CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Effect of Freeze-Thaw Cycles on Mechanical Properties of Jute Fiber Reinforced Concrete for Pavement

by

Muhammad Affan

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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.

CERTIFICATE OF APPROVAL

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Journal Article

1. Affan, M., and Ali, M. (2019). Experimental Investigation on Mechanical Properties of Jute Fiber Reinforced Concrete under Freeze-Thaw Conditions for Pavement Applications. *Materiales de Construccin, (ISI Impact Factor =1.803, Under review).*

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Abstract

Concrete is usually used as a construction material in many infrastructures; because of its performance and behaviour. Freeze-thaw is one of the major hazards for pavements; which they have to experience due to fluctuation in seasonal temperatures. Certain measures should be made to save the concrete pavements from the freeze-thaw deterioration at the time of construction. The behaviour of concrete during freeze-thaw can also be improved if the crack initiation is controlled. The use of fibers in concrete to improve its properties is very ancient. Fibers are used to enhance the properties of concrete like mechanical, absorption and crack control properties etc. Natural fibers have many advantages due to low cost, ease of availability and less hazard for health. Experiments are conducted for three different cycles (10, 20 and 30) of freeze-thaw. Single combination of mix design, water cement ratio, fiber type, fiber length and content are considered.

The overall aim of this study is to examine the behaviour of dynamic and mechanical properties of plain concrete (PC) and jute fiber reinforced concrete (JFRC) after subjecting to freeze-thaw cycles. The mix design ratio, which is used for preparation of PC is 1:2:3:0.6 (cement: sand: aggregate: water). Jute fibers are added in similar mix design ratio with a ratio of 5% by mass of cement for preparation of JFRC. Mechanical and dynamic properties of PC and JFRC specimens are measured by using ASTM standards. Procedure B is used as per ASTM standard C666/C666M-15, in which rapid freezing in air and thawing in water for freeze-thaw process. One cycle of freeze-thaw is completed by lowering the temperature from 4 to -18^{o}C and raising it back from -18 to 4^{o}C, in time not less than 2 hours and not more than 5 hours. After curing of specimens for 28 days before the start of freeze-thaw process, mass and dynamic properties are measured. After completion of freeze-thaw cycles mass of each specimen and dynamic properties are measured to check the effect of freeze-thaw process on PC and JFRC specimens. Empirical equations are developed and practical example is calculated by using experimental results of JFRC and PC.

Workability of JFRC is less than PC with same mix design and w/c ratio, due to which slump of JFRC is less than PC. JFRC specimens have low weight than PC specimens. Due to less weight densities of JFRC specimens are less than PC specimens. Percentage of loss in mass due to different freeze-thaw cycles is more in JFRC specimens as compared to PC specimens. Relative dynamic modulus of elasticity (P_c) of JFRC specimens is decreasing very slowly as compared to PC specimens which indicate JFRC specimens can bear more freeze-thaw cycles. Split tensile and flexural strengths of JFRC are increased up to 11% and 2% whereas, 16% decreased in compressive strength of JFRC specimens is observed as compared to PC specimens. Strengths of PC and JFRC are decreasing as number of freeze-thaw cycles are increased. Empirical equations are developed by using numbers of freeze-thaw cycles, loss in mass, compressive strength, flexural strength and compared with experimental results. Design thickness of rigid pavement is measured with help of obtained experimental results modulus of rapture (MoR), compressive strength and modulus of elasticity. The thickness of rigid pavement is reduced by using jute fibers in concrete as compared to normal concrete. An increase of 28% in pavement thickness is required by using normal concrete to resist the effect of 30 cycles of freeze-thaw. However, by using jute fibers, only 19% increase in thickness is required.

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Abbreviations

CE_p	Compressive energy absorption up to a peak load
CE_f	Compressive energy absorption frompeak load to final load
CET	Compressive total energy absorption
CTI	Compressive toughness index
f'_c	Compressive strength
S_c	Flexural strength
f_{st}	Split-tensile strength
FE_p	Flexural energy absorption up to a peak load
FE_f	Flexural energy absorption from peak load to finale load
FET	Flexural total energy absorption
FTI	Flexural toughness index
FRC	Fibers reinforced concrete
JF	Jute fibers
JFRC	Jute fiber reinforced concrete
PC	Plain concrete
SET	Split total energy absorption
SEM	Scanning electron microscope
SE_p	Split energy absorption up to a peak load
SE_f	Split energy absorption from peak load to final load
STI	Split toughness index
w/c	Water cement ratio
E_c	Elasticity modulus
P_c	Relative dynamic modulus of elasticity
n	Number of freeze-thaw cycles

MoR	Modulus of rapture
STM	Servo-hydraulic testing machine

Symbols

ξ	Damping ratio
Δ	Max deflection under flexural loading
δ	Strain

Chapter 1

Introduction

1.1 Background

Concrete structures experience degradation, when exposed to freeze-thaw conditions. In cold region, day and night time fluctuation in temperature can cause damages for hard materials like concrete. When water is frozen its volume increases up to 9% of the total volume due to expansion. Roads are used as a source of transportation, but in cold area due to change of temperature, damages are occurred. Due to fluctuation of temperature, cracks are formed and damages occurred which as a result reduced the life time, serviceability and strength of pavement. During the thawing process, water enters into the pavements through cracks and leak joints. At freezing stage, water that enters into the rigid pavement, froze and due to which expansion occurs. Which as a result forms cracks in rigid pavement and reduce the strength of pavement. Due to the freeze-thaw cycles, loss in mass, and change in mechanical, and dynamic properties occurs. Freeze-thaw is one of major factor to reduce the durability of concrete pavement because of fluctuation in temperature [1]. When concrete pavement are subjected to freeze-thaw cycles, loss in mass increased and relative dynamic modulus of elasticity decreased [2]. Li et al. [3] examined the effect of fluid on concrete pavements under freeze-thaw condition. After performing the experimental procedure, it was concluded that fluid was the primary factor to create cracks and cause damages in concrete at freeze-thaw conditions. It was also observed that fluid was primary factor to reduce the duration, serviceability, durability and strength of pavements under freeze-thaw condition.

1.2 Research Motivation and Problem Statement

Roads are used as a way of transportation to move from one station to another. Roads contribute in economic development and growth of country. Rigid pavements are preferred due to less maintenance and high load carrying ability. Demand for the safety of rigid pavement is increasing day by day. There are many ways to improve mechanical properties of concrete and bonding between concrete ingredients, but overall cost of pavement is increased by using them. Use of fibers in rigid pavements is best solution and fibers reduce the cost as well [4]. Hence the problem statement is:

"A major expense for government to repair and replaced the existing rigid pavements due to damage because of freeze-thaw process [5]. When rigid pavements experienced freeze-thaw cycles due to seasonal temperature fluctuation cracks are developed, water enters into pavement through cracks and from leaked joints and spalling occurs and mechanical properties changes [6]. Mechanical properties like compressive strength, tensile strength and MoR of pavement are affected by change in seasonal temperature [7]. Due to which rigid pavement becomes weak and failure occurs. Economically improvement in mechanical properties under freeze-thaw is an important issue. Fibers can be used to improve rigid pavements performance against temperature variation."

1.3 Overall Objective and Specific Aim

The overall objective of the research program is to have improved behavior of new concrete pavements after the exposure of freeze-thaw cycles by using fibers in concrete.

In this research work, an investigation has been carried out to study the improvement in mechanical properties of jute fiber reinforced concrete after exposure to different number of freeze-thaw cycles. PC is taken as a reference.

1.4 Scope of Work and Study Limitation

Two samples are use for an average [8-10]. Empirical equations are developed for measuring of compressive and flexural strength of PC and JFRC by using the experimental results.

Experiment is conducted for three different cycles (10, 20 and 30) of freeze-thaw. Single combination of mix design, water cement ratio, fiber type, fiber length and content is considered.

1.5 Brief Methodology

In this study, the mechanical properties of PC and JFRC are determined after subjecting to freeze-thaw cycles. The mix design ratio for PC and JFRC is same which is 1:2:3:0.6 (cement: sand: aggregate: water) except 50 mm long jute fibers with a ratio of 5% by mass of cement are used for preparation of JFRC. Properties like compressive strength, splitting tensile strength, flexural strength, density, loss in mass and dynamic properties are measured. ASTM standard C666/ C666M-15 [11] procedure B is used in which rapid freezing in air and thawing in water is used to create freeze-thaw process. Lowering the temperature from 4 to -18^{o}C and raising from -18 to 4^{o}C is complete one cycle. Dynamic properties and loss of mass is measured before the start of cycles and after completion of freeze-thaw cycles. For compression and splitting tensile strengths, cylinder are cast having size D-100 mm and H-200 mm. Whereas for flexural strength, beam-lets size 450 x 100 x 100 mm are cast.

1.6 Thesis Outline

There are six chapters in this thesis, which are as follows:

Chapter 1 consists of introduction section. Consequence of freeze-thaw cycles on rigid pavement is explained in this chapter. It also consists of research motivation and problem statement, objective and scope of work, methodology and thesis outline.

Chapter 2 contains the literature review section. It consists of background, Freeze-thaw behavior in rigid pavement, improvement in concrete due to fibers, fiber reinforced concrete in rigid pavement and summary.

Chapter 3 consists of experimental program. It contains background, ingredients, concrete preparation procedure, specimens details, testing procedures and summary.

Chapter 4 consists of experimental evaluation. It contains background, consequence of freeze-thaw cycles, dynamic properties, mechanical properties, fiber failure mechanism and summary.

Chapter 5 comprise of discussion on mechanical properties, empirical equations, practical examples and summary.

Chapter 6 includes conclusion and recommendations.

References are presented right after chapter 6.

Chapter 2

Literature Review

2.1 Background

Fibers are used to enhance concrete performance and mechanical properties since ancient time. Fiber reinforced concrete (FRC) has proved to have better energy absorption, toughness index and resistance against freeze-thaw affect. FRC has also shown better performance against dynamic loading. It is the need of the time to explore the effectiveness of natural fibers for enhancing the resistance against fluctuation of temperature, as natural fibers are cheap and environment friendly. Jute fiber is one of the natural fiber which is widely produced in South Asian countries.

2.2 Freeze-Thaw Behavior in Rigid Pavement

Adkins and Christiansen [12] examined that behaviour of concrete pavement under freeze-thaw conditions. Laboratory and field data were used to examine the performance of the pavement. With the increase in freeze-thaw cycles, stresses were developed which caused cracks and reduced the durability of pavements. Ozgan and Serin [13] reported that due to freeze-thaw cycles, changes in asphalt concrete pavement were observed. The comparison was made for before and after freeze-thaw cycles. It was cleared that pavement stability was decreased whereas, void ratio and ultrasonic velocity were increased due to freeze-thaw cycles. Amini and Tehrani [14] reported that the flow of water under freeze-thaw cycles caused more damages in pavement due to the fluctuation of temperature. Pan et al. [15] examined the consequence of freeze thaw-cycles on thermal characteristic and mechanical properties of concrete pavements. Thermal characteristic of concrete pavement was studied by using thermal constant analyzer. It was reported that freeze-thaw cause expansion in volume, which as a result decrease the mechanical properties and thermal conductivity. Tang et al. [16] reported that freeze-thaw cycles were major reason to cause damages in concrete pavement. Weight of prepared sample of rigid pavement, crack and strength were used to check the impact of freeze-thaw on rigid pavement properties. Jaskula and Judycki [17] examined the effect of freeze-thaw cycles on concrete pavement. Specimen of concrete pavement was prepared in laboratory. Single, 50 and 150 freeze-thaw cycles were applied on prepared specimens. Life of pavement was decreased due to application of freeze-thaw cycles. Hence freeze-thaw can affect the durability of concrete considerably, and new remedial measures during construction are still needed.

2.3 Improvement in Concrete Due to Fibers

Richardson [18] reported that durability of simple concrete could be enhanced by using fibers in concrete. Concrete properties were improved by using fibers in concrete like bonding strength, and tensile strength after subjecting to freeze-thaw cycles. Pliya et al. [19] examined the spalling in concrete against freeze-thaw. It was found that freeze-thaw was one of the major factor to reduce the strength of concrete. Spalling in concrete was reduced using fibers in concrete. Fibers were used to improve the durability and mechanical properties of concrete. Mu et al. [20] reported that fiber reinforced concrete (FRC) had better mechanical properties as compared to the concrete without fiber. Durability was especially important for these structures, which had to get environmental exposure like pavements. Use of fibers in concrete reduced the effect of spalling, increased the residual strength and increased the ability of concrete to resist the effect of the freeze-thaw process. Consequence of the freeze-thaw cycles with and without steel fiber reinforced concrete was investigated. Plain and steel fiber reinforced concrete with different water-cement ratio were compared. It was concluded that SFRC had shown better performance as compared to PC. Chakraborty et al. [21] investigated the properties of cement mortar by using jute fibers was observed. Properties of mortar (like compressive strength, and flexural strength) were increased by using jute fibers in cement motor. Kundu et al. [22] modified the mechanical properties of the non-pressure concrete pipe by using jute fibers. Lee and Barr [23] reported that fatigue behavior of concrete was improved by using fibers in plain concrete. Yap et al. [24] reported the improvement in mechanical properties of oil plam shell fiber reinforced concrete (OPSFRC) was observed by using fibers. Results had shown the improvement in compressive strength, tensile strength, and density. Kristina and Yadav [25] used jute fibers at a ratio of 0.5%, 1% and 2% in ordinary concrete to make jute fiber reinforced concrete and tests were performed to check the mechanical properties. Tests were performed after 7, 14,

Table 2.1: Effect of fibers in concrete

S.No	Reference	Fibers	Matrix	Conclusions
1	Zia and Ali [9]	Jute	Concrete	Jute fiber reinforced concrete (JFRC) can be effective and economical material.
2	Zakrai et al. [26]	Jute	Concrete	Conventional mix design (1:2:4). Significant improvement in flexure, compressive and tensile strengths.
3	Aziz and Mansur [27]	Jute	Concrete	Sand content doubled in mix design (1:3:1.5). Significant improvement in the energy absorption and toughness of JFRC.
4	Kundu et al. [22]	Jute	Concrete	Improved the mechanical properties of non-pressure concrete pipe
5	Chakraborty et al. [21]	Jute	Mortar	Improved the mechanical properties of cement mortar.

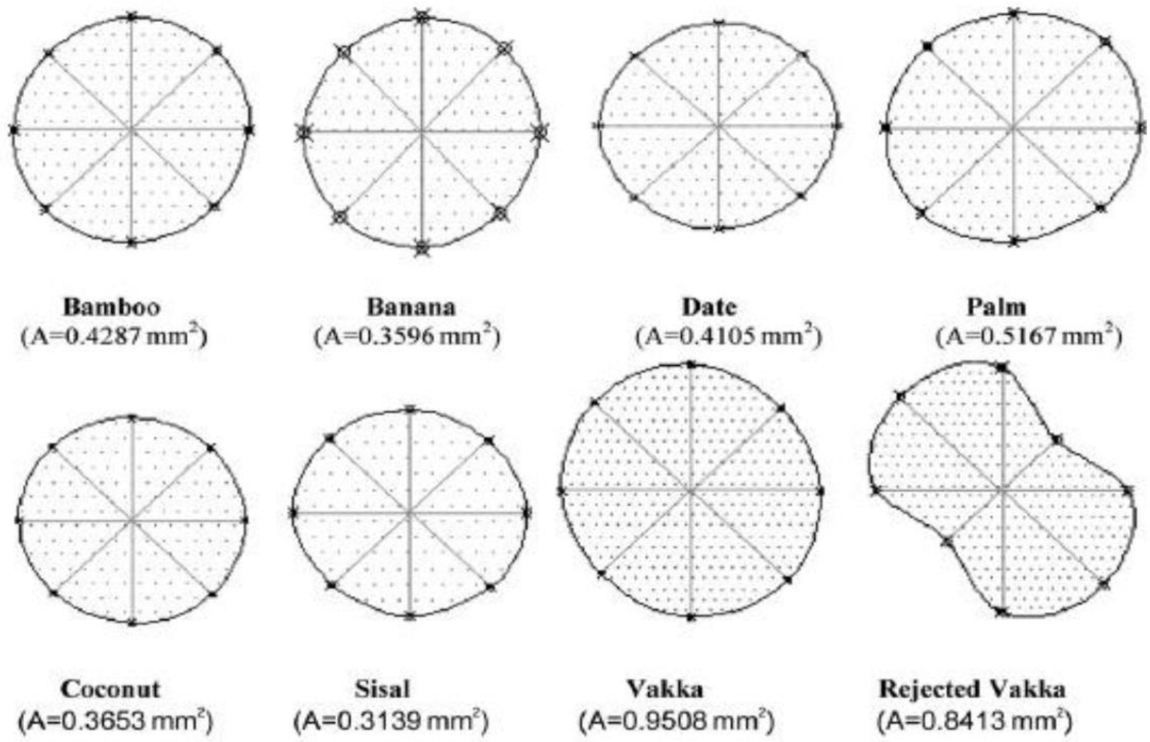


FIGURE 2.1: Cross section of some natural fibers Ali et al. [28].

28 and 56 days. Results had shown enhancement in mechanical properties of JFRC (like compressive strength, flexural strength, and split tensile strength). Salemi and Behfarnia et al. [29] examined the mechanical properties of fiber reinforced concrete having polypropylene fibers under freeze-thaw conditions and the results were matched with plain concrete. From the experimental results it was concluded that concrete having fibers could able to resist the effect of freeze-thaw process. Zia and Ali [9] reduced the seepage of canal-lining by using jute, nylon and polypropylene fiber with the ratio of 1:3:1.5:0.7 along with 50 mm long fibers with a ratio of 5% by mass of cement in concrete. Mechanical properties were measured by using PC as a reference. Results had shown that jute fiber reinforced concrete samples had better mechanical properties as compared to PC. Khan and Ali [30] used 50 mm long fibers with a ratio of 5% by mass of cement in concrete for controlling early age micro cracks and better results were obtained. Zakaria et al. [26] studied the effect of jute fibers as a reinforcing material in concrete. Specimens of standard size were tested for flexural strength, compressive strength and split tensile strength. Significant improvement in the mechanical

properties were observed by using jute fibers in concrete. Thus, natural fibers can be used to improve mechanical properties of concrete. The Durability of natural fiber is important because of the organic nature of natural fibers. There are different techniques reported by Filhao et al. [31] for improving the durability of natural fiber reinforced concrete, i.e. carbonation of matrix in a CO_2 rich environment, partial replacement of ordinary Portland cement by undensified silica fume, or blast furnace slag. As far as jute fiber is concerned, no study has been conducted for the estimating design life of natural fibers in concrete composite. The only disadvantage of using natural fibers in concrete composite is that a special consideration should be given to ensure its durability because of fibers organic nature. The durability of fiber reinforced concrete can be checked by comparing the strength increase or decrease after a certain period of time under different ageing conditions (e.g. alternate wetting and drying, environmental conditions etc.).

2.4 Fiber Reinforced Concrete in Rigid Pavement

Gupta et al. [32] evaluated the use of polyester fiber reinforced concrete in rigid pavement. It was reported that, by using polyester fibers in concrete mechanical properties (like compression strength, flexural strength and split tensile strength) were improved. Nobili et al. [4] monitored the polypropylene fiber reinforced concrete pavement for six months. Concrete pavement was built in Italy and direct stresses were measured. Results had shown that fibers in concrete had improved the durability of concrete pavement, provided a safe and cost-effective pavement. Graeff et al. [33] examined the fatigue and the crack mechanism of the concrete pavement by using recycled steel fibers in concrete. It was cleared from the results that recycled steel fibers improved the fatigue behaviour, micro crack mechanism and reduced the pavement thickness up to 26%. Patel and Patel [34] used jute fibers in concrete pavement. Mechanical properties were measured and it was cleared that, with the use of jute fibers, mechanical properties of concrete were increased as compared to plain concrete. Farooqi and Ali [35] studied the effect of fibers in rigid pavements by incorporating locally available natural fibers (wheat straw) in concrete. From results, it was cleared that fibers reduced the micro cracks. Split tensile strength of wheat straw-reinforced concrete (SWRC) was studied. It was also cleared that split toughness index (STI) of SWRC was more than that of reference plain concrete. Khan and Ali [36] studied the mechanical properties of FRC and its affects on concrete pavements. Human hair fibers and wave polypropylene fibers were used in concrete and PC was used as a reference concrete. Mechanical properties of human hair fiber reinforced concrete (HFRC) and wave polypropylene fiber reinforced concrete (WPFRC) were studied by performing the experimental procedure as per ASTM standards and compared with reference PC. Mechanical properties e.g. compressive, split tensile and flexural strength of HFRC and WPFRC were improved as compared to PC. The thickness of concrete pavement was reduced by using experimental outcomes of HFRC and WPFRC as compared to PC. Hence, many properties of rigid pavements can be improved by using fibers in concrete.

2.5 Summary

It is cleared from the literature review that fibers can be used in concrete to enhance the mechanical properties and resistance to freeze-thaw condition. Most of the researches are done on synthetic fibers. Synthetic fibers are normally expensive as compared to natural fibers. Secondly, natural fibers are environment friendly. Behavior of jute fibers in concrete under freeze-thaw conditions is still needs to be investigated.

As per author knowledge, no study has been conducted to evaluate the mechanical properties of jute fiber reinforced concrete for rigid pavements after subjecting to freeze-thaw cycles. In this study, consequence of different freeze-thaw cycles on jute fiber reinforced concrete is investigated. Dynamic and mechanical properties of JFRC are measured at different freeze-thaw cycles and compared with reference plain concrete.

Chapter 3

Experimental Program

3.1 Background

Use of fibers for enhancing the mechanical properties and resistance against freeze-thaw is increasing day by day. Increase in mechanical properties, toughness and energy absorption are the main advantages of fiber reinforced concrete. Effectiveness of jute fibers for enhancing the resistance against freeze-thaw cycles are explored through the experimental work. In this chapter, ingredients, concrete preparation procedure, specimens details and testing procedures are explained in detail.

3.2 Ingredients

For preparation of plain concrete (PC), ordinary Portland cement, fine and 3/4" down coarse aggregate are used. Properties of ordinary Portland cement are shown in Table 3.1. Sieve analysis of fine and coarse aggregate are shown in Table 3.2.

For the preparation of jute fiber reinforced concrete (JFRC) same ingredients are used along with the addition of 50 mm long jute fibers. The length of fibers is a point of discussion. Fibers should not be short, so that there is complete pull out

Table 3.1: Properties of cement

Chemical Composition (%)	Cement
CaO	61.70
SiO_2	21.00
Al_2O_3	5.04
Fe_2O_3	3.24
SO_3	1.51
MgO	2.56
Loss on ignition	1.83
Mechanical Properties	
Compressive Strength (MPa)	
3 days	27.38
7 days	33.64
28 days	47.27
Physical Properties	
Initial and final setting time (minutes)	175 and 375

from one side of fractured surface. Fibers should also not be long, so that there is balling effect during mixing. Many researchers also used fibers in concrete having

Table 3.2: Sieve analysis of fine and coarse aggregate

Sieve Size (mm)	Passing (%)		Specifications	
	FA	CA	FA	CA
25		100		100-100
19		89.0		90-100
10	100	20.8	100-100	20-55
4.75	99.6	1.1	95-100	0-10
2.38	98.0		80-100	
1.20	75.0		50-85	
0.60	55.0		25-60	
0.30	25.0		10-30	
0.15	11.4		0-15	

Table 3.3: Physical properties of jute fibers

Properties	Jute Fibers
Length (mm)	50
Diameter (μm)	10-50

length of 50 mm [9, 35,36]. Physical properties of used jute fibers are shown in Table 3.3.

3.3 Selection of Mix Design for Current Study

Jute fibers are used because of high energy absorption capacity, high breaking strength, cheaply available and local material [22,37]. Jute fiber reinforced concrete was used in rigid pavement and improvement in mechanical properties were observed [34]. 1% to 10% of fiber content by mass of cement are used along with fibers length of 10 mm to 50 mm. However optimum results were obtained by using 5% fibers content by mass of cement with 50 mm long [30,9]. So selected mix design ratio of PC and JFRC is 1:2:3:0.60 with the addition of 5% fibers content, by mass of cement and having 50 mm length. The reason for the same mix design for both mixes is to compare the results of JFRC with PC to check the effectiveness of jute fibers in same ratio of PC. Zakrai et al. [26] used 1:2:4 with jute fibers in concrete and improvement in mechanical properties were observed. In this current study, the aggregate content is reduced from 4 to 3 because to have more mortar available for grabbing fibers for high toughness and less compromise to compressive strength.

3.4 Concrete Preparation

Cement, fine aggregate and coarse aggregate are used at a ratio of 1:2:3 for the preparation of plain concrete along with water cement ratio (w/c) of 0.6. Same mix design ratio is used for jute fiber reinforced concrete with the addition of jute fibers having 50 mm length, which are added at a ratio of 5% by mass of cement. All materials are measured by mass. PC and JFRC are manufactured by using the non-tilting pivoting sort drum concrete mixer. For the manufacturing of PC, cement, sand and aggregate, all are placed into the drum of mixer along with water for three minutes. Workability of JFRC and PC specimens are measured before filling of moulds at fresh stage by using ASTM standard C143/C143M-15 [38]. For manufacturing of JFRC, a different approach is used [21]. Jute fibers are dipped into water for 24 hours, to absorb the require amount of water. Then, fibers are left in open air for 30 minutes. After that, materials are put into the mixer in layer forms in order to prevent from balling effect. One-third part of aggregate, sand, cement and jute fibres are placed into blender drum. The same process is repeated until the complete materials are placed into the blender drum. After complete placing of materials into the blender drum, about one-third of total water is spread all over the materials. The mixer is started and the remaining water is added slowly into the mixer. The mixer is rotated for six minutes to get uniform concrete. Slump test is executed before filling of JFRC into moulds. The value of

FIGURE 3.1: Slump of JFRC and PC

slump is less in case of JFRC as compared to PC as shown in Figure 3.1. This is due to the water absorption capacity of jute fibers. The difference could be more if the fibers are used into the dry condition, the value is less because jute fibers were already soaked into water for 24 hours [21]. Moulds are filled into three layers and in each layer, 25 times tamping is done with the help of the rod. Specimens of PC and JFRC are filled using same procedure. After two days, specimens are demoulded and placed into a water tank for curing of specimens for 28 days. After 28 days before the mechanical testing, the density of PC and JFRC is measured by dividing the mass of each specimen with their volume. ASTM standard C642-13 [39] is used for measuring the density of both PC and JFRC. Workability and density of JFRC is measured same as that of PC, because of non-availability of any standards for fiber reinforced concrete (FRC). The density of JFRC is less than PC, due to use of jute fibers and low weight of JFRC specimens as compared to PC. Value of slump and density of PC and JFRC are shown in Table 3.4. Slump of JFRC is 38% less than PC, whereas density of JFRC is 3.08% less than PC.

Table 3.4: Slump and density of PC & JFRC.

Type (1)	W/c Ratio (2)	Slump(mm) (3)	Density (Kg/m^3) (4)
PC	0.6	60±2	2526±5
JFRC	0.6	37±1	2450±3

Note: An average of two readings is taken

3.5 Specimens

For determining the properties of PC and JFRC under freeze-thaw conditions cylinders and beam-lets specimens are cast. The details of prepared specimens are shown in Table 3.5. An average of two specimens is used against each cycle and each test. From 32 specimens of the cylinders, 16 specimens are of PC and 16 of JFRC. From 16 PC and 16 JFRC cylinders, 8 cylinders of PC and JFRC are used for determining the compressive strength at 0, 10, 20, and 30 cycles of freeze-thaw. Whereas remaining 8 cylinder specimens of PC and JFRC are used for determining the split tensile strength at 0, 10, 20 and 30 cycles of freeze-thaw. From 16 cast beam-let specimens, 8 specimens are cast for PC and 8 for JFRC. Beam-lets of PC and JFRC specimens are used to measure flexural strength at 0, 10, 20 and 30 cycles of freeze-thaw. Before the start of the freeze-thaw process

TABLE 3.5: Detail of specimens prepared.

PC (1:2:3, w/c 0.6)	**JFRC** (1:2:3, w/c 0.6, 50 mm long length, 5% fiber by mass of cement)	**Properties required to be determined**
PC at 0 cycle, PC at 10 cycles PC at 20 cycle, PC at 30 cycles	JC at 0 cycle, JC at 10 cycles JC at 20 cycles, JC at 30 cycles	• Dynamic behavior as per ASTM C215-14 • Loss in mass* • Compressive cracking behavior (ASTM standard C39/C39M-18). ○ Stress-strain curve ○ δ (compressive strength) and ε_o (Strain) ○ CE_p, CE total, CTI
PS at 0 cycle, PS at 10 cycles PS at 20 cycles, PS at 30 cycles	JS at 0 cycle, JS at 10 cycles JS at 20 cycles, JS at 30 cycles	• Dynamic behavior as per ASTM C215-14 • Loss in mass* • Split cracking behavior (ASTM standard C496/C496M-17). ○ Splitting-tensile load-time curve ○ STS (Splitting-tensile strength) ○ SE_p, SE total, STI
PF at 0 cycle, PF at 10 cycles PF at 20 cycles, PF at 30 cycles	JF at 0 cycle, JF at 10 cycles JF at 20 cycles, JF at 30 cycles	• Dynamic behavior as per ASTM C215-14 • Loss in mass* • Flexural cracking behavior (ASTM standard C293/C293M-16). ○ Flexural load-deflection curve ○ MoR (Modulus of rapture) ○ FE_p, FE total, FTI

*Note: After completion of targeted cycles, loss in mass is measured.**

mass, dynamic properties and cracks or voids on the specimens are measured. After completion of each freeze-thaw cycle again mass, dynamic properties and crack or voids are measured for each specimen to observe the changes occurred in specimens due to the freeze-thaw process before placing the specimens into the servo-hydraulic testing machine for mechanical testing.

3.6 Testing Procedure

The loss in mass, relative dynamic modulus of elasticity, compressive strength, stress-strain curve, split tensile strength, load time curve, flexural strength and load-deflection curve are measured against 0, 10, 20 and 30 cycles of freeze-thaw.

3.6.1 Freeze-Thaw Process

Freeze-thaw process on the cylinders and beam-lets specimens of PC and JFRC is carried out as per ASTM standard C666/C666M-15 [11]. One cycle of freeze-thaw process is completed within 5 hours as per ASTM standard. One cycle of freeze-thaw process completion means, temperature changes from 4^oC to -18^oC and again from -18^oC to 4^oC. Relative dynamic modulus of elasticity (P_c) of each PC and JFRC specimen is calculated. Relative dynamic modulus of elasticity (P_c) is very important in case of the freeze-thaw process because when it value reaches by 60% of its original value, which is at zero cycle then freeze-thaw process needs to be stopped, or a number of freeze-thaw cycles reach to 300 cycles. For this purpose relative dynamic modulus of elasticity (P_c) and counting the number of freeze-thaw cycles are very important.

3.6.2 Dynamic Properties

Dynamic properties of the cylinders and beam-lets specimens of PC and JFRC are determined as per ASTM standard C215-14 [40] to find frequencies used to find damping ratio, relative modulus of elastictiy (P_c) is calculated as per ASTM C666/C666M-15 [11]. Frequencies, mass and (P_c) are measured at two stages, first before the start of the freeze-thaw process for each specimens and second, after completion of target freeze-thaw cycles.

3.6.3 Mechanical Properties

3.6.3.1 Compression Strength

Cylinders are used to measure the compressive strength of PC and JFRC specimens by using servo-hydraulic testing machine (STM) as per ASTM standard C39/C39M-18[10]. From the test results, compressive strength, strain and stress-strain curve are obtained. Compressive energy absorption (CE_p, CE_f and CTE) and compressive toughness index (CTI) are also calculated from stress-strain curve.

3.6.3.2 Splitting Tensile Strength

For measuring split tensile strength, standard size of PC and JFRC cylinders are used in servo-hydraulic testing machine (STM) as per ASTM standard C496/C496M-17 [41]. From test results split tensile strength and load deformation curve are obtained. Split tension energy absorption (SE_p, SE_f and STE) and split tension toughness index (STI) are calculated from the load deformation curve.

3.6.3.3 Flexural Strength

For measuring flexural strength, standard size of PC and JFRC beam-lets are used in servo-hydraulic testing machine (STM) as per ASTM standard C78/C78M-16 [42]. From test results, flexural strength and load-deflection curve are obtained. Flexural energy absorption (FE_p, FE_f and FTE) and flexural toughness index (FTI) are calculated from the load-deflection curve.

3.6.4 Fiber Breakage in Tested Specimens

Fractured surface of tested specimens is further examined at the micro level through the help of images. Images of tested specimens are taken to examine the consequence of freeze-thaw cycles on JFRC specimens. Purpose is to identify the failure mechanism and bonding of fibers with concrete ingredients.

3.7 Summary

PC Specimens are prepared with a mix design of 1:2:3:0.6. 5% of jute fibers by mass of cement are added to prepare JFRC with same mix design ratio. A total of 48 specimens in which 32 cylinders are used to find compressive and split tensile strengths and 16 beam-lets are used to find flexural strength at different freeze-thaw cycles. All specimens are tested to find relative dynamic modulus of elasticity, loss in mass and damping ratio.

Chapter 4

Experimental Evaluation

4.1 Background

Mix design ratio for PC is 1:2:3:0.6 (cement: sand: aggregate: w/c). Same mix design ratio is used for JFRC with the addition of 50 mm long jute fibers at a ratio of 5% by mass of cement. Experimental results of PC and JFRC specimens at different freeze-thaw cycles are discussed in this chapter.

4.2 Effect of Freeze-Thaw Cycles

The impact of freeze-thaw cycles on the surface of JFRC and PC cylinders and beam-lets are shown in Figure 4.1. The schematic diagram of each specimen is also made to see the crack propagation due to freeze-thaw cycles on the surface of JFRC and PC specimens. From Figure 4.1 it is cleared that, as the cycles are increased, cracks propagation is also increased. At 0 cycles of freeze-thaw there are a minimum number of surface voids on PC and JFRC specimen due to compaction, but after completion of 10 cycles of freeze-thaw number of surface voids and their size are increased as compared to 0 cycle of freeze-thaw. After completion of 20 cycles number of surface voids and their size are increased as compared to 10 cycles of freeze-thaw. After completeion of 30 cycles of freeze-thaw number of surface

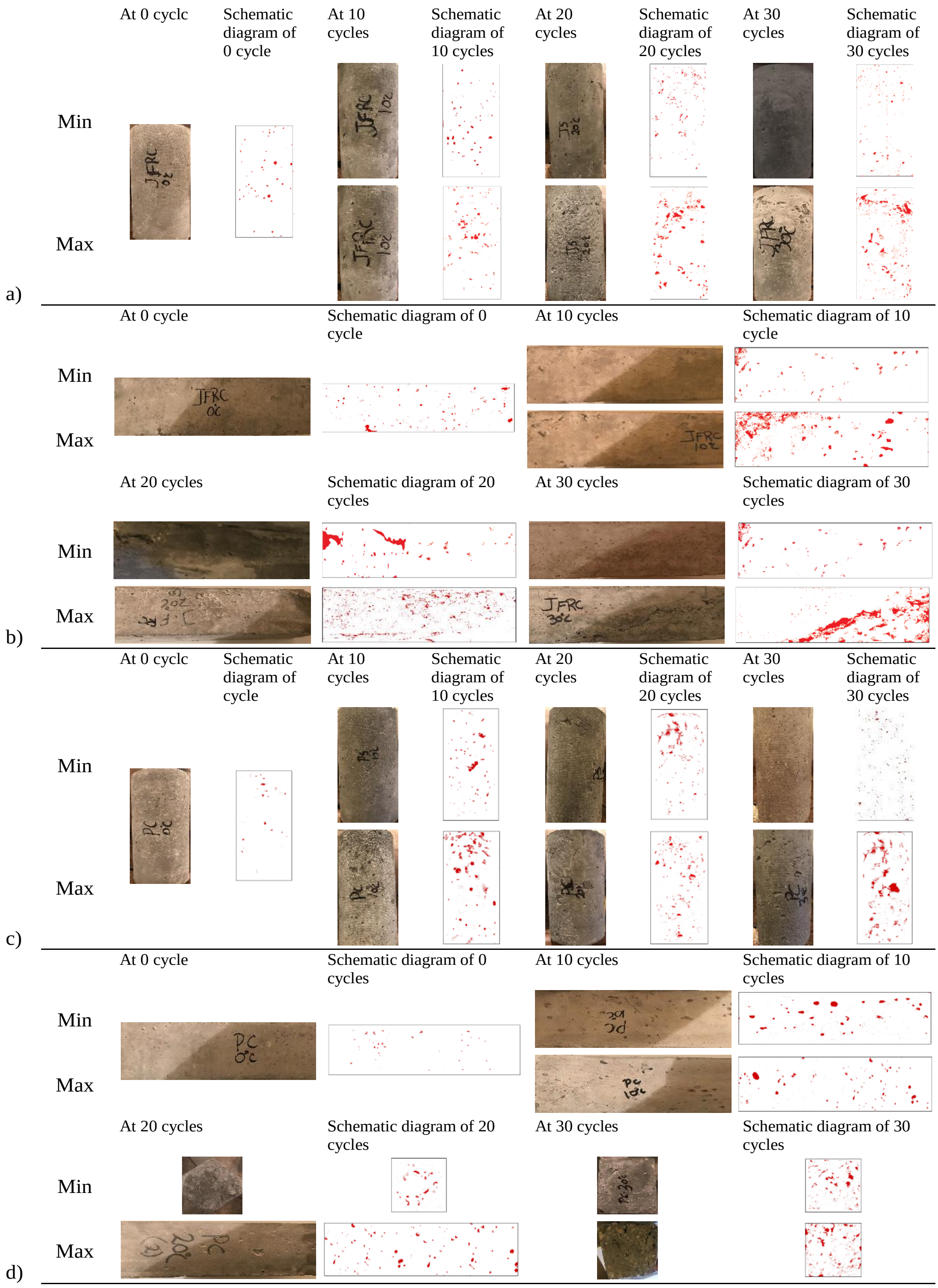


FIGURE 4.1: Crack propagation due to freeze-thaw at 0,10,20 and 30 cycles a) JFRC cylinders, b) JFRC beams, c) PC cylinders, and d) PC beams

Note: Schematic diagram shows the damages due to freeze-thaw at 0, 10, 20 and 30 cycles.

voids and their size are increased as compared to 20 cycles. This kind of trend is observed in both PC and JFRC specimens. So, as the freeze-thaw cycles increased the number of surface voids and their size are also increased. The number of surface voids and their size are increased due to water enters into the void at thawing process and which become freezes during freezing stage. During freezing stage, when water freezes the volume of water increase to 9% of its original volume as a result, an increase in the size of surface voids and a number of voids occur. Damages occurred in jute fiber reinforced concrete specimens are slightly more as compared to plain concrete specimens. This is due to the water absorbed behavior of jute fibers. Jute fiber absorbed water during casting, curing and thawing process. When absorbed water in JFRC specimens experience the freezing stage as a results expansion is occurred and cracks appeared in the samples. In case of JFRC cylinders and beam-lets specimens, only the top surface layer is damaged and crack propagation is increased as the number of freeze-thaw cycles increased. There are few small voids created on the surface of JFRC specimens. This is due to the strong bonding of jute fibers with concrete composite in JFRC specimens. Whereas, in the case of PC specimens deep voids are created on the surface of PC specimens. Number of deep voids are increased as the freeze-thaw cycles are increased. Due to the development of cracks in JFRC and PC specimens under freeze-thaw cycles. The loss in mass of JFRC and PC specimens is also increased as the number of freeze-thaw cycles are increased.

Percentage of loss in mass in PC and JFRC specimens due to freeze-thaw affect is shown in Table 4.1. Percentage of loss in mass occurred in PC cylinders is 0.38%, 0.63%, 1.13% and in PC beam-lets is 0.51%, 0.94%, 1.20% at 10, 20, and 30 cycles of freeze-thaw with respect to PC cylinders and beam-lets mass at 0 cycles of freeze-thaw. The percentage of loss in mass occurred in JFRC cylinders is 0.39%, 0.91%, 1.43% and in JFRC beam-lets is 0.64%, 1.07%, 1.86% at 10, 20, and 30 cycles of freeze-thaw with respect to JFRC cylinders and beam-lets mass at 0 cycles of freeze-thaw. From the Table 4.1 and Figure 4.1, it is cleared that the loss in mass occurred in JFRC specimens is more under the freeze-thaw condition as compared to PC specimens. However, the durability of natural fiber is a major concern because of organic nature of natural fibers. There are different techniques reported by Filhao et al. [31] for improving the durability of natural fiber reinforced concrete. i.e. carbonation of matrix in a CO_2 rich environment, partial replacement of ordinary Portland cement by undensified silica fume, or blast furnace slag. Working on similar lines, some techniques can be developed to treat the fibers so as to control the loss in mass. Fiber reinforced concrete behaves better under dynamic and mechanical loading, so if loss in mass of FRC is improved under freeze-thaw condition then fiber reinforced concrete rigid pavement behaves better as compared to PC.

TABLE 4.1: Loss in mass of PC and JFRC

Specimen	Symbol	Mass Before Freeze-Thaw (Kg)	Mass After Freeze-Thaw (Kg)	Loss in Mass (%)
(1)	(2)	(3)	(4)	(5)
Cylinder	PC_0	3.97±0.01	-	-
	PC_{10}	3.97±0.01	3.95±0.01	0.38±0.01
	PC_{20}	3.97±0.01	3.94±0.01	0.63±0.01
	PC_{30}	3.97±0.01	3.92±0.01	1.13±0.01
	$JFRC_0$	3.85±0.02	-	-
	$JFRC_{10}$	3.85±0.02	3.83±0.02	0.39±0.02
	$JFRC_{20}$	3.85±0.02	3.81±0.02	0.91±0.02
	$JFRC_{30}$	3.85±0.02	3.79±0.02	1.43±0.02
Beam	PC_0	11.71±0.02	-	-
	PC_{10}	11.71±0.02	11.65±0.02	0.51±0.02
	PC_{20}	11.71±0.02	11.60±0.02	0.94±0.02
	PC_{30}	11.71±0.02	11.57±0.02	1.20±0.02
	$JFRC_0$	11.41±0.03	-	-
	$JFRC_{10}$	11.41±0.03	11.34±0.03	0.64±0.03
	$JFRC_{20}$	11.41±0.03	11.29±0.03	1.07±0.03
	$JFRC_{30}$	11.41±0.03	11.20±0.03	1.86±0.03

Note: An average of four readings is taken in case of cylinder and an average of two readings is taken in case of beam-let.

4.3 Dynamic Properties

Dynamic properties of PC and JFRC cylinders and beam-lets specimens are measured. Dynamic properties are measured in two stages, one before the start of the freeze-thaw process and second after the completion of freeze-thaw cycles are shown in Table 4.2. Frequencies, P_c and damping ratio of PC and JFRC specimens is measured according to the ASTM standard C215-14 [40] and ASTM standard C666/C666M-15 [11]. For JFRC same standards are followed because of non-availability of standards. The transverse frequencies of each PC and JFRC specimen is measured before the start of freeze-thaw cycles and after the completion of freeze-thaw cycles. JFRC specimens have more transverse frequencies as compared to PC specimens. Measured transverse frequencies of both PC and JFRC specimens are decreasing as the number of freeze-thaw cycles are increased. With the help of measured transverse frequencies P_c of each specimen is measured as per ASTM standard C666/ C666M-15 [11]. JFRC cylinders and beam-lets specimens have more P_c as compared to PC cylinders and beam-lets at different freeze-thaw cycles. P_c of PC and JFRC cylinders and beam-lets is 100% at 0 cycles of freeze-thaw. After completion of 10 cycles of the freeze-thaw P_c of PC_{10} and $JFRC_{10}$ cylinders is 99.43% and 99.54%, whereas in case of PC_{10} and $JFRC_{10}$ beam-lets P_c is 99.56% and 99.77% as compared to the P_c value of PC and JFRC cylinders and beam-lets at 0 cycles of freeze-thaw. After completion of 20 cycles of the freeze-thaw P_c of PC_{20} and $JFRC_{20}$ cylinders is 98.59% and 98.97%, whereas in case of PC and JFRC beam-lets P_c is 99.05% and 99.47% as compared to the P_c value of PC and JFRC cylinders and beam-lets at 0 cycles of freeze-thaw. After completion of 30 cycles of the freeze-thaw P_c of PC_{30} and $JFRC_{30}$ cylinders is 97.76% and 98.28%, whereas in case of PC and JFRC beam-lets P_c is 98.59% and 99.24% as compared to the P_c value of PC and JFRC cylinders and beam-lets at 0 cycles of freeze-thaw. P_c is decreasing as the number of freeze-thaw cycles are increased. Due to the low reduction in P_c in case of JFRC specimens which means, JFRC specimens can even bear more freeze-thaw cycles as compared to PC specimens. Termination of the freeze-thaw process depends upon the value of

P_c. When the value of P_c for any specimen becomes less than 60% to the value at 0 cycles of freeze-thaw or freeze-thaw cycles reached up to 300 cycles freeze-thaw process needs to be terminated. Comparison in damping ratio of PC and JFRC specimens against their respective freeze-thaw cycles is shown in Table 4.2.

TABLE 4.2: Relative dynamic modulus of elasticity (ASTM C666/C666M-15)

Specimen	Symbol	Transverse Frequency at 0 Cycle (Hz)	Transverse Frequency After Cycles n_1* (Hz)	Relative Dynamic Modulus of Elasticity $P_C=(n_1^2/n^2)$ x100(%)	Damping Ratio ξ (%)
(1)	(2)	(3)	(4)	(5)	(6)
Cylinder	PC_0	4116±250	4115±180	100.00	2.12±0.08
	PC_{10}	4116±250	4099±150	99.43±0.2	2.35±0.05
	PC_{20}	4116±250	4082±200	98.59±0.5	2.78±0.10
	PC_{30}	4116±250	4065±165	97.76±0.3	3.69±0.09
	$JFRC_0$	5339±600	5339±300	100.00	3.42±0.05
	$JFRC_{10}$	5339±600	5326±415	99.54±0.3	4.04±0.07
	$JFRC_{20}$	5339±600	5311±270	98.97±0.4	5.45±0.05
	$JFRC_{30}$	5339±600	5293±200	98.28±0.1	6.19±0.04
Beam	PC_0	6582±200	6582±220	100.00	0.70±0.05
	PC_{10}	6582±200	6568±150	99.56±0.2	1.40±0.05
	PC_{20}	6582±200	6551±100	99.05±0.4	1.75±0.08
	PC_{30}	6582±200	6536±75	98.59±0.8	2.05±0.06
	$JFRC_0$	7840±400	7840±330	100.00	1.27±0.05
	$JFRC_{10}$	7840±400	7831±150	99.77±0.3	1.67±0.03
	$JFRC_{20}$	7840±400	7819±100	99.47±0.5	1.82±0.04
	$JFRC_{30}$	7840±400	7810±65	99.24±0.7	2.17±0.02

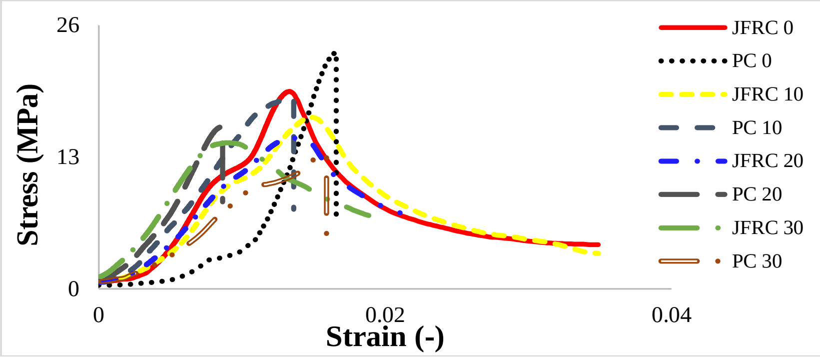
Note: 1. n_1=No. of freeze-thaw cycles (i.e. 10, 20, and 30).
2. An average of four readings is taken in case of the cylinder and an average of two readings is taken in case of beam-let.

Damping ratio of JFRC cylinders at 0, 10, 20, and 30 cycles of freeze-thaw is 3.42, 4.04, 5.45 and 6.19 percentage. Which is more than as compared to PC specimens against their respective freeze-thaw cycles specimens. Damping ratio of PC cylinders at 0, 10, 20, and 30 cycles of freeze-thaw is 2.12, 2.35, 2.78 and 3.69 percentage. Damping ratio of JFRC beam-lets at 0, 10, 20, and 30 cycles of freeze-thaw is 1.27, 1.67, 1.82, and 2.17 percentage. Which is more than as compared to PC specimens against their respective freeze-thaw cycles specimens. Damping ratio of PC beam-lets at 0, 10, 20, and 30 cycles of freeze-thaw is 0.70, 1.40, 1.75, and 2.15 percentage. From the test results, it is cleared that damping ratio of JFRC cylinders and beam-lets specimens are more than PC specimens. As a result, jute fiber reinforced concrete can behave more effectively as compared to plain concrete in rigid pavement. Damping ratio is increasing as the number of freeze-thaw cycles are increased in case of both JFRC and PC specimens.

4.4 Mechanical Properties

4.4.1 Compressive Strength, Behavior and Energy Absorption

Stress-stain curves of all PC and JFRC specimens after subjected to freeze-thaw cycles and compression testing are shown in Figure 4.2(a). The area under the stress-strain curve up to the peak stress is considered as the compressive absorbed energy up to peak stress (CE_p). The area under the stress-strain curve from the peak to the final stress is considered as the compressive absorbed energy from peak stress to final stress (CE_f). The total area under the stress-strain curve from the zero stress to the final stress is considered as the compressive total absorbed energy (CTE). The ratio among the compressive total cracked absorbed energy to the compressive absorbed energy up to peak stress (i.e. CTE/CE_p) is known as compressive toughness index (CTI). Crack propagation during mechanical testing is shown in Figure 4.2 (b). In the case of all PC specimens first crack is developed from 90% to 95% of peak loading. However, in the case of all JFRC specimens first crack is developed around 80% to 85% of peak loading. The first crack appears in a)



b)

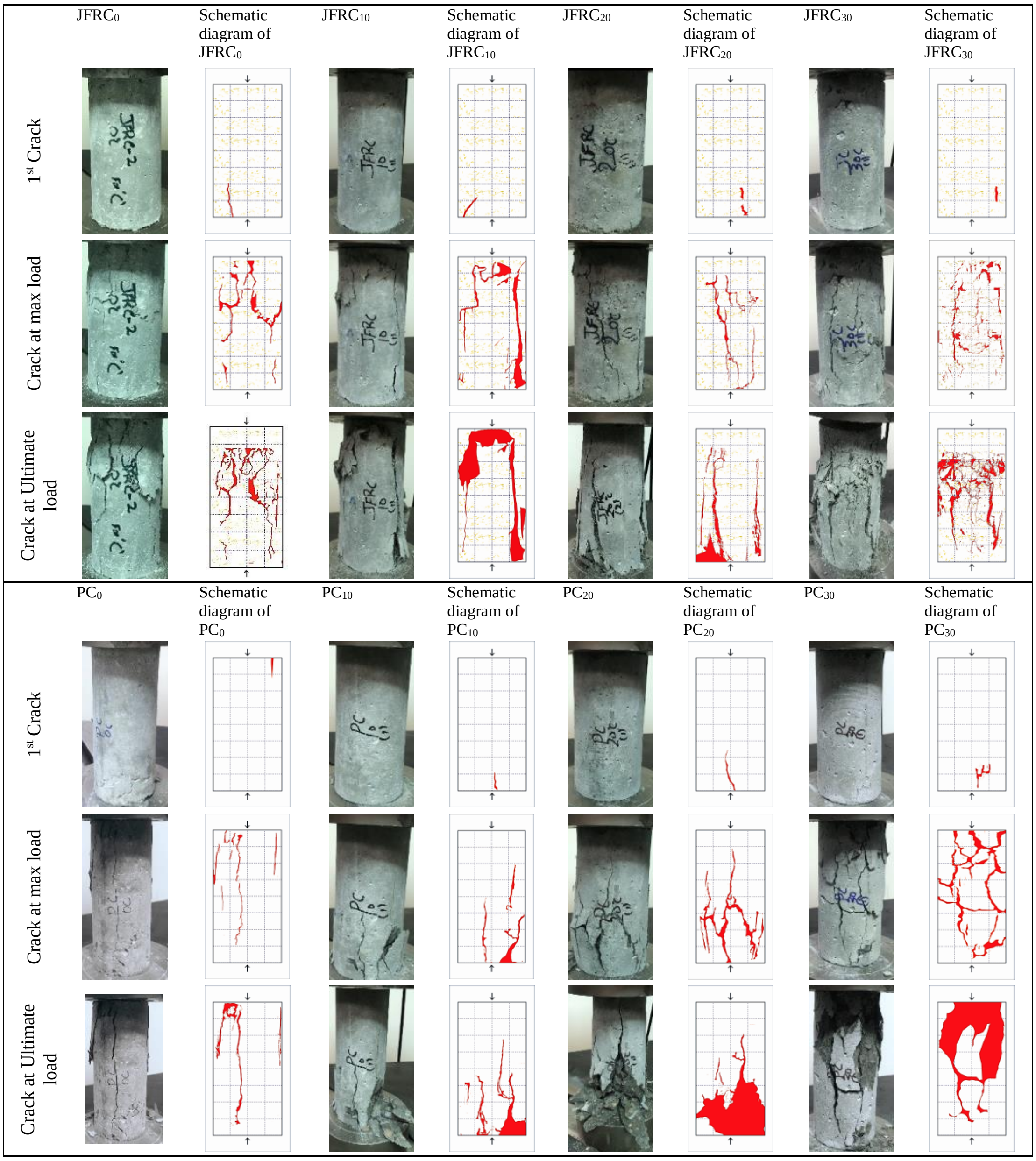


FIGURE 4.2: Compressive behaviour of JFRC and PC after 0, 10, 20, and 30 cycles of freeze-thaw. a) stress strain curve, and b) pictures of crack propagation during mechanical testing (real and schematic diagrams).

all JFRC specimens ($JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$) are very tiny in case of both length and width as compared to the first crack appeared in all PC specimens (PC_0, PC_{10}, PC_{20}, and PC_{30}). At peak loading number of cracks, their length and width are increased in all PC specimens as compared to cracks appeared in all JFRC specimens. At ultimate loading, some fragments of concrete are fallen down from all PC specimens whereas in case of JFRC specimens, the only number of cracks and their size are increased. JFRC specimens have shown better performance due to strong bonding of jute fibers with concrete ingredients.

TABLE 4.3: Compressive strength properties of PC and JFRC

Specimen	f'_c	E_s	Strain	Compressive Energy Absorption			CTI
			δ	CE_p (up to (L_p)	CE_f(L_p to L_f)	CTE	
	(MPa)	(MPa)	(-)	(MJ/m^3)	(MJ/m^3)	(MJ/m^3)	(-)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
PC_0	23.33±0.2	22860.85±98	0.022±.002	0.14±0.001	0.06±0.005	0.20±0.01	1.43±0.03
PC_{10}	18.85±0.3	20549.00±163	0.019±.003	0.12±0.003	0.07±0.005	0.19±0.03	1.58±0.02
PC_{20}	15.99±0.1	18926.01±59	0.015±.002	0.11±0.005	0.08±0.010	0.19±0.05	1.73±0.01
PC_{30}	13.41±0.5	17332.02±320	0.013±.005	0.09±0.006	0.09±0.020	0.18±0.06	2.00±0.02
$JFRC_0$	19.46±0.2	20878.84±107	0.018±.001	0.19±0.002	0.10±0.005	0.29±0.03	1.53±0.02
$JFRC_{10}$	16.91±0.4	19462.86±228	0.018±.002	0.16±0.004	0.12±0.010	0.28±0.05	1.75±0.02
$JFRC_{20}$	14.86±0.6	18245.02±365	0.018±.002	0.15±0.008	0.15±0.010	0.30±0.04	2.00±0.01
$JFRC_{30}$	12.85±0.4	16966.23±309	0.014±.004	0.13±0.003	0.18±0.020	0.31±0.03	2.38±0.02

Note: 1. f'_c: Compressive strength, CE_p: Compressive energy up to peak load, CE_f: Compressive energy from peak load to final load, CTE: Compressive total energy, and CTI: Compressive toughness index.

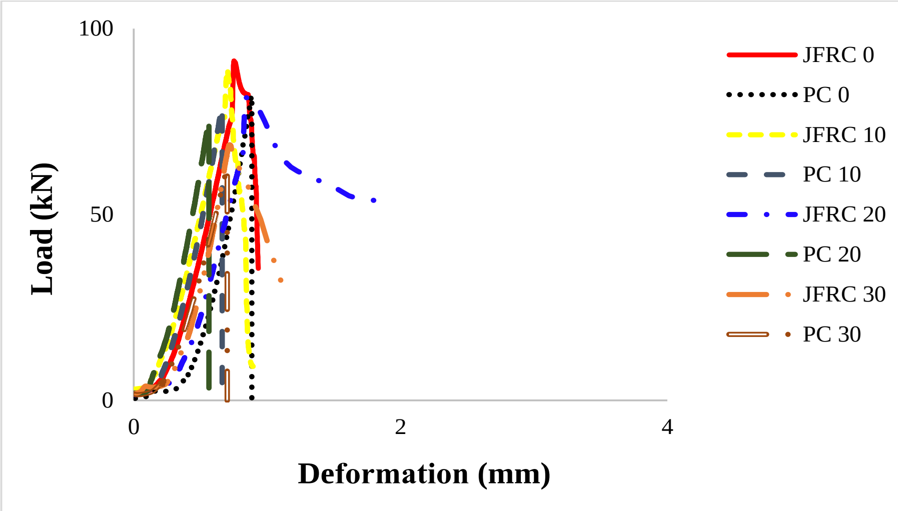
2. Note: An average of two readings is taken.

3. For compressive strength loading rate is 0.25Mpa/s according to ASTM standard C39/C39M-15a an average of min and max.

To check the fibers failure mechanism, all specimens of JFRC are broken intentionally. 50% of fibers are broken whereas 50% of fibers are pulled out from all JFRC specimens. In the case of JFRC and PC specimens, as the number of freeze-thaw cycles increased cracks propagation is also increased. Which is clearly seen through the schematic diagram of each specimen of JFRC and PC in Figure 4.2(b). From Table 4.3, it is cleared that as the number of freeze-thaw cycles are increased, compressive strength is decreased as compared to the previous number of freeze-thaw cycles of same specimens of JFRC or PC. Although compressive strength is decreased by using jute fibers in concrete, but at the same time micro cracks are reduced and toughness index and energy absorption are increased. This can lead to avoid deterioration of rigid pavement. On the other hand, a little decrease in compressive strength will also be encountered in design. In a comparison of compressive strength of PC specimens with JFRC specimens, PC specimens have more compressive strength as compared to JFRC specimens against their same respective freeze-thaw cycles. The decrease of 3.87 MPa, 1.94 MPa, 1.13 MPa, and 1.01 MPa in compressive strength of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ is observed as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. However, JFRC specimens have absorbed more energy as compared to PC specimens. Increment of 0.09 MJ/m^3, 0.09 MJ/m^3, 0.11 MJ/m^3 and 0.13 MJ/m^3 in CTE is observed in $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as comparison to $PC_{0,}$ $PC_{10,}$ $PC_{20,}$ and $PC_{30.}$ Energy absorption decreases as the number of the number of freeze-thaw cycles are increased.

4.4.2 Split-tension Strength, Behavior and Energy Absorption

Load time curves of all PC and JFRC specimens are shown in Figure 4.3 (a) after exposed to freeze-thaw cycles and split tension testing. The area under the load-time curve up to the peak load is considered as the split tensile absorbed energy up to peak load (SE_p). The area under the load-time curve from the peak load to the ultimate load is considered as the split tensile absorbed energy from peak



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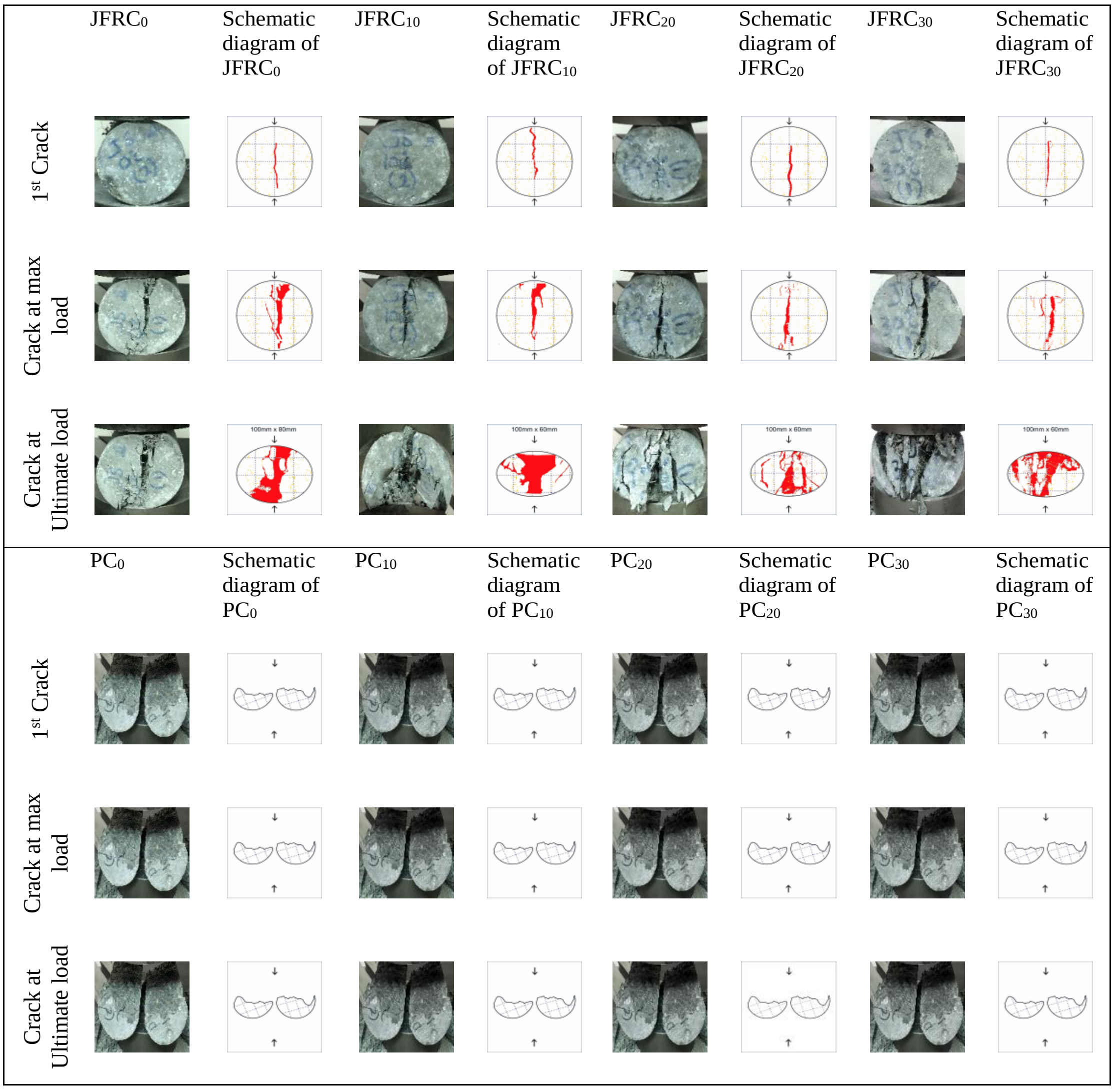


b)

FIGURE 4.3: Split tensile behaviour of JFRC and PC after 0, 10, 20, and 30 cycles of freeze-thaw. a) load deformation curve and b) pictures of crack propagation during mechanical testing (real and schematic diagrams).

load to ultimate load (SE_f). The total area under load-time curve from the initial application of load on specimens to the final load is known as the split tensile total absorbed energy (STE). The ratio among the split tensile total absorbed energy to the split tensile absorbed energy up to peak load (i.e. STE/SE_p) is known as split tensile toughness index (STI). Crack formation/propagation during mechanical testing is shown in Figure 4.3 (b). From 95% to 98% of the maximum load first crack is developed in all PC specimens. However, in the case of all JFRC specimens first crack is developed from 92% to 95% of maximum loading. First cracks in all JFRC specimens ($JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$) are very tiny in case of both length and width as compared to the first cracks appeared in all PC specimens (PC_0, PC_{10}, PC_{20}, and PC_{30}). At maximum loading, all PC specimens are broke down into two pieces. Whereas in the case of JFRC specimens at maximum loading number of cracks and their size are increased. However, at ultimate loading all specimens of JFRC are taking load even their size are changed under loading as shown in Figure 4.3 (b). Real and schematic diagrams are made for better observation of crack propagation as shown in Figure 4.3 (b). JFRC specimens have shown better performance due to strong bonding of jute fibers with concrete ingredients. To check the fibers failure mechanism, all specimens of JFRC are broken intentionally. 50% of fibers are broken down whereas 50% of fibers are pulled out from concrete. In the case of JFRC and PC specimens as the number of freeze-thaw cycles are increased, cracks propagation under mechanical testing is also increased. Which is clearly seen through the schematic diagram of each specimen of JFRC and PC in Figure 4.3(b). From Table 4.4. It is cleared that as the number of freeze-thaw cycles are increased, split tension strength is decreased as compared to the previous number of freeze-thaw cycles of same specimens. This kind of trend is observed in all PC and JFRC specimens under split tensile loading. In a comparison of the split tensile strength of PC specimens with JFRC specimens. JFRC specimens have more split tensile strength as compared to PC specimens against their same freeze-thaw cycles. Due to more tensile strength of JFRC, it can resist the early age micro cracks in rigid pavement much better than plain concrete. An increment of 0.3 MPa, 0.28 MPa, 0.16 MPa, and 0.11 MPa in split tensile strength of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$, respectively, is observed as comparison to PC_0, PC_{10}, PC_{20}, and PC_{30}, respectively. Furthermore, JFRC specimens have absorbed more energy as

TABLE 4.4: Split tensile strength properties of PC and JFRC

Specimen	f_{st}	Split Tension Energy Absorption			STI
		SE_p (up to L_p)	SE_f (L_p to L_f)	STE	
	(MPa)	(J)	(J)	(J)	(-)
(1)	(2)	(3)	(4)	(5)	(6)
PC_0	2.74±0.2	25.23±2	0	25.23±2	1
PC_{10}	2.64±0.1	23.41±3	0	23.41±3	1
PC_{20}	2.53±0.4	21.89±4	0	21.89±4	1
PC_{30}	2.16±0.3	20.01±2	0	20.01±2	1
$JFRC_0$	3.04±0.2	25.23±5	11.57±0.4	36.80±3	1.46±0.05
$JFRC_{10}$	2.92±0.3	23.79±3	12.13±0.8	35.92±1	1.51±0.04
$JFRC_{20}$	2.69±0.1	22.21±1	13.52±2	35.73±2	1.61±0.01
$JFRC_{30}$	2.27±0.2	20.07±3	14.48±1	34.55±2	1.72±0.02

Note: 1. f_{st}: Split-tensile strength, SE_p: Split-tensile energy absorption up to peak load, SE_f: Split-tensile energy from peak to ultimate load, STE: Split tensile total energy, and STI: Split tensile toughness index.

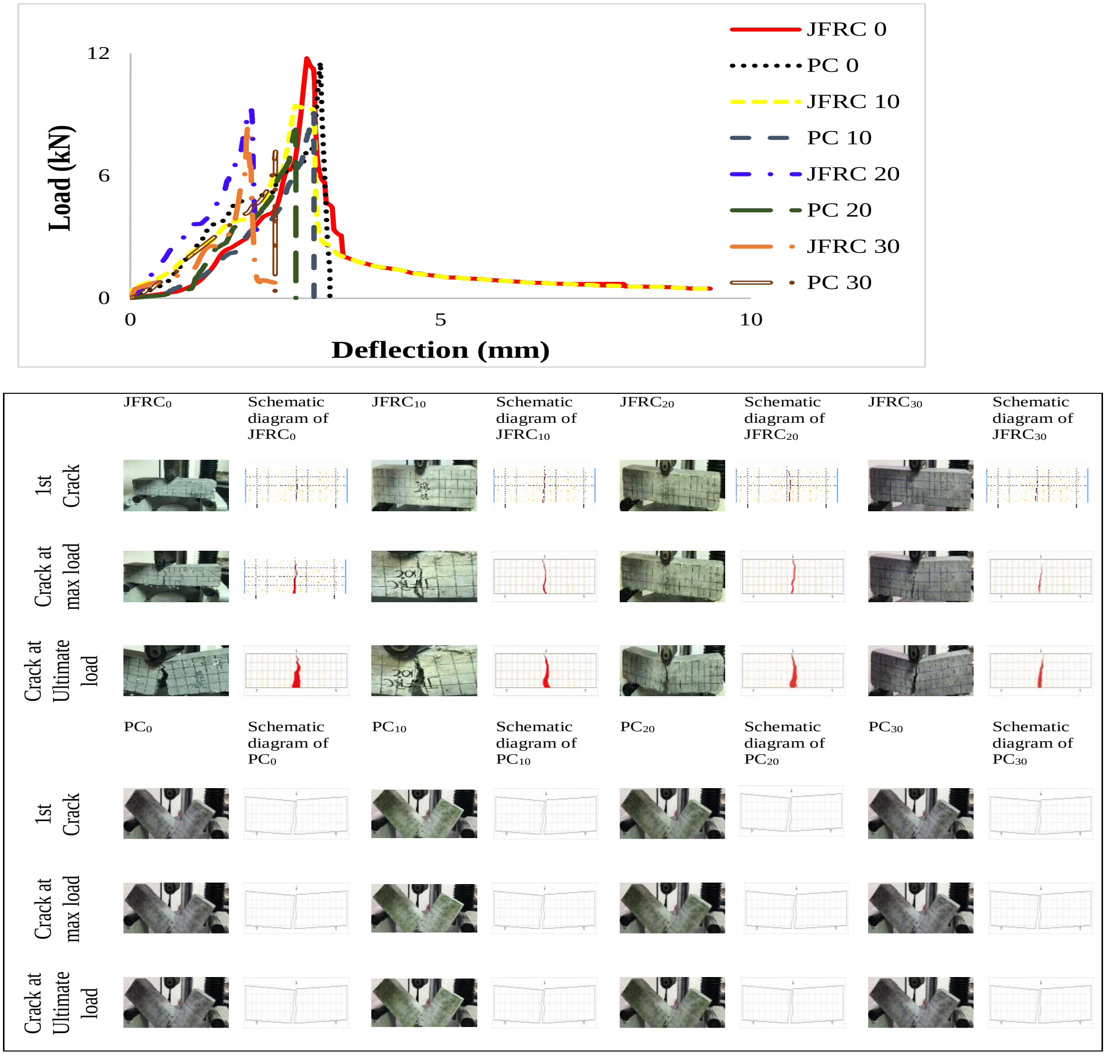
2. Note: An average of two readings is taken.

3. For split tensile strength loading rate for split tensile test is 1.05 MPa/Min according to ASTM standard C496/C496M—11 an average of min and max.

comparsion to PC specimens. Increment of 11 J, 12 J, 14 J and 16 J in STE is observed in $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. Energy absorption decreases as the number of the number of freeze-thaw cycles are increased in all JFRC and PC specimens. An increment in STI is also observed in all JFRC specimens as compared to PC specimens.

4.4.3 Flexural Strength, Behavior and Energy Absorption

Load-deflection curves of all PC and JFRC specimens are shown in Figure 4.4 (a). after subjected to freeze-thaw cycles and flexural testing. The area under the load-deflection curve up to the peak load is considered as the flexural absorbed energy up to peak load (FE_p). The area under the load-deflection curve from the peak load to the final load is considered as the flexural absorbed energy from peak loading to final loading (FE_f). The total area under load deflection curve from the initial application of load on specimens to the final load is known as the flexural total absorbed energy (STE). The ratio among the flexural total absorbed energy to the flexural absorbed energy up to peak load (i.e. FTE/FE_p) is known as flexural toughness index (FTI). Cracks propagation under flexural loading are shown in Figure 4.4 (b). The first crack is developed in all PC specimens at 99% of maximum loading. However, in case of all JFRC specimens first is developed from 93% to 95% of peak loading. First cracks in all JFRC specimens ($JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$) are very tiny in case of length and width as compared to first cracks are appeared in all PC specimens (PC_0, PC_{10}, PC_{20}, and PC_{30}). At peak loading, all PC specimens are broke down into two pieces. Whereas in the case of JFRC specimens at peak loading instead of breaking into two pieces size and length of cracks are increased. However, at ultimate loading all specimens of JFRC are sound good and cracks width are increased. The bottom and the top surface of all JFRC specimens are interconnected as shown in Figure 4.4 (b). Real and schematic diagrams are made for better observation of crack propagation. JFRC specimens have shown better performance due to the strong bonding of jute fibers with concrete ingredients. To check the fibers failure mechanism, all specimens of JFRC are broken intentionally. The ratio of breakage to pull out of fibers from concrete is 50:50. In the case of JFRC and PC specimens as the number of freeze-thaw cycles are increased, cracks propagation under mechanical testing are also increased. Which is clearly seen through the schematic diagram of each specimen of JFRC and PC as shown in Figure 4(b). From Table 4.5 it is cleared that as the number of freeze-thaw cycles increased, flexural strength is



a) b)

Figure 4.4: Flexural behaviour of JFRC and PC after 0, 10, 20, and 30 cycles of freeze-thaw. a) load deflection curve, and b) pictures of crack propagation during mechanical testing (real and schematic diagrams).

decreased as compared to the previous number of freeze-thaw cycles of same specimen. This kind of trend is observed in all PC and JFRC specimens under flexural loading. In a comparison of flexural strength of PC specimens with JFRC specimens, JFRC specimens have more flexural strength as compared to PC specimens against their respective same freeze-thaw cycles. Increment of 0.14 MPa, 0.24 MPa, 0.68 MPa and 0.89 MPa in strength is observed in $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$ and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. Furthermore, JFRC specimens have absorbed more energy as comparison to PC specimens. Increment of 2.18 J, 1.56 J, 1.99 J and 2.38 J in FTE is observed in $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$

and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. FTI of JFRC specimens is seen more as compared to PC specimens whereas, FTI of PC is equal to one due to existence of first crack and ultimate crack at same position.

TABLE 4.5: Flexural strength properties of PC and JFRC

Specimen	S_c	Max Deflection	Flexural Energy Absorption			FTI
		Δ	FE_p (up to L_p)	FE_{pe} (L_p to L_f)	FTE	
	(MPa)	(mm)	(J)	(J)	(J)	(-)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
PC_0	7.80±0.2	3.22±0.9	7.33±0.5	0	7.33±0.5	1
PC_{10}	6.12±0.1	2.96±0.6	6.90±0.8	0	6.90±0.5	1
PC_{20}	5.57±0.4	2.66±0.5	6.62±1	0	6.62±1	1
PC_{30}	4.85±0.3	2.33±0.5	6.03±3	0	6.03±3	1
$JFRC_0$	7.94±0.2	9.34±1	8.41±2	1.10±0.08	9.51±2	1.13±0.02
$JFRC_{10}$	6.36±0.2	7.94±0.8	7.31±3	1.33±0.05	8.46±3	1.19±0.03
$JFRC_{20}$	6.25±0.1	5.13±0.8	6.91±0.5	1.69±0.05	8.60±1	1.24±0.02
$JFRC_{30}$	5.74±0.2	4.33±0.6	6.40±0.6	2.01±0.07	8.41±1	1.31±0.02

Note: 1. S_c: Flexural strength, FE_p: Flexural energy absorption at peak load, FE_f: Flexural energy absorption from peak load from final load, FTE: Flexural total energy, and FTI: Flexural toughness index.
2. Note: An average of two readings is taken.
3. For flexural strength loading rate for the flexural test is 1.03 MPa/min according to ASTM standard C78/C78M-15b an average of min and max.

4.5 Fiber Failure Mechanism

Images of failure tested JFRC specimens under mechanical loading are shown in Figure 4.5. Bonding between fibers and concrete matric are studied through these images. Failure surface images of JFRC specimens after subjecting to freeze-thaw cycles and mechanical testing are shown in Figure 4.5. The Pullout of fibers from concrete is clearly evident from these images. It can be seen that there is a strong bonding between fibers and concrete ingredient from these images. Proper mixing of concrete is also seen through these images. Very few voids and size of voids are very small. After application of mechanical testing, concrete cracked and converted into small particles at ultimate load. From these images, it can be seen that broken particles of concrete are attached with each others due to fibers. Which indicates the strong bridging of fibers with concrete composites. From 0 cycle to 30 cycles of freeze-thaw, there is no change in bonding of jute fibers with concrete composites. Broken particles of concrete composites are attached with each other due to jute fibers.

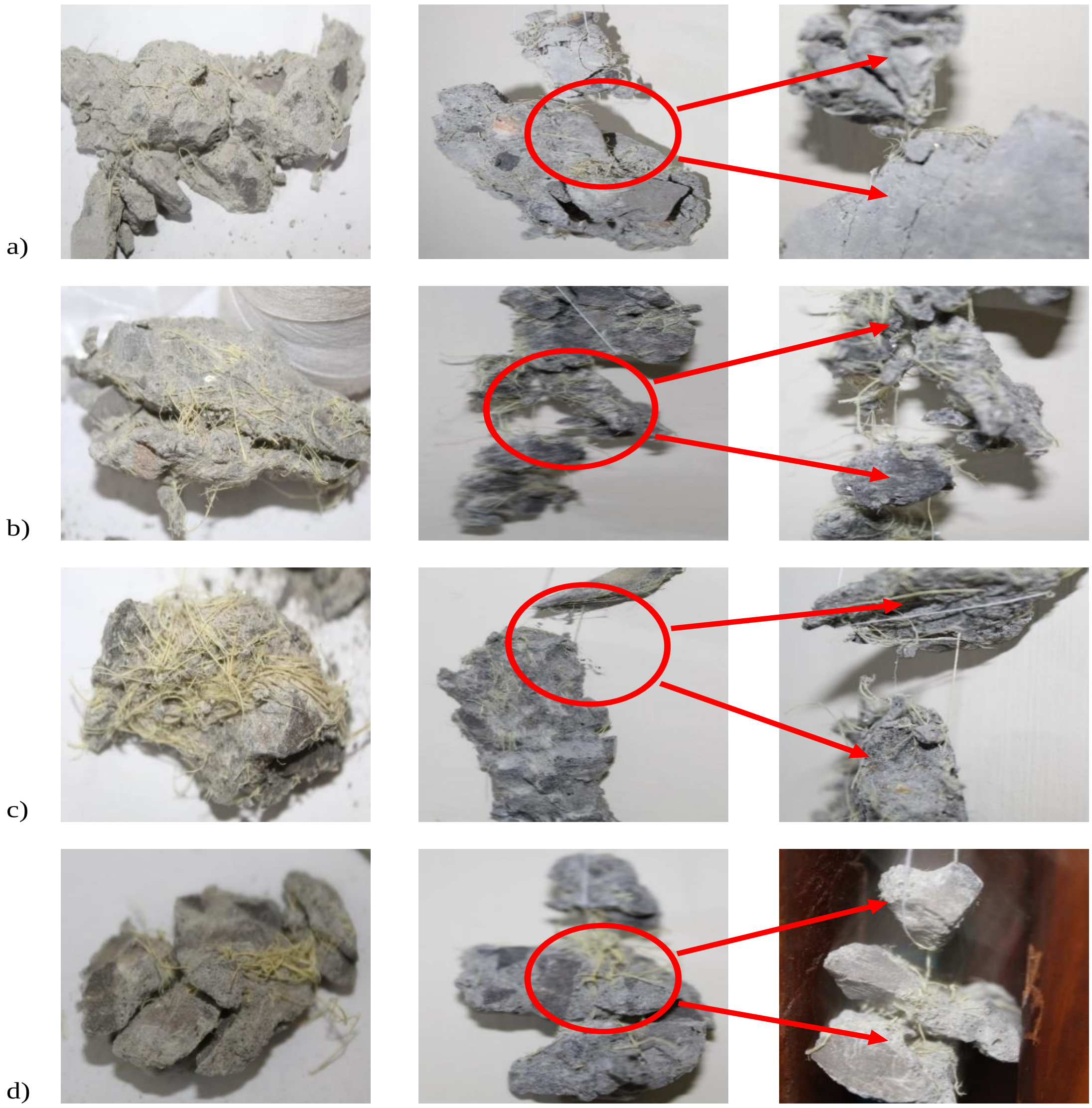


FIGURE 4.5: Fragment bridging in tested specimens. a) JFRC at 0 cycle of freeze-thaw, b) JFRC at 10 cycles of freeze-thaw, c) JFRC at 20 cycles of freeze-thaw, and d) JFRC at 30 cycles of freeze-thaw.

From Figure 4.5 strength of fibers is clearly imagined that even after the application of freeze-thaw cycles from 0 to 30 jute fibers are still having a bond and bridging with concrete particles. It can be seen that mostly fibers are a pullout from concrete instead of breaking into pieces even after application of mechanical loading. After testing the length of pullout fibers is 50 mm, which is the same length used during the preparation of JFRC. Voids due to fibers are not very deeper, which indicate better concrete mixing and bonding of fibers with concrete ingredients. From Figure 4.5, it can be concluded that fibers are a pullout from the test specimens of JFRC after application of mechanical loading and cavities are formed. Adequate bonding of fibers and concrete is also observed from these images. Furthermore, uniform mixing of concrete ingredient and fibers are also observed.

4.6 Summary

The mechanical properties, dynamic properties of PC and JFRC are determined. Image of selected JFRC specimens under mechanical loading are taken to analysis the behavior of fibers in concrete. Increment in all mechanical properties is observed except compressive strength of JFRC as compared to PC. For the result, it is observed that properties of JFRC is much better than PC. Images have shown better bonding of jute fibers with concrete matrix.

Chapter 5

Discussion

5.1 Background

The outcome of experimental testing from mechanical and dynamic properties are already explained in chapter 4. Significant improvement in the split tensile strength, flexural strength, energy absorption and P_c of JFRC are observed as compared to PC. Now it's time to develop a relationship between mechanical properties, percentage of loss in mass and number of freeze-thaw cycles. Some empirical equations are developed to find compressive and flexural strengths of PC and JFRC. Furthermore, a practical example is also solved using experimental results.

5.2 Energy Absorption and Toughness Index Compression

Fluctuation in seasonal temperatures causes damages and deterioration in concrete. Due to deterioration of concrete, changes in physical and mechanical properties occur. In this study due to freeze-thaw cycles, cracks are appeared on the surface of specimens. Cracks in specimens cause loss in mass. Due to which mass of specimen is decreased, dynamic properties and mechanical properties are also changed. The comparison of mechanical properties are shown in Figure 5.1. Horizontal line in bar graph shows the properties of PC at 0 cycles which is used as a reference to compare the effect of different freeze-thaw cycles on PC and JFRC specimens.

f'_c, CE_p, CTE and CTI of each specimen of JFRC and PC are compared and shown in Figure 5.1. Reduction of 16%, 8%, 5%, and 3%, is observed in compressive strength of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. Compressive strength of JFRC specimens are decreased because of natural fibers are used, as testified by other scholars [28]. The increment of 45%, 46%, 55%, and 65% is noticed in CTE of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. The increment of 6.84%, 11.67%, 19%, and 27% is noticed in CTI of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. An improved in energy absorption capability of each specimen of JFRC is observed as compared to its respective PC specimens because of high strength of jute fibers are used. The CTI of JFRC specimens are greater than PC specimens against their respective freeze-thaw cycles.

f_{st}, SE_p, STE, and STI of each specimen of JFRC and PC are compared and shown in Figure 5.1. An increment of 11%, 10%, 6%, and 4%, is observed in split tensile strength of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. An increment of 46%, 50%, 55 and 57% is noticed in STE of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. An increment of 45%, 50%, 60%, and 72% is noticed in STI of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. From the results it is cleared that specimens of JFRC have absorbed more energy as comparison to its respective plain concrete specimens. The STI of JFRC specimens is greater than one, whereas STI is equal to one in case of PC specimens. This is due to presence of initial and peak crack load at similar position. So, an enhancement in energy absorption ability and improvement in crack controlling mechanism can be certified by using fibers.

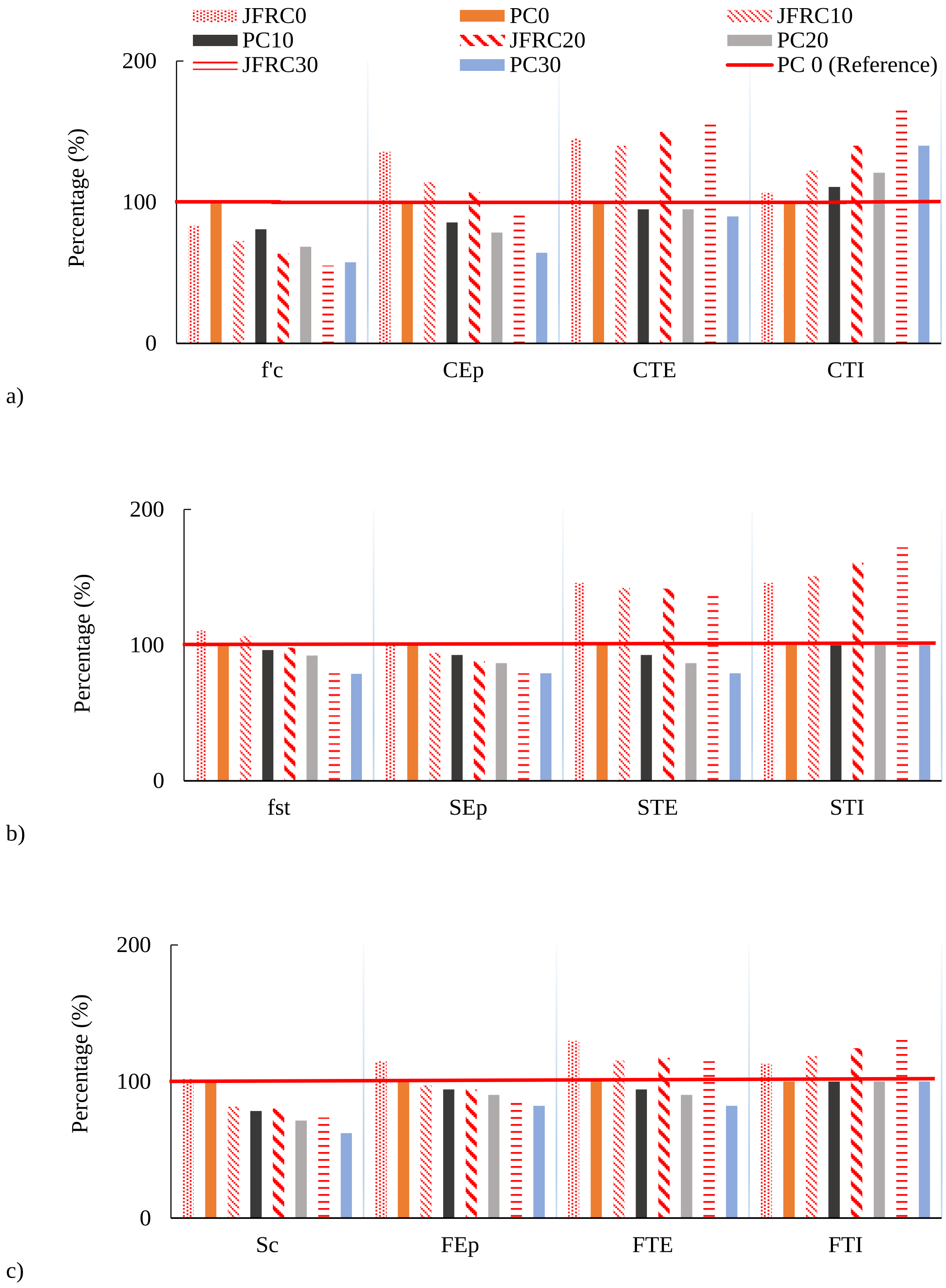


FIGURE 5.1: Comparison of properties of JFRC and PC subjected to 0, 10, 20, and 30 cycles of freeze-thaw. a) compressive properties, b) split tensile properties and c) flexural properties

S_c, FE_p, FTE, and FTI of each specimen of JFRC and PC are compared and shown in Figure 5.1. An increment of 2%, 4%, 9%, and 11%, is observed in flexural strength of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0,

PC_{10}, PC_{20}, and PC_{30}. An increment of 30%, 21%, 27%, and 32% is noticed in FTE of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. An increment of 13%, 18%, 24%, and 31% is noticed in FTI of $JFRC_0$, $JFRC_{10}$, $JFRC_{20}$, and $JFRC_{30}$ as compared to PC_0, PC_{10}, PC_{20}, and PC_{30}. Improvement in flexural properties of JFRC specimens is observed as compared to its respective PC specimens. The FTI of JFRC specimens is greater than one, whereas FTI is equal to one in case of all PC specimens, this is because of the presence of initial and peak crack load at the similar position. So, an enhancement in energy absorption ability and improvement in crack controlling mechanism can be certified by using the fibers.

5.3 Empirical Relation

Structural performance under freeze-thaw is related to its material properties. Performance of concrete directly affects the behavior of the structure. Performance of concrete under freeze-thaw can be related to its toughness, energy absorption and mechanical properties like compressive strength, flexural strength and split tensile strength. Sometimes concrete pieces start spalling before steel failure. Hence bonding of concrete with all ingredients is very important. Fibers are added in concrete to enhance the concrete strength and bonding under freeze-thaw cycles. Furthermore, toughness can be related to its spalling as it is similar to ductility. Fibers can change the concrete brittle behavior to ductile. Fibers are also helpful in minimizing the cracks number and their size. For better post crack behavior more energy absorption is required. Another purpose of fibers to use in concrete is that fibers increase the energy absorption as a result to enhance the concrete post crack behavior.

Empirical equations are developed with the help of obtained experimental results from mechanical and dynamic testing of freeze-thaw specimens to numerically predict the compressive strength and flexural strength of Pc and JFRC after subjecting to number of freeze-thaw cycles. Empirical equations are given below:

$f'_c = X_1 (3n-1)^2 - X_2 (3n-1) + X$ .... (5.1)

$S_c = Y_1 (4n-1)^2 - Y_2 (4n-1) + Y$.........(5.2)

Where f'_c is compressive strength, S_c is flexural strength, n is number of freeze-thaw cycles. X_1, X_2, Y_1 and Y_2 are constants and their values are $X_1 = 1/5000$, $X_2 = 1/11$, $Y_1 = 1/4545$, and $Y_2 = 1/20$. Whereas X and Y are coefficients and their values are; X = 19.2F, for PC F =1.1 and for JFRC F = 1 and Y =8f, for PC f =1 and for JFRC f =1.1.

Value of R^2 is used to measure the accuracy of developed equation. It is noticed that the range of R^2 varies from 98% to 99% which shows the accuracy of developed equations. R^2 values tell that there is very less error in the predicted equations. It is also cleared from the equations that there is a direct relationship between number of freeze-thaw cycles, loss in mass and mechanical properties. Results obtained from empirical equations are presented in Table 5.1. It can be seen that values of f'_c and S_c are obtained from empirical equations are very close to the experimental results of PC and JFRC specimens. Percentage of error in empirical result of compressive strength is -8% to 9% as compared to experimental results. Whereas percentage of error in empirical results obtained from developed equations

TABLE 5.1: Results from empirical equations and their comparison with experimental results

Specimens	Compressive Strength		Difference	Flexural Strength		Difference
	Experimental Results	Empirical Results		Experimental Results	Empirical Results	
	(MPa)	(MPa)	(%)	(MPa)	(MPa)	(%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
PC_0	23.33	21.21	9.08	7.80	7.85	-0.64
PC_{10}	18.85	18.65	1.05	6.12	6.18	-1.06
PC_{20}	15.99	16.45	-2.89	5.57	5.22	6.23
PC_{30}	13.41	14.61	-8.97	4.85	4.96	-2.39
$JFRC_0$	19.46	19.29	0.86	7.94	8.63	-9.24
$JFRC_{10}$	16.91	16.73	1.05	6.36	6.96	-9.51
$JFRC_{20}$	14.86	14.53	2.20	6.25	6.00	3.95
$JFRC_{30}$	12.85	12.69	1.22	5.74	5.74	0.00

of flexural strength is 6% to -9% as compared to experimental results. Hence we can conclude that mechanical properties of PC and JFRC specimens are directly calculated against different number of freeze-thaw cycles by using above developed empirical equations.

5.4 Implementation in Practical Applications

The application of vehicles load on rigid pavement is resisted by flexural strength of concrete. Purpose of steel reinforcements in rigid pavements to control crack propagation. Design example by Huang [43] is used for the calculation of the thickness of rigid pavements. Merritt et al. [44] said that two parameters affect the thickness of rigid pavements, modulus of rupture (MoR) and modulus of elasticity (E_c). These two parameters are used in this example keeping all the other parameters constant. Delatte [45] reported that ASSHTO recommends that compressive strength is used to calculate the modulus of elasticity. Modulus of elasticity doesn't affect the rigid pavement much. Therefore, the compressive strength of each specimen is used to measure their respective modulus of elasticity. All values are same in Huang design example except compressive strength, flexural strength and modulus of elasticity as calculated by [35,36]. ASSHTO equation is used to find the thickness of rigid pavement. Compressive strength, flexural strength and modulus of elasticity are different for each specimen. After using compressive strength, flexural strength and modulus of elasticity of each specimen along with example values, the thickness of rigid pavement required against each specimen is calculated. From Table 5.2 it is cleared that as the number of freeze-thaw cycles are increased, rigid pavement thickness is also increased to resist the effect of freeze-thaw cycles. Design thickness for PC specimens after subjecting to freeze-thaw cycles is more as compared to the respective JFRC specimens against same freeze-thaw cycles. The thickness of rigid pavements is reduced with JFRC due to its high MoR values as compared to their respective PC specimens against same freeze-thaw cycles. To resist the effect of 30 cycles of freeze-thaw, an increase of 28% in PC pavement thickness is required for carrying same load. In case of

JFRC, 19% increase in thickness is required to counter the effect of 30 freeze-thaw cycles. If the thickness of JFRC pavement is increased by 28% (i.e. required in case of PC for encountering 30 cycles affect), then the road can take more load.

TABLE 5.2: Thickness of rigid pavement using AASHTO equation for PC and JFRC

Specimen	Modulus of rapture S_c (MPa)	Compressive strength f'_c (MPa)	Elastic Modulus E_s (MPa)	Thickness h (mm)	Remarks
PC0	7.8	23.3	22860	180	Current Study
PC10	6.1	18.8	20549	200	
PC20	5.5	15.9	18926	210	
PC30	4.8	13.4	17332	230	
JFRC0	7.9	19.4	20878	170	
JFRC10	6.3	16.9	19462	190	
JFRC20	6.2	14.8	18245	200	
JFRC30	5.7	12.8	16966	215	

$$log_{10} W_{18} = Z_R S_o + 7.35 log_{10} (D+1) - 0.06 + \frac{log_{10}[\frac{\Delta PSI}{4.5-1.5}]}{1+\frac{1.624x10^7}{(D+1)^{8.46}}} log10 + (4.22-0.32\rho_t) [\frac{S'_{WSRC} C_d [D^{0.75}-1.132]}{215.63[D^{0.75}-\frac{18.42}{(\frac{E_c}{k})^{0.75}}]}]$$

Note:1. Using W_{18}= *5100,000,* Z_R *=1.64,* S_O*=0.29,* ΔPSI*=1.7,* P_t*=2.5, R=95,* P_O*=4.2, J=3.2,* C_d*=1, and k =72 Psi in AASHTO equation.*

2. AASHTO equation is used due to non-availability of equation for FRC to find pavement thickness.

Fibers are also used in concrete to improve the micro crack behavior. Khan and Ali [30] reported that fibers improved the tensile strength which as a result improve the macro crack behavior and enhance the durability of concrete. The tensile strength, energy absorption and toughness index of each JFRC specimens is much more than its respective PC specimens. Which as a result an enhancement in ductility, durability and performance of concrete. Better performance of concrete in term of life time with less damages.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

PC and JFRC specimens are investigated for the rigid pavements under 10, 20 and 30 cycles of freeze-thaw. Jute fibers are incorporated in concrete at a ratio of 5%, by mass of cement, having 50 mm length. For comparison of results, thickness of road pavement is calculated from obtained results of PC and JFRC. Following are main conclusions:

- Crack propagation is increased, as the number of freeze-thaw cycles are increased.
    - Percentage of loss in mass is more (up to 1.86%) in JFRC specimens as compared to PC specimens. This is due to the water absorption behavior of jute fibers.
- Damping ratio is increased (up to 6.19%) as loss in mass is increased.
    - JFRC can tolerate more freeze-thaw cycles, as relative dynamic modulus of elasticity of JFRC is decreasing very slowly as compared to PC.
- Mechanical properties are decreasing with an increase in freeze-thaw cycles.

  - JFRC has more split tensile and flexural strengths (up to 4% and 11%) respectively, and less compressive strength (up to 16%) as compared to PC.

- Bonding between jute fibers and concrete ingredients still exists in destructive samples subjected to freeze-thaw cycles.

- Empirical equations are developed to predict the compressive and flexural strengths with the help of number of freeze-thaw cycles and percentage of loss in mass.

- Thickness of concrete pavement can be reduced by using jute fibers in concrete as compared to normal concrete.

  - Increase in pavement thickness is 28% in case of PC to resist the effect of 30 cycles of freeze-thaw. Whereas, up to 19% increase in pavement thickness is required by using JFRC.

Base on observation and calculation, jute fibers can be used in concrete for the economical and better performance of rigid pavements.

6.2 Future work

Following are recommendations for future work:

- Durability of jute fibers in concrete over a long time of period is needed to be explored for different environmental conditions.

- Numerical or FE modelling is also helpful.

- Cost comparison of PC and JFRC is need to be studied, for implementation of concrete pavements.

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Annexure A

Results from the testing of mechanical properties (of remaining specimens)

a)

b)

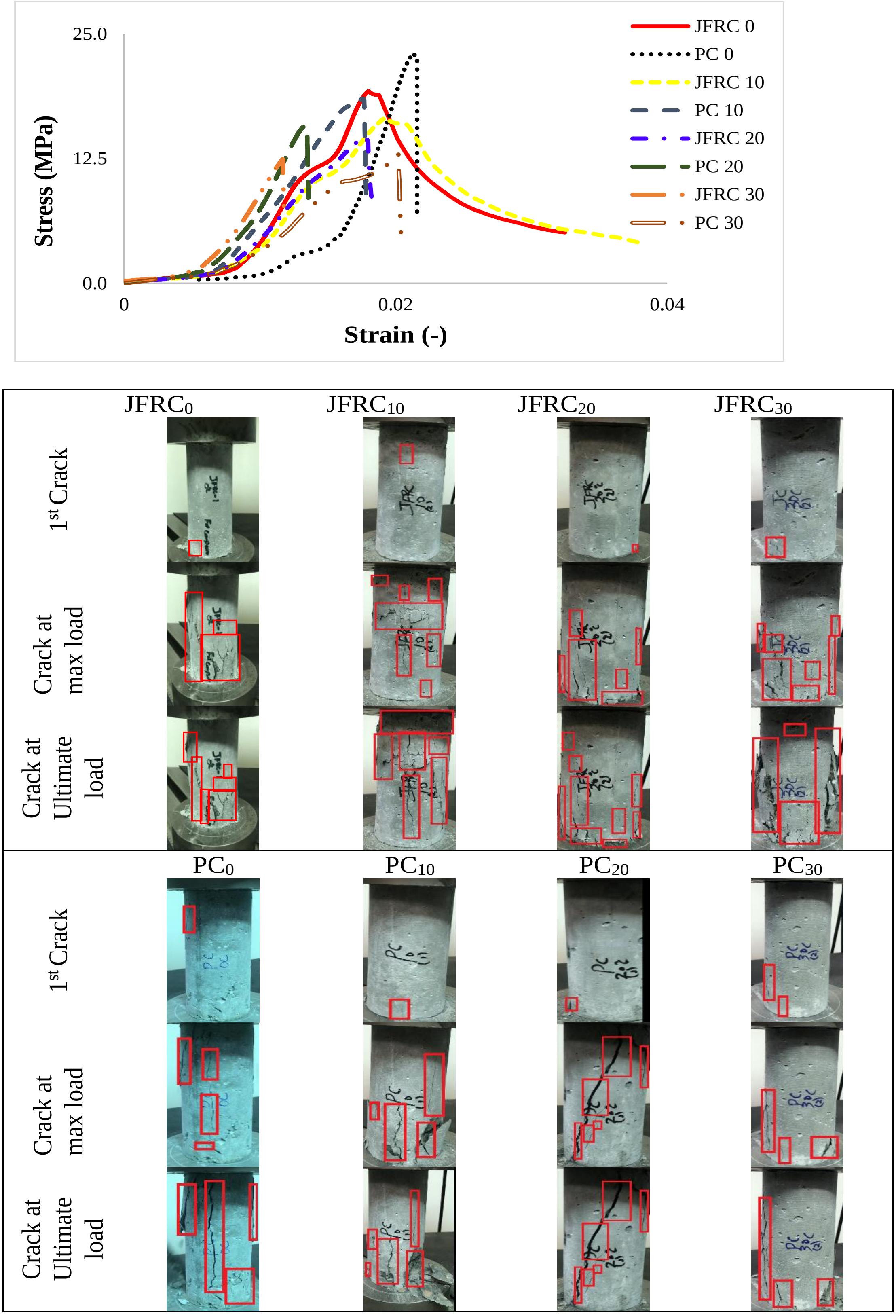
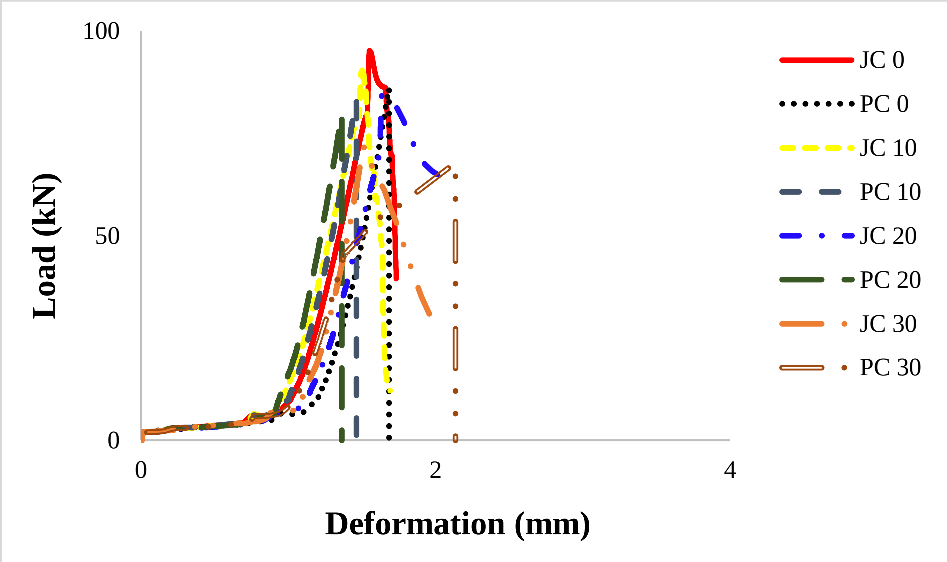
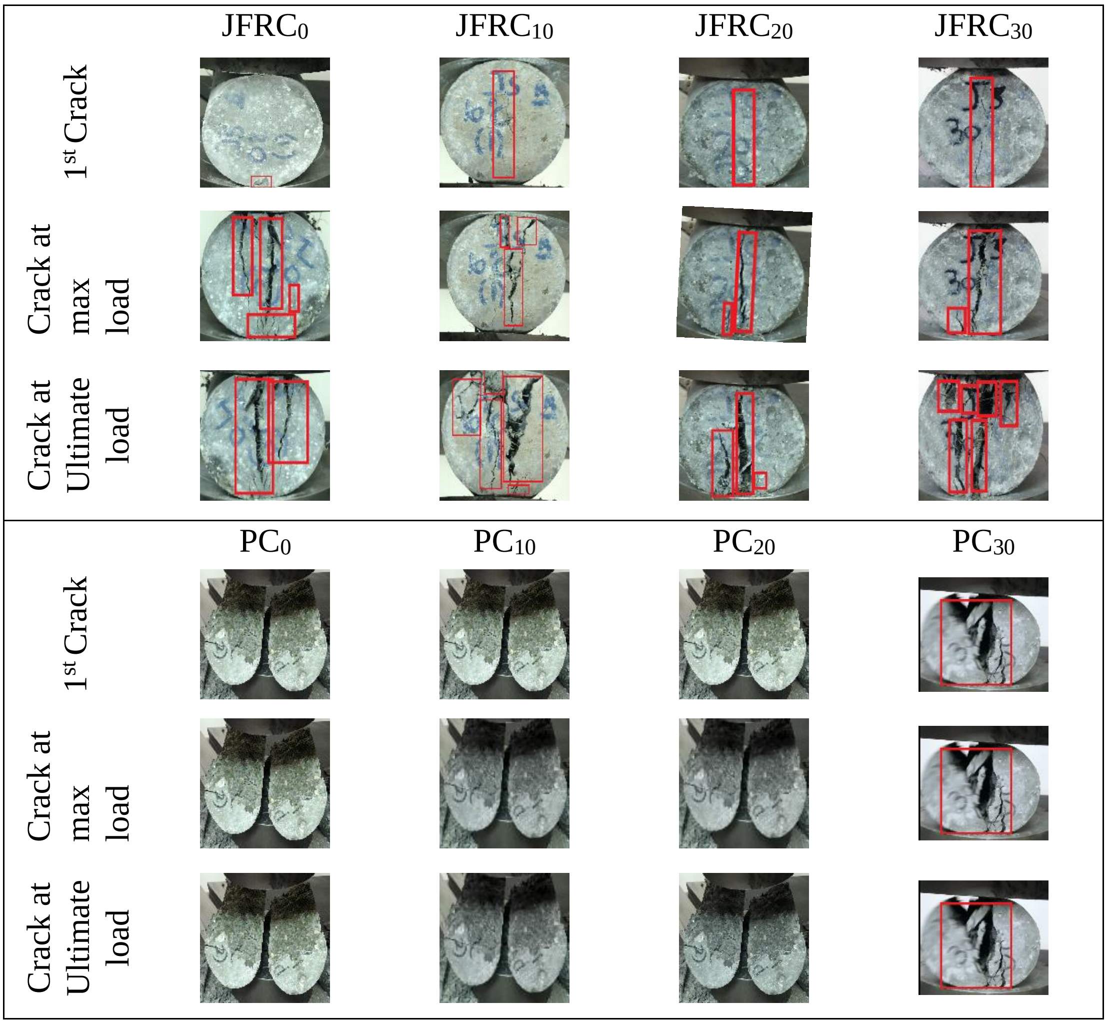


FIGURE A.1: Compressive behaviour of JFRC and PC after 10, 20, and 30 cycles of freeze-thaw. a) stress strain curve and b) picture of crack propagation during mechanical testing.

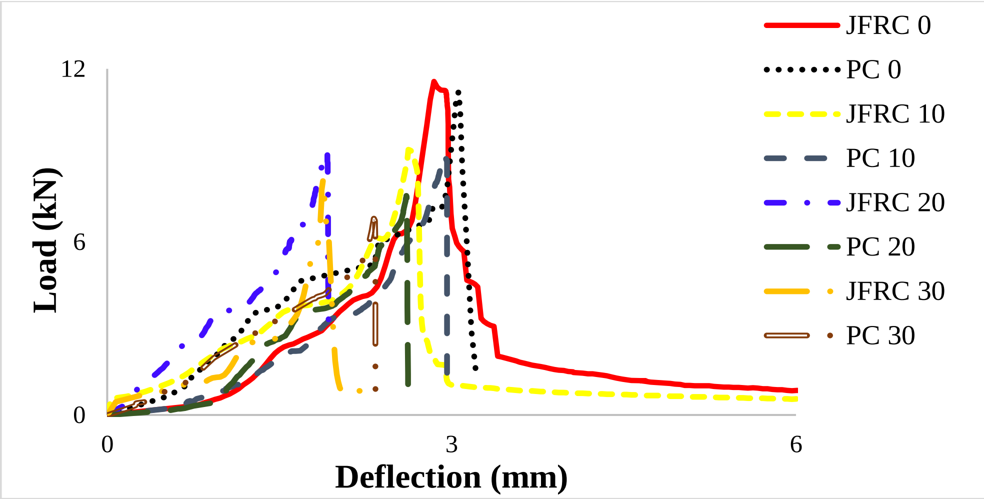


a)

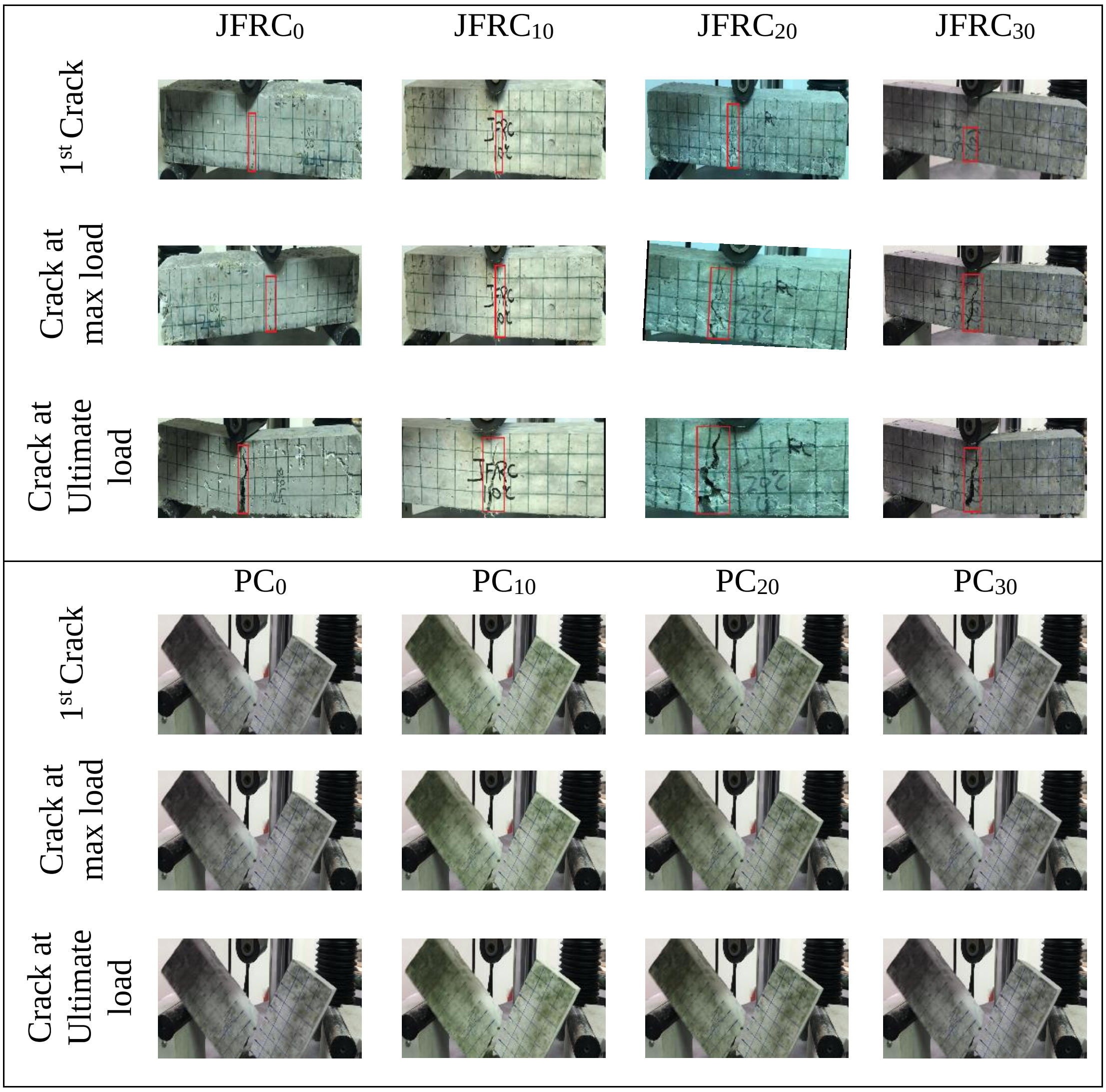


b)

FIGURE A.2: Split-tensile behaviour of JFRC and PC after 10, 20, and 30 cycles of freeze-thaw. a) load deformation curve and b) picture of crack propagation during mechanical testing.



a)



b)

FIGURE A.3: Flexural behaviour of JFRC and PC after 10, 20, and 30 cycles of freeze-thaw. a) load deflection curve and b) picture of crack propagation during mechanical testing.