CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Properties of Sustainable Concrete having Banana Fiber and Banana Leaf Ash for Enhanced Performance of Rigid Pavement

by

Minhas Shah

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in the

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This thesis is dedicated to:

My Father and Mother

Who supported me in this journey, And who have always been a symbol of

Affection, Happiness, and Bliss.

CERTIFICATE OF APPROVAL

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List of Publications

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Published Journal Article

1. Shah, M. and Ali,M. ”Fresh Properties of Concrete having Banana Leaf Ash and Banana Fibres.” *Sustainable Structures and Materials*, An International Journal 6, no. 1 (2023): 88-95.

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Abstract

Cement concrete pavements have relatively longer life as compared to flexible pavements. However, the use of cement in rigid pavement leads towards issues like shrinkage cracking during the curing phase that propagate towards macro-cracks. The appearance of cracks on the surface of pavement leads to deterioration which effects the functionality of the pavement, this deterioration starts at an initial service life of the pavement. Sustainable concrete, which is also known as green concrete, is a type of concrete that is produced using environmentally friendly materials and has a minimal impact on the surrounding environment. Fibers like; banana fiber, have the potential to enhance the concrete performance in regard to tensile strength and toughness while banana leaf ash increases the strength in compression concrete. The overall goal of the research program is to develop rigid pavements, that are more economical and have better structural performance as compared to conventional rigid pavements, using the available agricultural waste specifically banana leaf ash and banana fibers.

This specific study is being carried out to evaluate the mechanical properties and water absorption properties of concrete having banana leaf ash and banana fiber. The obtained mechanical values are then used as input for the mechanistic-empirical design of rigid pavement to evaluate the performance of the pavement designed using this new sustainable material. Hence it is important to find the mechanical properties of the concrete having banana fiber and banana leaf ash. 24 samples in total are cast, and a total of four batches of concrete are cast with each batch comprising 3 cylinders for compression testing, and 3 cylinders for split tensile testing. The first batch includes the PC samples which are used as reference samples and batches two, three, and four include concrete having fiber contents of 1%, 1.5%, and 2.5%, respectively. Each of these later discussed batches also contains 10 percent banana leaf which is used as a partial replacement for cement. The length of the fibers used is 50mm. Using the properties of the concrete mixes, rigid pavement is designed using the AASHTOWare MEPD software which predicts the performance of the pavements.

The addition of fibers of banana and partial replacement of cement with banana leaf ash shows that the compressive strength decreases 8%, 9%, 22% for C1, C2 and C3, respectively. However, the splitting tensile strength increases. The increase in strength in splitting tensile as compared to conventional concrete is 4%, 12%, 22% for C1, C2 and C3, respectively. Performance analysis using the AASHTOWare MEPD shows that, rigid pavement designed using C1, C2 and C3 concrete results in a better performing pavement, specifically C3. The failure against faulting for PC, C1, C2, and C3 pavements is predicted to be 24, 25, 27 and 28 years. Similarly, against IRI the failure prediction by MEPD is 34, 35, 37.5, and 40 years for PC, C1, C2 and C3, respectively.

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Abbreviations and Symbols

A	Aggregate
BF	Banana fiber
BFC	Banana fiber concrete
BLA	Banana leaf ash
C	Cement
C1	Concrete having 1% Banana fiber and 10% Banana leaf ash
C2	Concrete having 1.5% Banana fiber and 10% Banana leaf ash
C3	Concrete having 2.5% Banana fiber and 10% Banana leaf ash
CEF	Compressive energy absorbed after peak load
CEP	Compressive energy absorbed up to peak load
CET	Total compressive energy absorbed
CTI	Compressive toughness index
DEM	Dynamic modulus of elasticity
DMR	Dynamic Mmodulus of rigidity
Em	Energy-absorption up to maximum load
FEF	Flexural energy absorbed after peak load
FEP	Flexural energy absorbed up to peak load
FET	Total flexural energy absorbed
fl	Longitudinal frequency
fr	Torsional frequency
FRC	Fiber reinforced concrete
FS	Flexural strength
FTI	Flexural toughness index
ft	Transverse frequency

Hz	Hertz
JPCP	Jointed plain cement pavement
JWSRCP	Jointed wheat straw reinforced cement pavement
kg	kilogram
KN	kilo newton
MEPD	Mechanistic empirical pavement design
mm	millimeter
MoR	Modulus of rupture
MPa	Mega Pascal
NFRC	Natural fiber reinforced concrete
PC	Plain concrete
PRC	Plain reinforced concrete
S	Sand
s	Second
SC	Strength in Compression
SHTM	Servo-hydraulic testing machine
SP	Superplasticizer
STEP	Splitting tensile energy absorbed up to peak load
STS	Splitting tensile strength
TE	Total energy absorbed
TSTE	Total splitting tensile energy absorbed
TTI	Total toughness Index
w/c	Water-cement ratio
δ	Stress
m^3	Cubic meter
Δ	Delta
ξ	Damping ratio
P_{max}	Maximum load

Chapter 1

Introduction

1.1 Background

Rigid pavements are considered effective for heavy traffic vehicles, but the construction cost is very high. Moreover, the failures occurring on rigid pavement due to excessive loading are also an issue that needs consideration. Therefore, it is necessary to devise a method that will reduce material usage for rigid pavement construction. Sustainable concrete, or green concrete, is an eco-friendly building material created with environmentally conscious materials that have minimal impact on the environment [1–3]. Modern research is focused on the usage of cheap waste material in concrete to increase the performance of concrete. The beam or slab action of rigid pavements, under the application of vehicular load, makes it experience compressive and tensile stresses above and below the neutral axis, respectively. The use of banana leaf ash as a partial replacement for cement increases the compressive strength of concrete [4]. On the other hand, fibers in concrete increase the strength in tension of concrete by providing an anchoring effect [5]. According to the literature, almost 40 percent of the cracking appears on the surface of concrete structures before the concrete actually enters the solid state and of this 40 percent 80 percent is shrinkage cracking. Common concrete flaws include the lower mechanical properties, and high cost of construction. Lower mechanical properties lead towards distresses in the pavement but with the use of wastes like fibers and other materials in concrete the cost and distresses can be reduced with increased mechanical properties.

The values of modulus of elasticity and modulus of rupture is associated with the performance of the pavement, and increasing these properties results in a better performing pavement. Increasing the compressive strength can help in better performing pavements and modulus of rupture can be calculated using tensile strength. Kanning et al. [6] studied the compressive strength of PC and lime-based mixtures of banana leaf ash. It was found that banana leaf ash meets the requirements i.e. if the grinding time is for 30 minutes duration. These requirements include pozzolanic reactivity and uniform particle size distribution. These are met when grinding time is 30 minutes as per [4]. Another study on BLA revealed that using BLA 10-20 percent gives a higher value of compressive strength than the ordinary reference samples. Concrete samples with 10 percent BLA gave a compressive strength of 25 percent higher and samples with 20 percent BLA showed 40 percent higher compressive strength as compared to samples with 0 percent BLA content [7]. For pavement application, BLA concrete is a potential material that can help in developing sustainable rigid pavements, but there is also a need to increase the tensile strength of the concrete. It is evident that the use of BLA in concrete is very limited and the use of natural fibers with BLA needs to be studied to investigate the mechanical properties of this mixture. This scenario shows that the research gap needs to be filled on this topic. It is estimated that almost 4 giga tons of ordinary Portland cement were consumed during the year 2019 in the construction industry, mainly consumed by China, USA, India and Europe. About half of this OPC was consumed by China alone [9]. Using banana leaf ash in concrete increases the strength in compression of concrete hence, enhancing the elastic modulus of concrete. Moreover, using natural fibers in concrete results in an increase in tensile strength and toughness.

Mechanistic-Empirical pavement design is a method used for the evaluation of the pavement performance on the basis of the physical behaviour of the material and the empirical observations i.e. data from real world pavement performance.

MEPD takes into account climatic conditions, traffic loads, and pavement materials. This software can be used for assessing the performance of pavements designed using the properties of modern modified materials. A number of research is available on the usage of the MEPD approach. This approach has been used with the objective to evaluate the performance of rigid pavement concrete having different materials like fibers for the development of sustainable pavements. The aim of this research is to assess the influence of natural fibers and banana leaf ash on the mechanical and micro-structural properties of concrete for optimizing the structural performance of rigid pavements. The use of BLA also promotes the use of agricultural waste having low cost and having the capability to be used as the material of construction ultimately pushing the industry towards sustainability as the cement takes 10-15 percent volume of the concrete, making it one of the most widely used materials for construction [8]. The performance of the pavement can be analyzed for different sustainable concretes using the MEPD software which takes into account the IRI, faulting and the slab cracking.

1.2 Research Motivation and Problem Statement

Concrete roads are usually constructed to bear loads of heavy vehicles like trucks, busses, and trollies etc. However, these roads experience cracks from the very first day and serve for a design life of 25 years. It is important to mention that using fibers in concrete can delay the crack initiation as well as bridging the crack upon generation. The combined use of both (i.e. ash and fibers) is likely to have improved composite properties for better performance of concrete road. In addition, the partial replacement of cement with waste is a sustainable approach with less cost e.g. per 50 kg bag of cement costs Rs.1100/- whereas 50 kg binder (i.e. 45 kg cement and 5 kg waste ash) costs around Rs.1015/-. One can imagine the reduction in cost on a larger scale.:

To increase the performance of concrete pavements along with the promotion of sustainable materials, the construction industry is continuously seeking innovative solutions. In this context, sustainable materials like ashes and natural fibers *present an intriguing opportunity. However, there is a significant gap in research and practical application regarding the use of banana fibers and banana leaf ash in concrete for improving performance of rigid pavements.*

1.2.1 Research Questions

Following are research questions which are explored in this study:

- What is the effect of banana leaf ash and banana fiber on the dynamic properties of concrete?
- What is the combined effect of banana leaf ash and banana fiber on the mechanical properties of concrete?
- What is the effect of banana fibers and banana leaf ash on the water absorption property?
- What does the SEM imaging reveal about the behavior of the fibers in the fractured surface?
- How much of the pavement life increases or decreases against IRI and faulting, if the performance is evaluated using the properties of the sustainable concrete having banana fibers and banana leaf ash?

1.3 Overall Goal of the Research Program and Specific Aim of this MS Thesis

The overall goal of the research program is to develop new concrete having waste with no or minimum compromise on its properties for structural application.

The specific aims of this MS thesis are to experimentally study the effect of different proportions of banana fibers on concrete having constant banana leaf ash, and to predict the performance of rigid pavement using software.

1.4 Scope of Work and Study Limitations

The mechanical, dynamic and water absorption properties are determined for plain cement concrete and sustainable concrete having banana fiber and banana leaf ash concrete. SEM imaging is also carried out to observe the behavior of banana fibers at fractured surface. The relevant properties from mechanical testing are then first used for the design of rigid pavement and then for predicting performance using software.

The study is limited to determination of mechanical, dynamic, and water absorption properties of sustainable concrete having three fiber contents, having constant length, with fixed content of banana leaf ash. Physical validation is outside the scope of current research work. Abrasion test and freeze and thaw impact are out of the scope of this study as the main focus of the study is to find the mechanical, dynamic, and water absorption properties Only IRI and faulting are considered as performance indicators. The geographic scope of the study is limited. The optimized sustainable concrete tends towards homogeneity that is why homogenous layer is assumed in software.

1.4.1 Rationale behind Variable Selection

Banana leaf ash is selected based on its pozzolanic nature, potential to increase compressive strength and easy availability. On the other hand, fibers are selected on the basis of their property to oppose the crack formation and propagation with the enhancement of mechanical properties. Moreover, addition of both of these materials reduce the content of cement. 10% partial replacement of cement with banana leaf ash is selected based on optimization for improved mechanical properties by Tavares et al. [3]. 50 mm length of banana fibers is used for better performance as recommended by Akinyemi and Dai, [63]. Huang design example is used for comparison of design thickness and pavement performance as this example is a well-established reference in the field of pavement design [48].IRI and faulting are selected as the pavement performance indicators in current work because these provide valuable information regarding the ride quality and presence of distresses on the rigid pavement as indicated by [92].

1.5 Novelty of Work, Research Significance and Practical Implementation

To the best of the author's knowledge, there is a need to understand the properties of concrete that contains both banana leaf ash as partial replacement of cement and discrete reinforcement composed of banana fiber. At the same time, the main focus of this study is on the effects of different banana fiber percentages and constant partial cement substitution with banana leaf ash on concrete characteristics. Furthermore, AASHTOWare software is used to predict field performance, which includes IRI and faulting, in order to potentially apply the sustainable concrete under investigation to rigid pavement.

In the event that this research yields positive outcomes, the materials under investigation will help in the production of concrete that has enhanced properties as compared to conventional concrete, and its usage for pavement application can result in the reduction of cement usage for construction purpose with better performance. The abundant availability of banana leaves and the easy extraction of banana fiber, with their ability to enhance the mechanical properties of concrete, makes it a very good material to be used in the construction industry.

This research is a step forward for developing sustainable rigid pavements that will have better performance as compared to the conventional rigid pavement. These pavements will be containing lesser cement because of incorporation of banana leaf ash and banana fiber hence reducing the cost of construction and rehabilitation.

1.6 Brief Methodology

This experimental study consists of determination of mechanical, dynamic properties, water absorption, SEM imaging and pavement performance evaluation. The mechanical properties include compression testing and split tensile testing of the concrete. For each type of mechanical testing, three samples have been cast for each batch of concrete respectively. Three batches of concrete samples having banana fiber content 1, 1.5, and 2.5% are cast, each of these batches also contains 10 percent partial replacement of cement with banana leaf ash. The fiber length used is 50mm. Dynamic testing is performed on the concrete samples to find the damping ratio of the concrete along with the determination of the dynamic modulus of rigidity, dynamic modulus of elasticity, and the dynamic poisson's ratio. Water absorption testing include the testing of the cured concrete samples to check the potential of water absorption of the concrete. SEM imaging of the broken samples will be carried out to study the effect of fiber in concrete along with the effect of banana leaf ash in the enhancement of the properties of concrete. On the basis of the results acquired from the mechanical testing, pavement performance analysis is performed using the AASHTOWare ME pavement design software to assess the performance of the rigid pavement under different climatic and loading conditions. This performance is then compared with the performance of existing rigid pavement, constructed using conventional concrete, by using the design parameters in ME design software.

1.7 Thesis Outline

There are five chapters in this thesis, which are listed below:

Chapter 1: Chapter 1 is the introduction. This chapter explains the background about the thesis research, the motivation behind the research, the problem statement,research program's overall goal and the specific aim of the MS thesis, the scope of work, study limitations, methodology for the research and the outline of the thesis.

Chapter 2: Chapter 2 consists of the review of literature regarding the problems associated with rigid pavements, remedial measures for these flaws and their contribution towards pavement performance, properties of sustainable concrete having natural fibers and properties of sustainable concrete having natural ash, and development and performance of rigid pavements using sustainable concrete.

Chapter 3: Chapter 3 consists of the methodology regarding the specimen's testing. It covers the background, raw materials used, and treatment of the banana fiber. The mixing and casting procedure, details regarding the specimen, and methodology for testing of PC and concrete having banana fiber and banana leaf ash. At the end of the chapter the summary of chapter 3 has been included.

Chapter 4: Chapter 4 includes the results obtained after the testing. Moreover, analysis of the testing results has been mentioned in this chapter. It contains the background regarding the testing, characteristics of the different mixes that is the reference concrete and concrete having banana fiber and banana leaf ash, mechanical properties (SC and SS), dynamic properties, SEM analysis, and water absorption. At the end of the chapter a brief summary has been included.

Chapter 5: Chapter 5 consists of the discussions regarding the optimization of the mixes, pavement performance in terms of IRI and faulting using the mechanistic-empirical design approach. Moreover, the relationship between the banana fibers percentage and the performance of the pavements has been discussed. At the end of this chapter the whole discussion has been summarized.

Chapter 6: Chapter 6 is composed of the conclusions that are deduced after the analysis of the tests and the pavement performance results. Moreover, recommendations have been provided based on the conclusions. Chapter 6 is succeeded by references.

Chapter 2

Literature Review

2.1 Background

Due to the high load-carrying capacity rigid pavements are preferred over asphalt pavements. However, because of the high cost of construction and the distresses that appear on the rigid pavement like shrinkage cracking and bottom-up cracking these pavements are only constructed for heavy vehicular traffic. Enhancing the concrete's mechanical properties can help in the reduction of the crack generation probability. A simple method of doing this is to use additional materials in concrete that can result in the performance enhancement. Therefore, cutting down the overall cost of the concrete pavement by reducing the time of maintenance period. Currently, natural ashes are being investigated for their usage in concrete and results show enhanced strength properties by partial replacement of cement. This also helps in the reduction of usage of cement while usage of fibers help in stopping the initiation of cracks and enhanced mechanical properties, ultimately leading to cost saving.

There is a growing need for usage of these materials considering the cheap price and easy availability. Pakistan has an abundance of natural fibers specifically banana fibers. Separate studies are available on the use of banana fibers and banana leaf ash in concrete but no study comprising of both materials has yet been conducted. Therefore, thorough understanding of mechanical properties, and linear shrinkage behavior of banana fibers and banana leaf ash used in concrete is important, for using it in cement concrete roads. Figure 2.1 shows the schematic diagram of the literature carried out in this chapter. The literature has been divided into three main aspects converging from the material related flaws to the performance evaluation using sustainable materials.

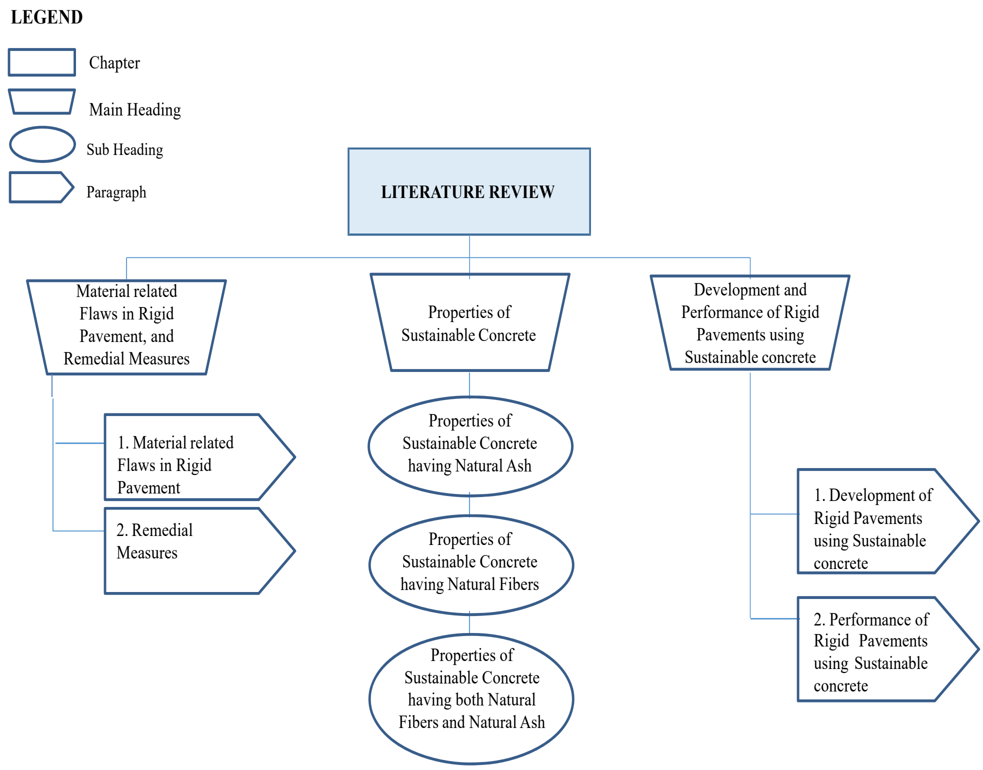


FIGURE 2.1: Schematic Diagram for Systemic Review of Literature

2.2 Material related Flaws in Rigid Pavements, and Remedial Measures

Material related flaws in rigid pavement include macro cracking due to shrinkage cracks, faulting and spalling. Moreover, the expensive nature is also a flaw. Cement concrete is usually used for the construction of Rigid Pavements. Owing to better serviceability the usage of cement concrete pavements has grown to a greater extent over the past few years in developing countries [7]. Because of its potential to bear heavy vehicles and prolonged life, it is widely used, but this type of pavement is expensive in comparison with the flexible pavement.The curing phase of concrete shrinkage and cracks appear due to multiple reasons ranging from temperature variation to humidity variation. These shrinkage cracks once generated, can lead towards cracking and compromises the durability of the pavement [31]. Shrinkage cracking in concrete in the early phase leads towards cracking issues hence reducing the durability of the pavement [82]. Figure 2.2 shows the shrinkage cracks at different stages from the initiation to the fracture of the pavement due to the increase in the crack width over time. The risk of

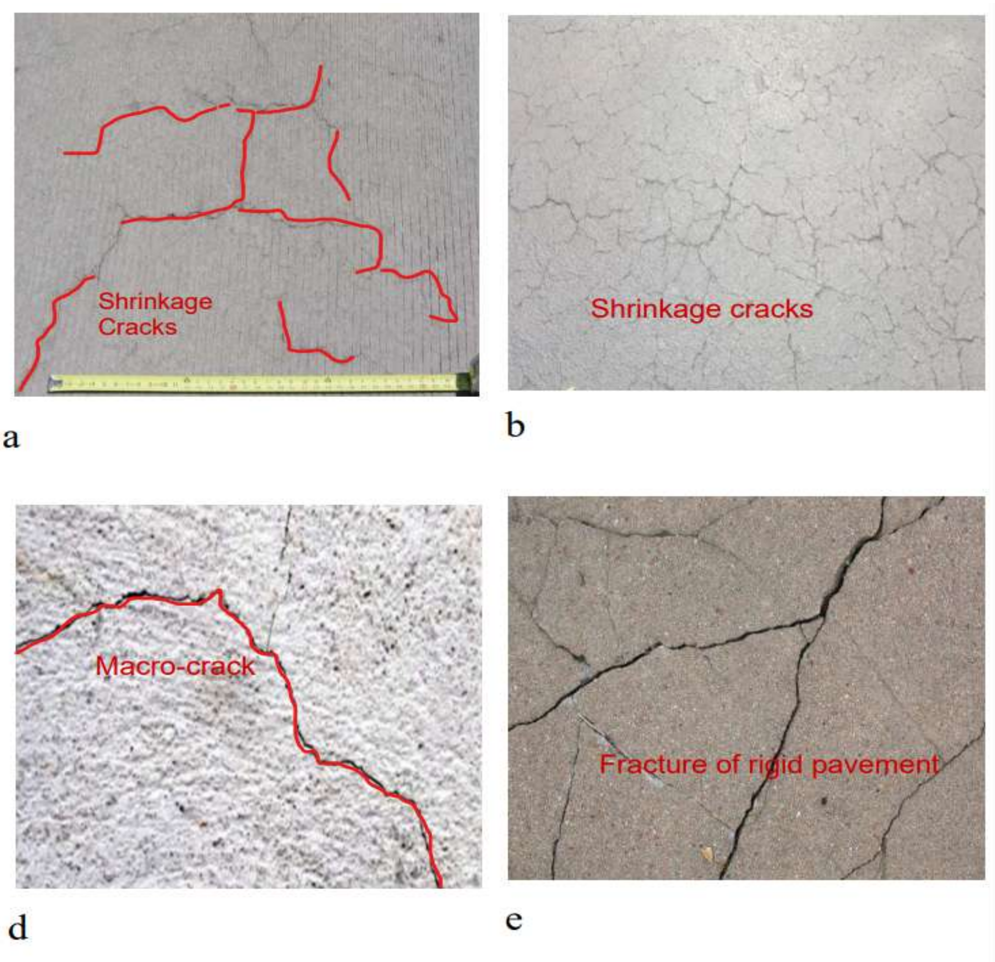


FIGURE 2.2: Shrinkage Cracks on Pavement. a) Shrinkage Cracking at Initial Stage, b) Shrinkage Cracking at Later Stage c) Macro-cracks , d) Fracture of Rigid Pavement

cracking in concrete is higher when shrinkage cracking takes place and this can lead towards the failure of the pavement [83]. Faulting is another type of flaw because of low tensile strength of concrete which causes curling hence resulting in faulting of rigid pavement [30]. Excessive curling and warping of concrete due to vehicular loading causes faulting in rigid pavements [78]. Thermal stresses on rigid pavement causes warping and curling of rigid pavements due to the low tensile strength of concrete which results in faulting of the pavement [79]. Water absorption in rigid pavements cause spalling of concrete due to the freeze and thaw cycle [84]. Water vapor pressure in concrete at high temperatures causes the spalling of the concrete [85]. Rigid pavements experience shrinkage cracking ultimately resulting in cracking, faulting due to the curling and warping of concrete, and spalling due to the absorbed water. All of these flaws lead towards the roughness issue hence compromising the riding quality of the pavement.

The remedial measures for avoiding the type of material related flaws include using different types of materials in concrete. Fiber reinforced concrete has gained much attention in the recent times due to its high tensile strength capacity which leads towards lesser linear shrinkage hence decreasing the chances cracking in rigid pavements [77]. When fibers are used in concrete, shrinkage cracks can be controlled to some extent because of the anchoring nature of fibers of concrete [86]. Vehicular load is transferred to the lower and upper surface of cracks which leads to the reduction of stress concentration at the tip of the crack. Hence, restricting the crack propagation gives the concrete ability to withstand the loads [13]. Usage of natural fibers in concrete result in the reduction of shrinkage cracks[8]. Addition of cellulose fibers in concrete result in reduction of formation of shrinkage cracks due to the enhancement of tensile strength [87]. Rambabu et al [34] performed an experimental investigation on the usage industrial waste like fly ash, rice husk ash and blast furnace slag for the production of sustainable concrete. It was concluded from the study that adding these materials to concrete increases the resistance to shrinkage cracking, adds to the durability and increases the resistance to abrasion. Fibers incorporated in concrete also increase the mechanical strength of concrete [9] which can result in higher resistance to curling and warping of concrete hence decreasing the faulting of pavement. Using glass fibers to enhance the mechanical strength can reduce the chances of faulting in concrete pavements [88]. Spalling in rigid pavements can be reduced using basalt fibers which give the bridging effect and resist the formation of micro cracks developed by the pore pressure [80]. Fibers used in concrete have a positive effect on spalling of concrete [81]. To avoid problems like shrinkage cracking, faulting and spalling different fibers can be used. These fibers and ashes can enhance the properties of the concrete and ultimately reduce the chances of formation of the above mentioned flaws.

2.3 Properties of Sustainable Concrete

Sustainable concrete, also referred as green concrete [1–3], is concrete that has been made using eco-friendly materials and have minimal impact on environment. An extensive research is available on the usage of natural ash in concrete for the enhancement of mechanical properties mainly the compressive strength. Moreover, natural ash can partially replace cement and reduce the cost as well as increase the compressive strength due to the pozzolanic nature of ash. The fine nature of ash makes is a very fit material to be used in concrete as a replacement of cement. On the other hand natural and artificial fibers have become a main focus for enhancement of properties of concrete. The anchoring effect of discrete fibers and the improved toughness they offer make them a suitable material to be used in concrete. Artificial fibers usually offer better performance but these fibers are expensive. On the other hand natural fibers are cheap and are easily available due to their use in agricultural industry.

2.3.1 Properties of Sustainable Concrete having Natural Ash

Concrete having waste materials has acquired a significant amount of attention with the advancement in the sustainable concrete technology. In the industry of construction the use of fly ash, bagasse ash, husk ash of rice and banana leaf ash has gained significant amount of attention [14]. Issues regarding the production of cement like fossil fuel consumption can be resolved by using ashes of agricultural waste from power plants that use biomass. The nature of these ashes is cementitious therefore these can be used as partial replacement to cement [15].

Byproducts of agricultural industries like corncob, rice husk ash, banana leaf ash, and sugarcane bagasse ash can be utilized as additive material because of the

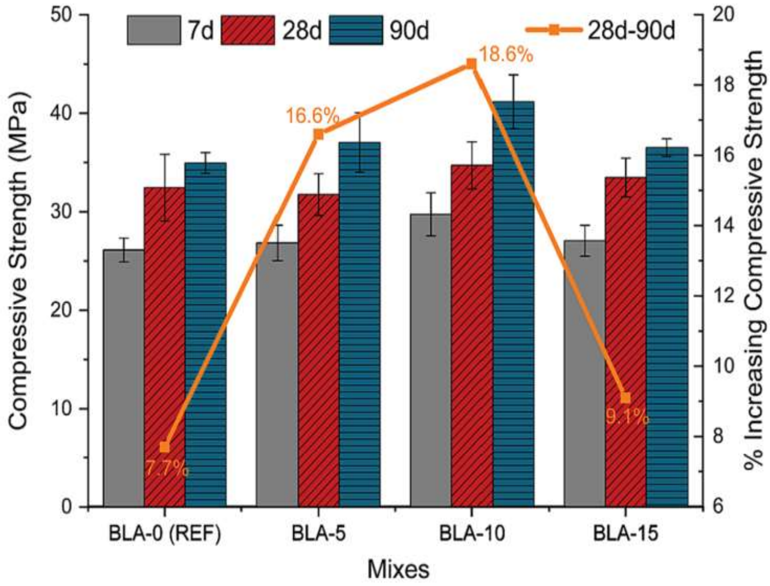


Figure 2.3: Compressive Strength of Banana Leaf Ash Concrete at 7, 28, 90 days [4]

pozzolanic nature of these ashes. Natural ashes usually contain calcium oxide (CaO), silicon oxide (SiO2), the presence of silicon oxide is very significant because of its potential to form the additional calcium silicate hydrate (C-S-H) by reacting with the calcium hydroxide that is formed during the hydration of cement which results in the formation of additional calcium silicate hydrate (C-S-H) [50] which results in the enhancement of mechanical properties of concrete. Natural ashes have tendency to increase the mechanical properties of concrete due to its composition.

Using banana leaf ash in concrete as partial replacement is an emerging research in modern times and its preparation is a significant part. 10 % banana leaf ash partially replaced with cement yielded in a higher strength in compression, this ash is prepared by heating banana leaves in furnace at a temperature of 900 degree Celsius to burn the inorganic substance and then it is ground in ball mill to obtain fine ash having a fineness of 593.3 m2/kg, which will have more surface area hence enhanced reactivity [4]. The pozzolanic nature and the filler effect of banana leaf ash along with the capacity of absorbing lesser water makes it worth for enhancing the strength in compression of concrete. Moreover, mechanical testing revealed better performance of sample with ash as partial replacement than PCC [8].Using banana leaf ash in concrete as a binder demonstrated strength of 7.9 MPa [10]. The application of BLA can enhance the properties up to some extent however, the use of natural fibers along with BLA can help stop the initiation of shrinkage cracks. Figure 2.3 shows the relationship between the compressive strength and the mix proportion of the banana leaf ash at different curing time duration. It can be seen in the figure that the maximum compressive strength achieved is 10 MPa more than that of reference sample after 90 days of curing. With the increased curing more strength can be observed for all other mixes. 10 percent of banana leaf ash, used as partial replacement of cement, gives the optimum compressive strength.

Natural ashes other than BLA also have tenancy to be used as partial replacement to cement. Tahir et al. [35] conducted a review of the literature on the usage of industrial based geo-polymers like the alkali activated fly ash. It has been concluded that fly ash can be used as a partial replacement of cement and using fly ash can enhance the compressive strength of concrete. Abbass and Singh [36] used fly ash based geo-polymer in concrete by using an alkali activator and basalt fibers, at the end of the experimental study it was found that using 10 percent fly

Table 2.1: Properties of Banana Leaf Ash [1]

CaO	**Al2O3**	**SiO2**	**MgO**	**Fe2O3**	**K2O**	**Na2O**	**P2O5**	**Others**
23.6	2.14	54.9	5.5	1.18	5.3	1.3	1.80	0.44

ash enhances the durability of the concrete and also the water absorption hence making it suitable for rigid pavement construction purpose. Mildawati et al. [37] conducted a study to find the mechanical performance of concrete having corn stalks ash. The experimental program included using corn stalks ash as different percentages and it was found that using 7 percent of this ash can increase the compressive strength of concrete up to 15 percent with no significant effect on the flexural strength of concrete. Trincal et al. [38] performed an extensive study to develop different strategies to reduce the shrinkage caused by the use of fly ash based geo-polymer and it has been suggested in the study that using fly ash based concrete decreases the durability of concrete but incorporation of admixtures or discrete fibers can reduce the probability of shrinkage up to 35 percent. Schrfl et al. [39] performed an experimental study to investigate the relationship between the absorption kinetics and retention for this reason the roller compacted fly ash concrete was also considered and it was found that the performance of this concrete against freeze and thaw was significant. Along with BLA, other ashes also has potency to increase the compressive strength but BLA is easily available as compared to other ashes.

The composition of BLA can help in deciding the effectiveness of it to be used as partial replacement of cement. Table 2.1 shows the properties of banana leaf ash. Banana leaf ash is basically the composition of calcium oxide (CaO), Silicon Oxide (SiO2) and it is classified as class F pozzolanic material [10]. Class F pozzolanic materials are typically high-calcium, low-silica materials that react with calcium hydroxide (Ca(OH)2) in the presence of water and form cementitious compounds [4]. These materials are commonly used as supplementary cementitious materials in concrete, and they can improve the durability, strength, and workability of concrete. Class F pozzolanic materials include fly ash, rice husk ash and silica fume. fly ash is a fine powder and it is formed by the burning of pulverized coal in electric power plants [101]. It is the most commonly used pozzolanic material, rice husk ash is a byproduct of rice milling that is produced when rice husks are burned at high temperatures. It is known for its high silica content and ability to improve compressive strength and reduce shrinkage in concrete. Silica fume is a fine powder produced by the combustion of silica or ferrosilicon alloys in electric arc furnaces [95]. The presence of silicon oxide is very significant because of its potential to chemically react with the calcium hydroxide which is produced during the cement hydration which results in the formation of additional calcium silicate hydrate (C-S-H) [50] which results in the enhancement of mechanical properties of concrete. The test used to determine the pozzolanic activity of banana leaf ash is the Chapelle's test [4], which is a test method for measuring the pozzolanic activity of fly ash and other pozzolans [10, 96, 102, 103]. The test involves preparing a cement paste blend of a standard Portland cement and the pozzolan being tested, molding the paste into prisms or cubes, curing them in a moist environment for 28 days, and then testing the samples for compressive strength. The pozzolanic activity index (PAI) of the material is then calculated based on the compressive strength of the test sample compared to a control sample containing only Portland cement. Hence, the composition of BLA is such that it has tendency to be used as partial replacement to cement and this can be verified by the PAI of the ash. PAI is determined using the Chapelle's test. Moreover, banana leaf ash has the potential to enhance the compressive strength by 10 % with 28 days of curing with optimum dosage.

2.3.2 Properties of Sustainable Concrete having Natural Fibers

It is a common practice in rural areas to use natural fibers for construction purposes. Natural fibers are not only used in concrete but also with soils to increase the stability due to the anchoring effect. These fibers are cheap in nature and are easily available. Jute fiber incorporated in concrete results in enhanced economy and effectiveness of concrete [16]. Jute fiber also increases the tensile toughness of the concrete having these fibers [17]. Bamboo fiber is effective in preventing the initiation and propagation of cracks in concrete [18]. Bamboo fiber also increases the thermal properties of concrete [19].Comparison of concrete having coir fiber with reference concrete shows an enhanced splitting tensile strength and compressive strength [20].Using natural fibers in concrete like bamboo, coir and jute fiber is an effective way of increasing concrete properties.

Banana fiber, due to its superior properties has also been used in concrete. Incorporation of banana fiber in concrete results in enhanced mechanical properties [21]. Usage of banana fiber in concrete for enhancing the mechanical properties is a sustainable way [22]. Extraction of natural fibers is usually done from plants and trees and these are environmentally safe. Using these natural fibers in concrete result in an enhanced flexural and tensile strength [23]. Workability of the concrete reduces

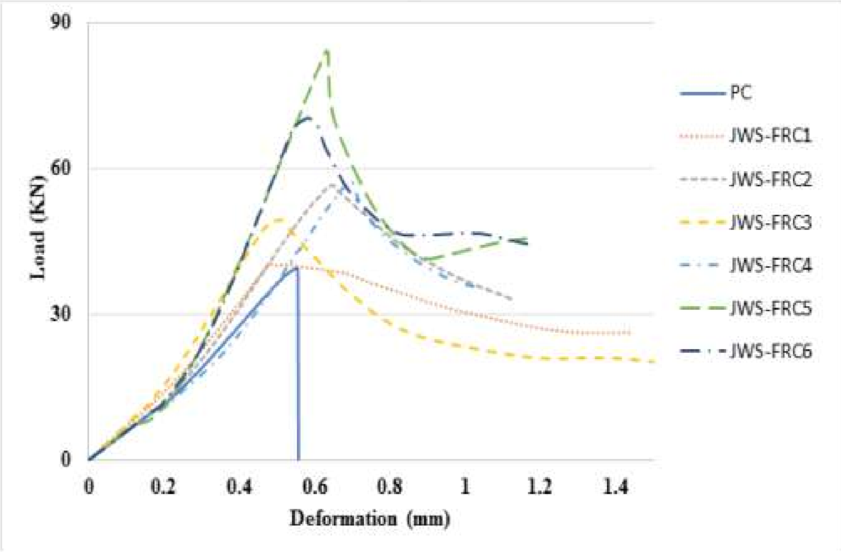


Figure 2.4: Load Deformation Curve for Concrete having Hybrid Fibers [106]

concrete reduces when these fibers are incorporated in concrete. The Lignocellulose nature of the natural fiber increases water absorption resulting in a decreased workability [24]. Increasing the content of banana fibers in concrete increases the tensile strength and impact resistance of concrete [25]. Harki et al. [40] has stated that rigid pavements have high compressive strength and low modulus of rupture that is why thick slabs are constructed. As per the study adding hybrid steel fibers can increase the compressive strength and also modulus of rupture of concrete hence making it possible to reduce the overall thickness of the rigid pavement. Using natural fibers in concrete increases the mechanical properties of concrete due to the anchoring effect. However, using low density fibers decreases the compressive strength of the concrete.

Along with single type of natural fibers, a combination of fibers has been also evaluated against mechanical performance. The different properties of different fibers help in the enhancement of the mechanical strength of the concrete. Affan and Ali [41] performed and experimental investigation on the effect of freeze and thaw on concrete having jute fibers for pavement application the study concluded with the results that using jute fiber results in reduced pavement thickness and

Table 2.2: Properties of Banana Fiber as per Literature

Parameter	**Range**	**Reference**
Cellulose (Percentage)	62 - 67	[51], [59], [60]
Moisture (Percentage)	10 - 11	[51], [59]
Elongation at break (Percentage)	4 - 9	[51], [60]
Young's Modulus (GPa)	1.5 - 5	[59], [60]

with the reduced thickness the performance is not compromised. In figure 2.4 the load-deformation curves of plain cement concrete and concrete having hybrid fibers has been shown. The maximum load is taken by JWS-FRC5 and the splitting tensile strength is more in all the fiber reinforced concrete samples due the bridging effect of fibers [106]. Diaz et al. [42] performed a study on polymeric fibers for improving the tenacity of the material. It was concluded that polymeric fiber concrete performs better than conventional concrete for pavement slabs. Santhosh et al. [43] performed an investigative study on the usage of polypropylene fibers in concrete for the fatigue performance evaluation of the concrete. Almost 50-90 percent of structural failure is due to the fatigue. Fiber reinforced concrete involves fibers that increase the integrity of the concrete. The study concluded that using polypropylene fibers not only increase the mechanical properties but also has a positive effect on the fatigue performance of the concrete. Khan et al. [44] performed an experimental study on the usage of silica fume with coconut fiber for its application in rigid pavement. It was concluded at the end of the study that using these materials reduces the overall thickness of rigid pavement up to 8 percent. Rashid et al. [45] carried out an experimental investigation on the use of steel fibers and polypropylene fibers in concrete for the enhancing the durability and it was found out that fiber reinforced concrete is more resistant to long term weathering action as compared to conventional concrete. Ali et al. [46] performed and extensive review on the usage of coir fiber in concrete and compared it with other types of natural fibers. The study concluded that pine apple fiber shows the best performance after banana fiber in terms of compressive strength. Moreover, the toughness increases significantly after the incorporation of fibers in concrete. Natural fibers increase the tensile strength and the energy absorption capacity of the concrete and out of these banana fiber shows better properties in terms of lesser water absorption and good tensile strength. Table 2.2 shows the properties of banana fiber. Different properties have been shown and their range values have been written based on the literature. Using artificial fibers like steel fibers also increase the compressive strength along with other properties but due to their expensive nature they are not considered sustainable. Moreover, the combined use of different natural fibers also increases the mechanical properties of concrete.

2.3.3 Properties of Sustainable Concrete having both Natural Fibers and Natural Ash

Using fiber in concrete increases the tensile strength of concrete and decreases the compressive strength and using natural ash in concrete increases the compressive strength of concrete. Hence it is important to discuss the addition of both of these materials in concrete and the behavior concrete exhibits after the addition of these materials. Akid et al. [52] conducted an experimental study on the usage of polypropylene fiber and fly ash in concrete for enhancing the mechanical properties of the concrete. Fly ash was used as partial replacement of cement in proportions 15 percent and 30 percent. On the other hand three different proportions of the polypropylene fiber was used. It was concluded that using 15 percent of fly ash and 0.12 percent of polypropylene increases the compressive strength of the concrete along with the enhancement of the durability of concrete. Jain et al. [53] used waste plastic bag fiber and fly ash in concrete. Addition of waste plastic bag fiber in concrete increased the split tensile strength of concrete with a reduction of compressive strength and fly ash increased the compressive strength of concrete. The combined usage of both waste plastic bag fiber and fly ash enhanced the durability and mechanical properties of concrete. Using natural fibers and natural ash in concrete helps in increasing the mechanical properties of concrete. Concrete having banana leaf ash leads to increase in the compressive strength[1, 9, 10] on the other hand concrete having banana fiber leads to increase in splitting tensile strength [21–23]. Considering the property of natural fiber to increase the tensile strength and energy absorption capacity and the property of natural ash to increase the compressive strength of concrete, a combination of both of these materials can have impact on the overall properties of concrete.

2.4 Development and Performance of Rigid Pavements using Sustainable Concrete

The development of sustainable pavements is a need of this era. Sustainable pavements can be constructed using sustainable concrete and in order to validate the results modern tools can be used. The incorporation of fibers in concrete reduces the content of other materials. Moreover, banana leaf ash can be used as a partial replacement for cement, this results in the reduction of CO2 emissions by reducing the amount of cement and incorporating waste agricultural material [1]. Using natural fibers results in enhanced mechanical properties[22]. Similarly, the usage of banana ash will result in a higher modulus of elasticity. This increase in the modulus of elasticity, when incorporated into the cement concrete pavement design equation, will result in a lesser thickness of the pavement or a better performance with the same thickness. Use of sustainable materials in concrete pavements will result in sustainable pavements as the cost of the pavement will be reduced. Moreover, the global warming potential of rigid pavement is 21 percent higher than for flexible pavement [26].Reducing the material consumption for cement concrete pavement will also help in reducing the global warming potential.

Reduced pavement thickness can be achieved using natural fibers in concrete. Using wheat straw in concrete for the construction of rigid pavement results in 7 percent lesser design thickness as compared to conventional concrete pavements [27]. For the design of rigid pavement as per AASHTO, equation 2.1 i.e. the

$$log_{10}W_{10} = Z_R S_o + 7.35\ log_{10}(D+1) - 0.06 + \frac{log_{10}\left[\frac{\triangle PSI}{4.5-1.5}\right]}{1+\frac{1.624\times10^7}{(D+1)^{8.46}}} + (4.22-0.32Pt)\left[\frac{S'_c C_d\left[D^{0.75}-1.132\right]}{215.63j\left[D^{0.75}-\frac{18.42}{\left(\frac{Ec}{k}\right)^{0.25}}\right]}\right] \quad (2.1)$$

conventional 1993 empirical equation is used. This is an empirical equation and it has limited accuracy and is limited to experimental data accuracy. However, Farooqi [54] introduced an incremental factor to the modulus of rupture in this

$$log_{10}W_{10} = Z_R S_o + 7.35\ log_{10}(D+1) - 0.06 + \frac{log_{10}\left[\frac{\triangle PSI}{4.5-1.5}\right]}{1+\frac{1.624\times10^7}{(D+1)^{8.46}}} + (4.22-0.32Pt)\left[\frac{s'_{WSRC}\ C_d\left[D^{0.75}-1.132\right]}{215.63j\left[D^{0.75}-\frac{18.42}{\left(\frac{Ec}{k}\right)^{0.25}}\right]}\right] \quad (2.2)$$

equation to account for the tensile strength given by the addition of wheat straw as given in the form of S(wsrc) in equation 2.2. Huang design example parameters have been used by [41, 48] to calculate the design thickness and then compare it with pavement thickness of sustainable concrete. The huang's design example acts as a bench mark for studies considering pavement thickness reduction. Furthermore, it is found that the modulus of rupture plays a governing role as compared to the elastic modulus of concrete. To evaluate the performance of rigid pavement using sustainable materials, mechanistic empirical pavement design approach is considered an accurate method because it considers the response of the pavement against loading and environmental conditions. Moreover, this approach can consider new materials like high performance concrete and fiber reinforced concrete [94]. The use of waste and other easily available materials can be used for the development of rigid pavement and for their design MEPD has superiority over the empirical design approach.

The performance of rigid pavement includes the performance of the pavement under vehicular and environmental loading conditions along with the properties of materials. The pavement response prediction is based on the combination of material data, climatic data and the traffic data that results in the predictive models of IRI and joint faulting and transverse cracking [90]. The pavement structure performance prediction in MEPD is based on the mechanical properties and the load distribution which result in the design indices including faulting and IRI [91]. Pavement cracking, spalling and faulting are functions of International roughness index. equation 2.3 [109] shows the relation between different distresses predicted by the AASHTOWare MEPD software and the International roughness

$$IRI = IRII + 0.013 \cdot CRK + 0.007 \cdot SPALL + 0.005 \cdot TFAULT + 0.4 \cdot C1 \cdot FT \quad (2.1)$$

where: IRI = Predicted IRI, in./mi, IRII = Initial smoothness measured as IRI, in./mi, CRK = Percent slabs with transverse cracks (all severities),
SPALL = Percentage of joints with spalling (medium and high severities),
TFAULT = Total joint faulting cumulated per mi, in., C1 = 0.8203 (constant value),
FT = International Roughness Index (IRI) faulting index, in./mi

index. The prediction of the values like spalling is related with the age of the pavement and the scaling factor which is related to the climatic conditions. Faulting is calculated based on the rainfall frequency and the properties of material [89]. As reduced IRI means the reduction in the formation of the distresses in the rigid pavement. IRI and faulting are the two performance indices given as output by the MEPD which depicts the field performance of the pavement[92]. IRI, faulting and cracking are distresses models given by the MEPD approach for the analysis of the pavement performance [93]. Structural response includes the performance of the pavement against loading and climatic conditions in terms of distresses formed and this response is indirectly related with roughness of pavement in mechanistic-empirical design approach.

Performance of the pavement is a significant factor as the safety of the road users and the durability of the pavement is related with it. A better performing pavement requires lesser amount of repairs. Farooqi [54] constructed the first fiber reinforced concrete and monitored the performance as shown in table 2.3. The results indicated that Jointed Wheat Straw Reinforced Cement Pavement (JWS-RCP) show better performance as compared to Jointed Plain Cement Concrete Pavement (JPCP). Modern methods include modeling of pavement via mechanistic empirical pavement design approach by using sustainable concrete properties, this approach helps in evaluating the performance of pavement in terms of IRI and faulting. Rainfall frequency and tensile strength of concrete have significant impact on the formation of faulting distress and increase in faulting [97]. Roughness is an important performance indicator in pavements and this roughness is related with the environmental factors and the deterioration of the pavement [98]. IRI is a key factor in assessment of the performance of a pavement [99]. Abdalfattah et al. [47] performed an experimental study on the usage of polyethylene for pavement construction and with the help of mechanistic empirical pavement

Table 2.3: Fiber Reinforced Concrete Pavement Performance [54]

Test Section	**Crack Progression**	**28-days**	**6 Mos**	**12 Mos**	**18 Mos**
1	**2**	**3**	**4**	**5**	**6**
[1]**JPCP**	Width Avg(mm)	-	0.11	0.14	0.16
	Length Max (m)	0.08	0.18	0.27	0.33
	Spacing Avg (m)	3.6	2.9	2.1	1.1
	Cluster (no.)	1	5	12	19
	Punch-out (no.)	-	2	4	9
[2]**JWSRCP**	Avg. Width (mm)	-	-	0.09	0.12
	Length Max (m)	0.03	0.08	0.12	0.19
	Spacing Avg (m)	4.6	4.1	3.3	2.1
	Cluster (no.)	-	-	3	6
	Punch-out (no.)	-	-	-	-

[1]JPCP: Jointed Plain Cement Pavement
[2]JWSRCP: Jointed wheat straw reinforced cement pavement

design approach the performance of the pavement was studied. It was concluded that using the mechanistic empirical pavement design approach helps in assessing the performance of new sustainable materials. Khan et al. [48] performed an experimental study on the usage of hair and wave polypropylene fibers in concrete for pavement application, the study concluded with a better performance of pavement. Hasani et al. [49] performed an experimental study on the usage of discrete natural fibers in concrete overlays and through numerical modeling the design of the pavement was optimized with 15 percent reduction in the thickness of the pavement due to the incorporation of the fibers in concrete. . Cho et al. [100] used low cost graphene oxide nano flakes to improve the performance of the pavement and it was concluded at the end of the study that this sustainable concrete results in better performance as compared to conventional pavement. The development of sustainable pavement is possible by using waste materials. Moreover, the validation of the results show that the performance of the pavements designed using these sustainable materials can result in better performance in terms of lesser roughness and faulting.

2.5 Summary

Reducing the potential of crack initiation and crack propagation can result in the enhancement of rigid pavements. This can be done by enhancing the concrete's mechanical properties. The mechanical properties can be enhanced using agricultural waste that includes banana fibers and banana leaf ash. With the enhancement of mechanical properties there is probability of reduction in the thickness of the pavement with improved performance this can prove to be very beneficial in terms of sustainability. In this chapter, the flaws in rigid pavements and their remedial measures, properties of concrete having banana fiber and banana leaf ash and development of sustainable pavements by the incorporation of fibers and banana leaf ash has been briefly reported.

Chapter 3

Experimental Program

3.1 Background

Organic ash, along with the use of natural fibers, have gained significant amount of attention in the concrete research domain because of the enhanced mechanical properties, easy availability, environment friendly nature and extremely low cost. The fiber that has been used in this research is the banana fiber due to its capability to enhance the mechanical properties of concrete and the ash used is banana leaf ash because of the reason that banana ash enhances compressive strength and this ash can be used as partial replacement of cement. As mentioned in the previous chapter it is important to study the behavior of concrete having banana leaf ash and banana fiber to use it in the design of rigid pavement to ensure that this concrete results in a more sustainable pavement. Therefore, the mechanical properties, dynamic properties, water absorption properties, and SEM imaging of concrete having banana leaf ash and banana fiber are considered. This chapter discusses the raw materials used in this research, treatment of banana fibers, the procedure of preparation and casting of plain concrete specimens, and, concrete specimens having banana leaf ash and banana fibers along with the methodology for testing these specimens and using the material properties for the design of rigid pavements using the mechanistic-empirical design approach.

3.2 Raw Materials

The materials used for preparing the reference concrete i.e. PC samples include Portland cement, sand, coarse aggregates. Cement used in this study is ordinary portland cement obtained from a local manufacturer i.e. Askari cement having 61.7% Cao, 21% SiO2, 5.04% Al2O3, 3.24% FE2O3, 2.56% MgO and 1.51% SO3. The maximum size of fine aggregate used was 4.8 mm and the type was quartz sand having a bulk density of 1527 kg/m3. On the other hand the coarse aggregate used was 12.5mm having a bulk density of 1506 kg/m3. Whereas, the preparation of sustainable concrete banana ash isused as partial replacement to cement and banana fiber is used as an addition. Figure 3.1 (a) shows the gradation curve for sand and gravels.

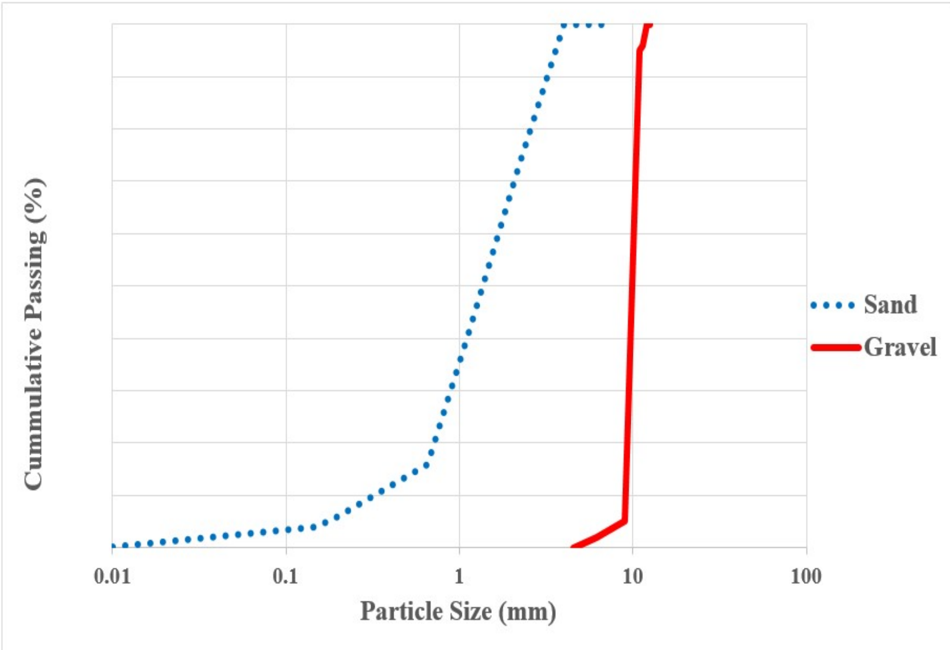
3.2.1 Banana Leaf Ash

Banana leaf ash is obtained from local market and similar procedure, as mentioned in literature, was adopted for the production of banana leaf ash used in this study. The fineness of BLA determined by the Blaine air-permeability apparatus using the ASTM C204 resulted in a fineness value of 586 m2/kg. The resultant ash consisted of crystalline phase as well as amorphous phase. The crystalline phase included calcite and quartz. Furthermore, the amorphousness degree is more than 80 percent for BLA. A value of 7.6 MPa was revealed by the determination of pozzolanic activity index using Chapelles test. As per the vendor the class of banana leaf ash as per ASTM 618-12 is class F and the chemical composition of the used banana leaf ash consists of aluminum oxide, silicon dioxide, iron oxide, calcium oxide and sulfur trioxide.

3.2.2 Banana Fibers

The locally available banana fiber, purchased from a local vendor, is used which is extracted from the banana plant. The percentage of cellulose is usually almost

62 to 67 percent which results in the degradation of the fiber over time hence it is important to treat the fiber before its use to remove the cellulose from the fiber.



a)

b)

Raw Fibers **Treated Fibers**

FIGURE 3.1: Raw Materials a) Gradation Curve b) Raw and Treated Banana Fibers

The elastic modulus of the banana fiber ranges from 1.5 to 5 GPa. However, the elastic modulus of the used banana fiber is 4.3 GPa with a tensile strength of 36 MPa. The density of the fibers used in this study is 788 kg/mm3 as provided by vendor. Researchers have used different methods for enhancing the properties of banana fiber for its usage in concrete. The fact that banana fiber is organic in nature makes it decomposable over time hence it is important to treat the fiber before using it in concrete. The treatment includes both chemical and physical treatment of the fibers. One way of removing the cellulose from the fibers is to soak the fibers in a calcium carbonate solution. The method adopted in this study is first cutting the fibers into the length of 50mm. Fiber cutting is done by combining the fibers together and cutting them in order to avoid variation in the length. Afterwards, the fibers are cleaned by soaking it in water and then soaking the cleaned fibers in a calcium carbonate solution having a concentration of 5 percent by weight. The fibers are soaked in solution for 24 hours and then it is washed using distilled water. Cellulose content reduced to 14% after treatment. The pictorial depiction of raw fiber and treated fiber has been shown in figure 3.1 (b). The treatment of the fiber is important because of the presence of cellulose which results in the degradation of the fiber over time. The water absorption of banana fibers used in this study is 63.5%. Length of 50mm is used on the assumption that theoretically half of the length of the banana fiber will remain embedded in the concrete matrix to resist small-scale cracks if the concrete undergoes ultimate failure.

3.3 Mix Design, Casting Procedure, Fresh Properties and Specimens

For the preparation of the concrete the mix design ratio used is 1:1.3:2.3 (C : S : A) this mix design is based on trial mixes to achieve a compressive strength of 30 MPa. The water cement ratio used is 0.48. The curing was done for 28 days and then water absorption test was carried out. Afterwards, dynamic and mechanical tests were performed. The current research is based on relative, i.e.

the reference specimens of plain concrete are tested under the same conditions as that of concrete having banana leaf ash and banana fibers. In addition strength properties at 60 and 90 days are out of the scope of work. The same mix design and water cement ratio is used for reference concrete as well as the concrete having banana fibers and banana leaf ash. Moreover, a superplasticizer has been used for increasing the workability of the concrete as the water cement ratio is kept very low. In case of sustainable concrete, 10% of cement has been partially replaced with banana leaf ash along with addition of 1%. 1.5%, and 2.5% of banana fiber

TABLE 3.1: Concrete Mixtures Design Proportions (kg/m3)

Sample	**C (kg)**	**S (kg)**	**A (kg)**	**Water Cement ratio**	**SP (%)**	**Banana Leaf Ash (kg)**	**Banana Fiber (kg)**
PC	312.96	432.07	751.19	0.48	1	-	-
C1	281.7	432.07	751.19	0.48	1	31.27	2.81
C2	281.7	432.07	751.19	0.48	1	31.27	4.22
C3	281.7	432.07	751.19	0.48	1	31.27	7.042

in C1, C2 and C3 samples respectively. The fiber content for C1, C2 and C3 is added with respect to cement mass. The length of banana fibers is 50mm. Banana fibers are added by the weight of binder in the concrete. It should be noted here that banana fibers are used as an addition and not a replacement. Table 3.1 shows the proportions of banana fiber, banana leaf ash and water cement ratio in each batch of concrete. Plain concrete is referred as PC while concrete incorporated with banana fiber and banana leaf ash is denoted by C1, C2 and C3.

For the production of both PC and concrete mixes having banana leaf ash and banana fiber, motor powered concrete mixer is used. To prepare the conventional concrete, water and the raw materials are dumped into the concrete mixer and then this mixer is made operational for three minutes. Afterwards, the concrete slump is determined using the slump cone apparatus. Moreover, using the compaction factor test, the compaction factor values are determined. In order to prepare the concrete having banana fibers and banana leaf ash, the material is dumped into the concrete mixer in different parts, specifically in three different parts. One third of the material is dumped into the mixer and the mixer is turned on for the dry mixing of the materials. Once the dry mixing has been achieved one third part of water is added to the mixer. Similarly, other parts of materials and the water is added into the mixer. After dumping each part into the mixer, the mixer is rotated for three minutes. Once the concrete is prepared it is poured into an open tray and workability tests are performed. These include the slump test and the compaction factor test. Once these tests are performed the molds are filled, each mold is filled in three layers with each layer being compacted using the rod by tamping 25 times. The diameter of the tamping rod is 16 mm and for compaction the tamping rod is dropped from a specific height. In case of the concrete having banana fibers and banana leaf ash, the molds are lifted and dropped to achieve proper compaction of the concrete. The drop height is almost 170-230mm which helps in reducing the air voids in the fiber reinforced concrete. Once the molds are filled they are kept for a single day to set and after 24 hours the molds are opened and the samples are kept in the curing tank for 28 days to gain maximum strength.

ASTM C143/C143M [67] standard has been used to determine the workability of plain concrete and C1, C2 and C3 in the fresh state. With the increase in the content of banana fiber in concrete decrease in workability trend. PC showed the maximum slump of 85mm. However, the values of slump for C1, C2 and C3 is 78mm, 71mm, and 38mm. The interlocking effect of banana fibers might be the cause of reduction in slump this is why a significant deviation in slump values is seen. A study conducted in CUST on concrete having banana fiber showed a declining trend of workability [64]. Similarly, another study conducted on the fresh properties of concrete having banana fiber showed a decrease in workability [104]. Ali et al. [105] conducted a study on the properties of banana fiber reinforced concrete and a decreasing trend in workability was observed. On the other hand using banana leaf ash in concrete results in the increase of workability. Mim et al. [10] conducted a study on concrete having banana leaf ash and it was observed that the workability increases with the use of banana leaf ash. Attia and Shymaa [65] also conducted a study on the properties of concrete having banana leaf ash and they reported a decreasing trend in workability with increased banana fiber content. The percentage reduction in the slump values i.e. workability is 8.2%, 16.4% and 55.3% for C1, C2 and C3 as compared to the PC. The minimum slump observed is for C3 as high content of banana fiber was used. Due to the retention and the confinement provided by fibers a decreasing trend is observed.

Both compaction factor test and slump cone test was performed on the PC, C1, C2, and C3 to get a robustness about the workability of investigated concrete. The compaction factor values observed for C1, C2, C3 and PC are 0.86, 0.84, 0.77 and 0.91. ASTM C642-13 standard is used for the determination of the fresh density of the PC and other concretes as well as no standard is available for fiber reinforced concrete. The densities observed are 2310 kg/m3, 2294 kg/m3, 2286 kg/m3, 2278 kg/m3 for PC, C1, C2 and C3, respectively. The percentage decrease in the fresh density as compared to plain concrete is 0.69%, 1.03%, and 1.4% for C1, C2 and C3, respectively. The presence of banana fibers can be the reason behind the decreasing density as these fibers have lower density. Hence, C3 shows the minimum density as highest amount of fiber is used in this concrete. These tests were performed to find robustness about the trend. Figure 3.2 shows the trends of tests performed on the fresh concretes.

For the splitting tensile and strength in compression concrete cylinders having a height of 200 mm and diameter of 100 mm are used. Moreover, for the water absorption test these very cylinder samples are used. For the research purpose, 24 samples are cast in total which consist of 24 cylinders. Each batch consists of 3 cylinder for compression test and 3 cylinders for split tensile test. Each specimen has been distinguished using markings on the samples. The current research is based on relative approach to check the effectiveness of banana leaf ash and banana fibers on concrete, i.e. the reference specimens of plain concrete are tested under the same conditions as that of concrete having banana leaf ash and banana fibers.

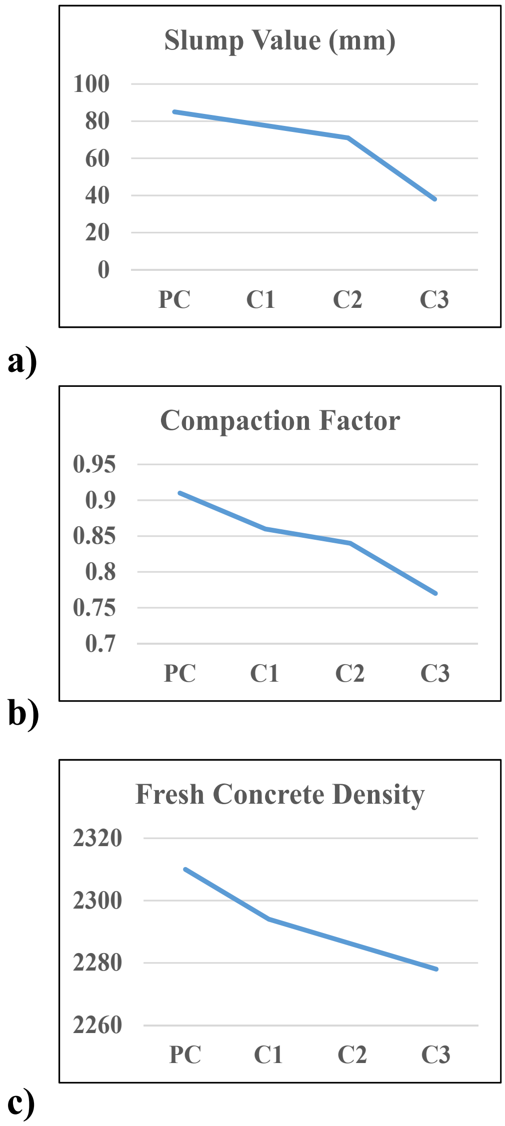


FIGURE 3.2: Fresh Concrete Properties a) Concrete Slump b) Compaction Factor C) Fresh Concrete Density

3.4 Procedure

The mechanical properties and water absorption are determined for the reference concrete as well as for C1, C2, and C3. All of these tests are performed as per the ASTM standards. In order to avoid the errors in the results mean values of two readings for each type of test has been taken. The testing setup has been shown in the figure 3.3a, 3.3b, and 3.3c for the performance of the test.

3.4.1 Dynamic Properties Tests

ASTM standards of C215-14 [69] the frequencies, damping ratio, dynamic poisson ratio, dynamic modulus of rigidity, and dynamic modulus of elasticity are determined. For the determination of the mentioned values cylinders are used. Longitudinal, transverse, and transverse frequencies are determined and based on the frequency other parameters are calculated. Figure 3.3. (d) shows the testing setup for dynamic testing

3.4.2 Mechanical Properties Tests

Compressive and splitting tensile tests have been performed as per ASTM C39 [70], and ASTM C496 [71], respectively using relevant test fixtures in STM. Compressive testing has been conducted on cylinders having a diameter of 100mm and height of 200mm. For the determination of strength in compression, the behavior under compressive loading, the energy absorbed before the peak load and the energy absorbed after the peak load till failure , the value of strain against the peak value of stress, the toughness indices for both the reference concrete and the concrete having banana fibers and banana leaf ash is in compliance with the ASTM C39 / C39M-17. In order to determine the splitting tensile strength, specimens having 100mm diameter and 200mm height are used and placed in the testing machine in horizontal direction for application of splitting tensile load .The behavior under splitting tensile loading, the energy absorption from initial load to peak load and the energy absorption from the peak load till failure, and the splitting tensile toughness indices for both the reference concrete and the concrete having banana fibers and the banana leaf ash, the followed standard is ASTM C496/C496M-11. Figure 3.3 (a) shows the test setup for compressive, figure 3.3 (b) shows the test setup for splitting tensile and figure 3.3 (c) shows the test setup for water absorption test.

3.4.3 Water Absorption Test

Water absorption test is conducted for all types of concrete mixes. For conducting of the test the samples are first dried until constant mass is achieved. Afterwards, this sample is placed in ventilated room having room temperature, then the water absorption is calculated similar method is used for the determination of the water absorption of the concrete having banana fibers and banana leaf ash. Figure 3.3 (c) shows the samples placed in the tank to absorb water in order to determine the water absorption test of the samples.

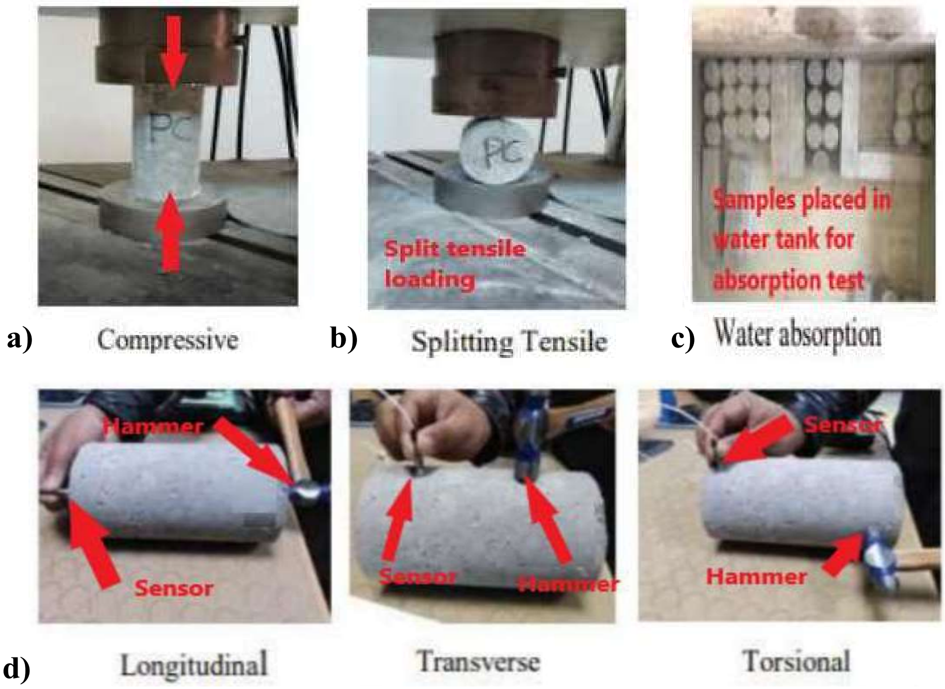


Figure 3.3: Test Setup a) Compressive Testing, b) Splitting Tensile Testing, c) Water Absorption, d) Dynamic Testing

3.4.4 SEM Analysis of Damaged Surfaces

For conducting the SEM analysis, a broken piece from the broken sample is used. Using the scanning electron microscope, imaging is done in order to find the failure mechanism of the concrete matrix. SEM also helps in determination of the behavior of the fibers during the failure. Three possible events can happen in case of natural fiber concrete. Either the fibers break during the test, pulled out of the matrix or provide bridging effect and results in ductile failure.

3.5 Procedure for Prediction of Rigid Pavement Performance

Mechanistic empirical pavement design approach uses the properties of the concrete material as input along with the load conditions, design life and weather conditions. MEPD allows for the inference of design which is difficult to justify based on the limited traffic levels and design which are covered by the road test.

TABLE 3.2: Design Considerations for Pavement Design

Parameter(s)	**Value(s)**
Equivalent Standard Axle Loads (W18)	12.67 x 10E6 ESALs
Reliability	95 %
Standard Deviation	0.35
Concrete Elastic Modulus	Variable for PC, C1, C2, C3, Book Design
Modulus of Rupture of Concrete	Variable for PC, C1, C2, C3, Book Design
Seasonal k-value	550 psi/in
Drainage Coefficient	1
Initial serviceability	4.5
Terminal serviceability	2.5
Δ PSI	2

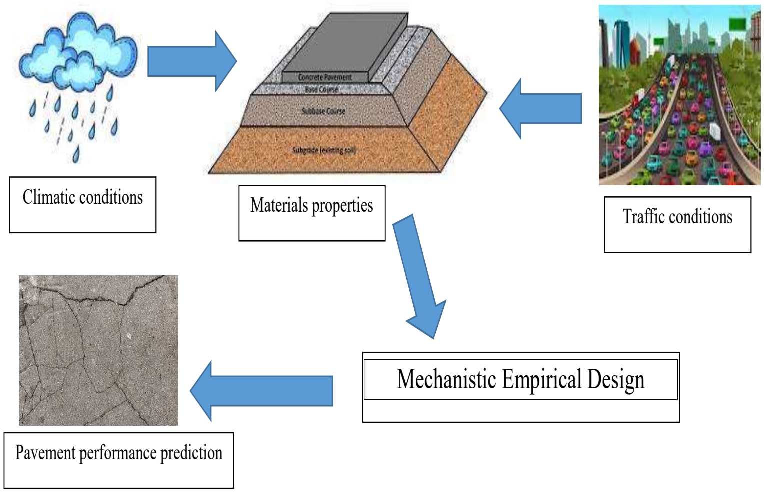


Figure 3.4: Mechanistic Empirical Pavement Design Procedure

Mechanistic deals with the physical causes of the stresses and the empirical part deals with determination of distresses based on the observed relationships. Figure 3.4 shows the procedure of mechanistic empirical pavement design procedure. First the traffic conditions and the average weather data are fed into the software along with design inputs. The average weather data of Islamabad has been shown in table 3.3. The rigid pavement is designed using the elastic modulus obtained from the mechanical testing of the specimens and the modulus of rupture obtained from empirical relation between splitting tensile strength and flexural strength. In the software part, a section of rigid pavement is modeled by inputting various parameters like thickness and mechanical properties of concrete. The model is based on the layered elastic model which assumes that the pavement layer is homogenous.

Based on these input values the AASHTOWare software performs the mechanistic empirical design and then predicts the performance of the pavement in the form of distress models and the predicted design life of the pavement. In MEPD, on trial basis, the design of the pavement structure is assumed initially along with the climatic conditions and traffic conditions. MEPD has the capability to predict the performance of the pavement against different climate and loading conditions.

Table 3.3: Average Temperature Data for Islamabad [54]

-	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Avg. Temp C	9.2 C	11.5 C	16.2 C	21.7 C	27.2 C	29.9 C	28.2 C	26.8 C	25.3 C	21.2 C	15.4 C	10.9 C
Min. Temp C	3.5 C	5.7 C	9.8 C	14.7 C	19.5 C	23.1 C	23.8 C	22.9 C	20 C	14.9 C	9.5 C	5.1 C
Max. Tempera-ture C	15.8 C	17.7 C	22.7 C	28.4 C	34.1 C	35.8 C	32.5 C	30.9 C	30.7 C	28.3 C	22.6 C	18.3 C
Precipitation / Rainfall mm (in)	70	123	127	83	36	65	174	162	73	31	29	39
	-2	-4	-5	-3	-1	-2	-6	-6	-2	-1	-1	-1
Humidity(%)	65%	65%	59%	49%	38%	43%	69%	77%	67%	53%	58%	61%
Rainy days (d)	5	7	8	6	5	6	14	14	7	3	2	3
avg. Sun hours (hours)	8.3	8.7	10	11.4	12.4	12.4	10.2	9.7	10.3	10.1	9.2	8.6

Based on this prediction the usage of the new material for the pavement application can be assessed."AASHTOWare" ME design software is used to assess the performance of the rigid pavement under different climatic and loading conditions. Design inputs have been shown in table 3.2 for performing performance evaluation. This performance is compared with the performance of existing rigid pavement, constructed using conventional materials, by using the design parameters in ME design software. The values of parameters used are shown in table 3.2. Material properties used are from the results obtained after the mechanical testing of the specimens, rest of values are taken from the AASHTO rigid pavement design manual. Both the rigid pavements are designed using these parameters in the "AASHTOWare" software to analyze the performance of the pavements designed using these materials under traffic loading. The climatic conditions used as input for the analysis have been shown in table 3.3 taken from [54]. This table contains the climatic data for all months of the year. The average temperature, rainfall, humidity and average sun hours for each month are entered into the "AASHTO-Ware" software. Furthermore, the traffic data is entered in the form of ESAL's taken from the AASHTO-II 45 design example as mentioned in the table 3.2. The output will be given as IRI and faulting prediction. High IRI value means increased roughness and decreased performance. Similarly, high level of faulting indicate that corrective actions are required like slab replacement of join sealing.

3.6 Summary

For the preparation of the reference concrete and the concrete having banana fibers and banana leaf ash the mix design used is 1:1.3:2.3. Water cement ratio used is 0.48 for both the reference concrete and concrete having banana fiber and banana leaf ash. The proportion of fiber in concrete is 1%, 1.5%, and 2.5 % by mass of cement, while the content of banana leaf ash is 10 percent which is partially replaced with Portland cement, with the same fiber length of 50mm banana fiber. The number of samples cast for this research include 12 beam-lets, 24 cylinders which make a total of 36 specimens. The conducted tests included fresh concrete tests i.e. slump test, compaction factor test, fresh density determination, hard concrete tests which include water absorption test and mechanical tests include compressive testing and split tensile testing of concrete. The results and analysis of these results are discussed in chapter 4.

Chapter 4

Results & Discussions

4.1 Background

For the casting of reference concrete and the concrete having banana fiber and banana leaf ash, the mix design ratio of 1:1.3:2.3 is used. The water cement ratio of 0.48 is used for all concrete mixes. For preparing the concrete having banana fiber and banana leaf ash (C1, C2 and C3), 10 percent cement is replaced with banana leaf ash and banana fibers are added in three different percentages i.e. 1 percent, 1.5 percent, and 2.5 percent by cement mass for C1, C2 and C3, respectively. Fibers used are of 50mm for banana fiber. Chapter 4 includes the detailed analysis of the results of testing done on the reference concrete and concrete having banana fiber and banana leaf ash.

4.2 Dynamic Properties

To find the effect of impact loading on the concrete, dynamic testing of reference concrete and concrete having banana fibers and banana leaf ash has been carried out. For the determination of dynamic testing, ASTM C666/C666M-15 and ASTM C215-14 standards have been used. The same standards have been used to determine the dynamic properties of concrete having banana fiber and banana

Table 4.1: Dynamic Properties of PC and Concrete Cylinders having Banana Leaf Ash and Banana Fiber

	FL (Hz)	**FT (Hz)**	**FTR (Hz)**	**Damping ratio (%)**	**DME (GPa)**	**DMR(GPa)**	**Poisson ratio(-)**
PC	5696±310	3564±465	3407±234	3.81±0.24	4±2.23	4.43±1.43	0.45±0.19
C1	5302±279	3475±387	3369±221	5.35±0.32	5.36±1.78	4.89±2.43	0.54±0.25
C2	3408±264	3401±321	3294±201	7±0.36	6.43±1.65	5.72±1.04	0.56±0.13
C3	3305±255	3302±295	1294±145	9±0.42	9.93±1.77	6.53±0.67	0.76±0.23

leaf ash due to non-availability of any specific standard. For obtaining appropriate and accurate results, two readings have been taken. Table 4.1 shows the dynamic properties of all batches of concretes. The damping ratio of C1 is 40% more than the reference cylinders. Similarly, for the damping ratio is increasing almost 83% in case of C2 cylinders and for C3 the the increase in the damping ratio is 136%. However, it is to be observed here that the damping ratio of C3 is more than all the other samples.The drastic change in frequency values and the damping ratio of C3 concrete can be attributed to the fiber distribution, and high percentage of fiber, affecting the response to dynamic loading. Furthermore, high fiber content results in higher energy dissipation within the material leading towards increased damping.

The increase in damping ratio with 1% addition of banana fiber and 10% banana leaf ash shows that the samples are capable of sustaining impact loads. However, with the increase in the content of fiber the damping ratio increases and 2.5% of fiber shows the maximum damping ratio. The dynamic modulus of elasticity increases up to 85% with the addition of 1% of banana fibers. With the increase in the content of banana fibers the dynamic modulus of elasticity increases as compared to the PC. The increase of dynamic modulus of elasticity in case of C1, C2 and C3 is 34, 60.43 and 148.25%, respectively. The dynamic modulus of rigidity also increases with the increase in the content of banana fibers.The results of dynamic testing conclude that the overall performance of C3 is better as compared to the reference concrete, C1 and C2. However, as compared to the reference concrete, C1 and C2 also perform well. This means that C3, C2 and C1 can increase the dynamic characteristics of the the rigid pavement.

4.3 Mechanical Properties

4.3.1 Properties under Compressive Loading

The stress strain curve has been shown in the figure 4.1 (a) on the other hand figure 4.1 (b) depicts the behavior of fracture of the specimens i.e. reference concrete and the concrete having banana fiber and banana leaf ash, under compression load. The phenomenon has been shown in three different stages which includes. The first stage is where the first crack appears, the second stage is where the specimens experienced the peak load and the third stage is where the ultimate load was experienced by the specimens. The first crack on the surface of reference sample and concrete samples having banana fiber and banana leaf ash that is C1, C2, and C3 is at 81 percent, 85 percent, 87 percent and 89 percent of their respective peak loads.

The width of cracks observed in the C1, C2 and C3 samples were significantly lesser than that of reference samples. The observed crack width is 82 mm, 73 mm, 71 mm, and 64 mm in reference samples and C1, C2, and C3, respectively. It can be seen clearly in the figure 4.1 (b) that the reference concrete sample splits into two parts with the appearance of cracks on the surface. However, C1, C2 and C3 samples remained together even after the appearance of cracks due to the bridging effect provided by the fibers. The strength in compression and respective strain along with the CEP, CEF, CET and CTI values have been shown in table 4.2.

The strength in compression shown by the PC sample was 30.5 MPa while the C1, C2 and C3 samples showed 28 MPa, 27.7 MPa, and 23.7 MPa. The reduction in the CS values for C1, C2 and C3 are 8.19 percent, 9.18 percent, and 22.29 percent. Concrete having banana leaf ash only lead to increase in the compressive strength[1, 9, 10]. However, in case of concrete having banana fibers and banana leaf ash the compressive strength is decreasing. The reduction in the values of CS is due to the incorporation of low density fibers. However, the reduction is not significant for the C1 and C2 due to the usage of lesser content of banana fibers.The mild slope of C1, C2, and C3 as compared to PC shows the reduced elastic modulus in concrete. This reduction in elastic modulus along with increment of modulus of rupture can lead the C1, C2 and C3 concretes to have reduced thickness of pavements. The values of strain for the PC, C1, C2 and C3 are 0.0021, 0.0023, 0.0028, and 0.0036, respectively. The highest strain value is for C3 having a peak strain of 0.0036. The strain for the PC sample is minimum due to the high compressive strength of the sample however, with the reduction in the compressive strength the strain values are increasing. C2 and C3 samples show a significant increase in the strain values which shows that they have high elongation property

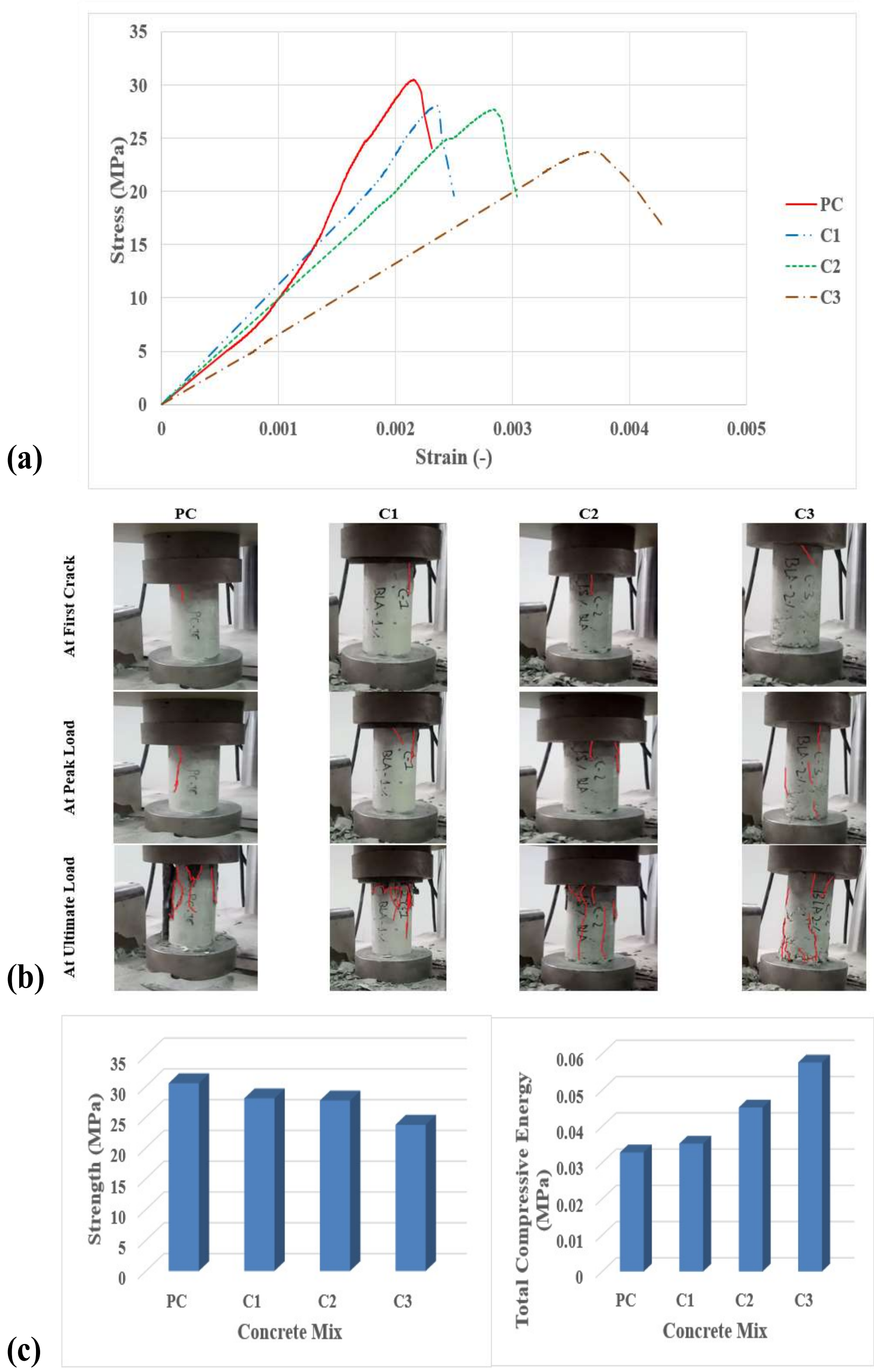


FIGURE 4.1: a) Stress - Strain Curve of Samples b) Failure Behavior c) Comparison of Compressive Properties

and due to this reason these samples can withstand shattering force and keep the matrix together during the loading. The increased strain value in the C1, C2 and

C3 samples can probably be because of the slippage effect of the fibers. When the fibers slip within the matrix under loading conditions, the deformation in the vicinity of fibers is different from overall deformation of the matrix which results in localized strain concentration leading to increased overall strain. The CEP values of reference concrete, C1, C2, and C3 are 0.028 MPa, 0.0318 MPa, 0.040 MPa and 0.045 MPa, respectively. Comparing these values show that the compressive energy at peak load is minimum for the PC where as the value is increasing for the C1, C2 and C3.

Table 4.2: Compressive Strength Properties of PC and Concrete having Banana Leaf Ash and Banana Fiber

Sample	CS (MPa)	Strain (-)	CEP (MPa)	CEF (MPa)	CET (MPa)	CTI(-)
PC	30.5±1.46	0.0021±0.0007	0.028±0.01	0.00435±0.004	0.032±0.0157	1.15±0.08
C1	28± 0.09	0.0023±0.0002	0.0318±0.0003	0.00346±0.0007	0.035±0.0003	1.10±0.007
C2	27.7±0.16	0.0028±0.0001	0.040±0.0028	0.0049±0.0003	0.045±0.0006	1.12±0.09
C3	23.7±0.54	0.0036±0.0012	0.045±0.003	0.0125±0.0003	0.057±0.001	1.27±0.07

The CEF values for PC is 0.0435 and the CEF values of C1 is lesser than PC whereas the CEF value of C2 is more than PC. The CEF value of C3 is maximum. The CEF values of C1, C2 and C3 are 0.00346 MPa, 0.0049 MPa, and 0.0125 MPa. The increase in the values of CEF is because of the energy absorption after the crack appearance due to the availability of banana fibers. This is why these samples outperformed the PC samples in the post crack energy absorption. The Values of CET are in increasing order from PC to C3. The value of C1 is lesser than that of C2 and C2 value is lesser than C3. The CET values for PC, C1, C2 and C3 are 0.032 MPa, 0.035 MPa. 0.045 MPa, 0.057 MPa. The increased value is mainly due to the post-crack energy absorption and to some extent because of the energy absorption pre cracking for C1, C2 and C3. The Value of compressive toughness index for PC, C1, C2, and C3 are 1.15, 1.10, 1.12, and 1.27. Figure 4.1 (c) shows the comparison of strength and total compressive energy of different mixes.

4.3.2 Properties under Split Tensile Loading

Figure 4.2 (a) shows the curve of load-deformation under the loading in splitting tensile, while the figure 4.2 (b) depicts the behavior of cracking of the specimens i.e. reference concrete and C1, C2, and C3 under the split tensile load. The cracking pattern shown are for initial cracks, crack at peak load and cracking pattern at the ultimate load. The specimens of PC and concrete having banana fiber and banana leaf ash depicts cracking at the corresponding peak loading values of 100 percent, 98 percent, 94 percent and 92 percent, respectively.

The width of the cracks of C1, C2, and C3 are much lesser than that of PC samples. The length of cracks observed for C1, C2 and C3 are 73 mm, 68 mm and 61 mm, respectively. However, the PC samples breaks into two pieces with the appearance of first crack on the surface. On the other hand the C1, C2 and C3 samples remains intact after the formation of the cracks It can be seen that the width of the cracks is less for the C1, C2 and C3 samples. At the peak load the width of the cracks increased to 78 mm, 72mm, 66 mm for the C1, C2 and C3 samples, respectively. Specimens containing banana fiber and banana leaf ash showed expansion of the cracks even at the ultimate loads .The crack width at the ultimate loads are 83 mm, 76 mm, 71 mm, for C1, C2 and C3, respectively.

The addition of fiber reduces the concrete's brittle behavior by lowering the crack width and due to the bridging effect the samples are not broken into two pieces after the appearance of the first crack. Therefore, it can be said that addition of fibers in concrete can help in enhancing the post crack behavior of the concrete mainly in the split tensile loading. The samples were intentionally broken into two pieces after the test to see the failure mechanism of the specimens. For the determination of the strength in splitting tension (STS), the maximum value of load is considered. The area under the curve before the peak load is defined as the pre-crack absorbed splitting tensile energy (STEP), while the energy absorbed after the peak load is called the energy absorbed post crack splitting tensile energy

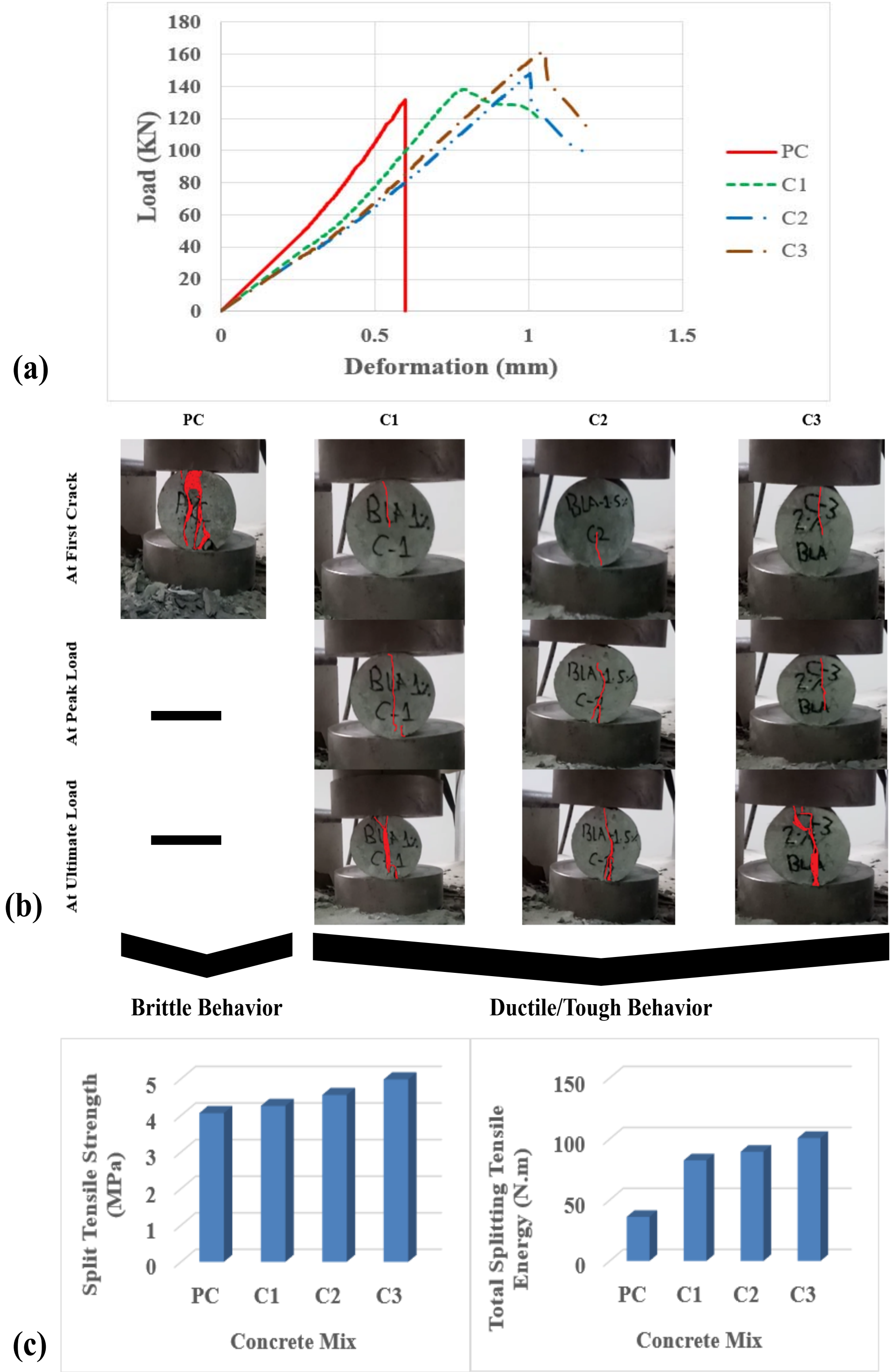


FIGURE 4.2: a) Load Deformation Curves of Samples b) Failure Behavior c) Comparison of Splitting Tensile Properties

(STEF). It is significant to observe that the STEP value and the TSTE values are same for the PC samples because the total energy absorbed by the PC was before the peak load and at peak load the sample was split into two pieces. The ratio between the TSTE and the STEP value gives the Splitting Toughness Index (STI).

The data obtained from the load deformation curve is provided in table 4.3. The values of STS, STEP, STEF, TSTE and STI have been given for PC, C1, C2 and C3 samples. The values of STS for PC, C1, C2 and C3 are 4.06 MPa, 4.26 MPa, 4.56 MPa, and 4.98 Mpa, respectively. It can be seen that the values of STS are in increasing order with the increase in the content of the banana fibers in concrete. Using banana fiber in concrete results in an increase in the splitting tensile strength and this strength increases with increased amount of fiber in concrete [21–23, 25, 110]. The value of STS for C1 has increased 4 percent, whereas for the C2 specimens the value has increased upto 12 percent and for C3 the value has increased up-to 22 percent. This shows that with the addition of banana fibers the splitting tensile strength of the concrete increases.

Table 4.3: Split Tensile Strength Properties of PC and Concrete having Banana Leaf Ash and Banana Fiber

Sample	STS (MPa)	STEP (N.m)	STEF (N.m)	TSTE (N.m)	STI (-)
PC	4.06±0.02	36.18±0.02	-	36.18±0.02	1±0
C1	4.26±0.01	50.03±0.09	32.53±0.06	82.56±0.06	1.65±0.01
C2	4.56±0.04	69.51±0.05	20.07±0.04	89.59±0.01	1.28±0.03
C3	4.98±0.03	80.82±0.04	20.03±0.07	100.85±0.07	1.24±0.07

The values of STEP for PC, C1, C2, and C3 are 36.18 N.m, 50.03 N.m, 69.51 N.m, and 80.82 N.m. The value of STEP is increasing for C1, C2 and C3. This increase in the STEP value is due to the energy absorption capacity of the natural fibers i.e. banana fibers. The values of STEF for the PC is zero because of the reason that no energy was absorbed after the peak load and the sample was broken into two pieces. However, the STEF values of C1, C2, and C3 exist because of bridging effect of fibers. The STEF value of C1 is more than C2. However, the STEF value of C3 is greater than C1 and C2.

The values obtained for the TSTE for PC, C1, C2 and C3 are 36.18 N.m, 82.56 N.m, 89.59 N.m, and 100.85 N.m, respectively. Comparing the results of PC and C1 it can be seen that more than 136% of the total splitting tensile energy has increased. Similarly, the C2 value is 147% more than the value of PC. C3 values are more than all of the samples. The banana fibers act as reinforcement, as the percentage of fibers increase the tensile stresses are effectively distributed making the concrete more resistant to cracking with increased energy absorption. Energy absorption after peak load is due to bridging effect of fibers. The ductile/tough failure behavior is also shown in figure 4.2, here it can be seen that the PC sample break into two parts after peak load whereas C1, C2 and C3 show a ductile/tough behavior because of the bridging effect of banana fibers. The toughness index for PC is 1 whereas the STI values for C1, C2 and C3 are 1.65, 1.28, and 1.24. Figure 4.2 (c) shows the comparison of tensile strength and total tensile energy of different mixes.

4.4 Water absorption

The absorption of water is actually the movement of water into the concrete samples due to the capillary action because of the pores in the concrete. The water absorption is the mass of the water absorbed by the sample divided by the mass

Table 4.4: Water Absorption (%) of PC and concrete cylinders having banana leaf ash and banana fiber

Parameters	**PC**	**C1**	**C2**	**C3**
Water Absorption	2.23%	2.51%	2.63%	2.72%

of the dry sample which is dried till constant mass is achieved. The values of the water absorption are depicted in the table 4.4. The water absorption values for PC, C1, C2 and C3 are 2.23%, 2.51%, 2.63% and 2.72%, respectively. The increase in the water absorption in case of C1 as compared to reference concrete is 12%, for C2 the increase is 17% and in case of C3 the increase in water absorption is 21%. The water absorption values for C2 and C3 are significantly higher as compared to PC. The increase in water absorption is not favorable especially for the case of rigid pavement as the absorbed water might damage the pavement due to the freeze and thaw effect. However, the increase in tensile strength due to banana fibers can potentially resist the cracking due to freeze and thaw effect.

4.5 SEM Analysis of Concrete Samples having Banana Leaf Ash and Banana Fiber

The imaging of the broken samples using the SEM technique shows that the concrete matrix has few air voids present. Moreover, the fiber breakage can be seen

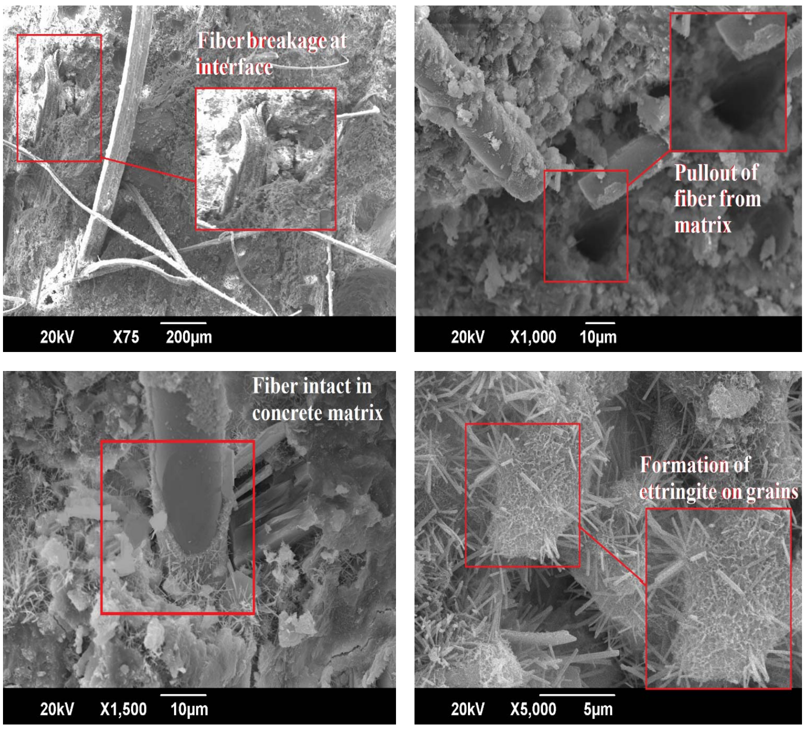


Figure 4.3: SEM of Damaged Surface of C3

in figure 4.3. similarly, the fiber pullout can also be seen in the figure 4.3. The SEM imaging also shows the formation of ettringite (Aft) which is actually a needle like structure that helps in the setting of the concrete during the hydration process. Image taken at 10 micro-meter zooming shows the pullout of fiber from the concrete matrix, which is due to the slippage of fibers from the concrete matrix. It is evident from the image that banana fibers provide bridging effect and provide higher tensile strength.

4.6 Summary

The properties under mechanical testing and water absorption have been determined. The mechanical testing reveals that the compressive strength reduces but for C1 and C2 the reduction is not significant. Similarly, the splitting tensile strength increases with the increase in the content of banana fibers. Water absorption test shows that due to the fibers in concrete the water absorption increases. The SEM analysis shows that fibers are either broken or pulled out of the concrete matrix.

Chapter 5

Practical Application

5.1 Background

The results of the tests conducted on the samples developed the basis for the practical application of the sustainable concrete to develop sustainable pavements. This is done by the comparison of the mixes for obtaining the optimized mix among all the mixes. The design of pavement using the AASHTOWare mechanistic empirical pavement design approach is then done using the values obtained for each mix, as it is very important to find relation between the obtained values and the pavement performance. This chapter discusses the optimization of mixes and then their implementation for designing pavements for studying the structural performance of these pavements.

5.2 Comparison for Optimized Mix

Concrete is a major civil engineering material that has wide application in real life. Concrete is generally used as structural material which bears different mechanical loads. The mechanical properties of the concrete are related to the performance of the concrete. Optimized mix is a mix having increment in large number of properties i.e. mostly governing for a specific application, with little compromise in few number of properties. In this study different parameters have been studied ranging from mechanical performance to performance of pavement. For the application of concrete in rigid pavements, mainly two aspects are considered i.e. the modulus of rupture and the modulus of elasticity. Moreover, other factors like water absorption and dynamic properties are also important. With the increase in both the values i.e. elastic modulus and modulus of rupture, the performance can enhance significantly. Moreover, the shrinkage cracking in rigid pavement leads towards the formation of other distresses in rigid pavement. Water absorption is another factor as water absorption can lead towards the early deterioration of the pavement due to the freeze and thaw effect of the infiltrated water [55]. For controlling the cracks in concrete and specifically in concrete pavements, it is required to increase the tensile strength such that the values increases the induced stresses, this way the cracks in the concrete pavement can be reduced [56]. Faulting is another issue that is caused by many factors but considering the curling effect of concrete it is important to mention the tensile strength of the concrete plays a significant role in the process of faulting. This is why it is important to consider all these parameters and suggest an optimized mix based on the results obtained in the previous chapter.

The performance of the specimens C1, C2 and C3 is better than the reference concrete in terms of splitting tensile strength and dynamic properties. However, in terms of compressive strength C1 shows comparatively better results as compared to C2 and C3, hence resulting in a higher value of modulus of elasticity. In case of tensile strength C3 shows the best performance. The strain values are also more for C3 as compared to the C1 and C2 samples. Similarly, the dynamic properties of C3 are better than other types. Increase in the values of concrete properties results in the formation of rigid pavements that are better performing. Farooqi and Ali [58] developed the first ever rigid pavement containing natural fibers and assessed the performance of this fiber reinforced concrete pavement, field evaluation of this pavement showed a better performance as compared to reference concrete pavement. This shows the practical application of fiber reinforced concrete and possibility of construction of rigid pavements using natural fibers concrete.

For the design of rigid pavements, the material properties that are used include, modulus of elasticity of the concrete and the modulus of rupture of the concrete, both of these properties are calculated directly from the compressive strength and tensile strength, respectively. Modulus of elasticity is a function of compressive strength and hence a concrete with higher compressive strength would be more feasible for its usage in rigid pavement. The mechanical testing revealed that due to the low density of the fibers the compressive strength of the concrete reduces with the increment in the content of fiber. On the other hand the modulus of rupture for C1, C2 and C3 increased significantly. Considering all the results on the specimens C2 can be considered an optimized mix as the compressive strength is reducing only 9.18% as compared to PC, the tensile strength is more than PC and C1. Moreover, the dynamic properties are comparatively better than PC and C1.

5.3 Performance of Sustainable Pavement

The prediction of the performance of the pavement is a significant factor in the analysis and design process. Therefore, MEPD software i.e. AASHTOWare software is used to predict the performance of the jointed plain concrete pavement (JPCP) by using the values obtained from the testing of the PC, C1, C2 and C3 samples. The prediction of the distresses in the form of international roughness index (IRI) and mean joint faulting. The development of cracks in continuously reinforced concrete pavement (CRCP) can develop similar type of distresses like JPCP. The design and analysis on the pavements was conducted for a design life of 50 years of service life. The input parameters given to the AASHTOWare include the climatic conditions, traffic inputs, design criteria and material inputs. AADT of 15000 vehicles per day with a rate of growth of 5% which equals Equivalent Single Axle Loads (ESALS) of about 12.67 million at the very end of design life of 50 years. The climatic conditions were fed into the software, this data has been shown in table 3.3. The pavement design is carried out for both PC and concrete having banana fiber and banana leaf ash i.e. C1, C2 and C3. The elastic modulus and modulus of rupture values used for this design are shown in table 5.1. The thickness of the pavement used for pavement performance evaluation is 270 mm for PC, C1, C2, and C3. It can be seen that PC thickness is more than the rest of the concretes. As discussed in section 2.4, Huang's concrete is considered as a bench mark in this study to show that despite the higher compressive strength of Huang's concrete as compared to the PC, C1, C2 and C3, the design thickness is least for C3 by using the same parameters which tells us that the modulus of rupture plays more vital role in design as compared to the elastic modulus.

The equation for the calculation of splitting tensile strength from the compressive strength of the concrete as given by ACI 318-05 [108] is as follows:

$$f_{\text{tensile}} = 0.56 \cdot \sqrt{f_c} \tag{5.1}$$

Similarly, the equation for calculation of flexural strength of concrete from the compressive strength as given by ACI 318R-14 [107] is as follows

$$f_{\text{flexural}} = 0.62 \cdot \sqrt{f_c} \tag{5.2}$$

Using equation 5.1 from ACI 318-05 [108] and equation 5.2 from ACI 318R-14 [107] equation 5.3 is derived i.e.

$$f_{\text{flexural}} = 1.11 \cdot f_{\text{tensile}} \tag{5.3}$$

This equation can be used to calculate the flexural strength from the tensile strength. The tensile strength is determined by performing the mechanical tests on the specimens and then using the above given equation, the flexural strengths are calculated. This flexural strength and the elastic modulus, calculated from the compressive strength, are used for designing rigid pavements and then the performance is evaluated using the AASHTOWare MEPD software. It can be seen in table 5.1 that the compressive strength of each concrete type has been written based on the compressive testing performed on the samples. Using this compressive strength the elastic modulus of concrete has been calculated. Similarly, the splitting tensile strengths of concrete batches mentioned in this table is also from

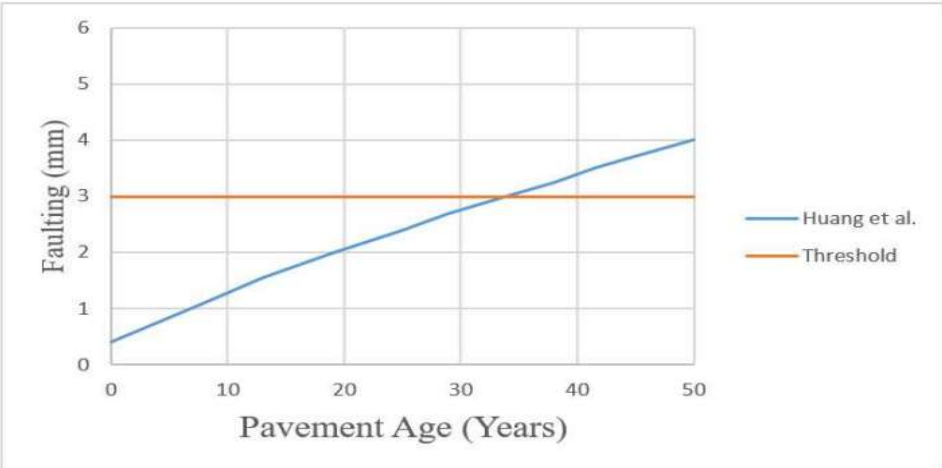
Table 5.1: Design Thickness Comparison

Concrete Type	CS (MPa)	Elastic Modulus (MPa)	STS (MPa)	MoR (MPa) $1.11 * f_{\text{tensile}}$	Pavement Thickness (mm)	Reference
PC	30.5	25956	4.06	4.51	270	current study
C1	28	24870	4.26	4.73	260	current study
C2	27.7	24736	4.56	5.06	250	current study
C3	23.7	22880	4.98	5.53	240	current study
Huang Design Example	53	34216	-	4.51	270	[62]

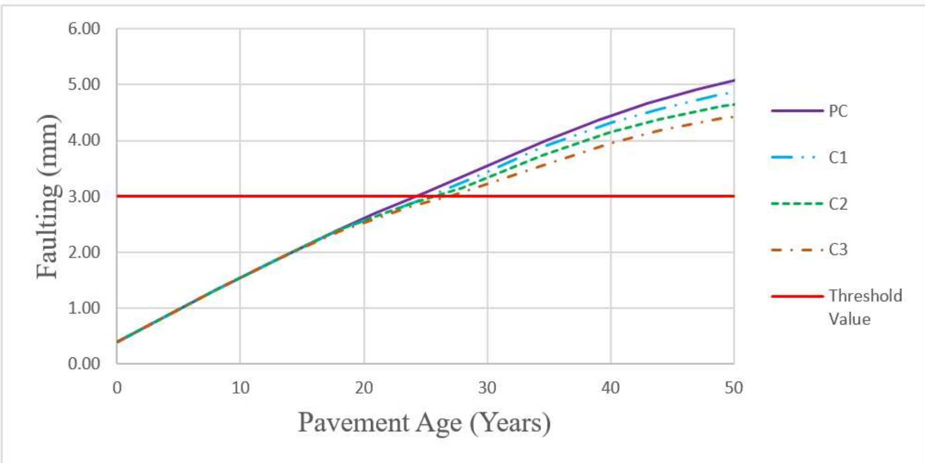
the splitting tensile strength test performed on the samples. Using this splitting tensile strength the modulus of rupture is calculated using the equation 5.3 $1.11 * f_{\text{tensile}}$ which is derived from equation 5.1 and equation 5.2. Both the equations 5.1 and 5.2 used are from ACI codes.

5.3.1 Rigid Pavement Faulting Prediction

Figure 5.1 (b) depicts the performance of each pavement designed in AASHTOware using the mechanistic empirical design approach. The red line shows the terminal or the threshold value for the corresponding distress or index value as given by



a)



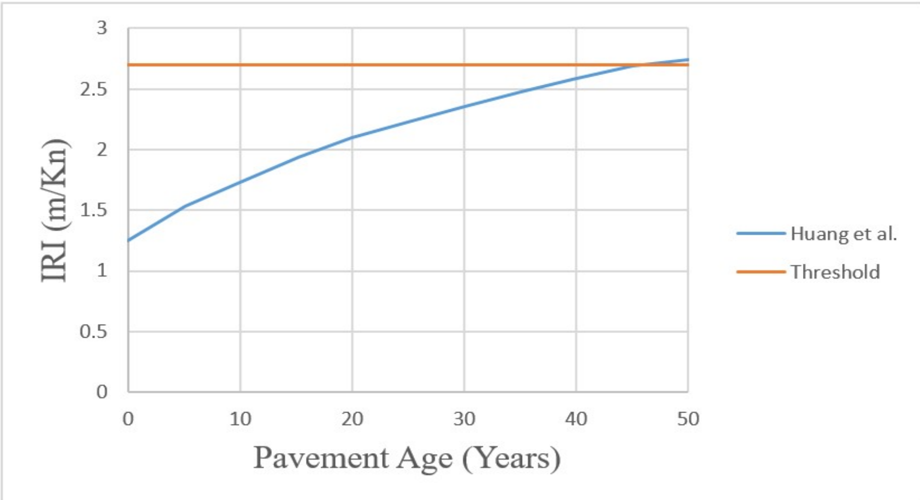
b)

FIGURE 5.1: Predicted Faulting Versus Pavement Age a) Huang Rigid Pavement b) Current Research

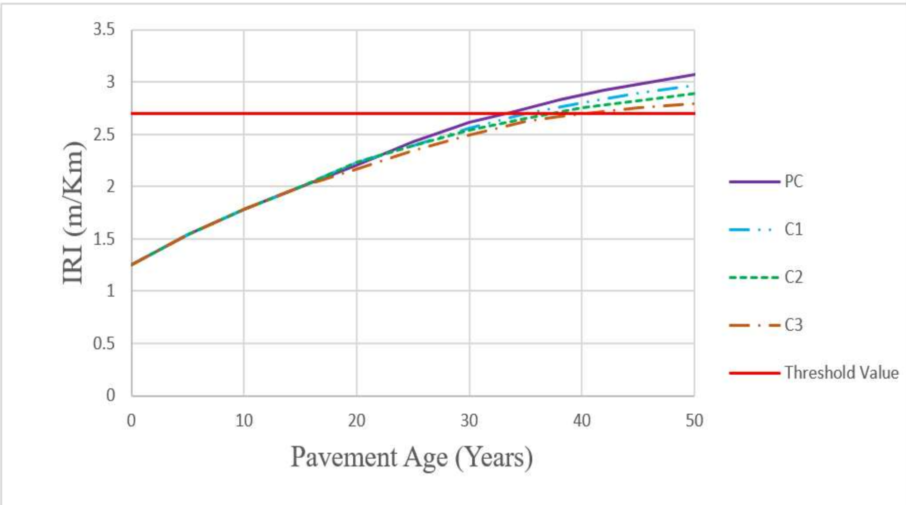
AASTHO [76]. It can be seen that the predicted faulting of the pavement designed using the reference material shows a significant amount of faulting at a very early stage of the design life whereas the C1, C2 and C3 show higher performance as compared to the reference concrete. Faulting predicted in pavement designed using the C3 concrete shows superior results as compared to other pavements. The faulting considered is in fact due to the curling and warping of rigid pavement that generates flexural stresses in the pavement. Due to higher calculated flexural strength of C3 concrete, the faulting predicted in the pavement is lower than all other mixes. The trend shows that with the increase in the flexural strength the predicted faulting age increases. It is to be noted here that the faulting is caused due to the curling of slab and not because of the soft sub-grade or pumping action. The prediction analysis shows that rigid pavement designed using reference concrete fails after 24 years whereas, C1, C2 and C3 fails after 25, 27 and 28 years, respectively. As shown in figure 5.1 (a), the pavement designed using Huang's design example shows that the failure happens at the age of 34 [62]. The modulus of elasticity for Huang's concrete is more as compared to reference concrete values in this study. However, the value of modulus rupture is equal to PC as shown in table 5.1. This concrete can be compared with reference concrete of this study. The percentage increase in age as compared to PC for C1, C2 and C3 is 4.16%, 12.50%, and 16.66%, respectively.

5.3.2 Rigid Pavement IRI Prediction

The International Roughness Index (IRI) prediction values show some what of similar trend as discussed in the previous section. The International Roughness Index increases with the appearance of other distresses on the rigid pavement. Due to the fact that C1, C2 and C3 showed lower compressive strength as compared to reference concrete. Moreover, due to the calculated higher modulus of rupture of C1, C2 and C3 concrete the possibility of other distresses also decreases. Hence, increasing the age to reach the threshold IRI of the pavement. Figure 5.2 (b) shows the relationship between IRI and the pavement age of the current study. The red line shows the threshold value as given by AASHTO [76]. It is evident from the graph that with the increase in the content of fiber the pavement age values are increasing. All of the mixes show almost similar behavior till the first 16-17 years of the design life. However, after 17 years the mixes show variating trend. The longest life predicted is for the C3 due to higher values of mechanical characteristics hence, lower chances of other distresses in this pavement. In terms of IRI the pavement failure prediction is 34, 35, 37.5, and 40 years for PC, C1, C2 and C3, respectively. Moreover, figure 5.2 (a) shows the IRI vs pavement age for pavement designed using values of Huang's design example, this pavement



a)



b)

FIGURE 5.2: Predicted IRI Versus Pavement Age a) Huang Rigid Pavement b) Current Research

crosses the threshold at 45 years. Considering the high values of modulus of elasticity as compared to the MoE of PC used in this study, the pavement age is more. IRI is a function of different distresses of rigid pavement. Hence, reduction in the IRI means reduction in the formation of distresses along with better performance in terms of ride quality.

5.3.3 Comparison of pavement age for IRI and Faulting

The performance prediction shows that the age for reaching faulting threshold increases with increase in the fiber content. Furthermore, as compared to IRI, faulting criterion showed a lesser life of the pavement. Due to the curling of slabs, faulting is a function of strains. All the batches containing banana fiber and banana leaf ash showed more life of the pavement as compared to the reference concrete. However, C3 shows more age against IRI prediction as compared to C1 and C2 i.e. the use of 2.5% banana fiber and 10% banana leaf ash showed

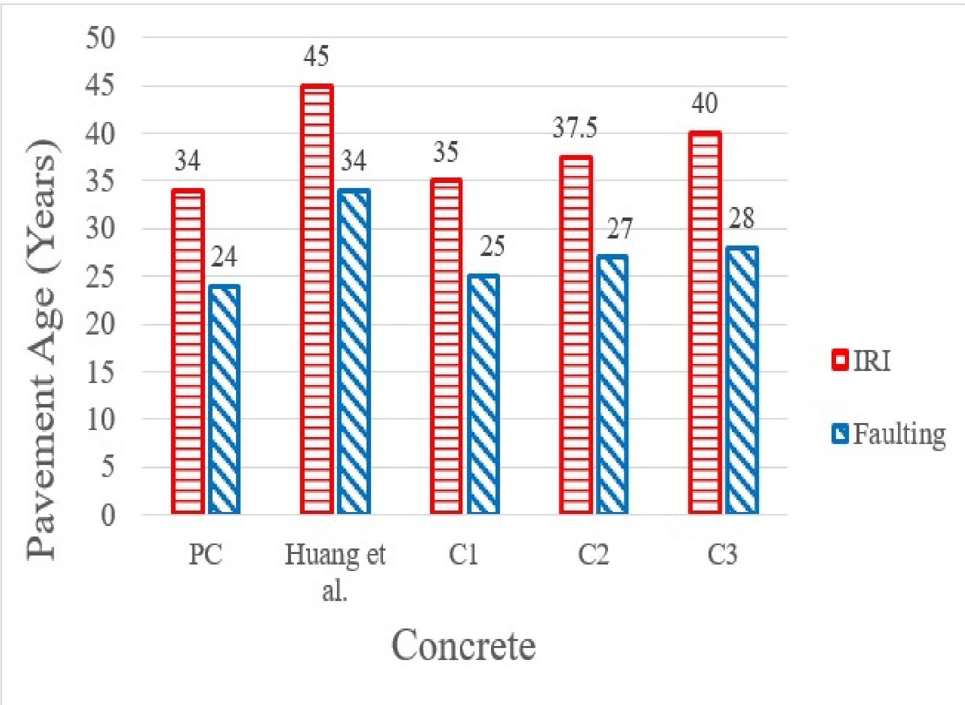


Figure 5.3: IRI and Faulting Relation between Pavement Age and Concrete Type

relatively longer life of 40 years, whereas the batches C1 and C2 showed a life of 35, and 37.5 years against IRI. The increase in the life of the pavement is an additional benefit along with environmental benefits and lower cost of construction. The improvement in the performance of the pavement is due to the higher value of the modulus of rupture. However, the reduction in the compressive strength did result in compromise in the performance of the pavement. From strength point of view C3 batch achieved the longest life span as compared to C1 and C2 batch. The longest life achieved for the pavement was from C3 that is 28 and 40 against faulting and IRI, respectively. This can be due to the higher flexural strength, calculated from the splitting tensile strength, as compared to C1 and C2. It can be seen in figure 5.3 that the failure age of the pavements increases with the increase in the content of banana fiber with constant amount of banana leaf ash. The failure age is higher in terms of IRI as compared to failure age in terms of mean joint faulting. Both of the factors have significance but faulting will be limiting factor as the failure age is achieved earlier in this case, calling for a rehabilitation of the pavement [92]. The increase in failure age for C3, is significant as compared to PC considering the partial replacement of cement with ash and reduction in the quantity of cement due to the usage of banana fiber.

TABLE 5.2: IRI and Faulting Values after Completion of Design Life

Concrete Type	IRI (m/Km)	Faulting (mm)
PC	3.1	5.1
C1	3.0	4.9
C2	2.9	4.6
C3	2.8	4.4
Huang Design Example	2.74	4.0

Table 5.2 shows the values of IRI and faulting for all type mixes used in this study. IRI and faulting are related as IRI is a function of faulting. Increase in the roughness causes impact loading on the pavement which can exacerbate the development of faulting on pavement [109]. This tabular comparison helps in identifying the best performing mix. Considering the deviation from the values of PC, C3 can be considered the best performing mix among C1, C2, and C3.

5.4 Impact of Extreme Conditions on Material Properties and Pavement Performance

Performance evaluation has also been conducted on samples exposed to extreme conditions. After exposing the samples to extreme conditions, dynamic tests, mass loss test, linear shrinkage test, and flexural test have been performed. The results of these tests have been shown in annexure A. The linear shrinkage and mass loss values are shown in table A1.The linear shrinkage values decrease with the increasing content of banana fibers. On the other hand the mass loss values increase with the increasing content of banana fibers having banana leaf ash in fixed proportion. Table A2 shows the dynamic values of the concrete exposed to extreme conditions. It can be seen that the damping capability increases with the increasing content of banana fibers having banana leaf ash in fixed proportion. Figure A1 shows the behavior of concrete exposed to extreme conditions under flexural loading. It can be seen that PC shows a brittle behavior and splits into two pieces at peak load whereas C1, C2 and C3 shows tough/ductile behavior due to bridging effect of fibers. C1, C2 and C3 show an increasing order of flexural strength and energy absorption capacity. These values have been shown in table A3, the deflection, maximum load, energy before and after peak have also been shown in this table. In annexure B, the performance of this concrete has been shown in the form of figures. In figure B1 (b) it can be seen that the performance of C1, C2 and C3 is in increasing order due to the increasing trend of flexural strength. Similarly. as shown in figure B2 the performance against IRI is also in increasing order for C1, C2 and C3 considering the increasing modulus of rupture. Figure B3 depicts the comparison failure age of all mixes against IRI and faulting.

5.5 Summary

The optimization of the mixes reveals that C2 exhibits superior properties compared to PC, C1 and C3. This is attributed to its higher splitting tensile, dynamic properties in comparison to C1 and little reduction in compressive strength, lesser water absorption as compared to C3. Furthermore, in terms of performance, C3 demonstrates better results as it has a longer service life compared to the other mixes. In terms of IRI the pavement performance prediction shows that the life of PC, C1, C2 and C3 till failure is 34, 37.5, 36, and 40 years, respectively. Similarly, the performance prediction against faulting shows that the life of pavement till failure is 24, 25, 27 and 28 years, respectively. Comparison of pavement failure in terms of IRI and faulting shows that the with the increase of banana fibers and the use of banana leaf ash, the pavement life increases. The life of pavement in terms of IRI is more as compared faulting.

Chapter 6

Conclusion and Recommendations

6.1 Conclusions

For the development of a sustainable concrete and then a sustainable pavement, banana leaf ash is used as partial replacement of cement and banana fibers are used in three different proportions i.e. 1%, 1.5%, and 2.5%. The mix design used is 1:1.3:2.3 with a water cement ratio of 0.48. Dynamic, mechanical, and water absorption are performed along with the micro-structural analysis. Moreover, the mechanistic-empirical pavement design software has been used for the evaluation of performance of the pavement designed using the sustainable concrete and following conclusions are drawn:

- The dynamic testing reveals that the damping ratio of C3 concrete is more as compared to the reference concrete, C1 and C2.
- Mechanical testing of the specimens reveal the strength in compression, splitting tensile strength, compressive toughness index,and splitting toughness index.The conclusions are discussed below
  - C1 shows the maximum compressive strength after PC. The reduction in compressive strength as compared to PC is 8%, 9% and 22%.

  - The splitting tensile strength of C1, C2 and C3 increased as compared to the reference specimens. The increase observed is 4%, 12% and 22% for C1, C2 and C3, respectively.

- Water absorption test reveals that water absorption increases 12%,17% and 21% for C1, C2, and C3 as compared to PC. C3 showed the maximum water absorption and PC showed the minimum water absorption.

- The SEM imaging of fractured surface reveals that some of the fibers broke during the failure and other were pulled out from the concrete matrix.

- Mechanistic empirical design approach reveals the performance of PC, C1, C2 and C3 samples. The performance of the pavements is as follows

  - In terms of IRI the pavement performance prediction shows that the life of PC, C1, C2 and C3 till failure is 34, 35, 37.5, and 40 respectively.
  - The performance prediction against faulting shows that the life of pavement till failure is 24, 25, 27, and 28 years for PC, C1, C2 and C3, respectively.
  - Comparison of pavement failure in terms of IRI and faulting shows that, with the increase of banana fiber the design life increases. The life of pavement in terms of IRI is more as compared to faulting.

Hence, based on the above results, concrete having banana leaf ash and banana fiber has great potential to be used in rigid pavements for more sustainability and better performance. The partial replacement can save the overall cost of the rigid pavement construction. Moreover, the use of banana leaf ash and banana fiber will result in pavements having performance better than normal concrete.

6.2 Future work

Based on the conclusions deduced from this research work, following are the recommendations for future work:

- Banana leaf ash should be used in different proportions by keeping the content of banana fiber constant, in order to find out an optimized dosage of banana leaf ash for better compressive strength.
- Prototype development using the concrete having banana fiber and banana leaf ash should be done in order to validate the real time performance using laboratory equipment.
- More natural ashes should be explored which have a similar nature to banana leaf ash in order to develop sustainable concrete.
- Properties of concrete having banana fibers and banana leaf ash should be evaluated for higher age i.e. 90 days of curing.
- The same combination should be used but different samples should be cast for mechanical testing and water absorption and mass loss test.
- Impact of abrasion and freeze and thaw in optimized sustainable concrete pavement should be evaluated.

Bibliography

[1] Boobalan, S. C., M. Salman Shereef, P. Saravanaboopathi, and K. Siranjeevi. "Studies on green concreteA review." Materials Today: Proceedings 65 (2022): 1404-1409.

[2] Sivakrishna, A., Adeyemi Adesina, P. O. Awoyera, and K. Rajesh Kumar. "Green concrete: A review of recent developments." Materials Today: Proceedings 27 (2020): 54-58.

[3] Chen, Huaguo, Cheuk Lun Chow, and Denvid Lau. "Developing green and sustainable concrete in integrating with different urban wastes." Journal of Cleaner Production 368 (2022): 133057.

[4] Tavares, J. C., Lucena, L. F., Henriques, G. F., Ferreira, R. L., and dos Anjos, M. A. Use of banana leaf ash as partial replacement of Portland cement in eco-friendly concretes. Construction and Building Materials, 346, 128467, 2022.

[5] Jamshaid, H., Mishra, R. K., Raza, A., Hussain, U., Rahman, M. L., Nazari, S., ... and Choteborsky, R. (2022). Natural Cellulosic Fiber Reinforced Concrete: Influence of Fiber Type and Loading Percentage on Mechanical and Water Absorption Performance. Materials, 15(3), 874.

[6] R.C. Kanning, K.F. Portella, M.R.M. Da Costa, R.F.K. Puppi Evaluation of Pozzolanic Activity of Banana Leaf Ash, in, in-house publishing, Porto (2011), p. 8.

[7] R.C. Kanning, K.F. Portella, M.O.G.P. Bragana, M.M. Bonato, J.C.M. Dos Santos Banana leaves ashes as pozzolan for concrete and mortar of Portland cement Constr. Build. Mater., 54 (2014), pp. 460-465.

[8] Y. Wang, Y. Shao, M.D. Matovic, J.K. Whalen Recycling combustion ash for sustainable cement production: A critical review with data-mining and time-series predictive models Constr. Build. Mater., 123 (2016), pp. 673-689.

[9] IEA, Cement, (2020). https://www.iea.org/reports/cement (accessed March 2, 2021).

[10] Mim, Nusrat Jahan, Md Montaseer Meraz, Md Hamidul Islam, Ehsan Noroozinejad Farsangi, Md Tanjid Mehedi, Sk Abdul Kader Arafin, and Rajesh Kumar Shrestha. "Eco-friendly and cost-effective self-compacting concrete using waste banana leaf ash." Journal of Building Engineering 64 (2023): 105581.

[11] A. Kronlf, M. Leivo, P. Sipari Experimental study on the basic phenomena of shrinkage and cracking of fresh mortar Cem. Concr. Res., 25 (8) (1995), pp. 1747-1754

[12] Meyer, D. M., and Combrinck, R. (2022). Utilising microCT scanning technology as a method for testing and analysing plastic shrinkage cracks in concrete. Construction and Building Materials, 317, 125895.

[13] Wang, D., Ju, Y., Shen, H., and Xu, L. (2019). Mechanical properties of high performance concrete reinforced with basalt fiber and polypropylene fiber. Construction and Building Materials, 197, 464-473.

[14] Kuntikana, G., and Singh, D. N. (2017). Contemporary issues related to utilization of industrial byproducts. Advances in Civil Engineering Materials, 6(1), 444-479.

[15] Lyra, G. P., Borrachero, M. V., Soriano, L., Paya, J., and Rossignolo, J. A. (2021). Comparison of original and washed pure sugar cane bagasse ashes as supplementary cementing materials. Construction and Building Materials, 272, 122001.

[16] Zakaria, M., Ahmed, M., Hoque, M., and Shaid, A. (2018). A comparative study of the mechanical properties of jute fiber and yarn reinforced concrete composites. Journal of Natural Fibers.

[17] Ammayappan, L., Chakraborty, S., Musthafa, I., and Pan, N. C. (2022). Standardization of a chemical modification protocol for jute fabric reinforcement. Journal of Natural Fibers, 19(2), 562-574.

[18] Dewi, S. M. (2019). Enhancing bamboo reinforcement using a hose-clamp to increase bond-stress and slip resistance. Journal of Building Engineering, 26, 100896.

[19] Tokoro, R., Vu, D. M., Okubo, K., Tanaka, T., Fujii, T., and Fujiura, T. (2008). How to improve mechanical properties of polylactic acid with bamboo fibers. Journal of materials science, 43(2), 775-787.

[20] Shah, I., Li, J., Yang, S., Zhang, Y., and Anwar, A. (2022). Experimental investigation on the mechanical properties of natural fiber reinforced concrete. Journal of Renewable Materials, 10(5), 1307.

[21] Tirkey, N., and Ramesh, G. B. (2018). Experimental study on the banana fiber reinforced concrete. International Journal of Pure and Applied Mathematics, 119(18), 2053-2056.

[22] Elbehiry, A., Elnawawy, O., Kassem, M., Zaher, A., Uddin, N., and Mostafa, M. (2020). Performance of concrete beams reinforced using banana fiber bars. Case Studies in Construction Materials, 13, e00361.

[23] Senthilkumar, K., Saba, N., Rajini, N., Chandrasekar, M., Jawaid, M., Siengchin, S., and Alotman, O. Y. (2018). Mechanical properties evaluation of sisal fibre reinforced polymer composites: A review. Construction and Building Materials, 174, 713-729.

[24] Ahamed, M. S., Ravichandran, P., and Krishnaraja, A. R. (2021, February). Natural fibers in concreteA review. In IOP Conference Series: Materials Science and Engineering (Vol. 1055, No. 1, p. 012038). IOP Publishing.

[25] Elbehiry, A., Elnawawy, O., Kassem, M., Zaher, A., and Mostafa, M. (2021). FEM evaluation of reinforced concrete beams by hybrid and banana fiber bars (BFB). Case Studies in Construction Materials, 14, e00479.

[26] Hossain, M. U., Wong, J. J., Ng, S. T., and Wang, Y. (2022). Sustainable design of pavement systems in highly urbanized context: A lifecycle assessment. Journal of Environmental Management, 305, 114410.

[27] Farooqi, M. U., and Ali, M. (2022). A study on Natural Fibre Reinforced Concrete from Materials to Structural Applications. Arabian Journal for Science and Engineering, 1-21.

[28] Abdalfattah, I. A., Mogawer, W. S., and Stuart, K. (2022). Recycled polyethylene (RPE) modified asphalt mixtures: Performance predictions using pavement Mechanistic-Empirical design and evaluation of return on investment. Construction and Building Materials, 356, 129164.

[29] Hasnat, M., Ghazavi, M., Farina, A., Seitllari, A., and Kutay, M. E. (2022). Effects of Polymer-Coated Rubber Technologies with Mechanistic-Empirical Performance Analysis. In International Conference on Transportation and Development 2022 (pp. 166-178).

[30] Ehsani, Mehrdad, Pouria Hamidian, Pouria Hajikarimi, and Fereidoon Moghadas Nejad. "Optimized prediction models for faulting failure of Jointed Plain concrete pavement using the metaheuristic optimization algorithms." Construction and Building Materials 364 (2023): 129948.

[31] Islam, Mohammad Momeen Ul, Jie Li, Rajeev Roychand, and Mohammad Saberian. "Investigation of durability properties for structural lightweight concrete with discarded vehicle tire rubbers: A study for the complete replacement of conventional coarse aggregates." Construction and Building Materials 369 (2023): 130634.

[32] Cho, B. H., and Nam, B. H. (2022). Concrete composites reinforced with graphene oxide nanoflake (GONF) and steel fiber for application in rigid pavement. Case Studies in Construction Materials, 17, e01346.

[33] Onuaguluchi, O., Ratu, R., and Banthia, N. (2022). Effect of sodium sulfate activation on the early-age matrix strength and steel fiber bond in high volume fly ash (HVFA) cement mortar. Construction and Building Materials, 341, 127808.

[34] Rambabu, D., Sharma, S. K., and Abdul Akbar, M. (2022). A review on suitability of using geopolymer concrete for rigid pavement. Innovative Infrastructure Solutions, 7(5), 1-25.

[35] Tahir, M. F. M., Abdullah, M. M. A. B., Abd Rahim, S. Z., Hasan, M. R. M., Saafi, M., Jaya, R. P., and Mohamed, R. (2022). Potential of industrial By-Products based geopolymer for rigid concrete pavement application. Construction and Building Materials, 344, 128190.

[36] Abbass, M., and Singh, G. (2022). Durability of rice husk ash and basalt fibre based sustainable geopolymer concrete in rigid pavements. Materials Today: Proceedings, 61, 558-570.

[37] Mildawati, R., Puri, A., and Handayani, M. Z. (2022). Effects of Corn Stalks Ash as A Substitution Material of Cement Due to the Concrete Strength of Rigid Pavement. Journal of Geoscience, Engineering, Environment, and Technology, 7(1), 21-26.

[38] Trincal, V., Multon, S., Benavent, V., Lahalle, H., Balsamo, B., Caron, A., ... and Cyr, M. (2022). Shrinkage mitigation of metakaolin-based geopolymer activated by sodium silicate solution. Cement and Concrete Research, 162, 106993.

[39] Schrfl, C., Erk, K. A., Siriwatwechakul, W., Wyrzykowski, M., and Snoeck, D. (2022). Recent progress in superabsorbent polymers for concrete. Cement and Concrete Research, 151, 106648.

[40] Harki, A., Khawaja, B. Q., Al Jawahery, M. S., and Abdulmawjoud, A. A. (2022). Hybrid Steel Fiber of Rigid Pavements: A 3D Finite Element and Parametric Analysis. Coatings, 12(10), 1478.

[41] Affan, M., and Ali, M. (2022). Experimental investigation on mechanical properties of jute fiber reinforced concrete under freeze-thaw conditions for pavement applications. Construction and Building Materials, 323, 126599.

[42] Diaz, Y. G., Torres-Ortega, R., Saba, M., Olave, A. B., and Sanchez, J. T. (2022). TheoreticalExperimental Comparison of Behavior Between Deformations of Rigid Pavement Reinforced with Fibers and of Conventional Slabs. International Journal of Pavement Research and Technology, 1-13.

[43] Santhosh, J. C., Samal, S. R., Ganesh, V. N., Pavani, D., and Sridhar, R. S. (2022). Experimental Investigation on the Effect of Polypropylene Fibers with Respect to the Fatigue Behavior of Rigid Pavement. In Recent Developments in Sustainable Infrastructure (ICRDSI-2020)GEO-TRA-ENV-WRM (pp. 383-395). Springer, Singapore.

[44] Khan, M., Rehman, A., and Ali, M. (2020). Efficiency of silica-fume content in plain and natural fiber reinforced concrete for concrete road. Construction and Building Materials, 244, 118382.

[45] Rashid, M. U. (2020). Experimental investigation on durability characteristics of steel and polypropylene fiber reinforced concrete exposed to natural weathering action. Construction and Building Materials, 250, 118910.

[46] Ali, B., Hawreen, A., Kahla, N. B., Amir, M. T., Azab, M., and Raza, A. (2022). A critical review on the utilization of coir (coconut fiber) in cementitious materials. Construction and Building Materials, 351, 128957.

[47] Abdalfattah, I. A., Mogawer, W. S., and Stuart, K. (2022). Recycled polyethylene (RPE) modified asphalt mixtures: Performance predictions using pavement Mechanistic-Empirical design and evaluation of return on investment. Construction and Building Materials, 356, 129164.

[48] Khan, M., and Ali, M. (2018). Effectiveness of hair and wave polypropylene fibers for concrete roads. Construction and Building Materials, 166, 581-591.

[49] Hasani, M., Nejad, F. M., Sobhani, J., and Chini, M. (2021). Mechanical and durability properties of fiber reinforced concrete overlay: Experimental results and numerical simulation. Construction and Building Materials, 268, 121083.

[50] M.J. McCarthy, T.D. Dyer, Pozzolanas and Pozzolanic Materials, in: Leas Chemistry of Cement and Concrete, Elsevier, 2019: pp. 363467. https://doi.org/ 10.1016/B978-0-08-100773-0.00009-5.

[51] Nguyen, T. A., and Nguyen, T. H. (2022). Study on Mechanical Properties of Banana Fiber-Reinforced Materials Poly (Lactic Acid) Composites. International Journal of Chemical Engineering, 2022.

[52] Akid, A. S. M., Hossain, S., Munshi, M. I. U., Elahi, M. M. A., Sobuz, M. H. R., Tam, V. W., and Islam, M. S. (2021). Assessing the influence of fly ash and polypropylene fiber on fresh, mechanical and durability properties of concrete. Journal of King Saud University-Engineering Sciences.

[53] Jain, A., Sharma, N., Choudhary, R., Gupta, R., and Chaudhary, S. (2021). Utilization of non-metalized plastic bag fibers along with fly ash in concrete. Construction and Building Materials, 291, 123329.

[54] Farooqi, U. (2020). Potential Utilization of Wheat Straw in Concrete for Pavement Applications from Engineering Perspectives. PhD Dissertation.

[55] Cui, J. H., Xie, Z. Q., and Xiao, H. J., Cause Analysis on the Cracks in Concrete Plate of Canal Lining. In Applied Mechanics and Materials Vol. 405, pp. 2596-2599, 2013.

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

[57] M. Ali, A. Liu, H. Sou, and N. Chouw, Mechanical and dynamic properties of coconut fibre reinforced concrete, Construction and Building Materials, vol. 30, pp. 814-825, 2012.

[58] Farooqi, U., and Majid, A. (2019, July). Construction practices for first ever wheat straw reinforced concrete pavement for light traffic. In Fifth International Conference on Sustainable Construction Materials and Technologies. International Committee of the SCMT conferences.

[59] Kiruthika, A. V., and Veluraja, K. (2009). Experimental studies on the physico-chemical properties of banana fibre from various varieties. Fibers and Polymers, 10(2), 193-199.

[60] Ernest, E. M., and Peter, A. C. (2022). Application of selected chemical modification agents on banana fibre for enhanced composite production. Cleaner Materials, 5, 100131

[61] Moradikhou, A. B., Esparham, A., and Avanaki, M. J. ,. Physical and mechanical properties of fiber reinforced metakaolin-based geopolymer concrete. Construction and Building Materials, vol.251, pp.118-965, 2020.

[62] Y.H. Huang, Pavement Analysis and Design, University of Kentucky, 2006, ISBN: 0131424734..

[63] Akinyemi, Banjo Ayobami, and Chunping Dai. "Development of banana fibers and wood bottom ash modified cement mortars." Construction and Building Materials 241 (2020): 118041.

[64] Abrar, Muhammad. "WORKABILITY OF BANANA FIBERS REINFORCED CONCRETE FOR EASY POURING". 3rd Conference on Sustainability in Civil Engineering (2021).

[65] Attia, M. M., and Shymaa MM Shawky. "Banana fiber reinforced concrete: A review." NY Sci. J 14 (2021): 48-55.

[66] American Society for Testing and Materials. "ASTM C204: Standard Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus." (2000)

[67] ASTM International. "ASTM C143/C143M-09-Standard Test Method for Slump of Hydraulic-Cement Concrete." (2009).

[68] ASTM International. "ASTM C642-13." Standard Test Method for Density, Absorption, and Voids in Hardened Concrete (2013).

[69] Designation, A. S. T. M. "C215-14, Standard Test Method for Fundamental Transverse, Longitudinal and Torsional Resonant, Frequencies of Concrete Specimens." ASTM International (2014).

[70] ASTM, C. "ASTM C39: Standard test method for compressive strength of cylindrical concrete specimens." ASTM international West Conshohocken, PA, USA (2001).

[71] ASTM International. "ASTM C496/C496M-17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens." (2017).

[72] ASTM. "ASTM C78standard test method for flexural strength of concrete (using simple beam with)." (2002).

[73] American Society for Testing and Materials. "ASTM C293, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)." Philadelphia: ASTM, 2001.

[74] American Society for Testing and Materials. "ASTM C642: Standard Test Method for Density, Absorption, and Voids in Hardened Concrete." Philadelphia: ASTM, 2001.

[75] Arooj, K, and Ali, M. "Mechanical, Dynamic and Absorption Properties of Hybrid Fiber Reinforced Concrete for Rigid Pavements Application." Masters in Civil Engineering, Capital University of Science and technology (2021).

[76] Transportation Officials. Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide. AASHTO, (2010).

[77] Zhao, Chenggong, Zhiyuan Wang, Zhenyu Zhu, Qiuyu Guo, Xinrui Wu, and Renda Zhao. "Research on different types of fiber reinforced concrete in recent years: An overview." Construction and Building Materials 365 (2023): 130075.

[78] Chen, Yu, and Robert L. Lytton. "Exploratory analysis of LTPP faulting data using statistical techniques." Construction and Building Materials 309 (2021): 125025.

[79] Sok, Tetsya, Young Kyu Kim, and Seung Woo Lee. "Numerical approach to predict zero-stress temperature in concrete pavements." Construction and Building Materials 262 (2020): 120076.

[80] Zhang, Wenbing, Danda Shi, Zhenzhong Shen, Wei Shao, Lei Gan, Yuan Yuan, Peng Tang, Shan Zhao, and Yuansheng Chen. "Reduction of the calcium leaching effect on the physical and mechanical properties of concrete by adding chopped basalt fibers." Construction and Building Materials 365 (2023): 130080.

[81] Ma, Xiaomeng, Jinlong Pan, Jingming Cai, Zhuoyang Zhang, and Jinsheng Han. "A review on cement-based materials used in steel structures as fireproof coating." Construction and Building Materials 315 (2022): 125623.

[82] Afroz, Sumaiya, Quang Dieu Nguyen, Yingda Zhang, Taehwan Kim, and Arnaud Castel. "Evaluation of cracking potential parameters for low to high grade concrete with fly ash or slag." Construction and Building Materials 350 (2022): 128891.

[83] Khan, Inamullah, Tengfei Xu, Arnaud Castel, Raymond Ian Gilbert, and Mahdi Babaee. "Risk of early age cracking in geopolymer concrete due to restrained shrinkage." Construction and Building Materials 229 (2019): 116840.

[84] Szafraniec, Magorzata, Zbigniew Omiotek, and Danuta Barnat-Hunek. "Water absorption prediction of nanopolymer hydrophobized concrete surface using texture analysis and machine learning algorithms." Construction and Building Materials 375 (2023): 130969.

[85] Zhang, Peng, Qiaoyi Han, Jingjiang Wu, Yong Zhang, and Tianhang Zhang. "Mechanical properties of nano-SiO2 reinforced engineered cementitious composites after exposure to high temperatures." Construction and Building Materials 356 (2022): 129123.

[86] Banthia, Nemkumar, and Rishi Gupta. "Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete." Cement and concrete Research 36, no. 7 (2006): 1263-1267.

[87] Zhang, Zhidong, and Ueli Angst. "Microstructure and moisture transport in carbonated cement-based materials incorporating cellulose nanofibrils." Cement and Concrete Research 162 (2022): 106990.

[88] Ali, Babar, Liaqat Ali Qureshi, and Sibghat Ullah Khan. "Flexural behavior of glass fiber-reinforced recycled aggregate concrete and its impact on the cost and carbon footprint of concrete pavement." Construction and Building Materials 262 (2020): 120820.

[89] Transportation Officials. Mechanistic-empirical pavement design guide: a manual of practice. AASHTO, 2008.

[90] ARA Inc. 2004b. Guide for mechanistic-empirical design of new and rehabilitated pavement structure, Part 3Design analysis chapter 4: Design of new and reconstructed rigid pavements. Washington, DC: National Cooperative Highway Research Program.

[91] Yang, Xu, Zhanping You, Jacob E. Hiller, Mohd Rosli Mohd Hasan, Aboelkasim Diab, and Sang Luo. "Sensitivity of rigid pavement performance predictions to individual climate variables using pavement ME design." Journal of Transportation Engineering, Part B: Pavements 146, no. 3 (2020): 04020028.

[92] Abd El-Hakim, Ragaa T., Gamal M. Elgendy, Sherif M. El-Badawy, and Mohamed Amin. "Performance evaluation of steel slag high performance concrete for sustainable pavements." International Journal of Pavement Engineering 23, no. 11 (2022): 3819-3837.

[93] Hall, Kevin D., and Steven Beam. "Estimating the sensitivity of design input variables for rigid pavement analysis with a mechanisticempirical design guide." Transportation Research Record 1919, no. 1 (2005): 65-73.

[94] MUKABI, John N. "Application of Recently Developed Mechanistic-Empirical Methods for the Design of Heavily Loaded Pavement Structures."

[95] Agarwal, S. K. "Pozzolanic activity of various siliceous materials." Cement and concrete research 36, no. 9 (2006): 1735-1739.

[96] Pourkhorshidi, A. R., M. Najimi, T. Parhizkar, F. Jafarpour, and B. Hillemeier. "Applicability of the standard specifications of ASTM C618 for evaluation of natural pozzolans." Cement and Concrete Composites 32, no. 10 (2010): 794-800.

[97] Ehsani, Mehrdad, Pouria Hamidian, Pouria Hajikarimi, and Fereidoon Moghadas Nejad. "Optimized prediction models for faulting failure of Jointed Plain concrete pavement using the metaheuristic optimization algorithms." Construction and Building Materials 364 (2023): 129948.

[98] Tahir, Muhammad Ahsan, Saadia Tabassum, and Abdur Rahim. "Impacts of pavement performance indicators on traffic oriented parameters and road safety." Mehran University Research Journal of Engineering and Technology 41, no. 4 (2023): 187-197.

[99] Kaloop, Mosbeh R., Sherif M. El-Badawy, Jungkyu Ahn, Hyoung-Bo Sim, Jong Wan Hu, and Ragaa T. Abd El-Hakim. "A hybrid wavelet-optimally-pruned extreme learning machine model for the estimation of international roughness index of rigid pavements." International Journal of Pavement Engineering 23, no. 3 (2022): 862-876.

[100] Cho, Byoung Hooi, and Boo Hyun Nam. "Concrete composites reinforced with graphene oxide nanoflake (GONF) and steel fiber for application in rigid pavement." Case Studies in Construction Materials 17 (2022): e01346.

[101] Abdulmatin, Akkadath, Weerachart Tangchirapat, and Chai Jaturapitakkul. "An investigation of bottom ash as a pozzolanic material." Construction and Building Materials 186 (2018): 155-162.

[102] een, Ferhat, Ahmet zbayrak, and Bekir Akta. "Experimental modal analysis of fly ash-based geopolymer concrete specimens via modal circles, mode indication functions, and mode shape animations." Cement and Concrete Composites (2023): 104951.

[103] Robl, Thomas, Robert Jewell, Tristana Duvallet, ERGN GLCAN, Robert Rathbone, and Anne Oberlink. "The Determination of Pozzolanic Activity:

Comparison of ASTM and EN Strength Activity Methods and Electrical Resistivity." Advances in Civil Engineering Materials 11, no. 2 (2022).

[104] Jameel, Muhammad Sohail, Muhammad Jawad Khan, Ali Raza, and Shah Rukh Khan. "Assessment of Workability of Banana Fiber Reinforced Concrete for Easy Pouring." (2022).

[105] Ali, Babar, Marc Azab, Hawreen Ahmed, Rawaz Kurda, Mohamed Hechmi El Ouni, and Ahmed Babeker Elhag. "Investigation of physical, strength, and ductility characteristics of concrete reinforced with banana (Musaceae) stem fiber." Journal of Building Engineering 61 (2022) 105024.

[106] Abrar, Muhammad. "Mechanical, Dynamic and Absorption Properties of Concrete with Hybrid Natural Fibers of Varying Lengths." PhD diss., CAPITAL UNIVERSITY, 2022.

[107] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14), American Concrete Institute, Farmington Hills, Mich., 2014.

[108] ACI Committee. (2005). Building code requirements for structural concrete (ACI 318-05) and commentary (ACI 318R-05). American Concrete Institute.

[109] Wang, Qiang, Mengmeng Zhou, Mohanad Muayad Sabri Sabri, and Jiandong Huang. "A Comparative Study of AI-Based International Roughness Index (IRI) Prediction Models for Jointed Plain Concrete Pavement (JPCP)." Materials 15, no. 16 (2022): 5605.

[110] Ali, M. F., Ali, S. H., Ahmed, M. T., Patel, S. K., and Ali, M. W. (2020). Study on strength parameters of concrete by adding banana fibers. Int. Res. J. Eng. Technol, 7(3), 4401-4404.

[111] Boobalan, S. C., M. Salman Shereef, P. Saravanaboopathi, and K. Siranjeevi. "Studies on green concreteA review." Materials Today: Proceedings 65 (2022): 1404-1409.

[112] Sivakrishna, A., Adeyemi Adesina, P. O. Awoyera, and K. Rajesh Kumar. "Green concrete: A review of recent developments." Materials Today: Proceedings 27 (2020): 54-58.

[113] Chen, Huaguo, Cheuk Lun Chow, and Denvid Lau. "Developing green and sustainable concrete in integrating with different urban wastes." Journal of Cleaner Production 368 (2022): 133057.

Appendix A

Table A1: Linear Shrinkage (%) and Mass Loss (%) of PC and Concrete having Banana Leaf Ash and Banana Fiber

Parameters	PC	C1	C2	C3
Linear Shrinkage	0.082	0.073	0.069	0.064
ML (%) at Temp 50(C)	-0.028	-0.037	-0.049	-0.053
ML (%) at Temp 75(C)	-0.039	-0.052	-0.065	-0.079
ML (%) at Temp 100(C)	-0.098	-0.113	-0.127	-0.139

TABLE A2: Dynamic Properties of PC and Concrete having Banana Leaf Ash and Banana Fiber

Concrete	**FL (Hz)**	**FT (Hz)**	**FTR (Hz)**	**Damping ratio (%)**	**DME (GPa)**	**DMR(GPa)**	**Poisson ratio(-)**
PC	3865±423	3529±463	3446±523	1.76±0.43	2.12±1.24	3.96±1.53	0.26±0.26
C1	3408±401	3298±432	3337±504	3.12±0.24	5.23±1.43	4.04±1.24	0.65±0.21
C2	3376±352	3165±397	2304±495	3.33±0.19	6.11±1.32	4.15±1.32	0.73±0.16
C3	2064±284	1667±353	1251±385	4.34± 0.17	6.57±1.27	4.31±1.43	0.76±0.14

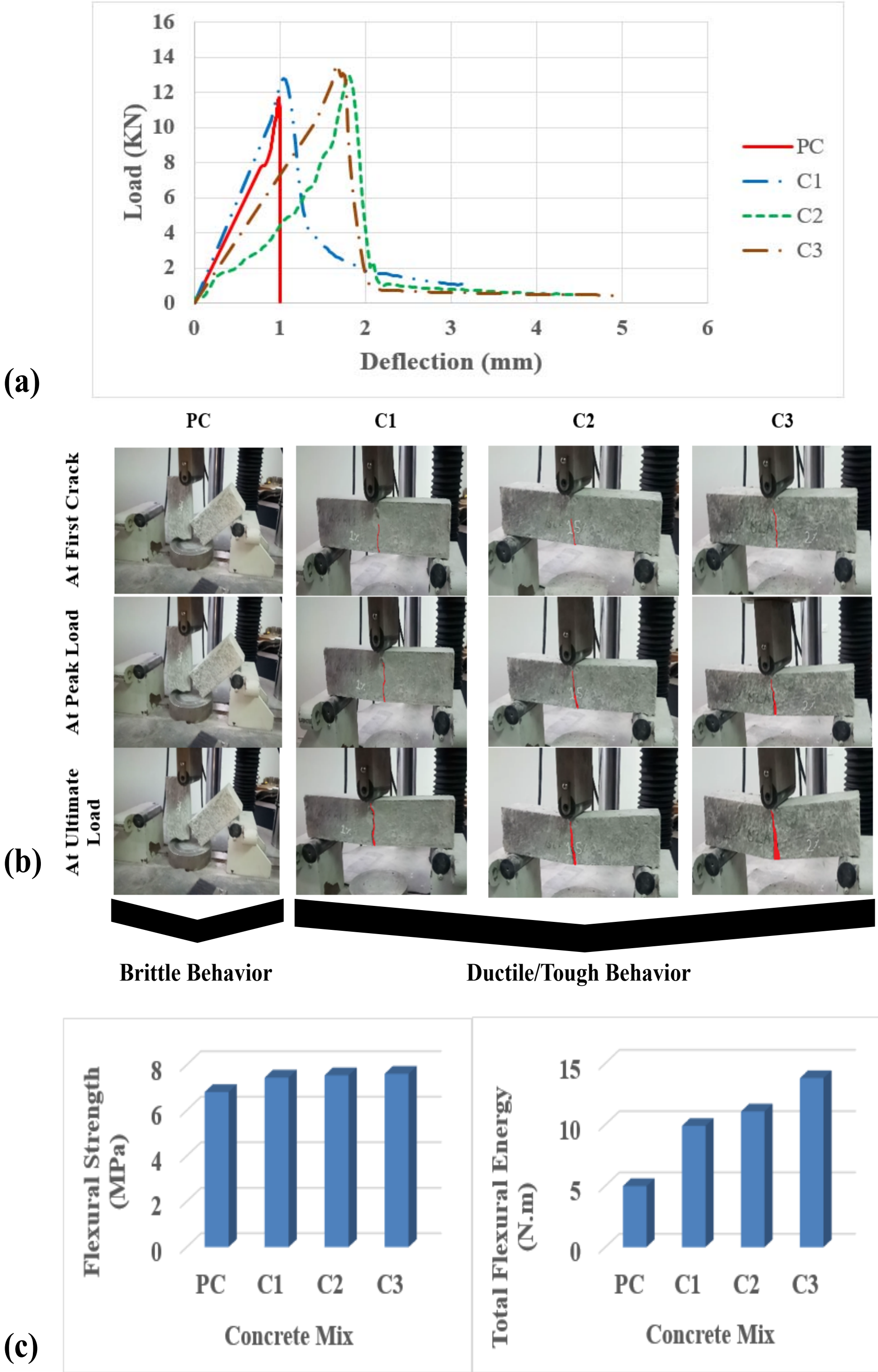
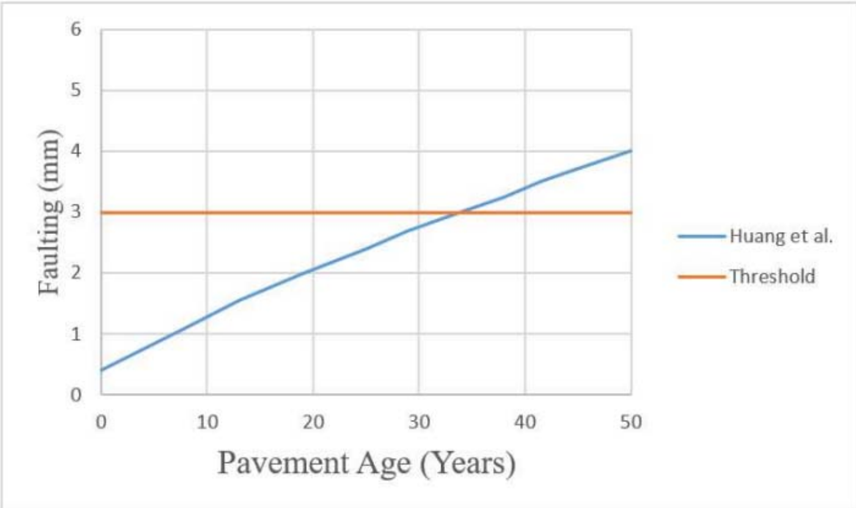


FIGURE A1: a) Load Deflection Curves of Samples b) Failure Behavior c) Comparison of Flexural Properties

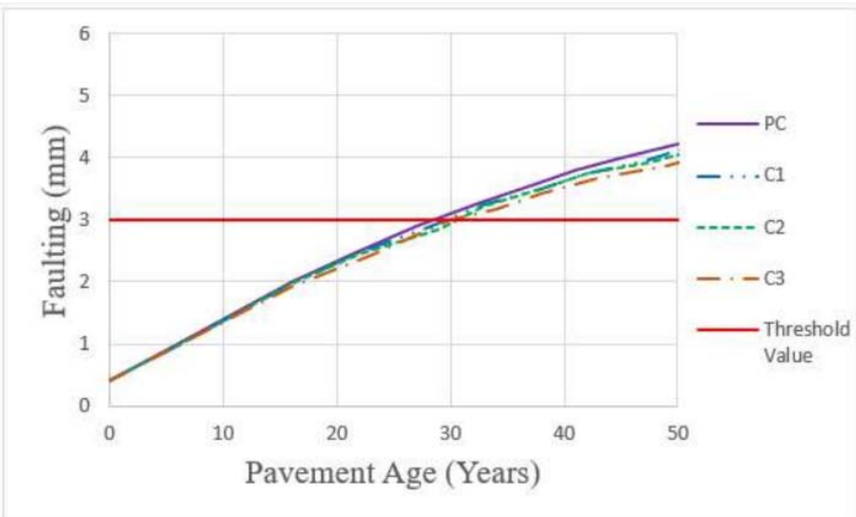
TABLE A3: Flexural strength properties of PC and Concrete having banana leaf ash and banana fiber

Sample	**MoR (MPa)**	**Δ (mm)**	**FEP (N.m)**	**FEF (N.m)**	**FET (N.m)**	**FTI(-)**
PC	6.81±0.44	1.00±0.02	4.98±0.58	-	4.98±0.58	1±0.00
C1	7.44±0.01	1.05±0.31	6.41±1.68	4.24±4.68	10.65±8.54	1.66±1.68
C2	7.54±0.07	1.82±0.09	8.33±0.21	2.75±0.84	11.07± 1.04	1.33±0.10
C3	7.61±0.07	1.74±0.57	11.21±3.12	3.45±1.53	14.66±1.59	1.31±0.23

Appendix B

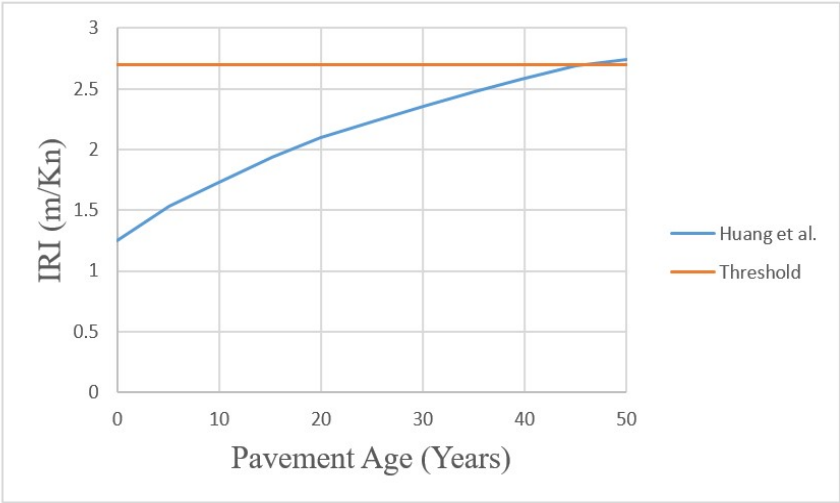


a)

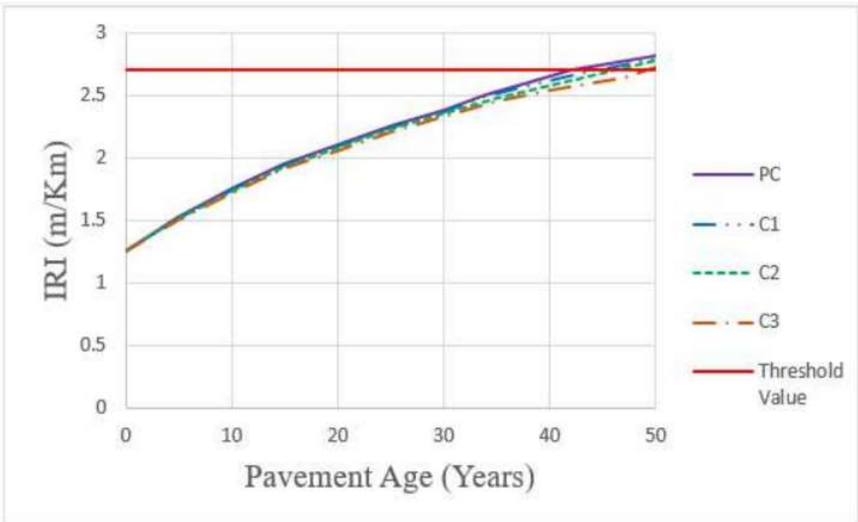


b)

FIGURE B2: Faulting vs Pavement Age for Pavement after Exposure to Extreme Temperatures a) for Huang Rigid Pavement b) Current Research



a)



b)

FIGURE B3: IRI vs Pavement Age for Pavement after Exposure to Extreme Temperatures a) for Huang Rigid Pavement b) Current Research

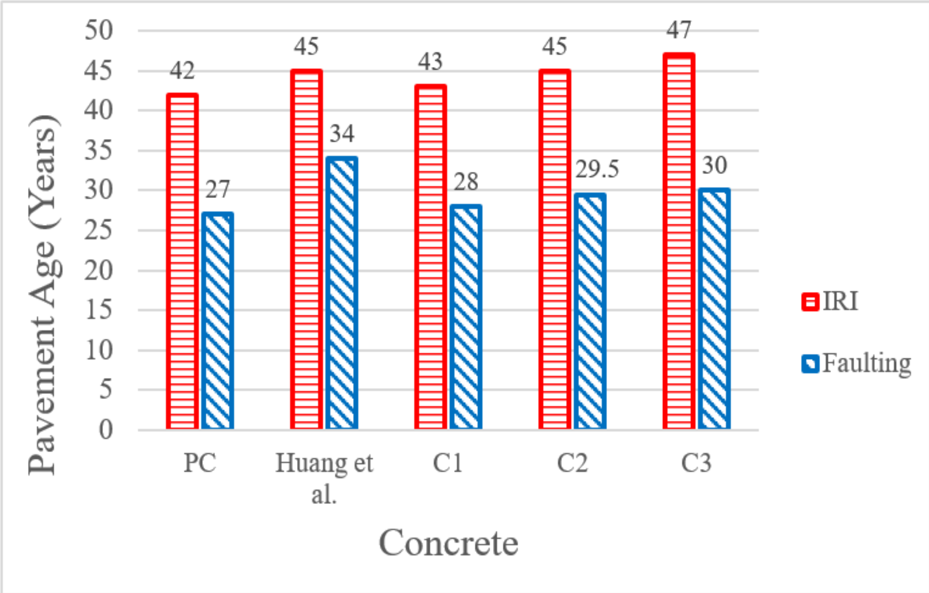


Figure B4: IRI and Faulting Relation between Pavement Age and Concrete Type after Exposure to High Temperature

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