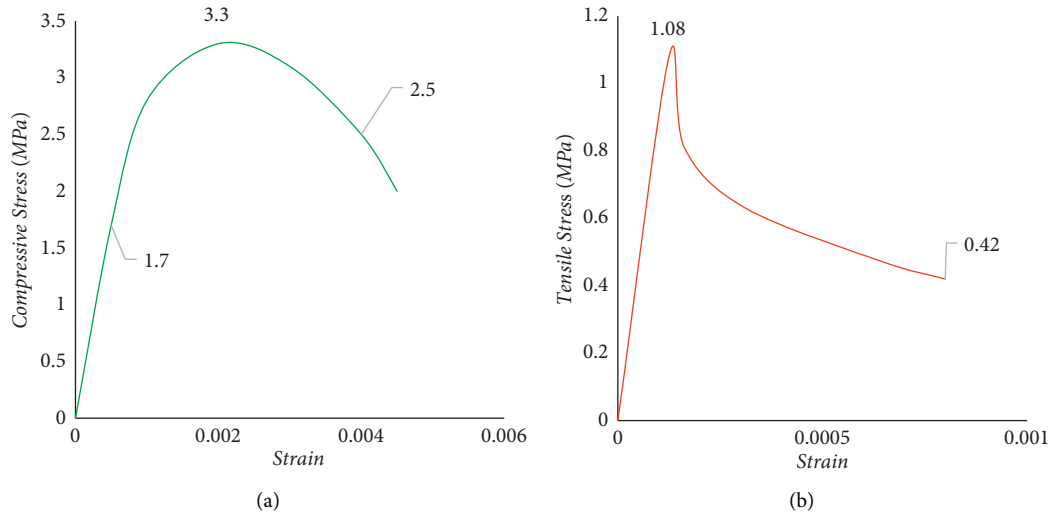


FIGURE 9: Stress-strain graph of (a) masonry compression and (b) masonry tension.

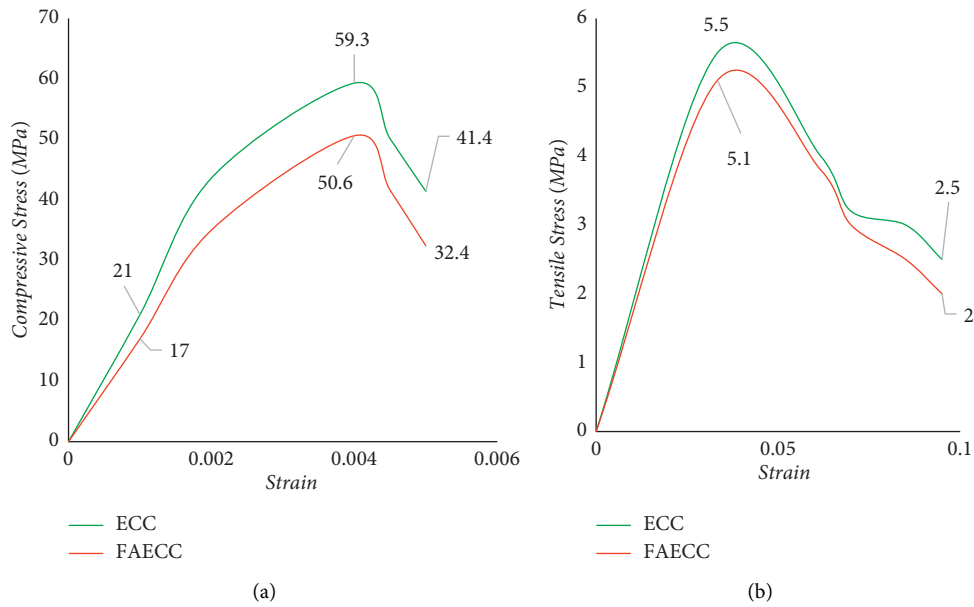


FIGURE 10: Stress-strain graph of ECC and FAECC under (a) compression and (b) tension.

TABLE 6: Compressive and tensile behavior of the masonry model.

Masonry			
Compression		Tension	
Yield stress (MPa)	Inelastic strain	Yield stress (MPa)	Cracking strain
1.7	0	1.08	0
2.8	0.001	0.81	0.00013
3.3	0.002	0.63	0.00025
3.1	0.003	0.47	0.00052
2.7	0.004	0.42	0.00064

ECC and FAECC strengthening, the spalling is completely prevented. This happens because ECC has a higher tensile strength and strain hardening behaviour, which causes only

microcracks to form. The point of contact between the masonry bed joints and the retrofitting material is a critical portion to be considered because the bed joints act like an

TABLE 7: Compressive and tensile behaviour of ECC and FAECC.

ECC				FAECC			
Compression		Tension		Compression		Tension	
Yield stress (MPa)	Inelastic strain	Yield stress (MPa)	Cracking strain	Yield stress (MPa)	Inelastic strain	Yield stress (MPa)	Cracking strain
21	0	5.5	0	38.2	0	5.1	0
43.6	0.002	5.1	0.037	45.3	0.002	4.3	0.035
59.3	0.004	4.7	0.042	50.6	0.004	4.0	0.037
50.1	0.0045	4.2	0.051	41.6	0.0045	3.7	0.048
41.4	0.005	3.5	0.057	32.4	0.005	3.1	0.052

interlock between the strengthening material on both faces of the masonry units. When load is applied, the faces of the masonry prism undergo tension, which pulls the strengthened layer out of plane. Since ECC and FAECC possess similar bond strength, the out-of-plane behaviour is also observed to be in a similar manner. The tensile property of the strengthening material also plays a major role in the confinement of masonry [41]. Hence, high tensile strength of ECC and FAECC also contributes to the control of out-of-plane behaviour and spalling of damaged masonry units. The stress-strain graph obtained from the experimental result was used to calculate the modulus of elasticity in addition to compressive strength. Finding the slope of the stress-strain curve determines the modulus of elasticity. Also, the strain values along the transverse and longitudinal direction were recorded and hence the ratio of transverse strain to longitudinal strain gives the Poisson ratio. It is observed that the masonry units strengthened by ECC and FAECC possess almost similar modulus of elasticity, which is higher than that of masonry units strengthened by normal mortar. Also, the Poisson ratio for all the three specimens matched with the previous studies conducted on clay brick masonry walls [42]. The acquired compressive strength of masonry walls strengthened by ECC and FAECC is also noted to be within the range of strengths obtained in previous studies made on masonry retrofitting [14, 33].

3. Numerical Analysis

All the elastic and plastic properties were collected from the experimental test involved and are further used for numerical modelling. A masonry model is made similar to the specimens used for the experimental tests and properties were loaded. Since the material is brittle and possess interactions, a Concrete Damage Plasticity (CDP) model is used along with cohesive surface parameters.

Concrete Damage Plasticity (CDP) model, which is typically favoured for brittle materials, may be used to simulate the nonlinear behaviour of masonry units in Abaqus [43]. To characterise the inelastic behaviour of the brittle material, the Concrete Damage Plasticity model combines the ideas of isotropic damaged elasticity with isotropic tensile and compressive plasticity. The failure mode of this model depicts that the crushing in compression and cracks in tension. Figure 8 shows the response of concrete under axial compression and tension, illustrated by concrete

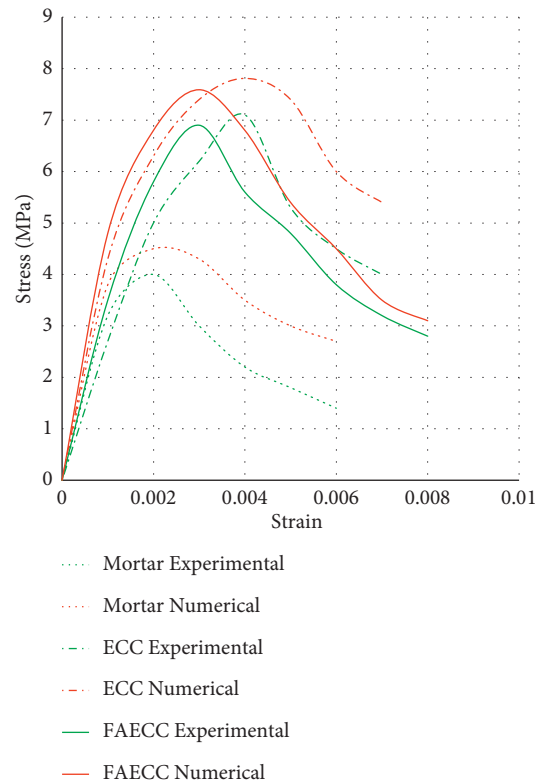


FIGURE 11: Stress-strain graph of masonry units strengthened by mortar, ECC, and FAECC.

damage plasticity. Figure 8(a) states that when a concrete material undergoes tension, it is subjected to a linearly elastic deformation until ultimate stress σ_{tu} . Microcracks begin to originate once the material reaches the failure stress. The softening stress-strain response beyond ultimate stress indicates further dispersion of microcracks, which promotes strain concentration within the concrete material. Figure 8(b) shows the stress-strain graph of a concrete material under uniaxial compression. The material under compression undergoes a linear response until yield point σ_{co} and beyond the ultimate stress σ_{cu} , the strain begins to soften gradually [44].

3.1. Model Input. The materials properties mentioned in Table 5 were used to model the masonry units. The mass density, Young's modulus, Poisson's ratio, and the dilation

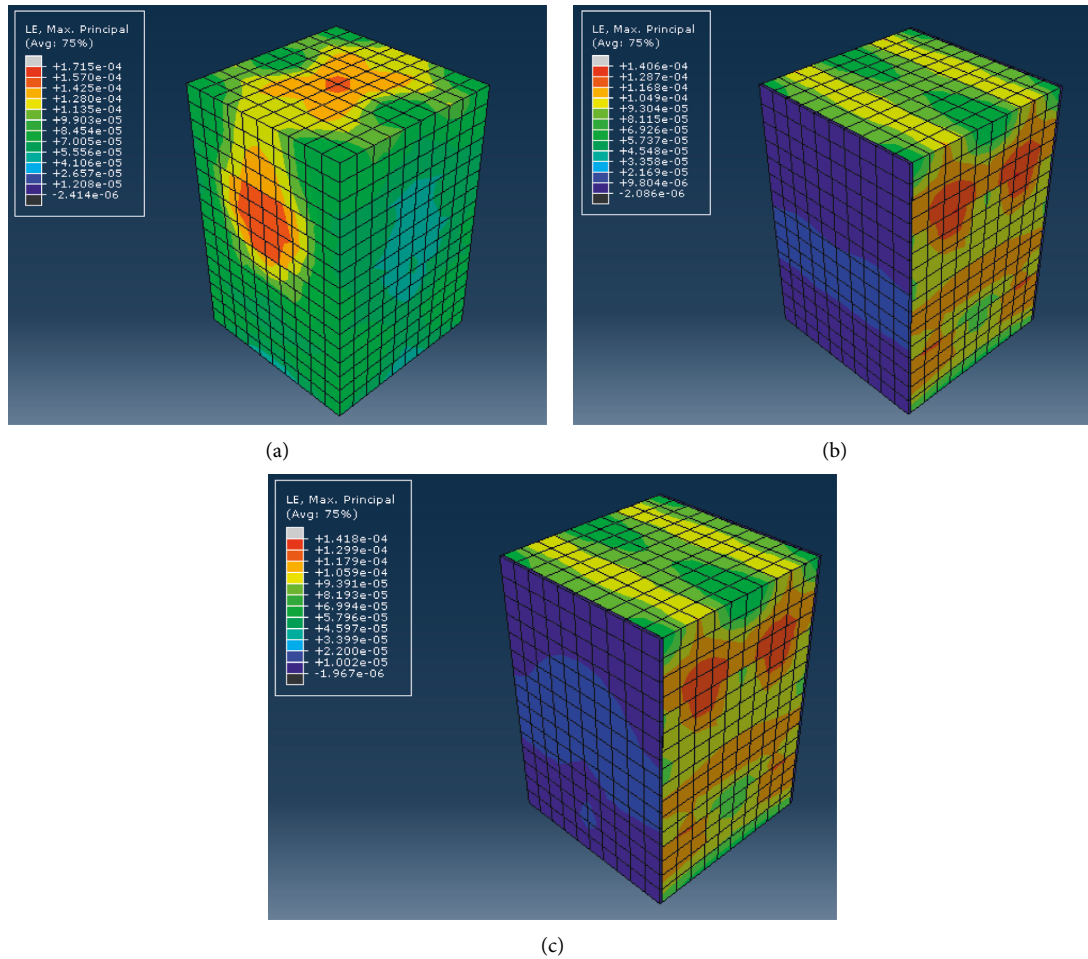


FIGURE 12: Principal strain of masonry strengthened by (a) mortar, (b) ECC, and (c) FAECC.

angle were collected from the experimental data. The value of eccentricity, ratio of initial biaxial compressive stress to initial uniaxial compressive stress (f_{bo}/f_{co}), and the ratio of second stress invariant on the tensile meridian to that on the compressive meridian (K) are the default values provided by Duval [44]. The compressive and tensile behaviour of the CDP model is derived from the experimental data of masonry and strengthening materials. As per Abaqus theory manual, the tension properties have to be applied from the ultimate point to the softening point and the compression properties have to be applied from the elastic limit to the softening point [44].

The stress-strain graphs of masonry compression and tension are shown in Figures 9(a) and 9(b). Also, the compressive and tensile stress-strain graph of ECC and FAECC are illustrated in Figures 10(a) and 10(b). Tables 6 and 7 list the values of stress-strain and damage statistics that were used in this model. The brick and the strengthening materials were connected by providing a hard contact and coefficient of friction values for each material. The coefficient of friction was calculated using the normal stress and shear stress of masonry units with mortar, ECC, and FAECC in accordance with Binda et al. [45].

3.2. Model Output. The stress-strain graph generated from the experimental tests and numerical analysis is shown in Figure 11. It shows that the maximum stresses obtained in numerical analysis has a difference of 8% for masonry units strengthened by mortar and 10% for masonry units strengthened by ECC and FAECC compared to the experimental results. The maximum stresses for all the three samples occur at the bottom edges, which then further leads to the centre of the masonry prism. It is also observed that the percentage strain for the strengthened masonry prism is highly improved as the stress induced in it was further increased.

The strain occurring on the masonry prism strengthened by mortar, ECC, and FAECC is shown in Figures 12(a)–12(c). The maximum strain occurring at the centre of the masonry units strengthened by normal mortar is observed and as a result vertical cracks are formed at the centre of the prism. In case of masonry units strengthened by ECC and FAECC, the strain hardens on the portion where the strengthening is made and hence cracking is controlled. The strain percentage is predominant on the masonry joints and as a result cracks originate from mortar bed, which is comparable to what was discovered experimentally.

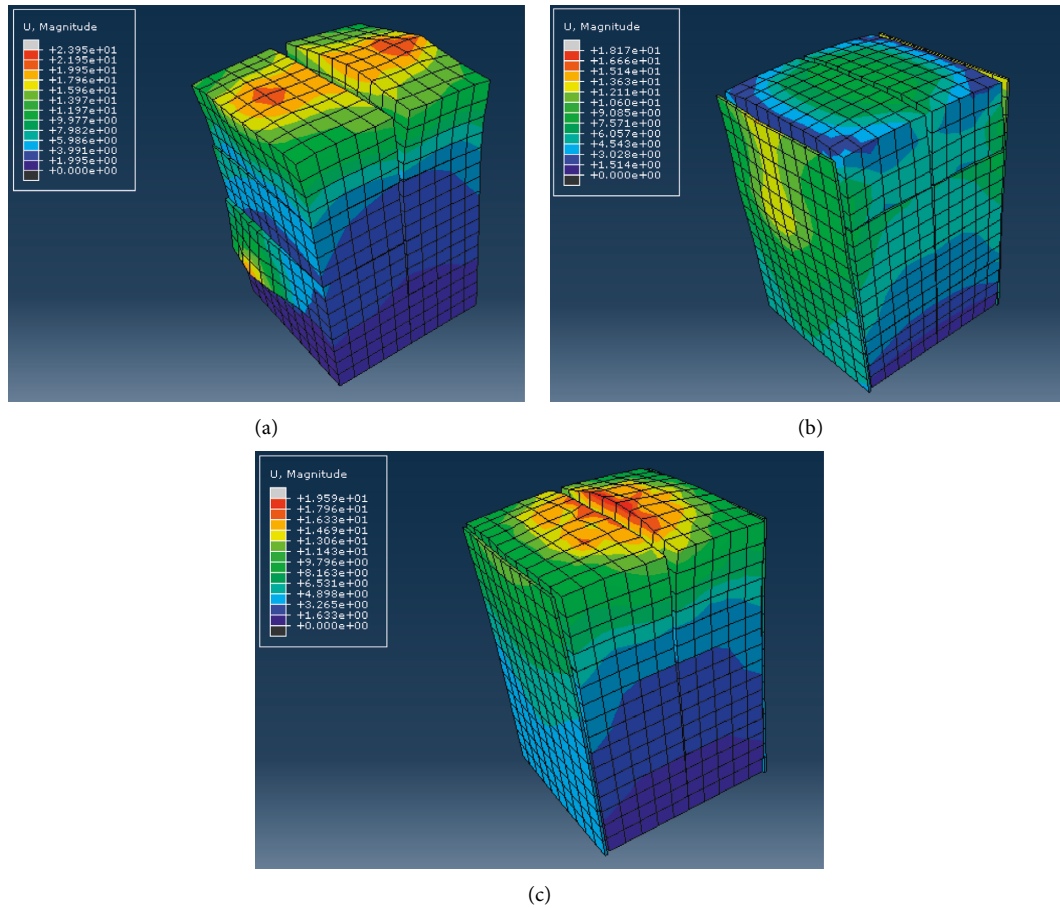


FIGURE 13: Deformed shape of masonry strengthened by (a) mortar, (b) ECC, and (c) FAECC.

Figures 13(a)–13(c) show the deformed shape of the masonry prism strengthened by mortar, ECC, and FAECC under compression in which the separation of joints and the retrofitting materials were clearly observed. When load is gradually applied, cracks originate from the mortar bed joints and thereafter lead to the separation of the strengthened layers, which is comparable to the failure found in experimental specimen. This clearly highlights the importance of bond strength in masonry prism and hence the increase in bond strength of the bed joint mortar will decrease the rate of deformation of masonry walls.

4. Conclusions

The primary goal of this research is to look at the feasibility of using ECC to strengthen masonry walls instead of standard retrofitting materials. For this purpose, an experimental and numerical analysis is carried out to determine the effectiveness of ECC on masonry walls. For mortar, ECC, and FAECC, tests including indirect tensile strength and compressive strength were performed. The bond strength of these cementitious materials on brick masonry walls is then determined using a triplet test. Following that, three sets of weak masonry units were chosen and strengthened using mortar, ECC and ECC with 40% fly ash on both the faces of the masonry units and is tested under

uniaxial loading. Then, the material properties were collected from the experimental tests and a numerical analysis is made using Abaqus software. Based on the experimental and numerical investigation of the masonry units and strengthening material, the following conclusions are made.

- (i) After 90 days of curing, ECC has a compressive strength 20% higher than conventional mortar and 17% higher than FAECC. Though ECC with fly ash showed lesser compressive strength after 28 days, the strength improved when the curing time was extended to 90 days. The indirect tensile strengths of ECC and FAECC were almost similar at the end of 90 days, which is 90% higher than the normal mortar.
- (ii) When compared to conventional mortar, ECC and FAECC achieve higher shear bond strength. At the end of 28 and 90 days, the shear bond strengths of ECC and FAECC were nearly identical. Microcrack behaviour is seen, which is caused by polypropylene and steel fibres holding the cement matrix; as a result, an increase in shear capacity is observed.
- (iii) The compressive strength of masonry units strengthened by ECC is higher than the masonry units strengthened by normal mortar and FAECC. But the crack patterns of masonry units

strengthened by ECC and FAECC were almost similar. The spalling of the damaged masonry unit is controlled by ECC and FAECC, which is due to its higher strain hardening capacity. When axial load is applied on masonry walls, the faces of the wall undergo tension, which pulls the strengthening material out of the plane. Hence, bond strength and tensile strength are important parameters to be considered when ECC and FAECC are used as a strengthening material on masonry walls.

- (iv) The stresses obtained from numerical analysis shows a difference of 8% for masonry units strengthened by normal mortar and 10% for masonry units strengthened by ECC and FAECC compared to the experimental results. Using a simple method, the micromodelling approach was successful in producing accurate results from masonry assemblages.
- (v) The crack patterns observed on experimental samples matched with those specimens speculated by the Finite Element models quite well. The experimental and computational stress distribution, failure load, and displacement results are also in good agreement.
- (vi) Though ECC and FAECC exhibit almost similar results in both experimental and numerical analysis, FAECC with 40% fly ash is highly recommended for masonry strengthening purpose due to its less heat of hydration.

Data Availability

The data used to support this study are provided within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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