Mechanical properties and flexural behaviour of fibrous cementitious composites containing hybrid, kenaf and barchip fibres in cyclic exposure

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Abstract: In this study, the mechanical properties and flexural behaviour of the fibrous cementitious composites containing hybrid, kenaf and barchip fibres cured in cyclic exposure were investigated. Waste or by-product materials such as pulverized fuel ash (PFA) and ground granulated blast-furnace slag (GGBS) were used as a binder or supplementary cementitious to replace cement. Barchip and kenaf fibre were added to enhance the mechanical properties and flexural behaviour of the composites. A seven mix design of the composites containing hybrid, kenaf and barchip fibre mortar were fabricated with PFA-GGBS at 50% with hybridization of barchip and kenaf fibre between 0.5% and 2.0% by total volume weight. The composites were fabricated using 50 × 50 × 50 mm, 40 × 40 × 160 mm and 350 × 125 × 30 mm steel mould. The flexural behaviour and mechanical performance of the PFA-GGBS mortar specimens were assessed in terms of load-deflection response, load compressive response, and crack development, compressive and flexural strength after cyclic exposure for 28 days. The results showed that specimen HBK 1 (0.5% kenaf fibre and 2.0% barchip fibre) and HBK 2 (1.0% kenaf fibre and 1.5% barchip fibre) possessed good mechanical performance and flexural behaviour. As conclusion, the effect of fibres was proven to enhance the characteristics of concrete or mortar by reducing shrinkage, micro crack and additional C-S-H gel precipitated from the pozzolanic reaction acted to fill pores of the cement paste matrix and cement paste aggregate interface zone between mortar matrix and fibre bonding.

Keywords: Composites; PFA; GGBS; flexural behaviour

1. Introduction

Pulverised Fuel Ash (PFA) and Ground Granulated Blast-Furnace Slag (GGBS) are supplementary cementitious materials that have been used widely in the concrete. They are used as cement replacement materials due to their chemical and physical composition containing a high value of silica, alumina and calcium. In addition, waste and by-products materials have been included in the concrete and mortar for the sustainability of green environment. For example, the gases emission from Portland cement can be reduced by replacement of waste materials, but still maintained the strength development of the cement.

Pulverised Fuel Ash (PFA) is a by-product of pulverised coal combustion in thermal power plants. It is removed as very fine spherical glassy particles by the dust collection systems from the exhaust gases of fossil fuel power plants before discharged into the atmosphere. The diameter of PFA particles is ranged from less than 1 µm - 150 µm, which is finer compared to the Portland cement [1]. The major chemical constituents in the PFA are silica, alumina and oxides of calcium and iron. PFA is widely used in cement and concrete because of its fineness, pozzolanic and sometimes self-cementitious nature that becomes the focus of most research conducted around the world. PFA particles are considered to be highly contaminated with potentially toxic trace elements, which condense from the flue gas[1-3].

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PFA from pulverized coal combustion is categorized as a pozzolan[4]. The pozzolanic properties of the PFA, including its lime binding capacity, make it useful for the manufacture of cement, building materials concrete and concrete-admixed products. The chemical composition of PFA including a high percentage of silica (60 - 65%), alumina (25 - 30%), magnetite, Fe_2O_3 (6 - 15%) enables it to be used in the synthesis of zeolite, alum, and precipitated silica. The other important physicochemical characteristics of PFA, such as bulk density, particle size, porosity, water holding capacity, and surface area make it more suitable as an adsorbent[1-4].

In contrast with PFA, GGBS produces blast furnace slag as a by-product during the manufacture of iron, and the amount of iron and slag obtained are of the same order. The slag is a mixture of lime, silica, and alumina, the same oxides that make up Portland cement, but not in the same proportion. This material is rapidly cooled to form a granulate and then ground to a fine white powder (GGBS), which has many similar characteristics to Portland cement[4]. Furthermore, Portland-slag cement and blast furnace cement are known as cementitious materials when GGBS is blended with Portland cement. The hydration mechanism of a combination of GGBS and Portland cement is slightly more complex than that of a Portland cement. This reaction involves the activation of the GGBS by alkalis and sulphates to form its own hydration products. Some of these combine with the Portland cement products to form further hydrates, which have a pore blocking effect. Typically, GGBS has been used at between 25% and 50% replacement of the Portland cement with or without the addition of lime. The pozzolanic secondary reactions associated with the hydration of GGBS utilised some of the excess calcium hydroxides in the pores and may reduce the risk and extent of any efflorescence[5]. The cementitious and pozzolanic behaviour of ground granulated blast furnace slag are essentially similar to that of high-calcium fly ash.

Besides that, the inclusion of fibres has been used to enhance the flexural behaviour while not only focus on the strength of mortar or concrete. The fibre is well-known in increasing ductility, shear strength, energy absorption capacity and damage tolerance in flexural and shear-critical members under reversed cyclic loading, structural performance and integrity, also reducing shrinkage[6]. The mechanism of localized reinforcing provided by the fibres contributes to minimize volume change, cracks initiation and propagations in the binder matrix[6-7]. Therefore, barchip54 and kenaf fibres have been proposed in this study to enhance the flexural behaviour characteristics.

BarChip54 is the latest generation structural fibre from Elasto Plastic Concrete. Featuring the latest design and manufacturing techniques BarChip54 possessed high usability, durability and service performance. BarChip54 is suitable for use in shotcrete, slab on grade and precast applications[6]. The advantages of barchip54 include low cost per Joule fibre, weatherproof pallet packaging, flexural toughness equal to steel, long-term durability (corrosion free), safe and light to handle than steel, reduce fire damage (anti-spalling) and reduce wear on concrete pumps and hoses.

On the other hand, the kenaf plant is composed of many useful components (e.g., stalks, leaves, and seeds) and within each of them, there are various usable portions (e.g., fibres and fibre strands, proteins, oils, and allelopathic chemicals)[8]. The yield and composition of these components can be affected by many factors, including cultivar, planting date, photosensitivity, length of growing season, plant populations, and plant maturity[9]. Kenaf filaments consist of discrete individual fibres, of generally 2 - 6 mm. Filaments and individual fibre properties can vary depending on sources, age, separating technique, and history of the fibres. The stem is straight and unbranched, composed of an outer layer (bark) and a core. It is easy to separate the stem into bark and core, either by chemicals and/or by enzymatic retting. The bark constitutes 30 - 40% of stem dry weight and shows a rather dense structure. On the other hand, the core is wood-like and makes up the remaining 60 - 70% of the stem dry weight[10]. The core reveals an isotropic and almost amorphous pattern, while the bark shows an orientated high crystalline fibre pattern.

The structure and content of the cell wall differ widely between different species and parts of the plants. The overall properties of kenaf fibre depend on the individual properties of each of its components[11]. The strength and stiffness of the fibres are provided by cellulose components via hydrogen bonds and other linkages. Hemicellulose is responsible for biodegradation, moisture absorption, and thermal degradation of the fibres. On the other hand, lignin (pectin) is thermally stable, but responsible for the UV degradation of the fibres. The primary (outer) cell wall is usually very thin (<1 lm), but the secondary cell wall is composed of three layers. Of these, the second layer is the thickest and is the major contributor (at 80 %) to the overall properties.

The secondary layer is formed by microfibrils, which contains larger quantities of cellulose molecules. The microfibrils run fairly parallel to each other and follow a steep helix around the cell. Furthermore, the microfibril is composed of alternating crystalline and amorphous regions; the crystallite size is approximately 5 - 30 nm in a lateral direction and between 20 - 60 nm along the axis. Therefore, the cellulose molecules pass through several crystallites along the axis. This is called a fringed-micelle structure. The active cultivation of kenaf has been reported for two main reasons[11]. First, kenaf absorbs nitrogen and phosphorus present in the soil. The average absorption rate for kenaf is 0.81 g/m^2 per day for nitrogen and 0.11 g/m^2 per day for phosphorus; these rates are several times higher than other fibres with a variety of stress. The other reason is kenaf accumulates carbon dioxide at a significantly high rate. The photosynthesis rate of kenaf is much higher than the photosynthesis rate of conventional trees[12]. To make kenaf becomes a successful alternative crop, it must be incorporated into value-added products. Traditionally, kenaf has been used as rope, canvas, sack, and recently, as an alternative raw material in pulp and paper industries to avoid the destruction of forests. It has also been used to make non-woven mat in the automotive and textile industries[13]. About 35% of kenaf is bast fibre, which is suitable for paper, textiles, and rope; and 65% is core[10].

Kenaf fibre could be utilized as a reinforcement material for polymeric composites and becomes an alternative to the glass fibre. Natural fibres such as kenaf have some advantages over traditional reinforcement materials such as glass fibre in terms of cost, density, renewability, recyclability, abrasiveness and biodegradability. The efficiency of the fibre reinforced composites depends on the fibre matrix interface and the ability to transfer stress from the matrix to the fibre. The main obstacle in using natural fibres in plastics is the poor compatibility between the fibres and the matrix. Nowadays, Kenaf is being used in paper production on a very limited basis. The bast fibres have been explored in various uses such as in the making of industrial socks to absorb oil spills, as well as making woven and non-woven textiles. The kenaf bast fibre is known to have high potential as a reinforced fibre in thermoplastic composites due to its superior toughness and high aspect ratio in comparison to other fibres. In addition, a tensile strength and modulus as high as 11.9 GPa and 60 GPa for a single fibre of kenaf, respectively[14].

2. Materials and methods

2.1 Material

2.1.1 Ordinary Portland cement

ASTM C150-17 Type I (conforming to the BS 12:1996) Portland cement with median particle size of 3.9 μm, specific surface area of 3310 cm^2/g and specific gravity of 3.15 was used in this study.

2.1.2 Pulverised fuel ash (PFA)

Pulverised fuel ash used in this study was collected from the precipitator unit of local coal fuelled power plant. Based on Blaine fineness analysis, PFA used has a specific surface area of 3244 cm^2/g and the specific gravity of 2.8.

2.1.3 Ground granulated blast-furnace slag (GGBS)

Ground granulated blast-furnace slag (GGBS) is a by-product from the blast-furnace used to make iron. Mixture of iron-ore, coke and limestone were fed into blast-furnace, which was operated at a temperature of about 1500 °C. Two products: molten iron, and molten slag were produced when iron-ore, coke and limestone melt in the blast furnace. The molten slag was lighter and float on top of the molten iron. The molten slag comprised mostly of silicates and alumina. The GGBS used in this study has specific surface area of 4650 cm^2/g and specific gravity of 2.86.

2.1.4 Fine Aggregate

The fine aggregate used was locally sourced quarzitic natural river sand in uncrushed form with a specific gravity of 2.6 and a maximum aggregate size of 300 μm. The maximum aggregate size was selected based on the previous trial mix that has been compared with Engineered Cementitious Composites materials. Based on the sieve analysis, 9% was the maximum percentage by mass passing 75 μm test sieve, which was considered as a fine natural aggregate for Class I. For the grading of fine aggregate, the sieve size for 300 μm was calculated based on the 68% overall limit with the limit for declared grading were C (5-40), M (5-48) and F (5-70). The fine aggregate was dried to saturated surface dry conditions for use as a constituent material in the mortar mixes. In this study, the river sand was cleaned from clay and impurities that could reduce the strength of the concrete and mortar. The fine aggregate was graded according to the overall grading limits of BS EN 12620: 2013[15]. The fineness modulus of the fine aggregate was determined to be 3.26.

2.1.5 Superplasticizer and Mixing Water

The high range water reduction agent used in the study was a polycarboxylic ether based superplasticizer with a relative density of 1.10 at 25 °C. Mixing water was attained from the potable water supply network.

2.1.6 Barchip fibre (BF)

Barchip 54 fibre is a synthetic fibre of modified olefin supplied by Elasto Plastic Concrete Inc. This fibre is inert to the majority of aggressive agents. Unlike steel fibre, the barchip fibre is engineered to bond with emboss treatment to have contour surface, in order to maximize the bonding effect with concrete or mortar matrix. The properties of Barchip fibre obtained from Elasto Plastic Concrete Pty Ltd, were presented in Table 1 and Figure 1.

2.1.7 Kenaf fibre (KF)

Kenaf is one of the natural fibres that are used as reinforcement in Polymer Matrix Composites (PMCs). Kenaf (Hibiscus cannabinus, L. family Malvacea) has been found to be an important source of fibre for composites, and other industrial applications. Kenaf is well known as a cellulosic source with both economic and ecological advantages. In 3 months after sowing the seeds, it is able to grow under a wide range of weather conditions, to a height of more than 3 m and a base diameter of 3 - 5 cm[14]. The specific characteristics of the Kenaf fibre obtained from Kenaf Malaysia Company at Mergong, Kedah as shown in Table 1. Figure 2 shows the treated kenaf fibre before and after cutting into 20 mm to improve the mortar matrix and strength of fibre. After the cutting process, the fibre dispersion was improved a lot and the clumping of fibre was reduced. It was proven in the trial mixes before put in the final mix proportion design.

Fibre properties	Barchip	Kenaf
Fibre length (mm)	54	60 (20)
Fibre width (mm)	0.52	15 - 30
Tensile strength (MPa)	550	350-600
Young's modulus (GPa)	8.2	-
Specific gravity	0.92	1.44

Table 1. Physical properties of barchip and kenaf fibre.

Figure 1. Barchip fibre.

Figure 2. Kenaf fibre before and after cut to length of 20 mm.

2.2 Methods

2.2.1 Mixture proportioning and mixing

The binder: sand was maintained constant at 1:0.35 for all mortar mixes produced. The Portland cement was partially replaced using PFA and GGBS at substitution levels of 10% and 40%, respectively by total binder weight based on past studies[16]. These correspond to BF: KF hybridization ratio of 0.5:2.0, 1.0:1.5, 1.5:1.0 and 2.0:0.5%. In addition, the mono or single fibre was also included at level of 2.5% for each fibre. The water/binder ratio constant at 0.25 for the mineralogical phase and superplasticizer were added until the slump flow at 200 ± 20 mm was measured. The various mix proportions of PFA-GGBS containing hybrid, kenaf and barchip fibres mortar based on ratio of material by total binder weight are summarized in Table 2.

Mix designation	Cement (kg/m3)	PFA (kg/m3)	GGBS (kg/m3)	Sand (kg/m3)	Water (kg/m3)	Kenaf Fibre(%)	Barchip Fibre(%)	SP Dosage(%)	W/B Ratio	Flow
C	696	139	556	487	348	0	0	1.5	0.25	180
K	696	139	556	487	348	2.5	0	3.0	0.25	220
B	696	139	556	487	348	0	2.5	2.0	0.25	200
HBK 1	696	139	556	487	348	0.5	2.0	2.0	0.25	200
HBK 2	696	139	556	487	348	1.0	1.5	2.0	0.25	200
HBK 3	696	139	556	487	348	1.5	1.0	2.0	0.25	200
HBK 4	696	139	556	487	348	2.0	0.5	2.5	0.25	220

Table 2. Mix proportion and workability of mortar mixes

2.2.2 Mixing, forming and curing

From each batch of mortar produced, a total of 3 units of 50 × 50 × 50 mm mortar cubes, 3 units of 40 × 40 × 160 mm mortar prisms and 2 units of 350 × 125 × 30 mm panels were moulded. The mortar specimens were used for mechanical strength and flexure behaviour characteristics tests. During the mixing of mortar mixes containing PC, PFA and GGBS (binder materials) were initially dry mixed at a low mixing speed for 3 min prior to the addition of fibres constituent materials. Further mixing sequences and durations were performed in accordance to standard procedures prescribed in ASTM Standard C305[17]. The superplasticizer was added until reach the flow is needed. Upon completion of the mixing, the flow test was determined using flow table test. The target flow for all sample was 200 mm. After that, the fresh mortar mix was poured into the mould in two layers. For proper compaction, each layer of the mix was vibrated for 10 s on a vibrating table. Moulded specimens were then cured in mould for 24 h prior, removed from their moulds, and cured in cyclic exposure of sea water and air curing (7 days in sea water and 7 days in air curing) until the testing ages of 28 days.

2.2.3 Mechanical strength and flexural behaviour characteristics

The compressive and flexural strength of fibrous cementitious composites containing hybrid, kenaf and barchip fibres mortar were determined in accordance with the procedures prescribed in ASTM Standard C109 and ASTM C348, respectively[18,19]. The reported flexural and compressive strengths at given ages of mortar were the average of the three numbers of specimens tested. The bulk density was measured before the cubes and prisms mortar were tested. The flexural behaviour characteristics was measured by data logger method[20] as shown in Figure 3. The load deflection relationship and load compressive strains behaviour relationship were analysed based on the graph. The crack development characteristic was also observed after the failure mode.

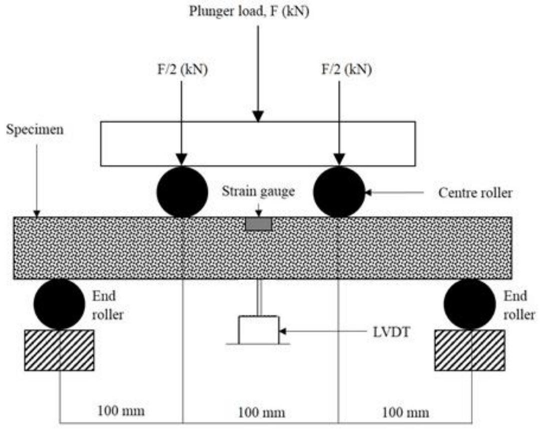

Figure 3. Schematic diagram of load and support arrangement panels test.

3. Result and discussion

3.1 Bulk density, compressive and flexural strength

Based on Table 3, the mechanical properties for all specimens were measured cured in cyclic exposure at the age of 28 days. From the test results, the inclusion of fibres such as barchip and kenaf in the cement mortar reduced the bulk density of mortar produced as compared to the control cementitious mortar for cyclic exposure regimes. Cement mortar containing higher additional kenaf fibre by total volume weight was found to have lower bulk density as compared to the other hybrid fibrous cement mortar and the control cement mortar for all ages.

Mix design	Bulk density (kg/m^3)	Compressive strength (MPa)	Flexural strength (MPa)
C	2223	66.07	6.82
B	2204	68.72	9.37
K	2159	43.95	7.45
HBK 1	2221	62.30	9.17
HBK 2	2202	58.49	8.10
HBK 3	2169	51.05	7.50
HBK 4	2184	46.27	7.73

Table 3. Mechanical properties of mortar hardened

Increasing level of additional kenaf fibre resulted in a lower bulk density of mix produced for all ages. This is due to the inherent high moisture absorption, which caused dimensional changes of the fibres. The changes led to micro cracking of the composite and degradation of bulk density of mortar[21]. The void/porous of mortar matrix was found when moisture in the hardened mortar has been released and reduced the bulk density.

At the age of 28 days, the increment of specimen B in compressive strength was found to be 4% higher than the control mortar. However, all specimens showed compressive strength more than 50 MPa, in align with the high strength concrete (HSC) except for specimen K and HBK 4 that have lower compressive strength at the age of 28 days with 43.95 and 46.27 MPa, respectively. This is due to the addition of the high volume of kenaf fibre that known as a natural fibre that affect the interfacial transition zone between the mortar matrix and fibre, and directly decreasing the compressive strength because of their own characteristics and durability as compared to the synthetic fibre like barchip fibre[22]. The compressive strength for specimens K, HBK 1, HBK 2, HBK 3 and HBK 4 were found to have lower percentages as compared to the control mortar with 33.48%, 5.7%, 11.47%, 22.73% and 29.9%, respectively.

The percentages of flexural strength for specimens B, K, HBK 1, HBK 2, HBK 3 and HBK 4 mortar were 37.39%, 9.24%, 34.46%, 18.77%, 9.97% and 13.34%, respectively, which were higher than the control mortar. These specimens were cured in cyclic exposure with constant PFA and GGBS of 10% and 40% by total volume binder weight. The observation is contributed by the rigorous early age pozzolanic reaction between the Portlandite mineral and PFA-GGBS. The effect of synthetic fibre also has improved the characteristics of concrete or mortar with reduced shrinkage, cracking and durability by stabilization of micro cracks and decreased in permeability[23].

3.2 Load deflection relationship of panels

The load deflection curves of panels for all specimens under flexural load was reported to have three distinct stages namely pre-cracking stage (steepest slope), multiple cracking stage (secondary slope with reduced gradient) and failure stage (ternary slope with very low gradient near to zero magnitude or negative value)[24]. The load versus mid-span deflection curves of the cementitious composites containing hybrid fibres are shown in Figure 4 for cyclic exposure.

In cyclic exposure durations, the mono (B & K) and hybrid (HBK 1-HBK 4) fibres composites were found to have higher flexural load and mid-span deflection compared to the control panel. Besides, the composite with 2.5% of barchip fibre (B) and hybrid fibres, HBK 1 (0.5% of kenaf fibre combined with 2.0% of barchip fibre) and HBK 2 (1.0% of kenaf fibre combined with 1.5% of barchip fibre) indicated higher degree of ductility and flexural load as compared to the other panels. On the other hand, the mono (K) and hybrid fibres (HBK 3 and HBK 4) showed higher flexural load but lower deflection capacity as compared with B, HBK 1 and HBK 2 composites panels but remained higher in flexural load and mid-span deflection as compared to the control panel. The highest flexural load and deflection capacity was recorded by the panel HBK 1 with combination of 0.5% kenaf fibre and 2.0% barchip fibre, with 46% higher than the control mortar. The inclusion of barchip fibre contributes to the high deformation stiffness and tensile strength. High volume of barchip fibre by total volume weight increased the load and mid-span deflection of fibrous cementitious composites containing hybrid, kenaf and barchip fibre.

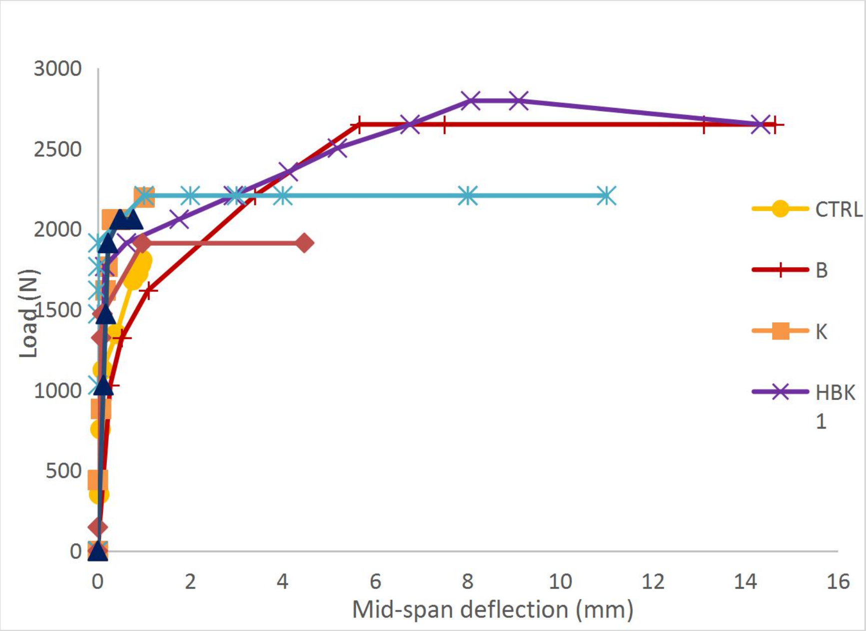

Figure 4. The relationship between load and mid-span deflection of mortar panels at the age of 28 days cured in cyclic exposure.

In addition, panels for all specimens contained kenaf and barchip fibre were found to be increased in both first crack and ultimate strength with growing volume fraction of barchip fibre while delaying crack initiation and propagation. It also provided higher stiffness and tensile capacity once the cracks started to appear. This means that the hybridization of kenaf (low modulus) and steel fibre (high modulus) fibres could improve the flexural strength[25,26], .

During the linear (before cracking appeared) deformation stage, panels for all specimens (B, K, HBK 1, HBK 2, HBK 3 and HBK 4) had exhibited higher degree of stiffness compared to the control panel. Therefore, it was evident that the mono and hybrid fibres in mortar matrix had significantly enhanced the stiffness of the mortar matrix under flexural loading.

During post-cracking deformation, the panels with the inclusion of mono and hybrid fibres were observed to have a higher flexural load and higher total mid-span deflection as compared to the control panel. The ultimate flexural load was found between 1.91 kN and 2.65 kN. Kenaf and barchip fibre had the ability to increase the flexural strength of the fibrous cementitious composites due to their high stiffness deformation and tensile strength. HBK 1 (0.5% kenaf and 2.0% barchip) was found to exhibit the highest bending stiffness with flexural load of 2.65 kN. Panels for specimen B, HBK 1 and HBK 2 containing high barchip fibre also exhibited a range of maximum mid-span deflection between 11.00 mm and 14.63 mm. Meanwhile, the range of the recorded mid-span deflection at maximum flexural load for the panels was 7 - 8 mm. This effective increment in flexural strength was possibly resulted from the improved compaction and homogeneity of fibre distribution in the mortar mixes and the ability of different types of fibre to restrain and bridge the cracks[27]. Therefore, the fibre distribution and types of fibre are important parts that could enhance and improve the flexural strength and deformation stiffness of the panels for all specimens.

3.3 Load compressive strain relationship of panels

The load and compressive strain relationship of panels for all specimens is expressed in Figure 5 in cyclic exposure durations. The initial stage of linear variation between flexural strength and upper fibre compressive strain represents the pre-cracked deformation stage or serviceability load range of the test panels. The second portion of linear relationship between flexural strength and compressive strain, which has lower gradient, represents post cracking deformation of the panels in flexure[28].

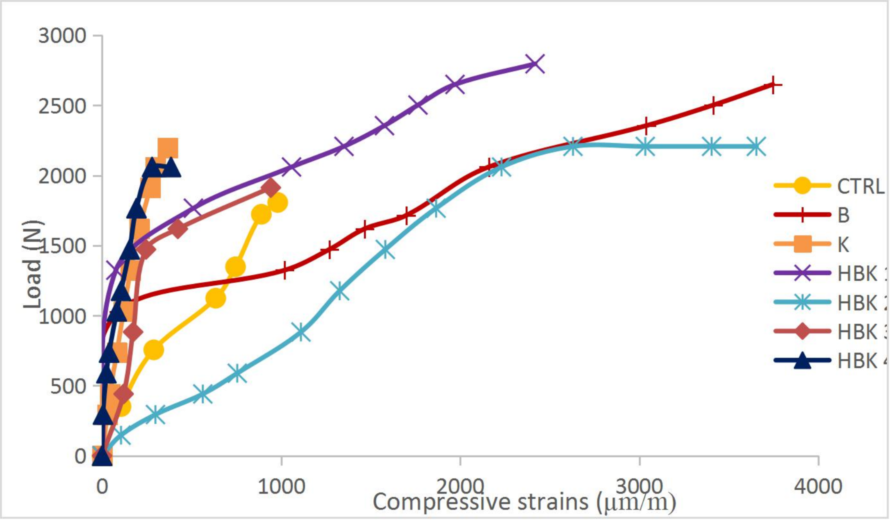

Figure 5. The relationship between flexural stress and compressive strains of mortar panels at the age of 28 days cured in cyclic exposure of sea water and air.

The panels for specimen B, HBK 1 and HBK 2 were observed to exhibit higher magnitude of compressive strain as compared to the control mortar panel. At the same stage of deformation, the highest degree of enhancement was observed on barchip and hybrid fibres with 10% PFA and 40% GGBS cement replacement, as the degree of the stiffness of the mortar matrix increased. The highest degree of compressive strain was observed for mono fibre inclusion level of 2.5% barchip (B) followed by HBK 1 (0.5% of kenaf fibre combined with 2.0% of barchip fibre) and HBK 2 (1.0% of kenaf fibre combined with 1.5% of barchip fibre). Panels K, HBK 3 and HBK 4 were observed to have a lower compressive strain but higher flexural load as compared to the control mortar panel at this pre-cracking stage.

During the post cracking deformation, panels B, HBK 1 and HBK 2 were observed to have higher stiffness of flexural stress and compressive strain of the mortar matrix as compared to the control mortar and other panels. Therefore, panel HBK 1 was found higher stiffness in flexural stress while panel B showed higher compressive strain as compared to other mortar panels in cyclic exposure.

3.4 Crack development characteristic

The results of crack width, crack spacing and number of crack for fibrous cementitious composites containing hybrid fibres cured in cyclic exposure are shown in Table 4.

Mix Designation	Crack Width (mm)	Number of Cracks	Crack Spacing (mm)
C	-	1	-
B	0.47	5	36
K	0.10	1	-
HBK 1	0.31	6	30
HBK 2	0.36	5	35
HBK 3	0.35	1	-
HBK 4	0.20	1	-

Table 4. Crack width, number of cracks and crack spacing of mortar panels.

The result showed the average crack width values of the tested panels at ultimate load. The highest magnitude of the crack width of 0.47 mm was observed for panel B while the lowest magnitude of 0.20 mm was shown by panel HBK 4. Higher magnitude of average crack widths at ultimate load recorded for panels B, HBK 1 and HBK 2 compared to other panels. It was due to the higher magnitude of ultimate failure load and corresponding higher degree of stress and strain sustained by the higher percentage inclusion of barchip fibre. Besides, panel K and HBK 4 exhibited a lower magnitude of crack width as compared to the control mortar. This is an indication that the inclusion of kenaf fibre in cementitious composite mortar enhances its crack arresting capability, which attributed to the enhancement in flexural strength of mortar as discussed in the earlier section.

Table 4 shows the number of cracks for fibrous cementitious composites containing hybrid, kenaf and barchip fibres. The results indicated panel B, HBK 1 and HBK 2 have more than one crack. The highest number of cracks was found for panel HBK 1 containing 0.5% of kenaf fibre and 2.0% of barchip fibre followed by B (2.5% barchip fibre) and HBK 2 (1.0% kenaf fibre + 1.5% barchip fibre) as compared to the other mortar panels. This could relate to the spacing of the cracks found for panel B, HBK 1 and HBK 2 with 36, 30, 35 mm in cyclic exposure.

3.5 Crack pattern of panels and failure mode

A major continuous crack at the top fibre was observed on all tested panels as shown in Figure 6. Therefore, this is the crack which triggered the ultimate failure of the test panels in flexure. Based on Figures 6, the large number of closely spaced cracks were observed to be developed on panel B, HBK 1 and HBK 2. Only flexural cracks were observed on all tested panels at ultimate failure. Therefore, it can be concluded that all the tested mortar panels failed in pure bending. The effect of the maximum shear force on the support of the test panels during ultimate failure did not exceed the shear capacity of them.

Figure 6. Crack pattern of test panels cured in cyclic exposure.

4. Conclusion

The mechanical properties and flexural behaviour of the fibrous cementitious composites especially for hardened mortar with the mono, B (2.5% of barchip) and hybrid fibres, HBK 1 (0.5% kenaf fibre and 2.0% barchip fibre) and HBK 2 (1.0% kenaf fibre and 1.5% barchip fibre) were found to have significant improvement. The effect of fibres was proven to enhance the characteristics of concrete or mortar by reducing shrinkage, micro crack and additional C-S-H gel precipitated from the pozzolanic reaction acted to fill pores of the cement paste matrix and cement paste aggregate interface zone between mortar matrix and fibre bonding.

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