Optimization of Flyash and Metakaolin Content in Mineral Based CFRP Retrofit for Improved Sustainability

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Abstract

The significance of rehabilitating deteriorated concrete structures subjected to inflated traffic volume, unprecedented live loads, structural ageing and other environmental impacts has been garnering attention in the recent years. Amidst a few conventional retrofit techniques, the application of externally bonded Fibre Reinforced Polymers (FRP) remains contemporary. It is a noteworthy reformation technique because of its durability, augmented mechanical performance and long-term cost-effectiveness. Epoxy resin is classified as a hazardous polymer (as per Globally Harmonised System of Classification and Labelling of Chemicals – GHS) and it has been the most sought bonding fix for several FRP retrofit approaches. Scientific and literature evidence demonstrate the health and environmental impacts concerned with the use of this noxious resin. The primary objective of this project is to optimize the mix proportion of a recently developed Mineral Based Composite (MBC) bonder by inducing varying amounts of industrial by-products such as fly ash and metakaolin. It was observed that a certain degree of this replacement resulted in achieving a higher degree of sustainability as the event-grade bonder could potentially eliminate the use of epoxy in FRP reformation. Experimental investigation as per Australian Standards AS 1012.1:2014 established the relation between brittle epoxy failure and thus rendering the up surged bonding capacity of MBC in extreme conditions proving as the desired substitute for epoxy resin. The investigative results obtained portray a suitable base for evaluating the optimal mix design proportion of the mineral composite bonder.

Keywords: rehabilitation, sustainability, MBC, epoxy, temperature, FRP retrofit, flyash, metakaolin

1. Research Background and Study of FRP Bonders

Structural health monitoring is an important aspect of extending the service life of any structure. In some cases, it can be done through regular maintenance but in cases of extensive damage due to natural disasters, the load carrying structural elements needs to be strengthened to prevent further failure. FRP rehabilitation intends to be one of the most economical ways to preserve structural integrity as well as to maintain aesthetics rather than demolition and reconstruction. The following literature study provides a brief overview of the environmental and human impacts due to epoxy resins that are being used in FRP retrofit thereby signifying the research and implementation of sustainable alternatives.

1.1. Significance of FRP retrofit for deteriorated concrete members

Fibre reinforced polymers are broadly used in almost every field of engineering as it attributes to superior characteristics when compared to other conventional materials as mentioned by Riahi [1]. When an existing civil structure has been analyzed to incur deterioration or any other form of functional deficiency, Bakis [2] suggests that the greatest challenge lies in choosing the right material and retrofit. Orosz [3] states that Mineral Based Composites are a recent advancement over the last decade and securing tremendous response thereby contributing to further research. In an experimental study, Blanksvärd [4]

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researched the consequences of chloride attack on shear strengthened RC beams against failure in places of heavy traffic movement. Externally bonded CFRP (Carbon Fibre Reinforced Polymer) technique with epoxy and cementitious bonding agents were tested for shear failure and found that the reduction of strains in steel stirrups, as well as surface cracks, were prominent with MBC bonder. On the other hand, Mahal [5] conducted tests using beams retrofitted with Carbon Fibre Reinforced Composites under diverse stress levels to determine the FRP's mechanical behavior. The resulting graph displayed a more gradual failure slope illustrating rupture followed by opposition to adhesive failure had eventuated in CFRP but abrupt failure in case of other retrofits. Raghavendra [6] conducted tests to compare the bonding strength of three different FRPs with both epoxy and MBC. The results proved that the strength of MBC retrofits was exceptional for CFRP in comparison to epoxy specimens which had reached fully failed and first-crack stages. With regards to the performance of CFRP with cement based and epoxy bonders, Hashemi [7] performed single-lap shear and flexural tests to evaluate the bond strength. Observations from bond slip response for cement-based bonder proved better than that of epoxy in regions subjected to higher temperatures, as the ultimate load reached was 80 % greater than epoxy bonding. Raghavendra [6] also verifies the excellent compressive and tensile resistance capability of carbon fibres with his experimental study conducted between E-glass, aramid and carbon fibre properties. Thus, FRP retrofit with a suitable bonder can act as a sound technique to improve structural stability and also prevent further damage.

1.2. Ill effects due to epoxy and mineral based composite as a sustainable alternative

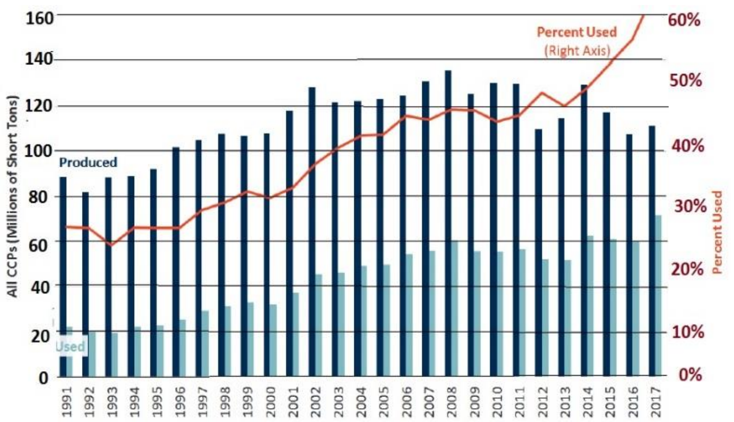
Even though epoxy and its associated resins are considered to be the primary bonding component in structural reformation activities, it involves a few demerits in practice. Firstly, it is a highly volatile liquid, vulnerable to freeze-thaw conditions as well as higher temperatures. Secondly, Wang [8] suggests that epoxy imposes adverse health risks as it can produce poisonous and corrosive smoke at slightly higher temperatures. Thirdly, epoxy resin application is greatly influenced by the presence of moisture variation. Therefore, it is susceptible to work in wet conditions or in offshore environments. Lithner [9] investigated the health hazards exhibited by various plastics, which constitute a global production of 245 million tons annually in 2008 and shockingly doubled over the last 15 years. The most hazardous ranking of polymers falls under category 1A or 1B with examples of polyurethanes, polyvinyl chlorides, epoxy resins, and styrenic copolymers. Prodi [10] seemed to have conducted a patch test on the population of North-Eastern Italy in order to investigate the effect of epoxy resins in contact with dermatitis (upper layer of the skin). It was observed that the sensitization on the human skin was 40.25%. In both sexes of woodworkers, chemical industry or construction workers, farmers and fishers, significant health effects were found due to working with epoxy resins. Eckardt [11] established that epoxy polymer causes angiosarcomas in the liver and creates asthma-like reactions because of the initiators that are used with epoxy resins. Therefore, awareness should be created amongst all construction workers regarding the elimination of epoxy in all possible aspects of infrastructural development.

1.3. Characteristic behavior of varying metakaolin induced cementitious mortar

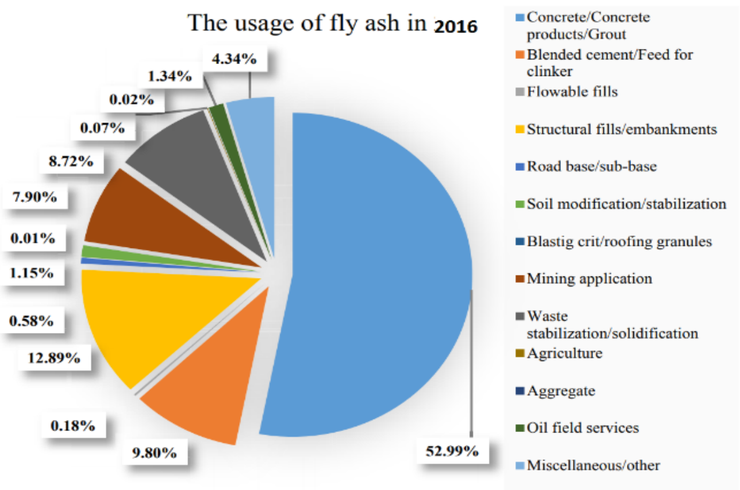
Bezerra [12] mentions that metakaolin is a finer clay powder when compared to cement and a by-product of controlled calcination of kaolin clay. The quality and reactivity of this mineral are strongly dependent on the characteristic of the raw material treated. In order to achieve a low impact innovative MBC bonder for FRP retrofits, it is appropriate to use recycled pozzolanic materials wherever feasible. During the experimental phase, Raffaele [13] developed a metakaolin based geopolymeric mortar for testing the external strengthening capacity of RC beams. He combined four formulations to obtain a varying composition of the activating solution in terms of SiO_2/Na_2O ratio and carried out four-points bending tests to reveal the enhanced mechanical resistance. The reinforced beams performed roughly twice to that of the control beam undoubtedly recognizing the excellent strengthening capability of metakaolin used with any mortar throughout the time. Further, Raghavendra [6] also used 10% metakaolin as a cement filler in obtaining the mix design for high-performance mineral bonder used in various FRP retrofits during his experimental methodology. The mechanical properties of the mineral bonded retrofit proved well with CFRP but GFRP tends to perform the least on the contrary. In another research study, Bezerra [12] investigated the effect of mineral additions in varying proportions in combination with Ordinary Portland Cement (OPC) for its influence on asbestos free fibre cement. Metakaolin particles were found to react with calcium hydroxide present in cement during the hydration process thus reducing the alkalinity of the mortar, improved toughness and a compressive strength of 40 - 80 MPa. Yip [14] performed microscopic analysis to study the behavior of mineral fillers replacement in metakaolin-based geopolymers. As the percentage of calcite replacements went higher, it was observed that the shrinkage increased thereby reducing the aging compressive strength. Moreover, Marcel [15] suggests that the development of aluminous cement replaced by 30% metakaolin mortar exhibited high thermal resistance as well as better flexural performance. Thus, the corresponding research findings relate to the improved efficiency of metakaolin additives in binding mortars for FRP retrofits as well as other general purposes.

1.4. Effect of flyash content as a cement replacement

Flyash is one of the most prevalent by-products of coal-fired power plants and its solid residues consist of very fine particles as stated by Zhuang [16]. Depending on the source of burnt coal, the properties of the resulting flyash can vary considerably. Zhuang also mentions that Class F fly ash is obtained from anthracite or bituminous coal and possess low calcium content. Further, 70% of its weight is inclusive of SiO_2, Al_2O_3, and Fe_2O_3 contents. Improper disposal of fly ash can be hazardous to the environment and recycling can be a sustainable alternative. A report by American Coal Association [17] illustrates that the usage of flyash is only 4.34% in concrete products and around 10% in cement manufacture which are very low when compared to the overall rise in the flyash market over the years as presented in Fig. 1(a). Likewise, Fig. 1(b) distinguishes the prime consumers for the recyclable flyash market in the US as of 2016.



(a) Overall production and usage of flyash from 1991-2017



(b) Consumers based on the flyash incorporation

Fig. 1 The production and usage of flyash as a recyclable product by various US consumers

Flyash seems to have a profound impact on strength development at later stages, reduces the risk of steel corrosion and naturally improves the intervention of chemical attack through reduced permeability. In a research project involving induced industrial waste, Yin [18] conducted tests on high-performance concrete containing ultra-pulverized flyash and superplasticizer. The results showed that the double effects from these components enhances workability, lowers the drying shrinkage, results in better durability and higher mechanical properties. Similarly, in Orosz [3] review paper, it is stated that Engineering Cementitious Composites (ECC) providing hybrid retrofit performance contains flyash to improve the rheology of mortar, preventing premature fibre rupture and also aids in a ductile failure. Geopolymers are a recent mortar development that is predominantly made up of flyash and metakaolin and can offer very high thermal resistance as proposed by Wang [19]. As the microstructural mechanical characterization of these geopolymers was conducted, the outcomes satisfied the industrial insulation standards with 40% replacement of flyash and the density of mortar reduced to a great extent. An identical examination involving the substantial enhancement of electromagnetic radiation with 25% flyash induced cementitious composites, Baoyi [20] successfully encountered the highest efficiency of wave absorption. Overall, it would be a positive approach if the flyash ending up in landfills could rather be made use for the preparation of a compatible non-radioactive pollutant mortar. A summary of the literature review clearly prioritizes the necessity of research investigations around the application of a sustainable mineral adhesive in order to refrain the rehabilitation out of epoxy involvement wherever possible. Further down the line, the use of heat-resistant CFRP retrofit techniques may be highly regarded for workshops and other power generating sectors with a sheer possibility of a fire hazard. Profuse incorporation of flyash and metakaolin as an alternative to cement will result in a range of benefits such as wider use of recycled materials, cost effectiveness, and sustainable future construction.

2. Experimental Methodology

2.1. Design parameters, pre-loading conditions and retrofit methodology

A total of 138 cylindrical samples with standard dimensions (Φ100×200 mm) were cast in Structures laboratory under Australian standards AS 1012.1: 2014. The concrete mix design involved the use of Portland Pozzolana Cement (PPC), fine aggregates involving manufactured sand and river sand followed by 10mm and 20mm irregular gravel as coarse aggregates. The final mix design calculated for M32 concrete mix taking moisture correction into account was 1: 0.18: 1.77: 0.66: 2.47 with the water-cement ratio being 0.58. After casting and 28 days of curing, the compressive test results obtained for full specimen failure was 45.05 MPa which is exemplary. Later, these samples were classified under three categories involving various levels of damage prior to retrofit. The first type is the control specimen with no initial induced damage acting as a benchmark for standard compressive strength. Besides the control specimen, other sets of samples were preloaded to 70% of their ultimate capacity (which is 30 MPa) to induce the first crack and they were denoted as partially failed. Apart from that, the third category is fully failed samples subjected to complete loss of strength and also considered as an integral part of the test criteria. All the visible damages were fixed using PPC application, cured for a week and the outer surface was ground to perform single wrap retrofits. A primary bonder coat is applied over the surface and the bi-directional FRP material encapsulates the specimen attributing to a fail-safe overlap of 75 mm. Test results obtained from Raghavendra [6] remained as a base for further investigation. Even though E-glass, aramid and carbon fibres were initially tested for studying the mechanical behavior of the FRP composite, the use of CFRP was prioritized for further research involving industrial by-products because of its high tensile strength (2.9 GPa) and excellent elastic modulus (525 GPa). In addition to that, CFRP exhibited very high fire resistivity, compatible with most of the resins and ideal for multi-layer solutions. Later, the second layer of bonder coating was applied to seal the surface properly and the specimens were allowed to cure for 7 to 28 days.Solar panels are made of an electrical assemblage of small solar cells which produce DC current through the photovoltaic effect by absorbing photons from sunlight. A simple model of a solar cell is shown in Fig. 2; it’s based on a current source, single diode, parallel resistance and a series resistance.

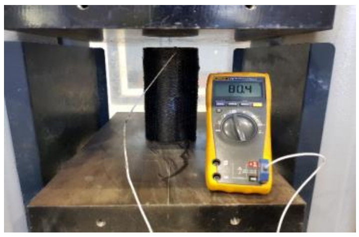
2.2. Essentialities for FRP retrofit bonder

Since FRP behavior is greatly influenced by proper material selection as well as being mindful of the costs involved and long-term durability with poor quality parent concrete, some of the key functionalities respective to the bonder are to be considered. Characteristic bond behavior, compatibility, adhesion between different materials and factors affecting the physical properties of FRP's can be overcome effectively by choosing a higher strain capacity resin bonder. The pre-meditated epoxy polymer (MasterBrace P-3500 and P-4500) incorporates Part-A and Part-B components applied over consecutive days and having a mix ratio of 1:3. The former is a colorless liquid whereas the latter is translucent blue and should be applied above 5℃ ambient temperature as per the safety data sheet supplied. As far as the proposed mineral bonder is concerned, the mix additives should procreate high strength, durability, and viscosity distinctively. Al-Abdwais [21] developed a bonding mortar consisting of OPC, micro-cement, water, silica filler, silica fume and superplasticizer (Viscocrete-500). The mortar proved to be efficient against flexural failure when compared to that of epoxy adhesive. In this study, pozzolanic cement with pre-existing flyash content was accounted as the fundamental bonding constituent, highly pulverized powder of high reactivity metakaolin (Metamax) with specific gravity of 2.5 g/cm3 as an accomplice strengthening agent, Class F fly ash waste from power station to control the water demand and bleeding characteristics, Viscocrete PC HRF-2 as Superplasticizer (SP) that works on most cement types and finally Sika VMA (Viscosity Modifying Agent) to control the rheology against particle segregation. The initial mineral bonding mix design referenced from Raghavendra [6] consisted of PPC, water, metakaolin, SP and VMA in the ratio 1: 0.37: 0.1: 0.03: 0.0004 per cylinder wrapping and allowing for 5% wastage.

2.3. Extracting calefaction and corrosion recordings

Once the desired properties of epoxy and MBC retrofitted samples were identified, they were then subjected to further investigation under elevated temperatures and prolonged exposure to marine corrosion. In order to experiment the thermal resistivity, CFRP retrofitted cylindrical samples were placed in a mechanical convection oven as demonstrated in Fig. 2(a) at a constant temperature of 100℃ for 24 hours. One sample under each bonder type had a K-type thermocouple embedded into it whilst wrapping as pictured in Fig. 2(b). Alongside the test, setup was an infrared thermometer that could detect the surface temperature using laser-induced blackbody radiation principle. For the entire duration of the experimental procedure, the thermal instabilities were constantly monitored at regular intervals and also in the event of insulated transportation of the hot specimens. The other end of the thermocouple was pinned to a Volt-ohm-milliammeter (VOM) multimeter in order to acquire accurate thermal recordings. Hawileh [22] experimented the limitation of elastic modulus and tensile capacity of carbon and glass FRP materials at elevated temperatures (25℃ - 300℃) in order to investigate the bonding effectiveness. Within a temperature range of 100-150℃, the specimens failed in a similar fashion whereas there were severe brittle ruptures and sheet splitting observed at much higher temperatures (200-250℃). Therefore, this project concentrates on the debonding effect of epoxy and mineral adhesives in FRP retrofit subjected to prolonged high temperatures.

(a) Placement of samples in fan-forced oven



(b) VOM measuring internal bonding temperature

Fig. 2 Hot sampling oven and temperature monitoring during analysis

Control and full damage criteria were taken into account as an average of 3 samples for each CFRP retrofit and constantly supervised for any discrepancy. Table 1 provides a detailed specification of the recorded surface and bonding temperatures as outlined by Infra-red thermometer and thermocouple propelled VOM. The test was completed in under 3 minutes from the time of sample seizure until the borderline when the compressive failure occurred.

Table 1 Temperature recordings at different test points

Sample test condition	Surface temp (^{0}C)		Bonding temp (^{0}C)	
	Epoxy	MBC	Epoxy	MBC
Inside Oven	98.7	95.0	97.4	96.6
On placement in CTM	66.5	77	85.2	88.2
On peak load	72.8	79.5	87.6	90.1
Post-failure removal	72.1	77.3	87.0	85.5

Similarly, the induced offshore corrosion involved placing the single wrapped CFRP samples in the marine environment for a period of 6 months to 1 year. The natural occurrence of periodic high and low tides apart from the seasonal effect made it more practical to the existing offshore conditions. The only drawback was that concrete had an increase in its strength due to aging and this performance could potentially affect the value of retrofitted specimen testing in contrast to the original value. Shubham [23] studied the mechanical properties characterization of varying flyash concentrations on FRPs coated with a silane coupling agent. The results showed that the tensile and the elongation break reduced with the increase in flyash content, however, the silanization process improved its toughness resulting in lower FRP damping capability. As a part of the research progress, the effect of recycled admixtures was proposed for further investigation.

2.4. Modifying the MBC admix with varying proportions of flyash and metakaolin

After basic bonding characteristics and extreme experimental results were obtained, the next step was to subjugate varying metakaolin and flyash proportions to partially replace the cement additive to achieve optimization. Morsy [24] studied the hydration characteristics of Nano-metakaolin (NMK) addition to flyash blended cement as it is believed that the amorphous silica reacts with calcium hydroxide to enhance the concrete performance. During the examination, the hydration age of the blended mortar was monitored to indicate that the NMK acts as an activator to promote pozzolanic reactivity to achieve high strength. Similarly, the microscopic study undertaken by Weng [25] indicated the quantification of residual efflorescence leftover when cement is replaced by varying ratios of metakaolin content. The results clarified that replacing 15% of metakaolin yielded lower efflorescence area, however compressive strength reduction was observed due to increases in metakaolin content.

In another scenario, Sahu [26] performed Scanning Electron Microscopic analysis and X-ray Diffraction (XRD) to study the morphology of flyash and identified the presence of SiO2 and Fe2O3 in major quantities. Class F fly ash used in this project originates from the combustion of bituminous coal as designated by American Society for Testing and Materials (ASTM C 618) and could potentially replace Portland cement ranging from 20% to 30%. Similarly, high reactivity metakaolin comparable to silica fume could boost the compressive strength as justified in literature study thereby maintaining workability and finishability. Fig. 3(a) whereas Fig. 3(b) represents the dry admix where PPC is replaced by flyash corresponding to 10% - 40% and investigated for performance reduction. The next step was to vary the metakaolin from 5% - 50% by itself with the rest of the admixtures remaining the same. After arriving on the optimal flyash and metakaolin contents individually, the final part of the testing involved keeping 30% flyash and 70% cement as constant and varying the metakaolin content in order to analyze the bonding efficiency outcomes. The objective was to obtain a sustainable and cost-effective replacement for cement without compensating on its bonding performance.

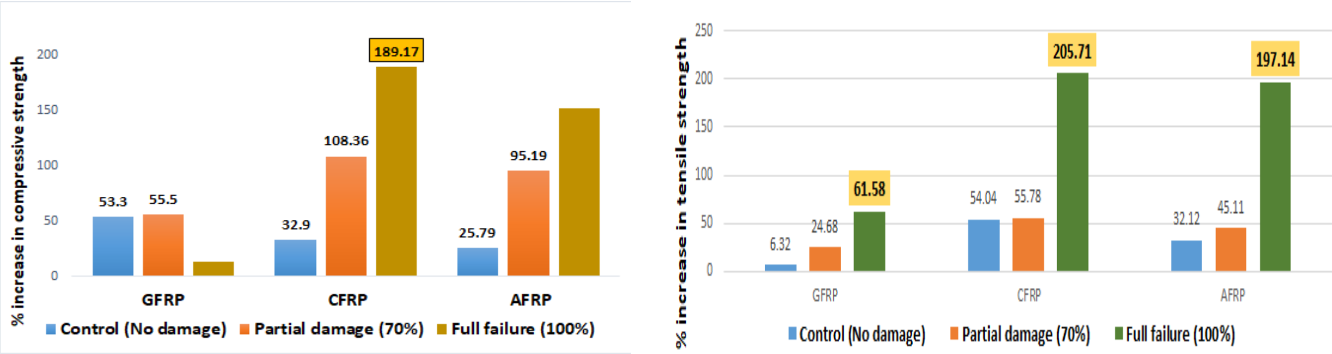
(a) Delamination failure in modified MBC samples

(b) Dry MBC mix before adding SP and VMA

Fig. 3 Addition of fly ash to cement and CFRP retrofitted specimens using this bonder

3. Research Outcomes and Discussion

The inferences from Raghavendra [6] experimental evaluation was considered as a reference for choosing the most durable CFRP material out of E-glass fibre, aramid (Kevlar-29) and carbon retrofits in terms of full failure against compressive and tensile retrofit behavior as shown in Fig. 4 (a) and (b) respectively. It was later decided to conduct further investigation and subject these samples under thermal and marine conditions.



(a) Compressive strength increase (%) (b) Tensile strength increase (%)

Fig. 4 Mechanical properties of GFRP, CFRP, and AFRP single wrap MBC retrofits

From the results obtained, Table 2 illustrates the compressive strength gained for 54 samples under every proposed test parameter. Standard error and deviation values were formulated for each retrofit with regard to measuring the accuracy of the sampling population and found to have a substantial variation in cases of epoxy and MBC values. Epoxy was distinctive as it displayed lower standard error values (1.79) whereas MBC exhibited quite a variation (4.44) for CFRP. However, it is to be noted that MBC samples for both AFRP (Aramid Fibre Reinforced Polymer) and GFRP (Glass Fibre Reinforced Polymer) retrofits had the error value range under the accepted limits and demonstrated little variation. The epoxy and MBC samples seemed to fail due to sudden rupture and not FRP delamination which proves its excellent bonding capacity.

Table 2 Strength comparison in CFRP single wrap under various testing conditions

CFRP retrofit type	Initial damage induced	Compressive strength (MPa)
Epoxy @ Room temperature	Nil	77.7
	70%	67.68
	100%	56.44
MBC @ Room temperature	Nil	64.52
	70%	62.78
	100%	57.92
Epoxy @ 100^{o}C temperature	Nil	55.52
	100%	38.34
MBC @ 100^{o}C temperature	Nil	56.81
	100%	53.34
Epoxy marine corrosion (6 months)	Nil	77.47
	100%	70.53
MBC marine corrosion (6 months)	Nil	66.04
	100%	60.39
Epoxy marine corrosion (1 year)	Nil	75.54
	100%	70.04
MBC marine corrosion (1 year)	Nil	69.18
	100%	67.03

The resulting outcomes amounted towards 20% strength reduction in both uncracked and fully failed epoxy retrofitted samples at high temperatures. On the contrary, an approximate loss of 5% strength for control MBC specimen and only 2% with full failure specimen were observed indicating excellent thermal insulation capability. According to the offshore test outputs, it can be noted that epoxy retrofit samples hold on well for 6 months but keeps deteriorating over time and loses its bonding capacity by 2.6% for control specimen and maintains negligible variation for fully failed specimens. Whereas, there was a strength increase of 6 MPa for 1 year salinated MBC failed sample when compared to its half-yearly counterpart. The outright results proved the bonding efficacy of mineral composites over instable epoxy. In later stages of experimentation, MBC refinement was trialed with varying amounts of flyash by compensating the cement content in admixing. As the pozzolanic cement usually consists of pre-meditated flyash, further addition of flyash had the potential to weaken the bonding characteristics. From Table 3, it was noted that 30% of flyash replacement works better in terms of sustainability and curtailing the material expenses that are required to fulfill the admix proportions. A total of 24 samples were accounted to carry out the test ranging from 10% to 40% flyash substitution.

Table 3 Mechanical properties of flyash induced MBC retrofit

Type of Specimen	Failure induced	% of flyash-cement replacement	% increase in compressive strength	% increase in tensile strength
Single wrap CFRP specimen with MBC retrofit	Nil	10	26.5	19.68
	100%	10	117.17	164.76
	Nil	20	17.89	11.52
	100%	20	100.85	128.96
	Nil	30	27.65	31.38
	100%	30	127.3	204.29
	Nil	40	21.18	9.79
	100%	40	111.43	134.15

Table 4 Effect of varying metakaolin in cement admix to test the bonding performance

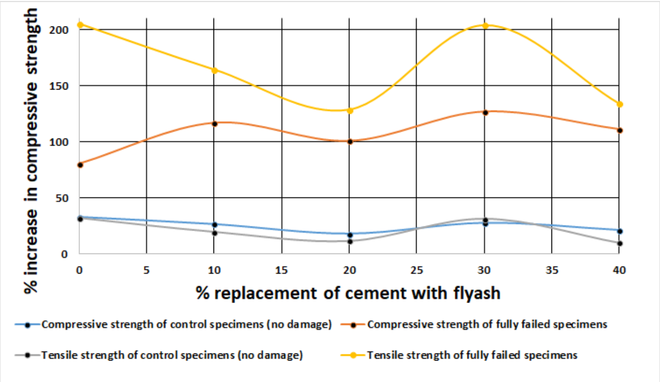
Type of specimen	Pre-induced damage	% of metakaolin addition to cement	Average compressive strength (MPa)	% increase in compressive strength
Control specimen	Nil	0	45.05	NA
	100%		20.03	
MBC retrofitted CFRP single wrapped specimen	Nil	5	66.62	47.88
	100%		41.52	107.29
	Nil	10	59.87	32.96
	100%		36.06	80.03
	Nil	20	58.90	30.74
	100%		34.73	73.39
	Nil	30	53.94	19.73
	100%		31.84	58.96
	Nil	40	47.10	4.55
	100%		29.25	46.03
	Nil	50	45.76	1.58
	100%		28.48	42.19

The new admix proportions worked out post-flyash-cement compensation resulted in the ratio 0.7: 0.37: 0.3: 0.1: 0.03: 0.0004 for cement, w/c ratio, flyash, metakaolin, SP and VMA. The maximum compressive strength upsurged to 127% and tensile strength attainment was 205% when 30% of cement was restored with Class F fly ash. Moreover, this proves that Portland pozzolana cement can accommodate additional flyash supplement up to a certain extent before compensating on its mechanical performance. Following that, a similar experimental procedure for the next set of 42 specimens continued with altering percentage of metakaolin about 10% to 50% reinstatement, the results were exemplary for 5% addition of metakaolin as illustrated in Table 4. Based on the commendable results obtained (compressive strength of 66.62 MPa with 107.29% overall strength improvement), it can be identified that 5% of metakaolin in contrast to the initial mix provides excellent bonding.

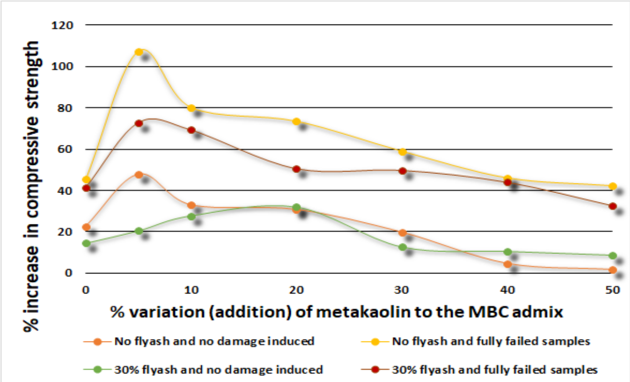
The metakaolin data represents diminishing performance as the amount of addition is increased up to 50%. This proves the fact that lesser addition of metakaolin provides greater strength and durability. Since metakaolin is finer than that of cement and lesser in weight, further addition of metakaolin can negatively modify the adhesion of MBC admixture to a greater extent as like in flyash. Therefore, it is critical in using the correct number of industrial by-products to the bonding admixture for enhanced behavior. As a means of further refinement, 30% of flyash as a constant cement substitute was tested for efficiency with varying metakaolin proportion. Table 5 provides a detailed description of constant flyash and varying metakaolin amounts to analyze the optimal requirement. Both fly ash and metakaolin retrofitted samples failed due to delamination and not rupture as like the original investigations.

Table 5 Performance of optimal flyash samples with varied metakaolin concentration

Type of Specimen	Failure induced	% Metakaolin addition to cement	Average compressive strength (MPa)	% Increase in strength
Standard specimen without retrofit	No failure induced (control specimen)	0	45.05	NA
MBC retrofitted CFRP single wrap specimen with 30% flyash		5	54.23	20.37
		10	57.51	27.66
		20	59.42	31.90
		30	50.72	12.59
		40	49.75	10.43
		50	48.93	8.61



(a) Flyash varied CFRP retrofit



(b) Metakaolin varied CFRP retrofit

Fig. 5 Mechanical properties of single wrap retrofits with varying proportions of industrial by-products

The final data obtained from 18 test samples derive a relation in contrast to the previous metakaolin outcomes. As a result of cement-flyash inducement, the metakaolin samples proved to be more efficient at 20% contrary to the 5% variation, leading to improved behavior. Fig. 5(a) quantifies the competency of supplemental flyash in MBC stickum to determine retrofit proficiency. Likewise, Fig. 5(b) provides a detailed description of flyash retrofitted CFRP samples subjected to varying amounts of metakaolin admix in order to obtain the optimal content requirement. The flyash only graph looks like a wavy pattern denoting a rise and fall of compressive strength for until 20% replacement for all categories with 30% being exceptional behavior. On the other hand, 30 % fly ash and 5% metakaolin for fully failed sample retrofit outperforms the rest for the inclusion of the maximum amount of industrial waste and achieving sustainability.

This result can be related to Alanazi's [27] split tensile test and slant shear test in order to identify the bond strength between Portland cement and geopolymer mortar containing metakaolin and silica fume embedded in various percentages. The analysis projected higher bond strength in the early stages but falls below the ACI requirement after 28 days of curing. Even though metaolin (alumino-silicate filler) may preserve the integrity of the concrete member, extensive addition will result in decreased bond strength. Otherwise, it is clear and evident from the graphs that 20% of metakaolin addition to pre-retrofitted MBC samples containing 30% of flyash provides the optimal performance for control sample without affecting the original bonding capacity significantly. Thus, the use of fly ash and metakaolin can help to overcome the cost involved in mineral-based CFRP retrofit to a certain degree. Furthermore, the mix proportion from the above data was finalized adhering to the ratio 0.7: 0.37: 0.3: 0.2: 0.03: 0.0004 for cement, w/c ratio, fly ash, metakaolin, SP and VMA for attaining optimized CFRP mineral bonding competency over epoxy resin.

4. Conclusive Remarks

Based on the experimental investigative evidence obtained from varying flyash and metakaolin inclusion, the following observations were furnished

- Even though CFRP fibre installation proves expensive, it can stabilize to perform under corrosive environments than other FRP types. Similarly, AFRP seems to be the second-best alternative followed thirdly by GFRP for increasing the lifespan of damaged RC structure. Also, the average standard error for MBC was 2.31 which slightly higher than 0.9 for epoxy still within the reasonably acceptable limit.
- It was also noted that MBC retrofitted CFRP samples displayed enhanced mechanical behavior when compared to epoxy specimens under higher levels of pre-induced damage. Moreover, prolonged exposure to high temperature and marine conditions was found to deteriorate epoxy bonding to a significant amount, therefore mineral based admixture can be a sustainable alternative for CFRP retrofits in these conditions.
- 30% of flyash-cement replacement and 5% of metakaolin addition to the original MBC mix provided excellent testing performance. Around 200% tensile strength improvisation was observed compared to un-retrofitted full failure specimen. Similarly, a lower amount of metakaolin resulted in higher bonding support.
- The common mode of failure for epoxy retrofitted sample was rupture whereas it was delamination in case of MBC. Moreover, all the test specimens were subjected to a wrapping overlap of 75mm to avoid any failure in the overlap region. This could be a commonality for retrofitting cylindrical columns under the influence of hoop stress but most RC beams allow only 3 wrapping faces and further research on this would be recommended.
- The integral part of this project involved efficient replacement of mineral composite bonder with a couple of industrial byproducts and successfully resulting in 30% flyash and 20% metakaolin addition thereby making it eco-friendlier. Overall, 50% of the MBC weight would include recycled products thus reducing the amount of landfill.

Conflicts of Interest

The authors declare no conflict of interest in experimental procedures and report generation.

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