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Compressive and Flexural Strengths of Bio-Recycled Concrete Incorporated with Kenaf Fibre

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ABSTRACT

Kenaf fiber (KF) has been applied in concrete to compensate for the weak tensile strength. Similarly, recycled concrete aggregate (RCA) is applied to reduce problems associated with waste concrete materials. However, both KF and RCA reduce the compressive strength (fck) of concrete. This study involves addition of calcite-producing bacillus subtilis bacteria to recycled aggregate concrete (RAC) incorporated with KF. The bacteria is added to concrete with varying proportions of RCA and KF to produce bio-fibrous recycled concrete (BFRC). The proportions of RCA are 0%, 25% 50% and 75% replacement of coarse aggregate, while KF are 0.2%, 0.5% and 1% of concrete. W/C of 0.45, 0.5, and 0.6 are applied to evaluate the effects of different w/c ratios. The properties evaluated are the fck and the flexural strength (ft) of the concrete samples at 28 days. The results showed that 0.2% KF in bio-concrete (BC) increases the fck by 12%; however, increasing above 0.2% decreases fck. KF in BC increases ft by 60%. Furthermore, 0.5% KF content resulted in highest ft of BRC. Increasing RCA content in bio-recycled concrete and BFRC decreases fck by 30% and 33%, respectively, as well as ft by 13% and 18%, respectively.

KEYWORDS

Bio-concrete; recycled concrete aggregate; kenaf fiber; compressive strength; flexural strength

关键词

生物混凝土; 再生混凝土骨料; 红麻纤维; 抗压强度; 抗弯强度

摘要

红麻纤维（KF）已成功地应用于混凝土中，以补偿较弱的抗拉和抗弯强度。同样，再生混凝土骨料（RCA）也被应用于减少与废弃混凝土材料处理相关的问题. 然而，KF和RCA都与混凝土理想抗压强度的降低有关. 本研究涉及在掺有KF的再生骨料混凝土（RAC）中添加产生方解石的枯草芽孢杆菌，以减轻抗压强度损失. 将枯草芽孢杆菌以不同比例的RCA和KF加入混凝土中，生产生物纤维再生混凝土（BFRC）. RCA的比例分别为天然粗骨料的0%、25%、50%和75%，而KF含量分别为混凝土的0.2%、0.5%和1%. 本研究采用0.45、0.5和0.6的水灰比来评估不同水灰比的影响. 评估的力学性能是混凝土样品在28天时的抗压强度（fck）和弯曲强度（ft）. 结果表明，生物混凝土（BC）中0.2%的KF可使fck增加12%，但增加0.2%以上会使fck降低. 在BC样品中加入KF可使ft增加60%. 此外，结果显示0.5%的KF含量导致BRC的最高ft. 此外，增加生物再生混凝土（BRC）和生物纤维再生混凝土（BFRC）中RCA的含量，fck分别降低30%和33%，ft分别降低13%和18%. 这些类型的混凝土适用于具有高弯曲和拉伸应力的结构构件的施工.

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Introduction

The availability of the constituents of concrete has made it a choice material for civil construction. This is coupled with other desirable properties such as durability and strength. Due to these properties, concrete has become a construction choice material, thus making it the second most utilized material on earth. More than 7 billion tonnes of concrete is produced globally every year (Allujami et al. 2022). Owing to this vast quantity of concrete production, two major problems have been on the horizon – greenhouse gases (GHG) production and concrete waste management. In reducing GHG resulting from concrete production, researchers have conceptualized methods of reducing the amount of concrete produced by reducing the quantity of concrete needed for the same job (Sun and Zhang 2021). These methods involve incorporating mineral admixtures into the concrete to increase strength, while reducing the sizes of structural members (Olabamiji et al. 2023). Admixtures such fly ash (Aslam et al. 2023; Wang et al. 2022), silica fume (Mastali and Dalvand 2018; Okashah et al. 2020) and ground granulated blast furnace slag (GGBS) (Liu et al. 2022; Tanwar et al. 2021) in concrete have shown tremendous increment in the strength of concrete. However, production of these admixtures requires large amount of energy, thus leading to increased GHG production (Zahmak et al. 2021). In addition, the use of these admixtures can be cost ineffective as they are very expensive (Kosukhin and Kosukhin 2021; Rath 2022).

Similarly, concrete waste from construction and demolition (C&D) has been managed over the years through the introduction of recycled concrete. Through this, about 70% of C&D concrete waste was recycled in 2020 (Wang et al. 2020). This idea was demonstrated by Allujami et al. (2022) where they showed that recycled aggregate concrete (RAC) with 50% recycled concrete aggregate (RCA) replacement of natural aggregate provided adequate compressive strength for concrete structural members. However, the use of RCA is hindered by poor properties resulting from the attached mortar on the surface around RCA (Shaban et al. 2019). The attached mortar is weak, and thus leads to inadequacies like high porosity, high water absorption (Kou and Poon 2013), low strength properties (Li et al. 2016), and less resistance to external environmental factors (Pedro, De Brito, and Evangelista 2017). In addition, the attached mortar creates a new "interfacial transition zone (ITZ)" in the areas between old and new cement paste matrix (Allujami et al. 2022). Furthermore, only the RCA from source concrete with up to 50 MPa is able to produce RAC with comparable strength to concrete from natural aggregates (Tabsh and Abdelfatah 2009). Adequate usage of RCA faces difficulties of proper selection of source and type to achieve comparable strength so as to allow for structural use (Zhou et al. 2021). Another major concern is that the acceptable performance of RAC remains within certain limits of the RCA replacement ratios that vary based on the type and source of RCA (Tayeh, Al Saffar, and Alyousef 2020).

Recently, the use of microorganisms has been applied by researchers to increase the strength of concrete (Abdulkareem et al. 2019; Akindahunsi, Adeyemo, and Adeoye 2021). These microorganisms use calcite produced via metabolism to fill up tiny voids in the concrete mix that leads to denser mix and increment in strength (Karimi and Mostofinejad 2020). Studies have shown that this increases the compressive strength of concrete by over 25% (Abdulkareem et al. 2019; Nain et al. 2019). Tayebani and Mostofinejad (2019) had the compressive strength of concrete increased by 34% by treating with *bacillus* pasteuri bacteria. Aruwan et al. (2021) showed that the compressive strength of bio-cement mortar increased by 17% when *bacillus Coagulans* was incorporated. Likewise, Parashar et al. (2021) achieved 28% increment in compressive strength via adding *bacillus subtilis* bacteria to clay concrete samples. Huseien et al. (2021) increased the compressive strength of concrete specimens by 30% when effective microorganism (EM) solution was applied to replace a certain percentage of water. Recently, Sharma et al. (2023) showed that the 28-day compressive strength of bacteria-treated RAC was nearly equal to normal concrete, but attain 40% more at 90 days. A study by Vaezi et al. (2020) showed that cement mortar from RCA treated with bacteria achieved 21% increment in compressive strength over normal cement mortar. In addition, the calcination process produces a self-healing phenomenon where cracks in concrete are filled by the calcite produced (Nodehi, Ozbakkaloglu, and Gholampour 2022). Luo et al. (2015) showed the ability of bacteria to heal up crack with width up to 0.8 mm in concrete specimens. Xu et al. (2019) presented an experimental study showing how a self-healing bacteria healed concrete with a 0.86 mm width crack. Evidently, calcite-producing bacteria improve the strength and crack healing properties of concrete.

On the other hand, studies have shown that incorporation of natural fibers increases the tensile strength, cracking resistance and energy absorption of concrete (Abbas et al. 2022; Karimi and Mostofinejad 2020). Kenaf fiber (KF) obtained from the kenaf crop is a typical natural fiber that has been applied in concrete technology and other fields. This is usually achieved by treating in NaOH to decrease its hydrophobic property while increasing the mechanical properties of the produced concrete (Baarimah et al. 2021). The versatility of KF, as shown in Figure 1 indicates that it is economical, eco-friendly and energy efficient (Mahzabin et al. 2018). Addition of KF in concrete not only helps in agricultural waste management of non-wood plants like kenaf but also improves concrete properties. Elsaid et al. (2011) also showed that KF increased the toughness and flexural properties of concrete. This improved the ductility of concrete and exhibited more distributed cracks. These findings were similarly shown by Ghadakpour et al. (2020) when they reported increased ductility in concrete when they added KF content of 0.25% to 0.75%. The drying shrinkage and autogenous shrinkage cracking of cement pastes decreased significantly when Guo et al. (2020) incorporated 0.5% KF. Addition of KF showed that the compressive strength of concrete decreased by about 12.2% to 46.2% as shown by Zhou et al. (2020). Zhang et al. showed that as the KF content in geopolymer concrete increased the compressive strength decreased by approximately 10.7% (Zhang et al. 2021). It was found that the compressive strength of 3D geopolymer concrete composite specimens decreased as the KF content increased (Kong et al. 2022). Recently, Abbas et al. (2023) utilized varying lengths and volumes of KF to improve concrete properties. Their study showed that the splitting tensile strength and flexural strength of concrete increased by 20% and 27%, respectively. However, the compressive strength decreased as the KF quantity increased and as the length of KF increased. Literatures have evidently showed that incorporating KF in concrete is a cheap means of improving certain properties. However, incorporating KF has been shown to decrease the compressive strength of concrete (Babatunde et al. 2018; Lam and Yatim 2015; Mahjoub et al. 2014). Thus, addition of KF increases properties such as split tensile strength, flexural strength, and ductility, while the compressive strength decreases due to increased porosity.

From the above literatures, it is evident that RCA addition to concrete enhances sustainable construction; however, it decreases concrete strength. Similarly, KF in concrete also enhances sustainability and increases the ductility of concrete, but decreases the strength. Thus, this study tends to alleviate the drawbacks (reduction in compressive strength) associated with both RCA and KF by

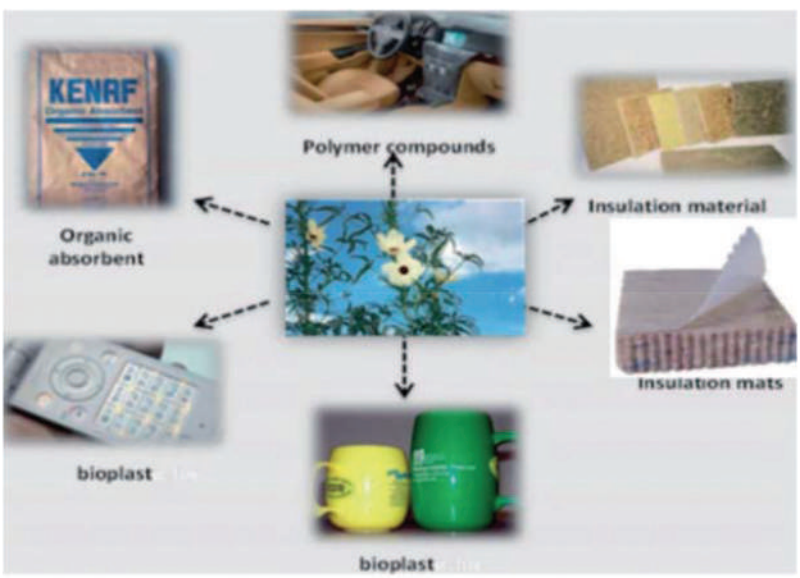


Figure 1. Versatile kenaf applications (Saba et al. 2015).

using calcite-producing *bacillus subtilis* bacteria. I Combinations of varying proportions of RCA and KF are incorporated into concrete with *bacillus subtilis* bacteria using different water-cement ratios (w/c). The proportions of RCA are 0%, 25% 50% and 75% replacement of natural coarse aggregate, and 0.2%, 0.5% and 1% of KF, while the w/c applied are 0.45, 0.5 and 0.6, respectively. The samples are water-cured and the compressive strength (f_{ck}) and flexural strength (f_t) of the concrete samples are measured at 28 days.

Experimental materials

Cement

Ordinary Portland Cement (OPC) that conforms to BS 12 1996 specifications (British Standard Institution 1996) is used as the binder in this research. This OPC is commercially available in local stores and produced by Cement Industries of Malaysia Berhad (CIMA). This is a multi-purpose cement suitable for most concrete works. The chemical constituents and physical properties of the OPC are shown in Table 1.

Fine and coarse aggregate

Well-graded natural river sand is used as the fine aggregate. The fine aggregate has a fineness modulus of 2.8, specific gravity of 2.64 and passed through 600 µm sieve. The coarse aggregate is from crushed igneous rock and has a specific gravity of 2.67. The maximum size of the coarse aggregate is 20 mm. The gradation curves of both fine and coarse aggregates are shown in Figure 2. Both aggregates used in this study conform to BS 882 (Institution 1992).

Bacillus subtilis *bacteria*

Bacillus subtilis spore strain was obtained locally in Kuala Lumpur. A Luria Bertani (LB) broth media solution containing 5.0 g yeast extract, 10 g tryptone, and 10.0 g NaCl in 950 ml water was used to culture the bacteria. The bacteria are inoculated in a laminar flow. A broth culture of *bacillus subtilis* is incubated on a rotatory shaker at 150 rpm and 37°C for 48 hrs. The concentration of the bacteria solution is 10^9 cells/ml. The broth culture is then introduced into the concrete by direct incorporation into the mixing water. Figure 3 shows the bacteria growth and culturing.

The hydrolysis of urea into carbonate and ammonium is catalyzed by urease. One mole of urea is hydrolyzed to 1 mol of ammonia and 1 mol of carbamic acid (Equation 1). It is spontaneously hydrolyzed to another 1 mol of ammonia and carbonic acid (Equation 2) (Hammes et al. 2003).

$$CO(NH2)2 + \mathrm{H2O} Microbialurease NH2COOH + NH3 \tag{1}$$

$$NH2COOH + H2OSpontaneousNH3 + H2CO3 \tag{2}$$

The further equilibration of these two products (NH_3 and H_2CO_3) in water resulted in the formation of bicarbonate (Equation 3) and 2 mol of ammonium and 2 mol of hydroxide ions (Equation 4). The hydroxide ions result in an increase in pH, thereby shifting the bicarbonate equilibrium, resulting in the formation of carbonate ions (Fujita et al. 2008) (Equation 5). This shift precipitates the metal ions.

Table 1. Chemical constituents and physical properties of cement.

	Chemical constituents								Physical characteristics	
Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	NaO	K_2O	SO_3	Colour	Specific gravity
Content (%)	21.3	3.78	3.75	63.8	1.77	-	-	2.88	Grey	3.0

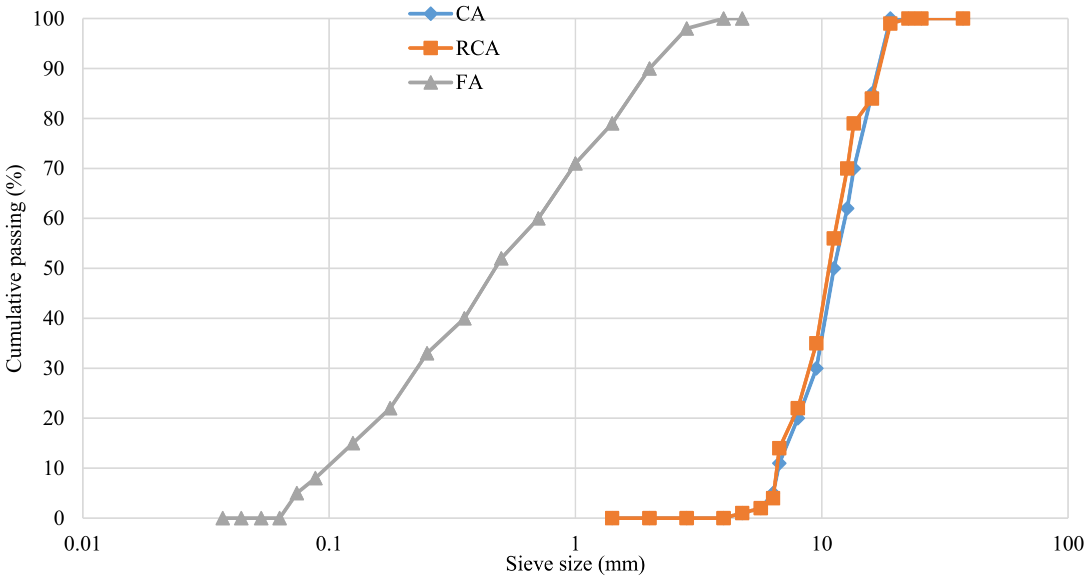


Figure 2. Gradation curves of aggregates.

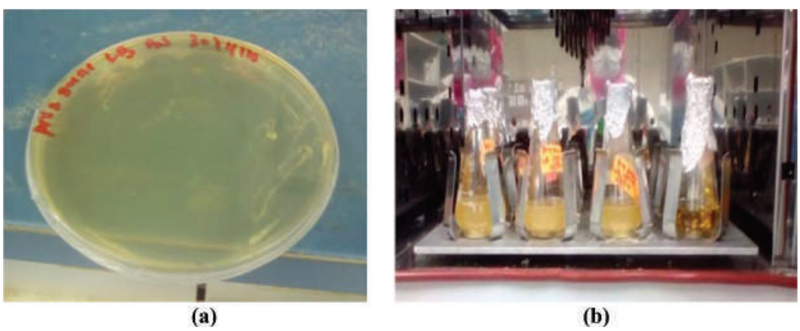


Figure 3. *Bacillus subtilis* bacteria. (a) bacteria growth: (b) bacteria culturing.

The local pH is increased by the formation of NH_4^+ and the reaction continues spontaneously to form calcium carbonate (Mitchell and Ferris 2005).

$$H_2CO_3 \leftrightarrow HCO^-{}_3 + H^+ \quad 3$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH^+{}_4 + 2OH^- \quad 4$$

$$HCO^-{}_3 + H^+ + 2OH^- \leftrightarrow CO^{2-}_3 + 2H_2O \quad 5$$

$CaCO_3$ precipitation occurs at the bacterial cell surface by using the concentration of Ca^{2+} and CO_3^{2-} in solution (Qian et al. 2010) (Equations 6, 7)

$$Ca^{2+} + \text{Bacterialcell} \rightarrow \text{Cell} - Ca^{2+} \quad 6$$

(a) (b)

Figure 4. Materials (a) recycled aggregate (b) kenaf fiber.

$$\mathrm{Cell} - \mathrm{Ca}^{2+}\mathrm{CO}^{2-}_{3} \rightarrow \mathrm{Cell} - \mathrm{CaCO}^{3} \quad (7)$$

Recycled concrete aggregate

The recycled concrete aggregate (RCA) was purchased from a local supplier in Kuala Lumpur. The RCA is derived from construction demolition waste, and has a continuous grading from 4.75 to 20 mm. The specific gravity of the RCA is 2.45, while the water absorption is 3.6. The gradation curve of RCA is shown in Figures 2, 4(a) shows the RCA.

Kenaf fiber

Locally produced and processed kenaf fiber (KF) was purchased from a company in Kuala Lumpur is used in this study. The KF is cut into 50 mm, and treated by using Sodium hydroxide (NaOH) solution to decrease its water sorptivity property and degradation rate (Baarimah and Mohsin 2018; Baarimah et al. 2021). Figure 4(b) shows the treated KF, while Table 2 presents the physical and mechanical properties.

Test concrete samples

The concrete samples used in this research has a mix ratio of 1:2:3 by weight, while the water/cement ratios considered are 0.45, 0.5, and 0.6. The compressive strength test concrete cube samples are 150 × 150× 150 mm, while the flexural strength (f_t) beams are 500 × 100 × 100 mm. A 50 ml of the prepared bacteria (*bacillus subtilis*) spore solution is added to the mixing water. A total of 153 test specimens are made for the experimental tests.

Table 3 shows the proportion (amount) of bacteria, RCA, and KF added to each concrete sample. The concrete samples are casted in molds, compacted mechanically with a vibration machine and demolded after 24 hrs. Thereafter, the concrete samples are cured in a water tank. Figs. 5(a, b) shows concrete cubes and beams samples for the compressive and flexural strength tests, respectively.

Table 2. Physical properties of kenaf fiber.

Physical properties		Mechanical properties	
Length (mm)	50	Tensile strength (MPa)	930
Density (g/cm^3)	1.5	Elastic modulus (GPa)	53
Diameter (µm)	65	Elongation at yield (%)	1.6

Table 3. Mix proportions of concrete.

Notation	Bacteria (ml)	Recycled concrete aggregate (%)	Kenaf fiber (%)
NC	-	0	0
BC	50	0	0
BRC1	50	25	0
BRC2	50	50	0
BRC3	50	75	0
BFC1	50	0	0.2
BFC2	50	0	0.5
BFC3	50	0	1
BFRC11	50	25	0.2
BFRC12	50	25	0.5
BFRC13	50	25	1
BFRC21	50	50	0.2
BFRC22	50	50	0.5
BFRC23	50	50	1
BFRC31	50	75	0.2
BFRC32	50	75	0.5
BFRC33	50	75	1

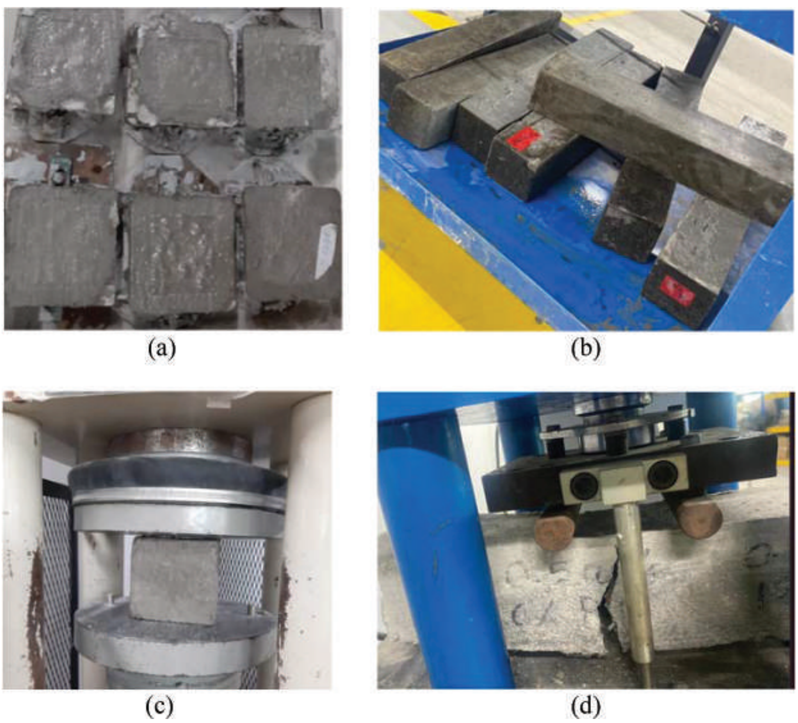


Figure 5. Test concrete sample and testing (a) compressive strength test cubes; (b) flexural strength test beams; (c) concrete cube testing; (d) concrete cube testing.

Testing

Workability, density, and water absorption

The workability of concrete samples is conducted by carrying out slump tests according to GB/T 50,080–2002. A cone frustum mold with a height of 300 mm, and top and bottom openings of 100 mm and 200 mm, respectively. The frustum mold is placed on a flat surface and filled with concrete by three layers. Each layer of concrete is tampered 25 times by using a 16 mm diameter rod. The density of the concrete samples is carried out according to ASTM C 642 (ASTM C642, A 2013). Water absorption test is carried out according to ASTM C 642 (ASTM C642, A 2013) to evaluate the concrete resistance to water penetration through its pores. The test specimens are 150 mm cube, and is carried out at the 28th day. The specimens are placed in an electric oven for 24 hrs at 110°C. The mass of the oven-dried concrete sample is measured and taken as m_d. The concrete sample is then immersed in water for 24 hrs, and removed from water. The water droplets on the concrete specimen are wiped off and the mass is measured and taken as m_w. The water absorption is calculated using Equation 1.

$$w = \frac{m_w - m_d}{m_d} \text{x}100$$

where w is the water absorption.

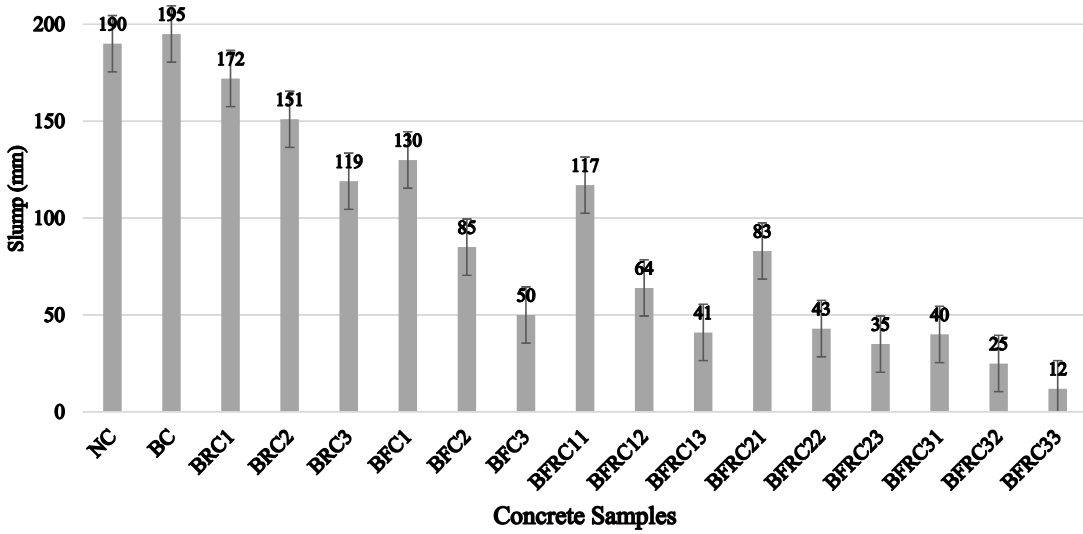
Mechanical properties

The mechanical properties of concrete samples evaluated are the compressive strength (f_{ck}) and flexural strength (f_t). The compressive strength is carried out after 28 days of water-curing according to ASTM C39 by using the universal testing machine. A constant loading rate of 0.6 MPa/s is applied to the 150 × 150× 150 concrete samples. Figure 5(c) shows a concrete sample placed in a universal testing machine that is about to be crushed. The flexural strength test is carried out using the 3-point bending test using the universal testing machine. The loading rate on the 500 × 100 × 100 mm concrete beam samples is 0.05 MPa/s. Figure 5(d) shows a crushed concrete beam sample in the universal testing machine. To reduce the effect of error, the average reading of a set of three samples is recorded as the final reading.

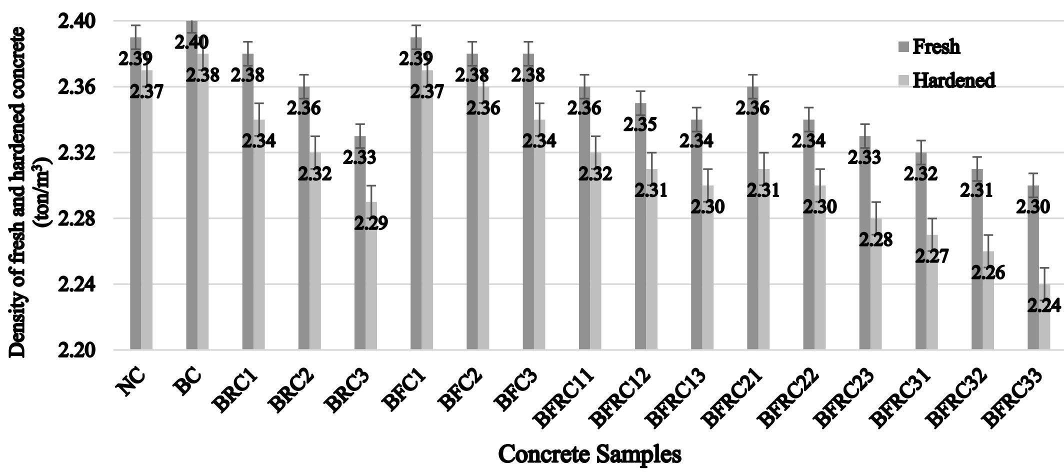
Workability, density, and water absorption results

The workability of concrete specimens is evaluated by carrying out slump test. The slump test value of each specimen at w/c of 0.5 is shown in Figure 7(a). The BC attained a slump value slightly higher (2.6%) than the NC. This increment is due to the constituents in the culture media applied in preparing the bacteria culture (Al-Sabaeei et al. 2022; Alshalif et al. 2022). The LB broth medium added to the concrete delays the polymeric reaction by reducing the molarity of NaOH solution (Rautray, Mohanty, and Das 2020). This results in increased setting and hardening times (Nishanth et al. 2023). On the other hand, the workability of specimens with RCA and KF decreased in workability as expected. This decrease in slump value of BRCs is due high water absorption associated with RCA (Allujami et al. 2022; Bahraq et al. 2022). As the RCA content in BRC increased, the workability of BRC decreased. Similarly, the workability of BFCs decreased (compared to BC) due to the water absorption property of KF (Elsaid et al. 2011; Lam and Yatim 2015). Increasing the KF content in BFCs leads to decreasing workability. The decrease in workability of BRC and BFC with increasing RCA and KF is considered statistically significant ($p < .05$). Furthermore, the addition of both KF and RCA to BC (BFRCs) further decreased workability. Slump values below 50 mm translate to low workability of concrete. In real-world construction process, this low workability decreases the ability of concrete to be mixed properly, transported, placed and compacted, thus, making construction difficult. Furthermore, low workability can lead to low-quality concrete (low strength and high permeability) due to high segregation of aggregates resulting from inadequate cement paste to provide lubrication.

The fresh and hardened densities of the concrete specimens at 0.5 w/c are shown in Figure 6(b). Both fresh and hardened density of the BC specimen were higher than the NC. The slight increment (0.4%) in the fresh BC is due to bacteria culture added during concrete mixing. Similarly, the hardened density increased as a result of calcination from the *bacillus subtilis* bacteria (Kaur, Singh, and Arora 2022). The calcite produced fill up tiny voids in the concrete, thus making the concrete denser. Furthermore, the addition of RCA to BC (BRCs) decreased both the fresh and hardened densities of



(a) Slump value of concrete samples at 0.5 w/c



(b) Densities of concrete samples at 0.5 w/c

Figure 6. Fresh properties of concrete samples at 0.5 w/c (a) Slump value (b) densities (c) water absorption.

the concrete. RCA are light-weighted due to existence of pores from attached mortar, and this leads to a decreased weight of concrete (Sanger et al. 2020). Similarly, the addition of KFs to BCs (BFCs) decreases the densities of concrete. This is due to the lightweight of the added KF and the presence of tiny pores in the bond between the KF and concrete matrix (Razavi 2017). Increasing the KF content in BC leads to decreasing densities of the concrete sample. Lastly, addition of both KF and RCA to BC (BFRCs) leads to further decrement in the densities of the BFRC concrete samples.

Figure 6(c) shows the water absorption of the concrete specimens at 0.5 w/c. The calcination process in the BC specimen decreased porosity that slightly decreases water absorption by 2.3%. This is similar to findings observed in previous studies (Kaur, Singh, and Arora 2022). Water absorption increases with the addition of RCA and/or KF of BC. In addition, increasing the RCA and/or KF contents increased the water absorption of the concrete specimen. RCA increases water absorption due to the high porosity property of RCA due to the presence of attached mortar. Similarly, water

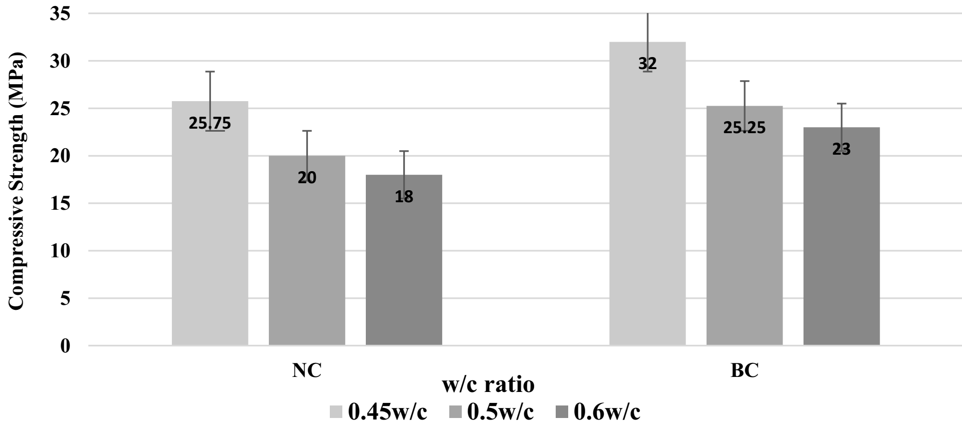


Figure 7. Compressive strength of normal concrete (NC) and bacteria concrete (BC).

absorption increases with KF content because addition of KF increases porosity of the concrete specimen (Yuan and Jia 2021).

The results showed that addition of bacteria increases workability, and setting and hardening times. This benefits field engineers in concrete works where concrete flowability is needed (increased workability), as well as concrete delivering at distant site where longer concrete setting and hardening times are required. The relationship between the hardened density and water absorption of concrete shows that higher density equates to lower water absorption. This simplifies the durability of concrete which reduces the infiltration of chemical compound that deteriorates concrete. These properties are very important in concrete structures in and around marine environment. The reduction in density in BRCs and BFCs is due to the addition of RCA and KF. RCA reduces density because of the pores in the attached mortars in the RCA, while tiny pores are formed between the bond between the KF and the concrete matrix. These pores decrease the strength of concrete and increase the porosity of the concrete. Increased porosity allows fluids (water, CO_2, Sulfate, etc.) to enter into concrete. The presence of these fluids in concrete leads to deterioration of the concrete.

Compressive strength results

The compressive strengths (f_{ck})of concrete samples at the 28th day are presented in this section. The samples are concrete without bacteria (normal concrete – NC); concrete with bacteria (bio-concrete – BC); concrete with bacteria and recycled aggregate (bio-recycled concrete – BRC); concrete with bacteria and KF (bio-fibrous concrete – BFC); and concrete with bacteria, fiber and recycled aggregate (bio-fibrous recycled concrete – BFRC). These results show the effects of bacteria, KF (different percentages), recycled aggregate (different percentages) and different w/c on the f_{ck} of concrete.

Effect of bacteria on the compressive strength of concrete

Calcite-producing *bacillus subtilis* bacteria is added to concrete to improve the compressive strength (f_{ck}). This is evaluated using three (3) different w/c (0.45, 0.55, and 0.6). The measured f_{ck} is presented in Figure 7 showing the values of NC and BC with the three w/c. From Figure 7, the f_{ck} of concrete increased when *bacillus subtilis* bacteria is added to concrete. For example, at 0.45 w/c, the f_{ck} increased by 24% from 25.8 MPa to 32 Mpa. Similarly, at 0.6 w/c, the f_{ck} increased by 28% from 18 MPa to 23 MPa. The *bacillus subtilis* in the concrete produced calcite via metabolism that fills up tiny voids in the concrete. This leads to a denser and more compact concrete, thus increasing the compressive strength (Abdulkareem et al. 2019; Iqbal, Wong, and Kong 2021). The increased f_{ck} provides structural benefit of using smaller structural members during design which decreases the structures overall dead load, thus, reducing the overall construction cost and time. Furthermore, the denser and more compact concrete created by adding bacteria increases the durability of the concrete as the porosity is decreased. Decreased porosity prevents harmful fluids that can degrade the concrete (or cause corrosion) from entering.

In addition, the f_{ck} decreased as the w/c increased in both NC and BC. For example, the f_{ck} of NC decreased from 25.8 MPa to 20 MPa when the w/c is increased from 0.45 to 0.55, while decreasing from 32 MPa to 25.3 MPa in BC. Increased w/c creates more voids in the cement matrix, thus a less compacted concrete is formed. This leads to a decrease of f_{ck} of concrete (Emadi and Modarres 2022; Karimipour, Edalati, and de Brito 2021).

Compressive strength of bio-recycled concrete

In the previous sub-section (5.1), incorporation of calcite-producing *bacillus subtilis*, has shown increment in the f_{ck} of concrete (BC). The results obtained by the addition of different percentages (25%, 50% and 75%) of RCA to the BC to form bio-recycled concrete (BRC) are shown in Figure 8. In Figure 8, the f_{ck} of BC is higher than all the BRC at the three w/c. At 0.45 w/c, the f_{ck} of BC attained 32 MPa, while BRC1 (BRC with highest f_{ck}) has 27.3 MPa. The decrement in f_{ck} is due to the presence of RCA characterized with higher water absorption of the aggregate and the weak residual mortar layer in BRC (Ozbakkaloglu, Gholampour, and Xie 2018).

It can also be seen in Figure 8 that the f_{ck} of BRC decreased as the RCA increased for all w/c. This is seen as the f_{ck} decreased from 27.3 MPa to 23 MPa to 19 MPa as the RA increased from 25% to 50% to 75% when the w/c is 0.45. Similarly, at 0.55 w/c, the f_{ck} decreased from 20 MPa to 18.8 MPa to 16 MPa as the RCA increased from 25% to 50% to 75%. This reduction of f_{ck} of BRC is in agreement with previous studies on RCA (Bhasya and Bharatkumar 2018; Quadir et al. 2016). In addition, the f_{ck} of BRC decreased as the w/c increased at all RCA contents. The f_{ck} decreased from 27.3 MPa to 20 MPa to 19 MPa as the w/c increased from 0.45 to 0.5 to 0.6 at 25% RCA. The decrement in f_{ck} aligns with the decrement observed in NC and BC (Figure 8).

A comparison of results in Figures 7 and 8 shows that BRC1 (BC with 25% RCA) has higher f_{ck} than NC at 0.45 and 0.6 w/c. BRC1 attained f_{ck} of 27.3 MPa and 19MPa, while NC attained 25.8 MPa and 18 MPa at 0.45 and 0.6 w/c, respectively. The f_{ck} of BRC1 and NC at 0.5 w/c are equal (19 MPa). The results in Figure 8 show that the f_{ck} decrement of concrete samples resulting from increased RCA is statistically significant ($p < .05$). These results further show that addition of bacteria to RAC can help to complement the loss of f_{ck} by increasing the f_{ck}.

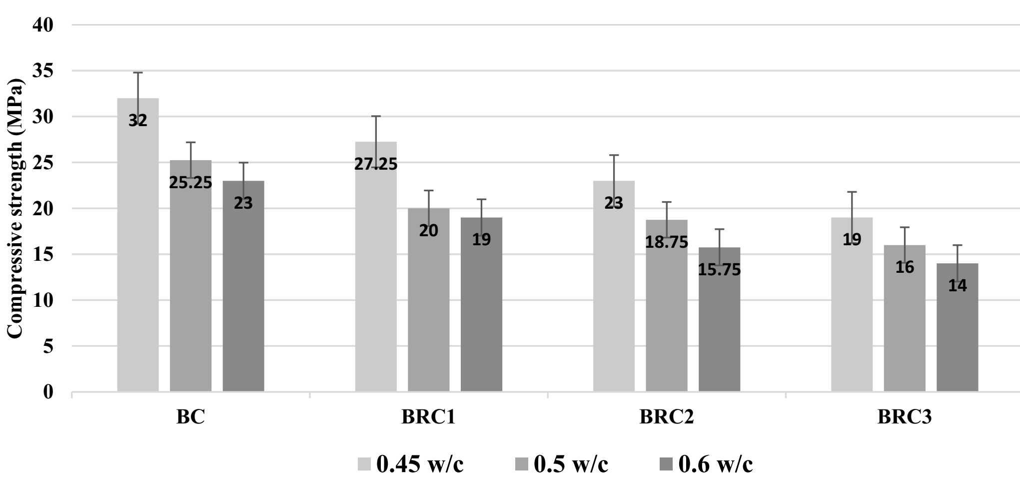


Figure 8. Compressive strength of bio-recycled concrete (BRC).

Compressive strength of bio-fibrous concrete

This section evaluates the effect of KF on the f_{ck} of bio-concrete (BC). The fiber contents in the BC are 0.2% (BRC1), 0.5% (BFC2) and 1% (BFC3). Similarly, the previously applied w/c (0.45, 0.5 and 0.6) remain the same. The f_{ck} of the bio-fibrous concrete (BFC) obtained by addition of fiber to BC is shown in Figure 9, including the f_{ck} of BC without fiber (0%). In Figure 9, incorporation of KF alters the f_{ck} of BFC. The f_{ck} of BFC decreased as the KF content increased in the BFC. At 0.45 w/c, the f_{ck} decreased by 43% from 35.8 MPa to 20.5 MPa as the KF content increased from 0.2% to 1%. Similarly, at 0.6 w/c, the f_{ck} decreased by 36% from 28.3 MPa to 18 MPa as the KF content increased from 0.2% to 1%. The addition of KF to concrete creates a weak interfacial transition zone between KF and cement matrix (Çomak, Bideci, and Bideci 2018; Zhou et al. 2020), thus increasing the KF content in the BFC increases the weak interfacial transition zone. This is despite the presence of calcite-producing bacteria *bacillus subtilis*. Furthermore, Figure 9 shows that the f_{ck} of BFC decreases as the w/c increases at all contents of KF. At 0.2% KF (BFC1), the f_{ck} decreased by about 21% from 35.8 MPa to 28.3 MPa as the w/c increased from 0.45 to 0.6. Similarly, at 0.5% KF (BFC2), the f_{ck} decreased by 29% from 27.3 MPa to 19.5 MPa as the w/c increased from 0.45 to 0.6.

Figure 9 also provides for comparison of the f_{ck} of BFCs and BC. At all w/c, the f_{ck} of BFC1 (0.2% KF) are higher than BC. The f_{ck} of BFC1 at 0.45 w/c is 12% higher at 35.8 MPa than the BC at 32 MPa. This is similarly seen at 0.6 w/c as the f_{ck} of BFC1 is 23% higher at 28.3 MPa than the BC at 23 MPa. The results indicate that low content of KF in bio-concrete (BFC1) increases the f_{ck}.

A comparison of the f_{ck} of BFCs and BC indicates a decrement that is statistically significant ($p < .05$). It can be concluded that the adding the appropriate percentage KF to BC has a positive effect on the f_{ck} of the cement composite and overcomes the effect of weak interfacial transition zone. The weak interfacial transition zone is created due to weak bond between the surface of the KF and concrete matrix which results from the smoothness of the KF. Incorporation of *bacillus subtilis* precipitates calcite in the matrix (and around the KF surface) that leads to stronger bond between the matrix and the KF. However, the strength of bond created (due to *bacillus subtilis*) will decrease as the KF content is increased, as the amount of calcite precipitated would not be sufficient. When this occurs, the f_{ck} decreases as cracks are extended along the direction of the KF distribution and failure occurs along this weak interfacial transition zone between KF and cement matrix (Zhou et al. 2020).

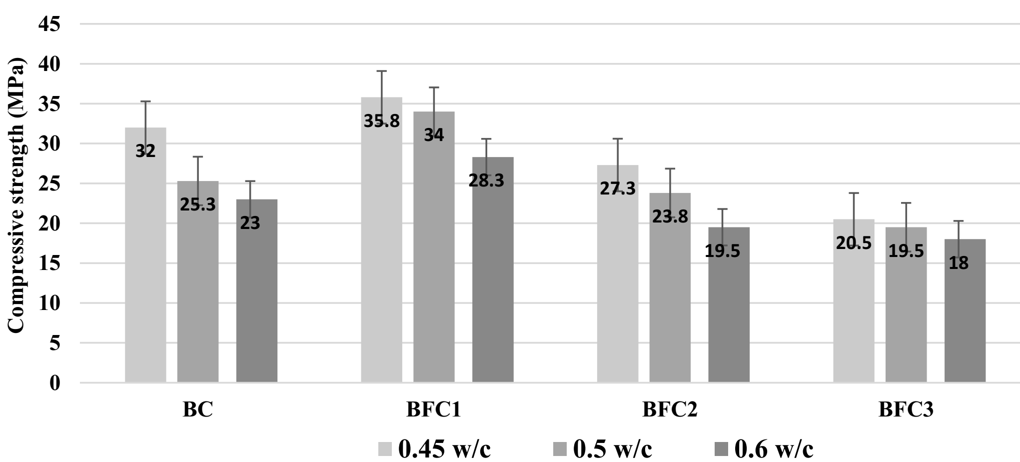


Figure 9. Compressive strength of bio-fibrous concrete (0% recycled concrete aggregate).

Compressive strength of bio-fibrous recycled concrete

The f_{ck} of bio-concrete incorporated with RCA and KF is presented in Figures 10 to 12. The contents of RCA are 25%, 50%, and 75%, while the KF contents are 0%, 0.2%, 0.5%, and 1%. In Figure 11, the f_{ck} results of the bio-concrete incorporated with 25% RCA and different percentages of KF are shown (BFRC11, BFRC12, and BFRC13). From Figure 11, the f_{ck} of BFRC decreases as the w/c increases. At 0.2% KF, the f_{ck} of BFRC11 decreased from 29 MPa to 19.5 MPa when the w/c increased from 0.45 to 0.6. This is a 32% decrement in the f_{ck} of BFRC11. Similarly, a 37% decrement in the f_{ck} of BFRC12 is observed when the f_{ck} decreases from 23 MPa to 14.5 MPa when the w/c increases from 0.45 to 0.6 (at 0.5% KF). This trend of decrement in f_{ck} as w/c increases can be seen in Figures 11 and 12 with 50% and 75% RCA, respectively. The decrement in f_{ck} is due to an increase in voids produced by the increase in w/c (Wang et al. 2020).

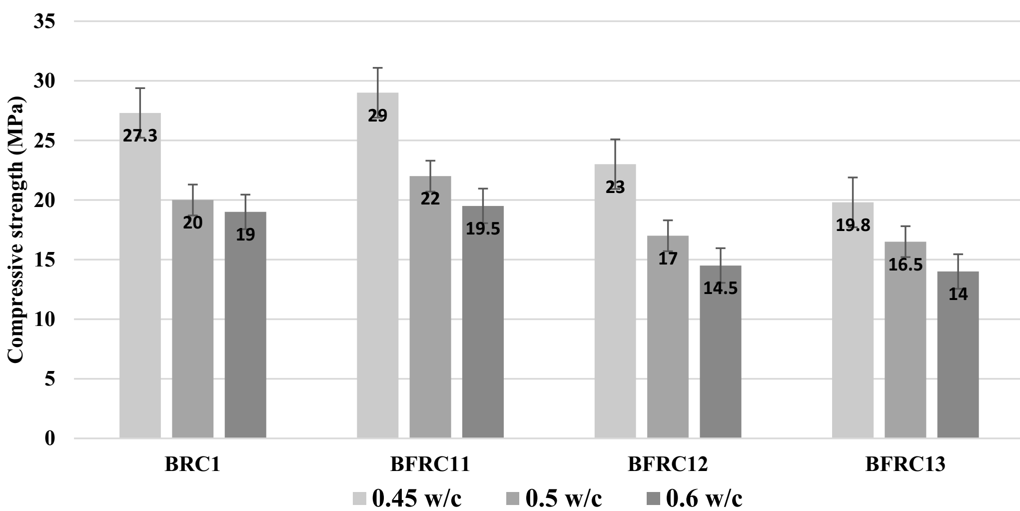


Figure 10. Compressive strength of bio-fibrous recycled concrete (25% recycled concrete aggregate).

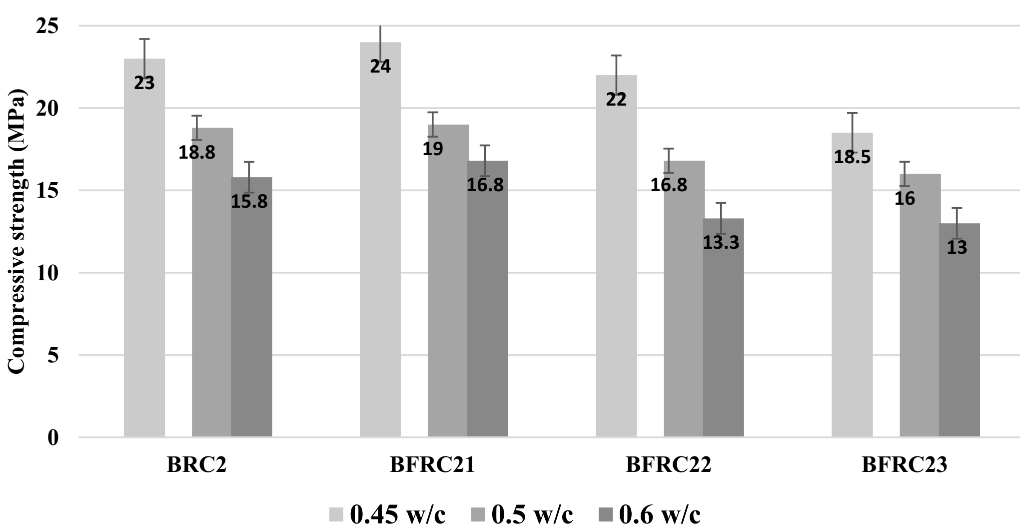


Figure 11. Compressive strength of bio-fibrous recycled concrete (50% recycled concrete aggregate).

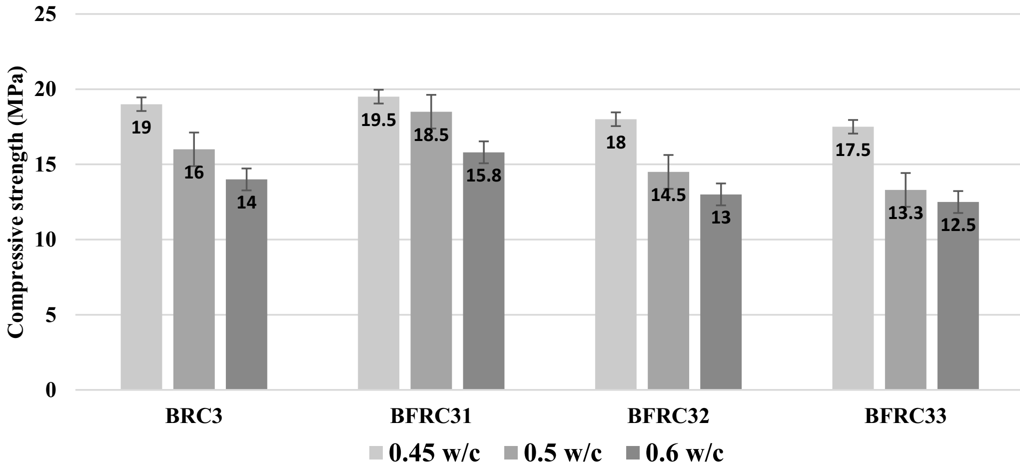


Figure 12. Compressive strength of bio-fibrous recycled concrete (75% recycled concrete aggregate).

In addition, the results in Figure 10 shows that BFRC11 has the highest f_{ck} among the three BFRCs. The f_{ck} decreased as the content of KF increased. For example, at 0.45 w/c, the f_{ck} decreased from 29 MPa to 23 MPa to 19.8 MPa as the KF increased from 0.2% to 0.5% to 1%. And at 0.5 w/c, the f_{ck} decreased from 22 MPa to 17 MPa to 16.5 MPa as the KF increased from 0.2% to 0.5% to 1%. This trend is seen in Figures 11 and 12 as well. In Figure 12, at 0.45 w/c, the f_{ck} decreased from 19.5 MPa to 18 MPa to 17.5 MPa as the KF increased from 0.2% to 0.5% to 1%. And at 0.5 w/c (Figure 12), the f_{ck} decreased from 18.5 MPa to 14.5 MPa to 13.3 MPa as the KF increased from 0.2% to 0.5% to 1%. This is due to the creation of a weaker interfacial transition zone (Çomak, Bideci, and Bideci 2018; Zhou et al. 2020) created as the KF content increased.

Furthermore, Figure 10 shows that BFRC11 attained a f_{ck} higher than BRC1. At 0.45 and 0.5 w/c, BFRC11 attained f_{ck} of 29 MPa and 22 MPa, while BRC1 attained 27.3 MPa and 20 MPa, respectively. This trend is seen in Figures 11 and 12 as well. In Figures 11 and 12, at 0.45 w/c, BRRC21 (24 MPa) and BRRC31 (19.5 MPa) attained higher f_{ck} than BRC2 (23 MPa) than BRC3 (19 MPa), respectively. This indicates that at lower content of KF (0.2%), *bacillus subtilis* bacteria is able to produce enough calcite that not only fills the voids in the concrete mix but also strengthens the interfacial transition zone that occurs between the KF and concrete mix.

A comparison of the results in Figures 10 to 12 indicates that the decrease in f_{ck} with increasing KF content in BFRC (at constant RCA) is not statistically significant ($p > .05$). Furthermore, the f_{ck} of the BFRCs decreased as the percentage of RCA increased. At 0.2% KF, the f_{ck} decreased from 29 MPa (BFRC11) to 24 MPa (BFRC21) to 19.5 MPa (BFRC31). Similarly, at 0.5% KF, the f_{ck} decreased from 23 MPa (BFRC12) to22 MPa (BFRC22) to 18 MPa (BFRC32). This decrease in f_{ck} is due to the increasing weak interfacial transition zone created as the RA increases (Kim et al. 2019).

Flexural strength

The flexural strengths (f_t) of concrete samples are presented in this section. The samples are concrete without bacteria (normal concrete – NC); concrete with bacteria (bio-concrete – BC); concrete with bacteria and recycled aggregate (bio-recycled concrete – BRC); concrete with bacteria and KF (bio-fibrous concrete – BFC); and concrete with bacteria, fiber, and recycled aggregate (bio-fibrous recycled concrete – BFRC). These results evaluate the effects of bacteria, KF (different percentages), recycled aggregates (different percentages), and different w/c on the f_{ck} of concrete.

Effect of bacteria on the flexural strength of concrete

The f_t of NC and BC are shown in Figure 13 indicates that the f_t of both NC and BC decreases as the w/c increases. For example, the f_t of NC decreases from 3.6 MPa to 2.6 MPa when the w/c increases from 0.45 to 0.6. Similarly, the f_t of BC decreases from 4 MPa to 3.1 MPa when w/c increases from 0.45 to 0.6. The reduction of f_t when w/c increases is due to the presence of additional voids in the concrete resulting from higher w/c. This result on w/c was similarly obtained in previous studies (Albano et al. 2009; Oad et al. 2019). The existence of voids leads to less cohesion in the concrete mix, thus, reducing the f_t.

Furthermore, Figure 13 shows that the presence of *bacillus subtilis* bacteria in concrete increases the f_t as BC at all three w/c have f_t higher than their corresponding NC with the same w/c. This increment in f_t is due to microbial activities of calcination that fills up tiny voids on the concrete mix (Al-Sabaeei et al. 2022; Alshalif et al. 2022). This leads to increased bond between the constituents of concrete. For example, at 0.45 w/c, the f_t of BC is 4 MPa, while the NC f_t is 3.6 MPa. This indicates about 8% increment in the f_t. Similarly, at 0.6 w/c, the f_t of BC is 3.1 MPa, while the NC f_t is 2.6 MPa. At higher w/c (0.6), the increment in the f_t is 15%. This result indicates that addition of *bacillus subtilis* bacteria to concrete increases the f_t. Although, addition of the bacteria to concrete increased the f_t, a statistical analysis showed that the increment is not significant ($p > .05$).

Flexural strength of bio-recycled concrete

The tensile strength (f_t) of bio-recycle concrete (BRC) is presented in Figure 14. As shown in Figure 14, the samples contain 25% RCA (BRC1), 50% RCA (BRC2) and 75% RCA (BRC3), as well as BC (0% RCA). Each sample is further examined with the three w/c (0.45, 0.5 and 0.6). In this section, no KF is added to the concrete samples. It can be seen in Figure 14 that the f_t of BRC decreased as the RCA increased for all w/c. This is seen as the f_t decreased from 3 MPa (BRC1) to 2.98 MPa (BRC2) to 2.6 MPa (BRC3) as the RCA increased from 25% to 50% to 75% when the w/c is 0.45. Similarly, at 0.5 w/c, the f_t decreased from 2.9 MPa (BRC1) to 2.63 MPa (BRC2) to 2.56 MPa (BRC3) as the RCA increased from 25% to 50% to 75%. The reduction of f_t of BRC is in agreement with previous studies on f_t using RCA (Shahjalal et al. 2021; Visintin et al. 2022). The decrease in f_t with increasing RCA content in BRC is statistically significant ($p < .05$). In addition, the f_t of BRC decreased as the w/c increased at all RCA contents. The f_t decreased from 3 MPa to 2.9 MPa to 2.7 MPa as the w/c increased from 0.45 to 0.5 to 0.6 at 25% RCA (BCR1). The decrement in f_t aligns with the decrement observed in NC and BC (Figure 13).

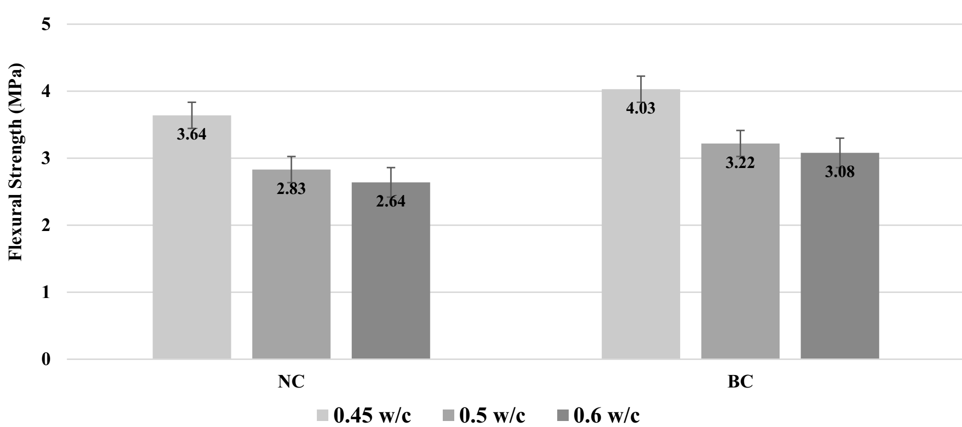


Figure 13. Flexural strength of normal concrete (NC) and bacteria concrete (BC).

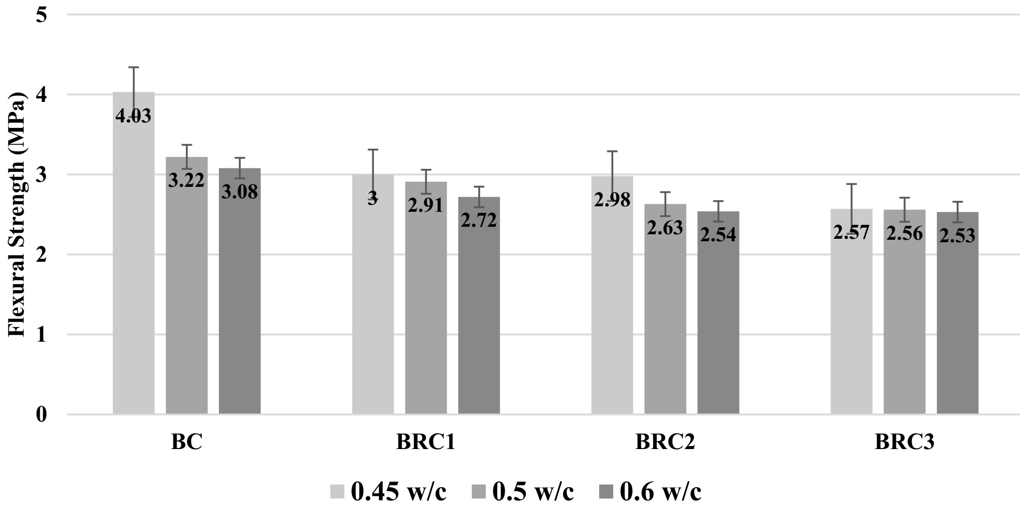


Figure 14. Flexural strength of bio-recycled concrete.

Furthermore, Figure 14 shows that the f_t of BC is higher than all the BRCs at the three w/c. At 0.45 w/c, the f_t of BC attained 4 MPa, while BRC1 (BRC with highest f_t) has 3 MPa. A comparison of the results in Figures 13 and 14 shows that BRC1 (BC with 25% RCA) has lower f_t than NC at 0.45 w/c. BRC1 attained f_t of 3 MPa, while NC attained 3.6 MPa at 0.45 w/c. However, at 0.5 and 0.6 w/c, BRC1 has slightly higher values of f_t than NC. BRC1 attained f_t of 2.9 MPa and 2.7 MPa, while NC attained 2.8 MPa and 2.6 MPa at 0.5 and 0.6 w/c, respectively. These results show that even with the presence of bacteria to the RAC (BRCs), the f_t of BRCs is lower than NC at 0.45 w/c. A comparison of the results in Figures 13 and 14 shows that at 0.45 w/c, all BRCs have lower f_t than NC. However, at 0.5 and 0.6 w/c, the difference between the f_t of BRC1 (2.9 MPa) and NC (2.8 MPa) is insignificant.

Flexural strength of bio-fibrous concrete

This section evaluates the effect of KF on the f_t of bio-concrete (BC). The KF contents in the BC are 0.2% (BRC1), 0.5% (BFC2) and 1% (BFC3). The w/c remain the same (0.45, 0.5 and 0.6). The f_t of the bio-fibrous concrete (BFC) obtained by addition of KF to BC is shown in Figure 15. In addition, the f_t of BC without fiber (0%) is also shown in Figure 15.

In Figure 15, the f_t of BFC increased as the KF content increased in the BFC. At 0.45 w/c, the f_t increased by 28% from 5 MPa (BFC1) to 6.4 MPa (BFC3) as the KF content increased from 0.2% to 1%. Similarly, at 0.6 w/c, the f_t slightly increased by 4% from 4.23 MPa (BFC1) to 4.52 MPa (BFC3) as the KF content increased from 0.2% to 1%. The increase in f_t with increasing KF content in BFC is statistically significant ($p < .05$). The high tensile strength of KF present in the BFC increases the flexural strength (Kang et al. 2011). Furthermore, Figure 15 shows that the f_t of BFC decreased as the w/c increased for all contents of KF. At 0.2% KF (BFC1), the f_t decreased by about 16% from 5.0 MPa to 4.2 MPa as the w/c increased from 0.45 to 0.6. Similarly, at 0.5% KF, the f_t decreased by 20% from 5.5 MPa to 4.4 MPa as the w/c increased from 0.45 to 0.6. Figure 15 also provides for comparison of the f_t of BFCs and BC. At all w/c, the f_t of all BFCs is higher than BC. The f_t of BFC3 at 0.45 w/c is 60% higher at 6.4 MPa than the BC at 4 MPa. This is similarly seen at 0.6 w/c as the f_t of BFC3 is 45% higher at 4.5 MPa than the BC at 3.1 MPa.

The results indicate that the high content of KF in bio-concrete samples (BFCs) increases the f_t. This result aligns with results in previous studies (Baarimah and Mohsin 2018; Mohsin, Baarimah, and Jokhio 2018). It can be concluded that the addition of KF to BC has a positive effect on the f_t of the cement composite.

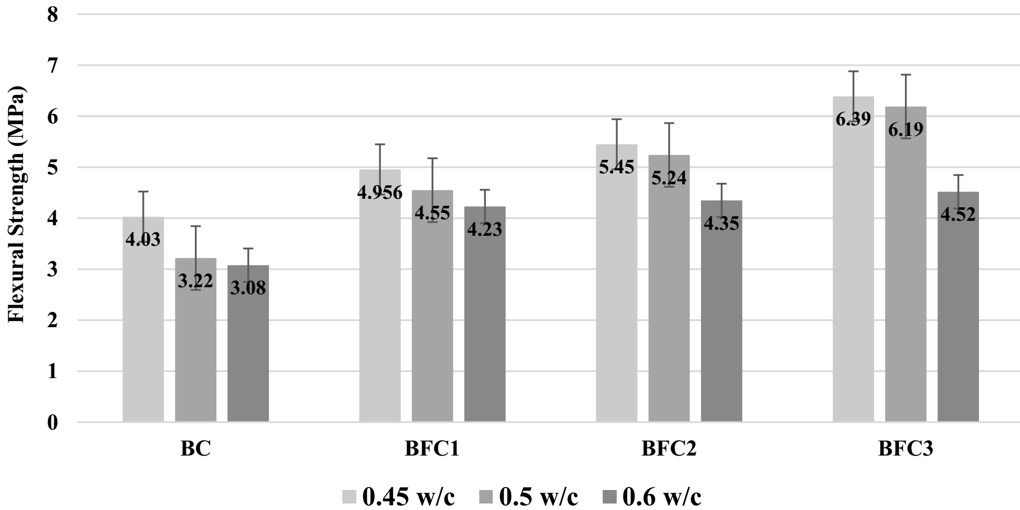


Figure 15. Flexural strength of bio-fibrous concrete (0% recycled concrete aggregate).

Flexural strength of bio-fibrous recycled concrete

The f_t of bio-concrete incorporated with RCA and KF are presented in Figures 16–18. The contents of RCA are 25%, 50%, and 75%, while the KF contents are 0%, 0.2%, 0.5%, and 1%. In Figure 16, the f_t of the bio-concrete incorporated with 25% RCA and different percentages of KF are shown (BFRC11, BFRC12, and BFRC13). From Figure 16, the f_t of BFRC decreases as the w/c increases. At 0.2% KF, the f_t of BFRC11 slightly decreased from 3.4 MPa to 3.1 MPa when the w/c increased from 0.45 to 0.6. This is a 9% decrement in the f_t of BFRC11. However, at 0.5% KF, the f_t of BFRC12 significantly decreased from 5.6 MPa to 4.1 MPa when the w/c increased from 0.45 to 0.6. This is 27% decrement in the f_t of BFRC12. This trend of decrement in f_t as w/c increases can be seen in Figure 17 (50% RCA) and Figure 18 (75% RCA) as well. The decrement in f_t is associated with void increment by the increase in w/c (Wang et al. 2020).

In addition, Figure 16 shows that BFRC12 has the highest f_t among the three BFRCs. The f_t increased as the content of KF increased from 0.2% to 0.5%, and decreased as the KF increased from 0.5% to 1%. For example, at 0.45 w/c, the f_t increased from 3.4 MPa (BFRC11) to 5.5 MPa (BFRC12), then decreased to 4.0 MPa (BFRC13) as the KF increased from 0.2% to 0.5% to 1%. Similarly, at 0.5 w/c, the f_t increased from 3.4 MPa (BFRC11) to 4.6 MPa (BFRC12), then decreased to 3.9 MPa (BFRC13) as the KF increased from 0.2% to 0.5% to 1%. This trend is seen in Figures 17 and 18 as well. In Figure 17, at 0.45 w/c, the f_t increased from 3.3 MPa (BFRC11) to 4.4 MPa (BFRC12), then decreased to 3.6 MPa (BFRC13) as the KF increased from 0.2% to 0.5% to 1%. And at 0.5 w/c as seen in Figure 17, the f_t increased from 3.0 MPa (BFRC11) to 4.0 MPa (BFRC12), then decreased to 3.3 MPa (BFRC13) as the KF increased from 0.2% to 0.5% to 1%. This result shows that the optimum KF content of BFRC is 0.5%. An increment of the KF content initially increases the f_t, peaked, and then decreases. This finding is similar to results presented in the previous literature (Elsaid et al. 2011).

Furthermore, Figures 16–18 show that all BFRCs attain higher f_t than their corresponding BRCs. They also show that the increase in the KF content is significantly statistically significant ($p < .05$). In Figure 16, the lowest f_t at 0.45 w/c attained is 3.4 MPa (BFRC11), while

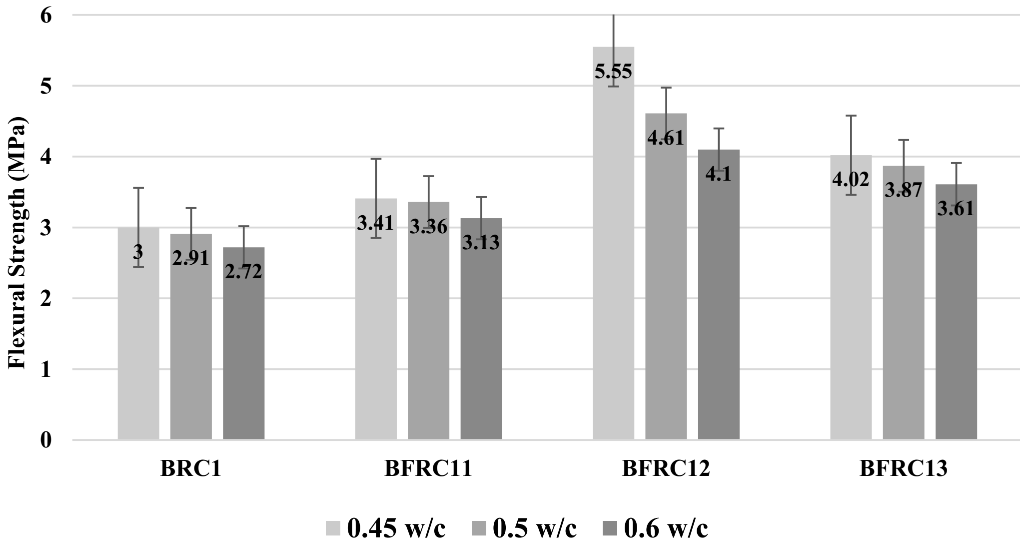


Figure 16. Flexural strength of bio-fibrous recycled concrete (25% recycled concrete aggregate).

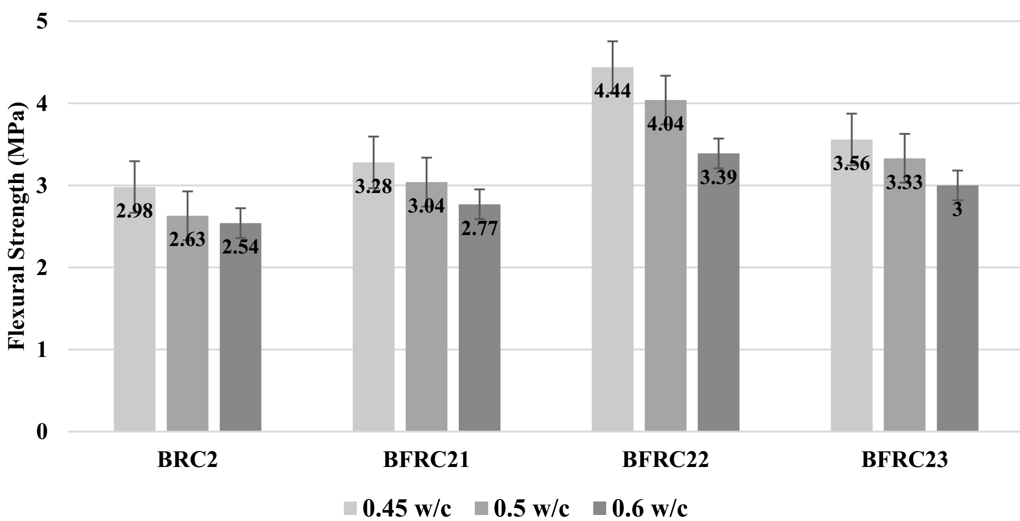


Figure 17. Flexural strength of bio-fibrous recycled concrete (50% recycled concrete aggregate).

the corresponding BRC attains 3 MPa. Similarly, in Figure 17 (50% RCA), the lowest f_t at 0.6 w/c attained is 2.8 MPa (BFRC21), while the corresponding BRC attained 2.5 MPa. This trend is also seen in Figure 18. These results in Figures 16–18 indicate that the presence of KF increases the f_t of BFRCs. A comparison of the f_t of BFC (Figure 15) and BFRCs (Figures 16 to 18) shows that at 0.2% and 1% KF, the BFCs (BFC1 and BFC3) have higher f_t than the corresponding BFRCs. However, at 0.5% KF and 0.45 w/c, BFRC12 (Figure 16) has higher f_t than its' corresponding BFC2 (Figure 15), although BFC2 has higher f_t than BFRC12 when the w/c are 0.5 and 0.6.

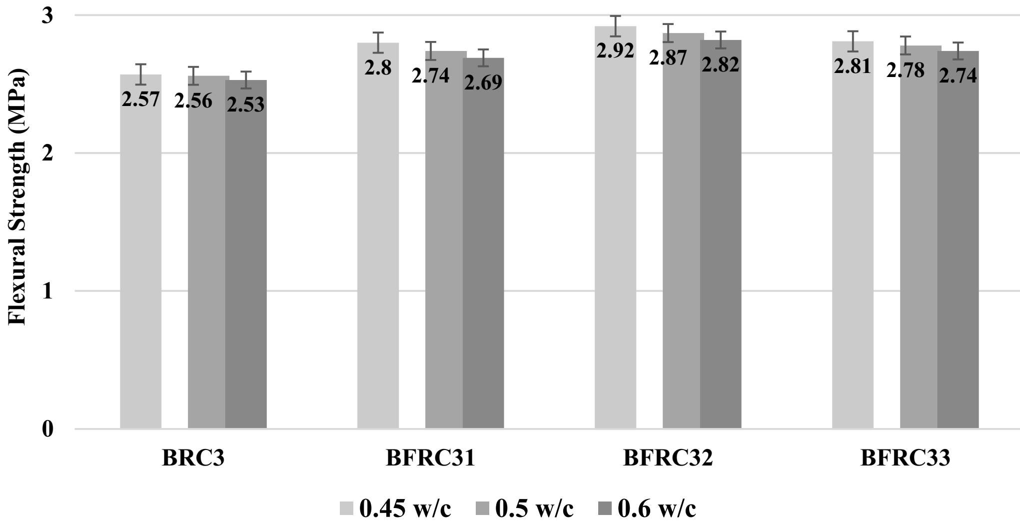


Figure 18. Flexural strength of bio-fibrous recycled concrete (75% recycled concrete aggregate).

Conclusions

In this paper, the mechanical properties (compressive and flexural strengths) of bio-fibrous recycled concrete are presented. Calcite-producing bacteria (*bacillus subtilis*) and kenaf fiber (KF) are incorporated into recycled aggregate concrete (RAC). Three different proportions each of KF, recycled concrete aggregate (RCA) and w/c are considered in the evaluation of the mechanical properties. The results of the experimental tests are summarized as follows:

- Incorporation of *bacillus subtilis* bacteria in concrete increases the compressive strength (f_{ck}) and flexural strength (f_t) of the concrete samples. At 0.45 w/c, the f_{ck} increased by 24% from 25.8 MPa (NC) to 32 MPa (BC), while the f_t increased by 8% from 3.7 MPa (NC) to 4.0 MPa (BC).
- Increment of w/c decreases both f_{ck} and f_t of the concrete samples. Increment of w/c from 0.45 to 0.6 decreases the f_{ck} of NC, BC, BRC1, BFC1, BFRC11, BFRC21, and BFRC31 by 30%, 28%, 30%, 21%, 33%, 30%, and 22%, respectively, while the f_t decreased by 28%, 23%, 16%, 10%, 15%, and 4%, respectively.
- The percentage of RCA decreased the f_{ck} and f_t of the concrete samples. Increasing the RCA content in BRC and BFRC from 25% to 75% at 0.45 w/c decreased the f_{ck} by 30% and 33% from 27.3 MPa (BRC1) and 29 MPa (BFRC11), to 19 MPa (BRC3) and 19.5 MPa (BFRC31) respectively.
- Incorporation of KF at 0.2% in BC (BFC1) produced the highest f_{ck}, even higher than BC. However, increasing the KF beyond 0.2% decreased the f_{ck} of the BFC samples. Increasing the KF content in BFC and BFRC from 0.2% to 1% at 0.45 w/c decreased the f_{ck} by 43% and 32% from 35.8 MPa (BFC1) and 29 MPa (BFRC11), to 20.5 MPa (BFC3) and 19.8 MPa (BFRC13) respectively. This indicates that at lower content of KF (0.2%), *bacillus subtilis* bacteria is able to produce enough calcite to not only to fill the voids in the concrete mix, but also strengthened the interfacial transition zone that occurs between the KF and concrete mix.
- This study showed that KF increased the f_t of the BFC samples. Increasing the KF content in BFC from 0.2% to 1% at 0.45 w/c increased the f_t by 28% from 5 MPa (BFC1) to 6.4 MPa (BFC3). In BFRCs, increasing the KF content from 0.2% to 0.5% increases the f_t, however, increasing from 0.5% to 1% decreased the f_t. The optimum KF content of BFRC is 0.5%.

Highlights

- Effects of bacteria, kenaf fiber, and recycled aggregate on compressive strength.
- Flexural strength performance of bio-fibrous recycled concrete.
- Workability evaluation of concrete containing bacteria, kenaf fiber, and recycled aggregate.
- Density of bio-fibrous recycled concrete.

Recommendations

Based on the findings and limitations of this research, future works are recommended. This includes the following:

- Evaluation of other properties such as tensile strength, impact strength, durability, microstructure and seismic behavior.
- Experimental testing on creep, shrinkage and durability properties of BRC, BFC, and BFRC.
- Incorporation of other types of fiber (steel, rubber, jute, coconut, and glass) in BC.
- Appraisal of the effect of KF on the properties of high-strength concrete.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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