Experimental Properties Evaluation of Fiber Reinforced Concrete related to Canal-lining

By

Asad Zia

(MCE153015)

MASTER OF SCIENCE IN CIVIL ENGINEERING
(With Specialization in Structures)

DEPARTMENT OF CIVIL ENGINEERING

CAPITAL UNIVERSITY OF SCIENCE & TECHNOLOGY

ISLAMABAD, PAKISTAN

AUGUST 2017

Experimental Properties Evaluation of Fiber Reinforced Concrete related to Canal-lining

By

Asad Zia

(MCE153015)

A research thesis submitted to the Department of Civil Engineering,
Capital University of Science & Technology, Islamabad, Pakistan
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING
(With Specialization in Structures)

DEPARTMENT OF CIVIL ENGINEERING

CAPITAL UNIVERSITY OF SCIENCE & TECHNOLOGY

ISLAMABAD, PAKISTAN

AUGUST 2017

CAPITAL UNIVERSITY OF SCIENCE & TECHNOLOGY
ISLAMABAD
Islamabad Expressway, Kahuta Road, Zone-V, Islamabad
Phone: +92 51 111 555 666, Fax: 92 51 4486705
Email: info@cust.edu.pk, Website: http"//www.cust.edu.pk

CERTIFICATE OF APPROVAL

Experimental Properties Evaluation of Fiber Reinforced Concrete related to Canal-lining

by

Asad Zia

MCE153015

THESIS EXAMINING COMMITTEE

S No	Examiner	Name	Organization
(a)	External Examiner	Engr. Dr. Prof. Ayub Elahi	UET, Taxila
(b)	Internal Examiner	Engr. Dr. Munir Ahmad	CUST, Islamabad
(c)	Supervisor	Engr. Dr. Majid Ali	CUST, Islamabad

____

Engr. Dr. Majid Ali
Thesis Supervisor
August, 2017

Engr. Dr. Ishtiaq Hassan	Engr. Dr. Prof. Imtiaz Ahmad Taj
Head of Department	Dean
Department of Civil Engineering	Faculty of Engineering
Dated: August, 2017	Dated: August, 2017

CERTIFICATE

This is to verify that Mr. Asad Zia has integrated all comments, suggestions and observations made by the external evaluators as well as the internal evaluators and thesis supervisor. His thesis title is: **Experimental Properties Evaluation of Fiber Reinforced Concrete related to Canal-lining.**

Forwarded for necessary action

____

Engr. Dr. Majid Ali
(Thesis Supervisor)

DEDICATION

This effort is devoted to my respected and cherishing parents, who helped me through each troublesome of my life and yielded every one of the comforts of their lives for my brilliant future. This is likewise a tribute to my best teachers who guided me to go up against the troubles of presence with ingenuity and boldness, and who made me what I am today.

Mr. Asad Zia
MCE153015

DECLARATION

This thesis is a presentation of my unique research work. Wherever commitments of others are included, each exertion is made to demonstrate this obviously, with due reference to the writing, and affirmation of communitarian research and exchanges. The work is carried out under the supervision of Associate Professor Engr. Dr. Majid Ali, at the Capital University of Science and Technology, Islamabad, Pakistan.

____

Mr. Asad Zia
MCE153015
Date: August, 2017

ACKNOWLEDGEMENTS

- Wealthiest thanks to **Almighty Allah** for a tremendous measure of vitality, power and the miraculous pushes occurring in a sweetly coordinated manner, only a few to mention, which drive our lives.
- I need to express my sincere thanks to **Associate Professor Engr. Dr. Majid Ali** under whose direction the research was led. His direction was precious at each progression of this work. His outstanding showing aptitudes helped me get a handle on the topic rapidly. His collaboration at every single phase of my basic choices at capital university has been significant.
- I thankfully recognize the affection and financial support received from **my parents** for MS studies.
- I would thank all my colleagues especially **Engr. Faheem Ahmad Gul** for his sincere help. Last but not the least, I would mention my family and friends whose prayers have enabled me to complete this task.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

A = Aggregate

C = Cement

CCE = Compressive cracked absorbed energy (MPa)

CPE = Compressive pre-crack absorbed energy (MPa)

CS = Compressive strength (MPa)

CTE = Compressive total absorbed energy (MPa)

CTI = Compressive toughness index (-)

FS = Flexure strength (MPa)

FCE = Flexural post-crack absorbed energy (kN.mm)

FPE = Flexural pre-crack absorbed energy (kN.mm)

FRC = Fiber reinforced concrete

FRCs = Fiber reinforced concretes

FTI = Flexural toughness index (-)

FTE = Total flexural absorbed energy (kN.mm)

JF = Jute fibers

JFRC = Jute fiber reinforced concrete

kN = kilo-Newton

LS = Linear shrinkage (mm)

mm = millimetre

MoR = Modulus of rupture (MPa)

MPa = Mega Pascal

NF = Nylon fibers

NFRC = Nylon fiber reinforced concrete

PC = Plain concrete

PPF = Polypropylene fibers

PPFRC = Polypropylene fiber reinforced concrete

S = Sand

SCE = Splitting-tensile post-crack absorbed energy (kN.s)

s = second

SPE = Splitting-tensile pre-crack absorbed energy (kN.s)

SS = Splitting-tensile strength (MPa)

STE = Splitting-tensile total absorbed energy (kN.s)

STI = Splitting-tensile toughness index (-)

WA = Water absorption (%)

W/C = Water-cement

Δ = Deflection (mm)

Δ_o = Deflection at maximum load (mm)

ε_o = Strain at the maximum stress (-)

ABSTRACT

Seepage is a major water loss from the canal as compared to the other forms of water losses. So, it becomes important to reduce this seepage loss to increase the conveyance efficiency. Concrete is commonly used for canal-lining to reduce seepage loss since concrete materials are usually available in the vicinities of the local farmers. Considerable seepage (15%-20%) has been observed even in the cement–concrete conventional sections. Concrete lining structure is identical to thin plate in which cracking occurrence is frequent. The performance of canals decreases with an increase in the rate of cracking in concrete canal-lining. The rate of cracking in canal-lining can be reduced by improving the flexure, compressive, and splitting-tensile strengths of concrete. Out of these, splitting-tensile strength of concrete plays a vital role in controlling cracks. The use of fibers for characteristics improvement of concrete is very ancient. Natural fibers include many benefits, like low cost due to its abundance, least health hazards, and flexibility. The use of synthetic fibers as reinforcement in matrix has also attained intentness by reasons of its high strength, less water absorption, and low density in nature.

The overall aim of the research program is to explore materials for better performance of canal-lining in terms of reduced water losses by controlling its rate of cracking due to alternate wetting and drying, and due to differential settlement, etc. The purpose of this work is to examine experimental behaviors of jute fiber reinforced concrete (JFRC), nylon fiber reinforced concrete (NFRC), and polypropylene fiber reinforced concrete (PPFRC) for controlling the rate of cracking in canal-lining. For this purpose, the mechanical properties, water absorption, and linear shrinkage of JFRC, NFRC, and PPFRC are determined experimentally as per ASTM standards. The properties of plain concrete (PC) are used as reference. The proportion of 1:3:1.5:0.7 (cement: sand: aggregate: water) is used for PC mix. The mixes of JFRC, NFRC, and PPFRC are manufactured by adding the JF, NF, and PPF, respectively, in the same mix design as that of PC. For production of each type of fiber reinforced composite (FRC), respective fibers having length of 50 mm are added in concrete by an amount of 5% (by mass of cement).

The specimens of both PC and FRCs were tested in the fresh and solid state. The FRCs were less workable when contrasted with PC for the same W/C ratio. Thus, the slumps of

JFRC, NFRC, and PPFRC were reduced by 61%, 36%, and 39%, respectively, than that of PC. As compared to compressive strength (CS) of PC, the CS of JFRC and NFRC decreased by 36% and 31%, respectively, and that of PPFRC improved by 1%. As compared to splitting-tensile strength (SS) of PC, the SS of JFRC and NFRC showed a decrease of 19% and 10%, respectively, and an improvement of 5% is observed in SS of PPFRC. An improvement of 8%, 10%, and 34% is observed in modulus of rupture of JFRC, NFRC, and PPFRC, respectively, as compared to that of PC. An increase of 87%, 127%, and 107% is observed in compressive total absorbed energy of JFRC, NFRC, and PPFRC, respectively, than that of PC. As compared to splitting-tensile total absorbed energy (STE) of PC, a decrease of 37% and 21% is observed in STE of JFRC and NFRC, respectively, and an increase of 11% is observed in the STE of PPFRC. And an increase of 53%, 68%, and 100%, in flexural total absorbed energy of JFRC, NFRC, and PPFRC, respectively, in comparison to that of PC. The enhancement of 124%, 127%, and 148% is observed in compressive toughness index of JFRC, NFRC, and PPFRC, respectively, than that of PC. An enhancement of 2%, 2%, and 3% is observed in splitting-tensile toughness index of JFRC, NFRC, and PPFRC, respectively, than that of PC. And by comparing to that of PC, an enhancement of 86%, 91%, and 94% is noticed in flexural toughness index of JFRC, NFRC, and PPFRC, respectively. As compared to PC, an increase of 8% and 1% is observed in water absorption (WA) of JFRC and NFRC, respectively, and a decrease of 4% is observed in the WA of PPFRC. Linear shrinkage 'LS' (% decrease) of JFRC and NFRC is 67% and 30%, respectively, more than that of PC. While LS (% decrease) of PPFRC is 15% less than that of PC. Empirical relations have been developed with the help of experimental data for prediction of WA and LS. The relationship between WA/LS and each of the CS, SS, SPE, and FPE are made because of their observed mutual coherence in experimental outcomes. There is a good agreement between the experimental and empirical values. The percentage error is 0.4%-20%. Among the tested FRCs, PPFRC showed the better performance. This may ensure to control the rate of cracking in canal-lining, ultimately improving its performance.

LIST OF INTENDED PUBLICATIONS

Intended journal article

- Zia A. and Ali M. (2017). Behavior of fiber reinforced concrete for controlling the rate of cracking in canal-lining. *Construction and Building Materials* (ISI Impact Factor = 2.421), (*Under Review*).

Intended referred conference article

- Zia A. and Ali M. (2017). Effectiveness of polypropylene fiber reinforced concrete in enhancement of long-term durability of hydraulic structures. 2nd International Conference on Frontiers of Composite Materials (ICFCM2017), Melbourne, Australia, 15-17 November, 2017, (Paper Accepted).

CHAPTER 1

INTRODUCTION

1.1 Prelude

Seepage loss (20%-30%) is a major reason of water loss from the canal as compared to the other forms of water losses (USBR 1978; Badenhorst et al. 2002). So, it becomes important to reduce this seepage loss for increasing the conveyance efficiency. Concrete is commonly used for canal-lining to reduce seepage loss, since concrete materials are usually available in the vicinities of the local farmers (Kasali and Ogunlela 2014). Concrete lining structure is identical to thin plate in which cracking occurrence is frequent (Kratz 1980). Kahlown and Kemper (2005) and USBR (1978) also reported occurrence of considerable seepage loss (15%-20%) even in the cement–concrete conventional sections. The better performance of concrete lining can help in reducing this water loss. The reasons accountable for those cracks comprise thermal stress (temperature variation), external load, differential settlement of the foundation, etc. (Bofang 1999; Cui et al. 2013). The properties which can enhance the performance of canal-lining are compressive, tensile, and flexure strengths of concrete. Out of these, tensile strength of concrete played a vital role in controlling cracks (Montañes 2006). Many engineering/mechanical properties (like flexural strength, tensile strength, fatigue resistant strength, abrasion and thermal impact) of composites (cement paste, mortar and/or concrete) can be efficiently improved by introducing fibers in composites (Mansur and Aziz 1982; Ali et al. 2016; Thakur et al. 2014; Ramakrishna and Sundararajan 2005). Fibers in concrete act as "crack arrester" (James et al. 2002; Kene et al. 2012). Al-Oraimi and Seibi (1995) verified that the enhancement in mechanical properties and impact resistance of concrete could be brought by use of even a low proportion of natural fibers. Artificial fiber reinforced concrete reduced the rate of cracking in canal-lining by enhancing its mechanical properties (Fang et al. (2011). It had been investigated that the addition of jute fibers in cement composites had substantially increased the tensile and flexural strengths and toughness (Liu et al. 2013). Cook et al. (1984) reported that nylon fibers exhibited good tenacity, toughness, and excellent elastic recovery. It also performed well under accelerated aging conditions (Khajuria et al. 1991). Fang et al. (2011) reported that the incorporation of polypropylene fibers in concrete significantly increased its splitting-tensile and direct tensile strengths along with an improvement in its frost resistance and impermeability. The overall aim of the research program is to explore materials for better performance of canal-lining in terms of reduced water losses by controlling its rate of cracking due to alternate wetting and drying and due to differential settlement, etc. In this research work, an investigation has been carried out to select the most suitable material out of plain cement concrete (PC), jute fiber reinforced concrete (JFRC), nylon fiber reinforced composite (NFRC), and polypropylene fiber reinforced concrete (PPFRC) for application of canal-lining.

1.2 Research motivation and problem statement

There is no life without water. Water should be conveyed at desired locations through canals without losses. Canal-lining is widely used as a water saving measure. However, cracking in concrete canal-lining is also observed. The initial micro crack in canal-lining converts to macro cracks with the passage of time, which accelerates the loss of water by allowing the seepage of water through the lining. The rate of cracking in concrete canal-lining can be reduced by improving the tensile strength of concrete (Montañes 2006). The concept of using fibers to improve the characteristics of concrete is very old. Natural fibers include many benefits, like low cost due to its abundance, biodegradability, and least health hazards. The use of synthetic fibers as reinforcement in matrix has also attained intentness by reasons of its high strength, less water absorption and low density in nature. Improved performance of canal-lining can be insured by controlling its rate of cracking. The loss of water cannot be reduced unless the crack formation is controlled and minimized. The reduction in rate of cracking can be based on mechanical performance criteria associated with enhanced post cracking behavior of fiber reinforced concrete. Thus, the problem statement is as follows:

> *"Canal-lining is widely used as a water saving measure. Cracking in canal-lining reduced its efficiency up to 70% (Swihart and Haynes 2002). One of major reasons for the increase in the rate of cracking in concrete canal-lining is thermal*

stress (Cui et al. 2013). Due to this, the performance of canals is decreased with an increase in water losses. Improving mechanical properties of concrete and controlling its linear shrinkage can limit cracking in canal-lining (Fang et al. 2011). So, to attain the high-performance concrete for canal-lining application, the fibers can be utilized in concrete. There is only one study regarding polypropylene fiber reinforced concrete for canal-lining application. The performance of other fibers in concrete for canal-lining application still need to be explored in detail."

1.3 Overall / specific research aims and scope of work

The overall aim of the research program is to explore materials for the better performance of canal-lining in terms of reduced water losses by controlling its rate of cracking due to alternate wetting and drying and due to differential settlement, etc.

The specific aim of this MS work is to examine the experimental behaviors of plain concrete, jute fiber reinforced concrete, nylon fiber reinforced concrete, and polypropylene fiber reinforced concrete for controlling the rate of cracking in canal-lining.

This particular objective is accomplished by the following tasks (defining the scope of present research work):

i. *To compute experimentally the mechanical properties (i.e. compressive, splitting-tensile, and flexural strengths), water absorption, and linear shrinkage of plain concrete, jute fiber reinforced concrete, nylon fiber reinforced concrete, and polypropylene fiber reinforced concrete. For this purpose, a total of 32 specimens i.e. 16 cylinders and 16 beam-lets were produced. 16 samples mean 4 with PC and 4 with each type of FRCs.*

ii. *To develop empirical relations*

iii. *Based on conducted investigation, to recommend suitable FRC for controlling the rate of cracking in canal-lining.*

1.4 Investigation methodology

In this experimental study, the mechanical properties of plain concrete (PC), jute fiber reinforced concrete (JFRC), nylon fiber reinforced concrete (NFRC), and polypropylene fiber reinforced concrete (PPFRC) are determined in laboratory. The mix design ratio for PC is 1:3:1.5:0.7 (cement: sand: aggregate: water). The fibers of jute, nylon, and polypropylene are added in concrete mixer for the production of JFRC, NFRC, and PPFRC, respectively. For production of each type of FRC, fibers having length of 50 mm and 5% contents, by mass of cement, are added in concrete. The workability of mixes of PC and FRCs is computed in fresh state by using the standard procedure of slump cone test. Standard specimens are cast and tested for determining the compressive, splitting-tensile, and flexural strengths, water absorption, and linear shrinkage of PC and considered FRCs in the hardened state. Servo-hydraulic testing machine is used for the strength testing of all specimens in order to get their pre-crack and post-crack behaviors.

1.5 Thesis outline

The thesis contains six chapters. These are:

Chapter 1 includes of introduction. It explains the sources of water losses in canal-lining, research motivation and problem statement, overall or specific research aims and scope of work, investigation methodology, and thesis outline.

Chapter 2 contains the literature review. It comprises of background, water losses in canal-lining and its sources, effectiveness of fiber incorporation in concrete for its properties improvement, fiber reinforced concrete in canal-lining, and summary of chapter 2.

Chapter 3 incorporates the test methodology. It covers the background, raw materials, the techniques of PC and FRCs mixing and casting, specimen details, testing methodologies, and summary of chapter 3.

Chapter 4 encompasses the results obtained from tests and their analysis. It describes the background, material-properties of the mixes (i.e. PC, JFRC, NFRC, and PPFRC), mechanical properties (CS, SS, and FS), LS, WA, and behavior of the specimens during the testing, and summary of chapter 4.

Chapter 5 encompasses of discussion. It consists of background, empirical equations between the water absorption or linear shrinkage and selected strength properties, role of mechanical properties of concrete in controlling the rate of cracking in concrete canal-lining, and summary of chapter 5.

Chapter 6 comprises of conclusions and recommendations.

Consecutive to the end of chapter 6, all the references are given.

Annexure A explains the details of compressive load-time curves and behavior of other tested specimens during the compressive strength test.

Annexure B explains the details of splitting-tensile load-time curves and behavior of other tested specimens during the splitting-tensile strength test.

Annexure C explains the details of flexural load-time curves and behavior of other tested specimens during the testing of the flexural strength test.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

There are many forms of water losses in canals. In comparison to other forms of water loss, seepage is a major water loss. Considerable seepage has also been observed in the concrete, which is commonly used for canal-lining to reduce the seepage loss. The performance of canals decreases with an increase in the rate of cracking in concrete canal-lining. The rate of cracking in concrete canal-lining can be decreased by enhancing the compressive, splitting-tensile, and flexure strengths of concrete. These properties can be improved by incorporation of fibers in concrete. In this chapter, the effectiveness of fiber incorporation in concrete and application of FRCs for canal-lining is discussed in detail.

2.2 Water losses in canal-lining and its sources

The movement of water in downward direction into soil or substratum from a source of supply like reservoir or irrigation channel is known as seepage (Michael 1978). When the water achieves the field, it had been evaluated that the losses due to seepage were equal to 45% of the total quantity of water provided at the head of the channel (Sharma and Chawla 1975). Seepage (20%-30%) is a major water loss from the canal as compared to the other forms of water losses (USBR 1978; Badenhorst et al. 2002). Luthra (1980) investigated the type and quantity of losses in canals. It was reported that, for unlined canals, the conveyance losses varied from 25% to 60%. Krishnamurthy and Rao (1969) studied the canal losses in gangal canal as pioneer and the seepage losses of 2.2 m^3/day/m was reported. Raja et al. (1983) evaluated the losses due to seepage from an unlined channel by using the nuclear technique and detailed that the losses due to seepage fluctuate from 1.3 to 4.3 m^3/1106 m^2 of the wetted surface area. For lined canal systems, depending on the lining material, the loss due to seepage was limited. Kraatz (1975) found that an average of 17.5% loss of flow occurred as seepage per km of irrigation canals in western Greece. So, it becomes important to reduce this seepage loss for increasing the conveyance efficiency. Karad et al. (2013) reported that, if lining is provided in minors, the seepage losses could be reduced by nearly 39%. Arshad et al. (2009) carried out an investigation to evaluate the differences in water losses through the lined and unlined watercourses in the specific territory of Indus Basin of Pakistan. Hydrogeologic characteristics of soil were considered same for all of these watercourses. Comparing the average water loss of 44% from lined and the average water loss of 66% from unlined watercourses, it was reported that the water loss decreased by 23% due to lining. Different types of materials had been applied by Irrigation Research Institute (1992) for the reduction of losses due to seepage from the watercourses. For this purpose, 16 watercourses were investigated. The results showed that water seepage losses from lined watercourses extended from 8 to 20% of inflow. Concrete is commonly used for canal-lining to reduce the seepage loss, because concrete materials are usually available in the vicinities of the local farmers (Kasali and Ogunlela 2014). Concrete lining structure is identical to thin plate in which cracking occurrence is frequent (Kraatz 1980). Kahlown and Kemper (2005) and USBR (1978) also reported the occurrence of considerable seepage (15%-20%) even in the cement–concrete conventional sections. The estimation of canal losses is beneficial in measuring the performance of the canal-lining. The better performance of concrete lining can help in reducing the water loss. The reasons accountable for those cracks comprise of thermal stress (temperature variation), external load, differential settlement of the foundation, etc. (Bofang 2013). Arshad et al. (2009) reported that the abundance of water leakage through the waterways was most likely because of cracks, disintegrated mortar, and structural failure of the lined walls. Cui et al. (2013) conducted an analysis on the causes of cracks in concrete canal-lining. Factors, responsible for cracks, were classified on the basis of data collected. Also, the method of 3D contact nonlinear finite element was used for a sensitivity analysis on these factors. Based on outcomes, it was reported that the factors responsible for concrete cracks were external loads, temperature difference, irregular settlement of foundation, expansion deformation of foundation soil, and humidity, etc. Observed cracks in concrete canal-lining of Ismaila distributary at a reduced distance of about 5000 feet (Sub-division Shehbaz Garhi, Division Swabi, KPK Department of Irrigation) are shown in Figure 2-1.

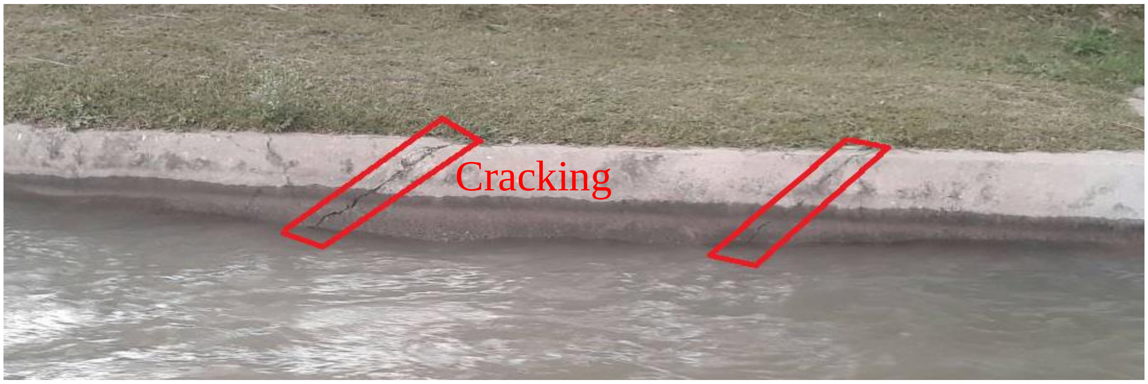

Figure 2-1 Observed cracks in concrete canal-lining of Ismaila distributary

2.3 Effectiveness of fiber incorporation in concrete for its properties improvement

The strength properties along with the rate of water absorption of jute, nylon, and polypropylene fibers as reported by James et al. (2002) are shown in Table 2-1. It can be observed that jute, nylon, and polypropylene fibers have high tensile strengths and elastic moduli and also having low tendency of water absorption. Among the easily and locally

Table 2-1 Strength properties of jute, nylon, polypropylene, glass, and steel fibers (James et al. 2002)

Fiber type	Tensile strength ksi	Elastic modulus ksi	Water absorption per ASTM D 570, percent by weight
Jute	36-51	3770- 4640	Not Available
Nylon	140	750	2.8-5.0
Polypropylene	20-100	500-700	Nil
Glass	450	9400	Not Available
Steel*	50-435*	29007*	Not Available

** Data from Banthia (2010)*

available fibers, the selected fibers possess good strength properties for the application of canal-lining. The good tensile strength of the selected fibers is likely to be helpful in controlling the formation of cracks due to the tensile stresses by enhancing the tensile strength of FRCs. The smaller water absorption of the selected fibers also compelled the concentration towards their use for the application of canal-lining as compared to other available fibers. The available type of glass fiber is not considered for the application of canal-lining due to the findings that glass (non-resistant to alkaline effects) fibers were chemically attacked by hydration products, leading to weak glass surface (Banthia 2010). It was also reported that the loss of fiber strength occurred due to growth of hydration products around the glass fibers, at an early stage of concrete curing (Bentur and Diamond 1984). The steel fibers are also not considered due to their corrosive nature. Due to the corrosion, the bond between the concrete and steel fibers is adversely affected.

Table 2-2 Advantages of jute, nylon, polypropylene, glass and steel fibers

Fibers	Advantages	References
Jute	Seven times lighter than steel fibers, high energy absorption capability, high breaking strength, cheaply available.	Kundu et al. (2012), and Ramaswamy et al. (1983)
Nylon	Strong, light weight, better resistive to heat and cold conductance, good tenacity, toughness, and outstanding elastic recovery, zero water absorption, stable, and exceptional capability of abrasion resistance.	Banthia (2010), James et al. (2002), and Cook (1984)
Polypropylene	Low specific gravity, more ductility, zero water absorption capacity, high elasticity and energy absorption, outstanding capability to oppose friction, bond by mechanical interaction with cement matrix and does not chemically interact with cement, lowest thermal conductivity among the available fibers.	Banthia (2010), James et al. (2002), Rice et al. (1987), and Galanti (1964)
Glass	Low density, more ductility, light weight, energy efficient.	Shakor and Pimlikar (2011) and James et al. (2002)
Steel	Hight density, more ductility, energy efficient, zero water absorption.	James et al. (2002)

Table 2-2 displays the advantages of the jute, nylon, and polypropylene fibers. It can be seen that, despite good strength properties, the used types of fibers also contain sufficient benefits reported by different researchers. The better tensile breaking strength, low density, low cost, and easy availability have made jute fibers distinguished from other natural fibers. The nylon fibers encompass number of benefits like better resistance to heat and thermal conductivity, zero water absorption and exceptional capability of abrasion resistance (Banthia 2010; Cook 1984; James et al. 2002). The polypropylene fibers also contain number of benefits like lowest thermal conductivity among the available artificial fibers, high energy absorption capability and zero water absorption (James at al. 2002; Banthia 2010; Galanti 1964). The glass fibers contain benefits like light weight and ductility (Shakor and Pimlikar 2011; James et al. 2002). But due to unavailability of alkaline resistant type of glass fibers at local level, the available type of glass fiber (non-resistant to alkaline effect) is not considered due to its less durable nature. Similar to glass fibers steel fibers also encompass benefits like zero water absorption and good ductility but due to corrosive nature the steel fibers are also ignored for the application of canal-lining. Thus, fibers are selected based on their good tensile strength, low/no water absorption, and easy availability at low cost.

The properties, which can enhance the performance of concrete canal-lining, are compressive, tensile, and flexure strengths of concrete. Out of these, the tensile strength of concrete played a vital role in controlling cracks (Montañes 2006). Many engineering/mechanical properties (like flexural strength, tensile strength, fatigue resistant strength, abrasion and thermal impact) of composites (cement paste, mortar and/or concrete) can be efficiently improved by introducing fibers in it (Thakur et al. 2014; Ali 2014; Ali 2016; Ramakrishna and Sundararajan 2005; Wambua et al. 2013; Aziz et al. 1981; Swift and Smith 1979; Cook et al. 1978; Racines and Pama 1978; Salyer 1975). Fibers in concrete act as "crack arrester" (Kene et al. 2012; James et al. 2002). The impact resistance and mechanical properties of concrete could be improved by use of even a low proportion of natural fibers (Al-Oraimi and Seibi 1995). Merta and Tschegg (2013) carried out an experimental investigation on fracture energy of concrete composites reinforced with natural fibers. It was found that the addition of natural fibers enhanced the fracture energy of composites. Joshi et al. (2004) reported that, in most of the cases, natural fiber reinforced composites were environmentally superior to glass fiber reinforced composites. Artificial fiber reinforced concrete reduced the rate of cracking in canal-lining by enhancing its mechanical properties (Fang et al. 2011). Wang et al. (1987) conducted an experimental study on synthetic fiber reinforced cementitious composites. Three types of tests (i.e. compaction tension, splitting-tensile, and flexure tests) were performed to study the tensile properties of concrete composites reinforced with acrylic, nylon, and aramid fibers. It was concluded that the properties of concrete composites were greatly enhanced by the incorporation of artificial fibers. It had been investigated that the addition of jute fibers in cement composites had substantially increased the tensile and flexural strengths, and toughness (Liu et al. 2013). It was investigated by different researchers that the jute fibers (i) acted as crack-arresters, (ii) absorbed a significant amount of energy after the occurrence of cracks, and (iii) carried a major portion of the tensile stress in the composite material (Zakaria et al. 2016; Zhou et al. 2013; Mansur and Aziz 1982; Gupta et al. 1978; Singh 1975; Siraskar and Kumar 1972). Kundu et al. (2012) investigated that jute fibers, having high tensile strength of 250–300 MPa, were about seven times lighter than steel fibers (having tensile strength of approximately 400-1200 MPa (Won et al. 2008)). Ramaswamy et al. (1983) examined the tensile elongation ratios and tensile-breaking strength of jute fiber. Two conditions were considered i.e. natural air-dry state and an alkaline environment (by submerging in the solution of sodium hydroxide having pH value of 11 for 28 days). It was reported that jute fiber had quite high breaking tensile strength of 2260 kg/cm^2 in natural dry state. During the period of immersion in alkaline medium, the loss of strength varied from 5% to 32%. Chandar and Balaji (2015) reported significant enhancement of 27%, 12%, and 44% in compressive, splitting-tensile, and flexural strengths, respectively, of concrete due to incorporation of jute fibers. Cook et al. (1984) reported that nylon fibers exhibited good tenacity, toughness, and excellent elastic recovery. Nylon fiber reinforced concrete (NFRC) performed well under accelerated aging conditions (Khajuria et al. 1991). Nylon fibers had the ability to act as crack arrestor (Sridhara et al. 1971). Nylon fibers were also effective in sustaining and enhancing the load carrying capability of concrete after the first crack (Goldfein 1965). Jagannathan et al. (2016) conducted an experimental investigation on the use of nylon fibers in concrete. It was concluded that NFRC had the ability to hold on the cracks of concrete. The addition of 1% nylon fibers enhanced the compressive, tensile, and flexural strengths by 7.5%, 9.6%, and 12.5% respectively, than that of plain concrete. The ductility of concrete was also improved. Subramanian et al. (2016) conducted an experimental investigation on concrete composite incorporating nylon fibers. The effects of adding nylon fibers in concrete of M20 grade on compressive strength of cubes and splitting-tensile strength of cylinders were evaluated. Four test groups were constituted with the nylon fiber percentages of 0%, 1%, 2% and 3%. The results showed that the incorporation of nylon fibers in concrete improved its compressive and splitting-tensile strengths. Al-Tayyib et al. (2013) reported that the inclusion of polypropylene fibers (PPF) in concrete improved the tensile and flexural strengths of concrete and also resulted in decrease of the drying shrinkage varied from 2% to 11% than that of plain concrete at an age of 70 days. Zollo (1984) investigated that the addition of PPF in concrete had increased its splitting-tensile and flexural strengths along with a significant reduction in shrinkage. Ramujee (2013) reported enhancement of 34% and 40% in compressive strength and splitting-tensile strength, respectively, of concrete due to incorporation of polypropylene fibers. Saadun et al. (2016) and Rajguru et al. (2014) also reported a significant increase in compressive, splitting-tensile, and flexural strengths due to incorporation of polypropylene fibers. Kakooei et al. (2012) investigated the influence of adding polypropylene fibers in concrete. Concrete samples were examined for its compressive strength, permeability and electric resistivity. The amounts of fibers used for production of concrete samples varied from 0 to 2 kg/m^3. It was concluded that the addition of PPF resulted in reduced permeability due to which the starting of the degradation process had been delayed. In addition to this, the amount of expansion and shrinkage of concrete were also reduced.

Previous studies that has been carried so far to study mix designs with fiber content and with fiber length of JFRC, NFRC, and PPFRC are given in Table 2-3. As a nutshell, JFRC has so far been studied for mix designs 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 by 1 m^3 of concrete, 1%, by mass of cement, 0.25% and 0.50%, by volume fraction of concrete, and with fiber lengths of 15 mm, 30 mm, 40 mm, and 50 mm. It was reported that compressive strength (CS), splitting-tensile strength (SS), and modulus of rupture (MoR) of JFRC came out to be 88%-128%, 78%-113%, and 90%-154%, respectively, of that of PC (Liu et al. 2013; Chandar and Balaji 2015; Kundu et al. 2012; Zakaria et al. 2016). NFRC has so far been studied for mix designs 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 fraction of concrete, and with fibre lengths of 12 mm, 20 mm, 24 mm, and 45 mm. It was reported that CS, SS, and MoR of NFRC came out to be 94%-127%, 94%-169%, and 93%-113%, respectively, of that of PC (Khan and Ali 2016; Jagannathan et al. 2016; Subramanian et al. 2016). PPFRC has so far been studied for mix

Table 2-3 CS, SS, and MoR of PC, JFRC, NFRC, and PPFRC by Previous Studies

Fiber Content	Mix Design ratio	Fiber Length (mm)	CS (%)	SS (%)	MoR (%)	References
PC	—	—	100	100	100	—
JFRC						
0.6 kg/m^3	1:1.74:3.24	30	119	—	154	Liu et al. (2013)
1%[a]	1:1.5:3	40	128	112	144	Chandar and Balaji (2015)
4.4 kg/m^3	1:1.5:2.7	50	106	—	111	Kundu et al. (2012)
0.25%[b]	1:1.5:3	15	105	105	119	Zakaria et al. (2016)
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	
NFRC						
5%[a]	1:3.33:1.67	50	94	108	103	Khan and Ali (2016)
1%[b]	1:1.22:2.8	45	108	110	113	Jagannathan et al. (2016)
1.5%[b]	1:1.22:2.8	45	94	94	93	
1%[b]	1:1.5:3	20	127	112	—	Subramanian et al. (2016)
2%[b]	1:1.5:3	20	107	169	—	
PPFRC						
0.25%[a]	1:1.5:3	24	106	172	-	Vairagade et al. (2012)
1.5%[b]	1:1.5:3	12	134	140	-	Ramujee (2013)
1%b	1:1.27:2.76	12	107	119	118	Rajguru et al. (2014)
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	Saadun et al. (2016)
2 kg/m^3	1:1.36:2.52	38	84	118	115	

Note: [a] content by mass of cement, [b] content by volume fraction of concrete.

designs 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 by 1 m^3 of concrete, 0.25%, by mass of cement, 0.25%, 1.5%, and 1%, by volume fraction of concrete, and with fibre lengths of 12 mm, 24 mm, 38 mm, and 54 mm. It was reported that CS, SS, and MoR of PPFRC came out to be 84%-134%, 107%-140%, and 102%-118%, respectively, of that of PC (Vairagade et al. 2012; Ramujee 2013; Rajguru et al. 2014; Saadun et al. 2016). The permeability of PPFRC has also been studied in terms of water penetration for mix design 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 by 1 m^3 of concrete and with fiber length of 12 mm. It was reported that water penetration depth came out to be 8.5 mm to 9.5 mm. The minimum water penetration depth was 7.7 mm for the specimen with 0.7 kg/m^3 of fiber content, which was 30% lower than that of PC (Ramezanianpour et al. 2013). PPFRC has also been studied for shrinkage for mix design of 1:1.62:2.48 with fiber contents of 0.05%, 0.10%, and 0.15%, by volume fraction of concrete, and with fiber length of 18 mm. A reduction of 40% was reported in drying shrinkage of PPFRC as compared to that of PC (Kumar et al. 2013). No research has been reported to study (at the same time) the effect of jute fibers, nylon fibers, and polypropylene fibers on the mechanical properties, water absorption, and linear shrinkage of concrete and their correlation.

2.4 Fiber reinforced concrete in canal-lining

Fang et al. (2011) studied the feasibility of the use of polypropylene fiber reinforced concrete in canal-lining. For this purpose, the effect of polypropylene fibers (PPF) on concrete shrinkage and crack resistance was analyzed. The properties of polypropylene fiber reinforced concrete were compared to that of standard plain concrete. It was reported that, incorporation of PPF in concrete enhanced its splitting-tensile and axial-tensile strengths, toughness, frost resistance, and impermeability. The incorporation of PPF in concrete effectively prevented and suppressed the crack formation in concrete. It was concluded that PPFRC could improve the performance of canal-lining.

2.5 Summary

There is only one limited study by Fang et al. (2011) on PPFRC for canal-lining application. On other hand, researchers have studied the mechanical properties (i.e. compressive, splitting-tensile, and flexural strengths) of FRCs along with the permeability and shrinkage of PPFRC only for other civil engineering applications. But an in-depth knowledge of mechanical properties of FRCs along with their water absorption and shrinkage are necessary for canal-lining application. To the best of authors knowledge, a detail study on the suitability of fiber reinforced concrete (FRC) with different fibers for canal-lining application has not been carried out up to now. The improved performance of canal-lining can be insured by controlling its rate of cracking. The loss of water cannot be reduced unless the crack formation is controlled and minimized. The initial micro crack in canal-lining converts to macro cracks with the passage of time, which accelerates the loss of water by allowing the seepage of water through the lining. The rate of cracking in concrete canal-lining can be reduced by improving the tensile strength of concrete. Improving mechanical properties of concrete and controlling its linear shrinkage can also limit cracking in canal-lining.

CHAPTER 3

TEST METHODOLOGIES

3.1 Background

Natural fibers have attained the attention because of the low cost, less health hazard, and flexibility. Artificial fibers also include many advantages like high strength, less water absorption and low density in nature. Jute fibers are good in energy absorption and also have high tensile breaking strength. Nylon fibers have good tenacity, toughness, and zero water absorption. Polypropylene fibers also include benefits like chemically inertness, zero water absorption and high tensile strength. As stated in the previous chapter that a detail study on the suitability of fiber reinforced concrete (FRC) with different fibers for canal-lining application has not been carried out up to now. Therefore, mechanical properties of FRCs along with the water absorption and linear shrinkage are studied. In this chapter, raw materials, the techniques of PC and FRCs mixing and casting, specimen details, testing methodologies are examined in detail in this chapter.

3.2 Raw materials

The ingredients utilized for the preparation of PC, JFRC, NFRC, and PPFRC includes Ordinary Portland cement, portable water, locally available sand, aggregates, jute fibers, nylon fibers and polypropylene fibers. The aggregates having maximum size of 38 mm are used.

3.3 Mix design and casting procedures

The ratio of 1, 3, and 1.5 is used for cement, sand, and aggregates, respectively, in mix design of PC with a water-cement (W/C) ratio of 0.7. The purpose behind utilizing more sand contrasted with total is that more mortar is accessible for grabbing fibers in case of FRCs. A saturated surface dry condition is missing. Therefore, a relatively high w/c ratio is used for the concrete mix. It may also be noted that no bleeding is observed during workability test and filling of moulds (which may insure no loss in strength of FRCs). The mix design for JFRC, NFRC, and PPFRC is the same as that of the PC except that 50 mm long respective fibers having content of 5%, by mass of cement, are added. All materials are batched by mass.

Concrete is prepared by using the non-tilting rotating type drum concrete mixer. For production of PC, all materials along with the water are poured in the drum of the mixer, and the duration for the rotation of mixer is three minutes. A slump test is conducted before pouring the PC into moulds. For preparing JFRC, NFRC, and PPFRC mixes, one third of all dry materials (in the sequence of aggregates, fibers, sand, and cement) are poured in layers in mixer drum. Then, the same process is repeated for the addition of remaining dry materials in the same sequence in the mixer. Initially, the two third of total water (as per W/C ratio of 0.7, similar to that of PC) is added, and the concrete mixer is rotated for a duration of three minutes. In the last phase, the rest of water is added and the rotation of concrete mixer is repeated for another period of three minutes. All FRCs mixes are workable at this stage and the fibers are approximately evenly dispersed. The slump tests for the JFRC, NFRC, and PPRFC are also performed before pouring the mixes into moulds. These tests are performed in the same manner as performed for that of PC. For filling the moulds with PC, the standard procedure (i.e. filling moulds with three layers and tempering each layer with 25 blows by 16 mm diameter rod) is adopted. However, for filling moulds with FRCs, in addition to standard procedure, the mechanism of lifting up of moulds to a distance of about 165 mm – 230 mm and then allowing it free fall to the floor is followed for possible self-compaction and removal of voids due to air from the FRCs. Selection of the best suitable method among the available methods for attaining an enhanced slump of FRCs is recommended. The curing of all specimens is carried out for 28 days before testing.

3.4 Specimens

Cylinders having diameter of 100 mm and height of 200 mm, for the tests of splitting-tensile and compressive strengths, and beam-lets of 100 mm width, 100 mm depth and 450 mm length, for flexure strength and linear shrinkage are prepared for PC and FRCs. For the test of water absorption, the broken beam-lets after flexure strength test are used. An average of two readings are taken to represent the properties of hardened concrete. Other researchers also reported results by taking average of two readings, even the average of crack length was presented (Lim et al. 2000). ASTM C39 also supports the average of two. A total of 32 specimens i.e. 16 cylinders and 16 beam-lets are produced. 16 samples mean 4 with PC and 4 with each type of FRCs. Labels PC, JF, NF and PPF are used for PC, JFRC, NFRC and PPFRC samples, respectively. Labels of C, S, F and L are marked additionally to indicate the specimens specified for the tests of compressive, splitting-tensile, and flexure strengths and linear shrinkage, respectively. 1 and 2 along with labels delineated the mark of the sample for each specimen.

3.5 Testing procedures

3.5.1 Slump test and density test

ASTM standard C143/C143M−15a is adopted for workability determination of both fresh PC and FRCs. The densities of both PC and FRCs in hardened state are measured as per ASTM standard C642-13. The procedure for measuring the workability and densities of FRCs is same as that of PC, due to non-availability of respective standards for FRCs.

3.5.2 Compressive strength test

Servo-hydraulic testing machine is used as per ASTM standard C39 / C39M-17 for compressive strength, compressive behavior, compressive pre-crack/post-crack energies, and compressive toughness index. The uniform distribution of load is ensured by capping each cylinder with plaster of paris prior to testing.

3.5.3 Splitting-tensile strength test

ASTM standard C496/C496M-11 is followed for testing of cylindrical specimens of PC and FRCs by using servo-hydraulic testing machine. The outcomes of tests include splitting-tensile strength, splitting-tensile behavior, splitting tensile pre-crack/post-crack energies, and splitting-tensile toughness index.

3.5.4 Flexural strength test

Following the ASTM standard C293 / C293M-16, servo-hydraulic testing machine is used for flexural strength test of all beam-lets. The flexure strength tests are performed to study the modulus of rupture (MoR), flexural behavior, flexural pre-crack/post-crack energies, and flexural toughness index.

3.5.5 Water absorption test

Water absorption test is performed as per ASTM standard C642-13, to determine the water absorption. The size of the specimens used for water absorption test is 100 mm x 100 mm x ~225 mm because the selected tested beam-lets in flexural strength tests are utilized for determining the water absorption. Only that halves of the tested beam-lets are selected which have no apparent crack in that portion.

3.5.6 Linear shrinkage test

As no single document is available for determination of linear shrinkage of hardened concrete. Therefore, ASTM C157/C157M-08, is employed to determine the length change for estimating the linear shrinkage of PC, JFRC, NFRC, and PPFRC by determining the change in length of beam-lets (OPSS LS-435 standard). The test is performed as per ASTM C157/C157M-08, with the exception that the test specimen sizes are 100 mm x 100 mm x 450 mm, and accordingly, the gauge length reference bar is used.

3.6 Summary

The proportion of concrete, sand, aggregates for PC and FRCs is 1, 3, and 1.5 with a w/c proportion of 0.7. In addition to that, 5% fiber content, by mass of cement, and fiber length of 50 mm are utilized in the case of FRCs. A total of 32 specimens i.e. 16 cylinders and 16 beam-lets are produced. ASTM standards are followed for the execution of slump, density, compressive, splitting-tensile, modulus of rupture, water absorption, and linear shrinkage tests. The properties of FRCs are also determined by using the same standards of ASTM. The investigation and results are talked about in detail in the next chapter (i.e. chapter 4).

CHAPTER 4

TEST RESULTS AND ANALYSIS

4.1 Background

The mix design ratio of 1:3:1.5 and a W/C ratio of 0.7 is used for casting the specimens of PC. The same mix design ratio is used for preparation of FRCs aside from addition of 5% fiber content, by mass of cement, having a length of 50 mm. This chapter contains the detail discussion on the results of the tests performed on the specimens of PC, JFRC, NFRC, and PPFRC.

4.2 Material properties of PC and FRCs

4.2.1 Slump and density

The values of slump for fresh PC, JFRC, NFRC, and PPFRC are displayed in the third column of Table 4-1. The slumps of PC, JFRC, NFRC, and PPFRC are 44 mm, 17 mm, 28 mm, and 27 mm, respectively. The FRCs are less workable when contrasted with PC for the same W/C ratio. Due to the retention and confinement effect of fibers, the reduced values of slump are observed in case of FRCs than that of PC. The reduction of 27 mm, 16 mm, and 17 mm has been observed in slump in the cases of JFRC, NFRC, and PPFRC, respectively, than that of PC. Thus, the slumps of JFRC, NFRC, and PPFRC are reduced by 61%, 36%, and 39%, respectively, than that of PC for the same W/C ratio. The slump of JFRC reduces most as compared to NFRC and PPFRC because of the high water-absorption capacity of jute fibers, being natural fibers. Other researchers also reported that the incorporation of fibers into a mix decreased the workability (Ozomaka 1976; Lewis and Mirihagalia 1979).

The fourth column of Table 4-1 displays the densities of the specimens of hardened PC, JFRC, NFRC, and PPFRC. The inclusion of fibers in FRCs caused a decrease in densities of FRCs compared to that of PC due to fiber low unit weight. The densities of PC, JFRC, NFRC, and PPFRC are 2204 kg/m^3, 2139 kg/m^3, 2182 kg/m^3, and 2191 kg/m^3, respectively. In contrast to that of PC, a decrease of 65 kg/m^3, 22 kg/m^3, and 13 kg/m^3, is observed in densities of JFRC, NFRC, and PPFRC, respectively. Hence, the densities of JFRC, NFRC, and PPFRC are reduced by 3%, 1%, and 0.6%, in comparison to that of PC. The density of JFRC is reduced by 2% and 2.4% as compared to that of NFRC and PPFRC, respectively. Hence, among the FRCs, the lowest density is observed for JFRC. This is because the unit weight of the jute fibers (being natural fibers) is less than that of nylon and polypropylene fibers.

Table 4-1 W/C ratio, slump, and density of PC, JFRC, NFRC, and PPFRC

Batch (1)	Water-cement ratio (2)	Slump (mm) (3)	Density (kg/m^3) (4)
PC	0.7	44	2204
JFRC	0.7	17	2139
NFRC	0.7	28	2182
PPFRC	0.7	27	2191

4.2.2 Compressive properties

4.2.2.1 Compressive behavior

Figure 4-1 displays the compressive stress-strain curves of PC, JFRC, NFRC, and PPFRC. Figure 4-2 shows the scenario observed during the testing of PC, JFRC, NFRC, and PPFRC specimens at first crack, cracks at the peak load and cracks at the ultimate load. Throughout the testing of PC, JFRC, NFRC, and PPFRC specimens, the expected behaviour is observed. Though, here in this work, the information such as (i) location and length of first crack, (ii) locations, length and number of cracks at the peak loads and (iii) locations, length and number of cracks at the ultimate loads has been exposed. The first crack in the specimen of PC, JFRC, NFRC, and PPFRC is observed at 86%, 99%, 86%, and 92% of their corresponding peak loads. The length and width of first crack in FRCs are much less than that in PC. The length of first crack in PC, JFRC, NFRC, and PPFRC is about 40 mm, 35 mm, 30 mm, and 20 mm, respectively, (refer to upper four photos in Figure 4-2). At the peak load as compared to PC, the observed number of cracks, cracks length and width are less in JFRC, NFRC, and PPFRC. At the peak load, the maximum crack lengths in the specimens of PC, JFRC, NFRC, and PPFRC are enlarged up to about 80 mm, 70 mm, 60 mm, and 55 mm, respectively, (refer to middle four photos in Figure 4-2). At the ultimate load, the crack lengths for the specimens of JFRC, NFRC, and PPFRC are further enlarged up to about 100 mm, 90 mm, and 80 mm, respectively, (refer to bottom respective photos in Figure 4-2). While in case of PC, a portion of specimen is detached. The specimens of FRCs do not shatter into pieces and show a relative ductile/tough mode of failure. The presence of jute, nylon, and polypropylene fibers in concrete bridge the cracks to resist the deformation. The use of fibers results in multiple more closely spaced cracks with reduced crack width and length for FRCs specimens. In the case of PC, the ultimate failure occurs along the narrow region where fewer cement particles existed around the aggregate particles and the breaking of aggregates is also observed because of its low crushing strength. In the cases of JFRC, NFRC, and PPFRC after the completion of test at the ultimate load, their intentionally broken specimens demonstrate that mostly the de-bonding of fibers in concrete mix is observed, rather than the breaking of fibers. For the failure of the jute fibers, the ratio is about 35:65 amongst fibers debonding and fiber fracture. In the case of nylon and polypropylene fibers, the ratios of nearly 70:30 and 85:15, respectively, are observed amongst fibers debonding and fiber fracture. The highest debonding and lowest fiber fracture is observed for the polypropylene fibers due to its better tensile strength and lower bond strength. Whereas, the lowest debonding and highest

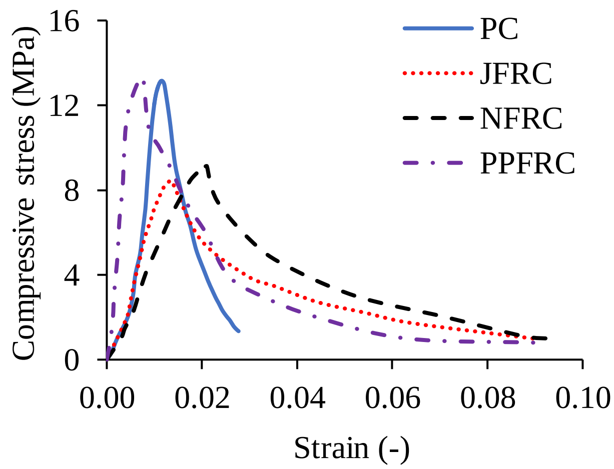

Figure 4-1 Stress-strain curves of PC, JFRC, NFRC, and PPFRC for compressive strength tests

fracture of fibers is observed in the case of jute fiber failure because of its low tensile strength and better bond strength. The bond strength can be improved by carrying out surface treatment of fibers which improves its surface roughness in order to provide a firm grip between the fiber and adjoining matrix. The additives can also be used to increase the bond strength amongst the fibers and matrix.

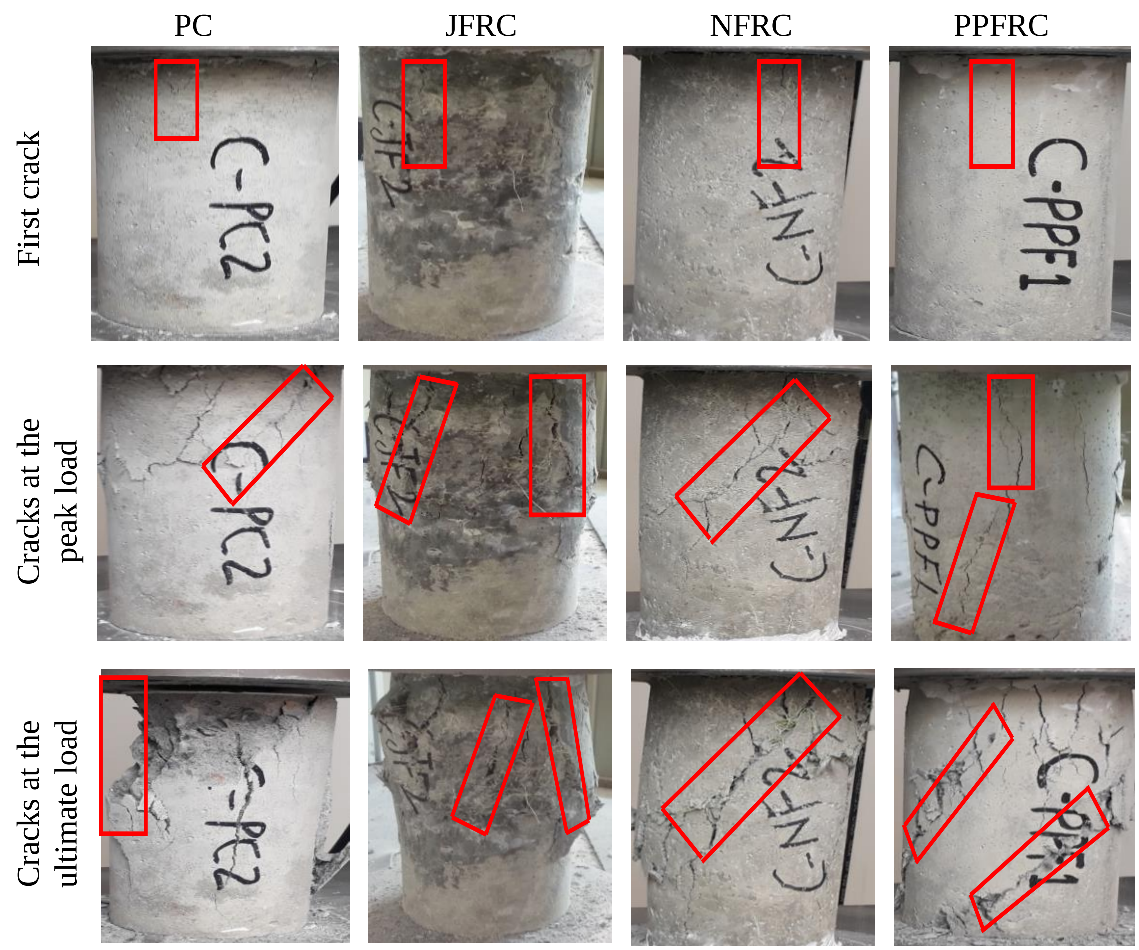

Figure 4-2 Development of cracks in the cylindrical specimens of PC, JFRC, NFRC, and PPFRC under compressive load

4.2.2.2 Compressive strength, compressive pre-crack/post-crack absorbed energies, and compressive toughness index

The compressive strength is considered equal to the largest value of stress from the stress-strain curves. The area beneath the stress-strain curve up to the stress of first crack is considered as the compressive pre-crack absorbed energy (CPE). The area beneath the stress-strain curve from the stress at first crack to the stress at the ultimate load is considered as the compressive cracked absorbed energy (CCE). The total area lying below the stress-strain curve from the point of zero stress to the stress at the ultimate load is considered as the compressive total absorbed energy (CTE). The ratio between the compressive total absorbed energy and the compressive pre-crack absorbed energy (i.e. CTE / CPE) is taken as the compressive toughness index (CTI). Table 4-2 displays the CS, CPE, CCE, CTE, and CTI of PC, JFRC, NFRC, and PPFRC. The CS of 13.2 MPa, 8.4 MPa, 9.1 MPa, and 13.3 MPa are observed for PC, JFRC, NFRC, and PPFRC, respectively. In contrast to CS of PC, a decrease of 4.8 MPa and 4.1 MPa was observed in CS of JFRC and NFRC, respectively. In comparison to that of PC, an increase of 0.1 MPa was observed in CS of PPFRC. Bayasi et al. (1993) and Tavakoli (1994) also found that polypropylene fibers had a moderately little ideal impact on compressive strength of concrete. The possible reason for relatively high CS of PC and PPFRC could be the better compaction in PC and PPFRC than that in JFRC and NFRC. The reason for decrease in compressive strengths of JFRC and NFRC could be addition of large amount of less dense jute and nylon fibers, which enhanced the heterogeneousness of mixes up to some extent. Another possible cause could be the presence of a relatively lesser amount of cement in the JFRC and NFRC due to the addition of large amount of fibers (being low dense fibers) in such a mix design ratio (1:3:1.5) that was similar to that of PC. The values of strain (ε_o) at the maximum stress of PC, JFRC, NFRC, and PPFRC are 0.012, 0.014, 0.021 and 0.007, respectively. An enhanced value of strain is observed for NFRC as compared to that of other investigated materials which ensures that NF have high elongation capability which permits it to hold the mixture together even at the time of breaking and thus prevents the effect of shattering force. Another reason can be the slippage of NF due to relatively less bond strength. The CPE of PC, JFRC, NFRC, and PPFRC are 0.06 MPa, 0.05 MPa, 0.06 MPa, and 0.05 MPa, respectively. As compared to CPE of PC, a decrease of 0.01 MPa is observed in CPE of both JFRC and PPFRC and CPE of NFRC remained similar to that of PC. The CCE of PC, JFRC, NFRC, and PPFRC are 0.09 MPa, 0.23 MPa, 0.28 MPa, and 0.26 MPa, respectively. In comparison to CCE of PC, an increase of 0.14 MPa, 0.19 MPa, and 0.17 MPa was observed in CCE of JFRC, NFRC and PPFRC, respectively. The CTE of PC, JFRC, NFRC, and PPFRC are 0.15 MPa, 0.28 MPa, 0.34 MPa, and 0.31 MPa, respectively. An increase of 0.13 MPa, 0.19 MPa, and 0.16 MPa is observed in CTE of JFRC, NFRC, and PPFRC, respectively, than that of PC. The increase in CCE and CTE of FRCs may be because of the addition of fibers, which enhances the post-crack energy absorption capabilities of concrete. The CTI of PC, JFRC, NFRC, and PPFRC are 2.50, 5.60, 5.67, and 6.20, respectively. In contrast to CTI of PC, an increase of 3.1, 3.17, and 3.70 is noticed in CTI of JFRC, NFRC, and PPFRC, respectively. Fiber addition have limited the size of cracks and bridged the cracks to reduce the deformation. The reason for the increase in CTI of FRCs is the presence of fibers of high percentage which provide considerable amount of resistance against stresses after the crack propagation. As a result of high post-crack energy absorption of FRCs as compared to that of PC, the toughness indices of FRCs are greater than that of PC. Thus, the compressive post-crack energy absorption capability and toughness of concrete can be improved by incorporation of fibers.

Table 4-2 CS, εo, CPE, CCE, CTE, and CTI of PC, JFRC, NFRC, and PPFRC

	Concrete type			
Parameters	**PC**	**JFRC**	**NFRC**	**PPFRC**
CS (MPa)	13.2	8.4	9.1	13.3
ε_o (-)	0.012	0.014	0.021	0.007
CPE (MPa)	0.06	0.05	0.06	0.05
CCE (MPa)	0.09	0.23	0.28	0.26
CTE (MPa)	0.15	0.28	0.34	0.31
CTI (-)	2.50	5.60	5.67	6.20

Note: CS = Compressive strength, ε_o = Strain at the maximum stress, CPE = Compressive absorbed pre-crack energy, CCE = Compressive cracked absorbed energy, CTE = Compressive total absorbed energy, CTI = Compressive toughness index.

The comparison of CS, CPE, CTE and CTI of PC, JFRC, NFRC, and PPFRC can be observed in the Figure 4-3. The reduction of 36% was observed in CS of JFRC than that of PC. This reduction in the compressive strength due to incorporation of natural fibers was also reported by other researchers (Ali et al. 2012; Ismail 2007; Ramaswamy et al. 1983;). So, by lowering the content of fibers may enhance the compressive strength of concrete. The decrease of 17% is noticed in CPE of JFRC in contrast to that of PC. An enhancement of 87% and 124% is observed in CTE and CTI, respectively, of JFRC as compared to that of PC. The reduction of 31% is observed in the CS of NFRC than that of PC. The CPE, CTE, and CTI of NFRC are improved by 0%, 127%, and 127%, respectively, than that of PC. As compared to CS of PC, an increase of 1% is observed in CS of PPFRC. In comparison to that of PC, a decrease of 17% is observed in CPE of PPFRC and an increase of 107% and 148% is observed in CTE and CTI, respectively, of PPFRC. The PPFRC outperformed its JFRC and NFRC companions in upgrading of CS and CTI. While the NFRC outperformed its JFRC and PPFRC in upgrading of CPE, CCE, and CTE. An improved post post-crack energy absorption capability of NFRC is observed as compared to JFRC and PPFRC due to incorporation of high content of high strength nylon fibers, which resists relatively more fragmentation of cylinder due to crushing load. The degradation in post-crack energy absorption of PPFRC as compared to NFRC may be due to presence of less volume of PPF in a such mix design ratio (1:3:1.5) as in NFRC because of high density of PPF as compared to that of NF. The improved CS and CTI of PPFRC may be due to the relatively well dispersal of the fibers through the concrete mix. The strength, absorbed energies, and toughness index of JFRC are very low as compared to that of NFRC and PPFRC because of the low strength and low density of jute

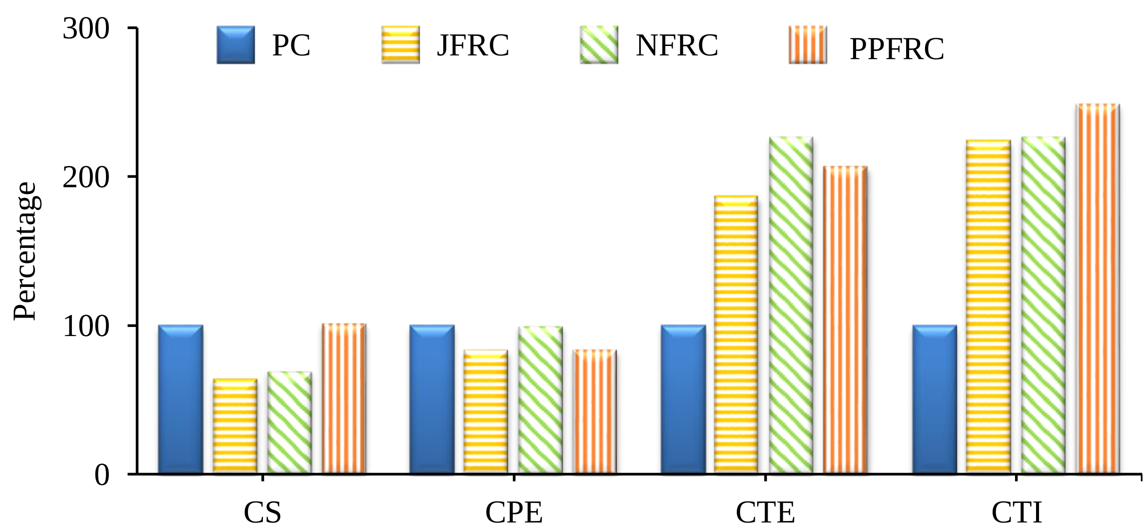

Figure 4-3 Comparison of compressive strengths, compressive pre-crack absorbed energies, compressive total absorbed energies, and compressive toughness indices of PC, JFRC, NFRC, and PPFRC

fibers as compared to that of PPF and NF. By comparing the results of compression strength tests of the investigated materials, the PPFRC demonstrates the better results in terms of enhanced CTI and CS. This ensures that PPFRC can resist well the effects of erosion and abrasion on canal-lining due to improved post cracking behavior (improved CTI) with highest value of CS among the investigated materials.

4.2.3 Splitting-tensile properties

4.2.3.1 Splitting-tensile behavior

Load-time curves under splitting-tensile loading are shown in Figure 4-4. Figure 4-5 displays the scenario observed during the testing of PC, JFRC, NFRC, and PPFRC specimens at first crack, cracks at the peak loads and cracks at the ultimate loads. Throughout the testing of PC, JFRC, NFRC, and PPFRC specimens, the anticipated splitting-tensile behaviour is observed. The upper four photos in Figure 4-5 show the first crack in PC, JFRC, NFRC, and PPFRC. The first crack in the specimen of PC, JFRC, NFRC, and PPFRC is observed at 100%, 93%, 98%, and 99% of their corresponding peak loads. The length and width of first crack in FRCs are much less than that in PC. The length of about 50 mm, 60 mm and 70 mm is observed for the first crack in JFRC, NFRC, and PPFRC. At this stage, it can be observed that the PC shatter into pieces adjacently to first crack without any time gap, while specimens of FRCs are held together because of the constrainment effect of fibers in specimens. At the peak load, as compared to PC, the observed number of cracks, cracks length and width at the peak load are less in JFRC, NFRC, and PPFRC as can be seen in the middle four photos of Figure 4-5. At this stage, the maximum crack lengths in the specimens of JFRC, NFRC, and PPFRC are enlarged up to about 65 mm, 70 mm, and 80 mm, respectively. The test is continued even after the peak load to observe the specimen behaviour. At the extreme load, there are multiple cracks and the maximum crack lengths for the specimens of JFRC, NFRC, and PPFRC are enlarged up to about 75 mm, 80 mm, and 90 mm, respectively, (refer to bottom four photos in Figure 4-5). As per expectations, for all the cases i.e. JFRC, NFRC, and PPFRC, the small size of first crack is observed than that of cracks produced at the peak and extreme loads. This shows that as soon as the cracking of concrete started, the fibers ensured the

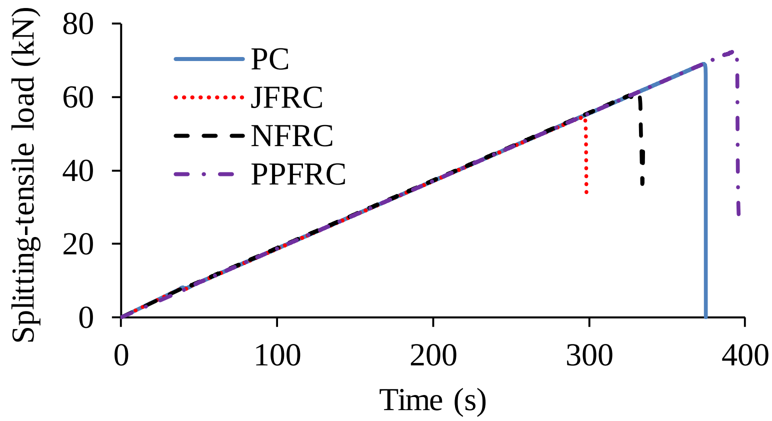

Figure 4-4 Load-time histories of PC, JFRC, NFRC, and PPFRC from the tests of SS

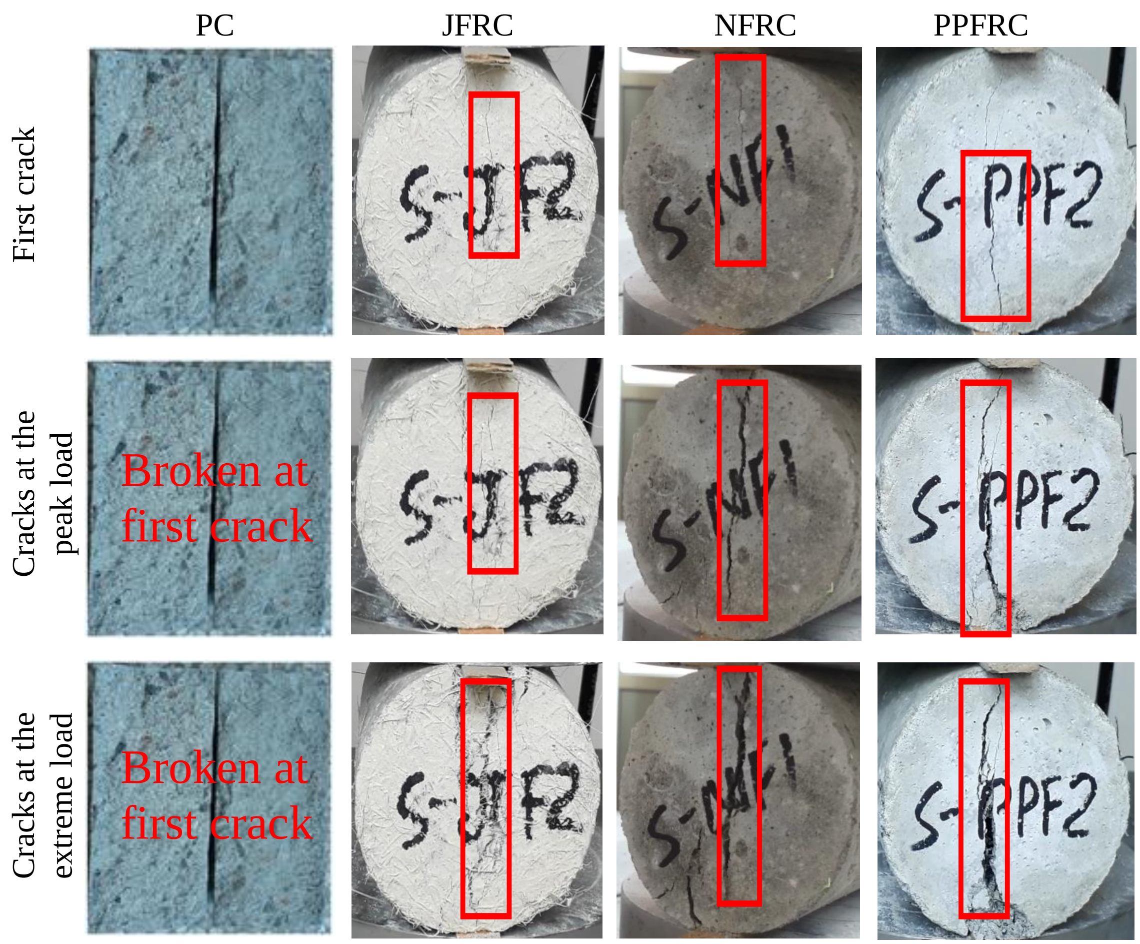

Figure 4-5 Development of cracks in the cylindrical specimens of PC, JFRC, NFRC, and PPFRC under splitting-tensile load

tough behavior of concrete by arresting the crack formation and propagation. So, by incorporation of fibers, the brittle character of concrete can be avoided by improving its post cracking behavior. The observation of fibers failure in case of FRCs has been carried out by intentionally breaking the cylinders into two portions. The visual inspection of JFRC cylinder shows that the ratio of about 30:70 exists for the failure of fibers between fiber pull-out and fiber fracture on the ruptured surface. In NFRC cylinder, the ratio of about 65:35 is observed for the failure of fiber between the pull-out and fracture of fibers on the fragmented surface of specimens. In case of PPFRC cylinder, the ratio of about 75:25 is observed for the failure of fiber between the pull-out and fracture of fibers on the fragmented surface of specimens. The highest debonding and lowest fiber fracture is observed for the polypropylene fibers due to its better tensile strength and lower bond strength. Whereas, lowest debonding and highest fracture of fibers is observed in the case of jute fibers because of its low tensile strength and better bond strength. The fiber pull-out is resulted due to smaller embedment length of fibers in any one broken side of the half cylinder. The existence of the smaller embedment length results in smaller bond strength than the fiber tensile strength. The equal embedment length of broken fibers is expected on each half of cylinders.

4.2.3.2 Splitting-tensile strength, splitting-tensile pre-crack/post-crack absorbed energies, and splitting-tensile toughness index

The largest value of load is considered from the splitting-tensile load-time histories of for the calculation of the splitting-tensile strength (SS). The area beneath the load-time history up to the load at first crack is considered as splitting-tensile pre-crack absorbed energy (SPE). The area beneath the splitting-tensile load-time history from the load at first crack to the peak load is considered as the splitting-tensile post-crack absorbed energy (SCE). It may be noted that the load at first crack and peak load are same in case of PC because it was splitted into two pieces at these stages. The total area lying below the splitting-tensile load-time history from the point of zero load to the peak load is considered as the splitting-tensile total absorbed energy (STE). The ratio between the splitting-tensile total absorbed energy and the splitting-tensile pre-crack absorbed energy (that is STE / SPE) is considered as the splitting-tensile toughness index (STI). Table 4-3 displays the

SS, SPE, SCE, STE, and STI of PC, JFRC, NFRC, and PPFRC. The SS of 2.1 MPa, 1.7 MPa, 1.9 MPa, and 2.2 MPa, are observed for PC, JFRC, NFRC, and PPFRC, respectively. In contrast to SS of PC, a reduction of 0.4 MPa, and 0.2 MPa is observed in the SS of JFRC and NFRC, repectively. And an increase of 0.1 MPa is observed in the SS of PPFRC. Tavakoli (1994) also reported an increase in SS of concrete due to addition of polypropylene fibers as observed in the current study in case of PPFRC. The values of SPE for PC, JFRC, NFRC, and PPFRC are 12973 kN.s, 7956 kN.s, 10017 kN.s, and 13978 kN.s, respectively. In comparison to SPE of PC, a reduction of 5017 kN.s and 2956 kN.s is observed in SPE of JFRC and NFRC, respectively. And an increase of 1005 kN.s is observed in SPE of PPFRC. In contrast to that of PC, a decreased value of SPE is noticed for JFRC and NFRC, due to presence of high percentage of low dense fibers in a mix design (i.e. 1:3:1.5) similar to that of PC. The incorporation of high dosage of fibers adversely affect the shear strength of JFRC and NFRC due to decrease in bond strength. And as a result, due to decreased value of shear resistance, it's become difficult for JFRC and NFRC to resist the early formation of first crack and thus SPE is reduced. While for PPFRC, the well dispersal and presence of relatively small dosage of polypropylene fibers (in the same mix design of 1:3:1.5) improved its resistance to shear forces by avoiding early formation of first crack. And thus, an improved value of SPE is observed for PPFRC than that of all investigated materials. The value of 0 kN.s, 178 kN.s, 229 kN.s, and 353 kN.s, are observed for SCE of PC, JFRC, NFRC, and PPFRC, respectively. In comparison to that of PC, 100 times increase is observed in SCE of JFRC, NFRC, and PPFRC, respectively. The improved SCE of FRCs shows that the post-crack energy absorption capability of FRCs are much greater than that of PC because of the crack bridging effect of fibers. The STE of PC, JFRC, NFRC, and PPFRC are 12973 kN.s, 8134 kN.s, 10246 kN.s, and 14331 kN.s, respectively. In comparison to STE of PC, a reduction of 4839 kN.s and 2727 kN.s is observed in the STE of JFRC and NFRC, respectively, and an increase of 1358 kN.s is observed in the STE of PPFRC. The STI of 1, 1.02, 1.02, and 1.03 are observed for PC, JFRC, NFRC, and PPFRC, respectively. An increase of 0.02, 0.02, and 0.03 is observed in STI of JFRC, NFRC, and PPFRC, respectively, than that of PC.

The SS, SPE, STE, and STI of PC, JFRC, NFRC, and PPFRC are compared in Figure 4-6. In contrast to that of PC, a reduction of 19%, 39%, and 37% is observed in SS, SPE,

Table 4-3 SS, SPE, SCE, STE, and STI of PC, JFRC, NFRC, and PPFRC

	Concrete type			
Parameters	**PC**	**JFRC**	**NFRC**	**PPFRC**
SS (MPa)	2.1	1.7	1.9	2.2
SPE (kN.s)	12973	7956	10017	13978
SCE (kN.s)	0	178	229	353
STE (kN.s)	12973	8134	10246	14331
STI (-)	1.00	1.02	1.02	1.03

Note: SS = Splitting-tensile strength, SPE = Splitting-tensile absorbed pre-crack energy, SCE = Splitting-tensile post-crack absorbed energy, STE = Splitting-tensile total absorbed energy, STI = Splitting-tensile toughness index.

and STE, respectively, of JFRC. In contrast to STI of PC, an increase of 2% is observed in STI of JFRC. When contrasted with that of PC, a decrease of 10%, 23%, and 21% is observed in SS, SPE, and STE, respectively, of NFRC. In contrast to STI of PC, an increase of 2% is observed in STI of NFRC. An improvement of 5%, 8%, 10%, and 3% is noticed in the SS, SPE, STE, and STI, respectively, of PPFRC in comparison to that PC. As a result of high post-crack energy absorption capability of FRCs as compared to that of PC, the toughness indices for the FRCs are greater than 1. While in case of PC, the STI is equal to 1 because of the existence of first crack load and peak load at the same point. So, an improved post-crack energy absorption capability and better crack arresting mechanism

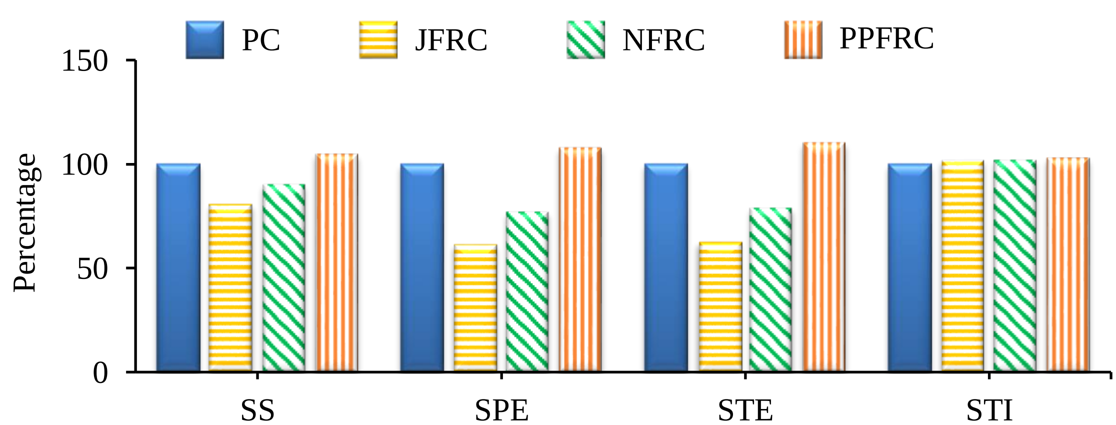

Figure 4-6 Comparison of the splitting-tensile strengths, splitting-tensile pre-crack absorbed energies, splitting-tensile total absorbed energies, and splitting-tensile toughness indices of PC, JFRC, NFRC, and PPFRC

can be ensured by introducing the fibers in concrete. As per the outcomes of splitting-tensile tests for the PC, JFRC, NFRC, and PPFRC, the PPFRC shows better results in terms of improved SS, SPE, SCE, STE, and STI as compared to other studied materials. The better results for PPFRC may be due to the random distribution and high tensile strength of PPF. The random distribution of fibers ensures the utilization of maximum fibers in improving the strength of PPFRC. So, it can be suggested that PPFRC can perform well in controlling the cracks due to tensile stresses because of its high governing splitting-tensile properties.

4.2.4 Flexural properties

4.2.4.1 Flexural behavior

Figure 4-7 displays the load-deflection curves for flexure strength test. Figure 4-8 displays the formation of first crack, cracks at the peak load, and cracks at the ultimate load in the beam-lets of PC, JFRC, NFRC, and PPFRC. The upper four photos of Figure 4-8 show the first crack in PC, JFRC, NFRC, and PPFRC beam-lets. The first crack in the beam-lets of PC, JFRC, NFRC, and PPFRC is observed at 100%, 97%, 99%, and 95% of their corresponding peak loads. The length of about 60 mm, 50 mm, and 50 mm is observed for first crack in JFRC, NFRC, and PPFRC, respectively. The length and width of first crack in FRCs beam-lets are much less than that in PC beam-lets. It can be observed that the PC beam-lets shatter into two pieces, while beam-lets of FRCs are held together because of the constrainment effect of fibers in beam-lets. At the peak load, as compared to PC, the observed number of cracks, cracks length and width at the peak load are less in JFRC, NFRC, and PPFRC. At this stage, the crack lengths in the specimens of JFRC, NFRC, and PPFRC are enlarged up to about 80 mm, 83 mm, and 76 mm, respectively, (refer to middle four photos in Figure 4-8). At the ultimate load, the crack lengths for the specimens of JFRC, NFRC, and PPFRC are enlarged up to about 94 mm, 94 mm, and 82 mm, respectively, (refer to bottom four photos in Figure 4-8). For better observation of fiber failure, the beam-lets of FRCs are intentionally broken into two portions. The visual inspection of fracture surface of JFRC shows that the ratio of about 30:70 exists between fiber pull-out from the matrix and fiber fracture. In NFRC beam-lets, the ratio of about

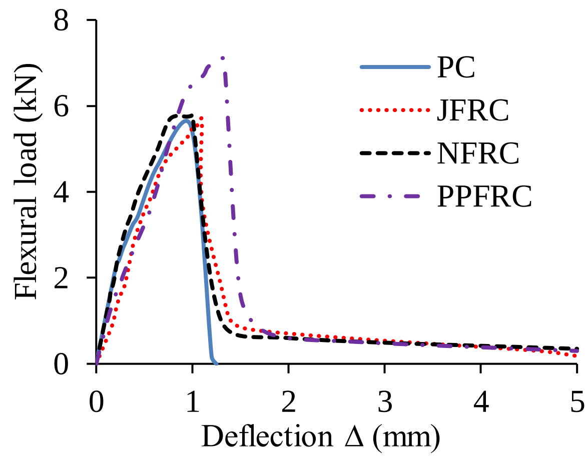

Figure 4-7 Load-deflection curves of PC, JFRC, NFRC, and PPFRC from flexure strength tests

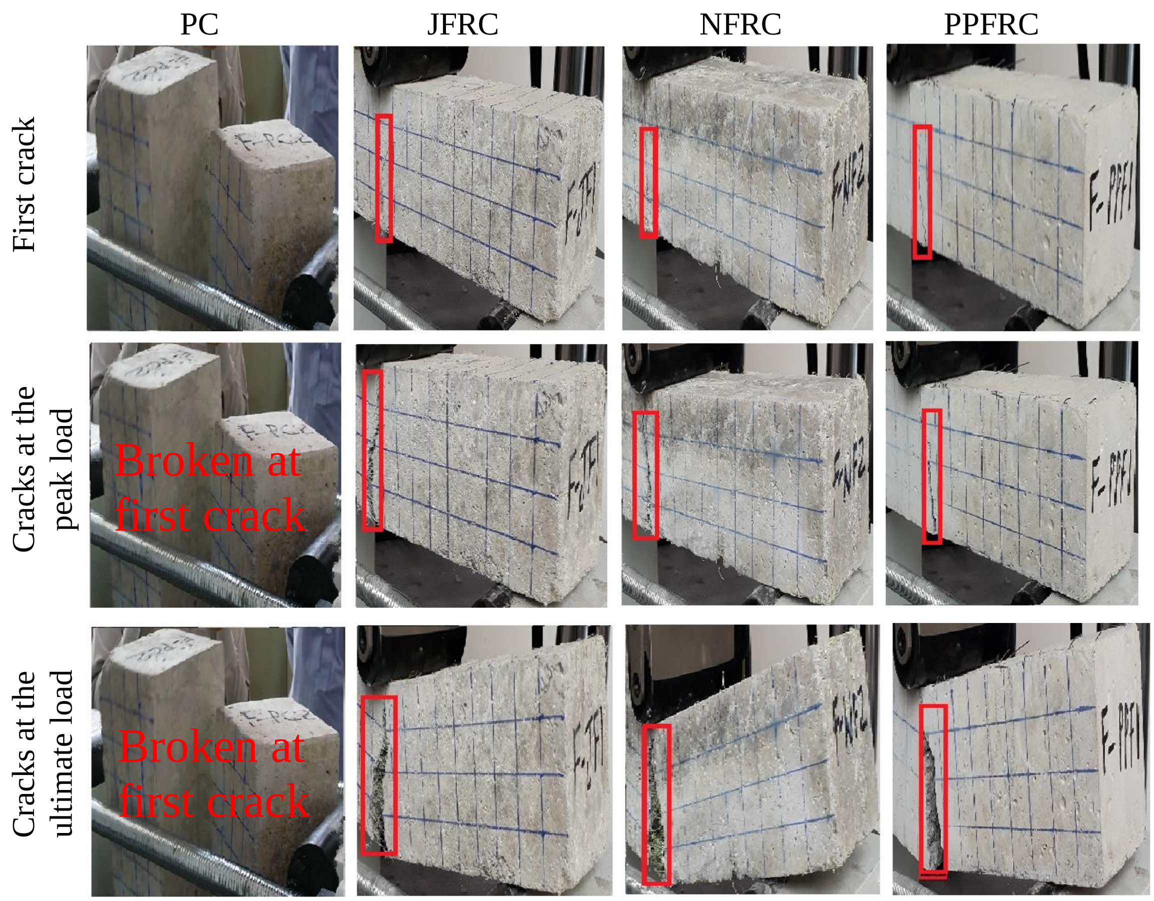

Figure 4-8 Development of cracks in the beam-lets of PC, JFRC, NFRC, and PPFRC under flexure load

60:40 is observed for the failure of fiber between the pull-out and fracture of fibers on the fragmented surface of specimens. In PPFRC beam-lets, the ratio of about 80:20 is observed for the failure of fiber between the pull-out and fracture of fibers on the fragmented surface of specimens. By visual inspection of the fractured surfaces of the beam-lets of FRCs, it is found that the random distribution and dispersal of polypropylene fibers is much better than that of nylon and jute fibers. In the case of flexure test, the reasons for fibers pull-out and fracture are identical to that of explained in preceding chapter of "splitting-tensile behavior".

4.2.4.2 Flexure strength, flexural pre-crack/post-crack absorbed energies, and flexural toughness index

The modulus of rupture (MoR) is calculated by considering the largest value of load from the load-deflection curves of flexure strength tests. The area beneath the load-deflection curve of flexure strength test up to the load at first crack is taken as the flexural pre-crack absorbed energy (FPE). It may be noted that the load at first crack and peak load are same in case of PC beam-let as it was broken into two halves at these stages. The area beneath the flexure load-deflection curve from the load at first crack to the ultimate load is considered as the flexural post-crack absorbed energy (FCE). The total area lying below the flexure load-deflection curve is considered as the flexural total absorbed energy (FTE). The ratio between the flexural total absorbed energy and the flexural pre-crack absorbed energy (that is FTE / FPE) is chosen as the flexural toughness index (FTI). Table 4-4 displays the MoR, Δ_o, FPE, FCE, FTE, and FTI of PC, JFRC, NFRC, and PPFRC. The values of 2.68 MPa, 2.90 MPa, 2.94 MPa, and 3.60 MPa, are observed for MoR of PC, JFRC, NFRC, and PPFRC, respectively. By comparing to that of PC, the MoR of JFRC, NFRC, and PPFRC enhances by an amount of 0.22 MPa, 0.26 MPa, and 0.92 MPa, respectively. The similar trend of the presence of increase in MoR and decrease in SS/shear strength for the same material was also reported by different researchers (Vitkar et al. 2017; Bei-xing et al. 2004). The deflections (Δ_o) at the peak load of PC, JFRC, NFRC and PPFRC are 0.99 mm, 1.10 mm, 1 mm, and 1.33 mm, respectively. A larger Δ_o is observed for PPFRC as compared to that of other studied materials. The possible reason can be the higher ratio (about 80%) of fiber pull-out in PPFRC. The FPE of PC, JFRC, NFRC, and

PPFRC are 4.09 kN.mm, 3.37 kN.mm, 3.60 kN.mm, and 4.11 kN.mm, respectively. As compared to PC, the FPE of JFRC and NFRC decreases by 0.72 kN.mm and 0.49 kN.mm, respectively, while that of PPFRC increases by 0.02 kN.mm. The reason for increased value of FPE is well dispersal and random distribution of PPF fibers which helps in resisting crack propagation. The FCE of JFRC, NFRC, and PPFRC are 2.91 kN.mm, 3.29 kN.mm, and 4.09 kN.mm, respectively. The FTE of PC, JFRC, NFRC, and PPFRC are 4.09 kN.mm, 6.28 kN.mm, 6.89 kN.mm, and 8.20 kN.mm, respectively. The FTE of JFRC, NFRC, and PPFRC increases by 2.19 kN.mm, 2.80 kN.mm, and 4.11 kN.mm, respectively, than that of PC. The FTI of 1, 1.86, 1.91, and 1.99, is observed for PC, JFRC, NFRC, and PPFRC, respectively. As compared to PC, an increase of 0.86, 0.91, and 0.99 is observed in FTI of JFRC, NFRC, and PPFRC, respectively. Better post-crack behavior and higher post-crack energy absorption of FRCs increases the flexure toughness indices of FRCs. The crack arresting mechanism and constrainment effect of jute, nylon, and polypropylene fibers resist the propagation of cracks which results in enhanced post-crack energy absorption of concrete.

Table 4-4 MoR, Δ_o, FPE, FTE, and FTI of PC, JFRC, NFRC, and PPFRC

	Concrete type			
Parameters	**PC**	**JFRC**	**NFRC**	**PPFRC**
MoR (MPa)	2.68	2.90	2.94	3.60
Δ_o (mm)	0.99	1.10	1.00	1.33
FPE (kN.mm)	4.09	3.37	3.60	4.11
FCE (kN.mm)	0.00	2.91	3.29	4.09
FTE (kN.mm)	4.09	6.28	6.89	8.20
FTI (-)	1.00	1.86	1.91	1.99

Note: FS = Flexure strength, Δo = Deflection at the maximum load, FPE = Flexural absorbed pre-crack energy, FCE = Flexural post-crack absorbed energy, FTE = Flexural total absorbed energy, FTI = Flexural toughness index.

Figure 4-9 presents the comparison of MoR, FPE, FTE, and FTI of PC, JFRC, NFRC, and PPFRC. In comparison to that of PC, an increase of 8%, 53%, and 86%, is observed in MoR, FTE, and FTI, respectively, of JFRC and a decrease of 18% is observed in FPE of JFRC. The MoR, FTE, and FTI of NFRC exceeds the corresponding properties of PC by an amount of 10%, 68%, and 91%, respectively, and a decrease of 12% is noticed in FPE of NFRC in comparison to that of PC. In contrast to that of PC, an increase of 34%, 0.5%, 100%, and 99%, is observed in MoR, FPE, FTE, and FTI of PPFRC, respectively. As per the outcomes of flexural tests for the FRCs, the PPFRC shows the better results in terms of improved MoR, FPE, FTE, and FTI as compared to its other two companions. The addition of PPF is seen to enhance the pre-peak as well as post-peak region of the load–deflection curve for PPFRC, also causing an increase in toughness index. On the basis of enhanced flexural properties of PPFRC, it can be suggested that PPFRC is likely to perform well in controlling the cracking of concrete due to differential settlement and external impact loads.

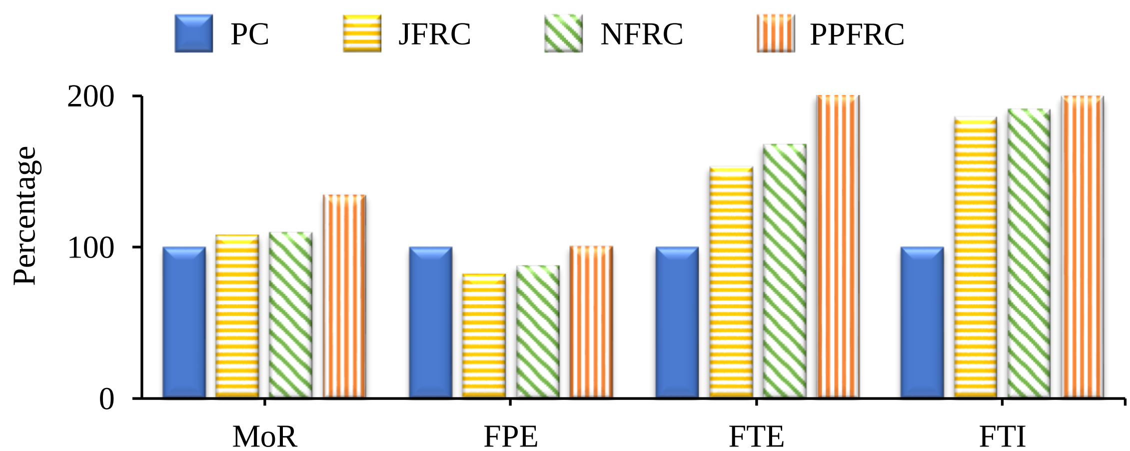

Figure 4-9 Comparison of the Flexure strengths, Flexural pre-crack absorbed energies, Flexural total absorbed energies, and Flexural toughness indices of PC, JFRC, NFRC, and PPFRC

4.2.5 Water absorption

Water absorption is defined as the transport of liquids in porous solids by virtue of surface tension acting in capillaries and is taken equal to the total mass of water absorbed by specimen divided by the total mass of specimen (Basheer et al. 2001; ASTM standard C642-13). Table 4-5 displays the water absorption of PC, JFRC, NFRC, and PPFRC. The WA of 2.41%, 2.61%, 2.44%, and 2.32% are observed for PC, JFRC, NFRC, and PPFRC, respectively. As compared to WA of PC, WA of JFRC and NFRC is increased by 0.2% and 0.03%, respectively. The possible reason for high WA of JFRC could be the high water-absorption capacity of jute fibers. Due to this, the high amount of water has been absorbed by JFRC as compared to other investigated materials. The water absorption of NFRC is little higher than that of PC due to the high porosity because of the presence of high content of nylon fibers which adversely affect the better compaction of NFRC. As compared to WA of PC, a decrease of 0.09% is observed in WA of PPFRC. The possible reason for less WA of PPFRC could be the zero water-absorption of polypropylene fibers, presence of suitable amount of fibers, and better compaction as compared to that of NFRC and JFRC.

Table 4-5 WA of PC, JFRC, NFRC, and PPFRC

	Concrete type			
Parameter	**PC**	**JFRC**	**NFRC**	**PPFRC**
WA (%)	2.41	2.61	2.44	2.32

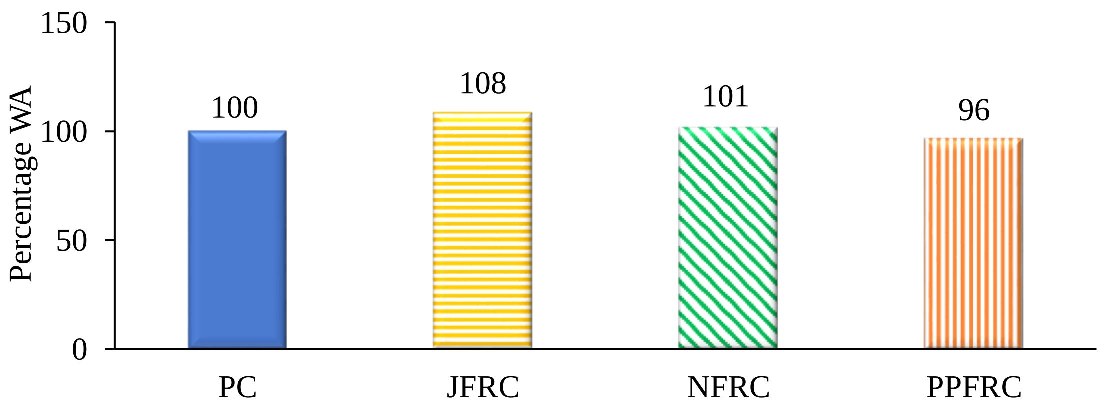

Figure 4-10 Comparison of WA of PC, JFRC, NFRC, and PPFRC

Figure 4-10 displays the comparison of results obtained from water absorption tests of PC, JFRC, NFRC, and PPFRC. As compared to WA of PC, an increase of 8% and 1% is observed in WA of JFRC and NFRC, respectively, and a decrease of 4% is observed in the WA of PPFRC. The final results of water absorption tests demonstrate that PPFRC outperformed the PC, JFRC, and NFRC in reducing the rate of water absorption. The reduction in the rate of water absorption for PPFRC may be resulted due to occurrence of the disturbance of the pore system due to the addition of specific amount of fibers into the concrete. Due to this, an effect of pore blocking and less capillary porosity produced due to the use of fibers. The same observation was made by Rostami et al. (2011) and Ramezanianpour et al. (2013). So, it can be concluded that, by the addition of fibers (having zero water absorption) into the concrete, the capillary porosity and conductivity amongst the pores can significantly be decreased. Thus, the PPFRC can be a better choice in controlling the rate of cracking in canal-lining due to alternate wetting and drying and freeze thaw effect because of presence of less number of pores.

4.2.6 Linear shrinkage

Linear shrinkage (LS) is taken as percentage increase/decrease in the length of the specimen (ASTM C531-00; OPSS LS-435 standard). Table 4-6 displays the test results of linear shrinkage (percentage decrease in length) for PC, JFRC, NFRC and PPFRC. The values of 0.090%, 0.150%, 0.117%, and 0.077% are observed for LS of PC, JFRC, NFRC, and PPFRC, respectively. As compared to LS of PC, an increase of 0.060% and 0.027% is observed in the LS of JFRC and NFRC, respectively, and a decrease of 0.013% is observed in the LS of PPFRC. The reduction in LS of PPFRC may be due to the random distribution of fibers and the presence of less number of voids as compared to other investigated materials (as proved by its lowest value of WA as compared to that of other investigated materials). An increase in the LS of JFRC and NFRC can be due to their high-water absorption capability. An increase in LS (contracting of hardened samples) is due to the loss of capillary water. So, the specimens having larger values of WA shows larger values of LS due to increase in loss of capillary water.

Table 4-6 LS of PC, JFRC, NFRC, and PPFRC

	Concrete type			
Parameter	**PC**	**JFRC**	**NFRC**	**PPFRC**
LS (% decrease)	0.090	0.150	0.117	0.077

Note: LS is reported to the nearest 0.001% of gauge length (ASTM C157/C157M-08)

Figure 4-11 displays the comparison of results obtained from linear shrinkage tests of PC, JFRC, NFRC, and PPFRC. In contrast to LS (% decrease) of PC, the LS of JFRC and NFRC are more (67% and 30%, respectively). However, in contrast to LS (% decrease) of plain concrete, the LS of PPFRC is 15% less. PPFRC outperforms the JFRC and NFRC by showing less LS due to high tensile strength of PPF as compared to that of other two fibers. The change in length of concrete specimen is due to the processes of wetting and drying. So, the less value of LS for PPFRC shows that it can perform well in limiting the tensile stresses due to alternate wetting and drying. As a result, it can be suggested that the cracks due to tensile stresses can be reduced effectively by incorporation of PPF in concrete canal-lining.

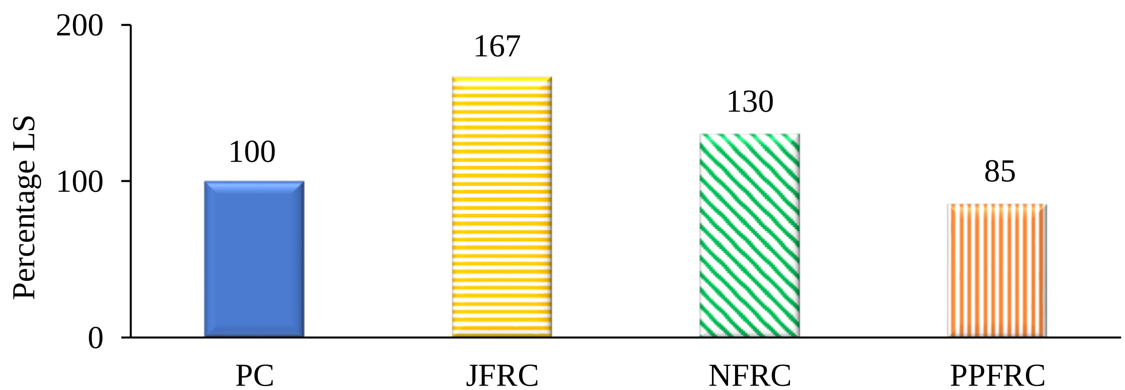

Figure 4-11 Comparison of LS (% decrease) of PC, JFRC, NFRC, and PPFRC

4.3 Summary

The mechanical properties, water absorption, and linear shrinkage of plain concrete (PC), jute fiber reinforced concrete (JFRC), nylon fiber reinforced concrete (NFRC), and polypropylene fiber reinforced concrete (PPFRC) with mix design ratio of 1:3:1.5 and W/C ratio of 0.7 are determined. In comparison to that of PC, decreased values of slumps and densities are observed for fiber reinforced concrete (FRCs). The compressive and splitting-tensile strengths of JFRC and NFRC are decreased in comparison to that of PC. Whereas, an increased value of compressive strength (CS) and splitting-tensile strength (SS) is observed for PPFRC, than that of respective PC. An increased value of modulus of rupture

(MoR) is observed for FRCs than that of PC. An increased linear shrinkage (LS) and water absorption (WA) has been observed for JFRC and NFRC as compared to that of PC. While a decreased LS and WA is observed for PPFRC as compared to that of PC. As compared to that of PC, an enhanced post-crack energy absorption and toughness indices are observed for FRCs. PPFRC outperforms all the investigated materials in upgrading CS, SS, MoR, CTI, STI, FTI, SPE and FTE. Also, decreased WA and LS of PPFRC are observed as compared to that of all other investigated materials. So, PPFRC is expected to perform well in controlling the rate of cracking in canal-lining.

CHAPTER 5

DISCUSSIONS

5.1 Background

The material properties (compressive, splitting-tensile, and flexure strengths), water absorption (WA), and linear shrinkage (LS), behavior during different loadings, mode of failure and the outcomes of the different tests has been explained in chapter 4. It is found that PPFRC outperforms all the investigated materials in upgrading most of the properties. In this chapter, the development of empirical relation between the WA or LS and the selected strength properties and correlation between the material properties and canal-lining performance has been explained.

5.2 Empirical equations

5.2.1 Empirical relation between water absorption and selected strength properties

Following empirical equations have been established with the help of experimental data by means of best fit curve (R^2 ranging from 0.70 to 0.93) along with the simplification of coefficients and exponents of input variables for numerically predicting the water absorption ‘WA’ (in %):

$WA = 3.7*CS^{-0.2}$ Eq 1

$WA = 3.2*SS^{-0.4}$ Eq 2

$WA = 13.2*SPE^{-0.2}$ Eq 3

$WA = 4.4*FPE^{-0.5}$ Eq 4

Where CS is compressive strength in MPa, SS is splitting-tensile strength in MPa, SPE is splitting-tensile pre-crack absorbed energy in kN.s, and FPE is flexural pre-crack absorbed energy in kN.mm.

Table 5-1 represents the experimental and empirical values of WA (in %). It can be observed that a correlation exists amongst the water absorption and each of CS, SS, SPE and FPE. An inverse relation has been found amongst the linked properties and WA. So, it will be true to say that an improved strength properties of a material can result in reduction in WA. The theoretical value of WA (i.e. 2.33%) calculated by Eq 2 for PPFRC is the closest to the experimental value of WA (i.e. 2.32%) for PPFRC. Only a slight difference of 0.1% exits between the experimental and empirical values of WA of PPFRC. Likewise, for all types of investigated materials, the same trend (i.e. least difference) is observed between the experimental and theoretical values calculated by Eq 2.

Table 5-1 Experimental and theoretical values of WA of PC, JFRC, NFRC, and PPFRC

	WA (%)				
Specimens	**Exp**	**Eq 1**	**Eq 2**	**Eq 3**	**Eq 4**
PC	2.41	2.21	2.38	1.99	2.18
JFRC	2.61	2.42	2.59	2.19	2.40
NFRC	2.44	2.38	2.48	2.09	2.32
PPFRC	2.32	2.21	2.33	1.96	2.17

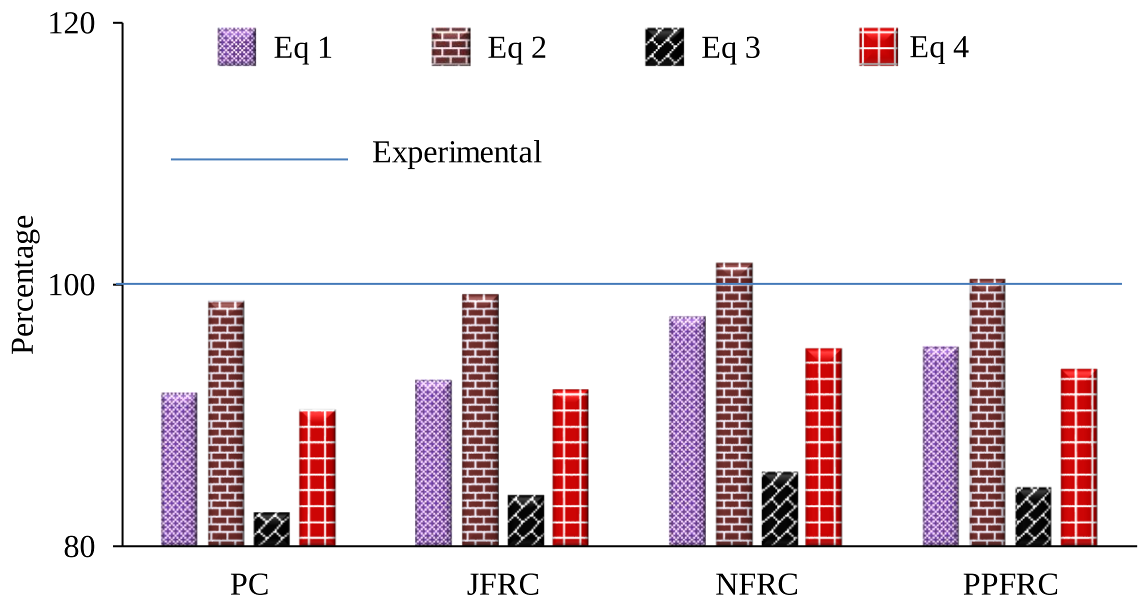

Figure 5-1 Comparison of values of WA of PC, JFRC, NFRC, and PPFRC obtained from experimental tests, Eq 1, Eq 2, Eq 3, and Eq 4

Figure 5-1 represents the comparison between the experimental and empirical values of WA. It can be observed that the WA obtained by using Eq 1 is closer to that of experimental value as compared to the values of WA calculated by using Eq 2, Eq 3 or Eq 4. This shows the existence of a close correlation between the WA and splitting-tensile strength (SS) of a material. There is a good agreement between the experimental and empirical values of WA. The percentage errors of 2%-8%, 0.4%-2%, 14%-17%, and 5%-10% are observed for Eq 1, Eq 2, Eq 3, and Eq 4, respectively.

5.2.2 Empirical relation between linear shrinkage and selected strength properties

Following empirical equations have been established with the help of experimental data by means of best fit curve (R^2 ranging from 0.91 to 0.99) along with the simplification of coefficients and exponents of input variables for numerically predicting the linear shrinkage 'LS' (in %):

$$LS = 1.6 * CS^{-1.2} \quad \text{Eq 5}$$

$$LS = 0.6 * SS^{-2.5} \quad \text{Eq 6}$$

$$LS = 4140 * SPE^{-1.14} \quad \text{Eq 7}$$

$$LS = 5 * FPE^{-2.9} \quad \text{Eq 8}$$

Where CS is compressive strength in MPa, SS is splitting-tensile strength in MPa, SPE is splitting-tensile pre-crack absorbed energy in kN.s, and FPE is flexural pre-crack absorbed energy in kN.mm.

Table 5-2 represents the experimental and empirical values of LS (in % decrease). It can be observed that a correlation exists amongst the linear shrinkage and each of CS, SS, SPE and FPE. An inverse relation has been found amongst the linked properties and LS. So, it will be true to say that improved strength properties of a material can result in reduction in LS. The theoretical value of LS (i.e. 0.078%) calculated by Eq 7 for PPFRC is the closest to the experimental value of LS (i.e. 0.077%) for PPFRC. Only a slight difference of 0.001% exists between the experimental and empirical values of LS of PPFRC. Likewise, for all types of investigated materials, the same trend (least difference) is observed between the experimental and the theoretical values of LS calculated by Eq 7.

Table 5-2 Experimental and theoretical values of LS of PC, JFRC, NFRC, and PPFRC

	LS (% decrease)				
Specimens	**Exp**	**Eq 5**	**Eq 6**	**Eq 7**	**Eq 8**
PC	0.090	0.072	0.093	0.085	0.084
JFRC	0.150	0.124	0.159	0.148	0.147
NFRC	0.117	0.113	0.120	0.114	0.121
PPFRC	0.077	0.071	0.083	0.078	0.082

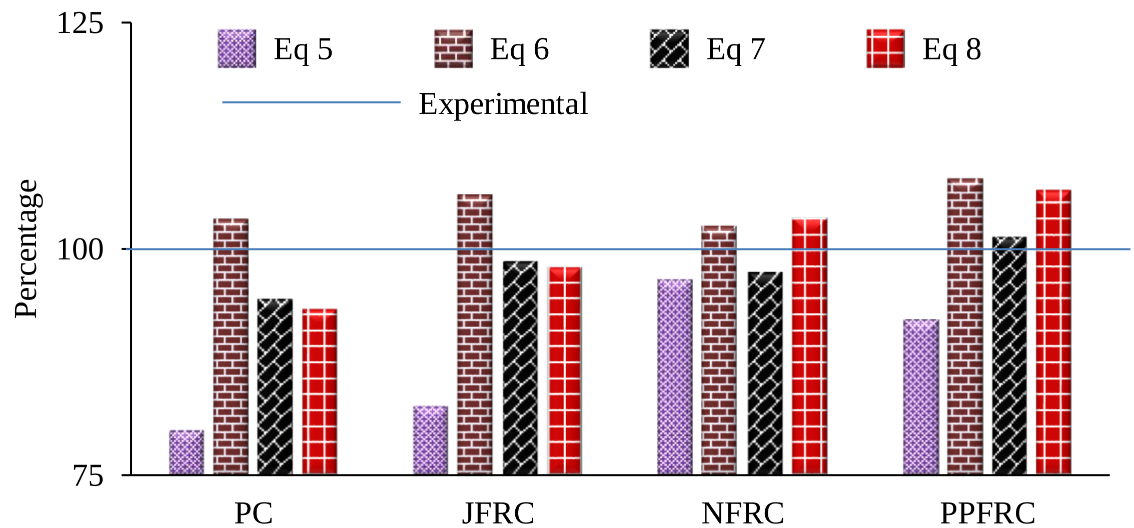

Figure 5-2 Comparison of values of LS of PC, JFRC, NFRC, and PPFRC obtained from experimental tests, Eq 5, Eq 6, Eq 7, and Eq 8

Figure 5-2 represents the comparison between the experimental and empirical values of LS. It can be observed that the LS obtained by using Eq 7 is closer to that of experimental value as compared to the values of LS calculated by using Eq 5, Eq 6 or Eq 8. This shows that a strong correlation exists between the splitting-tensile pre-crack absorbed energy (SPE) and LS of a material. There is a good agreement between the experimental and empirical values of LS. The percentage errors of 3%-20%, 3%-8%, 1%-6%, and 2%-7% are observed for Eq 5, Eq 6, Eq 7, and Eq 8, respectively.

5.3 Relationship between material properties and canal-lining performance

The rate of cracking in concrete canal-lining can be related to number of factors like shrinkage, water absorption, permeability, differential settlement, and tensile strength, etc. (Cui et al. 2013). Cracking due to shrinkage can be avoided if the tensile stresses induced by shrinkage are less than the tensile strength of concrete. This shows that the tensile strength of concrete has a key role in controlling its shrinkage cracks. An increase in the rate of water absorption of concrete canal-lining increases its rate of deterioration (Reinhardt 1997). The differential settlement of concrete structure introduces the bending stresses into it. The cracking due to differential settlement can be avoided if the flexural strength of concrete also known as bend strength exceeds the bending stresses. So, the role of flexural strength of concrete in controlling the rate of cracking due to bending is also required to be considered. The brittle characteristic of concrete is also one of the causes that contribute in increasing the rate of cracking. For this reason, it is required to increase the toughness and post-crack energy absorption of concrete in order to get ductile/tough mode of failure. So, it is important to explore materials in terms of less shrinkage and water absorption along with the better mechanical properties (especially tensile and flexural strengths and toughnesses) for reducing the rate of cracking in canal-lining.

In present study, the experimental behaviors of PC, JFRC, NFRC, and PPFRC for controlling the rate of cracking in canal-lining are examined. The PPFRC shows higher values of compressive, splitting-tensile, and flexural strengths as compared to that of other investigated materials. An increase in CTI, STI, FTI, STE, and FTE of PPFRC is also observed as compared to that of other investigated materials. The reduced values of WA and LS are observed in case of PPFRC as compared to that of other investigated materials. So, in the case of PPFRC, the rate of cracking in canal-lining can be less, conclusively it is highly likely to improve the performance of canal-lining in terms of reduced water losses. Improved ductility of canal-section is also expected in case of PPFRC as compared to other materials due to increased values of toughnesses of PPFRC. It is also important to mention that NFRC and JFRC also showed improved values of CTI, STI, FTI, CTE, and FTE as compared to that of PC. This shows that the use of JFRC and NFRC can be a good choice as compared that of PC due to their better post-crack behavior and high post-crack energy absorption capabilities.

5.4 Summary

Empirical relations are developed between WA/LS and each of the CS, SS, SPE, and FPE with the help of experimental data because of their mutual coherence in studied parameters. A good relation among the experimental and empirical values is found i.e. an error of as low as 0.4% and as high as 20% is observed. A strong relation between the material properties and the performance of canal-lining has been discussed. A significant role of different types of material properties in controlling the different types of possible cracks in concrete canal-lining is also discussed. As compared to PC, the FRCs are expected to perform better in controlling the rate of cracking in canal-lining because of their better post-crack behaviors and high post-crack energy absorption capabilities. As per the final recommendations, PPFRC is expected to be more effective for performance improvement of canal-lining as compared to other investigated materials.

CHAPTER 6

CONCLUSIONS AND RECCOMENDATIONS

6.1 Conclusions

The various types of FRCs, which can improve the performance of canal-lining by decreasing the rate of cracking, are discussed. Artificial and natural fibers can play a vital role in improvement of mechanical properties of concrete. In this study, the experimental behaviors of jute, nylon, and polypropylene fiber reinforced concrete (JFRC, NFRC, and PPFRC, respectively) are explored in order to check their suitability to control the rate of cracking in canal-lining. The considered parameters for material properties include compressive, splitting-tensile, and flexural strengths, water absorption, and linear shrinkage. The properties of PC are taken as reference. The FRCs are prepared by the fiber addition of 5% content, by mass of cement, and 50 mm length in the same mix design of PC i.e. 1:3:1.5. Following characteristics are observed during the investigation:

- For the same ratio of water-cement, the slump of JFRC, NFRC, and PPFRC are decreased by 61%, 36%, and 39%, respectively, than that of PC. The densities of JFRC, NFRC, and PPFRC are reduced by 3%, 1%, and 0.6%, respectively, in comparison to that of PC.
- As compared to compressive strength (CS) of PC, the CS of JFRC and NFRC are decreased by 36% and 31%, respectively, and that of PPFRC is improved by 1%. As compared to splitting-tensile strength (SS) of PC, the SS of JFRC and NFRC shows a decrease of 19% and 10%, respectively, and an improvement of 5% is observed in SS of PPFRC. An improvement of 8%, 10%, and 34% is observed in modulus of rupture of JFRC, NFRC, and PPFRC, respectively, as compared to that of PC.
- An improvement of 87%, 127%, and 107% is observed in compressive total absorbed energy of JFRC, NFRC, and PPFRC, respectively, than that of PC. As compared to splitting-tensile total absorbed energy (STE) of PC, a decrease of 37% and 21% is observed in STE of JFRC and NFRC, respectively, and an increase of 11% is observed in the STE of PPFRC. And an increase of 53%, 68%, and 100%, in flexural

total absorbed energy of JFRC, NFRC, and PPFRC, respectively, is observed in comparison to that of PC.

- The enhancement of 124%, 127%, and 148% is observed in compressive toughness index of JFRC, NFRC, and PPFRC, respectively, than that of PC. An enhancement of 2%, 2%, and 3% is observed in splitting-tensile toughness index of JFRC, NFRC, and PPFRC, respectively, than that of PC. And by comparing to that of PC, an enhancement of 86%, 91%, and 99% is noticed in flexural toughness index of JFRC, NFRC, and PPFRC, respectively.
- As compared to water absorption (WA) of PC, an increase of 8% and 1% is observed in WA of JFRC and NFRC, respectively, and a decrease of 4% is observed in the WA of PPFRC. Linear shrinkage 'LS' (% decrease) of JFRC and NFRC is 67% and 30%, respectively, more than that of PC. While LS (% decrease) of PPFRC is 15% less than that of PC.
- Empirical relations have been developed with the help of experimental data for prediction of WA and LS. The relationship between WA/LS and each of the CS, SS, SPE, and FPE are made because of their observed mutual coherence in experimental outcomes. There is a good agreement between the experimental and empirical values. The percentage error is 0.4%-20%.

Based on the outcomes and examined behaviors, JFRC, NFRC, and PPFRC are likely to be effective in controlling the rate of cracking in canal-lining. Among the investigated types of FRCs, PPFRC is likely to be more effective in controlling the rate of cracking in canal-lining because of the highest improvement in most of the investigated properties as compared to other studied materials.

6.2 Recommendations

Following are the recommendations:

- Performance of the prototype model of canal section made with PPFRC is necessary in comparison to that with PC in order to proceed towards its practical applications.
- The cost-effective analysis of PC and PPFRC for application of canal-lining needs to be investigated.

- Behavior of fresh FRC in standard tests e.g. slump cone test and compaction factor tests etc. keeping in mind its placement in canal-lining.

REFERENCES

Ali, M. (2014). Seismic performance of coconut-fibre-reinforced-concrete columns with different reinforcement configurations of coconut-fibre ropes. *Construction and Building Materials*, 70, 226-230.

Ali, M. (2016). Use of coconut fibre reinforced concrete and coconut-fibre ropes for seismic-resistant construction. *Materiales de Construcción*, 66(321), 073.

Al-Oraimi, S. K., & Seibi, A. C. (1995). Mechanical characterisation and impact behaviour of concrete reinforced with natural fibers. *Composite Structures*, 32(1-4), 165-171.

Al-Tayyib, A. J., Al-Zahrani, M. M., & Al-Sulaimani, G. J. (1988). Effect of polypropylene fiber reinforcement on the properties of fresh and hardened concrete in the Arabian Gulf environment. *Cement and Concrete Research*, 18(4), 561-570.

Arshad, M., Ahmad, N., Usman, M., & Shabbir, A. (2009). Comparison of water losses between unlined and lined watercourse in Indus Basin of Pakistan. *Pakistan Journal Agriculture Sciences*, 46(4), 2076-0906.

ASTM C39 / C39M-17, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2017, www.astm.org

ASTM C143 / C143M-15a, Standard Test Method for Slump of Hydraulic-Cement Concrete, ASTM International, West Conshohocken, PA, 2015, www.astm.org

ASTM C157 / C157M-08(2014)e1, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete, ASTM International, West Conshohocken, PA, 2014, www.astm.org

ASTM C293 / C293M-16, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading), ASTM International, West Conshohocken, PA, 2016, www.astm.org

ASTM C496 / C496M-11, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2004, www.astm.org

ASTM C531-00(2012), Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes, ASTM International, West Conshohocken, PA, 2012, www.astm.org

ASTM C642-13, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, ASTM International, West Conshohocken, PA, 2013, www.astm.org

Aziz, M. A., Paramasivam, P., & Lee, S. L. (1981). Prospects for natural fiber reinforced concretes in construction. *International Journal of Cement Composites and Lightweight Concrete*, 3(2), 123-132.

Badenhorst, J. W., De Lange, M., Mokwena, M. E., & Rutherford, R. J. (2002). Water conservation and water demand management in agriculture: development of water management plans by irrigation water suppliers in South Africa. *ICID Eighteenth Congress Best Paper for 6th Hassan Ismail Award Paper, Montreal.*

Banthia, N. (2010). Report on the physical properties and durability of fiber-reinforced concrete. *ACI 544.5 R-10, Reported by ACI Committee 544*, 1-3.

Basheer, L., Kropp, J., & Cleland, D. J. (2001). Assessment of the durability of concrete from its permeation properties: a review. *Construction and Building Materials*, 15(2), 93-103.

Bayasi, Z., & Zeng, J. (1993). Properties of polypropylene fiber reinforced concrete. *Materials*, 90(6), 605-610.

Bei-xing, L., Ming-xiang, C., Fang, C., & Lu-ping, L. (2004). The mechanical properties of polypropylene fiber reinforced concrete. *Journal of Wuhan University of Technology--Materials Science Edition*, 19(3), 68-71.

Bentur, A., & Diamond, S. (1984). Fracture of glass fiber reinforced cement. *Cement and Concrete Research*, 14(1), 31-42.

Bofang, Z. (2013). *Thermal stresses and temperature control of mass concrete*. Butterworth-Heinemann.

Chandar, S. P. and Balaji, C. J. (2015). Experimental study on the mechanical properties of concrete mixed with jute fiber and steel fiber. *International Research Journal of Engineering and Technology*, 1(2),77-82.

Cook, D. J., Pama, R. P., & Weerasingle, H. L. S. D. (1978). Coir fiber reinforced cement as a low cost roofing material. *Building and Environment*, 13(3), 193-198.

Cook, J. G. (1984*). Handbook of Textile Fibers*, Morrow Publishing Company, Ltd., Durham, England, 261-283.

Cui, J. H., Xie, Z. Q., & Xiao, H. J. (2013). Cause analysis on the cracks in concrete plate of canal lining. *Applied Mechanics and Materials*, 405, 2596-2599.

Fang, H. G., Liu, P. H., & Zhang, T. (2011). Experimental investigation on the polypropylene fiber concrete performance of yellow river canal lining in the middle line of South-to-North water transfer project. *Applied Mechanics and Materials*, 52, 1987-1991.

Galanti, A. V. (1964). Polypropylene fibers. M.Sc. thesis, *Department of chemical engineering, Newark college of engineering*, New Jersey.

Goldfein, S. (1965). Fibrous reinforcement for portland cement. *Modern Plastics*, 42(8), 156-160.

Gupta, N. D., Paramasivam, P., & Lee, S. L. (1978). Mechanical properties of coir reinforced cement paste composites. *Housing Science*, 2(6), 391-406.

Irrigation Research Institute. (1992). Studies on water losses from watercourses and their lining measures. *Lahore, Pakistan*.

Ismail, M. A. (2007). Compressive and tensile strength of natural fiber-reinforced cement base composites. *Al-Rafidain Eng*, 15(2), 42-51.

Jagannathan, S., Rangasamy, S., & Kumarasamy, K. (2016). An experimental investigation on nylon fibre (textile waste) reinforced concrete. *Journal of Recent Research and Applied Studies*, 3(15), 70-74.

James, I. D., Gopalaratnam, V. S., & Galinat, M. A. (2002). State-of-the-art report on fiber reinforced concrete. *Manual Concrete Practice*, 21, 2-66.

Joshi, S. V., Drzal, L. T., Mohanty, A. K., & Arora, S. (2004). Are natural fiber composites environmentally superior to glass fiber reinforced composites?. *Composites Part A: Applied Science and Manufacturing*, 35(3), 371-376.

Kahlown, M. A., & Kemper, W. D. (2005). Reducing water losses from channels using linings: Costs and benefits in Pakistan. *Agricultural Water Management*, 74(1), 57-76.

Kakooei, S., Akil, H. M., Jamshidi, M., & Rouhi, J. (2012). The effects of polypropylene fibers on the properties of reinforced concrete structures. *Construction and Building Materials*, 27(1), 73-77.

Kasali, M.Y., & Ogunlela, A.O. (2014). Evaluation of the strength of some potential local irrigation canal lining materials from moisture-density relationship. *Ethiopian Journal of Environmental Studies & Management*, 7(4), 445-451.

Karad, M. M., Panke, R. A., & Hangargekar, P. A. (2013). Seepage losses through canals & minors. *International Journal of Engineering Research and Technology*, 2(11), 1125-1134.

Kene, K. S., Vairagade, V. S., & Sathawane, S. (2012). Experimental study on behavior of steel and glass fiber reinforced concrete composites. *Bonfring International Journal of Industrial Engineering and Management Science*, 2(4), 125.

Khajuria, A., Bohra, K., & Balaguru, P. (1991). Long-term durability of synthetic fibers in concrete. *Durability of Concrete. Second International Conference*, 2, 126-46.

Khan, M., & Ali, M. (2016). Use of glass and nylon fibers in concrete for controlling early-age micro cracking in bridge-decks. *Construction and Building Materials*, 125, 800-808.

Kundu, S. P., Chakraborty, S., Roy, A., Adhikari, B., & Majumder, S. B. (2012). Chemically modified jute fiber reinforced non-pressure (NP) concrete pipes with improved mechanical properties. *Construction and Building Materials*, 37, 841-850.

Kraatz, D. B. (1980). Irrigation Canal Lining. *China Water Power Press, China.*

Kraatz, D. B. (1975). Reduction in conveyance losses in sandy soils. *Soils Bull Food Agric Organ UN.*

Krishnamurthy, K., & Rao, S. (1969). Theory and experiment in canal seepage estimation using radioisotopes. *Journal of Hydrology,* 9(3), 277-293.

Kumar, R., Goel, P., & Mathur, R. (2013). Suitability of concrete reinforced with synthetic fiber for the construction of pavements. *Proceedings of the 3rd International Conference on Sustainable Construction Materials and Technologies*. Kyoto Research Park, Kyoto, Japan, August 18-21. Paper e197.

Lewis, G. and Mirihagalia, P. (1979). Natural vegetable fibers as reinforcement in cement sheets. *Magazine of Concrete Research*, 31(107), 104-8.

Lim, C. C., Gowripalan, N., & Sirivivatnanon, V. (2000). Microcracking and chloride permeability of concrete under uniaxial compression. *Cement and Concrete Composites*, 22(5), 353-360.

Liu, B., Zhang, L. Z., Liu, Q. X., & Ji, T. (2013). Study on behaviors of jute fiber reinforced cement based materials. *Applied Mechanics and Materials*, 253, 508-511.

Luthra, S. D. L. (1980). Conveyance losses in lined irrigation canal systems—A brief review. *Water and Energy International*, 37(3), 329-336.

Mansur, M. A., & Aziz, M. A. (1982). A study of jute fiber reinforced cement composites. *International Journal of Cement Composites and Lightweight Concrete*, 4(2), 75-82.

Merta, I., & Tschegg, E. K. (2013). Fracture energy of natural fiber reinforced concrete. *Construction and Building Materials*, 40, 991-997.

Montañes, J. L. (2006). Hydraulic canals: design, construction, regulation and maintenance. *Hydraulic canals: design, construction, regulation and maintenance.*

Michael, A. M. (1978). *Irrigation: Theory and Practice*. Vikas publishing house.

Ozomaka, O. J. (1976). Characteristics of akwara as a reinforcing fiber. *Magazine of Concrete Research*, 28(96), 162-1-67.

OPSS LS-435, Method of Test for Linear Shrinkage of Concrete, Ministry of transportation, Ontario Laboratory Testing Manual, 2001.

Racines, P. G., & Pama, R. P. (1978). A study of bagasse fiber-cement composite as low-cost construction materials. *Proceedings International Conference on Materials for Developing Countries*, 191-206.

Raja, R. K., Kumar, A., & Chhabra, S. S. (1983). Estimation of seepage losses from an unlined channel-a field study by nuclear techniques, proceeding, Volume II—Hydraulics, CBIP. *Fiftieth Annual Research and Development Session. Simla, Himachala Pradesh*.

Rajguru, R. S., Ghode, A. R., Pathan, M. G., & Rathi, M. K. (2014). Effect of volume fraction of polypropylene fiber on mechanical properties of concrete. *International Journal of Engineering Research and Applications*, 1(4), 67-69.

Ramakrishna, G., & Sundararajan, T. (2005). Impact strength of a few natural fiber reinforced cement mortar slabs: a comparative study. *Cement and Concrete Composites*, 27(5), 547-553.

Ramaswamy, H. S., Ahuja, B. M., & Krishnamoorthy, S. (1983). Behaviour of concrete reinforced with jute, coir and bamboo fibers. *International Journal of Cement Composites and Lightweight Concrete*, 5(1), 3-13.

Ramezanianpour, A. A., Esmaeili, M., Ghahari, S. A., & Najafi, M. H. (2013). Laboratory study on the effect of polypropylene fiber on durability, and physical and mechanical characteristic of concrete for application in sleepers. *Construction and Building Materials*, 44, 411-418.

Ramujee, K. (2013). Strength properties of polypropylene fiber reinforced concrete. *International Journal of Innovative Research in Science, Engineering and Technology*, 2(8), 3409-3413.

Reinhardt, H. E. (Ed.). (1997). Penetration and permeability of concrete: barriers to organic and contaminating liquids *(Vol. 16). CRC Press.*

Rice, E. K., Vondran, G. L., & Kunbargi, H. O. (1987). Bonding of fibrillated polypropylene fibers to cementitious materials. *MRS Online Proceedings Library Archive*, 114.

Rostami, V., Shao, Y., & Boyd, A. J. (2011). Durability of concrete pipes subjected to combined steam and carbonation curing. *Construction and Building Materials*, 25(8), 3345-3355.

Saadun, A., Mutalib, A. A., Hamid, R., & Mussa, M. H. (2016). Behaviour of polypropylene fiber reinforced concrete under dynamic impact load. *Journal of Engineering Science and Technology*, 11(5), 684-693.

Salyer, I. O., Ball, G. L., Usmani, A. M., & Workminister, D. W. (1975). Development of low cost roofings from indigenous materials of developing nations. *AID/US*, 190.

Sharma, H. D., & Chawla, A. S. (1975). Manual of canal lining. *Technical Report No. l4*. Central Board of Irrigation and Power New Delhi.

Shakor, P. N., & Pimplikar, S. S. (2011). Glass fibre reinforced concrete use in construction. *International Journal of Technology and Engineering System*, 2(2), 632-634.

Singh, T. P. (1975). Structural properties of fiber reinforced concrete. M.Sc. Thesis, *Dept. of Civil Eng, University of Roorkee, India.*

Siraskar, K. A., & Kumar, S. (1972). Fiber reinforcement for shatter proofness of concrete. *Proceedings Symposium on Modern Trends in Civil Engineering, University of Roorkee, India*, 254-59.

Sridhara, S., Kumar, S., & Sinare, M. A. (1971). Fiber reinforced concrete. *Indian Concrete Journal*, 45(10), 428-30, 433.

Subramanian E. S., Vaishnave V.R., and Vignesh V.T.S. (2016). Experimental investigation of concrete composites using nylon fiber. *International Journal of Engineering Sciences & Research Technology*, 5(12), 998-1002.

Swift, D. G., & Smith, R. B. L. (1979). The flexural strength of cement-based composites using low modulus (sisal) fibers. *Composites*, 10(3), 145-148.

Swihart, J., & Haynes, J. (2002). Canal-lining demonstration project year 10 final report.

Tavakoli, M. (1994). Tensile and compressive strengths of polypropylene fiber reinforced concrete. *Special Publication*, 142, 61-72.

Thakur, V. K., Thakur, M. K., & Gupta, R. K. (2014). Graft copolymers of natural fibers for green composites. *Carbohydrate Polymers*, 104, 87-93.

USBR. (1978). Drainage Manual. *A water resources technical publication*, US Government Printing Office: Denver, Colorado, second printing; 287.

Vairagade, V., Kene, K., & Deshpande, N. (2012). Investigation of compressive and tensile behavior of fibrillated polypropylene fibers reinforced concrete. *International Journal of Engineering Research and Applications*, 2(3), 1111-1115.

Vitkar, A., Kawde, P., Mavchi, S., & Kuwar, P. (2017). Experimental study of jute fiber with optimum replacement of natural sand with artificial sand. *International Research Journal of Engineering and Technology*, 4(4), 3313-3316.

Wambua, P., Ivens, J., & Verpoest, I. (2003). Natural fibers: can they replace glass in fiber reinforced plastics?. *Composites Science and Technology*, 63(9), 1259-1264.

Wang, Y., Backer, S., & Li, V. C. (1987). An experimental study of synthetic fiber reinforced cementitious composites. *Journal of Materials Science*, 22(12), 4281-4291.

Won, J. P., Park, C. G., Lee, S. W., Jang, C. I., & Won, C. (2008). Effect of crimped synthetic fibre surface treatments on plastic shrinkage cracking of cement-based composites. *Magazine of Concrete Research*, 60(6), 421-427.

Zhou, X., Ghaffar, S. H., Dong, W., Oladiran, O., & Fan, M. (2013). Fracture and impact properties of short discrete jute fiber-reinforced cementitious composites. *Materials & Design*, 49, 35-47.

Zakaria, M., Ahmed, M., Hoque, M. M., & Islam, S. (2016). Scope of using jute fiber for the reinforcement of concrete material. *Textiles and Clothing Sustainability*, 2(1), 11.

Zollo, R. F. (1984). Collated fibrillated polypropylene fibers in FRC. *Special Publication*, 81, 397-410.

ANNEXURES

Annexure A

Compressive stress-strain curves and tested samples of PC, JFRC, NFRC, and PPFRC (i.e. remaining specimens)

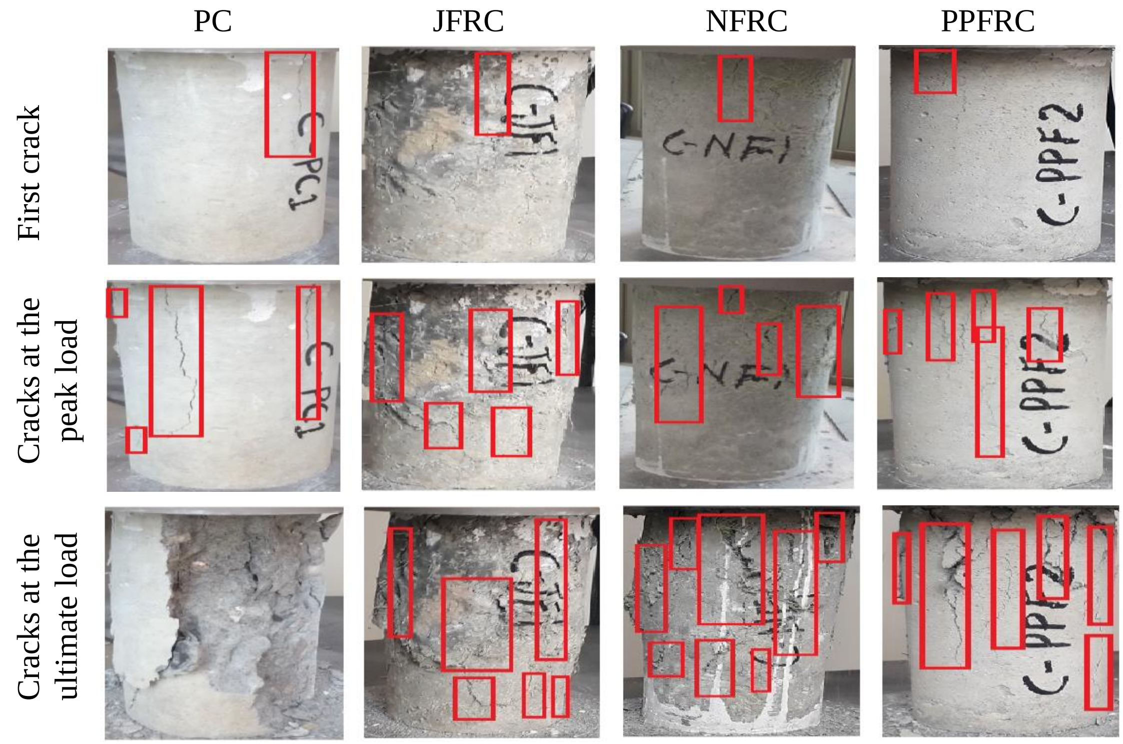

Figure A1 Development of cracks in the cylindrical specimens of PC, JFRC, NFRC, and PPFRC under compressive load

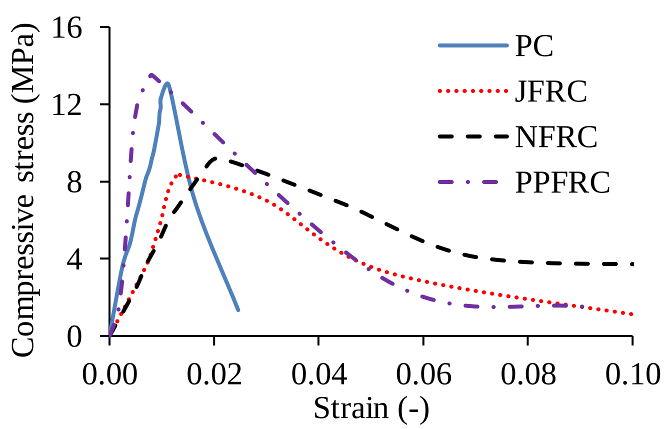

Figure A2 Stress-strain curves of PC, JFRC, NFRC, and PPFRC for compressive strength tests

Annexure B

Splitting-tensile load-time curves and tested samples of PC, JFRC, NFRC, and PPFRC (i.e. remaining specimens)

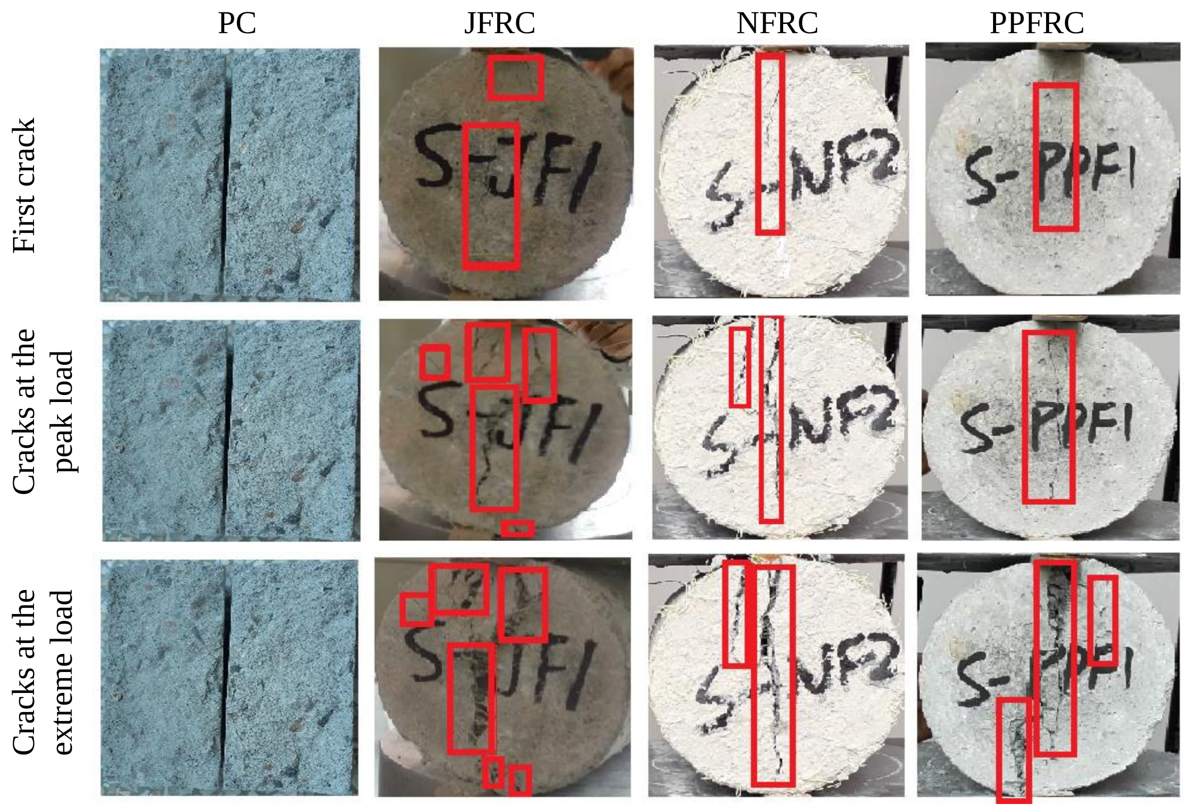

Figure B1 Development of cracks in the cylindrical specimens of PC, JFRC, NFRC, and PPFRC under splitting-tensile load

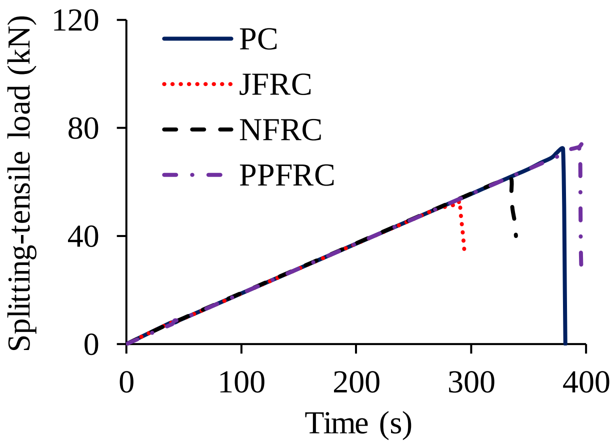

Figure B2 Load-time histories of PC, JFRC, NFRC, and PPFRC from the tests of SS

Annexure C

Flexural load-deflection curves and tested samples of PC, JFRC, NFRC, and PPFRC (i.e. remaining specimens)

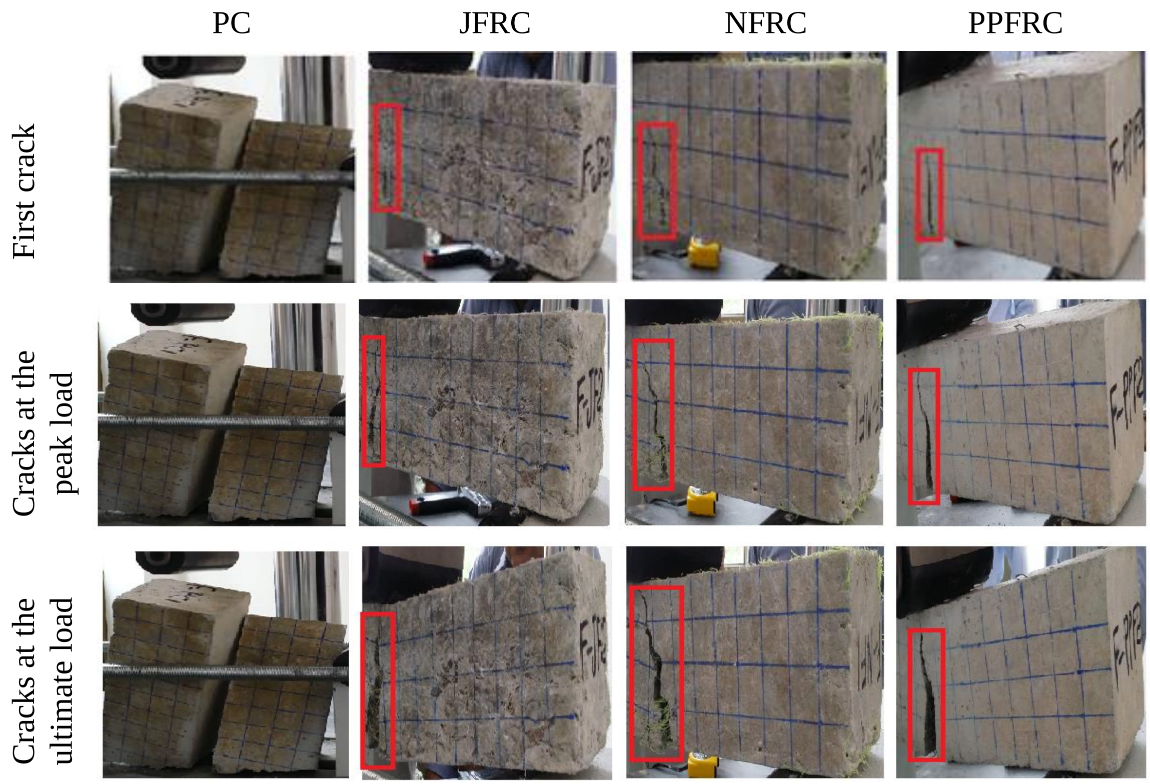

Figure C1 Development of cracks in the beam-lets of PC, JFRC, NFRC, and PPFRC flexure load

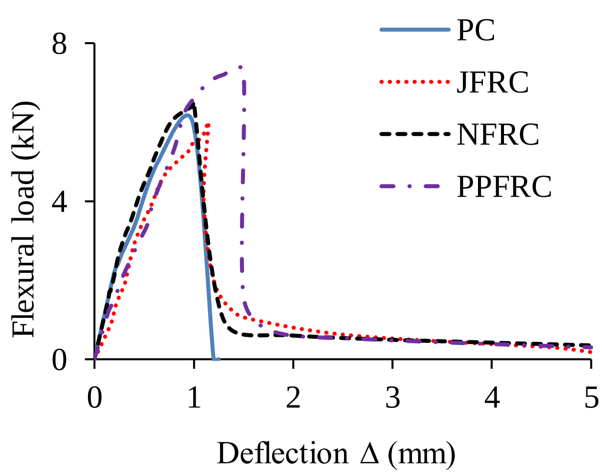

Figure C2 Load-deflection curves of PC, JFRC, NFRC, and PPFRC from flexure strength tests