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Review Paper

Concrete canals lining with modern materials: A Review of hybrid fiber reinforced concrete

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Abstract: Water losses in irrigation canals occur during the process of water transportation, with seepage loss being the main contributor to total water loss in irrigation conveyance. Cracks and settlement are the most problematic factors affecting canal lining structures, leading to reduced performance of irrigation canals due to issues such as sediment deposition, waterlogging, and leakage. Seepage losses typically range from 20 % - 30 %, but this can be reduced to 15 % - 20 % with the use of canal lining. However, the concrete lining structure, being a thin plate, is prone to high rates of cracking, which weakens the performance of canals. Therefore, it is crucial to enhance the flexure and splitting-tensile strengths of concrete to control the rate of cracking in the canal lining. The splitting-tensile strength of concrete is particularly important in crack control. Hybridization of fibers, such as combining polypropylene and jute fibers, can efficiently enhance flexural toughness, flexural strength, and fracture energy more than using a single type of fiber. The overall aim of this review is to summarize the literature on the use of modern materials to reduce water losses in concrete canal lining. Initially, hybrid fibers (one natural fiber and one artificial fiber) are selected to explain the behavior of hybrid fiber reinforced concrete (HFRC). The crack arresting mechanism of HFRC can help reduce losses in concrete canal lining. The findings of this review will be valuable as a reference for both industry practitioners and academic researchers interested in the development of hybrid fiber reinforced concrete materials, particularly for canal lining applications.

Keywords: Hybrid fiber, Reinforced concrete, Polypropylene fiber, Jute fiber, Canal lining.

1. Introduction

Poor drainage, irrigation field percolation, inadequate water management, seepage losses from unlined irrigation systems, and low-lying locations are all factors that contribute to these problems [1]. Specific generalized equations were obtained for constructing the smallest earthwork cost, and least cost lined sections of a parabolic shape using the results of a direct optimization approach and error reduction or regression analysis. Similarly, limitations on canal size and velocity of flow in the canal were determined using another equation [2]. Compared with simulated and noted flows at the tail control of the Right Bank Main Canal of Kangsabati Irrigation Project, the model works adequately for most irrigation issues. The various simulation outcomes suggested that the advanced model can be utilized as a good tool for hydraulic simulation of the canal system [3]. The resistance equation determines uniform flow in a canal. The most commonly applied formula for resistance is Manning's equation, which is suitable for rough conditions because it yields the same minimum area. Furthermore, the semi-circular section is assumed to have the lowest flow perimeter and flow area [4]. Natural fibers such as jute, hemp, flax, and sisal have been utilized in structural applications, such as the construction of building and housing materials [5]. The incorporation of natural fibers such as jute, coir, hibiscus sisal, and cannebinus in composites has improved the impact resistance by 3 - 18 times compared to that of a plain mortar slab [6]. According to the findings, natural

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Fig. 1 – Various hybrid fibers and single fiber used in cementitious materials: (a) Steel fiber and Carbon fiber [15]; (b) Basalt fiber and Polypropylene fiber [16]; (c) Jute fiber, Polyvinyl alcohol fiber and Nylon fiber [17]; (d) Jute fiber [18]; (e) Steel fiber, polypropylene and polyvinyl alcohol [19]; (f) Jute fiber [20]; (g) Jute fiber [21]; (h) Polypropylene fiber, Polyvinyl alcohol fiber and Steel fiber [22].

fiber composite plates and channel sections containing jute, flax, and hemp fibers are subjected to compression. The primary mechanical properties of concrete indicated are to be considered average [7]. Research has revealed that heat treatment is one of the most suitable treatment approaches for improving the mechanical properties of woven jute fiber (JF) reinforced polymer (RP). Furthermore, woven JF-RP is a relevant material that can be utilized to enhance the flexural strength of reinforced concrete beams [8]. Jute fiber reinforced polypropylene matrix composites were produced by compression molding. It was concluded that E-glass fiber-based composites exhibited almost twice the mechanical properties compared to JF composites [9]. Ceramsite concrete exhibits relatively higher self-shrinkage and drying shrinkage, which adversely affects its mechanical strength and durability, posing a challenge to broader practical applications. Moreover, an increase in the content of the shrinkage-reducing agent results in early micro-expansion of Ceramsite concrete, which is generally considered unfavorable. The optimal content of the shrinkage-reducing agent and polypropylene fiber (PF) is determined to be 3 % and 0.3 %, respectively [10].

The experimental results demonstrated that the addition of PF to high-performance concrete enhanced its waterproofing ability and resistance to chloride penetration, while having minimal impact on the workability of the composite. Incorporating PF into the concrete mixture resulted in a reduction in pore size, decreased porosity, improved bonding between $Ca(OH)_2$ and C-S-H (calcium hydroxide and calcium silicate hydrate), and a significantly denser interfacial transition zone [11]. While the inclusion of fibers did not result in significant improvements in the ultimate load-displacement capacity, the experimental investigation revealed that the utilization of PF substantially increased displacement ductility [12]. In various grades of Fiber-Reinforced Concrete (FRC), slag was added as a cement substitute to enhance the composite's resistance against chloride penetration. The properties of microfibers made from PF are influenced by the types and volume content of fibers used. The study concluded that a low volume content of PF shows promise [13]. The addition of hybrid steel fibers (SF) and micro PF does not have a significant impact on the flexural strength of self-consolidating concrete beams at room temperature. However, when compared to the use of only micro-PF or macro-PF, the inclusion of hybrid SF and micro-PF has shown to have a more significant effect on the behavior of structural self-consolidating concrete beams [14]. In Fig. 1 various hybrid fibers and single fiber used in cementitious materials are shown.

The performance of hybrid fiber-reinforced self-compacting concrete with crimped steel fibers (SF), PF, class F fly ash, and colloidal nano-silica was evaluated. A rapid chloride penetration test was conducted to assess the durability of the hardened concrete. The production of self-compacting concrete reduces the generation of noise from vibrators during construction [23]. The study observed a synergy effect when hybrid SF and PF were used together, resulting in an improved flexural behavior of the Hybrid Fiber-Reinforced Concrete (HFRC). The results demonstrated an enhancement in impact resistance and mechanical properties of self-consolidating concrete through the incorporation of fibers. This improvement was significantly influenced by the type of fiber, volume fraction, and concrete mixture. Additionally, the optimization method revealed that the combination of mono-fiber reinforced self-consolidating concrete with 1.5 % of recycled steel fibers (RSF) achieved the most outstanding impact resistance and mechanical properties at the lowest cost. Furthermore, the mixture reinforced with a hybrid combination of 1 % industrial SF and 0.5 % RSF also exhibited excellent performance in terms of impact resistance and mechanical properties [24].

2. Optimization of Hybrid Fibers Reinforced Concrete (HFRC)

2.1. Flaws in Concrete (strength point of view)

Concrete is commonly utilized as a construction material. However, it is subjected to various constraints in engineering applications due to its lower ductility, high brittleness, weak tensile strength and strain, and lower impact toughness [25, 26, 27]. One of the main deficiencies of plain concrete is its lower ductility, tensile strength, flexural strength, and related properties [28]. Plain concrete is well known for its crumbly characteristic [29]. Concrete is an extensively used material for various engineering applications, such as road, bridge, architectural, and hydraulic engineering. However, plain concrete, while effective in compression, is typically prone to breakage due to its low ductility and lower tensile strength [30]. Construction materials such as cement, sand, and granite are typically in high demand in the construction industry. Among them, concrete serves as the primary and universally utilized cementitious material in civil engineering constructions. Due to its widespread use and high demand globally, concrete has become the foremost construction material. Its multifaceted characteristics, specific relationships, and economic usefulness enable it to efficiently meet the requirements and demands of various construction projects [31]. Portland cement concrete forms a liquid mass that can be easily molded into shape when the aggregate is combined with dry cement and water. Concrete is widely regarded as the most commonly used construction material due to its high compressive strength, long service life, and cost-effectiveness [32]. However, it is less effective in tension and has lower resistance to cracking. To overcome these limitations, fiber-reinforced concrete has been developed [33, 34]. It has been observed that PF has a significantly greater toughening effect on geopolymer compared to SF, PVA fiber, or BF in cement-based materials. This makes it feasible to produce high-toughness materials by reinforcing geopolymer with PF [35].

2.2. Fibers in Concrete (mix design)

It has been found that the jute fiber reinforced polymer (JFRP) strengthening technique significantly enhances the flexural strength of rusted beams. However, it should be noted that the ultimate load capacity of the beams decreases during the high corrosive phase [36]. The study revealed that the split-tension and flexural strengths of concrete were improved by 8 % and 20 % respectively. It was noted that the addition of short jute fiber (JF) in composites allowed for a reduction of approximately 28 % in the amount of reinforcement steel required in slabs [37]. SF, macro-PF, and mixtures of macro-PF and micro-PF were used to investigate early-age fracture tests on concrete beams. The enhancement in the post-cracking response of SF with age was attributed to increases in crack resistance and fiber pull-out. Mixtures of micro-PF and macro-PF exhibited superior resistance against crack occurrence and fiber pull-out compared to macro-PF alone [38]. A novel concept was introduced to study the behavior and transport properties of the composite, preplaced aggregate fiber reinforced concrete (PAFRC), with the addition of waste polypropylene carpet fibers. Palm oil fuel ash was incorporated as a partial replacement for cement. However, the PAFRC composites showed a significant improvement in the tensile strength of the composites [39]. The incorporation of PF enhanced the durability and mechanical properties of roller-compacted concrete mixtures containing waste white cement bypass dust. Additionally, it decreased manufacturing costs and reduced environmental pollution by minimizing the disposal of waste materials in landfills [40].

Table 1 – Different fibers with strength properties [41, 42].

Fiber Type	Tensile Strength (MPa)	Elastic Modulus (GPa)
Jute	248-351	26-32
Polypropylene	137-689	3.4-4.8
Nylon	965	5.17
Glass	3102	64.8
Steel	344-2999	200

Table 1 displays different types of fibers along with their corresponding tensile strength, elastic modulus, and water absorption percentage. Polypropylene fiber exhibits good tensile strength. The values for various properties associated with different fiber types provide valuable information for the utilization of fibers in concrete. It is worth noting that JF and PF demonstrate average tensile strengths and elastic moduli, as well as lower water absorption capacities [41]. Among the readily available fibers that are locally accessible, the selected fibers exhibit good strength properties for canal-lining applications. The excellent tensile strength of these preferred fibers is suitable for controlling crack development caused by tensile stresses, thereby improving the tensile strength of FRC. Additionally, the minimal water absorption of the chosen fibers makes them particularly suitable for use in concrete canal lining applications compared to other available fibers. However, for the concrete canal lining application, the type of glass fiber available is not taken into account. This is because research has shown that glass fibers, which are not resistant to alkaline conditions, chemically react with hydration products, resulting in a weakened glass surface [41, 42].

It was found that the reduction in fiber strength occurred due to the formation of hydration products surrounding the glass fibers during the early stages of concrete composite curing. The corrosive nature of steel fibers severely damages the bond between the steel fiber and concrete. The results demonstrate that the use of PF has a positive impact on the cyclic and monotonic behaviors of the composite, particularly in terms of post-cracking behavior. The percentage of shear cracks in polypropylene fiber-reinforced concrete (PFRC) was higher than in PC [43]. It was concluded that the incorporation of 1-2 kg per 1 m^3 of self-compacting concrete with a fiber length of 9-15 mm enhances its technical and physical properties. The flexural strength is improved by 10 %, and shrinkage deformations are reduced by 75 % compared to PC [44]. The theory of fiber crack resistance states that when tensile stresses are applied to a load, cracking occurs. However, the fibers bridge these cracks and transfer the load to the upper and lower surfaces, reducing stress concentration at the crack tip. This limits further crack propagation and enables the material to withstand loads. Therefore, the addition of fibers to cement-based materials primarily improves their properties by preventing crack expansion in the matrix and increasing the strength and fracture energy of the material [45].

2.3. Concrete Behaviour with Artificial and Natural Fibers (with emphasis to canal lining application)

There are numerous commercially available categories of fibers, such as glass, steel, synthetic, and various natural fibers. Nowadays, two micro-reinforced materials, namely glass fiber (GF) and PF, are utilized to increase the strength of concrete. This study revealed that the optimal fiber content is influenced by the water/binder ratio [46]. The major issues with PC are its lower ductility, flexural strength, and tensile strength. The findings have revealed that the inclusion of hybrid recycled steel polypropylene fiber enhances

Table 2 – Various hybrid fibers with diameter, density, and strength properties [19, 52, 53, 54, 55, 56, 57, 58].

	Fiber	Diameter (mm)	Density (g/cm^3)	Elasticity Modulus (GPa)	Tensile Strength (MPa)
1	Polypropylene	-	0.91	3.5	350
	Steel	-	7.8	210	800
2	Polypropylene (Straight)	0.019	0.91	3.5	350
	Macro polymeric (Crimped)	0.78	0.91	3.6	500
3	Polypropylene (PP)	0.03	0.91	3.0	270
	Polyvinyl alcohol (PV)	0.03	1.3	8.0	1000
	Steel	0.22	7.85	200	1200
4	Polypropylene	30	0.91	3.0	270
	Basalt	15	2.56	75	4500
5	Polypropylene	0.08	0.91	4.2	400
	Carbon	0.007	1.8	240	4000
6	Polypropylene	0.048	0.91	4.0	400
	Steel	0.2	7.85	200	2800

the mechanical properties and impact resistance of the concrete. The use of recycled steel fiber (RSF) specifically leads to an enhancement in compressive strength compared to PF [28]. The addition of fibers into the concrete mixes can be the perfect option for recovering the issues of the brittle nature of concrete. The use of carbon fiber (CF) in hybrid and single states improved the CF-reinforced polymers confined lightweight aggregate concrete toughness, whereas the PF revealed minor effects on the properties of lightweight aggregate concrete [47]. The discarded waste tires are becoming a problematic concern for the environment worldwide due to difficulties in their disposal and their health hazards. Experimental results have shown that a concrete mix with hybrid fibers, specifically PF and micro steel fiber (MSF), exhibits superior splitting tensile and compressive strengths, as well as a higher modulus of elasticity compared to other concrete mixes [48]. Incorporating two different types of fibers, namely PF and crimped SF, can improve the mechanical properties of concrete and create a better synergy effect with a suitable mix. It has been reported that the percentage of fiber volume content has a positive effect on tensile and flexural strengths, as well as enhancing the strength of the first crack [49]. The involvement of fiber reinforcement in the strength of a composite begins when cracking is introduced, which enhances the post-cracking behavior through improved stress transfer provided by the bridging of fibers to the cracked sections. Experimental results have shown that the potential for enhancing penetration resistance in SF reinforced concrete is significantly greater compared to PF or polyvinyl alcohol fiber (PV) reinforced concrete [50]. The study revealed that replacing PC with HFRC (i.e., PF and SF) in sensitive sections of a structure, such as the beam bottom, beam-column joint, and column base, can significantly enhance the overall structural response. As a result, there has been an increased utilization of HFRC in repairing damaged infrastructures over the past few decades [29].

Table 2 presents different hybrid fibers with their respective diameters, densities, and strength properties. The properties of fibers such as polypropylene, steel, macro polymeric, basalt, carbon, aramid, and macro Polypropylene are combined to prepare a hybrid concrete mixture. The hybridization of fibers with different densities, diameters, elastic moduli, and tensile strengths can result in higher mechanical properties of the concrete composites [51]. Prototype walls were constructed using ordinary concrete and JFRC, with the addition of steel rebars and glass fiber reinforced polymer (GFRP) rebars. The obtained results demonstrated that the GFRP-reinforced concrete walls with JF outperformed the other mixtures in terms of control [59]. The addition of artificial and natural fibers can enhance the flexural and tensile strength of concrete. BF and PF were mixed in proportions of 0.6 %, 1.3 %, and 2.5 % of the total cement weight, respectively.

According to the test results, the optimal proportions for BF and PF in the total cement weight were determined to be 2.5 % and 0.6 %, respectively. The use of BF and PF significantly improved the ductility of the beams [60].

2.4. Hybrid Fibers in Concrete (mix design and behaviour)

The utilization of hybrid fibers, specifically hooked-end-SF at 0.50 % and PF at 0.66 was employed to prepare self-consolidating concrete. The hybrid hooked-end-PF fibers improved the yielding resistance and exhibited a low stiffness degradation rate. On the other hand, the PF reinforcement enhanced the ductile behavior of the structural concrete [61].

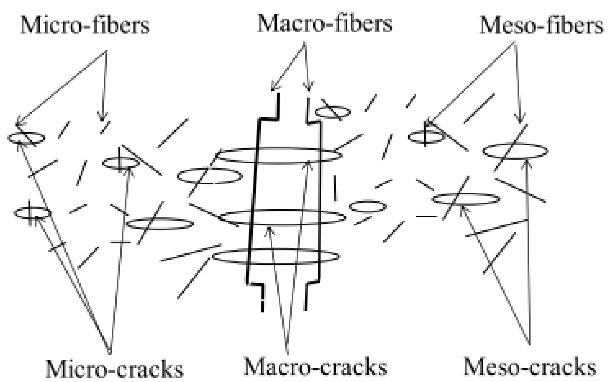

Fig. 2 – Schematic diagram of multi-level crack bridging mechanism [62].

In Fig. 2 schematic diagram of multi-level crack bridging mechanism is shown [62]. Multi-scale hybrid fibers were incorporated into the composite to enhance its resistance against cracks. The use of SF−$CaCO_3$ whisker-BF reinforced concrete resulted in improvements of up to 9.5 in split-tensile strength, 66 in compressive strength, and 24 in flexural strength compared to plain concrete (PC) [62].

CF, PF, and aramid fibers (AR) are effective in enhancing the initial mechanical properties of HFRC, particularly the flexural and tensile strengths. The aspect ratio of the fibers has a minimal influence on the tensile-to-compressive-strength ratio (TC-R) and flexural-to-compressive-strength ratio (FC-R) during the early stages of HFRC. In contrast, the tensile strength was approximately 1/15th of the compressive strength, which was consistent with PC. However, the average FC-R of HFRC was 11.57 which was comparable to PC [63].

The utilization of hybrid fibers with optimized content can enhance the mechanical properties of concrete. The highest improvement in strain at peak stress was achieved with a volume content of 0.75 macro polymeric fiber (MPF) and 0.5 PF, resulting in enhancements of 4.7 and 14.1 compared to PC. However, a higher enhancement of 9.4 was achieved in HFRC with a volume content of 0.2 PF and 0.8 MPF [52]. The inclusion of hybrid steel-polypropylene fibers in ultra-high-performance concrete (UHPC) not only provides support for constructing durable structures but also enhances the failure pattern of UHPC. In UHPC mixtures containing 1.5 or 1.75 SF with high strength and modulus, increasing the volume fraction of PF is preferable to achieve suitable toughness and a deformed shape, which contributes to the constructive effect on the interfacial bond of SF [55].

Fig. 3 illustrates the cracking mechanism by multi-scale hybrid fibers in different stages: micro-cracking, meso-cracking, and macro-cracking. The addition of fly ash enhances the cement-matrix, while $CaCO_3$ whisker provides crack arresting mechanism against micro-cracks. Basalt fiber and SF contribute to crack resistance at later stages. The failure of the specimen occurs in the macro-cracking stage.

Table 3 presents the raw materials, mix proportions, and the corresponding increased strengths of HFRC. It can be observed that the addition of a hybrid content of 0.9 polypropylene fiber and 1.5 steel fiber enhances the compressive strength (C-S), flexural strength (F-S), and splitting tensile strength (S-T-S) of the concrete composites. Similarly, the addition of a hybrid content of 0.1 % polypropylene fiber and 0.9 % steel fiber increases the C-S and S-T-S of the concrete composites. Further, the hybrid content of 0.1 % macro polypropylene fiber and 0.1 % basalt fiber increases the C-S and F-S of the concrete composites.

The hybrid effect of micro-PF significantly enhanced the residual flexural strength of cement mortar when subjected to heating up to the melting point of the fibers (160 °C). Superior hybrid results for both compressive and tensile strength were noted with mass ratio of BF to PF as 1:2, although 6 kg/m^3 was a complete mass of fibers. Hybrid basalt-polypropylene fiber reinforced concrete exhibited a greater tensile strength improved by 24 % and compressive strength improved by 14

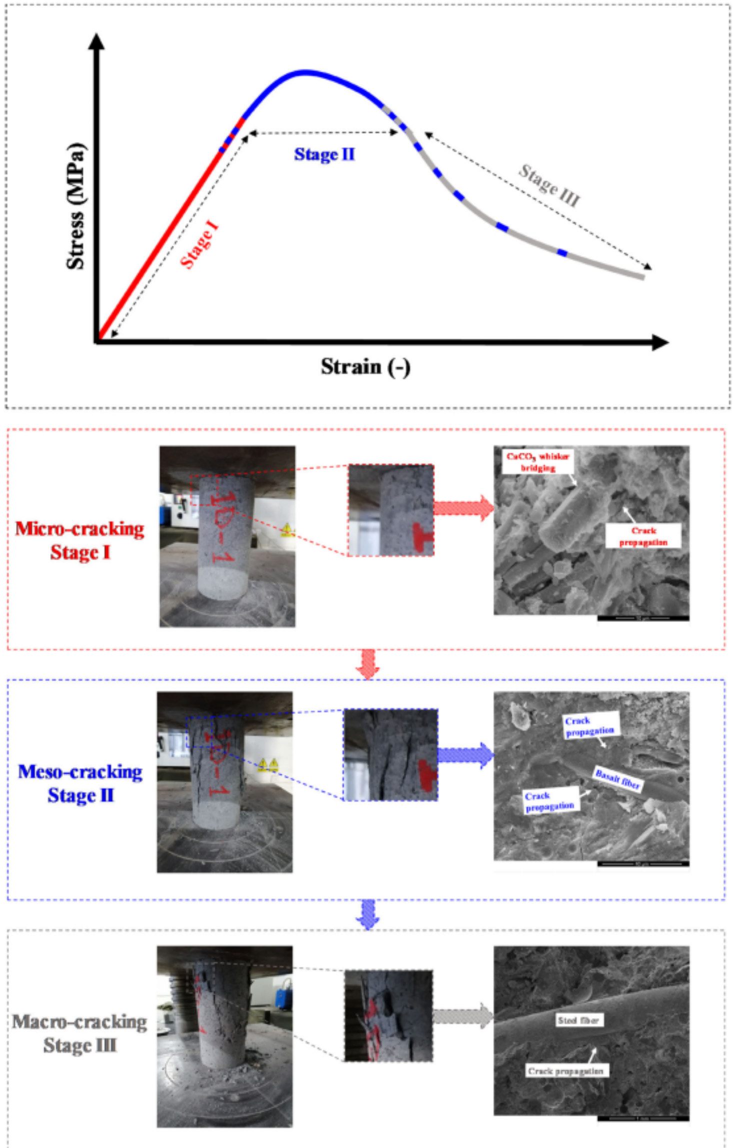

Fig. 3 – Multi-level crack arresting mechanism at different stage [64].

% as per PC [30]. In Fig. 4 behavior of PC and HFRC under split-tension load is shown. Increasing the fiber content in CFRC generally leads to a decrease in compressive strength. However, CFRC with 1 % fiber content exhibits higher compressive strength compared to plain concrete (PC). The compressive strength of CFRC increases by up to 9 % with 1 % fiber content but decreases by 6 % and 10 % with 2 % and 3 % fiber content, respectively. The reduced compressive strength at higher fiber content may be attributed to the formation of voids [67].

3. Durability of Fiber Reinforced Concrete (FRC)

3.1. Durability Flaws in Concrete

Researchers are paying increasing attention to the durability of civil infrastructure as the use of concrete structures continues to rise. In the field of civil engineering, research on the durability of concrete structures has recently emerged as an important topic [68]. Furthermore, alkali-aggregate interaction, carbonation, and loading can all cause significant damage to concrete, leading to a reduction in both its usability and durability. Accidents resulting from

Table 3 – Raw material, mix proportion and increased strengths of HFRC [19, 48, 51, 57, 65, 66].

Sr. No.	Raw material	Mix proportion (by volume of PC)	Strength increased	Authors
1	Cement, Sand, Aggregate, Silica Fume, Fly Ash, Slag, Water, Polypropylene (P-P) and Steel (S) fiber.	1: 1.14: 1.95: 0: 0: 0 & w/c ratio 0.35. P-P-F length = 12 mm. S-F length = 30 mm. Hybrid Fiber (H-F) = (P-P+S) content = (0.6+0.5, 0.9+0.5, 0.5+1.5; 0.6+1, 0.9+1, 1+1.5; 0.6+1.5, 0.9+1.5, 1.2+1.5 %).	F-S = Increased 5.88 MPa. S-T-S = Increased 4.45 MPa. As per PC. With 0.9+1.5 % H-F content.	[51]
2	Cement, Sand, Aggregate, Silica Fume, Fly Ash, Slag, Water, Polypropylene (P-P), Polyvinyl alcohol (P-V-A) and Steel (S) fiber.	1: 0.51: 0: 0: 0.12: 0 & w/c ratio 0.28. P-P-F length = 15-18mm. P-V-A length =12-15mm. S-F length = 12-14mm. Hybrid Fiber (H-F) = (P-P+S) content = (0.5+1.5, 0.67+1.33, 1+1, 1.5+0.5 %). (P-V-A+S) content = (0.5+1.5, 0.67+1.33, 1+1, 1.5+0.5 %).	C-S, F-S & S-T-S increased.	[19]
3	Cement, Sand, Aggregate, Silica Fume, Fly Ash, Slag, Water, Polypropylene (P-P), Steel (S) fiber and Crumb Rubber.	1: 1.68: 1.15: 0: 0: 0 & w/c ratio 0.45. P-P-F length = 3 mm. S-F length = 21 mm. Hybrid Fiber (H-F) = (P-P+S) content = (0+1, 0.1+0.9, 0.175+0.825, 0.25+0.75, 1+0 %).	C-S = Increased 48.02 MPa with 0.1+0.9 % H-F content. S-T-S = Increased 5.09 MPa with 0.1+0.9 % H-F content. As per PC.	[48]
4	Cement, Sand, Aggregate, Silica Fume, Fly Ash, Slag, Water, Macro Polypropylene (M-P-P) and Basalt (B) fiber.	1: 2.34: 3.09: 0: 0: 0 & w/c ratio 0.68. M-P-P-F length = 60 mm. B-F length = 20mm. Hybrid Fiber (H-F) = (P-P+B) content = (0+0.1, 0.3+0.1, 0.7+0.1, 0.1+0.1 %).	C-S = Increased 10 %. F-S = Increased 20 %. With (0.1+0.1 %) H-F content as per PC.	[57]

Note: Compressive strength (C-S), Flexure strength (F-S) and Splitting tensile strength (S-T-S).

damage to reinforced concrete caused by the service environment and exposure to toxic substances are widespread in real construction due to a lack of attention given to the earliest durability concerns [68]. The ability of a structural element to maintain its functionality and suitability throughout the intended service life, considering the environmental impact defined by the design as well as maintenance and usage requirements, is referred to as concrete structure durability [68]. Many of the durability issues associated with concrete, especially in harsh environmental conditions, are influenced by its porous structure and transport characteristics, particularly within the surface layer of the concrete. This surface layer acts as the primary barrier against harmful elements [69]. The deterioration of rebar in reinforced concrete is caused by aquatic environments and chloride ions present in de-icing salt. Corrosive ions in acidic conditions can also lead to concrete corrosion and expansion damage. Concrete structures in use are subjected to freeze-thaw cycles in the cold environments of the northern regions, resulting in devastating consequences [70]. The total air-void content, average chord length, spacing factor, and total chord length of the air voids can all be reduced by hybridization with SF (superplasticizer) and PF [71].

3.2. Adopted Remedial Measures

Most concrete durability problems, especially in harsh environmental conditions, are influenced by the pore structure and transport characteristics of concrete, particularly within the outer surface. This surface acts as

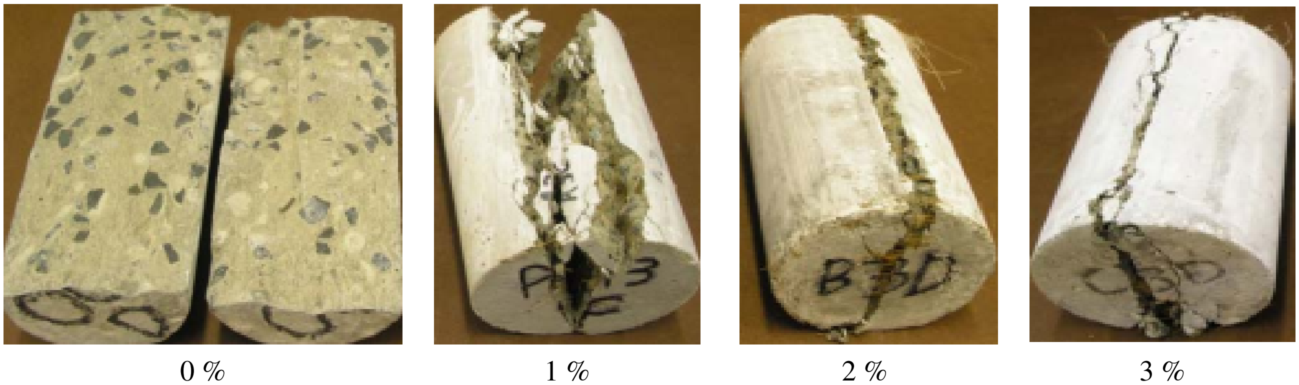

Fig. 4 – Behaviour of PC and CFRC under split-tensile strength [67].

the primary line of defense against harmful substances [69]. Polypropylene fiber-reinforced concrete exhibits more reliable performance in terms of mechanical and durability characteristics when compared to PC [11]. The study focused on the long-term durability of steel fiber-reinforced concretes. The specimens were subjected to specific laboratory conditions for 18 months, simulating severe environmental conditions. The compressive strengths of the control samples were compared to those of the samples exposed to severe weathering conditions. The study concludes that fiber-reinforced concrete exhibits durability even under severe weathering conditions [72]. The study focused on the applications of fiber-reinforced concrete in repair scenarios. Fiber-reinforced concrete has the ability to slow down concrete deterioration and protect reinforcing steel bars from corrosion. FRC is resistant to harmful liquids and gases, and it exhibits high durability even in adverse weather conditions [73]. An experiment was conducted to compare the performance of high-performance polypropylene fiber-reinforced concrete and steel fiber-reinforced concrete with varying percentages of fiber content. The addition of fibers to the concrete mix resulted in a reduction in the depth of chloride ion penetration. In this regard, high-performance polypropylene fiber-reinforced concrete proved to be more effective than steel fibers. Additionally, the water absorption test revealed that the inclusion of fibers in the concrete mix can reduce its water absorption capacity by 50 % [74]. The resistance of fiber-reinforced concrete to acid attack was investigated in a research laboratory by immersing samples in acetic acid for 27 months. The results indicated that lower pH solutions significantly reduced the residual strength and toughness of the concrete, although fiber-reinforced concrete exhibited superior durability compared to normal concrete.

In Table 4, the characteristics of different fibers from previous studies are presented. It is evident that these fibers offer excellent strength properties and various advantages, as highlighted by several investigators. Jute fibers stand out from other natural fibers due to their superior tensile fracture strength, lower density, affordability, and easy availability. Polypropylene fibers also possess several advantages, such as low thermal conductivity compared to other synthetic fibers, high energy absorption capacity, and zero water absorption. Glass fibers offer benefits like ductility and lightweight. However, it is not recommended to use the available variety of glass fibers (non-resistant to alkaline conditions) due to their low durability and unavailability of alkaline-resistant types locally. Similarly, steel fibers exhibit advantages such as zero water absorption and excellent ductility. However, their corrosive nature makes them unsuitable for application in concrete canal lining. Therefore, the selection of fibers is based on their superior tensile strength, low or zero water absorption capacity, and cost-effectiveness.

The effect of fibers on the freezing-thawing and sulfate resistance of shotcrete was investigated in an experimental study. The test results revealed that the addition of fibers to shotcrete significantly enhanced its frost resistance and resistance to sulfate corrosion, attributed to the significantly dense microstructure [81]. Another experimental study was conducted to investigate the influence of small fiber properties on the freeze endurance of fiber-reinforced cementitious mixes. The research demonstrated that the addition of fiber to

Table 4 – Characteristics of different fibers from previous studies [41, 42, 75, 76, 77, 78, 79].

Fiber	Advantages	References
Jute	Seven times lighter than steel fibers. High energy absorption capacity. High breaking strength, cheaply available.	[75, 77]
Polypropylene	Low specific gravity, more ductility, zero water absorption capacity, high elasticity and energy absorption, outstanding capability of oppose friction, bond by mechanical interaction with cement matrix and does not chemically interact with cement, lowest thermal conductivity among the available fibers.	[41, 42, 79, 80]
Nylon	Strong light weight, better resistive to heat and cold conductance, good tendency, toughness, and outstanding elastic recovery, zero water absorption stability, and exceptional capability of abrasion resistance	[41, 42, 76]
Glass	Low density, more ductility, light weight, energy efficient.	[42, 78]
Steel	High density, more ductility, energy efficient, zero water absorption.	[42]

cementitious composites enhanced their resistance to freeze-thaw cycles, while also highlighting the role of fiber properties in contributing to this improvement [82]. The inclusion of fibers in canal lining reduces crack propagation and, consequently, minimizes water losses. However, due to issues related to incorrect bonding and scattering, the presence of fibers in concrete, such PF, serves as a crack arrester while also impacting the fresh and hardened properties of the concrete [83].

3.3. Ageing Condition and Concrete Behaviour

The study results demonstrated the impact of harsh exposure environments on the performance of epoxy adhesive-bonded joints in concrete reinforced with glass fiber-reinforced polymers (GFRP). The specimens were subjected to three different aging conditions in the research laboratory for a period of approximately 9 months [84]. The objective of this study is to investigate the impact of environmental weathering on pre-stressed concrete beams. The beams consisted of one control mix, two beams with steel fiber-reinforced concrete, two beams with polypropylene fiber-reinforced concrete, and one beam with a combination of both fibers. The specimens were exposed to the open air in a naturalistic environment for a duration of 36 months. The results indicated that PF exhibited greater durability after exposure to natural weathering [85]. In this study, the durability of the bond between concrete and carbon fiber-reinforced polymer (CFRP) reinforcing systems was tested under rapid aging environments, such as at 40 degrees Celsius and 95 % relative humidity, for a duration of 21 months [86]. The deterioration process of epoxy coupons was observed through submersion in water or exposure to relative humidity for various durations: 100 % throughout, 2, 4, 8, and 12 weeks at temperatures of 30°C and 60°C. Based on the findings, researchers proposed conducting an 8-week submerged water test at the optimal temperature estimated in the field to assess the durability of fiber-reinforced polymers [87]. The research investigated the influence of hydrothermal aging-induced plasticization on the bond behavior of carbon fiber-reinforced polymer (CFRP) concrete joints. Following immersion in water at 30°C for durations ranging from 5 to 74 days, the overall failure load was reduced by 41 % and 67 % respectively [88].

A durability test was conducted on a hybrid fiber concrete cube by immersing it in various immersion mediums, including 5 % HCl, 5 % H_2SO_4, 5 % NaCl, and 5 % NaOH. Initially, the concrete cube was cured in a 5 % HCl solution for a duration of 84 days. Subsequently, the compressive strength of the cube was assessed at 28-day intervals. The same procedure was repeated to determine the compressive strength of concrete cubes immersed in the other mediums [89]. In all immersion media, the compressive strength of hybrid fiber concrete (HFC) samples showed significant enhancements compared to plain concrete samples. For example, the HFC samples exhibited improvements of

16.34 %, 19.05 %, 17.66 %, and 23.08 % in compressive strength in acid, sulfate, chloride, and alkaline media, respectively, when compared to plain concrete. This improvement can be attributed to the inclusion of fibers in HFC, which effectively filled the pores of the concrete and increased its load-bearing capacity [1].

The study investigated the impact of field exposure and rapid aging on the performance of FRP-strengthened notched beams subjected to a three-point bending test. The results revealed that rapid hygrothermal aging at 60°C tended to provide a conservative estimate of bonding capacity. However, hygrothermal aging through soaking at 30°C for 2 months produced values that were comparable to those observed in specimens exposed to field conditions for 18 months [90]. Rapid chloride permeability experiments were conducted for durations of seven days, 14 days, 28 days, and 56 days. Concrete samples were prepared with the incorporation of PF ranging from 0.1 % to 0.3 % and glass fibers ranging from 0.2 % to 0.4 %. The results demonstrated that the addition of both PF and glass fibers reduced the permeability of the concrete [11]. The interlocking bricks used for the mortar-free column were made from a novel material called coconut fiber reinforced concrete (C-FRC). C-FRC was produced using a mix design ratio of 1:4:2:0.64, which consisted of cement, sand, aggregates, and water. The concrete mixture included coconut fibers with a length of 5 cm, comprising 1 % of the fiber volume in relation to the mass of the concrete [91]. The performance of glass fiber-reinforced polymer (GFRP) reinforced concrete slabs, constructed using seawater-mixed concrete, was tested over the course of one, six, twelve, and twenty-four months under various environmental conditions. It was observed that the ultimate capacity of GFRP-RC slabs was influenced by the type of concrete mixture design and accelerated aging exposure [92].

3.4. FRC Durable Behaviour

The properties investigated in polypropylene fiber reinforced fly ash concrete included workability of fresh concrete, water absorption, unit weight, porosity, drying shrinkage, freeze-thaw resistance of hardened concrete, sorptivity coefficient, compressive strength, and modulus of elasticity. The study concluded that incorporating fly ash and PF in concrete enhances its durability [93]. Polypropylene fibers have been observed to effectively reduce shrinkage cracks and enhance the load-bearing capacity of concrete composites [94]. An investigation was conducted to assess the durability of plant fiber-reinforced alkali-activated composites under indoor, outdoor, and bagged conditions. The durability test, conducted over 360 days, revealed that the indoor specimens retained the highest percentage of bending strength, followed by the bagged samples, and finally, the outdoor samples [95].

In all immersion media, the compressive strength of hybrid fiber concrete (HFC) samples exhibited significant enhancements compared to plain concrete samples. For example, the HFC samples demonstrated improvements of 16.34 %, 19.05 %, 17.66 %, and 23.08 % in compressive strength in acid, sulfate, chloride, and alkaline environments, respectively, when compared to PC. This improvement can be attributed to the inclusion of fibers in HFC, which effectively fill the concrete's pores and increase its load-bearing capacity [89]. Polypropylene fibers have a positive impact on durability in terms of water absorption through immersion and capillarity. In polypropylene fiber-reinforced concrete, there is an 8 % reduction in water absorption. Conversely, the inclusion of steel fibers leads to a significant increase in water absorption by 5 % and sorptivity coefficient by 10 % compared to the control mix. When exposed to long-term natural weather conditions, fiber-reinforced prestressed concrete girders exhibited greater durability. Microstructural investigations of polypropylene fiber-reinforced concrete showed promising results in terms of durability, in contrast to steel fiber-reinforced concrete [85]. Reducing the presence of voids in concrete, which can be evaluated through water absorption, can enhance its toughness and post-cracking behavior. Concrete with improved toughness is more likely to enhance the long-term durability of hydraulic structures. Therefore, a material's superior post-cracking behavior can contribute to enhancing the long-term serviceability of a structure [96]. The study concluded by examining the behavior of concrete reinforced with soaked wheat straw, boiled wheat straw, and chemically treated wheat straw. It was reported that soaked wheat straw reinforced concrete, with a 1 % content, exhibited a significant increase of 91 % in compressive toughness index, 92 % in flexural toughness index, and 105

PC CFRC PC CFRC

(a) (b)

Fig. 5 – Graphical representation of coir fiber reinforced concrete specimens for (a) S-T-S of coir fiber reinforced concrete; and (b) F-S coir fiber reinforced concrete [99].

% in splitting-tensile toughness index compared to plain concrete (PC) [97]. For enhanced performance at an affordable cost, locally available natural fibers with superior tensile strength, such as sisal, can be incorporated into plaster with a water-to-cement ratio (W/C ratio) of 0.67. It is recommended to add 2 % fibers by weight of cement. To achieve optimal results, it is advisable to apply a thin fibrous plastering layer with a thickness of 8 to 10 mm [98]. Fig. 5 shows the pictorial view of the specimens for S-T-S (Split-Tensile Strength) of coir fiber reinforced concrete (CFRC) and F-S (Flexural Strength) of coir fiber reinforced concrete [99].

4. Canal Sections

4.1. Performance of Different Canal Sections

An assessment was conducted on the efficiency of an irrigation water conveyance canal located in northern Iran. The findings revealed that the canal, in its current operational and physical condition, was insufficient in adequately distributing the available water among all upstream and downstream consumers satisfactorily. The results indicated that implementing the proposed modifications would reduce the measure of inequality by 71.7 %, thereby leading to a more equitable enhancement in the overall efficiency of the canal [100]. Irrigation canals play a crucial role in providing moisture to plants. The efficiency of the Mundoghat canal is assessed using several indicators in a modest approach. The indicators revealed that the Mundoghat canal has an availability of 82 %, reliability of 77 %, equality of 86 %, and a transportation capacity of 89 % [101]. Manning's roughness values and Kostiakov soil infiltration variables were determined by applying Manning's equation and a surface irrigation simulation model. By utilizing optimal ratios of input rate and cut-off ratio, and taking into account temporal variations in soil infiltration and Manning's roughness, it is possible to improve water application performance and ensure sustainable utilization of limited water resources [102]. These findings present encouraging evidence of the potential for irrigation management independence to enhance water management effectiveness. However, it is important to note that these findings should not be interpreted as direct consequences of water user association efficiency. Instead, the results suggest that foundational community factors and social relationships may have an impact on both water user association efficiency and on-farm water use efficiency performance [103]. Due to sediment deposition, waterlogging, and leakage, the performance of irrigation canals has been compromised, potentially leading to a decrease in the amount of water available for agricultural production. This, in turn, affects the demand for water and can result in insufficient water capacity for farming activities. It has been concluded that improperly designed outlets can cause several issues, including variations in discharge coefficients, inequitable water distribution, canal siltation, inadequate water availability at lower outlets, lack of incentives for water conservation, and insufficient drainage. Faulty outlets are also a major contributing factor to canal siltation [104].

4.2. Flaws/Defects in Canal Lining Sections

The destruction of the canal lining due to frost heaving and the stress distribution identified by the mechanical model can serve as references for designing canal linings. It has been observed that the highest normal stress and tangential stress increase with improvements in the subgrade coefficient and frost heave quantity, while the shear modulus and transition section length decrease. Through the investigation of a water transportation lined canal in the Xinjiang Tarim irrigation district, it was found that the extreme normal stress in the critical lining cross-section exceeds its tensile strength. This repetitive occurrence leads to a detrimental cycle of frost heave, leakage, damaged lining, and further intensified frost heaving in the canal water transportation system [105]. Water scarcity has led farmers in irrigation districts to turn to groundwater as an alternative resource. In such circumstances, reducing water losses resulting from inappropriate operational management within the districts can help mitigate the increasing trend of groundwater overexploitation [106]. Seepage from unlined irrigation canals is a significant contributor to groundwater recharge in various regions worldwide, especially in arid and semi-arid areas. In the case study of the Ismailia canal, the main distribution canal of the River Nile in Egypt, it was observed that seepage losses occur along its entire length of 129.5 km. In this scenario, the minimal seepage losses amount to approximately 7.3 % of the total canal discharge [107].

The most challenging issues in canal lining structures are cracks and settlement. Establishing a reliable correlation between frozen soil and canal lining is crucial for quantitatively simulating the damage process of the lining through mechanical assessment and direct shear tests. Large volumes of migrating water accumulate and freeze beneath north-facing slopes, posing a significant risk of damage to the lining [108]. Fig. 6 shows observed cracks in concrete canal lining, including: a) diagonal cracking, b) concrete deterioration, and c) relatively parallel cracking [109].

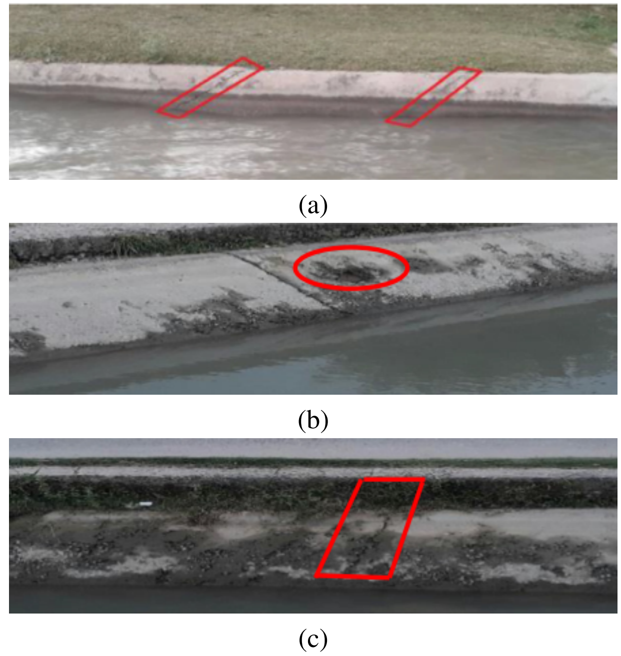

Fig. 6 – Observed cracks in concrete canal-lining, a. diagonal cracking, b. concrete deterioration and c. relatively parallel cracking [109].

4.3. Remedial Measures Adopted for Losses Reduction in Developing Country

The ultimate goals of the irrigation system model provide managers with a practical approach to establish a canal water supply program that aims to maximize irrigation performance while minimizing the risk of excessive burden [110]. The expansion of irrigated agriculture leads to waterlogging and salinization problems in agricultural fields due to significant seepage into the groundwater. These issues are primarily caused by poor water management, percolation from irrigation areas, inadequate drainage, substantial seepage losses from unlined irrigation networks, and the presence of low-lying regions [111]. An irrigation canal is a hydraulic network designed to transport water from water sources such as rivers and dams to various users. In order to meet the water demands of canal water consumers, the water manager must monitor all water supplies throughout the irrigation period and adjust the positions of canal gates in real-time based on water requirements [112]. Effective management of irrigation canals is crucial for efficient water distribution. In the case study of the Chinese South to North Water Diversion Project, which utilized various sensors, comprehensive measures were implemented through numerical simulation. Experimental results under multiple test conditions showed that employing a Reward Network process can lead to significant efficiency improvements compared to state-of-the-art model-free methods [113]. The model is built upon the Saint-Venant equations and incorporates the Hartree approach. The precision and effectiveness of the algorithm were evaluated through two evaluations conducted by the ASCE Committee on Canal Automation Algorithms. The solution that demonstrated the highest performance across various systems is the one that leverages the advantages of this method [114]. A water balancing technique allows for the tracking of various volume inputs within a system, including conveyed water, water abstractions, surface runoff or precipitation, approved and unapproved consumption, and water losses within canals. The findings indicate that water losses resulting from canal system flows can be a significant contributor to non-revenue water, accounting for nearly half of its total volume. These losses are primarily caused by metering errors and canal leakage [115].

A study was conducted on an irrigation district in southern California, where remotely sensed outputs and ground-based data were combined in a geographical information system environment to quantify various drainage and irrigation efficiency indicators. Based on the outcomes of two indicators assessing the magnitude and uniformity of groundwater depth, it was found that the extensive system of open drains is operating at an optimal level [116]. A hydrological irrigation optimized modeling system was developed to optimize irrigation techniques for a conventional rice irrigation network in Central Vietnam. The simulations indicated that the reservoir's initial water level is crucial: below 90 %, insufficient water may be available for the entire cropping field, with levels below 70 % limiting the field to 75 %. Implementing alternative wetting and drying techniques can reduce water usage by up to 10 % [117]. To enhance farmer cooperation and social capital, development agents should facilitate the organization of farmer communities, such as farming cooperatives, enabling them to actively participate in the maintenance of interactive irrigation infrastructure. Additionally, irrigated farmland should be allocated to farmers who have a moderate capacity for cost and can consistently contribute to the maintenance of the irrigation system [118].

4.4. Role of FRC in Canal Sections

With The concrete splitting tensile strength was enhanced with the increase in SF content. Initially, the splitting tensile strength also increased with the increase in PF content, but later it started to decrease [119]. Polypropylene fiber was incorporated as reinforcement at volume contents of 3 kg/m, 6 kg/m, and 10 kg/m in high-strength self-consolidating concrete. Fiber-reinforced concrete has been widely used in various construction applications, and several testing procedures have been established to assess its mechanical performance [120]. Jute hemicellulose can be extracted from JF by immersing them in an alkaline solution. The overall mechanical and physical tests, as well as SEM analysis, demonstrated that the proper utilization of JF effectively addresses microcracks in the composite, reduces the porosity of the concrete structure, and helps prevent the formation of new cracks [121]. The use of inside curing in ultra-high-performance concrete (UHPC) enhanced the strength of the composite; however, it also increased the risk of spalling at higher temperatures . Among all the mixtures, a volume content of 0.5 % of alkali-activated fly ash (AJF) was found to be the most optimal option [122]. Fig. 7 represents the graphical depiction of the bridging effect exhibited by specimens with sisal fiber-reinforced plaster (a) and rice straw-reinforced plaster (b) [123].

(a) (b)

Fig. 7 – Graphical representation of bridging effect of concrete specimens with (a) Sisal fiber reinforced plaster; and (b) Rice straws reinforced plaster [123].

Engineered cementitious composite (ECC) incorporating waste fine river sand (WSRS) and PF is an economical and sustainable cement-based composite material known as WSRSPP-ECC. This material exhibits deformation hardening and multi-cracking properties, making it suitable for engineering applications. The combination of WSRSPP-ECC, achieved by substituting polyvinyl alcohol fiber (PVF) and silica sand with PF and waste fine river sand, can result in cost savings while preserving physical efficiency. This combination effectively addresses issues related to river channel sedimentation and blockage [124].

Fiber-reinforced concrete (FRC) is being used in the construction and repair of dams and other hydraulic structures to enhance resistance to cavitation and severe erosion caused by the impact of large waterborne debris [125]. Fiber-reinforced concrete pavements have been proven to be more efficient than conventional reinforced concrete pavements in several aspects. FRC has been successfully utilized in various applications, including slabs on grade, architectural panels, precast products, offshore structures, structures in seismic regions, thin and thick repairs, crash barriers, footings, hydraulic structures, and many more [126].

5. Design of Canal Sections

5.1. Issues in Normal Canal Lining Construction

Water losses at the delivery level averaged approximately 50 %, but through the improvement of real-time canal operation, including self-regulation, these losses could be reduced to less than 10 %. Furthermore, a reduction in water usage and peak demand could allow for a decrease in water withdrawals from reservoirs and rivers, as well as improvements in transport and distribution infrastructure such as canals and pumping stations [127]. Operational strategies for canal irrigation systems are often designed based on historical irrigation management practices in various Chinese irrigation districts. However, the more water is retained in the canal system, the greater the additional irrigation water lost due to leakage. Therefore, it is crucial to establish irrigation water allocation patterns for canal systems, appropriately schedule the operations of canal networks, and achieve improved system efficiency [128]. Deep percolation (DP) losses were investigated under drip and flood irrigations. The simulated results indicated that yearly DP losses for flood irrigation were approximately 347 mm, which was higher compared to drip irrigation, where the losses were about 93 mm. This suggests that flood irrigation accounted for around 56 % of water supply losses, while drip irrigation accounted for approximately 20 % [129].

The effects of frost heaving on the structure were found to be diverse, with concrete cracks occurring in various locations and directions. The primary factor contributing to frost heave is the restriction imposed by the canal lining on the deformation of frozen soil. Consequently, the frost heaving action of frozen soil on the canal lining slab can be categorized into standard frost heave force and transverse frost heave force, leading to a complex bending condition for the slab lining [130].

5.2. Design of Canal Sections

An updated tool for soil and water assessment was used to simulate hydrological processes under various water-saving scenarios in the Yangshudang watershed within the Zhanghe Irrigation networks in Hubei Province, China. The results indicated that irrigation performance and water-saving potential improved with the implementation of water-saving measures [131]. A novel construction called the rotary gate is introduced for regulating and controlling flow in canals with semi-circular or semi-elliptical cross-sections. The effects of gate opening angles on flow depths, discharge measurements, and coefficients of discharge in free flow were investigated using various methods [132]. For example, improving the design of irrigation canals can reduce water losses caused by seepage and evaporation. In this study, a proposed particle swarm optimization technique was applied to design the El-Sheikh Gaber canal in the north Sinai Peninsula, Egypt, and the resulting dimensions were compared to the actual canal dimensions. The findings demonstrate a decrease in total cost ranging from 28 % to 41 % [133]. When designing irrigation canals, various parameters and steps need to be considered, including depth, flow rate, side slopes, bottom depth, and lined sections. Estimating the normal depth is particularly important in irrigation canal design. Additionally, the normal depth serves as a significant variable in studying non-uniform flow. The resistance equation for open channels is used to determine uniform flow in a canal, with Robert Manning, an Irish engineer, credited for developing the most widely used resistance equation,

$$V = \frac{1}{n} R^{2\backslash 3} S^{1\backslash 2} \tag{1}$$

Where, V = average velocity of flow; n = Manning's roughness coefficient; So = channel bed slope; and R =A/P i.e. hydraulic radius defined as the ratio of flow area A to the flow perimeter P as shown in Equation 1. Triangular sections are commonly used for transporting minor discharges, with a side slope of 1 horizontal to 1 vertical. For medium discharges, rectangular sections are the most commonly adopted canal shape, while they are not recommended for transporting larger discharges. This is because vertical sidewalls in rectangular sections require greater thickness to withstand earth pressure, whereas sloped side walls require less thickness. In irrigation canals, semicircular sections are frequently used for minor flows, while circular sections are preferred for larger flows. Circular sections have the smallest flow perimeter for a given area and provide the highest flow velocity [134, 135]. Equations specific to the design parameters of canal sections with reduced seepage loss were developed for each of the three canal shapes. This was achieved by employing a nonlinear optimization approach that utilized seepage loss equations and the general uniform flow equation. Among the three optimal sections, the trapezoidal section yielded the least amount of seepage loss. Additionally, the cross-sectional area between the three optimal sections was found to be the smallest [136]. A rigid boundary canal is designed for uniform flow conditions. Typically, an average flow velocity ranging from 0.6 to 0.9 m/sec is sufficient to prevent sedimentation when the silt load of the flow is low, while a velocity of 0.75 m/sec is generally enough to prevent vegetation growth. Therefore, the minimum acceptable velocity can be assumed to fall within the range of 0.75 to 0.9 m/sec [2].

5.3. Material Related Variables in Design Equation

The rate of cracks in a lined concrete canal is influenced by various factors such as permeability, shrinkage, water absorption, tensile strength, and differential settlement [137]. Controlling shrinkage cracks is possible unless the tensile stresses resulting from shrinkage are greater than the concrete's tensile strength. This highlights the importance of concrete's tensile strength in preventing shrinkage cracking. Additionally, the rate of deterioration of a lined concrete canal increases as the rate of water absorption rises [138]. Bending stresses occur in a concrete structure as a result of differential settlements in the concrete canal lining. If the flexural strength of concrete, also known as bending strength, exceeds the bending stresses, cracks caused by differential settlement can be minimized. The study revealed several advantages of woven JF reinforced polymer (RP) retrofitting arrangements over CF-RP and GF-RP retrofitting arrangements. Furthermore, the use of woven JF RP retrofitting arrangements transformed the brittle failure mode of beams into a ductile failure mode [139]. The quantity of water flowing in canals is influenced by various factors, including the canal's slope, shape, and roughness. Manning's equation is used to describe this relationship. In both natural and constructed canals, the Manning's roughness coefficient is affected by canal irregularity, surface roughness, silting, scouring vegetation, canal alignment, canal size and shape, discharge, blockage, suspended material, seasonal variation, and bed loads [140]. When assessing bedload transport and the aquatic biological environment in rivers, it is crucial to quantify the initial mobility of sediment in open channels with vegetation [141]. During the design process of a canal with a uniform depth profile that corresponds to the required discharge, using a Manning's coefficient is sufficient for maintaining effective conditions. However, as the condition of the canal deteriorates due to obstacles, vegetation overgrowth, and sediment deposition, the discharge of the canal decreases [142]. Based on the findings, the values of Manning's roughness were determined by using Manning's velocity equation at specific measurement locations along the primary, secondary, and tertiary irrigation canals in the study area. The equation for the roughness coefficient is shown below:

$$n = \frac{R^{2\backslash 3} S^{1\backslash 2}}{V} \tag{2}$$

Where n = Manning's roughness coefficient of canal; R = hydraulic radius; S = slope; and V = velocity. At each measurement location, the value of R was calculated as the ratio of the cross-section area to the water's height A and wetted perimeter P. The average velocity at the measurement stations on such canals was used to determine the V [107, 143].

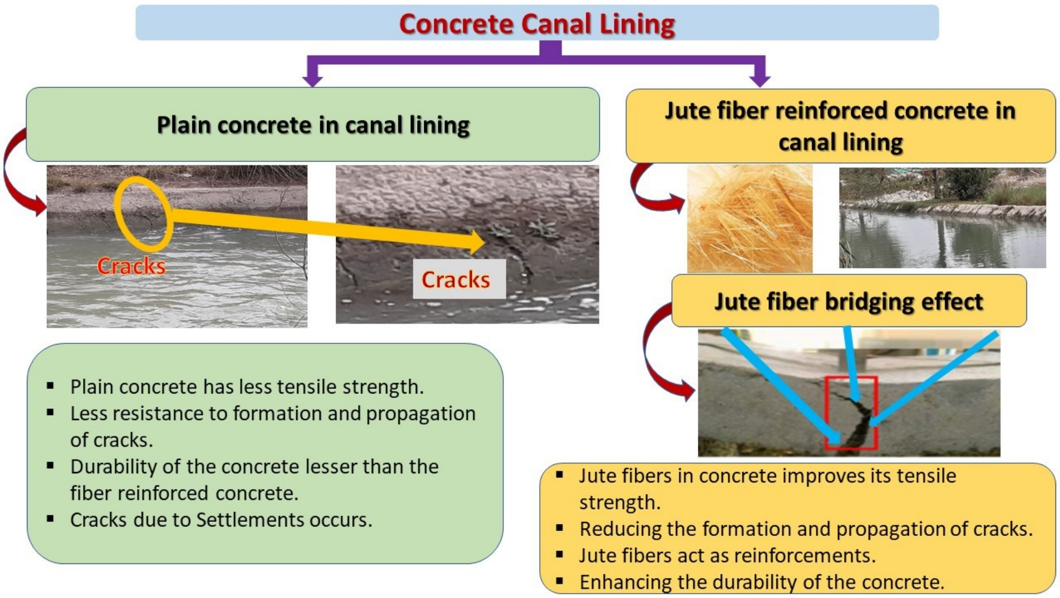

Fig. 8 – Pictorial view of concrete canal lining with PC and JFRC.

5.4. Effectiveness of FRC

Natural JF (jute fiber) can be a beneficial material for enhancing the strength of Fiber Reinforced Composites (FRC). Research investigates the impact of JF on the tensile and compressive strengths of these composites. It was observed that the experimental strengths deviated by approximately 5 % from the predicted values, indicating some variation in the optimum values [144]. Observations revealed that paver blocks containing 1 % modified JF (jute fiber) by weight exhibited enhanced strength characteristics. Specifically, compared to plain blocks, the modified blocks demonstrated a significant increase in flexural strength (49 %), compressive strength (30 %), and flexural toughness (166 %) [145]. To examine the seismic behavior of high-performance polypropylene fiber-reinforced lightweight aggregate concrete (HPPLWC) columns, seven samples were tested alongside three lightweight aggregate concrete (LWAC) column samples. The lower cycle reciprocating loading was applied during the testing process. It was observed that the incorporation of extra high-performance PF (polypropylene fiber) effectively prevented crack growth and improved the failure mode of the composites. Notably, the high-performance PF had a significantly greater impact on the ductility and energy dissipation of the samples compared to increasing the stirrup ratio [146]. The results of the study indicated that the inclusion of waste polypropylene carpet fiber and palm oil fuel ash (POFA) in concrete led to improvements in one-year drying shrinkage, creep performance, and concrete strength. The combination of carpet fibers and POFA contributed to enhanced long-term compressive strength of the concrete [147]. The loss in permeability of the PFRC (Polymer Fiber Reinforced Concrete) was studied. The results indicate that the addition of PF (Polymer Fiber) improves the impact of curvature and roughness on the permeability of damaged concrete [148]. The study investigated the impact of a fast, acid-catalyzed sol-gel silica nano-coating on the mechanical strength of draw-wire PF (Polymer Fiber) used as dispersed reinforcement in Fiber Reinforced Concrete (FRC). The findings revealed that the silica coating provides greater benefits in terms of enhancing the bond strength between the fiber and the matrix [149]. Due to their low cost and high specific strength, natural fibers are often utilized as alternatives to artificial fibers like GF (Glass Fiber) and CF (Carbon Fiber). Moreover, reinforcing polyester bars with natural yarns leads to a remarkable enhancement in the stiffness, tensile strength, and ductility of the composites [150]. In coir fiber reinforced concrete with a 3 % coir fiber content, the S-T-S (Splitting Tensile Strength) and M-O-R (Modulus of Rupture) are improved. The pullout of fibers remains consistent even with higher coir fiber content. By implementing chemical coatings on the fibers to limit fiber pullout, it is possible to further increase the M-O-R [67].

Table 5 – Mix design, fiber length and mechanical properties of FRC from previous studies.

Fiber content	Mix design ratio	Fiber length (mm)	C-S (%)	S-T-S (%)	MoR (%)	References
PC	-	-	100	100	100	-
			JFRC			
0.6 kg/m^3	1:1.74:3.24	30	119	-	154	[153]
1 %[a]	1:1.5:3	40	128	112	144	[164]
4.4 kg/m^3	1:1.5:2.7	50	106	-	111	[75]
0.25 %[b]	1:1.5:3	15	105	105	119	[162]
0.50 %[b]	1:1.5:3	15	98	78	90	
0.25 %[b]	1:2:4	15	102	101	111	
0.50 %[b]	1:2:4	15	88	113	101	
			PFRC			
0.25 %[a]	1:1.5:3	24	106	172	-	[163]
1.5 %[b]	1:1.5:3	12	134	140	-	[156]
1 %[b]	1:1.27:2.76	12	107	119	118	[157]
0.25 %[b]	1:1.27:2.76	12	103	107	105	
1 kg/m^3	1:1.36:2.52	54	104	113	102	[159]
2 kg/m^3	1:1.36:2.52	38	84	118	115	
			NFRC			
5 %[a]	1:3.33:1.67	50	94	108	103	[165]
1 %[b]	1:1,22:2.8	45	108	110	113	[155]
1.5 %[b]	1:1,22:2.8	45	94	94	93	
1 %[b]	1:1.5:3	20	127	112	-	[158]

[a] content by mass of cement,

[b] content by volume fraction of concrete.

The utilization of surface-modified JF as reinforcement in concrete paver blocks has been proven to enhance their mechanical properties and prolong their service life. This improvement can potentially reduce the life cycle cost associated with the paver blocks [145]. The incorporation of jute fiber in concrete resulted in improved mechanical strength, including compressive, split tensile, and flexural strength. Additionally, the inclusion of JF enhanced the durability performance of the concrete, including improvements in density, water absorption, dry shrinkage, and resistance to acid [151]. To achieve optimal strength, a volume fraction of 1 % of nylon and JF is recommended for cement concrete [152]. Flexural strength and impact resistance tests were conducted on small slab panels made of PC and JFRC, both with and without steel reinforcements. The results showed a significant enhancement in the impact resistance of the concrete with the incorporation of jute fibers. In fact, the impact resistance of JFRC was found to be up to six times higher compared to PC [37]. In Fig. 8 pictorial view of concrete canal lining with PC and JFRC are shown.

Table 5 presents the mix design, fiber length, and mechanical properties of FRC from previous studies. The results of previous investigations on JFRC, Natural Fiber Reinforced Concrete, and Polypropylene Fiber Reinforced Concrete (PPFRC) mix designs, including fiber content and fiber length, are presented. For JFRC, mix proportions of 1:1.74:3.24, 1:1.5:3, 1:1.5:2.7, and 1:2:4 with fiber contents of 0.6 kg and 4.4 kg per 1 m^3 of concrete, 1 % by mass of cement, 0.25 %, and 0.50 % by volume content of concrete were used. The fiber lengths were 15 mm, 30 mm, 40 mm, and 50 mm. The developed compressive strength (C-S), splitting tensile strength (S-T-S), and modulus of rupture (MoR) of JFRC were found to be in the range of 88 % - 128 %, 78 % - 113 %, and 90 % - 154 %, respectively, compared to Plain Concrete (PC). For NFRC, mix proportions of 1:3.33:1.67, 1:1.22:2.8, and 1:1.5:3 with fiber contents

Fig. 9 – Cracks experimental behaviour for JFRC compressive testing [37].

of 5 % by mass of cement, 1 %, 1.5 %, and 2 % by volume content of concrete were used. The fiber lengths were 12 mm, 20 mm, 24 mm, and 45 mm. The developed C-S, S-T-S, and MoR of NFRC were found to be in the range of 94 % - 127 %, 94 % - 169 %, and 93 % - 113 %, respectively, compared to PC. For PPFRC, mix proportions of 1:1.5:3, 1:1.27:2.76, and 1:1.36:2.52 with fiber contents of 1 kg and 2 kg per 1 m^3 of concrete, 0.25 % by mass of cement, 0.25 %, 1.5 %, and 1 % by volume content of concrete were used. The fiber lengths were 12 mm, 24 mm, 38 mm, and 54 mm. The developed C-S, S-T-S, and MoR of PPFRC were found to be in the range of 84 % - 134 %, 107 % - 140 %, and 102 % - 118 %, respectively, compared to PC. The permeability of PPFRC was also reported for water penetration using a mix proportion of 1:1.38:1.75 with fiber contents of 0.5 kg, 0.7 kg, 0.9 kg, 1.5 kg, 2 kg, and 4 kg per 1 m^3 of concrete with fiber lengths of 12 mm. The water penetration depth ranged from 8.5 mm to 9.5 mm. The specimen with 0.7 of fiber content showed the lowest water penetration depth of 7.7 mm, which was a 30 % decrease compared to PC. For PPFRC with a mix proportion of 1:1.62:2.48 and fiber contents of 0.05 %, 0.10 %, and 0.15 % by volume content of concrete, and a fiber length of 18 mm, a 40 % decrease in drying shrinkage was observed compared to PC. To date, no research has been conducted to compare the effects of JF and PF on the mechanical characteristics, water absorption, and linear shrinkage of concrete. Table 5 presents the mix design, fiber length, and mechanical properties of FRC from previous studies. The results of previous investigations on JFRC, Natural Fiber Reinforced Concrete, and Polypropylene Fiber Reinforced Concrete (PPFRC) mix designs, including fiber content and fiber length, are presented. For JFRC, mix proportions of 1:1.74:3.24, 1:1.5:3, 1:1.5:2.7, and 1:2:4 with fiber contents of 0.6 kg and 4.4 kg per 1 m^3 of concrete, 1 % by mass of cement, 0.25 %, and 0.50 % by volume content of concrete were used. The fiber lengths were 15 mm, 30 mm, 40 mm, and 50 mm. The developed compressive strength (C-S), splitting tensile strength (S-T-S), and modulus of rupture (MoR) of JFRC were found to be in the range of 88 % - 128 %, 78 % - 113 %, and 90 % - 154 %, respectively, compared to Plain Concrete (PC). For NFRC, mix proportions of 1:3.33:1.67, 1:1.22:2.8, and 1:1.5:3 with fiber contents of 5 % by mass of cement, 1 %, 1.5 %, and 2 % by volume content of concrete were used. The fiber lengths were 12 mm, 20 mm, 24 mm, and 45 mm. The developed C-S, S-T-S, and MoR of NFRC were found to be in the range of 94 % - 127 %, 94 % - 169 %, and 93 % - 113 %, respectively, compared to PC. For PPFRC, mix proportions of 1:1.5:3, 1:1.27:2.76, and 1:1.36:2.52 with fiber contents of 1 kg and 2 kg per 1 m^3 of concrete, 0.25 % by mass of cement, 0.25 %, 1.5 %, and 1 % by volume content of concrete were used. The fiber lengths were 12 mm, 24 mm, 38 mm, and 54 mm. The developed C-S, S-T-S, and MoR of PPFRC were found to be in the range of 84 % - 134 %, 107 % - 140 %, and 102 % - 118 %, respectively, compared to PC. The permeability of PPFRC was also reported for water penetration using a mix proportion of 1:1.38:1.75 with fiber contents of 0.5 kg, 0.7 kg, 0.9 kg, 1.5 kg, 2 kg, and 4 kg per 1 m^3 of concrete with fiber lengths of 12 mm. The water penetration depth ranged from 8.5 mm to 9.5 mm. The specimen with 0.7 kg/m^3 of fiber content showed the lowest water penetration depth of 7.7 mm, which was a 30 % decrease compared to PC. For PPFRC with a mix proportion of 1:1.62:2.48 and fiber contents of 0.05 %, 0.10 %, and 0.15 % by volume content of concrete, and a fiber length of 18 mm, a 40 % decrease in drying shrinkage was observed compared to PC. To date, no research has been conducted to compare the effects of JF and PF on the mechanical characteristics, water absorption, and linear shrinkage of concrete.

The study also demonstrates the advantages of polymer fiber when used in composites exposed to higher temperatures. The presence of fibers in a mixture increases the resistance of concrete to spalling and ensures a safe environment with minimal pore pressure in the composite microstructure under elevated heat conditions. Consequently, the variation in compressive strength of the composite is minimal [166]. The proposed conversion relations among the strength indexes for recycled concrete with a 50 % replacement ratio are simple and achievable, considering the different content of Blast Furnace slag (BF). These relations demonstrate the composite influence between BF and recycled coarse aggregate, providing insights into the reinforcing mechanism of BF on RC [167].

Fig. 9 illustrates the behaviour of JFRC specimens and the progression of cracks. The stress-strain curves for PC and JFRC are presented. In PC, the first crack appears at 99 % of the maximum load, while in JFRC, it occurs at 88 % of the maximum load. The cracks in JFRC are significantly smaller in width and length compared to PC. As PC reaches its maximum load, the number and size of cracks increase significantly, whereas JFRC exhibits fewer cracks. At the ultimate stage, fragments of concrete detach from the top of PC specimens, while JFRC only experiences an increase in the number and size of cracks. The improved performance of JFRC can be attributed to the bridging effect of JF. To understand the failure mechanism of the fibers, deliberate breaking of JFRC specimens is conducted, resulting in 70 % fiber breakage and 30 % fiber pull-out. The higher breakage of JF is due to their lower tensile strength [37].

6. Discussion

The rapid growth in the construction sector's infrastructure utilizes massive amounts of energy and natural resources, resulting in human-caused emissions. Nowadays, one of the primary goals of the century is to follow a roadmap towards sustainable development, achieving a balance between current socio-economic requirements and a sustainable, greener environment for future generations. In this context, the construction industry plays a crucial role in meeting these three sustainability objectives. Cement-based composites, as the most widely used material in the construction field, are instrumental in creating a secure and sustainable environment for the global population. The annual global cement production currently exceeds 4.4 billion tons, with a projected increase to over 5.5 billion tons by 2050 [1]. On the other hand, cement-based composites possess inherent weaknesses, including low tensile strength and vulnerability to cracking [2, 3]. Incorporating natural and artificial fibers into concrete can help mitigate environmental pollution and promote sustainability in concrete production. Fiber reinforced concrete has a wide range of applications, including sewer pipes, precast concrete panels, thin concrete shell roofs, and tunnel linings.

The Fig. 10 presents a percentage comparison of the environmental impacts of ordinary facades reinforced by steel reinforcement (ORC) and three types of textile reinforced concrete (TRC). The global warming potential (GWP) was 100 % for V1 ORC, while V2 (TRC-glass) and V4 (TRC-basalt) had a GWP of 50 %, and V3 (TRC-carbon) had a GWP of 75 %. The abiotic depletion (ADP) increased to 200 % for V2 compared to 100 % for V1, with V3 at 90 % and V4 at 80 %. Furthermore, the ozone depletion increased to 300 % when ORC (V1) was replaced by TRC (V2, V3, and V4)

Therefore, natural fibers are emerging as a long-term solution to address the inherent flaws of traditional cement composites with minimal negative environmental consequences. Natural fibers not only help reduce global warming potential and energy usage but also contribute to lower production costs and environmental benefits. Natural fiber reinforced concrete is less expensive to produce, requires less energy, and has a positive environmental impact. The high environmental effectiveness of natural fiber reinforced concrete is a crucial consideration in construction to mitigate environmental impacts while maintaining desired mechanical properties [4]. While investigators have placed significant emphasis on the mechanical properties of FRC, they have often neglected to thoroughly examine the environmental effects of natural fibers used in construction. The environmental repercussions of various types of natural fibers have been overlooked. This study aims to provide a comprehensive exploration of the environmental

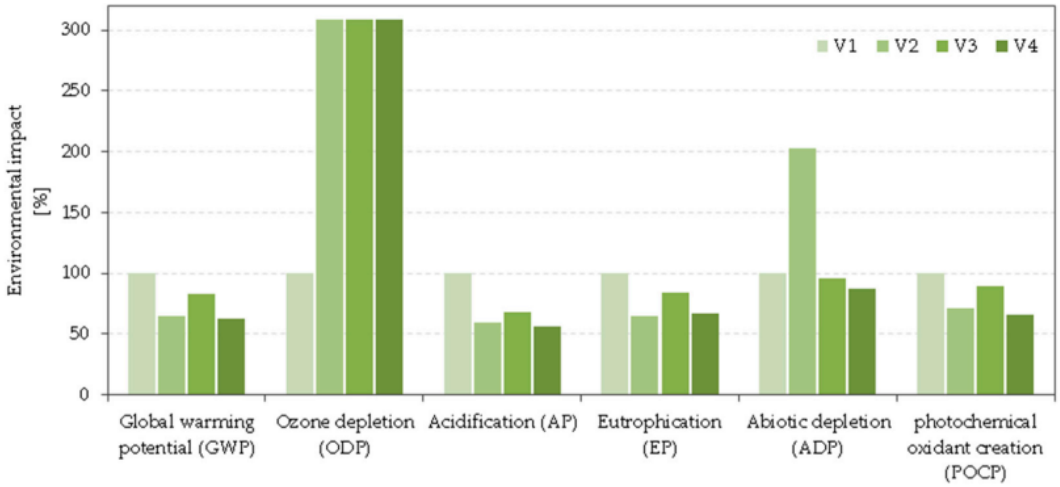

Fig. 10 – Percentage comparison between ORC and TRC on assessed environmental impacts [168].

impacts associated with different waste natural fibers and waste artificial fibers reinforced cement composites. The study focuses on evaluating the mechanical, environmental, and economic performance of these materials. Ultimately, the study proposes different levels of FRC, offering readers guidance in selecting the most suitable cement composite that balances superior mechanical performance, minimal environmental impacts, and cost effectiveness for concrete canal lining.

7. Conclusions

1. Using natural and artificial fibers in concrete reduces pollution, enhances sustainability, and provides a long-term solution to the limitations of traditional cement composites with minimal environmental impact.
2. This review examines the mechanical, environmental, and economic aspects of waste natural fibers and waste artificial fibers reinforced cement composites. It suggests optimal fiber-reinforced composite levels for selecting the most suitable cement composite with improved mechanical performance, minimal environmental impact, and cost-effectiveness for concrete canal lining.
3. Jute and other natural fibers have been proven to enhance the strength of fiber-reinforced concrete (FRC), resulting in improved mechanical properties such as tensile and compressive strengths, flexural toughness, and energy dissipation.
4. Previous studies have demonstrated that the use of various fibers, including jute, natural, and synthetic fibers, in fiber-reinforced concrete (FRC) with different fiber content and length leads to enhanced mechanical properties. These improvements include reduced water penetration, drying shrinkage, and superior mechanical performance compared to plain concrete.
5. Incorporating hybrid fibers in concrete canal lining increases flexural and tensile strength, thereby minimizing seepage losses during the water transport process in irrigation canals.
6. Hybrid fibers, like polypropylene and jute fibers, can enhance concrete's mechanical properties, improve durability, and reduce crack propagation in canal lining. Incorporating hybrid fibers in canal lining reduces cracks and settlement in lined canal structures, minimizing issues such as sedimentation, leakage, waterlogging, and improving the overall performance of irrigation canals.
7. Prototype canal sections with hybridized fiber-reinforced concrete can prevent cracks, enhance canal efficiency, and address construction-related weaknesses in canal lining design.
8. Hybrid fibers can effectively reinforce concrete and address its limitations. In real field canals, utilizing hybrid fiber-reinforced concrete for lining can minimize water losses.
9. Further study should be carried out to investigate the in-depth behavior of hybrid fiber reinforced

concrete for concrete canal lining application and optimize the content of fibers for the best performance.

CRediT authorship contribution statement:

Ali Rehman: Conceptualization, Methodology, Investigation, Formal analysis, Writing-original draft preparation, Writing-Review & editing.
Majid Ali: Conceptualization, Methodology, Investigation, Writing-review & editing, Supervision.

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.

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