Developments in the Built Environment 16 (2023) 100262

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.sciencedirect.com/journal/developments-in-the-built-environment

Experimental and predictive evaluation of mechanical properties of kenaf-polypropylene fibre-reinforced concrete using response surface methodology

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A R T I C L E I N F O

Keywords:
Predicted mechanical properties
Kenaf and polypropylene fibre
Fibre-reinforced concrete
Energy
Response surface analysis

A B S T R A C T

Fibre-reinforced concrete (FRC) is an emerging construction material. However, improving its mechanical properties using sustainable materials remains a concern. In this paper, a combination of experimental and numerical techniques is applied to investigate the combined influence of kenaf (K) and polypropylene fibre (PPF) on the mechanical properties of KPPFRC. The optimal design component of Response Surface Methodology was utilised with combined fibre content between 0.5% and 2%. The results show a general increase in the mechanical properties with KF being the main contributing factor, and corresponding decreases in all responses with the increase in PPF. Nonetheless, the predicted optimal volume fraction of 1.5% consisting of 1.0 kg kF and 0.51 kg PPF gives a 100%, 174% and 100% rise in compressive, split tensile, and flexural strength respectively compared to the control sample. Hence, these optimal proportions of KF and PPF can be utilised as an eco-friendly sustainable material in concrete.

1. Introduction

Concrete has long dominated the construction industry as a popular construction material because of its strength, durability and versatility. However, the evolution of complex construction methodologies has revealed some of its limitations that need to be addressed to meet modern requirements. These limitations include low tensile and flexural strength, which makes it prone to cracking and fracturing under tension. Add to that, the amount of CO_2 emission resulting from the production process of concrete has a high environmental impact. Thus, as part of the effort to actualise sustainable development goals, there have been long-growing concerns about the need for environmentally friendly construction materials with improved properties. In response to these concerns, research efforts have been made to explore the use of industrial, household and recyclable materials as alternative construction materials to foster environmental harmony (Huzhi et al., 2019). While recycled materials are widely accepted as environmentally friendly alternative construction materials (Tahmoorian et al., 2019), they do not seem to address all the raised concerns. In this regard, the use of fibre-reinforced concrete has shown promising characteristics in terms of improving tensile strength, crack resistance and durability (Ahmad and Zhou, 2022; Torgal and Jalali, 2011; Muda et al., 2016a, 2016b). This is

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https://doi.org/10.1016/j.dibe.2023.100262
Received 29 August 2023; Received in revised form 22 October 2023; Accepted 29 October 2023
Available online 6 November 2023

achieved through the use of natural and synthetic fibre as an effective way of utilising environmental waste (Merli et al., 2020).

In addition to poor ductility, regular concrete is prone to structural cracks caused by dry shrinkage which makes it susceptible to potential failure in concrete elements/structures. Conventionally, reinforcement steel has been used to produce concrete with improved tensile strength, commonly termed reinforced concrete (RC). Similarly, the application of fibre to produce fibre-reinforced concrete (FRC) has been practised for decades to achieve the same aim. Unlike in RC, where reinforcing bars are specifically designed for the tensile zone of the structural element, fibres are randomly distributed throughout the concrete (Behbahani et al., 2011).

Generally, randomly distributed fibres in FRC prevent crack spread and expansion into the concrete matrix which enhances the post-cracking ductility of the concrete under static and dynamic loading. The effectiveness of fibre in improving post-cracking ductility depends on its distribution in the concrete, which is influenced by components such as quantity, aspect ratio and shape. Hence, to ensure the selection of a suitable mix design for a specific project, it is important to thoroughly and comprehensively investigate variables that affect post-fracture ductility (Yoo and Banthia, 2019).

1.1. Literature review

Several techniques have been used to enhance the mechanical properties of concrete through the incorporation of single or hybrid fibres. The inclusion of fibrous materials in FRC offers several advantages over conventional concrete, such as improved tensile strength, crack resistance, impact resistance, and durability. Once added in the concrete, the fibres act as a cleavage inhibitor, develops mechanical properties, resists the impact of concrete, and reduce its brittleness (Sanjeev and Nitesh, 2020). FRC's improved properties can reduce the need for conventional reinforcement for both structural and non-structural applications such as tunnel linings, thin overlays, and shotcrete. For this reason, the combined behaviour with other types of concretes for enhanced performance and functionality have been investigated in previous studies. This includes the performance of fibrous material in self-compacting concrete (SCC) (Yehia et al., 2016), high-performance concrete (HPC) (Travush et al., 2018), ultra-high-performance concrete (UHPC) (Hussein and Amleh, 2015), hybrid fibre-reinforced concrete (HFRC) (Banthia and Gupta, 2004), and lightweight fibre reinforced concrete (LWFRC) (Esmaeili et al., 2023).

Furthermore, the effect of various parameters of hybrid fibre in concrete have also been investigated. For instance, One of such studies explored the influence of varying fibre sizes on the compact capacity of FRC (Aydin, 2007). The study hypothesized that by increasing the amount of paste in a concrete mixture, it is possible to achieve higher self-compressive capacity in concrete containing adequate fibre size and dosage while maintaining high workability. Also, another study found that the length and amount of fibre as well as the use of basalt strands can reduce concrete workability and increase the rupture coefficient (Iyer et al., 2015). In a related study, the impact of combining shredded drink cans and steel fibres of varying volume fractions on the mechanical properties and impact resistance of concrete was presented (Syamsir et al., 2020). The study recorded improvement in concrete strength, particularly in terms of compressive strength, bending strength, and indirect tensile strength. Furthermore, the impact resistance of fibre-reinforced concrete was also reported to have improved compared to the normal concrete.

The Mechanical properties of kenaf and kapok Fiber Reinforced Hybrid Polyester Composite as documented by Bhambure et al. (2023) demonstrates improvement in tensile and impact strength of hybrid composites with equal contribution of kenaf and kapok fibre reinforcement. The study also highlights that increasing kapok fibre content resulted in decreased bending strength and bending modulus of the composite, providing insights into the relationship between fibre content and mechanical strength. Another study compared the tensile properties of kenaf fibre-polypropylene composites with other natural and synthetic fibre composites (Saad et al., 2022). The study highlighted the superior performance of the kenaf-polypropylene system. It also presented the potential for improving composite toughness through hybridization strategies by combining optimised kenaf fibres with other natural or synthetic fibres.

In an experimental study on the mechanical properties of hybrid (steel-kenaf) fibre reinforced concrete, it was reported that incorporating hybrid fibres in concrete mix significant improve the compressive, tensile and flexural properties of concrete by approximately 50%, 53%, and 46% respectively, compared to using just one type of fibre (Mohsin et al., 2023). Similarly, steel-kenaf fibres were also found to improve the compressive and flexural strength of concrete. In particular, specimens with 2% hybrid fibres showed better flexural performance and exhibited better failure behaviour than specimens without fibres.

Another study investigated the impact of incorporating hybrid steel-polypropylene fibres on the mechanical properties of high-strength concrete. The study reported similar improvements in the compressive, tensile, and flexural strength of the concrete compared to using just one type of fibre. Furthermore, the resulting concrete exhibited higher residual compressive strength when exposed to high temperatures by maintaining 87%, 65%, and 42% of its initial strength at temperatures of 200 °C, 400 °C, and 600 °C, respectively. In contrast, control specimens without fibres could only tolerate temperatures not exceeding 200 °C after which it experience explosive thermal spalling (Tawfik et al., 2022).

Similarly, another study explores the use of hybrid fibres (steel and polypropylene) to enhance the mechanical properties of high-performance concrete (HPC). The experimental results demonstrate that the addition of 1% hybrid fibres to HPC improves its strength compared to high-strength concrete (HSC) and single fibres with HPC (Prabath et al., 2022).

The effect of multi-scale polypropylene fibre (PPF) hybridization on the mechanical properties of roller-compacted concrete (RCC) has also been studied. The study examines the compressive strength, splitting tensile strength, and uniaxial tensile test of RCC reinforced with micro-, macro-, and hybrid polypropylene fibres at different ages (3, 7, 14, 28 days). The results show that the incorporation of PPF improves the strength and toughness of the polypropylene fibre-reinforced roller-compacted concrete (PFRCC), with the best performance observed for multi-scale PFRCC. The study also proposes a uniaxial tensile constitutive equation for PFRCC and a fibre hybrid effect function. The findings suggest that micro-PPF primarily strengthens RCC before 7 days of curing, while macro-PPF plays a major role in reinforcing the concrete after that. Overall, the hybridization of three types of PPF positively affects the mechanical properties of RCC (Liang et al., 2022).

Albeit different types of fibres have been studied, the need to explore their combined influence on the properties of fibre-reinforced concrete is crucial to the realisation of sustainable development goals. Four basic fibre classifications have been identified, namely, polymers, metallic, inorganic, and carbon-based fibres (Ranjbar and Zhang, 2020) but have been broadly categorised as natural and synthetic fibres. For this particular study, Kenaf fibre (KF) and Polypropylene fibre (PPF) which are classified as natural and synthetic fibres respectively are considered (Muda et al., 2016b).

Kenaf fibre is a product of the kenaf plant, originally from Africa but with more than 70% produced in South Asia. According to a report, the kenaf plant is produced in more than 20 countries yielding a total of 216,200 tons in 2014 and 2015 (Chu et al., 2021). Kenaf plant has several advantages as a sustainable material, including rapid growth which guarantees high volume production of raw materials within a short period and at low cost. Thus, kenaf fibre is cheaper than glass and carbon fibres, costing 0.53 US$ per kilogram while glass and carbon fibres cost 3.25 US$/kg and 500 US$/kg respectively (Adole et al., 2019). Furthermore, kenaf plants produce 6–10 tons of dry fibre per acre annually, which is four times the amount of fibre produced by pine trees. This is in addition to its high CO2 absorption level and low production energy requirement (EsmaeilpourShirvani et al., 2019).

Due to its high stiffness and aspect ratio compared to other fibres, KF is commonly used as reinforcement in thermoplastic composites. Its tensile strength ranges from 157 MPa to 600 MPa, while the modulus of elasticity and the average ultimate tensile strain range from 12,800 MPa to 34,200 MPa and 0.015 to 0.019, respectively. However, its high-water absorption, low durability and poor fibre-matrix adhesion resulting from the composition of hemicellulose, lignin and pectin have been reported as serious concerns. These issues result in hydrophilic properties making it less compatible to interact with hydrophobic matrices. As a result, kenaf fibre forms a weak bond between the fibres and matrices. On the other hand, polypropylene fibre (PPF) is a synthetic fibre derived from the thermoplastic polymer polypropylene. It is deeply crystalline with high resistance to chemical and bacterial aggressions. PPF is also lightweight, corrosion-resistant, strong and has high stiffness and resistance. Due to its versatility, its industrial applications cover a wide spectrum including construction, textile and automotive.

The inclusion of PPF in a concrete mix is well-known to enhance the concrete's strength and control plastic shrinkage fracture, dry shrinkage stress and increase freeze and thaw resistance. These qualities make it an eco-friendly alternative to steel fibre (Shi et al., 2020). In addition, it has a contrasting behaviour with the kenaf fibre and, thus, can suitably complement its shortcomings when combined in a composite matrix. The inclusion of PPF in concrete has been acknowledged to reduce water permeability by blocking small cracks within a concrete matrix and reducing the proliferation of cracks while also ensuring the controlled pressure spreads to the edge of the crack. Additionally, it increases the bending strength of concrete due to its high modulus of elasticity.

Although studies on the performance of several hybrid fibres including steel, aramid, kenaf and polypropylene in concrete have been conducted, most of these studies especially those containing kenaf and polypropylene have not taken into account the correlational influence that exists between each response. They have mostly focused on lightweight, foamed concrete, mortar and plaster. Thus, considering the need for the utilisation of sustainable material in structural concrete, this paper aims to bridge that gap by exploring the influence of variation of kenaf and polypropylene volume fraction on the mechanical properties of concrete. The goal is to leverage the outstanding properties of kenaf fibre and enhance them with PPF to improve the loading capacity, ductility, split tensile strength and flexural strength of structural concrete at an optimised content by utilising the flexibility of the response surface methodology in the design expert software.

2. Material and experimental methods

2.1. Material

Material and testing procedures in this study are performed according to the provisions of the ASTM standards.

Grade 35 concrete made with Ordinary Portland Cement (OPC) Type 1 was used in accordance with the specifications of ASTM C150/C150 M. The OPC oxide composition as determined using X-ray Fluorescence Spectroscopy (XRF) is shown in Table 1.

The aggregate used is crushed granite in the range of 4.75 mm–20 mm according to ASTM C33/C33 M, with the fine aggregate making up 60%–75% of the total volume of concrete. Clean water conforming with ASTM C1602/C1602M − 18 was used.

Two types of fibres were considered as reinforcement in the concrete, kenaf fibre (KF) and polypropylene fibre (PPF), classified as natural and synthetic fibres respectively as shown in Fig. 1(a and b). The KF, with 1400 kg/m^3 density was extracted from the kenaf bast strands and cut to 50 mm average lengths.

High moisture absorption and poor adhesion between natural fibres in a composite matrix can create void spaces and weaker joints in a fibre-reinforced concrete matrix (Bhambure and Rao, 2021). Therefore, to address these issues the kenaf fibre was first treated in 6% sodium hydroxide (NaOH) solution for 3 h, rinsed and soaked in water for 24 h, dried in open air for 24 h and then in an oven for 6 h at 80 °C.

Table 1
Chemical composition of OPC.

Oxides	Composition (%)	ASTM C150 Limits (%)
Lime (CaO)	64.54	60 - 67
Silica (SiO_2)	21.28	17 - 25
Alumina (Al_2O_3)	5.60	3.0–8.0
Sulphur Trioxide (SO_3)	2.14	1.0–3.0
Magnesia (MgO)	2.06	0.1–4.0
Iron Oxide (Fe_2O_3)	2.36	0.5–6.0
Alkalies (K_2O, Na_2O)	0.44	0.4–1.3
P_2O_5	0.17	
TiO_5	0.51	
Loss of Ignition (LOI)	0.64	3.0 max

Fig. 1. (a) Processed Kenaf fibre (b) Polypropylene.

This approach has been proven to be effective in improving the performance of natural fibre in concrete. The treated kenaf sample was tested for density and mechanical properties and then cut into the required dimensions. The measured density was used to determine the fibre volume fractions in the mix. The KF was particularly selected for its several advantages including average tensile strength ranging from 157 MPa to 600 MPa, modulus of elasticity and average ultimate tensile strain ranging from 12,800 MPa to 34,200 MPa and 0.015 to 0.019, respectively.

Similarly, Polypropylene was adopted for its exceptionally high tensile strength, high coefficient of expansion and low modulus of elasticity, and its ability to reduce cracks due to its malleability and flexural strength. Previous studies have proven its capability to increase fracture toughness, ductility and resistance to impact.

2.2. Experimental design

2.2.1. Preliminary analysis

The specific gravity of the coarse and fine aggregate samples was determined based on the provisions of ASTM C127-15 and ASTM C128-15 respectively. The distribution of the aggregate sample was determined through sieve analysis, using a vibrating sieve shaker machine to pass a 6 kg aggregate sample through a set of sieves. In each case, the set of sieves is tightly positioned and vibrated for 10 min on the machine.

As indicated in Fig. 2(a), the coarse aggregate passing sieve 20 mm, 10 mm and 4.75 mm was 100%,48.8% and 4.8% respectively with a fineness modulus of 5.464. On the other hand, Fig. 2(b) illustrates a well-graded distribution with uniformity coefficient (C_u), and coefficient of gradation (C_c) of 7.5 and 2.89 respectively.

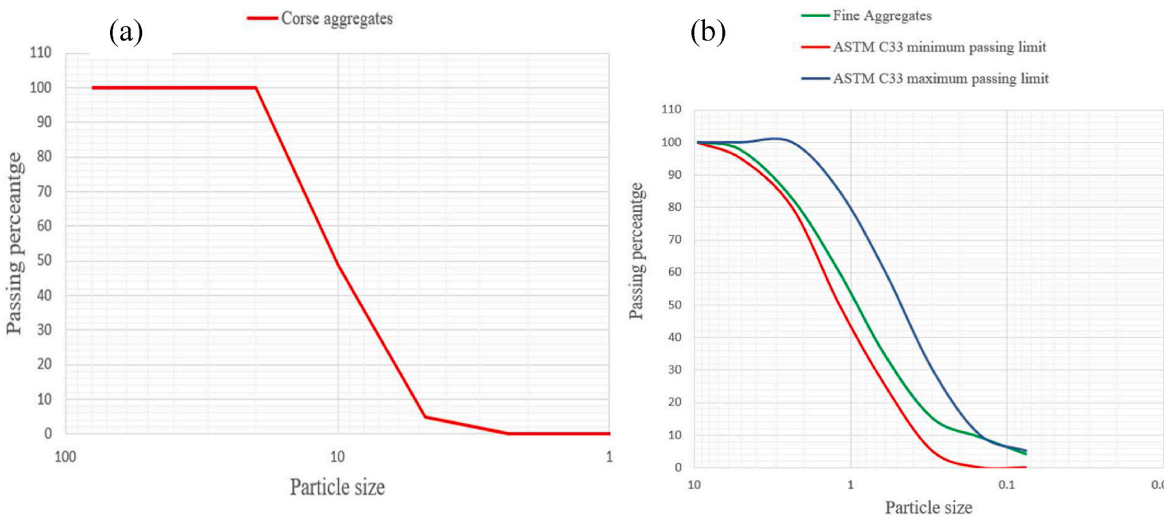

Fig. 2. Grain size distribution (a) Coarse aggregate (b) Fine aggregate.

2.2.2. *Concrete mix design*

The concrete mix used for the experimental investigation consisted of 340 kg cement, 190 kg water, 515 kg fine aggregate and 1385 kg of coarse aggregate in each mix with varying fibre content as shown in Table 2. The control sample is represented as CS while FRC-#% represents the specimen containing varying percentages of combined kenaf and polypropylene fibres. The mix design is according to the ACI 211.1–91 provisions which involve the selection of slump range and corresponding water content, followed by w/c, cement content, and total quantity of aggregate. The quantity of fibre in each mix is calculated as a percentage of the total volume of the sample. In each case, the fibres are added to the mix after achieving an adequately homogenous mix.

Cubes of 100 mm dimension were prepared for the compression test, 100 mm × 100 mm x 500 mm prism are used for flexural tests, while cylinders of 100 mm diameter and 200 mm depth are used for the split tensile test.

2.2.3. *Workability of concrete mix*

The workability of each fresh concrete mix was determined to ensure adequate consistency of the sample using the slump test as highlighted in ASTM C143/C143 M.

Before each slump test, the cone's inner surface was cleaned and moistened with water to allow smooth removal. The conical mould was then placed on a solid truly horizontal surface, filled with concrete in four layers. Each layer was compacted with 25 evenly distributed strokes using an iron rod before adding the next layer. After the final layer, all excess concrete was removed and the surface was levelled. Thereafter, the cone was slighted up gradually and placed next to the concrete sample. With the iron rod placed horizontally across the empty cone and spanning across the displaced concrete sample, the difference in height between the displaced concrete sample and the cone was measured as the slump.

Table 2
Varying fibre content in experimental concrete mix.

Mix design	Kenaf fibre (Kg)	Polypropylene fibre (Kg)
CS	0	0
FRC-0.5%	0.299	0.233
FRC-1.0%	0.598	0.459
FRC-1.5%	0.897	0.688
FRC-2.0%	1.196	0.981

2.2.4. *Mechanical characterization of KPPFRC samples*

For each of the concrete mixes, thirty concrete samples were prepared and cured at room temperature. Three mechanical tests consisting of destructive tests, namely compressive strength test, split tensile strength test and flexural strength test were conducted on each of the hardened concrete samples at 7 and 28 days. Table 3 illustrates the sample specification and schedule of the test. All concrete cubes, prism and cylinders were adequately vibrated to expel trapped air bubbles in the concrete, after which the samples were stored to solidify in the mould under standard laboratory temperature for 24 h. Thereafter, samples were de-moulded, weighed, labelled, and cured in a bath of pure water.

2.2.4.1. Compressive strength test. The compression test on the cube samples was performed following ASTM C109/C109M − 02 using a universal testing machine (UTM) available at the Civil engineering laboratory of the University Tenaga Nasional (UNITEN), Malaysia. The load was gradually applied at a rate of 140 kg/cm^2/min.

2.2.4.2. Split tensile strength test. The tensile strength of concrete is important because it greatly influences the size and extent of cracking concrete structures. Cracks emanate in concrete when the tensile strength exceeds the required limit. Thus, the use of direct tension testing of concrete tensile strength is frowned upon due to its low strength and brittle nature. The test described herein was conducted using a Universal testing machine (UTM) in accordance with ASTM C496 C496/C496M − 17, 2011. Upon complete curing age, each cylindrical sample is removed, air-dried, weighed and pivot lines are drawn on the edge to ensure alignment on the same axis. With the sample drum placed inside the bearing for fixation, and the bearing aligned centrally on the main board of the UTM, the upper crosshead

Table 3
Specimen specification and concrete tests.

Tests	Sample shape and dimension (mm)		No. of samples	Curing age	Reference standard
Compressive strength test	Cube	100*100*100	15 15	7 days 28 days	ASTM C109/ C109 M
Flexural strength test	Prism	100*100*500	15 15	7 days 28 days	ASTM C293/ C293 M
Spilt tensile strength test	Cylinder	150R * 300	15 15	7 days 28 days	ASTM C496/ C496 M

was lowered gradually until contact was established with the sample. Then loading was gradually applied in the range of 0.7–1.4 Mpa/min until failure.

2.2.4.3. Flexural strength test. The flexural test was conducted to determine the bending strength of the concrete as highlighted in ASTM C293/C293 M, 2022. Each concrete sample was positioned horizontally over the loading points, and the load was gradually applied through the sample's upper central surface until failure.

2.3. Prediction models and response surface analysis

The Response Surface Analysis (RSA) is a statistical approach adopted in optimizing a process or product. It involves examining how different component variables interact to influence the outcome. The interactions between variables are represented graphically (response surface) to illustrate how one certain response(s) changes with a variation of one or more variables. The RSA is implemented using several tools including Minitab and design expert software. In this study, the latter, Design-Expert V13:2021 was adopted because of its versatility.

As a globalized technique classified as Response Surface Methodology (RSM), its application includes the development of mathematical models for the prediction of correlation between responses and factors, generation of experimental design and determination of optimum mix proportions by establishing the targets for both responses and factors.

The randomised optimal (custom) design model was adopted for its flexible design structure to accommodate custom models. The mix proportions of input variables, i.e., Kenaf and Polypropylene fibre were generated using upper and lower limits volumetric fractions of 0.266 and 1.197; and 0.233 and 0.689 respectively. Using the regression models developed from experimental results, responses of designed mix proportions were predicted and analysed using linear regression without transformation.

Depending on the relationship between the response(s) and factors a linear or polynomial response model is adopted as shown in equations (1) and (2).

$$f = \beta_0 + \beta_1 x_i + \beta_2 x_{ii} \ldots \beta_n x_n + \varphi \tag{1}$$

where f and x represent the factor x and variable respectively. Also, β_0 is the intercept at $x_i = x_j = 0$, β is the coefficients.

$$f = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j>1}^{n} \beta_{ij} x_i x_j + \varphi \tag{2}$$

where i and j denote linear and quadratic encrypted quantities, and n is the numerical variables.

Analysis of variance (ANOVA) was performed for each response data to establish the mean variability between the experimental and predicted mechanical properties through the measure of statistical significance which must have a 95% confidence level. The statistical significance is determined using the value of probability ($p-$ *value*) being presented as $p-$ *value* ≤ 0.05. In each case the $p-$*value* s, *lack of fits*, *standard deviations*, and adjusted and predicted coefficient of determinations (R_a^2 *and* R_p^2) are evaluated. This is followed by the diagnostic analysis of the correlation between the responses and variables to reveal varying relationships between predicted and actual responses, number of runs and residuals, etc. Finally, the graphical representation of the model responses is generated and analysed.

3. Analysis and discussion

3.1. Workability properties

The average slump values of each concrete mix as shown in Fig. 3 decreases with an increase in the fibre content. When compared with the control sample (CS), a slump reduction of 6.19%, 15.38%, 28.34% and 38.32% were observed with 0.5%, 1%, 1.5% and 2% fibre content respectively. This indicates the influence of the water absorption property of the kenaf as a natural fibre. In addition, this can be generally attributed to the greater surface area created by the combined fibres which tend to attract more cement paste wrapped around the clump fibre thereby restricting the flow of aggregate due to reduced lubrication from the cement paste which is very high to an extent that even admixtures may not help. A similar pattern in concrete workability reduction due to the inclusion of polypropylene and glass fibres (Haddaji et al., 2021), Sisal and Coconut fibres (Wongsa et al., 2020) and polypropylene, alkali-resistant glass, and lignin fibres (Su et al., 2019) have been reported. Abbas et al. (2023), also reported a similar trend with kenaf fibre in geopolymer concrete. Nonetheless, despite the high slump reduction, reduction in bleeding and separation in concrete constituents have been observed. However, further studies intended to explore ways of improving slump retention while ensuring adequate workability.

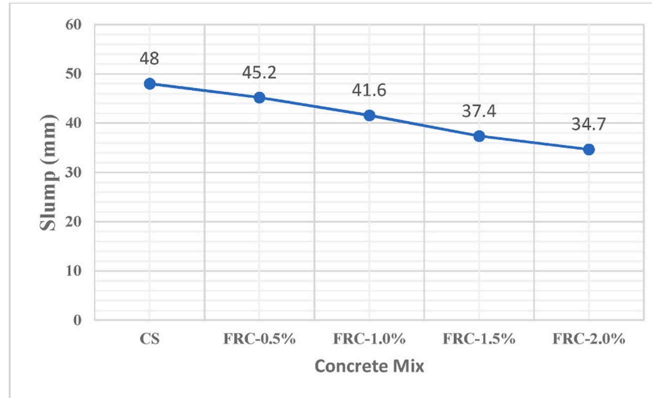

Fig. 3. Variation of slump with fibre content.

3.2. Mechanical properties

3.2.1. Compressive strength

Fig. 4 compares the average compressive strength of concrete samples reinforced with kenaf and polypropylene at 7 and 28-day curing ages.

The experimental test results show fluctuations of compressive strength at both 7 and 28 days for the fibre volume fractions investigated under the same curing condition. When compared with the control sample having compressive strengths of 20.81 N/mm^2 and 35.6 N/mm^2 at 7 and 28days, all samples containing fibre yield lower compressive strengths except at 1.5% fibre content where the optimum compressive strength was recorded with an average increase of 3.97% and 1.68% (i.e., 21.67 N/mm^2 and 36.21 N/mm^2) at 7 and 28 days respectively. Nonetheless, an increase in compressive strengths was observed in samples containing varying fibre contents (i.e., 0.5%, 1.0% and 1.5%) with values of 19.65 N/mm^2, 20.58 N/mm^2 and 21.67 N/mm^2 at 7 days and 32.24 N/mm^2, 34.64 N/mm^2, 36.21 N/mm^2 at 28days respectively, with a decrease in compressive strength observed in samples containing 2% fibre content.

The reduction in compressive strength can be attributed to factors like the dominant characteristics of kenaf fibre, which as a hydrophilic fibre has higher water content to achieve adequate workability and in turn, affect the average compressive strength (Brown et al., 2002; Mehta and Monteiro, 2014; Bagherzadeh et al., 2012). On the other hand, the hydrophobic nature of the collated polypropylene fibre used must have compensated the shortcoming of the kenaf fibre through the creation of an improved mechanical bond between the fibre matrix thereby resulting in the gradual increase in the compressive strength (i.e., from 0.5% to 1.5% fibre content). Thus, the experimental result suggests that

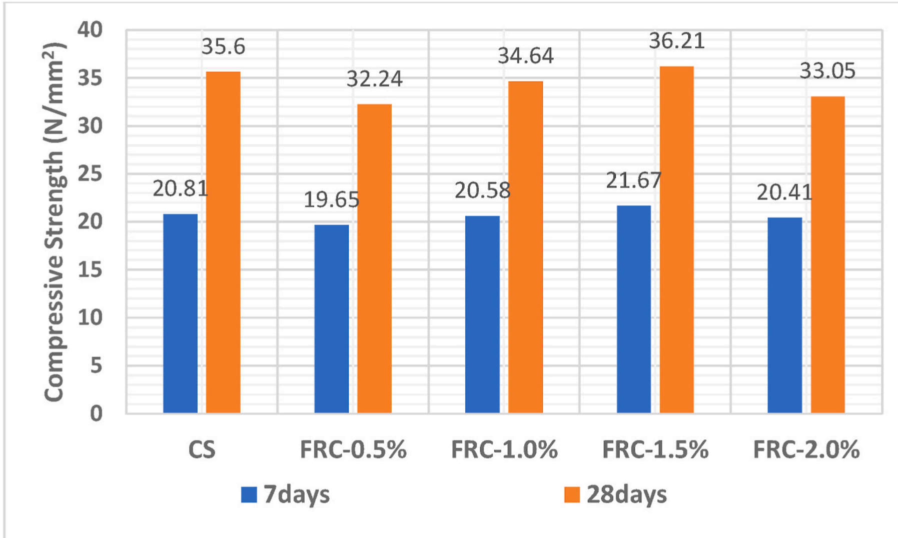

Fig. 4. Compressive strength at 7 days with varying percentages of kenaf and polypropylene fibre.

the inclusion of kenaf and polypropylene indicates no significant influence on compressive strength.

3.2.2. *Split tensile strength*

Thirty cylindrical concrete samples, three samples for each mix design were subjected to split tension loading according to ASTM C496/C496 M standards at 7- and 28-day curing ages. The experimental results as shown in Fig. 5 show a continuous increase in the split tensile strength, unlike what was observed in the compressive strength. This was anticipated because of the combined contribution of the kenaf and polypropylene fibres. The increase is attributed to the ability of the fibres to bridge the crack in the tension zones (Gholampour et al., 2022; Mohammadhosseini et al., 2018). Upon splitting, the bridging effect of the fibre strands at the crack zone tends to transfer the stresses from the concrete matrix to the fibres thereby increasing the tensile strain capacity of the concrete matrix and consequently the tensile strength of the fibre-reinforced matrix. The increase in split tensile strength is consistent with the increase in fibre content as well as the curing age.

At 7 days, the optimum split tensile strength was at 1.5% fibre content, with a 21.51% increase compared to the control sample. A continuous increase is similarly observed with increasing fibre content in the following order, 17.9%, 19.33% and 18.88% with 0.5%, 1.0% and 2.0% fibre content respectively. In each case, all samples with volume fibre content had higher split tensile strength than the control sample.

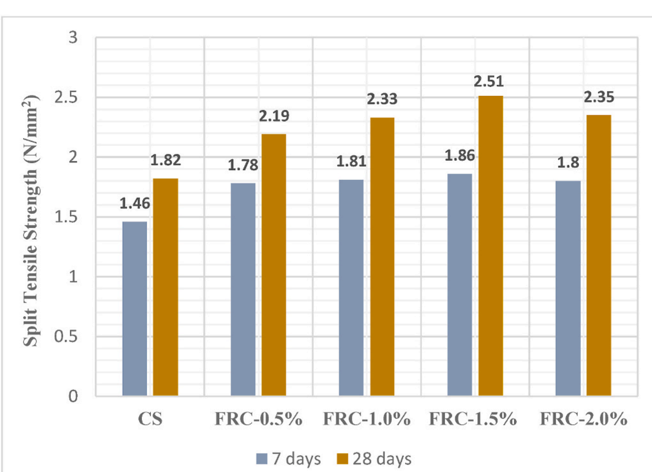

Fig. 5. Split tensile strength at 7 and 28 days with varying percentages of kenaf and polypropylene fibre.

A similar trend is observed at 28-day as shown in Fig. 5 with the highest split tensile strength obtained at 1.5% fibre as 2.51 N/mm^2, which is 27.5% higher than the control sample. At 0.5%, 1.0% and 2.0%, an increase of 22%, 17% and 23% were recorded compared to the control sample. This contrasts with the compressive strength results, where all fibre volume fractions considered had lower compressive strength than the control sample, except at 1.5%. The improved split tensile strength is significant and impressive.

Furthermore, at both curing ages, the inclusion of 2.0% fibre content caused a slight drop in split tensile strength to 1.81 N/mm^2 and 2.35 N/mm^2 which is 2.7% and 6.5% at 7 days and 28days respectively when compared with split tensile strength at 1.5% fibre volume fraction. The decrease here is attributed to the fibre content exceeding the optimum content thereby distorting the fibrous matrix.

Similar fluctuations of split tensile strength in FRC have been reported with an increase in fibre volume fractions. For example, an increase in split tensile increase with increasing sisal or jute fibre has been reported followed by a decrease in the strength once the fibre content exceeds the optimum content (Silva et al., 2020). The same trend was also observed with increasing fibre length, which can also be translated into content (Noor Abbas et al., 2023).

3.2.3. *Flexural strength test*

The flexural strength of thirty concrete prism samples was tested using the average load-midspan deflection method according to ASTM C293/C293 M. Fig. 6 compares the Flexural strength of fibre-reinforced concrete samples with varying volume fractions of kenaf and polypropylene fibre at 7 days and 28 days curing ages.

The inclusion of kenaf and polypropylene fibres in the concrete can be seen to have significantly enhanced the flexural behaviour at all volume fractions of the fibre content considered as well as the curing ages.

With increasing fibre volume fractions, the improvement of flexural strength at 7 days is significant, with the highest being 7.75 N/mm^2 at 1.5% fibre content which is equivalent to 17.45% higher than the control sample. Similarly, values of 6.87 N/mm^2, 7.23 N/mm^2 and 7.19 N/mm^2 were achieved at 0.5%, 1.0% and 2.0% respectively, corresponding to increases of 6.83%, 11.4% and 11% compared to the control sample. A similar trend was observed at 28 days with the highest value of 9.591 N/mm^2 at 1.5% fibre content which is 18.67 % higher than the control sample.

The increase in flexural strength resulting from increasing fibre content is attributed to the interaction of the fibre within the crack at the

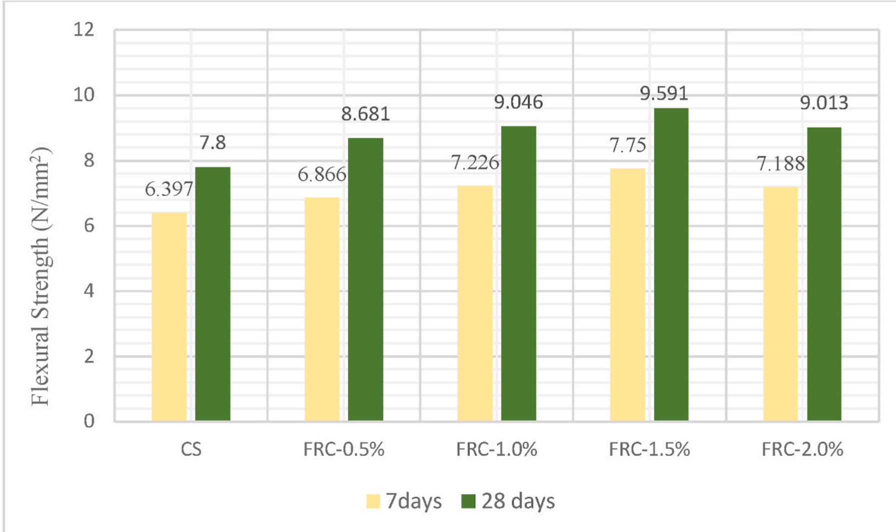

Fig. 6. Flexural Strength at 7 and 28 days with varying percentages of kenaf and polypropylene fibre.

tensile zone of the prism samples which significantly restricts further crack propagation thereby maintaining the concrete surface from stretching. Thereby introducing a relaxation mechanism for the micro-cracks zone. On the other hand, the drop in flexural strength is due to the inclusion of high porosity resulting from nonuniformity in fibre distribution which significantly affects the concrete matrix.

3.3. Response surface methodology

3.3.1. Regression models and predicted responses

Table 4 depicts the predicted 28-day mechanical properties of the kenaf-polypropylene fibre-reinforced concrete. The predictions were based on the actual regression models for compressive strength, split tensile and flexural strength respectively developed from experimental data. All developed models are adequate, having significant p-values <0.05, non-significant lack of fits >0.05, the difference between R^2_{adj} and $R^2_{adj} < 0.2$ with adequate precision values greater than 4.

The predicted responses are represented by Equations (3)–(5) with the compressive strength represented by the linear model and the split tensile and flexural strength by cubic models. The letters A and B represent kenaf and polypropylene fibre respectively.

$$f_{cst28} = 32.39 + 42.32A - 54.28B \tag{3}$$

$$f_{sts} = 2.17 + 4.3A - 5.85B - 0.074A*B + 065A^2 + 0.68B^2 + 18.22A^2B - 22.49AB^2 - 5.13A^3 + 8.87B^3 \tag{4}$$

$$f_{fl28} = 8.27440 + 13.94A - 19.32B + 0.11AB + 1.34A^2 + 3.08B^2 + 57.65A^2B - 71.44AB^2 - 15.92A^3 + 27.7B^3 \tag{5}$$

Table 4
Predicted mechanical properties with varied Kenaf and Polypropylene fibre.

Run No	Variables (kg)		Responses (Mpa)		
	Kenaf	Polypropylene	Compressive strength	Split Tensile strength	Flexural strength
1	0.996	0.538	55.061	3.618	13.106
2	1.196	0.654	59.296	3.896	13.956
3	0.819	0.656	33.600	2.330	9.020
4	0.815	0.974	7.801	0.810	4.162
5	1.196	0.981	33.046	2.350	9.015
6	0.819	0.656	33.600	2.330	9.020
7	0.634	0.781	−18.567	0.975	4.723
8	0.299	0.233	32.335	2.181	8.645
9	0.598	0.495	34.640	2.330	9.046
10	0.496	0.712	7.226	0.731	3.970
11	0.631	0.233	54.823	3.552	12.965
12	0.634	0.781	11.035	0.975	4.723
13	0.819	0.656	33.600	2.330	9.020
14	0.996	0.538	55.061	3.618	13.106
15	0.316	0.233	33.487	2.251	8.866
16	0.897	0.688	36.314	2.510	9.551

3.3.2. Analysis of variance for predicted mechanical properties

The ANOVA results of the fitted model are presented in Table 5 to show the level of significance of each component.

All model components are significant except the term of split tensile and flexural strength. Thus, the non-significant terms were not considered in the adjusted models. The dominance significance of the model terms implies that there is only a 0.01% chance that an F-value of such magnitude resulting from noise could occur. In addition, the difference between R^2_{adj} and R^2_{adj} for all the models are less than 0.2 indicating the validity of the models.

The coefficients estimate represents the expected change in response per unit change in factor value with all other factors remaining constant.

3.3.3. Correlation of KF and PP fibre on mechanical properties

The correlational influences of kenaf and polypropylene fibres on the mechanical properties of hybrid FRC are presented through response surface plots in Figs. 7–9. The higher surface curvatures indicate a greater level of influence between the factors on responses (Shi et al., 2022).

Fig. 7 shows a two-dimensional (2D) and three-dimensional (3D) representation of the relationship between kenaf and polypropylene fibres on the compressive strength of the hybrid concrete. The 2-D plot

Table 5
ANOVA validation for fitted regression models.

Response	Model terms	F-value	p-value	Significance	R^2_{adj}	R^2_{pred}
Compressive strength	Model	37.51	0.0001	Yes	0.8296	0.7451
	A	36.38	0.0001	Yes		
	B	45.77	0.0001	Yes		
Split tensile strength	Model	21779.51	0.0001	Yes	0.9999	0.9920
	A	11756.03	0.0001	Yes		
	B	8998.06	0.0001	Yes		
	AB	8.21	0.0286	Yes		
	A^2	13.18	0.0110	Yes		
	B^2	0.0936	0.7700	**No**		
	A^2B	7580.07	0.0001	Yes		
	AB^2	10835.90	0.0001	Yes		
	A^3	223.99	0.0001	Yes		
	B^3	495.62	0.0001	Yes		
Flexural strength	Model	11204.83	0.0001	Yes	0.9999	0.9824
	A	5939.41	0.0001	Yes		
	B	4646.46	0.0001	Yes		
	AB	4.02	0.0917	Yes		
	A^2	6.50	0.0435	Yes		
	B^2	0.2579	0.6297	**No**		
	A^2B	3877.05	0.0001	Yes		
	AB^2	5585.45	0.0001	Yes		
	A^3	110.29	0.0001	Yes		
	B^3	246.89	0.0001	Yes		

*A = Kenaf, B = polypropylene.

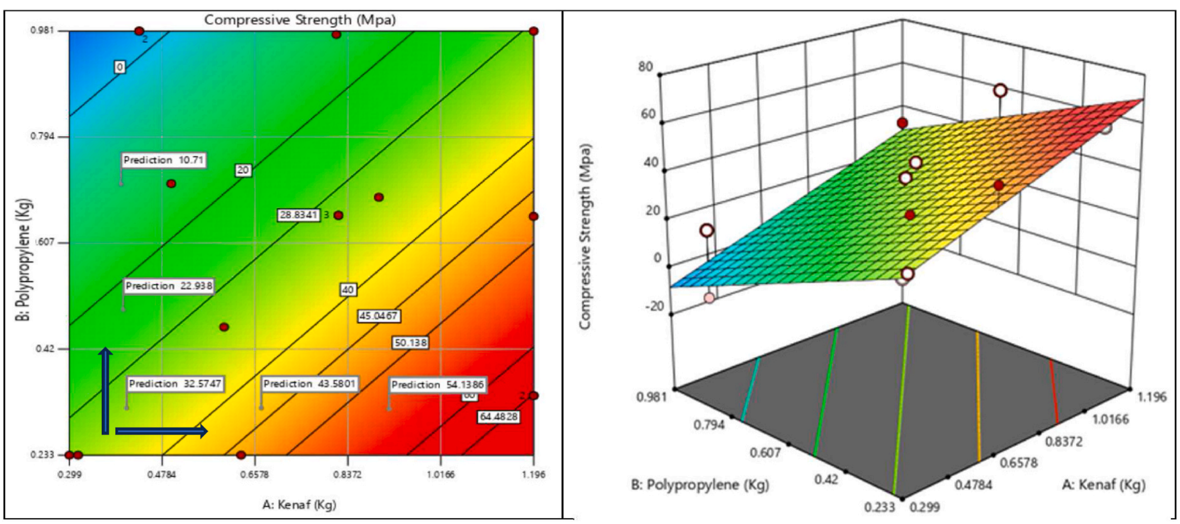

Fig. 7. Response surface plots for the influence of kenaf and polypropylene fibres on compressive strength.

indicates that a higher compressive strength is achieved with kenaf fibre in the range of 0.6578 kg–1.196 kg and polypropylene in the range of 0.233 kg–0.607 kg as illustrated in the red colour region, resulting in a combined volume fraction of 0.891%–1.803% of kenaf and polypropylene. This represents an increase in compressive strength of up to 100% compared to the control sample (i.e., 35.6Mpa).

The 3D plot highlights the instrumental role of PPF in enhancing compressive performance, with an optimal combination of 1.196 kg of kenaf and 0.333 kg of polypropylene. The plot further reveals that while increasing kenaf fibre increases compressive strength, there is a continuous decrease with increasing volume fraction of polypropylene, which implies that a combination of higher kenaf quantity and lower polypropylene provides improved compressive strength. It is worth noting that the relationship detailed here is more elaborate compared to the experimental results.

The correlation observed here reveals an interesting improvement in compressive strength that results from the hybrid complementary relation. This is in contrast to previous studies that have observed a decrease in compressive strength in kenaf-reinforced concrete (Zhou et al., 2020; Md Sadiqul Hasan et al., 2015; Elsaid et al., 2011) and an appreciable increase in polypropylene fibre-reinforced concrete (Zhao et al., 2021; Martínez-Barrera et al., 2014).

Furthermore, unlike the experimental result presented in section 3.2.1 where a maximum increase of 1.68% is recorded at 1.5% fibre volume fraction, containing 0.897 kg of KF and 0.688 kg PPF, the hybrid performance is significantly more effective.

Fig. 8 shows the combined influence of kenaf and polypropylene fibres on the split tensile strength of hybrid concrete. The highest tensile strength is observed when the volume fraction of kenaf is between 0.6578 kg and 1.0166 kg and polypropylene in the range of 0.233 kg–0.70 kg as illustrated in the 2D plot. Conversely, combining kenaf fibre in the range 0.299–0.6578 kg with polypropylene results in a continuous decrease in split tensile strength, as demonstrated by the diminishing green to blue colour in both 2D and 3D response plots. However, the split tensile strength gradually increases at a higher volume of polypropylene.

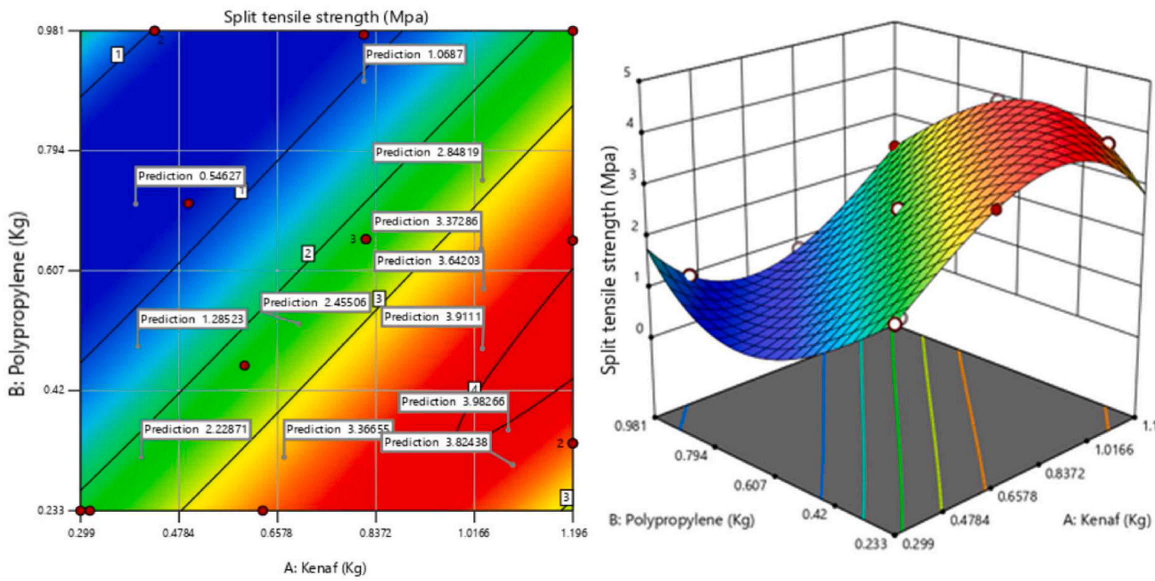

Fig. 8. Response surface plot for the influence of kenaf and polypropylene on split tensile strength of hybrid concrete.

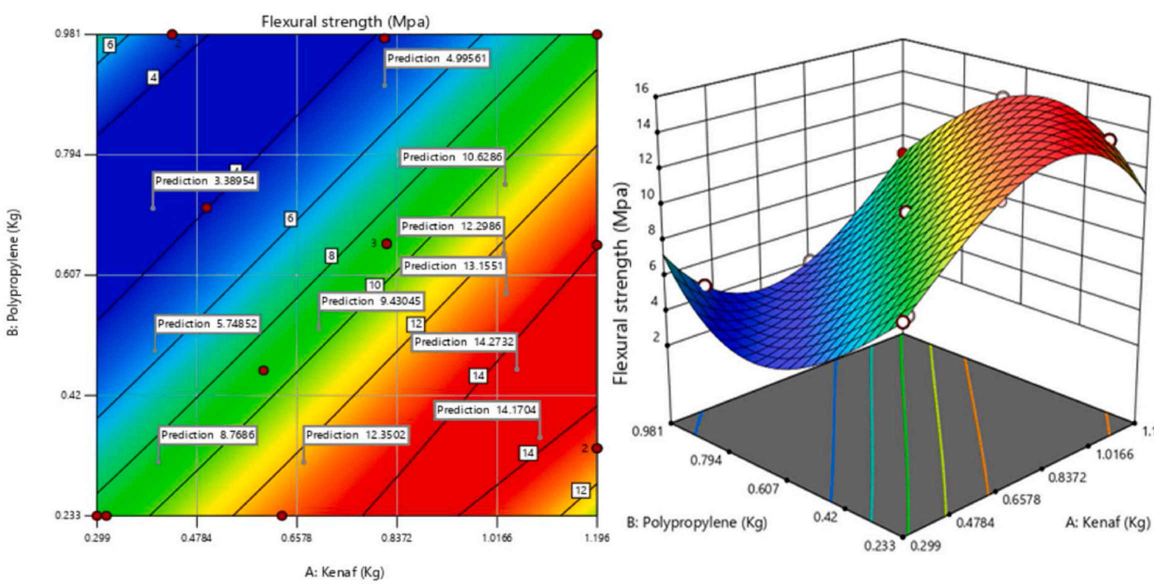

Fig. 9. Response surface plot for the influence of kenaf and polypropylene on the flexural strength of hybrid concrete.

Based on the 3D plot analysis, the best kenaf and polypropylene fibre volume for achieving optimal tensile strength is 1.0166 kg kenaf and 0.42 kg polypropylene. This content results in a tensile strength increase of up to 174% compared to the control sample having 1.46Mpa. The inclusion of polypropylene fibre has been reported to increase the split tensile strength of concrete by up to 40% with a 1%–1.5% proportion but decreases afterwards (Ramujee, 2013; Hsie et al., 2008). The adequacy of polypropylene in reducing crack width, bridging cracks and increasing the concrete toughness is the main reason for its increased split tensile strength in concrete. The high Young's modulus of kenaf has also been reported to contribute to increasing split tensile strength.

Fig. 9 shows the correlational influence of kenaf and polypropylene fibres on the flexural strength of hybrid concrete. The highest flexural strength was attained with kenaf fibre in the range of 0.6578 kg–1.016 kg and polypropylene in the range of 0.233 kg–0.794 kg, resulting in increased flexural strength of up to 100%. The improved flexural strength is attributed to the adequacy of the fibres to prevent the propagation of micro-cracks thereby prolonging the breaking point of the concrete.

3.4. Graphical optimization of kenaf-polypropylene content

The overlay plots as illustrated in Fig. 10a, b and c show individual optimal regions for achieving the most precise compressive, split tensile and flexural strength respectively. In each case, the desirability limit of the responses is one, which is considered the acceptable limit according to the design expert's manual. The optimization adopted in the software is based on the method developed by Derringer and Suich (1980).

Fig. 10(a) highlighted regions of desirable kenaf-polypropylene combinations that will yield compressive strength in the range of 36–60Mpa. The true yellow region represents contour areas within which compressive strength in the described range can be obtained with a 95% confidence interval (CI), while the faded yellow region represents areas out of the described limit. The same can be observed for split tensile strength (3Mpa–4Mpa) and flexural strength (5Mpa–15Mpa) as shown in Fig. 10(b,c) respectively. Moreso, within the CI region

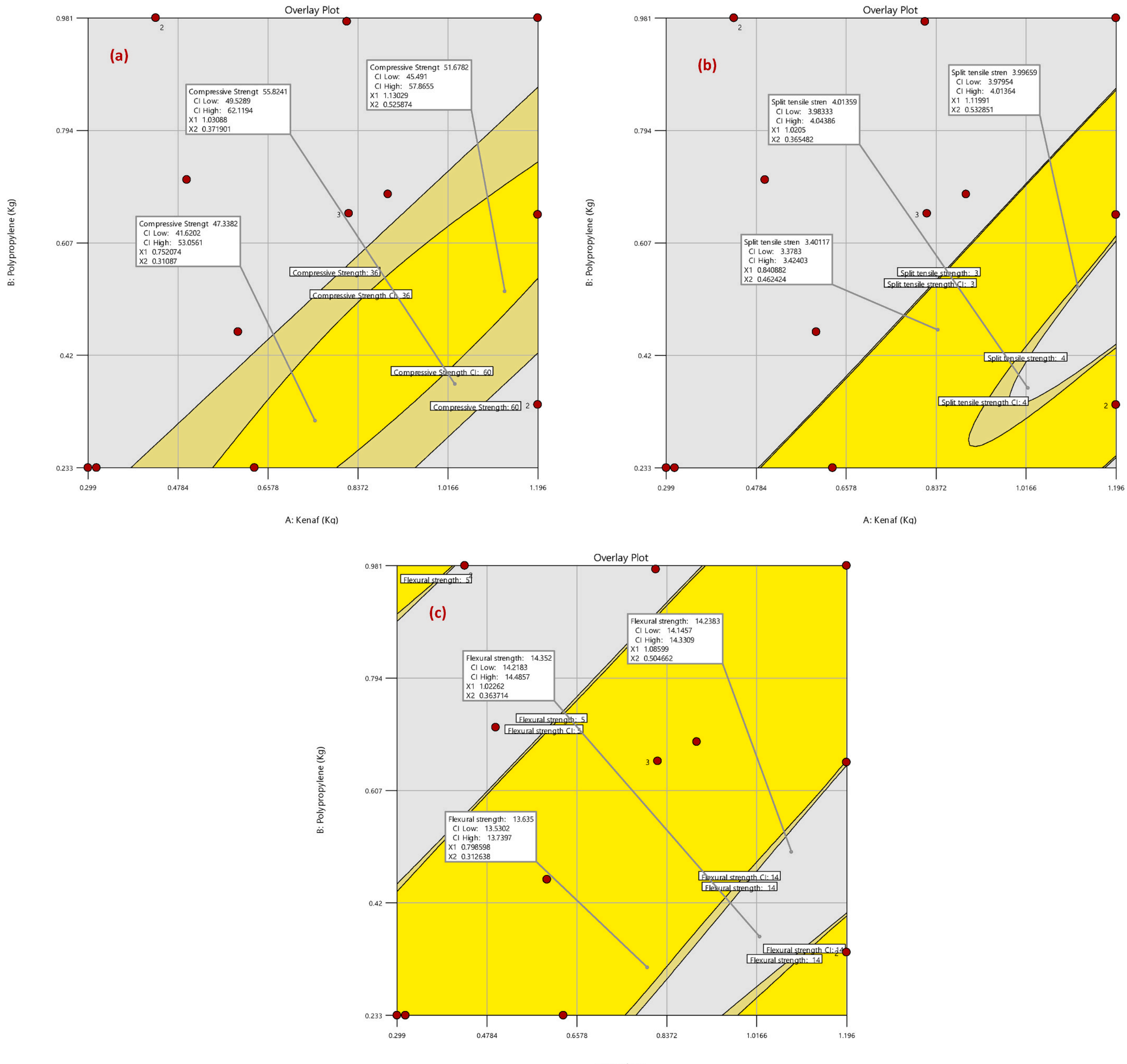

Fig. 10. Overlay plots of predicted responses (a) compressive strength (b) Split tensile strength (c) Flexural strength.

(yellow), up to a maximum of 57Mpa, 3.4Mpa and 13.7Mpa in compressive, split tensile and flexural strength can be respectively obtained using the corresponding fibre content.

Furthermore, Fig. 11 shows a combined graphical optimization plot of the combined responses. It is noted that with 1.51% fibre content containing 1.0 kg kenaf and 0.51 kg polypropylene fibre, responses of 52Mpa, 3.8Mpa, 13.7Mpa equivalent 140%, 104% and 76% increase in compressive, split tensile and flexural strength is achieved. The optimal fibre volume fraction is in strong agreement with the experiment results.

4. Conclusion

A combination of experimental and response surface analysis is used to investigate the combined influence of kenaf and polypropylene fibres on fresh and, mechanical properties of kenaf-polypropylene fibre-reinforced concrete. The study utilised a combined fibre volume fraction ranging from 0.5% to 2.0% in grade 35 concrete. Regression models developed from experimental data were used to simulate the predicted responses using response surface methodology, and an optimised fibre volume fraction was proposed. The results of the study have provided valuable insight into the correlational relationship that exists between the varying content of kenaf and polypropylene fibre on the mechanical and fresh properties of concrete. Based on the findings, the following specific conclusions are highlighted:

- The inclusion of the combined fibre brings about a substantial reduction in concrete bleeding, with a consequent decrease in workability.
- The mechanical properties are directly proportional to kenaf content and inversely to polypropylene.

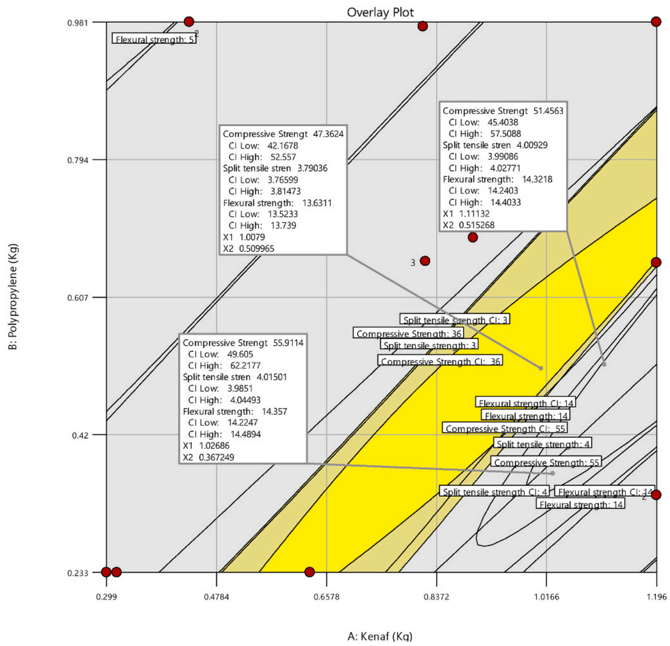

Fig. 11. Graphical Optimised plots of combined responses.

- The inclusion of hybrid Kenaf-polypropylene fibre in concrete contributes significantly to the improvement of the mechanical strength of the Kenaf-polypropylene fibre-reinforced concrete.
- Experimental test is not sufficient for investigating the correlational influence of hybrid fibre in concrete.
- An optimised volume fraction of 1.51% and a significant increase of up to 100%, 174% and 100% in compressive, split tensile, and flexural strength respectively can be achieved with a 95% confidence interval.
- An appropriate proportion of kenaf and polypropylene fibres can be utilised to produce eco-friendly concrete with improved properties.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Bing and Grammarly GO to paraphrase. After using this tool/service, the author (s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

Acknowledgement

The authors are grateful to acknowledge the IRMC UNITEN and the Institute of Energy Infrastructure (IEI) for the lab facilities and financial support provided through Bold Publication Fund "J510050002-IC-6 BOLDREFRESH2025—CENTRE OF EXCELLENCE".

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