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Original Article

Flexural and Shear Behaviour of Reinforced Concrete Beams Modified with Polyethylene Terephthalate Fibre and Blue Gum Eucalyptus Wood Ash

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Abstract - *The production of conventional reinforced concrete is encountered with reduced ductility, reduced deflections before failure and increased crack widths. The construction industry is currently focused on improved knowledge of reinforced concrete beams, primarily on using alternative materials to produce concrete that can improve concrete properties and produce eco-friendly concrete. This paper studies the flexural and shear performance of reinforced concrete beams modified with 1.5% polyethylene terephthalate (PET) fibres and 5% blue gum wood ash (BGWA) replacing cement. Four beams were subjected to flexural failure testing, while the other 4 beams were subjected to shear failure testing. The behaviour of the tested beams was assessed based on cracking behaviour, ductility, load-deflection responses, load-strain responses, ultimate loads, flexural behaviour and shear behaviour. For modified concrete beams with and without shear reinforcement, the ductility increased by 4.8% and 6.3%, respectively, compared with control concrete beams. The combination of PET fibres and BGWA in concrete beams with shear reinforcement increased the number of cracks, ultimate loads, and ultimate deflections compared with control concrete beams. Moreover, flexural and shear capacities increased for reinforced concrete beams containing PET fibres and BGWA than control concrete. Eventually, a reinforced concrete beam modified with PET fibres and BGWA was suggested to be a promising candidate for structural members exposed to seismic loads. The combination of PET fibres and BGWA in concrete could provide a new concrete composite with improved ductility, increased flexural capacity, enhanced shear capacity and decreased crack width.*

Keywords - *Reinforced concrete, Polyethylene terephthalate, Blue gum wood ash, Flexural strength, Shear strength.*

1. Introduction

Industrialisation and urbanisation, accompanied by population growth, have increased tremendously in several countries. This has generated huge waste materials, including polyethylene terephthalate (PET) bottles. Conventional reinforced concrete illustrates limitations in ductility and increased crack widths [1]. Continuing efforts have been made to improve the ductility behaviour of reinforced concrete members. On the other hand, cement is an expensive and active ingredient of concrete used as a binding agent when combined with water. Supplementary cementitious materials (SCMs) have been comprehensively studied as partial cement replacements [2]–[10]. Among the SCMs is blue gum wood ash (BGWA), and it has been observed to be a partial replacement of cement [11], [12]. While researchers have attempted to study the ductility of reinforced concrete beams, efforts are still required to study the flexural and shear performance of reinforced concrete modified with PET fibres and BGWA.

The international yearly production of Portland cement concrete is estimated to be more than 10 billion tonnes [13]. The growing demand for concrete has made the need for cement production and aggregate extraction extreme, causing an environmental problem that is likely to keep increasing in the future [14]. Important progress has been made in the construction industry to discover ways to use alternative materials for concrete products that can improve their properties and reduce environmental impacts. A lot of studies on SCMs are pointing towards a partial or total replacement of Portland cement with industrial and manufacturing by-products, agricultural wastes and domestic wastes [2], [6], [8], [10]. This way, some percentages of cement could be replaced with any of these SCMs. It could result in reduced cement consumption, thereby generating lower greenhouse emissions, great cost savings, strengthening the economy and reducing the dumping loads for landfills [15].

Waste management in this modern age is becoming more expensive in most countries, especially under-developed countries. Proper waste disposal is essential not only for the sustainability of the environment but also for disease prevention. Plastics currently play a massive role in our daily lives and are utilised in many manufacturing areas. Tonnes of plastic products are moulded daily, even as the waste continues. It is reported that 1,000,000 plastic bottles are bought every minute or 20,000 per second, and 480 billion were sold in 2016 [16]. The previous study also indicated that less than 50% of the bottles are collected for recycling, whilst 7% have turned into new bottles. Because plastic bottles are non-biodegradable, an enormous amount of plastic waste continues to build up worldwide, with industrialised nations contributing to the largest amounts of plastic waste. It is well known that most plastic wastes come from packaging and containers. The amount of land required for landfills is of increasing concern everywhere in the world. It shows an urgent need to develop reasonable disposal methods [17]. On the other hand, cement is composed primarily of silica and lime, forming essential cementing compounds, including tricalcium-silicate (C_3S) and dicalcium-silicate (C_2S). Any alteration in silica composition will consistently influence the strength properties of cement, which is expected when wood ash is used to partially replace any grades of cement for concrete production [18].

Several issues require solutions in the production of conventional reinforced concrete beams. First, concrete is a brittle material, and its brittleness makes it rely on composite performance from reinforcement to contribute to increased ductility during loading. Unfortunately, conventional reinforcement detailing may not be sufficient to withstand huge seismic demands as the structural members become slender [19]. The second important issue is that the use of conventional reinforced concrete beams has left propagation of crack width uninhibited, a phenomenon strongly related to reduced ductility [1]. Increasing crack width in conventional reinforced concrete beams could create durability problems in concrete when subjected to flexural load. The third issue in conventional concrete is that the production of its constituent materials is not eco-friendly. However, it is recognised that introduction of alternative materials has the potential to create eco-friendly concrete. This study offers solutions to problems of reduced ductility, increased crack width and environmental challenges through the inclusion of PET and BGWA. Satisfactory reinforced concrete performance must be associated with increased ductility, reduced crack width and eco-friendliness. Including PET and BGWA in concrete makes it possible to overcome the problems of durability, crack width and environmental pollution.

2. Materials and Methods

2.1. Materials

The materials used in this research included Ordinary Portland Cement (OPC) CEM I with a minimum compressive strength of 42.5 MPa following 28 days of curing, fine aggregates, coarse aggregates, portable water, PET fibres, BGWA generated from blue-gum wood (Eucalyptus) and high tensile reinforcements. PET fibres were prepared with an aspect ratio of 25, of which each fibre was 100 mm in length and 4 mm in width. 30 PET fibre samples were randomly selected to measure their thicknesses using a Hercules digital caliber. Cement and BGWA in this study gave specific gravity values of 3.27 and 2.75, respectively. The BGWA was acquired locally from a pulp and paper mill. Then it was transported to the laboratory at Jomo Kenyatta University of Agriculture and Technology (JKUAT) to be used in this research. The chemical compositions of OPC and BGWA are presented in Table 1. From Table 1, BGWA shows 76.30% of lime (CaO) and 0% Silica (SiO_2). Hence, BGWA is a high lime (CaO) content pozzolanic material in accordance with the standard [20]. Fine aggregate (river sand) of specific gravity of 2.51 was purchased from Meru in Kenya and conformed with the standard's specifications [21]. The aggregate was washed and air-dried under the standard [22]. Well-graded coarse aggregate (ballast) was purchased from Nairobi in conformity with the standard [21] and with a specific gravity of 2.60. High tensile reinforcing steel bars of sizes 8 mm and 12 mm showed yield strength values of 510.556 MPa and 666.007 MPa, respectively. Gradations of fine aggregate and coarse aggregate have been presented in Figs. 1 and 2.

Table 1. Chemical Properties of Cement and BGWA

Material	CaO	SiO_2	Fe_2O_3	Cl	Al_2O_3	P_2O_5	S	K_2O	TiO	MnO	Sr	Zr	ZnO	Ba	Rb
OPC	89.91	4.5	3.31	-	2.28	1.15	3.04	0.17	0.26	0.04	0.16	0.04	0.04	-	-
BGWA	76.3	_	0.77	2.62	1.47	5.32	1.14	8	0.09	3.52	0.47	0.05	0.02	0.13	0.03

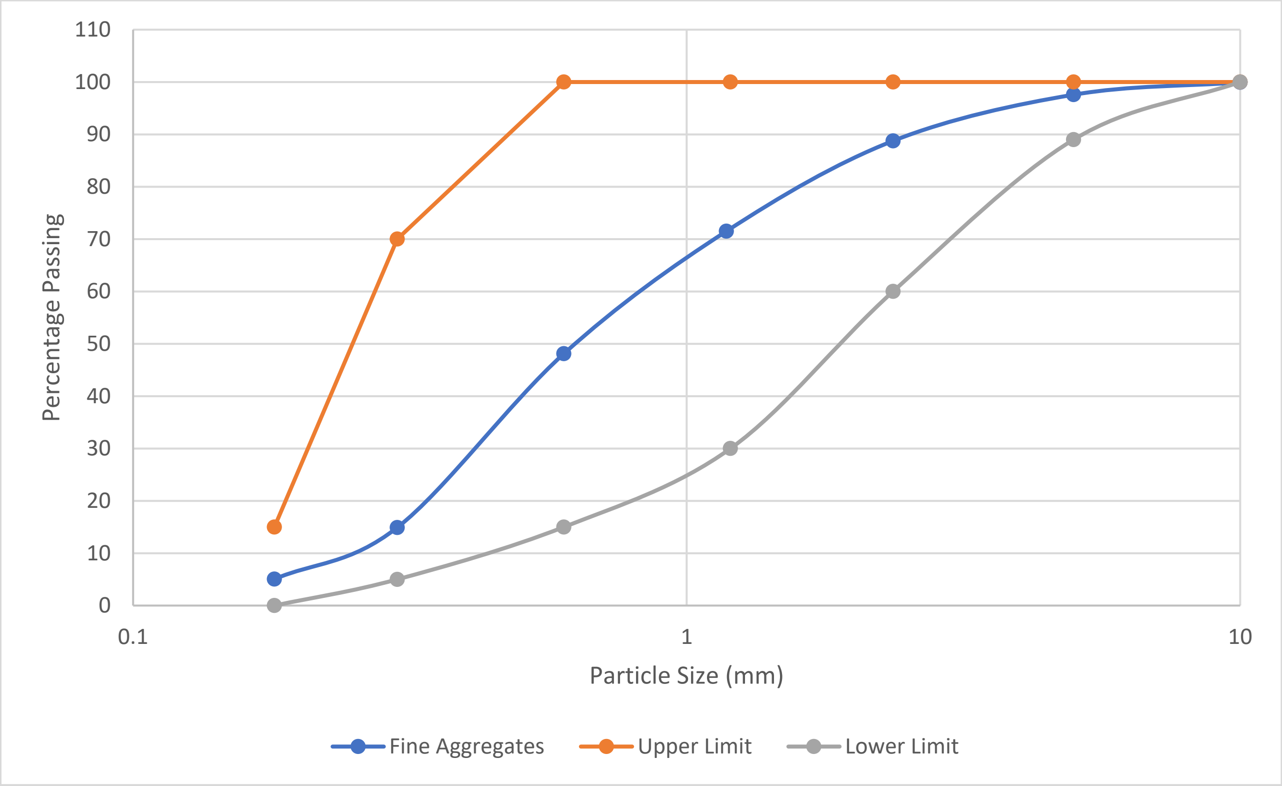

Fig. 1 Grading Curves of Fine Aggregates

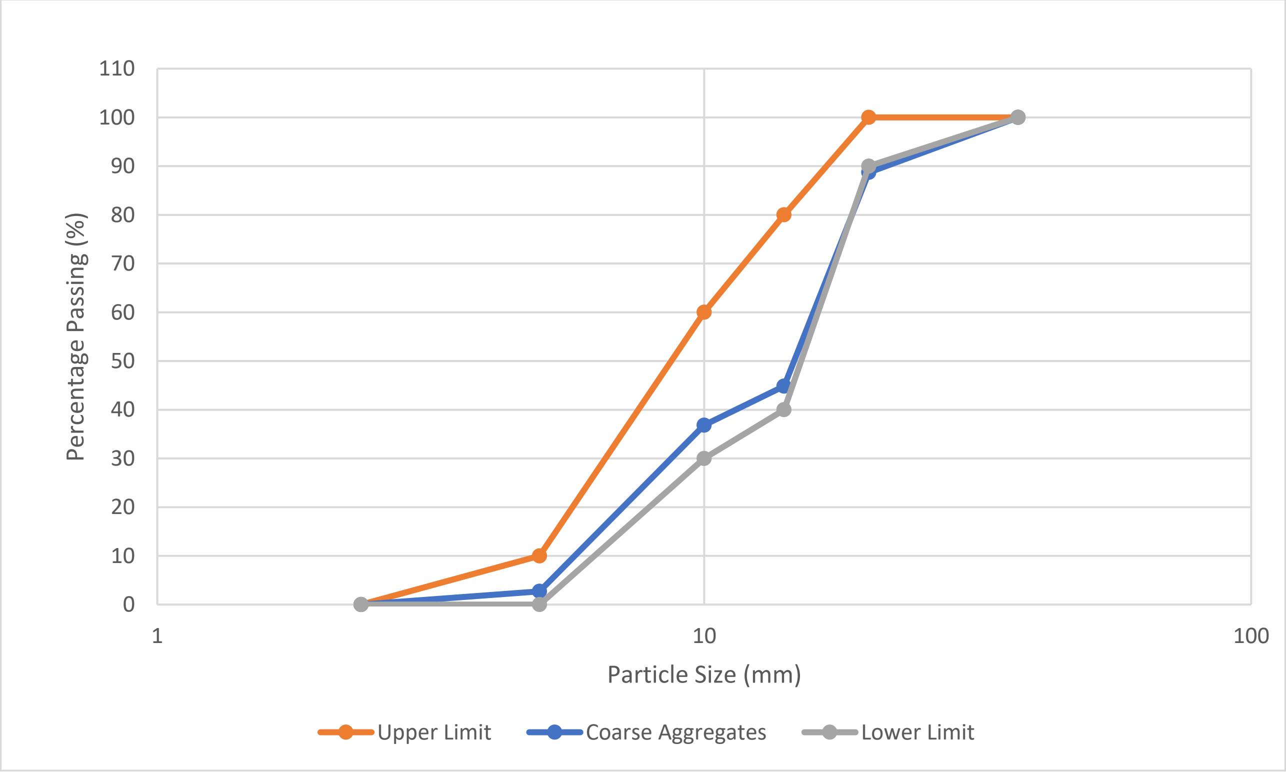

Fig. 2 Grading Curves of Coarse Aggregates

2.2. Methods

2.2.1. Concrete mixes and fresh and hardened concrete tests

British Research Establishment (BRE) was used during the concrete mix design of class 30 concrete. Documentation of the mix design is presented elsewhere [23]. Before the selection of the mix design, trial mixes were done, and the results showed that a water-cement ratio of at least 0.55 was to be applied to get slump values between 30 to 60 mm. The compressive strength tests were done using 100 x 100 x 100 mm cubes, and the cubes were exposed to a 28-days curing period, as was the case with beams in conformity with the standard [24]. The slump experiments were conducted according to the standard [25]. A conical mould with a bottom diameter of 200 mm, a top diameter of 100 mm and a height of 300 mm was used.

2.2.2. Instrumentation and details of the test beam

Investigation of the flexure and shear performance involved the fabrication of 8 beams under the standard [26]. The design of the beams was done in accordance with the standard [27], while bending, scheduling and dimensioning of steel bars were performed in conformity with the standard [28]. These beams had the same sizes, i.e. length of 2000 mm, a height of 200 mm and a width of 150 mm. The timber moulds made of 8 mm plywood were prepared, and the steel reinforcement bars were transferred in the moulds with provisions of 25 mm concrete covers using spacers. The stirrups were provided throughout the beam length for the beams tested in flexure, as illustrated in Figure 5. Figure 4 shows the beam without shear reinforcement tested in shear. The strain gauges were embedded on the mid-spans of the top concrete surface, strain gauge 1 (SG1) and bottom surface of the beams (SG2) to obtain the distribution of strains around the sections. Other electrical resistance strain gauges were attached to the centres of longitudinal reinforcement (SG3) and the shear reinforcement (SG4) to measure the induced flexural strains and shear strains, respectively. Because the strain gauges were to be placed on a smooth surface, the bench grinder was used to smoothen steel surfaces.

Special care was considered during the embedding of strain gauges. Concrete was then cast into the moulds and vibrated using a poker vibrator. Special care was also considered during concrete placement and vibration so as not to cause damage to strain gauges. After 24 hours, the samples were demoulded before being covered by wet gunny bags for moist curing. The specimens were kept in the laboratory for 28 days. Because, in practice, it is common to cast cubes alongside casting beams, several cubes were cast and cured for 28 days. The mixes for the cubes were coded 0A0F (control concrete) and 5%A1.5F (5% BGWA and 1.5% PET fibres).

2.2.3. Beam testing

The beams were fabricated in the Structural and Materials Laboratory of JKUAT, where the testing of the beams was also conducted. Four beams, each of length 2000 mm simply supported over a length of 1800 mm, were tested in flexure. Two beams of the four beams were produced using conventional methods of producing concrete. Every mix for the reinforced concrete beams was tested twice to enhance the validity of the results. The other two beams were produced with 1.5% PET fibres and 5% cement replacement by BGWA. A similar testing approach was used for the other reinforced concrete beams tested in shear.

Four-point load method was used for tests on flexure and shear performance. The setup of the beam is demonstrated in Figure 3. The beams were positioned on a pair of supports having a clear span of 1800 mm. The deflections of the beams were monitored by Linear Variable Differential Transducer (LVDT) positioned at the mid-span of the beams during loading. The LVDT was connected to a data logger during the loading phase. The load was applied using a 400 kN hydraulic jack, and a 200 kN capacity was used in measuring the load applied. With further load increase, the beams were monitored to obtain the behaviour of the beams up to failure. The possible effects of the inclusions of BGWA and PET were investigated in this research. The cubes were also tested to check if the concrete attained its required strength of 30 MPa.

Fig. 3 Four-Point Load Test Setup

3. Results and discussions

3.1. Compressive strength results

The 28-days compressive strength findings have been presented in Figure 6. As seen from the figure, the inclusion of PET fibres and BGWA resulted in reduced compressive strength of modified concrete compared with control concrete. For concrete cubes cast during the casting of reinforced concrete beams without shear reinforcement, compressive strength was reduced by 21.2% compared to control concrete. On the other hand, concrete cubes cast during the casting of reinforced concrete beams with shear reinforcement exhibited a 19.4% strength reduction compared with control concrete.

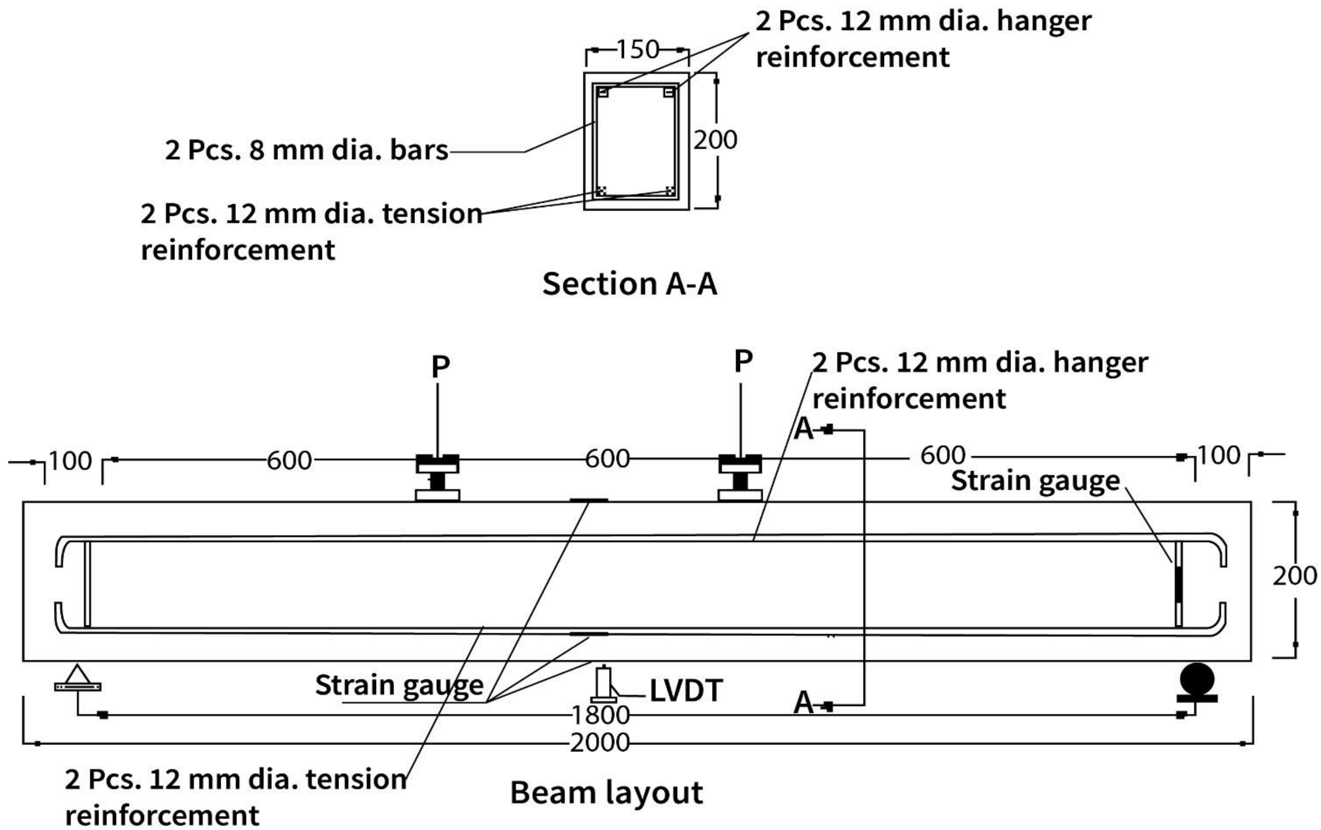

Fig. 4 The layout of a beam designed without shear reinforcement

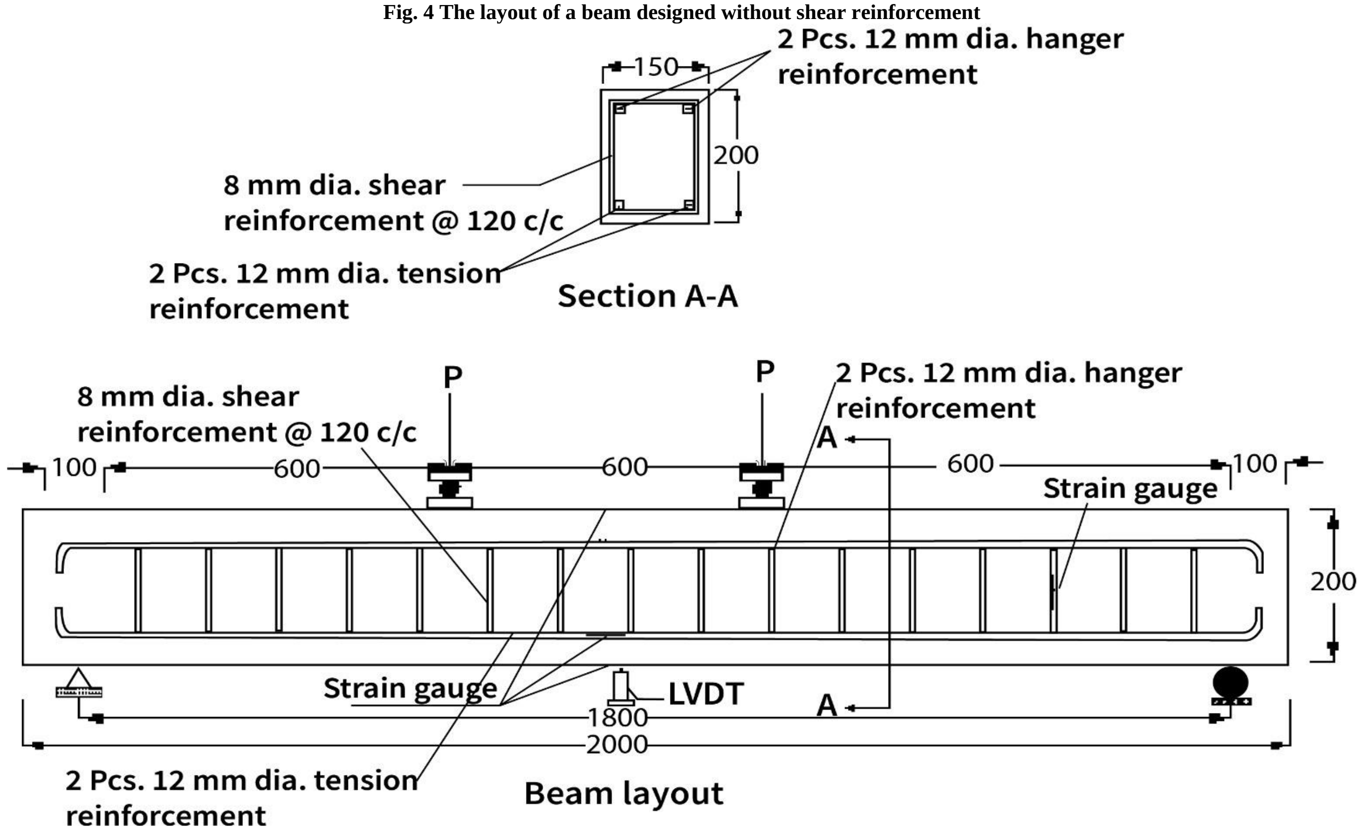

Fig. 5 The layout of a beam designed with shear reinforcement

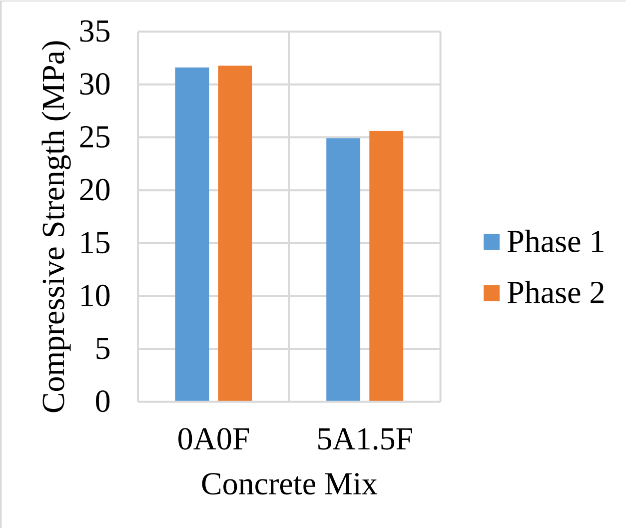

Fig. 6 Compressive Strength Findings of Developed Mixes for Phase 1 (Cubes Cast During Concrete Casting of Beams without Shear Reinforcement) and Phase 2 (Cubes Cast During Concrete Casting of Beams with Shear Reinforcement)

Compressive strength results were utilized to verify the concrete's characteristic strength during the beams' casting. From Figure 6, the characteristic strength of 30 MPa was only exceeded for control concrete following 28 days of concrete curing. In another study [29], the inclusion of PET fibres decreased the compressive strength of concrete. The preceding study reported that this was attributed to reduced adhesion existing between PET fibre surfaces and concrete matrix. Elsewhere, concrete's early strength was reduced due to the inclusion of BGWA [30]. In this study, the inclusion of PET and BGWA was suggested to reduce concrete compressive strength.

3.2. Load-deflection curves

This section presents findings from the flexural and shear performance of concrete beams modified with 1.5% PET fibres and 5% cement replaced by BGWA. These findings were compared with those obtained from conventional concrete beams (0% PET fibres and 0% BGWA).

3.2.1. Findings of Beams Tested without Shear Reinforcement

Fig. 7 shows the behavior of the beams without shear reinforcement under load in terms of load-deflection characteristics. During the loading process, the longitudinal reinforcements yielded, and shear cracks started developing. Looking closely at the figure, it is clear that the modified concrete beams developed increased ultimate load compared to the control concrete beam. This behaviour occurred for beams with or without shear reinforcements. Beyond the ultimate load, the applied load gradually decreased up to the occurrence of a sudden drop.

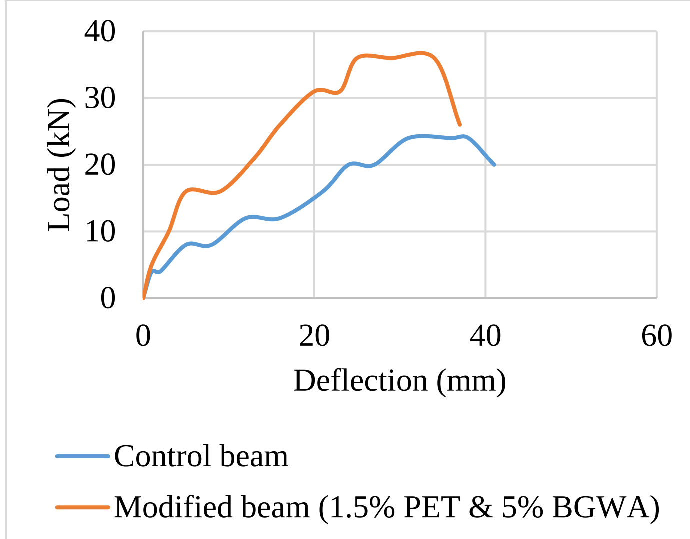

Fig. 7 Load-Deflection Curves of Beams without Shear Reinforcement

From the findings in Fig. 7, the conventional (control) and modified concrete beams initially exhibited distinct load-deflection curves until the ultimate loads with rapid reductions in initial stiffness at the appearance of major shear (diagonal) cracks. By comparing the load-deflection curves, the modified concrete beam showed a higher capacity to deflect than the control concrete beam. Unlike conventional concrete beams, PET fibre and BGWA-modified concrete beam attained a significantly higher ultimate load. The modified concrete beam also exhibited superior post-crack behavior compared with the conventional concrete (control) beam. The addition of PET fibres and BGWA did not interfere with the displacement or negatively influence the outcomes of beam results. In another study [31], adding recycled PET fibres (at 5% and 10%) to the reinforced concrete beams did not lower the deflection of the modified beams compared with the control reinforced concrete beam specimens. Moreover, during the cracking stage of the foregoing study, concrete beams containing recycled PET fibres at 10% showed that the first crack load increased by 32.3% compared with normal concrete beams.

3.2.2. Findings of Beams Tested with Shear Reinforcement

Fig. 8 shows the control and modified concrete beams with shear reinforcement load-deflection curves. As expected, there was a sudden drop in the load beyond the failure. Compared with the previously discussed beams, the ultimate loads for the beams with shear reinforcement were higher for both control and modified beams. This kind of performance was attributed to the increased stiffness of the beams due to the inclusion of shear reinforcement. The introduction of shear reinforcement at a reduced spacing in reinforced concrete beams increases the likelihood of increased beam stiffness [32]. The flexural capacity was increased in this foregoing study, where shear reinforcement spacing was reduced.

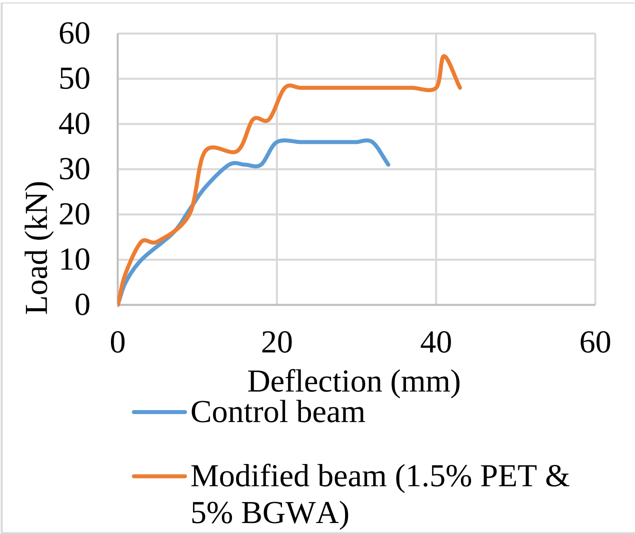

Fig. 8 Load-Deflection Curves of Beams with Shear Reinforcement

The results demonstrate that the deformation capacity of the beams improved with the addition of PET fibres and BGWA. This increase in deformation capacity for the modified beams illustrated the increased ductile performance of the modified beam compared with the control beam. Thus, the inclusion of PET fibres and BGWA was suggested to help the beams to experience enhanced deflections before failure. Interestingly, the ability of modified concrete to undergo many deflections was considered significant for structural members subjected to seismic loading. It should be kept in mind that the beams with shear reinforcement exhibit flexural failure and illustrate some elements of shear failure. Beams also illustrated higher load capacity with shear reinforcement than those without shear reinforcement. Another study [41] concluded PET fibres and stirrups performed considerably well and contributed substantially to flexural and shear modes of failure of beams. The graphs in Figure 8 show that the load still increased after steel yielding. This hypothesis has been validated by another study [34], and researchers in the previous study found that after the steel bar in the concrete beam yields, the load can still steadily increase.

3.3. Ductility Characteristics

Ductility is vital in providing bending moment redistribution along the beam as longitudinal steel reinforcements yield, resulting in the redundant behavior of statically indeterminate structures. Ductility property is essential in reinforced concrete structural systems as this parameter is related to the behavior of structures subjected to dynamic loads generated by seismic tremors. In such circumstances, the ductility of the structural elements must be predicted and quantified in detail to avoid the buildings' severe damage and brittle failures. The ductility index can be expressed as a ratio of ultimate deflection to deflection at first yield, as presented in Equation 1.

Table 2. Summarised Ductility Results for Beams without Shear Reinforcement

Parameters	Control beam	Modified beam
Pcr (kN)	8	16
Δcr (mm)	5	5
Py (kN)	20	31
Δy (mm)	24	20
Pu (kN)	24	36
Δu (mm)	38	34
μ	1.6	1.7

Table 3. Summarised Ductility Results for Beams with Shear Reinforcement

Parameters	Control beam	Modified beam
Pcr (kN)	10	14
Δcr (mm)	3	5
Py (kN)	31	48
Δy (mm)	15	19
Pu (kN)	36	55
Δu (mm)	31	42
μ	2.1	2.2

$$\mu = \frac{\Delta u}{\Delta y} \tag{1}$$

where μ is the ductility index, Δu is the ultimate deflection, and Δy is the deflection at first yield. Tables 2 and 3 present the tests' load and deflection readings and the ductility indices for conventional and modified beams with or without shear reinforcement. In the tables, Pcr, Py, and Pu are the initial cracking load, first yield load and ultimate load, respectively. Δcr is the deflection at the first crack.

The ductility index of the modified concrete beam with shear reinforcement improved by 4.8%, while the modified concrete beam without shear reinforcement improved by 6.3%, compared with the control beam. The improvements in the ductility indices for beams with shear reinforcement (stirrups) might be owed to PET fibres' micro-crack interlocking nature, giving the specimen strength to absorb stress. The increment in the ductility for beams without shear reinforcement (stirrups) can also be attributed to the micro-crack interlocking nature of PET fibres that bridged the cracks of horizontal shear stresses that occur along with bending stresses. It was also suspected that BGWA contributed to enhanced flexibility in modified concrete. In another study [11], adding 5% BGWA to replace cement decreased the brittleness of stabilized marine clay. In this study, the addition of PET fibres and BGWA in reinforced concrete beams was suggested to have increased the ductility behaviour in both cases considerably compared to control beams. Other researchers [35] observed that the inclusion of PET strips used along with the longitudinal and shear reinforcements improved ductility in reinforced concrete beams. The effect of incorporating PET fibres was investigated in the previous study, and the beams containing these fibres had increased ductility compared with control beams. The findings in this study suggest that the method of determining ductility yields significant results.

3.4. Load-strain (concrete) curves

3.4.1. Findings of Beams Tested without Shear Reinforcement

The experimental results for load-strain relationships of reinforced beams without shear reinforcement are shown in Figure 9. In Figure 10, the load strain relationships of reinforced beams with shear reinforcement are exhibited. Figures 9 and 10 show that the modified beams exhibited greater strains than the control beams. Unfortunately, from the load-strain curves, it is noticed that none of the beams showed a linear elastic response with respect to load applications.

The experimental results of the load-strain curves presented in Figures 9 and 10 show progressive load-strain relationships. The load drops are observed after attaining ultimate loads for both beams. These figures show stress relaxations for both control and modified beams. It is known that stress relaxation is the stress reduction (generated from load) when the material is subjected to a constant strain [36]. The stress relaxation phenomenon would have been apparent had stress-relaxation tests been conducted. Further future research to capture this interesting phenomenon is therefore proposed. Flexural strains were induced at the bottom and top (hanger) steel bars of the longitudinal tension reinforcements in the beams in response to load applications.

3.4.2. Findings of Beams Tested with Shear Reinforcement

Figures 11 and 12 show the load-strain curves for concrete beams with shear reinforcement (stirrups) for both concrete and steel strains. The relationships between loads applied and induced strains are observed for all tested beams. It can be seen in the figures that after the yielding of steel, rapid increments in strains are observed. In another study [34], a conclusion was drawn that steel yielding and concrete cracking could occasion a rapid strain increment within the longitudinal reinforcement steel bars. In the previous study, because of the existence of the fibre-reinforced polymer (FRP) bar, the plastic development of the steel bar was partially suppressed, and the length of the tensile steel bar that reached the tensile yield strength became longer.

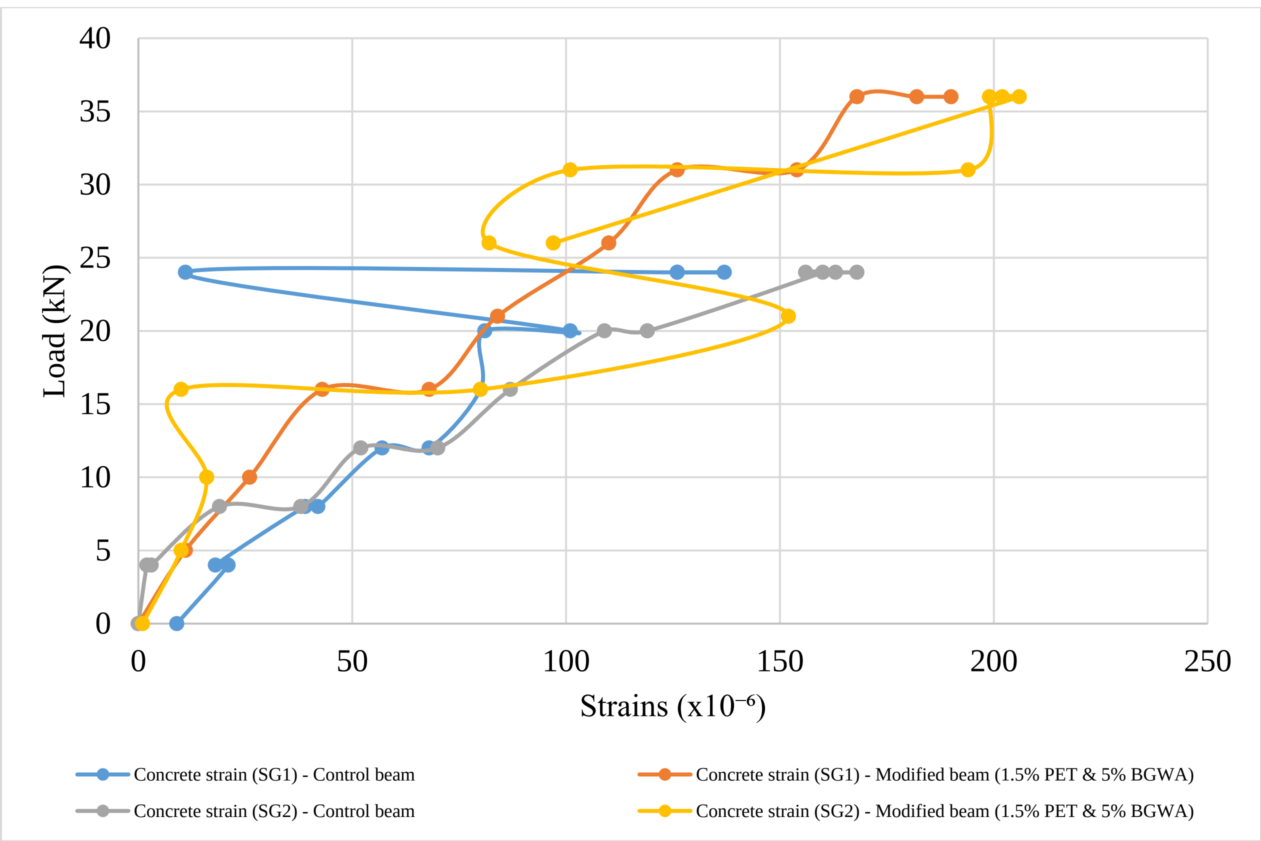

Fig. 9 Load-Strain (Concrete) Curves of Beams without Shear Reinforcement. In the Figure, SG1 and SG2 Imply Readings of Strain Gauges Embedded at the Mid-Spans of the Top Concrete Surface and Bottom Concrete Surface Respectively

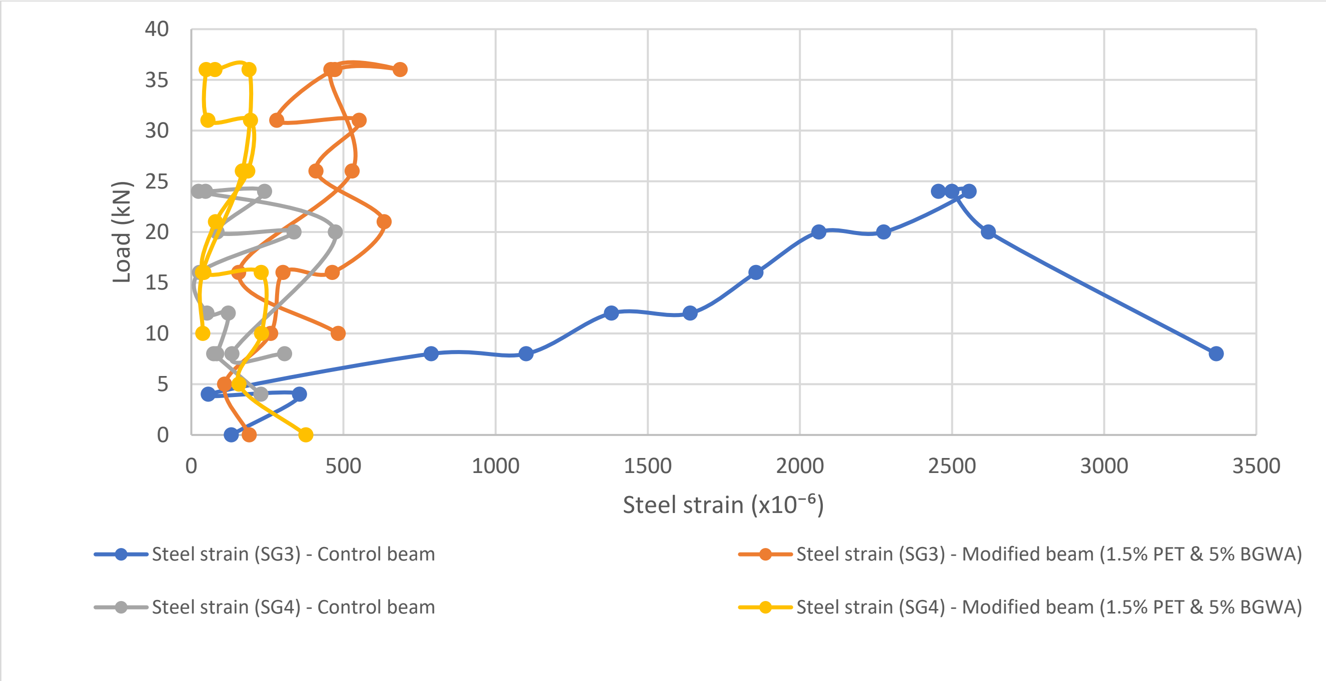

Fig. 10 Load-Strain (Steel) Curves of Beams without Shear Reinforcement. In the Figure, SG3 and SG4 Imply Readings of Strain Gauges Attached to the Centres of Longitudinal Reinforcement and Shear Reinforcement Respectively

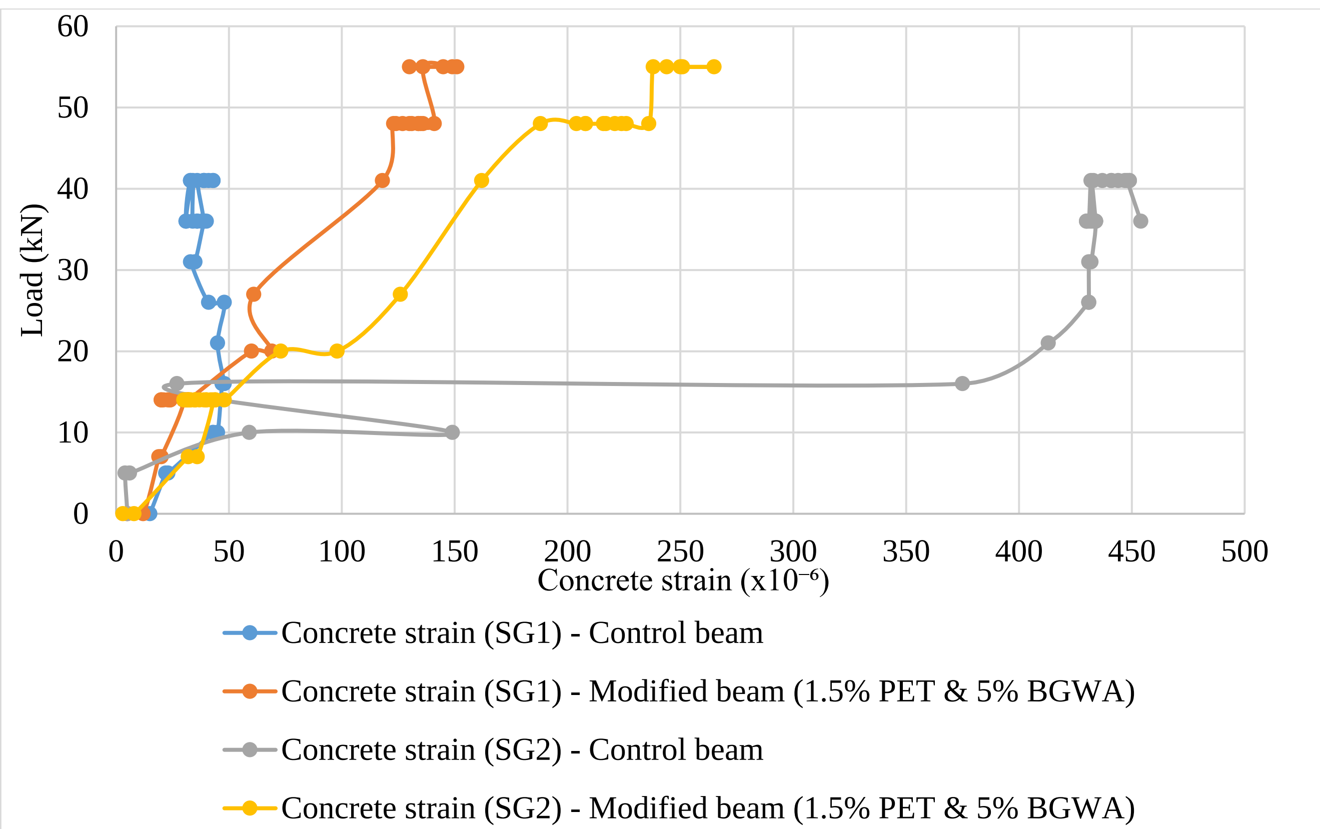

Fig. 11 Load-Strain (Concrete) Behavior of Beams with Shear Reinforcement. In the Figure, SG1 and SG2 Imply Readings of Strain Gauges Embedded at the Mid-Spans of the Top Concrete Surface and Bottom Concrete Surface Respectively

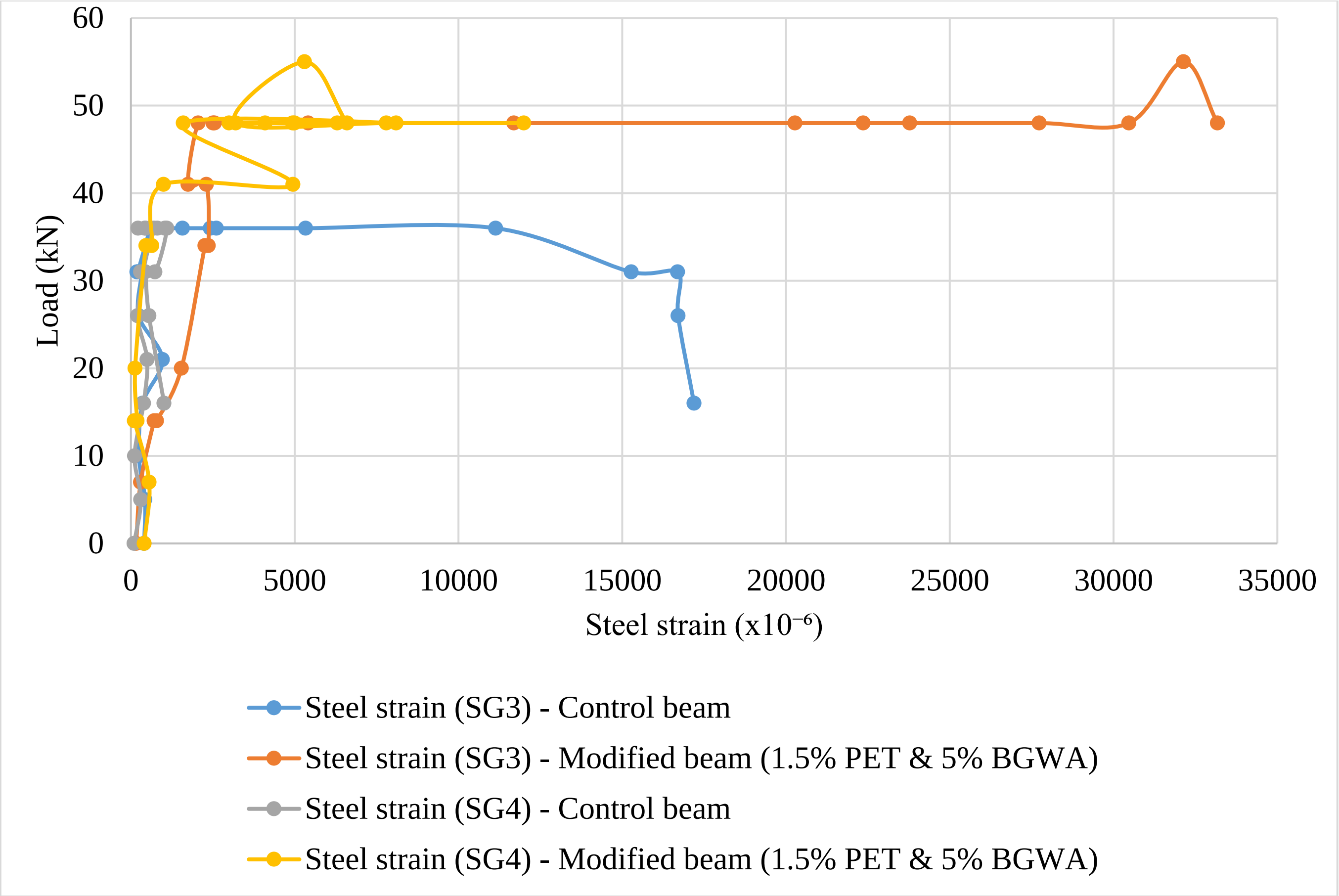

Fig. 12 Load-Strain (Steel) Behavior of Beams with Shear Reinforcement. In the Figure, SG3 and SG4 Imply Readings of Strain Gauges Attached to the Centres of Longitudinal Reinforcement and Shear Reinforcement Respectively

In general, it was observed that modified beams (i.e., those containing 1.5% PET fibres and 5% high calcium (CaO) volume BGWA) exhibited incomparable strain responses compared with those of the conventional beams and did not achieve the same ultimate loads as those of control beams. In Figure 12, it is also observed that all the beams initially maintained approximately a constant flexural strain as the load increased. In Figures 11 and 12, stress relaxations can also be observed for both control and modified concrete beams, although their interpretation is not straightforward in this study. Further future research on stress-relaxations of modified beams using stress-relaxations tests is proposed.

3.5. Cracking modes and failure patterns of beams

3.5.1. Findings of Beams Tested without Shear Reinforcement

Figures 13 and 14 show the physical failure pattern of beams without shear reinforcement. At the initial stages of loading, the diagonal cracks began to develop as the load increased. The diagonal cracks propagated from the mid-height of the beams towards the support or the loading point, and a sudden failure was observed after the maximum load was attained. Shear–compression failure near the support or loading point was observed for both the control beams and modified beams. It was also observed that PET fibres and BGWA added to the modified beam affected the failure pattern and enhanced the beam's tensile stresses.

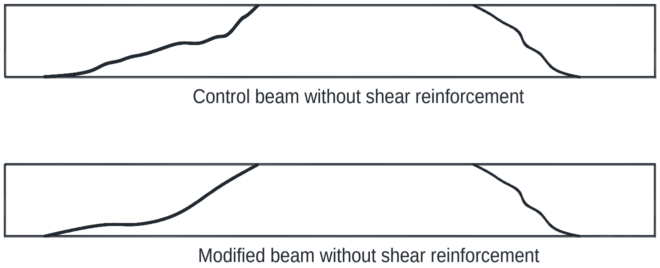

Fig. 13 Crack Distributions at Failure

The experimental results for both beams without shear reinforcement in Figures 13 and 14 show the cracks formed for both the control and modified beams. The initial cracks occurred along the beam parallel to the force applied.


Fig. 14 Failure Pattern of Control Beam (Top) and Modified Beam (Bottom) without Shear Reinforcement

After that, the sliding failure suddenly occurred after the ultimate load was attained. It was noticed that diagonal tension cracks occurred for both control and modified concrete beams. The diagonal cracks were observed to be propagating towards the loading vicinities. No significant flexural cracks were observed for the beams without shear reinforcement, and the beams failed in shear entirely. It is known that concrete shear failure (diagonal tension) is naturally brittle and sudden [37]. Diagonal tension failure of concrete beams with tensile (flexural) reinforcement only undergoes sudden failure with or without any warning. In this study, both beams in Figure 14 failed in shear, indicating that the absence of shear reinforcement was the cause of such failure. Together with findings from the load-deflection graphs, the inclusion of PET and BGWA in concrete beams increased the ductility of the beams. In addition, the findings in Table 2 also prove that modified concrete developed increased flexibility compared with control concrete.

3.5.2. Findings of Beams Tested with Shear Reinforcement

Figures 15 and 16 show the failure patterns of beams with shear reinforcement. The flexural cracks were observed in the initial stages of load application in the pure bending vicinities. As loading increased, beams with shear reinforcement (stirrups) exhibited very small shear cracks for both the control and modified beams. The observed failure mode was mainly flexural in nature, and it was anticipated due to the incorporation of the stirrups. The utilisation of shear reinforcement obviously prevented significant shear cracking close to the supports, unlike the beams without shear reinforcement previously discussed. It is reported that shear reinforcements transfer stresses between shear cracks, thereby preventing shear failure, increasing strength and increasing flexibility [38]. Another important observation was that the modified concrete beams illustrated branched cracks compared with control concrete beams. In another study [39], the failure mode of beams shifted from flexure to flexure-shear due to the incorporation of carbon fibre-reinforced polymers (CFRPs) and basalt fibre-reinforced polymers (BFRPs) bar specimens. The probable reason, according to the authors, was the use of fibre-reinforced polymers (FRPs) stirrups which were not able to resist cracking due to low modulus of elasticity.

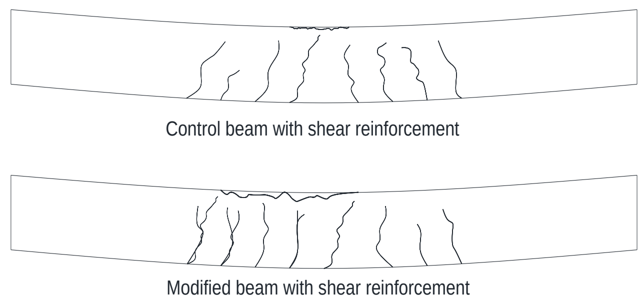

Fig. 15 Crack Distributions at Failure


Fig. 16 Failure Patterns of the Control Beam (Top) and Modified Beam (Bottom) with Shear Reinforcement

Figures 15 and 16 show that multiple flexural cracks were experienced for the modified beams compared with the control beam. In addition, the crack widths for the modified beam seemed to decrease compared to the control beam. The probable justification for the reduced crack width phenomenon in modified concrete could be the role of PET fibres in stitching the cracks developed, thereby delaying their widening. In addition, the high content of CaO in BGWA was speculated to have increased the bonds during an interaction between cement and BGWA, resulting in reduced crack width. The findings of high CaO content in BGWA leading to strong bonds in stabilized marine clay in another study [11] support this observation. In the previous study, cement replacement with 5% wood ash was observed to improve cohesion, unlike replacements beyond 5%.

Therefore, as long as cement replacements with BGWA remain minimal, BGWA does not cause weak bonding in cement-based composites. Although the beams were designed for flexural load, the flexural failure seemed slightly changed to flexure-shear failure throughout the loading process. In conjunction with enhanced deflection findings of modified concrete compared with control concrete previously explained, these findings extend the probable applications of concrete modified with PET fibres and BGWA in seismic applications. It is also worth noting that the compression zone of modified concrete suffered from an increased degree of concrete crushing compared to control concrete. It could be attributed to the enhanced deformation capacity of modified concrete beams under loading, resulting in increased strains.

3.6. Flexural Strength of Beams

The maximum loads achieved by the specimens were recorded, and the flexural strengths were calculated for both modified and control concrete beams using Equation 2.

$$\mathrm{fb} = \frac{\mathrm{PL}}{\mathrm{bd}^2} \tag{2}$$

Where *f*b is the flexural strength in MPa, P is the maximum load in N, L is the supported length in mm, b is the thickness of the specimen in mm and d is the depth of the specimen in mm.

The flexural capacities were determined using the maximum loads recorded for both the control and modified concrete beams. The calculated flexural strengths for control and modified concrete beams were 16.7 MPa and 25.5 MPa, respectively. The flexural strength of the modified concrete beam increased compared with the control beam. A probable reason for the increased ability of the modified beam to withstand failure in bending was believed to be the addition of PET fibres to the concrete mix, which might have played a role as a reinforcing material. BGWA, as a partial cement replacement, has also been observed to promote bonding in cement-based composites elsewhere [11]. Because of this, cracks that formed at the initial stages of loading were prevented from widening. The findings in this study demonstrate that the test methods used were satisfactory.

3.7. Comparison of Shear Strength Behavior of Beams

The shear strengths for beams without shear reinforcement have been summarized in Table 4. From Table 5, the shear strengths for the beams with shear reinforcement are tabulated. The experimental results illustrate that the ultimate shear load for beams with shear reinforcement was relatively higher than those without shear reinforcement. It translated to the development of maximum shear strengths for beams with shear reinforcement compared to those without shear reinforcement.

Additionally, the moment capacities of all the beams were determined as the ratio of the ultimate shearing moment, Mu to the flexural moment, Mf. Flexural moment and ultimate shear moment were calculated using Equations 3 and 4.

$$Mf = 0.15bd^2fcu \tag{3}$$

$$Mu = Pmax\ a_v/2 \tag{4}$$

Where fcu is the compressive strength of the concrete as determined by the 28 days cube strength of the specimen, b is the breath of the beam, d is the effective depth of the beam specimen, $Pmax/2$ is the maximum shear load of the beam calculated as half of the maximum applied load and a_v is the clear shear span of the beam.

Tables 4 and 5 also show that the experimental ultimate shear moment increased for the modified beam, i.e. with 1.5% PET fibres and 5% BGWA as a partial cement replacement. It was observed that the modified beams illustrated increments in shear loads. The values for design concrete shear Vc were calculated by Equation 5 under the standard [27].

$$\mathrm{vc} = \frac{0.79}{\gamma\mathrm{m}}\left(\frac{100\mathrm{As}}{\mathrm{bvd}}\right)^{1/3}\left(\frac{400}{\mathrm{d}}\right)^{1/3} \tag{5}$$

Where γ_m is the material factor for concrete taken as 1.25, d is the effective depth of the beam, b_v is the breath of the beam, and As is the area of reinforcement. For concrete mixes with a compressive strength greater than 25N/mm², the value in Equation 4 was multiplied by a factor $\left(\frac{\mathrm{fcu}}{25}\right)^{1/3}$ where f_{cu} is 28 days compressive strength of the concrete mix under the standard [27].

The concrete shear contribution, Vc was observed to decrease for the modified beams with 1.5% PET fibres and 5% BGWA for beams with and without shear reinforcement. This could be owed to the fact that the strength of the mixes reduced as cement was replaced with BGWA. However, the percentage reduction in concrete shear contribution was 6% for the beam without shear reinforcement and 7.8% for the beam with shear reinforcement. These percentage reductions were calculated compared to the concrete shear contribution of control beams. Other authors [40] concluded that the shear behavior of conventional-strength RC beams and ultrahigh performance fibre-reinforced concrete (UHPFRC) layers were affected significantly by the change in the shear span-to-depth ratio. However, the influence of the shear span-to-depth ratio is not reflected in current design code equations. Accordingly, design formulas are proposed for estimating the shear performance of conventional-strength RC beams and UHPFRC, considering the influence of the shear span-to-depth ratio.

Table 4. Shear Strength Behaviour of Beams without Shear Reinforcement

Specimen Type	Beam L/ eff L, m	a_v/d, d=161mm	Average Cube Strength at 28 Days MPa	Ultimate Shear Load, kN	Flexural Moment, Mf, kNm	Ultimate Shear Moment, Mu, kNm	Moment Capacity, Mu/Mf	Shear Limit, N/m^2	Vc N/m²	Vc+0.4, N/m²
Control Beam	2/1.8	3.11	31.61	24	18.44	6	0.33	3.54	0.50	0.9
Modified Beam (1.5% PET & 5% BGWA)	2/1.8	3.11	24.91	36	14.53	9	0.62	3.54	0.46	0.86

Table 5. Shear Strength Behaviour of Beams with Shear Reinforcement

Specimen Type	Beam L/ eff L, m	a_v/d, d=161mm	Average Cube Strength at 28 Days MPa	Ultimate Shear Load, kN	Flexural Moment, Mf, kNm	Ultimate Shear Moment, Mu, kNm	Moment Capacity, Mu/Mf	Shear Limit, N/m^2	Vc N/m²	Vc+0.4, N/m²
Control Beam	2/1.8	3.11	31.78	36	18.53	11.5	0.62	3.54	0.51	0.91
Modified Beam (1.5% PET & 5% BGWA)	2/1.8	3.11	25.6	48	14.93	22	1.47	3.54	0.47	0.87

4. Conclusion

The experimental findings of control and modified concrete beams with or without shear reinforcements are discussed. The following conclusions have been drawn based on the findings presented in this research.

- The ductility increased by 4.8% and 6.3% for modified beams with and without shear reinforcement, respectively, compared with control concrete beams. Reinforced concrete beams modified with PET fibres and BGWA are promising candidates for structural members exposed to seismic loads.
- The combination of PET fibres and BGWA in concrete beams with shear reinforcement increased the number of cracks, ultimate loads, and ultimate deflections compared with control concrete beams. This investigated combination continued to increase the number of cracks as the loading increased to ultimate failure loads.
- Using PET fibres and BGWA in concrete beams narrowed the crack width. By comparing modified beams and control beams, the findings illustrated that modified concrete beams had reduced crack width. PET fibres and BGWA were suggested to present successful reinforced concrete mixtures with promising beneficial durability effects in structural members.
- Both flexural and shear capacities increased for reinforced concrete beams containing PET fibres and BGWA compared to control concrete beams. The findings alleviate the lack of information concerning PET fibres and BGWA in concrete beams with or without shear reinforcements.
- Including PET fibres and BGWA in reinforced concrete beams was suggested to create eco-friendly structural concrete members without affecting the concrete's durability and elasticity properties. Utilizing PET fibres and BGWA was concluded to assist in developing sustainable concrete that can accomplish better economical building designs.
- The numerical and analytical studies are not included in this paper. The findings from flexural and shear experiments in this study could provide a novel database which could assist in validating numerical and analytical investigations.

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