AMERICAN UNIVERSITY OF BEIRUT

# EVALUATION OF SUSTAINABLE CONCRETE PRODUCED WITH INDUSTRIAL HEMP AND RECYCLED AGGREGATES

by
NOUR HUSSEIN CHERKAWI

A thesis
submitted in partial fulfilment of the requirements
for the degree of Master of Engineering
to the Department of Civil and Environmental Engineering
of the Maroun Semaan Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
September 2019

AMERICAN UNIVERSITY OF BEIRUT

# EVALUATION OF SUSTAINABLE CONCRETE PRODUCED WITH INDUSTRIAL HEMP AND RECYCLED AGGREGATES

by
NOUR HUSSEIN CHERKAWI

Approved by:

Dr. Bilal Hamad, Professor — Advisor
Civil and Environmental Engineering

Dr. Ghassan Chehab, Associate Professor — Member of Committee
Civil and Environmental Engineering

Dr.Mohamad Farran, Professor — Member of Committee
Agriculture

Date of thesis defense: September 9, 2019

## AMERICAN UNIVERSITY OF BEIRUT

## THESIS, DISSERTATION, PROJECT RELEASE FORM

Student Name: Cherkawi Nour Hussein
Last First Middle

● Master's Thesis ○ Master's Project ○ Doctoral Dissertation

☐ I authorize the American University of Beirut to: (a) reproduce hard or electronic copies of my thesis, dissertation, or project; (b) include such copies in the archives and digital repositories of the University; and (c) make freely available such copies to third parties for research or educational purposes.

☒ I authorize the American University of Beirut, to: (a) reproduce hard or electronic copies of it; (b) include such copies in the archives and digital repositories of the University; and (c) make freely available such copies to third parties for research or educational purposes
after: **One --- year from the date of submission of my thesis, dissertation, or project.**
**Two --- years from the date of submission of my thesis, dissertation, or project.**
**Three X years from the date of submission of my thesis, dissertation, or project.**

Signature Date
Nour 19 - 09 - 2019

# ACKNOWLEDGMENTS

I would like to express my sincere appreciation to my advisor Prof. Bilal Hamad for his continuous support, guidance and technical advices through all my thesis stages. I would also like to thank Dr.Ghassan Chehab for his technical advices and valuable time through the learning process of my master and Dr.Mohamad Farran for his support and time for reading my dissertation.

I also express my profound gratitude to Ms.Zakia Deep for her administrative assistance and to Mr.Helmi Khatib, Ms. Dima Hassanieh and Mr. Abed El-Sheikh for their technical advices and help.

I am deeply thankful to my friends Dr.Zeinab el Mawla and Eng.Fatima Hamadeh and Dr.Samer Ghoson for their continuous support in each stage of my thesis.

Finally, I would like to thank my family, my main support system to complete this journey.

# AN ABSTRACT OF THE THESIS OF

Nour Hussein Cherkawi for Master of Engineering
Major: Civil engineering

Title: Evaluation of sustainable concrete produced with industrial hemp and recycled aggregates

Hemp and Recycled Aggregate Concrete (HRAC) is a sustainable concrete material prepared by partial or full substitution of natural coarse aggregates with a combination of recycled concrete aggregates (RCA) and industrial hemp fibers. The application of HRAC offers multiple benefits related to sustainable development. The new material would help in resolving the depletion of natural aggregate resources, mitigate the negative environmental impact of the construction and demolition waste (CDW) material of concrete-based structures, incorporate renewable and agricultural industrial hemp fibers as partial substitute of natural aggregates, and solve socio-economic problems associated with illegal farming of hashish, the illegal sister plant of Hemp, in Hermel-Bekaa (Lebanon) and elsewhere.

The objective of the study is to achieve a concrete mix that incorporates RCA and is reinforced by industrial hemp fibers while assuring that the designed mix meets the requirements of high performance concrete including workability and durability. Tests would include plastic state slump and hardened state mechanical properties such as compressive strength, tensile splitting strength, modulus of elasticity, and flexural strength of standard beams. Also several characterization tests will be performed on the recycled aggregates and hemp fibers treated with different treatment types.

CONTENTS

# ILLUSTRATIONS

# TABLES

# CHAPTER 1

# INTRODUCTION AND BACKGROUND

## 1.1 Introduction

Portland Cement Concrete (PCC) can be considered as the most widely used construction material locally and all over the world. However, like many other industries, the construction industry is rendering its practices towards being more sustainable and environment-friendly. Thus, various stakeholders are paying efforts to adopt sustainable aspects by introducing green concepts into this sector's practices. These new concepts aim at minimizing the depletion rate of natural resources and lessening the negative social and environmental impacts. In light of these efforts, the commonly used conventional PCC mixes have been claimed to be non-environmental friendly due to several concerns related to the depletion of natural resources and high energy consumption needed for the production of its raw materials. Examples of sustainable techniques that are used to reduce the impact of PCC production on natural resources include the use of renewable resources, the implementation of energy-efficient systems, the use of recycled materials, and the use of "green" construction materials such as natural fibers in concrete mixes.

## 1.2 Construction demolition waste

Construction and demolition wastes (CDW) are produced worldwide due to the development of cities and/or resulting from emergencies such as earthquakes and wars.

CDW can be defined as a mixture of surplus materials generated during new construction, renovation, and demolition of buildings, roads, bridges, and other structures (Cheng and Ma, 2013). These wastes have become an extra burden on the environment especially in countries that have no plans for recycling and reusing. Therefore, the incorporation of such wastes in PCC mixes has become a commonly proposed dual solution in minimizing waste disposal and conserving natural resources.

In Lebanon, significant amounts of CDW have been produced in the last few years. This is due to the boost in construction activities that led to the annual production of 500,000 Tons of CDW in the city of Beirut by the demolition of a large number of existing old facilities either because of the limited land for new development or due to the fact the existing buildings have structurally defected. Besides, the 2006 Israeli war on Lebanon and the Nahr El Bared conflict in North Lebanon in 2007 can be considered as major reasons for the boom in CDW production estimated to be 5.5 million cubic meters and 0.6 million cubic meters, respectively. A study conducted by Tamraz (2011) has shown that 85% by weight of CDW is composed of cementitious products.

Moreover, the construction sector produces another source of cementitious-based CDW that comes from PCC quality control procedures. Common practice requires the sampling and laboratory testing of standard cylinders. These tested PCC cylinders constitute a significant portion of the dumped CDW. A typical PCC ready mix plant generates between 20 and 80 Tons of waste per month. Thus, the accumulation of such CDWs has had a detrimental impact on the environment especially in developing countries that lack plans and methods to manage, handle, and dispose of dismantled waste properly.

In light of what preceded, many countries have set initiatives to make use of such wastes that can be considered as valuable misused resources. Many practices involved the utilization of the cementitious portions of CDW as recycled concrete aggregates (RCA). In 2004, the Federal Highway Association (FHWA) in the USA reported that 38 States recycle concrete as an aggregate base for roadways and 11 States incorporate recycled aggregates into newly produced PCC mixes. States that use recycled aggregate concrete (RAC) have reported that PCC with RCA equally performs as the conventional PCC prepared with natural coarse aggregates (NCA). CDW usually contains intrusions such as metals, wood, glass, plaster, etc. Therefore, the first concern reported in almost all of the research studies is the removal of those materials to maintain a high quality of RCA. Also, care must be taken to prevent contamination by other materials that can be troublesome, such as asphalt, soil and clay balls, chlorides, glass, gypsum board, sealants, paper, plaster, wood, and roofing materials. Also, the American Concrete Institute (ACI) Committee 555 report (2001) stated that the recycling of concrete is a relatively simple process. After the removal of the non-cementitious component, RCA can be produced by breaking and crushing existing concrete into a material with a specified size and quality. The quality of RCA is very dependent on the quality of the recycled material used.

### 1.3 Fibers

Encapsulating natural resources in concrete to produce eco-friendly concrete is one of the main research interests. Fiber-reinforced concrete is a green concrete composed of cement, water, and aggregates and randomly dispersed discontinuous fibers. Concrete is a material strong in compression but weak in tension and has a low fracture toughness. To prevent failure of concrete, a material having high tensile strength and a suitable thermal behavior such as steel and fibers is used. Adopting fibers in reinforced concrete dates back to an early age where horsehair and straws were adopted to strengthen mudbricks. In 1990, the concept of using asbestos was initiated. Eleven years later, the concept of incorporating fibers in concrete is introduced. Back to 1950, subsequently to the classification of asbestos as health risk fiber reinforced concrete has become the concern of researchers. In 1963, a turning point was made validating the usage of fibers in concrete. Since then and after 2000, all types of fibers are used in the structural concrete element.

Lebanon evidently lacks any guidelines on the use of RCA (Srour et al. 2012). However, few research studies have been conducted targeting the management and use of CDW in Lebanon (Tamraz 2011, Srour et al. 2013, and Al Hassanieh et al. 2016). Recently, research on the use of RCA in PCC has been accomplished by Dawi et al. (2015) as part of a Master's thesis work at AUB. The source of RCA was normal and high strength concrete cylinders, after being tested and crushed, from local batching plants. The main findings of this research show that the replacement of natural coarse aggregates (NCA) with different percentages of recycled coarse aggregates (RCA) did not harm the consistency of fresh concrete. As for hardened plain concrete properties, average reductions of 9.8%, 13.46% and 9.23% were recorded in the ultimate compressive strength, splitting tensile strength and flexural strength, respectively. The reductions were not affected by the percentage replacement used. The strength reduction that was noted in the plain concrete tests did not harm the structural behavior of reinforced concrete beams prepared by replacing portion (40%) or all (100%) of the natural coarse aggregates with recycled coarse aggregates. There was no significant difference in the ultimate load reached or load-deflection behavior of beams tested to fail in the flexural or shear or bond splitting of the concrete cover in the splice region that could be related to the percentage replacement of NCA with RCA. Results of this research program support the recommendation of the usage of RCA in PCC, produced by crushing tested concrete cylinders, in the concrete construction industry.

In addition, another study investigated the properties of fine RCA aggregates in comparison with that of local limestone aggregates (Al Hassanieh et al. 2015). This study has proven the use of a 30% replacement of fine aggregates with RCA in asphalt concrete mixes. In addition, physical and chemical material characterization tests were conducted to determine the properties of RCA as compared to NCA. One of these tests was the scanning electron microscopy (SEM) to evaluate the difference in surface texture between NCA and RCA. The results showed that RCA processes a rougher surface and larger surface area per unit mass of aggregates. Therefore, the results of such tests can be utilized to better understand the effect of replacing natural aggregates with RCA and thus changing the mix proportions accordingly.

Another area that Lebanon is struggling with is the agricultural sector which is facing high production costs and minimal profit. Consequently, the Lebanese farmers shifted toward illegal and more profitable plants such as hemp that is commonly known as “hashish”. The government officials have been trying to find alternative types of agriculture; however, all these efforts have not been fully successful. Lately, the Ministry of Agriculture (MoA) and the United Nations Development Program (UNDP) are implementing a project that monitors the farming of industrial hemp and its use in legal activities such as construction. Note that one of the main targets of the UNDP project was to provide farmers with legal plantation alternatives instead of the illegal hemp, one of which was the industrial hemp plant that is drug-free and commonly planted worldwide. According to the most recent Agricultural Census (2010 – 2011) published by the

Ministry of Agriculture (MoA) and the Food and Agriculture Organization (FAO) in 2014, the total agricultural area is estimated at 332,000 hectares (32% of total Lebanon surface area). A total of 230,000 hectares is cultivated of which half is irrigated. Twenty five percent of Lebanon cultivated area, around 57,600 hectares of the cultivated land (of which 55% irrigated) are located in the Baalbek – Hermil area and planted mainly with annual crops such as cereals, pulses, tubers, industrial crops, and permanent crops such as stone fruits, olives, grapes and pome fruits. Fallow and abandoned lands were estimated to be around 5,360 and 16,760 hectares, respectively. The Baalbek – Hermil area has been known for the cultivation of the drought-resistant illicit crop, commercial hemp (*Cannabis sativa L.*). The Lebanese government has banned the cultivation of this rain-fed crop since the leaves and flowers of commercial hemp contain high levels of a psychoactive compound (Δ-9-tetrahydrocannabinol) known as THC (House et al. 2010). There are no precise figures for the area of the commercial hemp cultivation but the government eradicated 3,500 hectares in 2011; little eradication was performed in 2015 and no eradication has been implemented in 2016. The UNDP and MoA report (2011) shows the results of a trial where different industrial hemp varieties, with very low THC levels, were cultivated under irrigated conditions (seeds sown in July) in Tel Amara of the Lebanese Agricultural Research Institute. The varieties Futura 75 and Carmen were selected the most suitable for North Bekaa Valley area as they showed better performance in terms of grain and straw yield while demonstrating higher resistance to fungal diseases. It is worth mentioning that the varieties planted in this study did not reach their standard heights. In addition, since the plants were kept to mature in the field, the resulting fibers were considerably lignified which make them difficult to clean and usable only in some non-woven industrial fiber applications; probably as insulating materials. Despite the agronomic success, and its proven productivity in comparison with cereals and pulses, it was concluded that hemp will not be easily adopted by farmers as an alternative to illicit crop cultivation (which results in a profit of more than $8,000/hectare) unless value-added processing was established in Lebanon. Hence, selling hemp as raw material (i.e. straw, seeds) will not generate sufficient revenue to attract farmers, as such a financially sound hemp processing business is the only means for promoting hemp cultivation in Lebanon.

In line with the above, and in order to partially solve the socio-economic problems growers in Baalbek – Hermil face it is expected, with making the required lobbying campaigns and launching awareness programs, that the public and private sectors would be more prone to invest in the cultivation of an industrial crop. Consequently, a renewed interest in the industrial hemp is being envisaged as a drought resistant plant cultivated to produce: (i) seeds with high market demand as birds feed (Farran et al. 2014) or to be cold pressed for the production of high quality hemp oil for human consumption and for manufacturing cosmetic products, (ii) high quality fibers for the textile industry, (iii) special type of fibers to fortify the concrete mix, (iv) environment friendly insulating materials, and (v) straw for animal feedings or as bedding materials in animal houses.

A feasibility study was conducted by Awwad et al. (2012a and 2012b) on the cultivation of industrial hemp conducted by the UNDP and MOA’s project where it showed that the farming of this crop is a beneficiary business, and would be strongly supported by the use of hemp fibers in concrete, resulting in demand increase and a prospering agricultural crop.

### *1.3.1 Importance of fiber reinforced concrete*

- **Durability**

Concrete is a brittle material susceptible to cracking at the plastic and hardened stage. Plastic shrinkage takes place when the evaporated water at the concrete surface, which is very weak in tension, exceeds the amount of bleeding water- causing volume changes therefore, surface cracking. However, at the hardened state water present in concrete pores tends to evaporate resulting in volume changes that being restricted by the aggregate and steel reinforcement initiates cracks. To mitigate concrete cracking, the fiber reinforced concrete concept is implemented. Dispersed fibers reduce, at the plastic stage, the development of large capillaries rising water thus inhibiting the formation of plastic settlement cracking and lowering concrete permeability. At the hardened state, FRC increases concrete resistance to abrasion and impact forces. When concrete is compressed, fibers hold the concrete together therefore, reducing shattering forces. Besides, uniform bleeding of concrete due to the blocking mechanism of fiber maintains a constant water-cement ratio at the surface of concrete presenting a higher abrasion resistance. Moreover, fibers assure uniform dispersion of impact throughout the concrete increasing ability of concrete to impact forces. Failure modes of concrete beams with and without hemp fibers are shown in Figure 1.

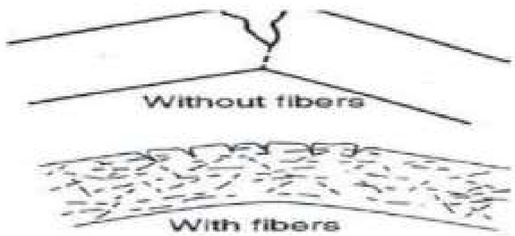



Figure 1. Failure of Concrete with and without fibers

- **Concrete property**

Implementing fibers in concrete affects the concrete properties differently. Although compressive strength is the main concrete property but fibers affect mostly the flexural strength of concrete. Studies indicated that FRC has minor outcome on concrete compressive strength (0% to 15% improvement) while it increases flexural strength and toughness of concrete. Toughness is the capability of a material to absorb the energy when stressed without fracturing and it is manifested by the area under stress-strain curve. Fibers increase flexural strength and toughness up to 4 times and 40 times respectively (*Figure 2*). Moreover, studies indicated that the fibers increase concrete tensile strength.

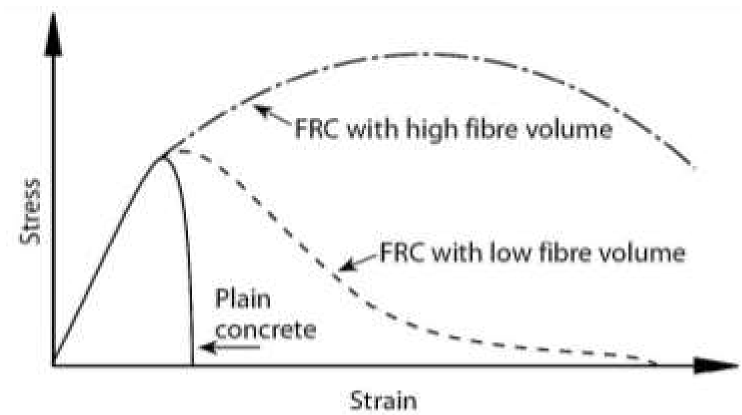



Figure 2. Stress-Strain curve of concrete with and without fibers

### *1.3.2 Type of fibers*

In the last 30 years, after, extensive research on FRC, different types of fiber were found suitable for various concrete applications. Steel, glass, synthetic and natural fibers are the main fibers forms implemented in concrete.

a. *Steel fibers* (*Figure 3*) are widely used in concrete applications. Multiple shapes, such as hooked, straight, paddled, rounded and mesh are thin with a small diameter ranging between 0.25mm to 0.75 mm.Steel fibers, having a significant high tensile strength of 1700 N/m$^2$,improve flexural strength, impact resistance and fatigue strength of concrete. Corrosion and rusting of steel may limit its use at the concrete surface but it can be used in conjunction with a reinforcement steel bar in roads overlay, bridges deck and thin shells and plates.

Figure 3. Steel fibers

b. *Glass fibers* (*Figure 4*), recently engaged in concrete, have many useful advantages. This material provides GFRC with an insulation property besides cracks propagation control, matrix strengthening when concrete is subjected to mechanical and thermal stresses. The main disadvantage of this material is its brittle and low creep behavior. GFRC is generally employed in exterior buildings envelope and in architectural precast concrete.

Figure 4. Glass fibers

c. Synthetic fibers (*Figure 5*) are manufactured polymer-based material encapsulated in concrete. Carbon, nylon, polyester, polypropylene and polyethylene are the common forms of synthetic fibers. Synthetic fibers that do not corrode are characterized by low water absorption and shrinkage property, in addition to its high resistance to chemicals.

   SNFRC reduces plastic and settlement cracks, increases energy absorption therefore concrete toughness and increases its resistance to impact.

Figure 5. Polypropylene fibers

d. Natural fibers, locally widely existing, are green material used in concrete as an alternative to steel and synthetic fibers. These fibers are divided into vegetable origin (wood,hast,leaf and seed/fruit fibers) and animal origin (wool, hair, and silk fibers).Their main advantages are the low energy consumption and low cost relative to other concrete material. Studies revealed using natural fibers increases the ductility and flexural strength of concrete but stressed the durability concern issue because natural fibers degrade in alkaline environment.

**1.4 Research objectives**

The work in this research studies the influence of using recycled aggregate along with hemp fibers on concrete properties. For a better understanding of concrete mixes behaviour. Phase one is set to explore the mineralogical, chemical and physical properties of hemp fibers. Phase two is divided into two tasks. The first task is to select the optimal treatment of hemp fibres that is able to enhance its surface thus resulting in better adhesion with concrete mixes. The second task is to select the best cocrete ix including the optimal variables investigated in this research.

**1.5 Research significance**

The significance of the proposed research program is three-fold: (i) it mitigates the shortage problem in natural resources, (ii) it provides a mean for the consumption of CDW by replacing different percentages of natural coarse aggregates (NCA) with recycled concrete aggregates (RCA), and (iii) it incorporates renewable and agricultural industrial hemp fibers as partial substitute of natural aggregates. Attaining a hemp recycled aggregate concrete (HRAC) mix using locally available recycled and natural materials will have significant implication on the concrete industry in Lebanon and worldwide. The application will be in normal strength reinforced concrete. The significance of the research is also reflected in testing the hypothesis that partial substitution of natural aggregates with a combination of hemp and RCA would not lead to reduction in the plastic and hardened mechanical properties of concrete.

### 1.6 Research methodology

The extensive experimental program throughout this thesis consists of two main phases: material characterization and mesoscale level testing. Material characterization involves the selection of the optimum fibers treatment by conducting chemical, physical and mineralogical tests (SEM, XRD, TGA, tensile strength) to understand the effect of the applied chemicals on the tensile strength, thermal and physical properties of the hemp.. Mesoscale testing was completed to study the effect of different variables (fiber length, MSA, fiber treatment) incorporated in the concrete properties, therefore choosing the optimum concrete mix used in future work.

### 1.7 Thesis outline

This thesis involves six chapters. Chapter one consists of an introduction to the concept of implementing hemp recycled aggregate concrete and the motivation towards green concrete in addition to the research methodology and objective. Chapter two presents a literature review of incorporating recycled aggregate and hemp fibers in concrete on the international and local levels. The third chapter lists the different materials used in the experimental program. The fourth chapter examines the microstructure of the hemp fibers, while the fifth chapter explains the experimental plan and illustrates the results of concrete testing. Chapter six includes the findings summary and the conclusion.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Relevant Literature – Fiber reinforced concrete

In 2012, Islam, S., Hussain et al. investigated the properties of fiber-reinforced composite concrete in a comparative manner for both normal-strength concrete (NSC) and high-strength concrete (HSC). Ten mix batches of NSC and HSC with coconut coir fiber volume dosage of 0%, 0.5%, and 1.0% indicated a reduction in concrete workability as the fiber dosage increased. Moreover, the compressive strength of NSC and HSC decreased compared to plain concrete.

Ferdiansyah, T., & Abdul Razak, H 2011, explored the mechanical properties of black sugar palm fiber-reinforced concrete. Three fibres lengths of 15, 25, and 35 mm in 4 volume fractions, namely 0.2%, 0.4%, 0.6%, and 0.8%, were utilized to report the values of compressive, flexural, toughness, first crack deflection, first crack toughness, and toughness indices for ages up to 90 days. Results indicated that the addition of palm fibers slightly increased the flexural strength of concrete while it had no significant effect on the compressive strength. Furthermore, an optimum mix of 0.8% Volume fraction and 35 mm length fiber led to a higher toughness and ductility compared with other mixes.

John Branston et al. 2017, studied the effect of two types of basalt fiber, plain chopped (BF) .In addition, a new basalt concrete reinforcement product called minibars (MB) on the mechanical properties of concrete. Concrete specimens having different lengths and dosages of fibers showed that fiber dosages beyond 12 kg/m3 and 40 kg/m3 of BF and

MB, respectively caused fibers balling and workability issues. In addition, flexural loading indicated that the increase of fiber dosage increased first-crack strength for both types but in the case of MB the first crack was difficult to recognize because of the ductile failure .An optimum flexural behavior was recorded for 50 mm and 12kg/m$^3$ dosage for BF whereas 20 kg/m$^3$ dosage was significant for MB.

Ivanka Netinger Grubeša et al. 2018 studied the influence of hemp fibers on concrete fire resistance. SEM, TGA/DSC, FTIR and crystallinity index technics were utilized to characterize polypropylene and hemp fibers treated differently. All concrete mixtures were heated up to 400 °C. Results illustrated the hemp fibers had no effect on residual values of the compressive strength, modulus of elasticity, whereas SEM indicated that hemp fibers partially disintegrated at high temperature ,therefore, it can be used in fire resistance concrete.

In 2018, Wasim Abbass,et al. implemented a testing program investigating the mechanical behavior of concrete by adding hooked ended fibers. Three lengths (40, 50, and 60 mm) and two diameters (0.62 and 0.75 mm) were used with three water-to-cement ratios (0.25, 0.35, and 0.45).Steel fibers were employed with three volumes fractions, 0.5%, 1.0%, and 1.5%.

Steel fibers had a more significant effect on moderate strength concrete rather than on high strength matrix. On the other hand, the highest increase in tensile strength (47%) was recorded for 1.5% fiber content, 60mm length and w/c of 0.45.

In a study illustrated by M.M. Kabir et al. in 2013, hemp fibers were treated with alkali, acetyl and silane chemicals. Scanning electron microscope (SEM), fourier transform infrared (FTIR) spectroscopy, thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC) were performed to study the influence of treatments on the main constituents of fibers such as cellulose, hemicellulose and lignin.SEM .Results indicated that the reaction of chemical treatments with the main component of fibers led to a change in its structure. Alkalisation and acetylation reduced the amount of hemicellulose, lignin, and revealed cellulose microfibrils on the fiber surface. Contrarily, silane treatments covered the surface and filled the spaces among the microfibrils.FTIR showed removal of hemicellulose and lignin from the fiber surface while silane had no effect. In addition, results of TGA revealed that hemicellulose is the most reactive component compared to cellulose which is thermally stable and lignin that was decomposed over a wide range of temperatures.

In 2018, Abdul Qadeer Dayo et al. evaluated the effect of ethanol, alkali and silane treatments on the waste hemp fibers. Characterization tests revealed that the silane treatment caused a rougher fibers surface causing a better adhesion with the matrix and a higher thermal stability due the presence of high –OH group. Even more, mechanical tests indicated that a 25 volume percentage of silane treated fiber-reinforced composites had better results compared with alkaline and ethanol washed fiber treatment.

In 2018, R. Sepe focused on the effect of silane and alkaline treatment on hemp fibers reinforced composites. Different dosages of chemical treatments were applied; 1% and 5% for alkali and silane treatment and an additional dosage of 20% for silane treatment. Mechanical tests indicated that the silane treatment improved slightly the flexural and tensile strength while the alkaline treatment removed hemicellulose and lignin but led to fibrillation issue causing an easier pull out .Moreover, silane treatment of 1% was the optimum dosage for fiber treatment.

S. Sair et al. 2017 studied the influence of silane and alkaline treatment on the mechanical and thermal properties of hemp fibers composite. Dosage of alkaline treatment ranged from 2%to 8% whereas 100 ml of silane treatment having a concentration of 0.2 mol/L were mixed with 8% NaOH solution. Results revealed that an optimum dosage of 8% alkaline treatment improved the mechanical properties of hemp fibers and roughened its surface allowing a better adhesion with concrete. In addition, thermal conductivity presented a slight increase depending on treatment concentration indicating the insulation properties of hemp. Moreover, the double treatment of amino alkaline treatment indicated an optimum behavior of the matrix.

In 2017, Mohsen Ahmadi et al. investigated the mechanical properties of the concrete containing recycled steel fibers along with recycled aggregate. Natural coarse aggregates were replaced by recycled aggregate with 0, 50 and 100%, with fiber percentage of 0.5 and 1% of concrete volume. Results indicated a decrease in indirect tensile, compressive and flexural strength with the increase of the percentage of aggregates replacement. Whereas, the increase of percentage of fibers to 1% indicated an increase in tensile and flexural strength. Moreover, the addition of fibers by 0.5% and 1% illustrated an increment then a decrease of compressive strength.

Chandra Sekhar Das et al. 2019 evaluated the influence of incorporating polypropylene fiber in low strength recycled aggregate concrete. Concrete specimens incorporating 0.5%, 0.75% and 1% Polypropylene fibers in both natural aggregate concrete and recycled aggregate concrete (100% replacement of natural coarse aggregate) were tested. Outcomes revealed that RCA has a lower density when compared to NCA and a further decrease is noted with the increase of fiber dosage. In addition, compressive, flexural and split tensile strength of RCA decreased with the increase of fiber content up to 0.5%. A similar trend of stress-strain curve of RCA and NCA is observed.

An experimental program performed at AUB by Awwad et al. 2012 investigated the effect of adding hemp fibers on concrete mechanical properties. Natural fibers were added to the concrete mix to compensate for the reduction of the coarse aggregate quantity (Awwad et al. 2012a). The hemp fibers were used in different volumetric percentages (0.5, 0.75 and 1%) of the concrete volume. In addition, the coarse aggregate reduction was applied in different volumetric percentages (10, 20 and 30%) of the concrete volume. Mechanical tests of standard cubes and beams resulted in a decrease of compressive strength of mixes containing hemp fibers with a reduction of coarse aggregate but in a more ductile behavior when it came to flexural strength tests.

In a second study by Awwad et al., the hemp fibers were added in different volumetric percentiles (0.5, 0.75, or 1%) of the concrete volume, with a coarse aggregate reduction (10, 20, or 30%) of the concrete volume (Awwad et al. 2012b). A wide variety of tests was performed on all mixes including compressive strength, tensile strength, splitting tensile strength, modulus of elasticity, thermal conductivity, density, and slump tests. It was concluded that by adding 0.75–1.0% hemp fibers to the concrete with 20–30% coarse aggregate reduction, a new concrete mix could be produced. Although the new concrete mix might have lower compressive strength by about 25%, a ductile behavior was reached, the material was more flexible with 20–30% decrease in the modulus of elasticity, the splitting tensile strength was not affected, and the thermal conductivity was reduced 25–35%. In terms of workability, the 0.75% hemp mixes slump was satisfactorily ranging from 100 to 150 mm; whereas, with 1.0% hemp mixes, the slump reached the minimum allowable about 70 mm and the higher volumetric ratio is not recommended.

In a third study, Awwad et al. investigated the structural behavior of a sustainable green concrete material developed in earlier research studies (Awwad et al. 2014). Eighteen structural beam specimens were tested to fail in flexure, shear, and bond splitting modes. A control mixture and two concrete mixtures reinforced with hemp fibers but lower coarse aggregate contents were adopted. Three concrete beams were tested: control with no fibers, 0.75% hemp-20% coarse aggregate reduction, and 1% hemp-20% coarse aggregate reduction mixtures. The tested hemp-reinforced concrete specimens have shown adequate structural performance and ductile post- ultimate load-deflection behavior, which may be favorable under dynamic loading. One adverse effect was that the compressive strength was reduced by 20 to 30%, which was expected because of the removed coarse aggregates. Therefore, it was recommended not to use this material in pure compression members such as columns. In all beam types, it was noticed that the addition of the hemp fibers led to a ductile behavior after the peak load was reached. For the hemp fiber reinforced beams, the peak loads were comparable to the control beams for each of the three investigated modes of failure while a 20% reduction in the coarse aggregates was possible. The ratio of deflections at failure load to maximum load was almost doubled when comparing hemp beams (0.75% and 1.0%) with control beams. Moreover, based on the crack width measurements at different locations on every beam type, a greater number of fine cracks were observed in the hemp fiber-reinforced beams indicating a better bond between hemp reinforced concrete and reinforcing steel. As for flexure beams, the stresses in the main bottom reinforcing bars were close to the yield limit. Consequently, the flexure beams' ductility after the peak load could be attributed to both the hemp-reinforced concrete and the main reinforcement. On the other hand, for the shear and bond beams, the stresses in the main bottom reinforcing bars were lower than the yield limit. Thus, the shear and bond beams' ductility could be mainly attributed to the hemp-reinforced concrete rather than the main reinforcement.

### 2.2 Recycled aggregate concrete

Han et al. reported on tests of the shear capacity of reinforced concrete beams cast with different percentage replacements of natural coarse aggregates (NCA) with recycled coarse aggregates (RCA) (Han et al. 2001). Variables in the test included the span to depth ratio (1.5, 2, 3, and 4); the type of aggregates that included natural, washed recycled and non-washed recycled aggregates; and the amount of shear reinforcement used in the specimens (0, 0.089, 0.507, and 0.823 percent). Crack patterns, modes of failure, and load-deflection behavior were monitored and compared for twelve tested simply supported beams. It was found that the ACI Building Code ACI 318-12 equations overestimated the shear capacity of RAC beams with a span/depth ratio greater than 3. The paper stressed that further investigation should be made to test the conclusions.

Gholamrezal el al. published the results of flexural strength tests of RAC beams. Variables included the percentage replacement of NCA with RCA, and the flexural reinforcement percentage (Gholamrezal el al. 2009). The Equivalent Mortar Volume (EMV) method of mix design was used. Values of cracked, yield, and ultimate moments in addition to service, yield, and ultimate deflections were measured and compared. In addition, actual service deflections were compared with predicted service deflections according to the codes. The results indicated comparable flexural strength when using recycled aggregates and proportioning them according to the EMV method. It was also found that ACI Building Code equations over-estimated the modulus of rupture.

Kim and Yun tested 144 pullout specimens to investigate the influence of recycled coarse aggregates on the bond behavior of deformed bars in concrete (Kim and Yun 2012). The variables included the aggregate size, percentage replacement of NCA with RCA, the reinforcing bar direction (vertical and horizontal), and the reinforcing bar location (75 and 225 mm from the bottom). Results showed that for the same percentage replacement of NCA with RCA, the bond strength increased while decreasing the maximum recycled concrete aggregate size. Results also showed that the increase in the percentage replacement had a negative impact on the compressive strength. The top-bar effect was very significant with bottom cast bars performing better than top cast bars at all ages.

Jia Hu et al. investigated mechanical properties and uni-axial compression stress-strain relation of recycled coarse aggregate concrete subjected to salt-frost cycles. Recycled concrete aggregate with water cement ratio of 0.45 and 0.35 and 100% replacement of natural aggregate were tested for the mass loss, relative dynamic modulus of elasticity, cubic compressive strength, splitting tensile strength and stress-strain relationship for recycled aggregate concrete after exposure to salt-frost cycles (SFC).The resistance of concrete to salt –frost decreased with the increase water-cement ratio. Moreover, loss of mass increased then decreased slightly when the moduli of elasticity reached its peak failure. Moduli of elasticity increased with the increase in rate.All mechanical properties except for RAC’s peak strain, indicated a drop in results when SFC increased.

In 2009, S.C. Angulo et al. investigated the chemical-mineralogical characterization of recycled aggregate from demolition waste. The experimental plan consisted of Analytical techniques such as X-ray fluorescence, semi-quantitative X-ray diffraction, thermogravimetric analysis and 33% HCl selective dissolution test has been performed on three types of recycled aggregate to understand the behavior of recycled aggregate concrete.

XRF results indicated that the tested aggregates were mainly composed of SiO2 (48.0–84.2%), Al2O3 (5.0–17.2%) and CaO (2.4–13.9%), followed by high LOI values (3.4–19.6%). Weight loss recorded by TGA, was interpreted ; loss between 110 °C and 400 °C was the result of C-S-H gel decomposition , 400°C and 550 °C from portlandite decomposition where as volatile loss originated from $CO_2$ between 550°C and 700°C. XRD identified the presence of quartz and alkaline feldspars originally found in rocks while calcite, illite, kaolinite and gibbsite were related to the presence of binder, clay and ceramic.

M.C. Limbachiya et al. 2007 inspected the effect of chemical and mineralogical characteristics of three types of coarse recycled aggregate on concrete performance. The outcome of XRF test demonstrated that the natural aggregate is mainly composed of $SiO_2$, while recycled aggregate has a noticeable CaO composition attributed to the original adhered mortar. XRD results illustrated similar peaks of all recycled aggregate. In addition,$CaCO_3$ and feldspar peaks recognized in the recycled aggregate analysis is absent in natural aggregate analysis .These peaks refer to the presence of adhered mortar and brick/ceramic content of aggregate.

In 2011, M. Martín-Morales et al. characterized recycled aggregate originated from demolition and construction waste based on the Spanish structural code. Geometrical, physical-mechanical and chemical tests were performed on recycled aggregate. Geometrical assessments such as particle shape, size distribution and percentage of fines met the code requirement. Chemical tests such as chloride content revealed values less than 0.05% falling within the code permissible limit whereas water-soluble sulfates indicated a value of 1.52%, which is higher than the authorized code content indicating a possible durability issues. Density and water absorption (physical-mechanical tests) revealed a lower density and higher water absorption of recycled aggregate due to the original adhered mortar.

In a study illustrated by L. Evangelista (2017), different physical, chemical and mineralogical tests were performed to characterize the recycled aggregate originated from old commercial concrete. According to XRD results, natural aggregate indicated the crystalline phase of quartz and potassium feldspar whereas recycled aggregate showed calcite, quartz, gypsum,feldspar and sodium feldspar. Quartz and feldspars were referred to the siliceous natural sand; however, the highest identified peak of calcite was originated from the attached cement mortar and the original composition of recycled aggregate. In addition SEM, revealed an irregular rough shape and high surface area showing a high mortar content with a little amount of natural aggregate. The thermal analysis test, demonstrated four main phases of mass loss. Phase one detected the loss of free and adsorbed water from aggregate surface and pores when the temperature was up to 200°C. Phase two ranging between 200 °C and 400°C identified the loss of water in C-S-H gel , third phase extending to 550°C spotted the dihydroxylation of calcium hydroxide whereas the the decarbonisation of calcium carbonate was recognized in the last phase when the temperature was between 820°C and 880°C.

As part of the Master Thesis research requirement at AUB, Dawi (2015) investigated the mechanical and structural performance of concrete elements by partially substituting natural coarse aggregates with recycled aggregates sourced from tested and crushed cylinders in concrete batching plants. In the first phase of the research program, an extensive concrete batching and testing program was conducted to achieve two optimum normal and high strength concrete mixes which fits the criteria of recycled aggregate concrete (RAC) as far as workability, homogeneity, and performance. Besides the concrete strength, the other main variable was the percentage replacement of natural coarse aggregates with RCA (20, 40, 60, 80, or 100%). Normal strength tested cylinders were used as source of the recycled aggregates for the normal strength concrete (NSC) mix and high strength concrete cylinders were used for the high strength concrete (HSC) mix. Tests on the trial batches included plastic state slump and hardened state mechanical properties including cylinder compressive strength, cylinder tensile splitting strength, modulus of elasticity, and standard beams flexural strength. The results indicated no significant negative effect on the consistency or slump of the different recycled aggregate concretes; and average reductions of 9.8, 13.5, and 9.2% in the standard cylinder compressive strength and standard cylinder splitting tensile strengths and standard beam flexural strength, respectively. In the second phase, the assessment of the flexure, shear, and bond and anchorage characteristics of reinforcing bars embedded in NSC structural beam elements prepared using the optimum normal strength RAC batch achieved in the first phase, was targeted. The strength reduction that was noted in the findings of the first phase of the research did not have a negative impact on the structural behavior of reinforced concrete beams prepared by replacing a portion or all of the natural coarse aggregates with RCA. Two replacement percentages were chosen in the second phase to cover an average replacement percentage of 40% and a total replacement percentage of 100% of NCA with RCA. There was no significant difference in the ultimate load reached or load-deflection behavior of beams tested to fail in flexural or shear or bond splitting of the concrete cover in the splice region that could be related to the percentage replacement of NCA with RCA.

### 2.3 Summary of Findings from the Experimental Literature Review

Significant researches investigated the effect of hemp fibers and recycled aggregate in concrete to assess the effect each of these two materials on fresh and hardened concrete properties. A summary of the mentioned studies is illustrated below:

- The addition of coconut coir fiber decreased concrete workability and compressive strength as the fiber volume increased.( Islam, S; Hussain et al. 2012; and John Branston et al 2017)
- Incorporating steel fibers in concrete had a higher effect on moderate strength concrete and increased the tensile strength 47% at fiber content of 1.5% of concrete volume (Grubeša et al. 2018)
- Hemp fibers can be considered as a fire resistance material in concrete with no effect on concrete compressive strength (Abbas,et al. 2018)
- Studies investigating the effect of chemical treatment (Silane, alkali and acetyl) revealed different results. Some researchers found Alkaline treatment as an

optimum treatment (Sair et al. 2017), others realized that silane treatment had higher performance on the employed hemp (Sepe 2018, Dayo et al. 2018 )

- Implementing 1 % of steel fibers along with recycled aggregate indicated a decrease in compressive strength and an increase in tensile and flexural strength (Ahmadi et al. 2017)
- Mixes enclosing polypropylene fiber along with recycled aggregate revealed a decrease in compressive, flexural and splitting tensile strength of RCA with the increase of the fiber content up to 5% (Das et al. 2019)
- Hemp fibers added in different volumetric percentages (0.5, 0.75 and 1%) of the concrete volume along with a reduction in different volumetric percentages of coarse aggregate (10, 20 and 30%) of the concrete volume decreased the compressive strength of standard cubes but increased the ductility of concrete when subjected to flexural loads. Moreover, employing 0.75–1.0% hemp fibers to the concrete with 20–30% coarse aggregate reduction lead to an optimum ductile behavior despite 25% reduction of compressive strength (Awwad et al. 2012).
- An adequate performance and ductile post-ultimate load-deflection behavior of structural beams containing hemp fibers was recorded. Noticing a decrease in compressive strength it is recommended to avoid hemp fiber concrete in pure compression members such as columns (Awwad et al. 2014).
- Recycled aggregates added to concrete led to decrease in density and increase in water absorption due to the original adhered mortar.
- RA decreases compressive strength, flexural and tensile strength up to 13.5% but has no significant effect on NSC structural beams (Dawi et al. 2015)

## 2.4 Limitations addressed in Literature

Previous studies emphasized on hemp reinforced concrete properties. It consisted of investigating the effect of chemicals on the properties and surface of the fibers to achieve better bond between the matrix by performing mineralogical, physical and chemical tests. Moreover, other researches focused on the effect of hemp on the concrete properties such as compressive, flexural and tensile strength on the mesoscale and structural scale. On the other hand , many experimental plans shed the light on the influence of adding recycled aggregate on concrete properties and its durability. Some researches were dedicated to study the effect of old adhered mortar and the interfacial zone on the concrete properties. Recent studies were interested in adding steel and propylene fibers along with recycled aggregate in concrete to illustrate the effect of this combination but no research emphasized on the use of hemp fibers along with recycled aggregate in concrete mixes.

# CHAPTER 3
# TEST MATERIALS

## 3.1 Introduction

Based on the literature review presented in Chapter Two, the main objective of this thesis is to study the validity of producing a green concrete encapsulating natural and recycled resources which are hemp fibers and recycled aggregate respectively. An extensive understanding of the newly incorporated material in concrete at microscale and mesoscale is required to assess the possibility of adopting HRCA.

In this chapter, a detailed description of the adopted materials in the experimental program is presented, including hemp fibers, recycled aggregates and natural aggregates. .Moreover, the specimen preparation is illustrated throughout the chapter.

## 3.2 Test Materials

In this section, the characteristics of hemp fibers, recycled aggregates, natural aggregates and cement are presented.

### *3.2.1 Hemp fibers*

In the last decade, studies focused on the implementation of hemp fibers in concrete. They are natural resources, widely available and are characterized by a high tensile strength and are capable of strengthening concrete by increasing its flexural and tensile properties. Moreover, hemp fibers prevents crack propagation at the early and hardened stages of concrete. Adding hemp to concrete requires a specific chemical treatment of the fibers to improve adhesion bond between fibers and the concrete matrix. Proper preparation of the treated material is required to ensure a proper behavior when mixed with concrete. Hemp fibers, implemented in the experimental program, were imported from Hemp Traders, USA.

### *3.2.2 Hemp fibers treatment*

Hemp fibers are mainly constituted of cellulose, hemicellulose, and lignin (*Figure 6*). Cellulose surrounded by hemicellulose and lignin is considered the major component of hemp. Crystalline and amorphous regions are identified in the hemp structure. In the cellulose area, intensely linked hydroxyl groups are present whereas at the amorphous region (hemicellulose and lignin surface) these groups are loosely linked and therefore they react with free water in the atmosphere giving the hemp fiber its polar and hydrophobic character. Because of these hemp characteristics, poor adhesion between fiber and concrete matrix is found. To enhance the mechanical and thermal properties of HRC, a strong bond between fibers and the concrete matrix is required. This is achieved by conducting chemical treatments on the hemp surface to reduce impurities and strengthen the bond with the concrete matrix.

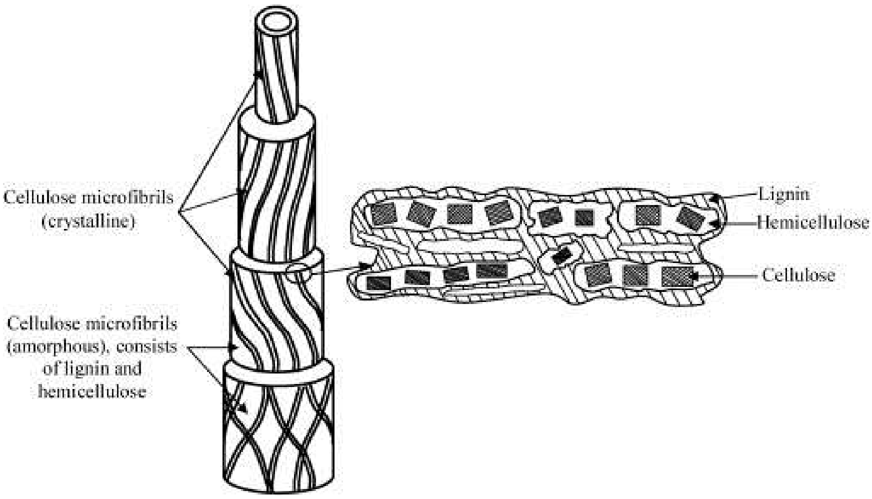



Figure 6. Structure of hemp fiber

Alkali treatment (*Figure 7* and *Figure 8*): Fibers are soaked in hydroxide sodium solution at 6% by weight for 48 hours. 720 grams of solid sodium hydroxide are mixed with 12 liters of distilled water. After 2 days, hemp fibers are removed from the solution that earns brown color and are washed with distilled water until the solution becomes clear. Then, the fibers are left to dry at room temperature.

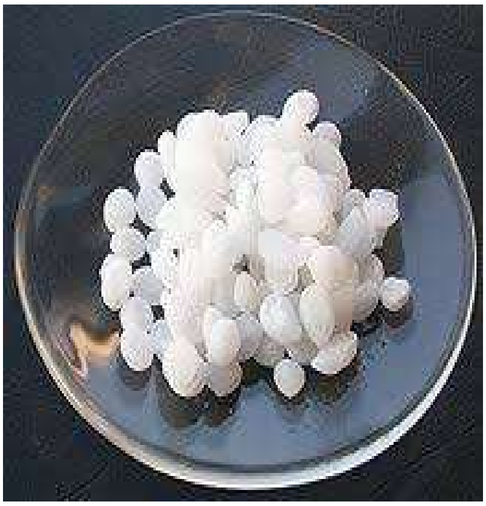
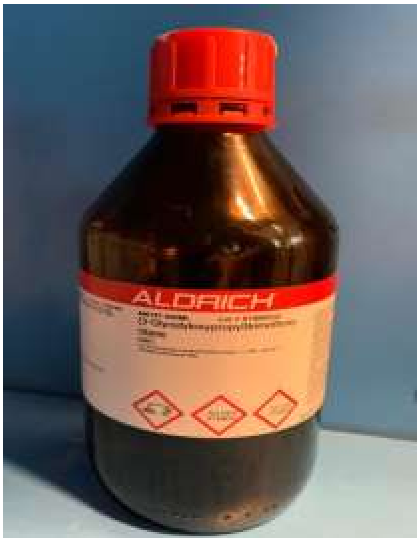


Figure 7. Solid Sodium Hydroxide

Figure 8. Hemp socked in alkaline solution

Silane treatment (*Figure 9*): Fibers aretreated using a solution of 3-glycidoxypropyltrimethoxysilane and ethanol solution in a 1:1 ratio. The pH of this solution is adjusted to 4 using 2% glacial acetic acid. The solution is then stirred for 2 hours before the fibers are added. Then the fibers are washed with water and left to dry at room temperature.




*A* .Silane solution


*B.* Ethanol solution


*C.* Hydrochloric acid

Figure 9: Solutions used in silane treatment

Acetyl treatment: Alkaline-treated fibers are soaked in glacial acetic acid for 1 h and are then soaked in acetic anhydride containing one drop of concentrated H2SO4 for 5 minutes. Washed fibers are left to dry at room temperature.

### *3.2.3 Hemp fibers preparation*

Randomly packed fibers require suitable preparation to guarantee a proper usage of the material in concrete mix. First, all impurities present between hemp are carefully removed then fibers are arranged in a straight bundles shape. Second, after being chemically treated, these fixed end bundles, are then marked every two or three cm to ensure accurate cutting of the fibers. Finally, Fibers are cut and ready to be used in concrete. Hemp fibers preparation is shown in *Figure 10*

Figure 10: Preparation of hemp fibers

### 3.2.4 Hemp tensile strength

Tensile strength is a main property of hemp fibers that are added to reinforce the concrete weakness in tension. To assess the fiber's tensile strength, a test was done using the Universal Testing Machine (UTM) (Figure 11). The top and bottom of the fiber were glued to cardboard to avoid direct contact with the grips of the testing machine(Figure 12). A gage length of 100 mm and a crosshead speed of 10 mm/min were used. To measure the cross -sectional area of the fibers, each fiber was assumed to have a rectangular cross-section. The width and thickness of the tested fibers were measured using a digital caliper with a precision of 0.01 mm. Due to the high variability in the dimensions of the fibers, the width and thickness of each fiber were taken measured at five different positions along its length and the average of those values was considered.

Figure 11. Hemp mounted in UTM machine

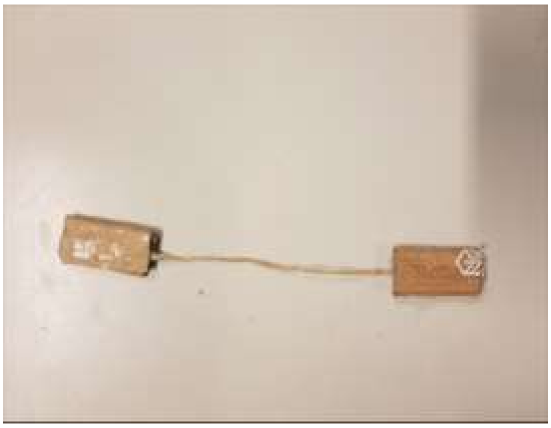


Figure 12. Tensile strength hemp sample

The results of the tensile strength test are summarized in the Table 1 below. It is important to note that the results were discarded when the fiber failure happened in the proximity of the cardboard or due to its slippage from the cardboard. The acetyl treated fibers resulted in the highest tensile strength, while the silane treated fibers had the lowest strength.

*Table 1. Tensile strength results for different treatments*

| | **Treatment** | | | |
|---|---|---|---|---|
| | Untreated | Alkali | Silane | Acetyl |
| **Average tensile strength (MPa)** | 241.01 | 231.01 | 224.82 | 249.59 |

### 3.3 Coarse aggregate

Coarse aggregates are defined as the aggregate retained on sieve No.4 (4.75 mm). Throughout the experimental plan, natural and recycled aggregate having two maximum aggregate sizes of 10 and 20 mm were implemented. Natural aggregates were provided by ARACO ready-mix plant whereas recycled aggregates were obtained from the tested and crushed Portland Cement Concrete cylinders in ARACO ready-mix plant, Beirut. To identify aggregate properties, acceptance tests were performed. A gradation test was performed according to ASTM C33, where permissible upper and lower boundaries of aggregate were selected based on sieve No.6. The selection of the sieve is restricted by the nominal size of aggregate. After sieving the sample, retained aggregates on nominal size sieve of 1”, 3/4”, 3/8”, No.4 and No.8 are recorded. Results of gradation test are shown in Figure 13, Figure 14, Figure 15 and Figure 16.

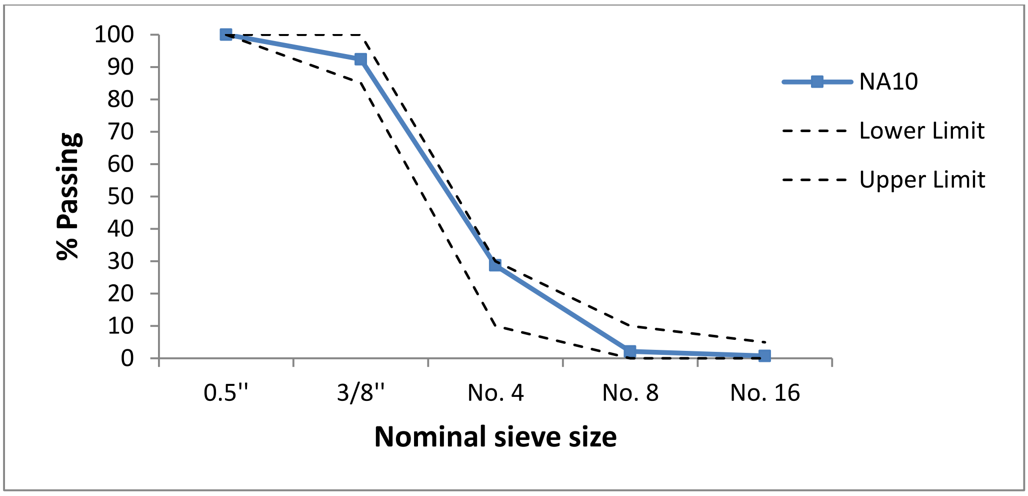



Figure 13. 10 mm natural coarse aggregates gradation

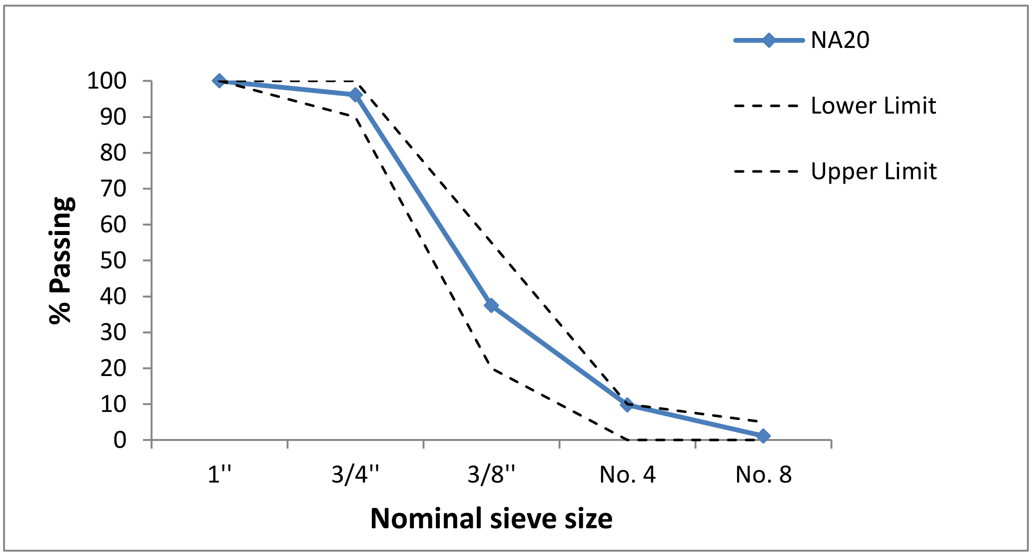



Figure 14. 20 mm natural coarse aggregates gradation

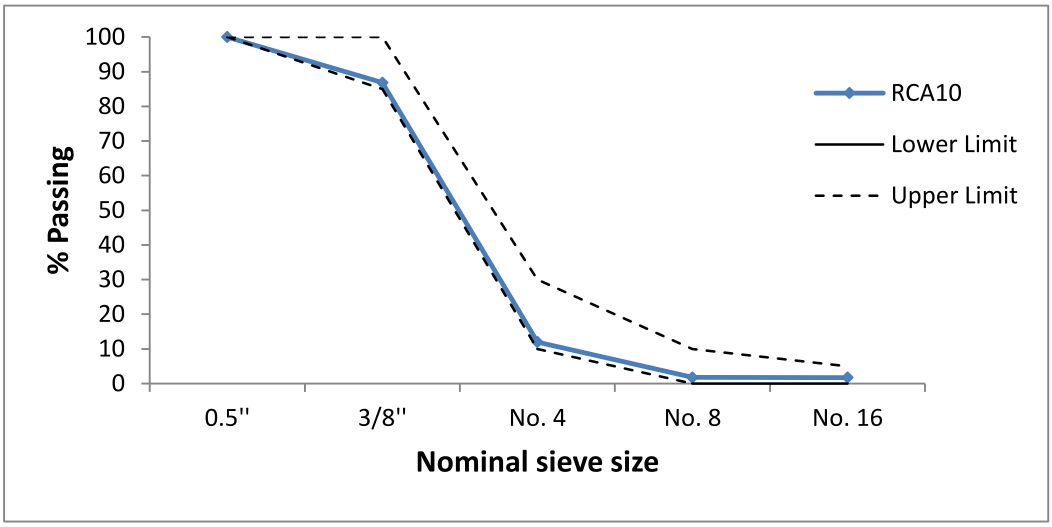



Figure 15. 10 mm recycled coarse aggregates gradation

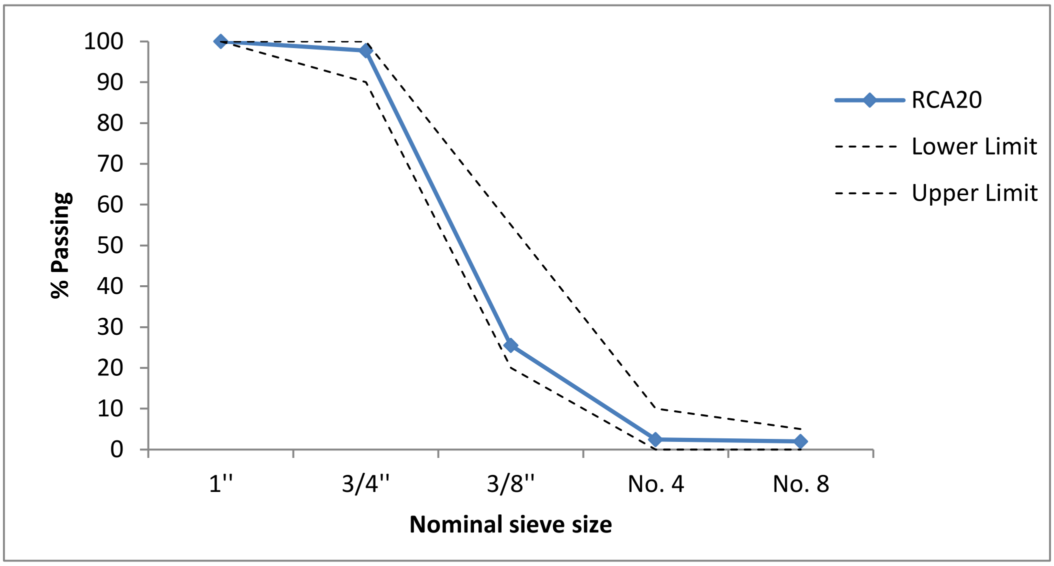



Figure 16. 10 mm recycled coarse aggregates gradation

Water absorption and bulk specific gravity are two main properties of coarse aggregates. Based on ASTM C127, washed aggregates sample is oven-dried to constant mass at a temperature of 110 ± 5°C then removed and left to cool at air temperature. Next, the sample is immersed in water for 24 hours and then is laid on an absorbent clothing to make sure that all water visible films are removed (Figure 17). The sample is weighted and the mass is recorded as saturated surface dry (B).Then, the water is which the sample was Immersed is placed in a water container and record the sample water apparent mass (C). Finally, the sample is dried and the weight is reported as its oven-dried mass (A).

- *Specific gravity* = $\frac{A}{B-C}$
- *Absorption%* = $(\frac{B-A}{A})*100$

Figure 17. Removing surface water off aggregate using an absorbent clothing

To estimate the resistance to degradation of aggregate resulting from impact and abrasion actions, the Los Angeles test (ASTM C131) was performed. Firstly, the weight of washed and oven-dried aggregate was recorded (C) .Afterward, aggregates were placed in the Los Angeles Test machine which is equipped with steel balls(Figure 18). The machine was set to rotate 500 revolutions at 30 RPM (Figure 19). The ground material is then sieved using 1.7 mm sieve. Later, the retained materials are washed and oven dried at 100°C. Finally, the weight of aggregate (Y) is recorded.

- *Percent of* loss $=(\frac{C-Y}{C})*100$

Figure 18. Steel balls of Los Angeles

Figure 19. Los Angeles Abrasion test

*Table* 2. Aggregate properties

| | NCA | | RCA | |
|---|---|---|---|---|
| | NCA20 | NCA10 | RCA20 | RCA10 |
| **Specific gravity (Oven-Dry)** | 2.59 | 2.63 | 2.30 | 2.35 |
| **Absorption (%)** | 1.93 | 1.63 | 5.37 | 4.91 |
| **Dry rodded unit weight ($kg/m^3$)** | 1653 | 1579 | 1401 | 1386 |
| **Wear (%) (Los Angeles Abrasion)** | 22.16 | | 29.04 | |

### 3.4 Fine aggregates

Fine aggregates are defined as the aggregate passing sieve No.4 (4.75 mm). In this research, Egyptian sand was used in the concrete mixes. According to ASTM C33, sand gradation should fall between an upper and lower limit. Gradation results (Figure 20) indicated that the Egyptian sand almost falls within the acceptable range.

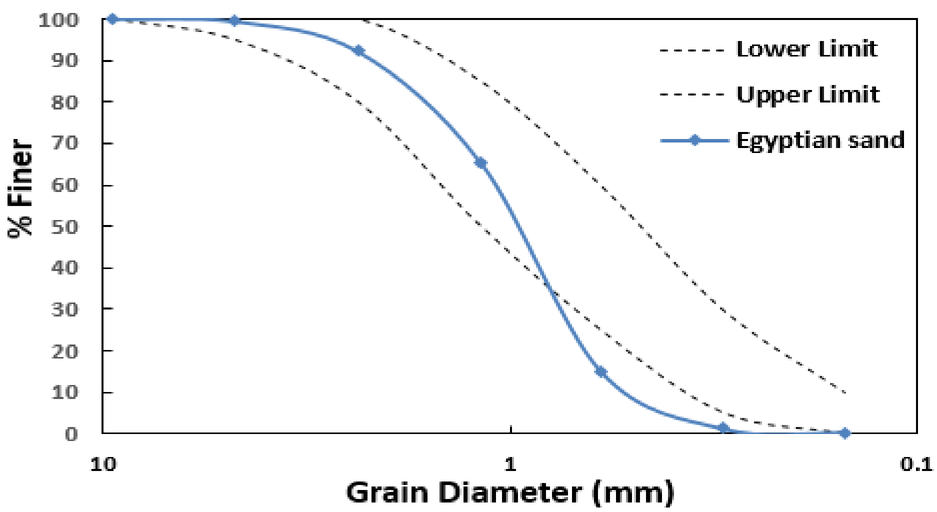



Figure 20. Grain distribution of sand

### 3.5 Superplasticizer

Recycled aggregates holding adhered cement on its surface increase water absorption and consequently decrease the concrete workability. Therefore, adding superplasticizer to the mixes was necessary to maintain workability. Sikament NN was the adopted superplasticiser in the concrete mixes (*Figure 21*). This Sika product is a high range water-reducing admixture and is an excellent material to improve workability of concrete. It complies with ASTM C 494 Type F and B.S. 5075 Part 3 for superplasticizers. It is used at a dosage between 0.6% and 3% by weight of cement and is packed at a temperature between 5 °C and 35°C.


Figure 21.Sikament superplasticizer

# Chapter 4
# MICROSTRUCTURE AND HEMP CHARACTERIZATION

## 4.1 Introduction to Microstructures

HRAC is a sustainable concrete incorporating two types of sustainable components: recycled aggregates and hemp fibers. For a better understanding of concrete behavior, material characterization was a must to set a clear link between concrete hardened properties at the mesoscale level and the constituent material at the microstructure level. Material characterization is a procedure where the material structure is measured. It includes microscopical, mineralogical, elemental and thermal techniques. Hemp microstructure is mainly studied to assess the effect of the treatment on the fiber surface, to acknowledge its crystallinity characteristics and to investigate its thermal behavior. On the other side, Physical properties of aggregates such as size, shape, angularity, and pore distribution are the main factors determining the quality of aggregates.

## 4.2 Scanning Electron Microscope (SEM)

SEM is a type of electron microscope that scans a sample with a high-energy focused beam of electrons. The electrons interact with the sample atoms generating signals collected by the detector that include information describing the surface topography and morphology.

Scanning Electron Microscopy (SEM) images were taken using a TESCAN MIRA3 LMU with an OXFORD EDX detector. First, the sample is fixed into the sample stub using carbon tape to ensure an adhesive bond. Second, the sample is coated with a 20 nm layer of gold to improve conductivity and to avoid charging to obtain clear images. Third, the SEM chamber is vented to reach the nominal pressure, the sample is inserted in the chamber, and the stub is tightened. Fourth, the pumps are turned to reach vacuum and then the voltage is sat at 8 kV. To acquire a focused image, autofocus is clicked and the magnification zoom level is set at 50 microns. Afterwards, the pad spot is changed to zero, WD to 5 mm and the image scroll-down is fixed at a lower rate, and the image is taken.

Figure 22. SEM chamber

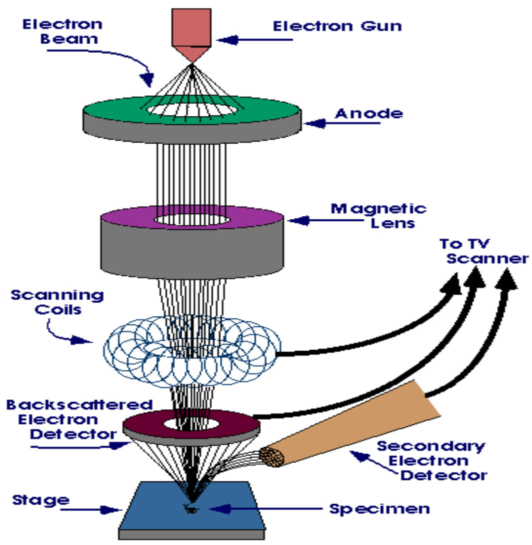



Figure 23. SEM concept

## SEM Results

The microstructures of the fibers are shown in *Figure 24*: a and b for the untreated fibers, c and d for the alkali treated fibers, e and f for the silane treatment, g and h for the acetyl treatment. The images of untreated fibers show the presence of hemicellulose and impurities, which are mainly lignin, wax, and pectin. These impurities could affect negatively the bond between the fibers and the cement matrix. After the alkali and acetyl treatments, the majority of hemi-cellulose and the impurities have been removed and the surface of the fiber became rough. On the other hand, after the silane treatment, some impurities were still present on the fiber's surface and silane particles that remained after the washing of the fibers were noticed.

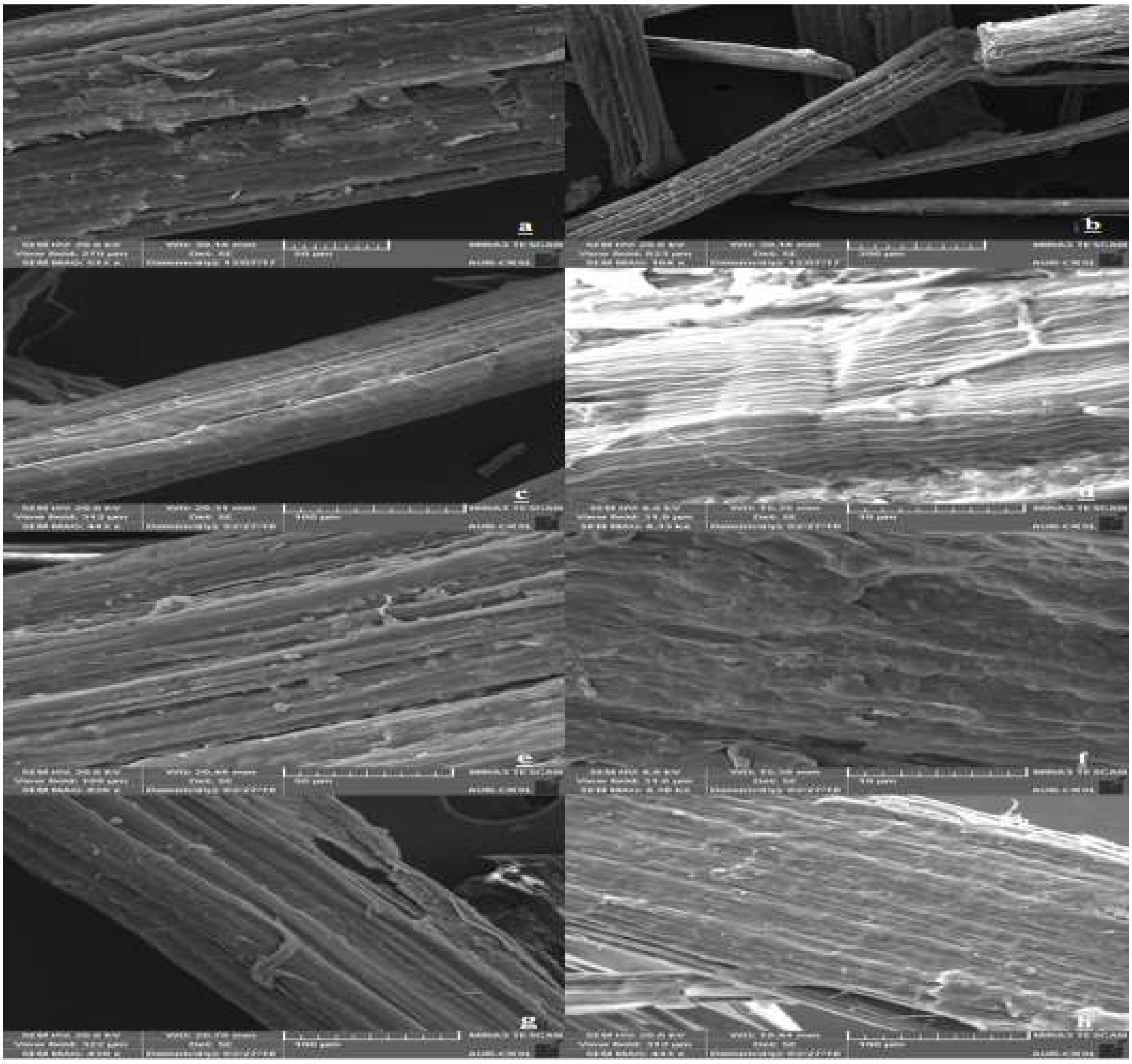



Figure 24. SEM images of hemp fibers

*a and b: untreated fibers,* *c and d: alkali treated fibers*

*e and f: Silane treated fibers,* *g and h: Acetyl treated fibers*

### 4.3 X-Ray diffraction

To study the crystal structure of hemp fibers XRD analysis is performed. This mineralogical test identifies the crystalline phases in a material providing information about its chemical composition. An incident X-ray beam that is directed at the sample generates a diffracted beam, and then a diffracted unique pattern that indicates the sample's crystalline structure is collected (*Figure 25*). The X-ray Diffraction (XRD) analysis of the fibers was done with a BRUKER D8 Advance X-Ray diffractometer in a θ–2θ configuration using CuKα source (λ = 1.54 Å) at 40 kV and 40 mA. The scanning was done in step mode with a step size of 0.02° in the angular range of 5–45°.

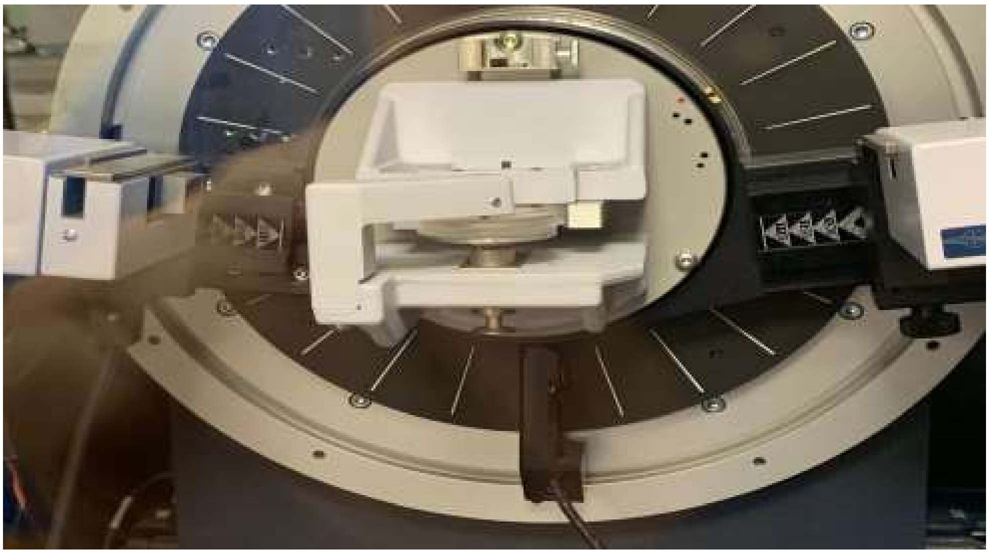


Figure 25. XRD chamber

The steps of the XRD test are as follows:

- Prepare the sample by grinding it to a powder level.
- Place the powder into the sample holder using a spatula until it is filled, well-leveled and free of voids.
- Open the XRD chamber, insert the sample holder on the round plate and make sure that it is in contact with the three supports from the top.
- Click on the diffract measurement center icon to open the software.
- Under the commander, adjust the voltage to 40 kV AND 40 mA.
- Set the angular range starting a theta of 5° until 45°.
- Start the test and save the results when it ends.
- After the test is done, export the image and recognize each peak either by literature or by using “Diffrac Eva”.

The result of XRD test of the treated and untreated hemp fibers is shown in *Figure 26*.

**XRD results**

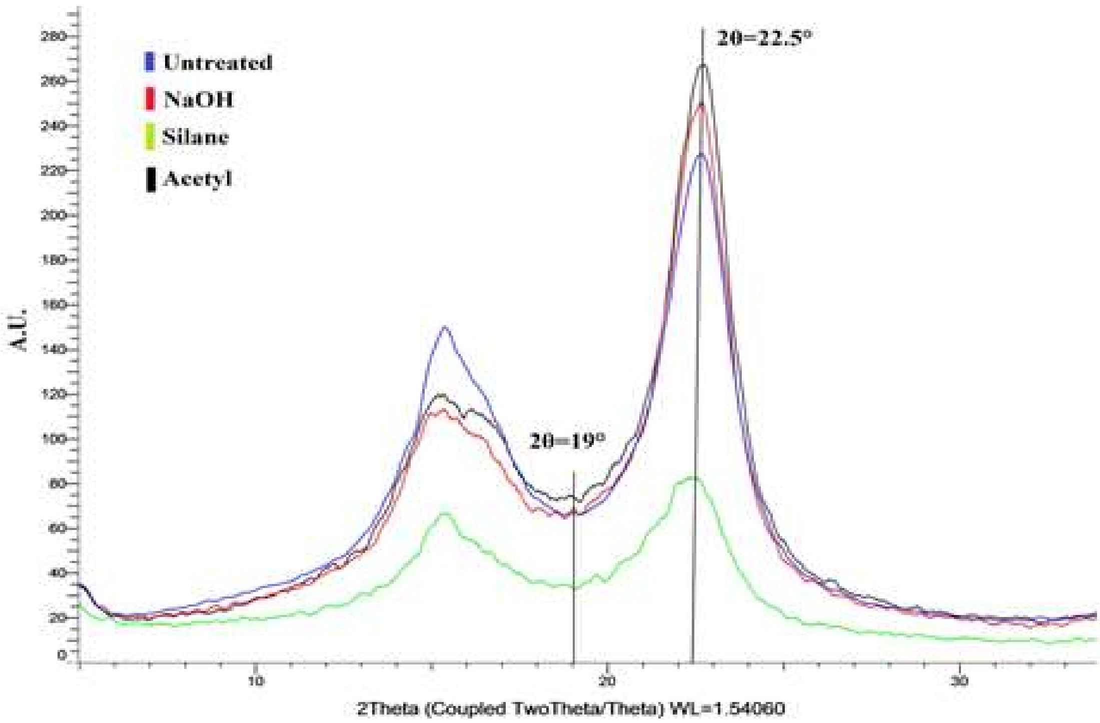



Figure 26. XRD results of hemp fiber

X-ray diffractograms of untreated and treated hemp fibers show a major crystalline peak that occurs around 2θ = 22.5° which corresponds to the crystallographic plane of cellulose (Equation 1). It can be observed that the intensity of this peak differs between untreated and treated fibers which indicates a variation in the crystallinity of the fibers. More specifically, alkali and acetyl treatments have increased the intensity of this peak while silane treatment decreased it. Hemp fibers are semi-crystalline and their tensile strength has a proven relationship with its crystal content.

To quantitatively study the effect of the treatments on the fibers, the Crystallinity Index ($I_c$) was calculated.

$$I_c = \left(\frac{I_{002} - I_{am}}{I_{002}}\right) \times 100 \quad \textbf{Equation4.1}$$

Where $I_{002}$ is the maximum intensity of diffraction of the peak at a 2θ angle of 22.5°, and $I_{am}$ is the intensity of diffraction of the amorphous material at a 2θ angle of 19°. It can be observed that the alkali and the acetyl treatments gave the highest $I_c$ of the hemp fibers (refer to Table 3).

*Table 3. Crystallinity index of hemp*

| | $I_{002}$ | $I_{am}$ | $I_c$ (%) |
|---|---|---|---|
| Untreated | 226 | 67 | 70.35 |
| Alkali | 250 | 67 | 73.20 |
| Silane | 83 | 31 | 62.65 |
| Acetyl | 268 | 74 | 72.39 |

### 4.4 Thermogravimetric Analysis

The TGA test is performed to monitor continuously the weight of the sample when it is being heated to high temperatures, and here to study the mass variation of the sample. The thermogravimetric analysis (TGA) of the fibers was done using NETZSCH TG 209 F1 LIBRA. The temperature range from 30 to 550°C with a heating rate of 10°C/minute in a nitrogen atmosphere. TGA is used to study the thermal degradation and mass stability of the untreated and treated fibers.

The test consists of the below procedure:

1. Grind hemp to a powder form using a grinder equipped with a ball mill (*Figure 27*)
2. Using the microbalance weigh the mass sample excluding the crucible mass (*Figure 28*).
3. Place the crucible and the sample in any of the 63 positions available of the TGA autosampler (*Figure 29*).
4. Open NETZSCH software, create a new file, select the chosen position, and insert the mass sample.
5. Choose the nitrogen atmosphere and set the initial and final temperature range.
6. Run, save the results, and export as an

Figure 28. Hemp sample prepared for TGA test

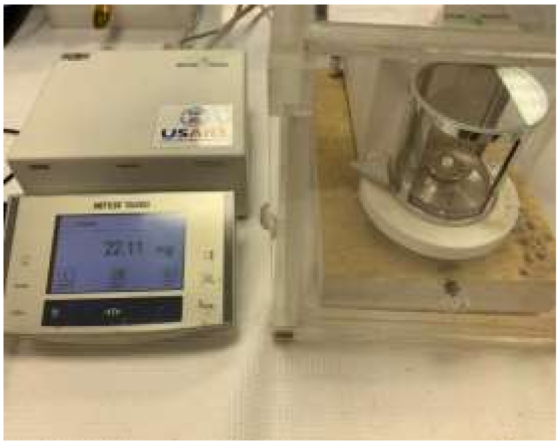


Figure 27. Microbalance

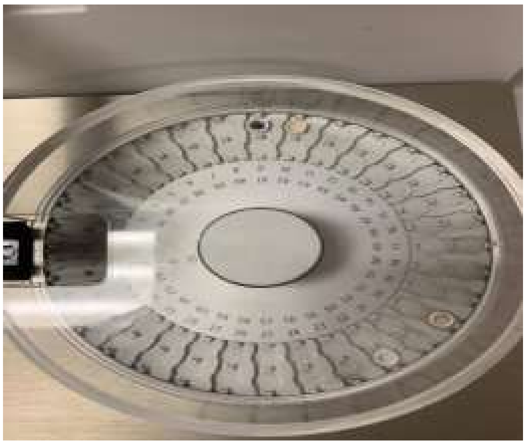


Figure 29. TGA sample holder

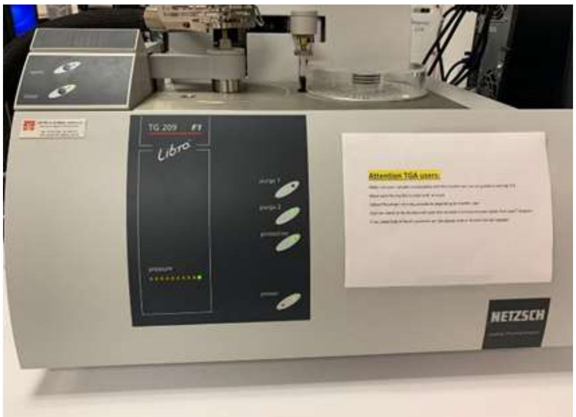



Figure 30. TGA test equipment

**TGA results**

It can be deduced from the TGA curves shown in Figure 31 that the hemp fibers decompose quickly after 250°C, and are completely decomposed at 370°C. This is because the main constituents of the fiber, which are cellulose, hemicellulose and lignin, have similar degradation temperatures.The small initial loss of weight is due to the moisture that exists in the fibers. Also, the TGA curves show that the alkali and acetyl treatments improved the thermal stability of the fiber while the silane treatment had no significant effect.

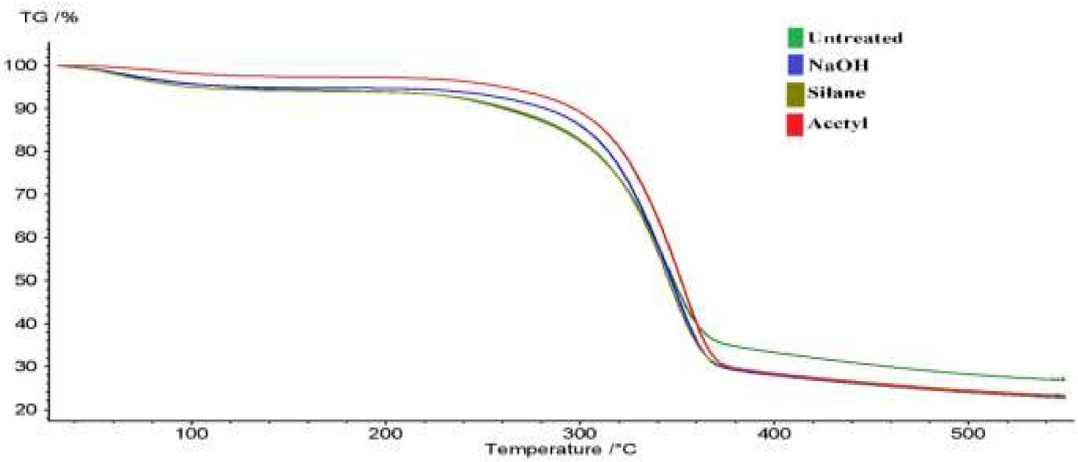



Figure 31. TGA result of hemp fibers.

## 4.5 Conclusions

1- SEM results indicated that alkaline and acetyl treatments improved the hemp surface by removing the impurities while the silane treatment was ineffective.

2- Alkaline and acetyl treatments increased the crystallinity index of fibers whereas the silane treatments had no significant effect on hemp

3- The TGA results illustrated that silane treatments had no effect on hemp thermal behavior while the alkaline and acetyl treatments improved the thermal stability of hemp.

# Chapter 5

# CONCRETE TESTING AND RESULTS

## 5.1 Introduction

The concrete cylinders and beams prepared throughout the experimental program were subjected to mechanical tests besides measuring the slump of the different concrete mixes: compressive strength, flexural strength, splitting tensile strength, modulus of elasticity. Durability tests were also conducted: water absorption, freezing thawing, and thermal conductivity test. Concrete specimens were divided into two main groups as shown in Table 4. Group one incorporates maximum size aggregate (MSA) of 10 mm whereas the second group has MSA of 20 mm.

In mixes with hemp fibers, the aggregate content was subjected to a reduction of 20% by volume of concrete.

## 5.2 Testing Plan

To study the effect of variables on concrete properties, different mixes were prepared, each having different variables as summarized in *Table 4*. The number of replicates for the different tests are shown in *Table 5*. The variables included:

1. **Hemp length:** To find the optimum behavior of HRAC, effect of fiber length is investigated. Based on literature, long and short fibers decrease the mechanical properties of concrete; consequently, average lengths of 20 mm and 30 mm were checked.
2. **Hemp treatment:** Hemp fibers are natural resources that hold impurities on its surface. In order to mitigate the effect of impurities and improve surface

roughness, thus providing a better bond with concrete, two types of treatments were checked: alkali (T1) and acetyl (T2) treatments.

3. **Maximum aggregate size:** Influence of maximum size aggregate on concrete properties was studied by checking two sizes in the mentioned below mixes: 10 mm and 20 mm.
4. **Type of aggregates:** Comparison of physical and mechanical properties of concrete mixes containing recycled aggregate to those having natural aggregates with a percentage of replacement of 0% and 50% was performed.

A 3-part notation system was used to identify the concrete mix. The first part refers to the type of aggregates (N for natural, R for mixes 50% replacement of natural aggregates with recycled aggregates) and the MSA(10 mm or 20 mm). The second part refers to the use of hemp fibers(H20 is 20 mm fiber length and H30 is 30 mm fiber length). The third part of the notation refers to the type of fibers treatment (T1 or T2).The molds used for the different testes specimens are shown in Figure 32, Figure 33 and Figure 34.

*Table 4. Concrete mixes variables*

| | Mix No. | Mix ID | MSA (mm) | % Replacement of NCA by RCA | Fiber Length (mm) | Fiber Treatment |
|---|---|---|---|---|---|---|
| **Group 1 MSA = 10 mm** | 1 | N10 (Control10) | 10 | 0 | - | - |
| | 2 | R10 | 10 | 50 | - | - |
| | | | | | | |
| | 3 | N10-H20-T1 | 10 | 0 | 20 | Alkali |
| | 4 | R10-H20-T1 | 10 | 50 | 20 | Alkali |
| | 5 | R10-H20-T2 | 10 | 50 | 20 | Acetyl |
| | | | | | | |
| | 6 | N10-H30-T1 | 10 | 0 | 30 | Alkali |
| | 7 | R10-H30-T1 | 10 | 50 | 30 | Alkali |
| | | | | | | |
| **Group 2 MSA = 20 mm** | 8 | N20 (Control20) | 20 | 0 | - | - |
| | 9 | R20 | 20 | 50 | - | - |
| | | | | | | |
| | 10 | N20-H20-T1 | 20 | 0 | 20 | Alkali |
| | 11 | R20-H20-T1 | 20 | 50 | 20 | Alkali |
| | 12 | N20-H20-T2 | 20 | 0 | 20 | Acetyl |
| | 13 | R20-H20-T2 | 20 | 50 | 20 | Acetyl |
| | | | | | | |
| | 14 | N20-H30-T1 | 20 | 0 | 30 | Alkali |
| | 15 | R20-H30-T1 | 20 | 50 | 30 | Alkali |
| | 16 | R20-H30-T2 | 20 | 50 | 30 | Acetyl |

*Table 5. Replicates of specimens for each test*

| Test | Replicates at 7 days | Replicates at 28 days | Replicates for long term testing |
|---|---|---|---|
| **Compressive strength** | 2 | 3 | 2 |
| **Split tensile strength** | - | 2 | 2 |
| **Flexure beams** | **-** | 2 | 2 |
| **Modulus of Elasticity** | - | 2 | 2 |
| **Freeze and thaw** | - | 1 | - |
| **Wetting and drying** | | 2 | 1 |
| **Absorption** | - | 3 | - |
| **Thermal** | - | 1 | - |

Figure 32. Cylinders molds (15x30 cm*)*

Figure 33. freeze and thaw mold (7.5x10x40.5 cm)

Figure 34. Compressive strength molds

According to standards, each experimental test requires a specific dimension and shape of concrete samples, thus specimen preparation followed ASTM C78 for flexural concrete beams and ASTM C39 for standard cylinders subjected to compressive strength test as illustrated in *Table 6*.

*Table 6. Mold dimensions for the hardened concrete tests.*

| **Test** | **Dimension (cm)** | **Material** |
|---|---|---|
| **Compressive strength** | 10x20 | PVC |
| **Split tensile strength** | 10x20 | PVC |
| **Flexure beams** | 10x10x35 | Plywood |
| **Modulus of Elasticity** | 15x30 | Steel |
| **Freeze and thaw** | 7.5x10x40.5 | Humboldt moulds |
| **Wetting and drying** | 10x20 | PVC |
| **Absorption** | 10x20 | PVC |
| **Thermal** | 30x30x5 | Plywood |

## 5.3 Material preparation

All constituents of the concrete mixes (Fine and coarse aggregates, hemp, water and cement) were well prepared. Suitable material preparation results in a workable and cohesive concrete matrix leading to an accurate concrete properties.

Sand should be sieved to eliminate impurities. Clean sand is put in the oven for 24 hours to remove all humidity (Figure 35). Before mixing, sand is removed from the oven and left to cool at room temperature. Coarse aggregates, whether natural or recycled, need to be well washed to remove all dust and impurities stuck on the surface. After washing, coarse aggregate are put in the oven for 24 hours one day prior to mixing to remove water from the pores. Then, the aggregates are removed and left to cool at room temperature. It is important to ensure that the FA and CA are in SSD status and cooled enough to prevent the evaporation of mixing water.

Figure 35. Oven-dried sand prior to mixing

After treatment, hemp fibers cut into two and three cm length have a bundle form. A well dispersion in hair shape to prevent concrete balling is necessary (Figure 36)

Figure 36. Dispersion of the hemp fibers.

Water used in the mix should be distilled water at ambient room temperature. As for cement added to concrete mix, it is important to ensure that the cement bag is well closed and far from any humidity and air (Figure 37).

Figure 37. Weighed cement prior to mixing

## 5.4 Concrete mix design

Concrete mix design is the selection of the optimum proportion of the constituent materials of concrete to reach the required workability of fresh concrete, the targeted compressive strength of hardened concrete, and durability aspects, in the most economical way. The consistuents of a concrete mix are shown in Figure 38. Two concrete mixes, one for each MSA (10and 20mm) mixes, were designed to reach a compressive strength of 30 MPa. It should be noted that coarse aggregate volume was reduced by 20% of total concrete volume when hemp fibers were incorporated in the mix.

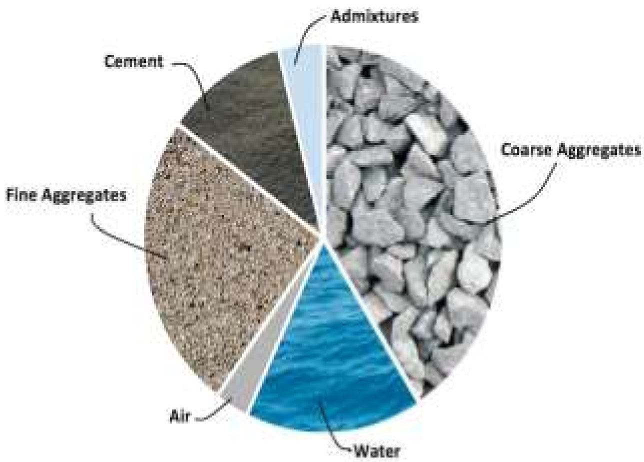



Figure 38. Constituents of the concrete mix

Based on the stipulated Tables in ACI 211.1-91 presented in the appendix below, the mix design criteria are as follows:

- Hemp fibers volume is 0.75% of total concrete volume.
- Reduction of coarse aggregate by 20% of total concrete volume.
- Intended slump=150 mm to 175 mm.

Batching weights are the SSD taking into account the absorption of the aggregates and are listed in *Table 7*.

*Table 7. Batching weight at SSD for the two mixes.*

| | Mix ID | Cement ($Kg/m^3$) | Water ($Kg/m^3$) | NCA ($Kg/m^3$) | RCA ($Kg/m^3$) | Sand ($Kg/m^3$) | Fibers ($Kg/m^3$) |
|---|---|---|---|---|---|---|---|
| **Group 1 MSA = 10 mm** | N10 (Control10) | 450 | 243 | 652 | 0 | 930 | - |
| | R10 | 450 | 243 | 326 | 326 | 930 | - |
| | | | | | | | |
| | N10-H20-T1 | 450 | 243 | 355.5 | 0 | 930 | 10.5 |
| | R10-H20-T1 | 450 | 243 | 177.75 | 177.75 | 930 | 10.5 |
| | R10-H20-T2 | 450 | 243 | 177.75 | 177.75 | 930 | 10.5 |
| | | | | | | | |
| | N10-H30-T1 | 450 | 243 | 355.5 | 0 | 930 | 10.5 |
| | R10-H30-T1 | 450 | 243 | 177.75 | 177.75 | 930 | 10.5 |
| | | | | | | | |
| **Group 2 MSA = 20 mm** | N20 (Control20) | 400 | 216 | 905 | 0 | 763 | - |
| | R20 | 400 | 216 | 452.5 | 452.5 | 763 | - |
| | | | | | | | |
| | N20-H20-T1 | 400 | 216 | 603 | 0 | 763 | 10.5 |
| | R20-H20-T1 | 400 | 216 | 301.5 | 301.5 | 763 | 10.5 |
| | N20-H20-T2 | 400 | 216 | 603 | 0 | 763 | 10.5 |
| | R20-H20-T2 | 400 | 216 | 301.5 | 301.5 | 763 | 10.5 |
| | | | | | | | |
| | N20-H30-T1 | 400 | 216 | 603 | 0 | 763 | 10.5 |
| | R20-H30-T1 | 400 | 216 | 301.5 | 301.5 | 763 | 10.5 |
| | R20-H30-T2 | 400 | 216 | 301.5 | 301.5 | 763 | 10.5 |

### 5.5 Concrete mixing

Further to the material preparation, concrete mixing is ready to be performed. The experimental plan batching was performed using a mixer and following ASTM C129. First, coarse aggregates were added to the rotating container with some quantity of mixing water and were left for few minutes. Meanwhile, the hemp fibers were dispersed slowly to prevent balling of hemp. Then, sand was added to the mixer with the continuous dispersion of hemp. After few rotations, the lubricant (water and superplasticizer already mixed) fibers were added to the mix along with the addition of cement. To prevent cement and particle evaporation, the mixer opening was firmly closed. Finally, after 2 to 3 minutes of rotations, the mixer is turned off allowing the mix to rest for two minutes and then suitably placed in the panel to avoid concrete segregation (Figure 39).General view of the prepared molds prior to casting is shown in

*Figure 40*.

Figure 39. Mixed concrete in the panel prior to placement in the molds,

Figure 40. General view of formwork used in all tests.

### 5.6 Placing and curing of concrete

According to ASTM C192, concrete cylinders need to be placed in three layers each rodded 25 times (rod needs to be round, straight with at least one hemispherical end), and the outside of mold is tapped 10-15 times with a mallet. Whereas the beams are filled in two layers each rodded 25 times. View of the prepared samples after casting is shown in Figure 41.

After a minimum of one day, the formwork is removed and the concrete specimens are placed in a curing room to acquire its maximum strength. Cylinders and beams are placed in water containers in *Figure 42*.


Figure 41.Concrete specimens after stripping the molds.

Figure 42. Concrete Specimen Curing

## 5.7 Testing Procedure, Analysis and Results.

### *5.7.1 Slump Test*

Consistency of the reinforced concrete is an important factor to assess the fluidity of concrete mix. It provides information on the workability, ease of casting of concrete on sites or in the laboratory. This test was performed on all sixteen mixes cast in the experimental plan. To complete the slump test in accordance with ASTM C143, clean the internal surface of the steel mould and place it on a horizontal base plate. Fill the mould in three equal layers, each layer rodded 25 strokes in a uniform way .The strokes should penetrate 1 in. the underlying layer. At the surface of the final layer, remove all excess material with a trowel. Finally, raise the mould vertically and slowly, invert the mould, and record the difference between the top of the mould seel and the concrete cone (Figure 43). View of the slump values for the different mixes are listed in *Table 8* and presented in *Figure 44* and *Figure 45*.

Figure 43. Slump test of concrete

*Table 8. Slump tests results*

| | Mix ID | Slump (cm) | | Mix ID | Slump (cm) |
|---|---|---|---|---|---|
| **GROUP 1** **MSA=10 mm** | N10 (Control10) | 23 | **GROUP 2** **MSA=20 mm** | N20 (Control20) | 20 |
| | R10 | 22 | | R20 | 20 |
| | | | | | |
| | N10-H20-T1 | 16 | | N20-H20-T1 | 14 |
| | R10-H20-T1 | 13 | | R20-H20-T1 | 10 |
| | | | | N20-H20-T2 | 12 |
| | R10-H20-T2 | 14 | | R20-H20-T2 | 11 |
| | | | | | |
| | N10-H30-T1 | 13 | | N20-H30-T1 | 14 |
| | R10-H30-T1 | 13 | | R20-H30-T1 | 10 |
| | | | | R20-H30-T2 | 12 |

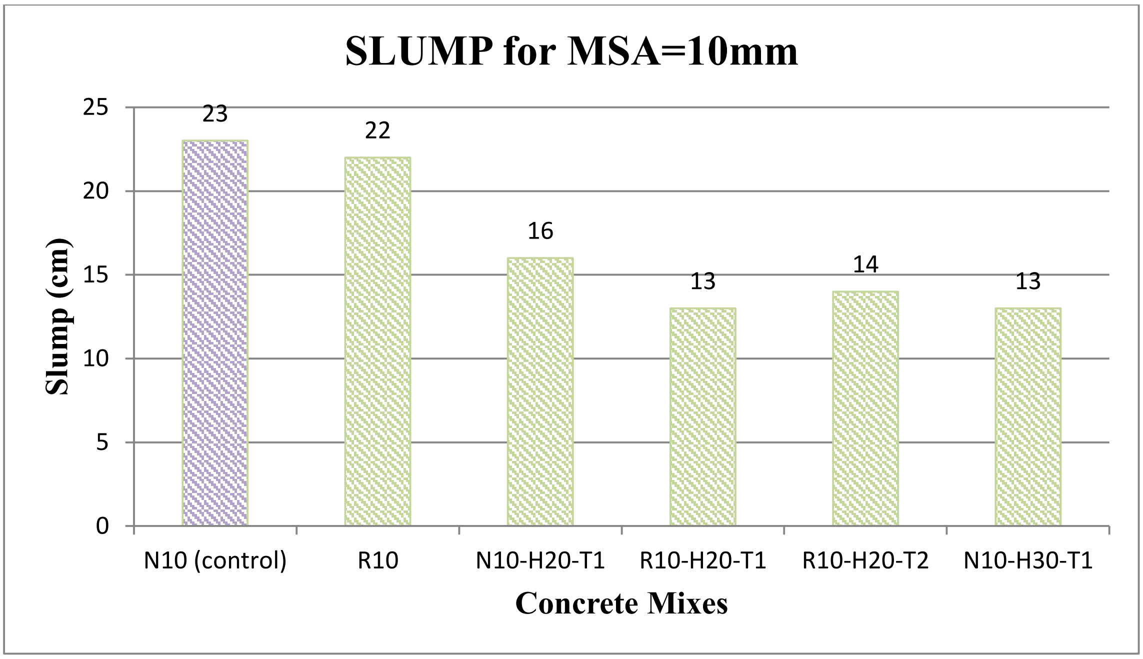



Figure 44.Variation of concrete slump of mixes with MSA=10 mm

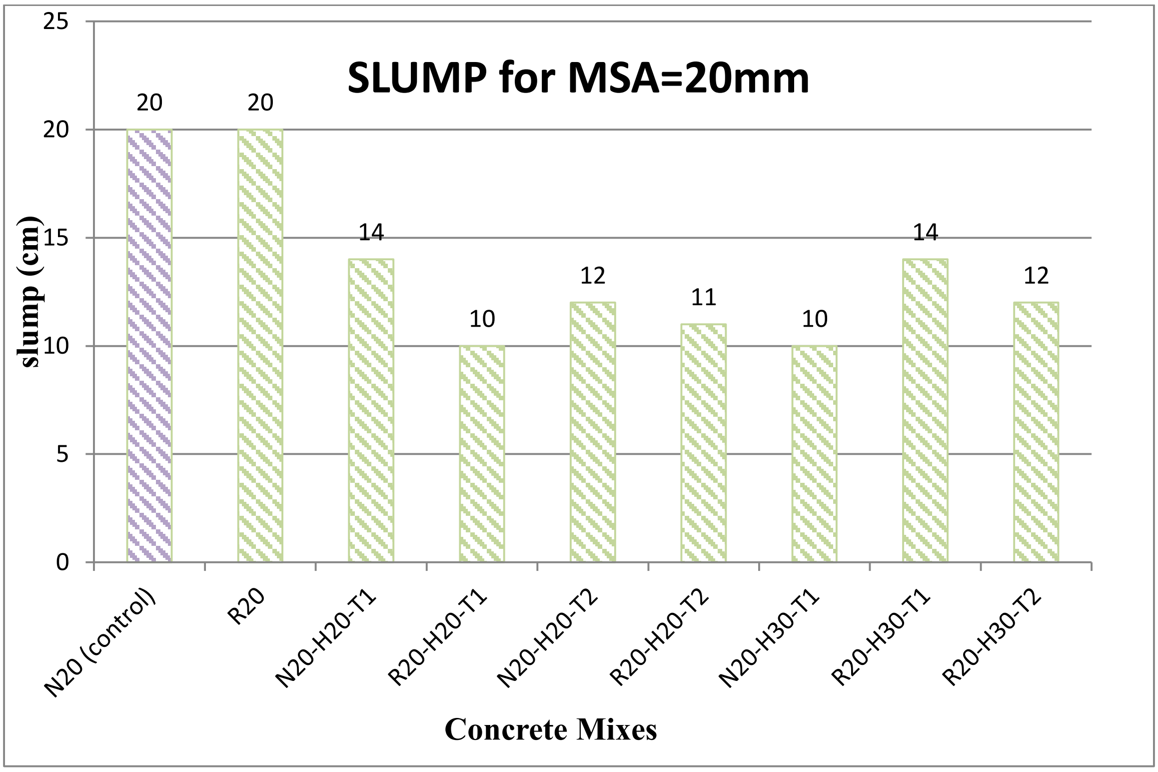



Figure 45. Variation of concrete slump of mixes with MSA=20 mm

Control mixes for both MSA series, resulted in slump values ranging between 20 and 30 cm. Mixes with 50% replacement of NCA by RCA did not present any significant effect on slump. Whereas, mixes containing both hemp fibers and recycled aggregates showed a significant decrease in slump with values ranging between 10 and 14 cm. The results remain in the acceptable range and the reduction refers to the high absorption of the mix's water by the hemp fibers.

### *5.7.2 Compressive strength*

Concrete is a material characterized by its high ability to withstand compression forces. The concrete compressive strength test was applied in accordance with ASTM C39. All cylinders should be capped with sulphur as per ASTM C167 (*Figure 46*) to ensure a uniform load distribution along the surface. Specimen diameters and lengths should be measured in two locations at right angles to calculate an accurate cross-sectional area (*Figure 48*). For a proper testing, the cylinders are well centered in the compression-testing machine, and then load is applied at a rate of 1.25mm/min until failure occurs.

Afterward, the ultimate force applied is recorded and the compressive strength is calculated. View of different tested cylinders are shown in Figure 49. Control specimens and specimens with 50% replacement of RCA by NCA presented a similar mode of failure. Concrete Cylinders showed a brittle failure with crack propagation. Whereas, the specimens incorporating hemp fibers did present a more ductile behaviour  Average compressive strength test results are listed in Table and shown in Figure  for MSA of 10 and 20 mm, respectively.


Figure 46. Capped compressive strength specimen

Figure 47. Compressive strength concrete specimen


*Figure 48* . Measuring length of compressive strength specimen

*(a). Specimen N10* *(b) Specimen R20* *(c) Specimen R20-H30-T1*

Figure 49. Different mode of failure of concrete specimens subjected to compression

Average compressive strength test results are listed in *Table 9* and shown in Figure 50 and Figure 51 and for MSA of 10 and 20 mm.

*Table 9 . Average compressive strength test results.*

| | Mix ID | Compres--sive Strength (MPa) | Ratio relative to N10 | | Mix ID | Compres--sive Strength (MPa) | Ratio relative to N20 |
|---|---|---|---|---|---|---|---|
| **GROUP 1 MSA=10 mm** | N10 (Control) | 38 | - | **GROUP 2 MSA=20 mm** | N20 (control 20) | 39 | - |
| | R10 | 34.25 | 0.9 | | R20 | 35 | 0.9 |
| | | | | | | | |
| | N10-H20-T1 | 23 | 0.61 | | N20-H20-T1 | 28 | 0.72 |
| | R10-H20-T1 | 24.5 | 0.64 | | R20-H20-T1 | 25 | 0.64 |
| | | | | | N20-H20-T2 | 27 | 0.69 |
| | R10-H20-T2 | 24.5 | 0.64 | | R20-H20-T2 | 25 | 0.64 |
| | | | | | | | |
| | N10-H30-T1 | 24 | 0.63 | | N20-H30-T1 | 32 | 0.82 |
| | R10-H30-T1 | 24 | 0.63 | | R20-H30-T1 | 26 | 0.67 |
| | | | | | R20-H30-T2 | 25 | 0.64 |

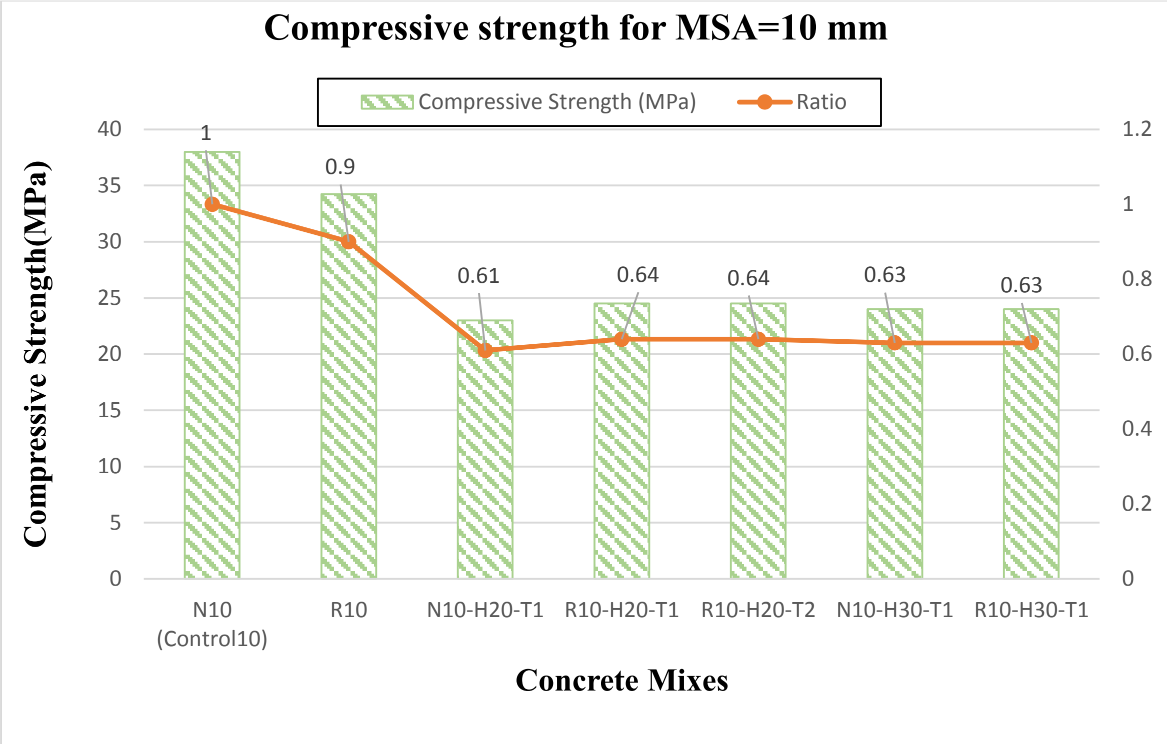



Figure 50. Average compressive strength values for concrete mixes with MSA=10 mm

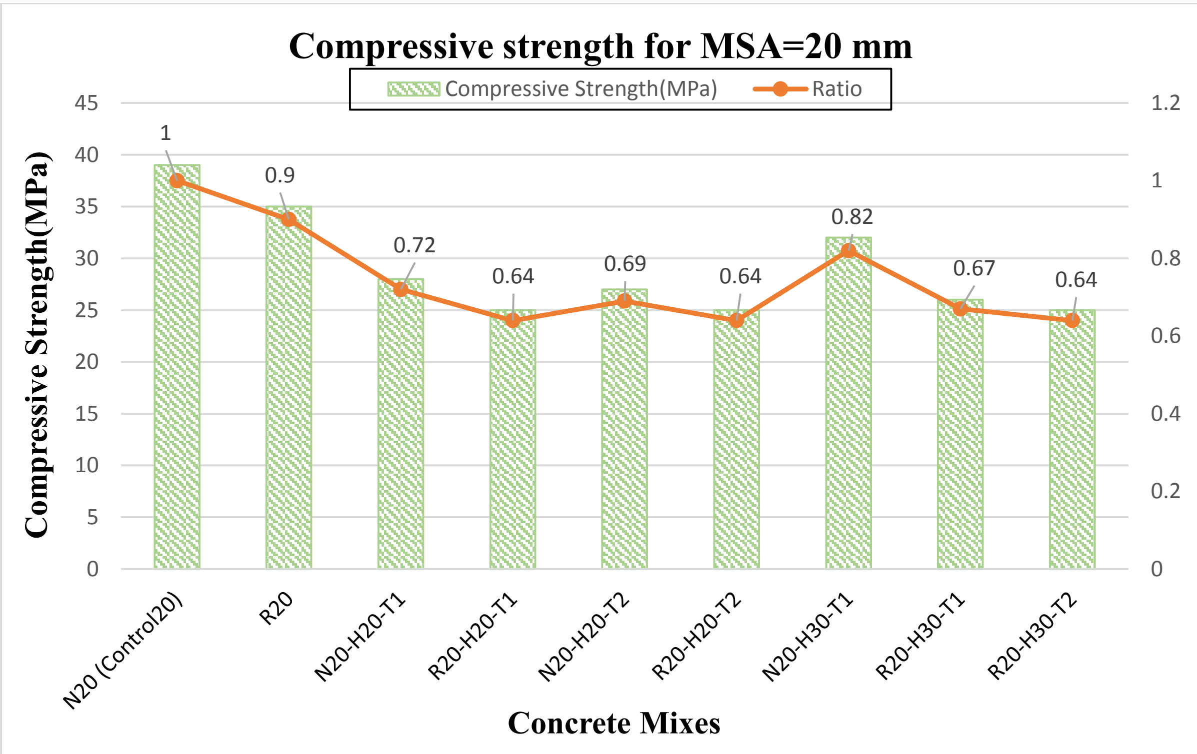



Figure 51. Average compressive strength values for concrete mixes with MSA=20 mm

Compressive strength test results at 28 days, indicates that the replacement of 50% of NCA by RCA reduce the compressive strength of concrete by approximately 10%. However, when hemp fibers were introduced and the coarse aggregate content was reduced by 20%, the compressive strength of the five mixes of Group 1 with MSA of 10 mm and with different fiber lengths and fiber treatments was reduced by 36 to 39% as compared with the control mix N10. The performance of the three HRAC mixes was similar to mixes without RCA. In Group 2 with MSA of 20 mm, the reduction in compressive strength relative to the control mix N20 ranged between 18 and 31% for the three mixes with hemp fibers but without RCA. The reduction was more pronounced for the four HRAC mixes and was similar to the HRAC mixes of Group 1, and ranged between 33 and 36%.

Reduction in compressive strength, when including hemp fibers in the mix, is due to the fact that hemp fibers cannot resist a compressive force and the fact that coarse aggregates content is reduced. The results indicate that concrete mixes with an MSA of 20 mm tend to have a slightly higher compressive strength than those with an MSA of 10 mm, but identical otherwise.

### *5.7.3 Splitting tensile*

Tensile strength is one of the main properties of concrete that is highly susceptible to tensile stress due to different load applications. Tensile strength is determined in accordance with ASTM C496. This test is done by an indirect method because applying uniaxial tensile loading to the specimen can not be achieved. Initially, it is made sure that the two ends of the specimen are on the same axial place.

Then, the specimen is set between two plates of 4mm width Afterward, the load is continuously applied at a rate of 2mm/min until failure occurs. The setup is shown in Figure 52.

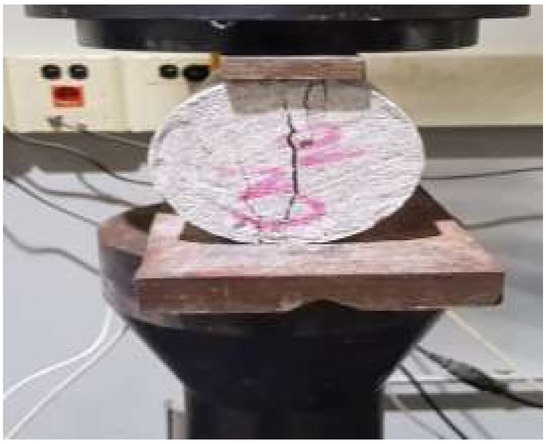
The tensile strength is calculated using Eq. 5.1.

$$T = \frac{2P}{\pi L D} \qquad \text{Equation (5.1)}$$

- T = splitting tensile strength (kPa)
- P = Ultimate applied load (kN)
- L and D are the specimen's length and diameter, respectively. (m)

Views of different specimens after failure are shown in Figure 53.

Figure 52. Tensile strength set-up



*(a). Control Specimen N10*

*(b). Failure of hemp mix under tensile loads*

*(c). Cracks bridging due to hemp*

Figure 53. Different mode of failure for concrete specimens subjected to tensile strength

Average tensile strength values for the different tested specimens are listed in *Table 10* and shown in Figure 54 and Figure 55.

*Table 10.Average tensile strength of concrete mixes*

| | **Mix ID** | **Splitting tensile strength (MPa)** | **Ratio relative to N10** | | **Mix ID** | **Splittin g tensile strength (MPa)** | **Ratio relative to N20** |
|---|---|---|---|---|---|---|---|
| **GROUP 1 MSA=10 mm** | N10 (Control10) | 2.24 | - | **GROUP 2 MSA=20 mm** | N20 (Control20) | 2.64 | - |
| | R10 | 2.21 | 0.99 | | R20 | 2.53 | 0.96 |
| | | | | | | | |
| | N10-H20-T1 | 2.08 | 0.93 | | N20-H20-T1 | 2.51 | 0.95 |
| | R10-H20-T1 | 2.1 | 0.94 | | R20-H20-T1 | 2.31 | 0.88 |
| | | | | | N20-H20-T2 | 2.55 | 0.97 |
| | R10-H20-T2 | 2.14 | 0.96 | | R20-H20-T2 | 2.52 | 0.95 |
| | | | | | | | |
| | N10-H30-T1 | 1.94 | 0.87 | | N20-H30-T1 | 2.3 | 0.87 |
| | R10-H30-T1 | 1.99 | 0.89 | | R20-H30-T1 | 2.1 | 0.8 |
| | | | | | R20-H30-T2 | 2.4 | 0.91 |

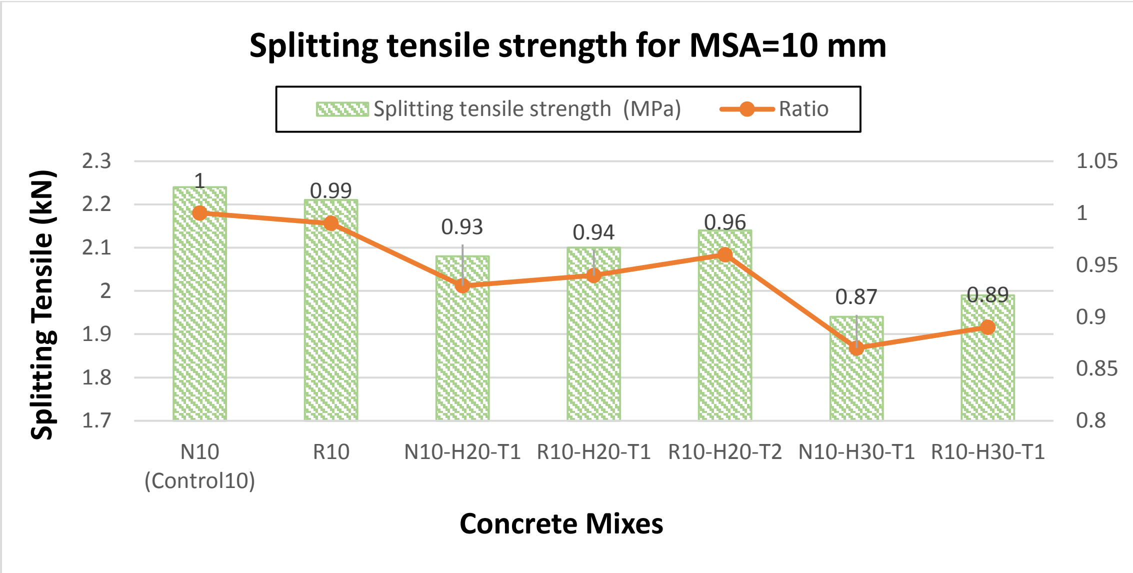



Figure 54.Average tensile strength result for concrete mixes with MSA=10 mm

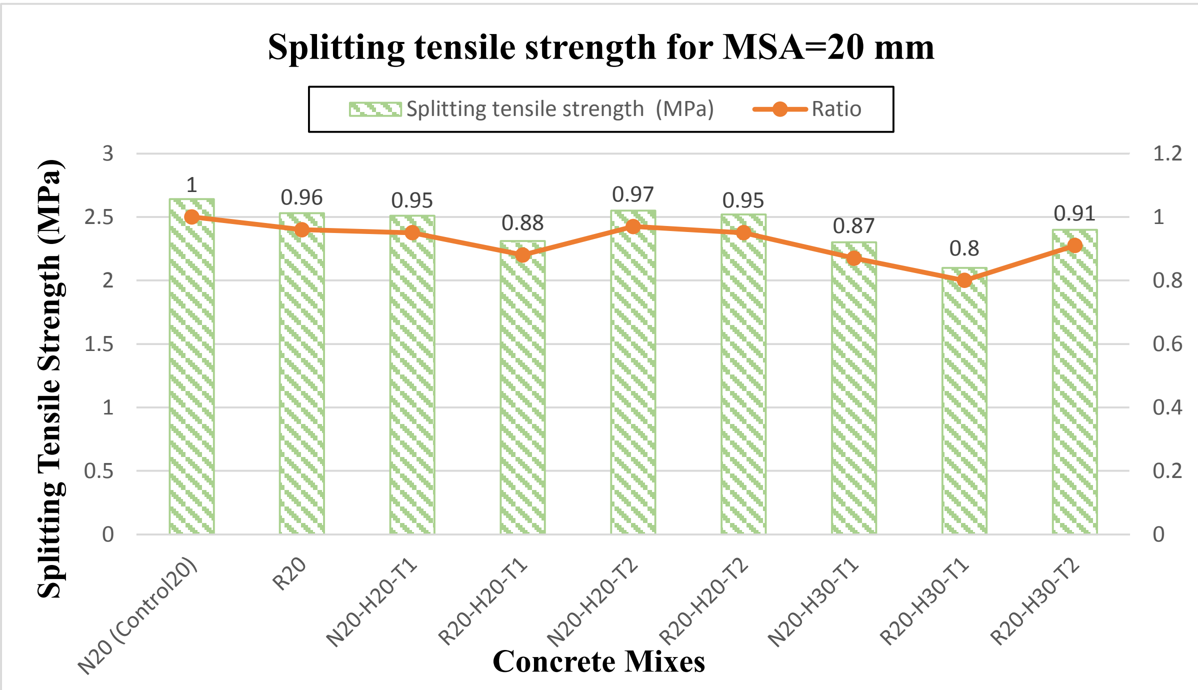



Figure 55. Average tensile strength result for concrete mixes with MSA=20 mm

Test Results shown in Table 5 indicate that mixes containing 50% replacement of NCA with RCA and with no fibers had a splitting tensile strength very similar to the control mixes with a reduction of 4% for both MSA. Mixes with hemp fibers in both groups of different MSA (10 and 20 mm) had similar tensile strength regardless of fiber length or fiber treatment or whether a 50% replacement of NCA with RCA was used. The reduction in splitting tensile strength of the 5 mixes with fibers in Group 1 with MSA of 10 mm relative to the control mix N10 ranged between 4 and 13% with an average of 8.2%. For Group 2 with MSA of 20 mm, the reduction relative to N20 ranged between 3 and 20% with an average of 9.6%. The results show that production of HRAC would not lead to a reduction in the splitting tensile strength not as significant as the reduction in compressive strength.

### *5.7.4 Flexural Strength*

Flexural strength is the maximum stress at the outer fiber on either the compression or the tension face of the standard beam specimen. For a better understanding of fibers effect on the flexural and toughness capacity of concrete, flexural testing was performed in compliance with ASTM C78. The flexural test was done on simply supported beams with third-point loading. The beam was divided into three strips and a two-point load was applied on the middle strip's edges. The deflection was measured at the beam mid-span using a dial gage. The values of the ultimate flexural strength or modulus of rupture (MOR) are presented in *Table 11. Results of modulus of Rupture.*and plotted in *Figure 56* and *Figure 57*for MSA of 10 and 20 mm, respectively.

The moist-cured sample is loaded continuously without shock at a rate that increases the extreme fiber stress between 0.86 and 1.21 MPa/min until failure occurs.

The modulus of rupture is computed using Equ.5.2

$$R\ (MOR) = \frac{P*L}{b*d^2} \quad \text{.......................................................... Equation (5.2)}$$

- P = maximum applied load indicated by the testing machine(N)
- L, b and d are respectively the span length, the average width and average depth of the specimen in mm.

*Table 11. Results of modulus of Rupture.*

| ` | Mix ID | Modulus of Rupture (MPa) | Ratio relative to N10 | | Mix ID | Modulus of Rupture (MPa) | Ratio relative to N20 |
|---|---|---|---|---|---|---|---|
| **GROUP 1 MSA=10 mm** | N10 (Control10) | 5.1 | - | **GROUP 2 MSA=20 mm** | N20 (Control20) | 5.25 | - |
| | R10 | 4.8 | 0.94 | | R20 | 4.57 | 0.87 |
| | | | | | | | |
| | N10-H20-T1 | 4.95 | 0.97 | | N20-H20-T1 | 5.1 | 0.97 |
| | R10-H20-T1 | 4.35 | 0.85 | | R20-H20-T1 | 4.65 | 0.89 |
| | | | | | N20-H20-T2 | 4.65 | 0.89 |
| | R10-H20-T2 | 4.2 | 0.82 | | R20-H20-T2 | 4.5 | 0.86 |
| | | | | | | | |
| | N10-H30-T1 | 4.8 | 0.94 | | N20-H30-T1 | 4.95 | 0.94 |
| | R10-H30-T1 | 4.2 | 0.82 | | R20-H30-T1 | 4.5 | 0.86 |
| | | | | | R20-H30-T2 | 4.5 | 0.86 |

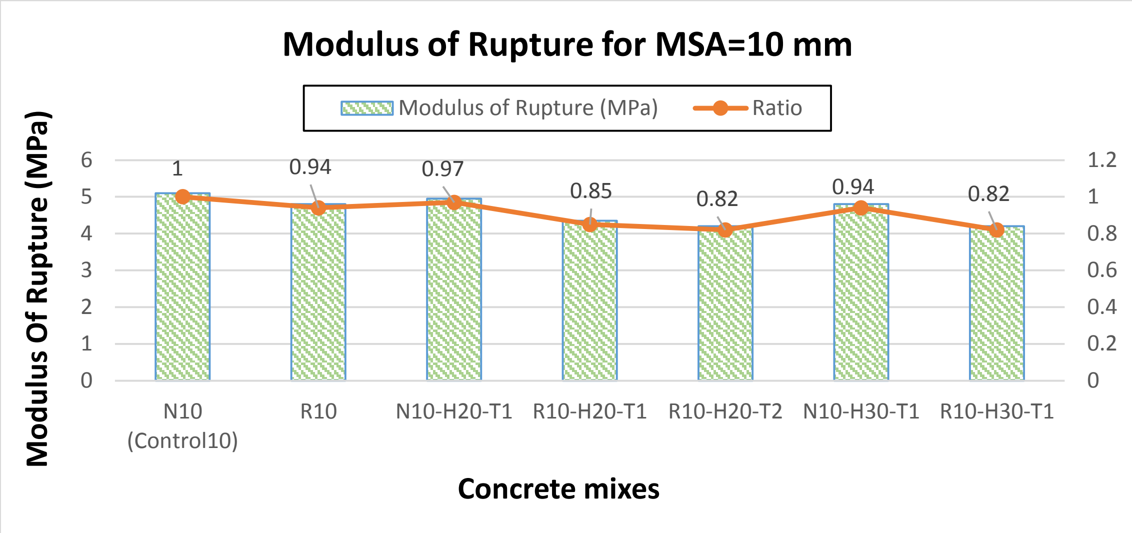



Figure 56. Modulus of rupture results for concrete specimens with MSA=10 mm

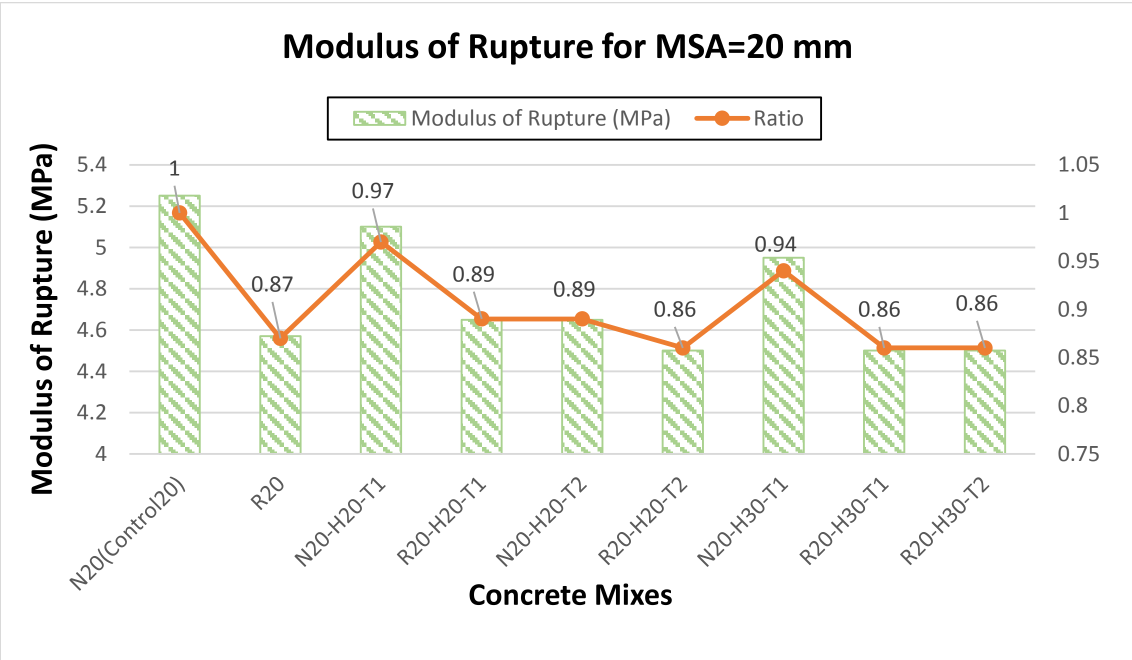



*Figure 57. Modulus of rupture results for concrete specimens with MSA=20 mm*

The MOR decreased by around 6% when 50% of NCA of MSA of 10 mm was replaced by RCA. The reduction was 13% for MSA of 20 mm. In Group 1 with MSA of 10 mm, when hemp fibers were incorporated in the mix accompanied by 20% reduction of coarse aggregates, the reduction relative to the control mix N10 was 3 to 6% for mixes with no RCA and was 15 to 18% for the three HRAC mixes. In Group 2 with MSA of 20 mm, the reductions relative to N20 were 3 to 11% for mixes without RCA and 11 to 14% for the five HRAC mixes.

Overall the reductions in flexural strength for the HRAC mixes due to the incorporation of hemp fibers, reduction in coarse aggregate content, and replacement of 50% of NCA with RCA, were less significant than the reductions reported above for the compressive strength. Moreover, the fiber length (20 or 30 mm) and the fiber treatment (alkali or acetyl) did not affect the trend of the test results. Views of different specimens after failure are shown in Figure 58 and Figure 59.A brittle failure of all tested beams without hemp fibers are observed.The first flexural crack, noticed approximately at mid-span, was destructive and propagated rapidly. Although the concrete beams reinforced with hemp fibers failed at a lower load, the concrete specimens showed a more ductile behavior.The crack initiated at mid-span did not propagate due to the bridging effect of hemp fibers.

Figure 58. Flexural failure of mix with hemp

Figure 59. Flexural failure of mix without hemp

The load-deflection curves of the flexural beams are presented in Figure 61 for Group 1 of mixes with MSA of 10 mm and in Figure 60 for Group 2 of mixes with MSA of 20 mm. Both Figures indicate that mixes without hemp fibers, with or without RCA replacement of NCA, show brittle behavior with no load-deflection history after reaching ultimate. However, mixes containing hemp fibers in both groups with different MSA (10 or 20 mm), with or without RCA replacement of NCA, have a ductile behavior after the peak load with considerable load-deflection history after ultimate. The high ductility and energy absorption of the fiber mixes is demonstrated by the larger area under the load-deflection curves. This can be explained by the fact that when cracks start to appear in the beams with hemp fibers, the fibers bridge over the cracks and prevent a brittle failure of the beam.

The results indicate that although the production of HRAC mixes, where NCA is replaced by a combination of RCA and hemp fibers accompanied by a reduction in the coarse aggregate content, would lead to an average of 15% reduction in flexural strength, however the load-deflection history becomes ductile.

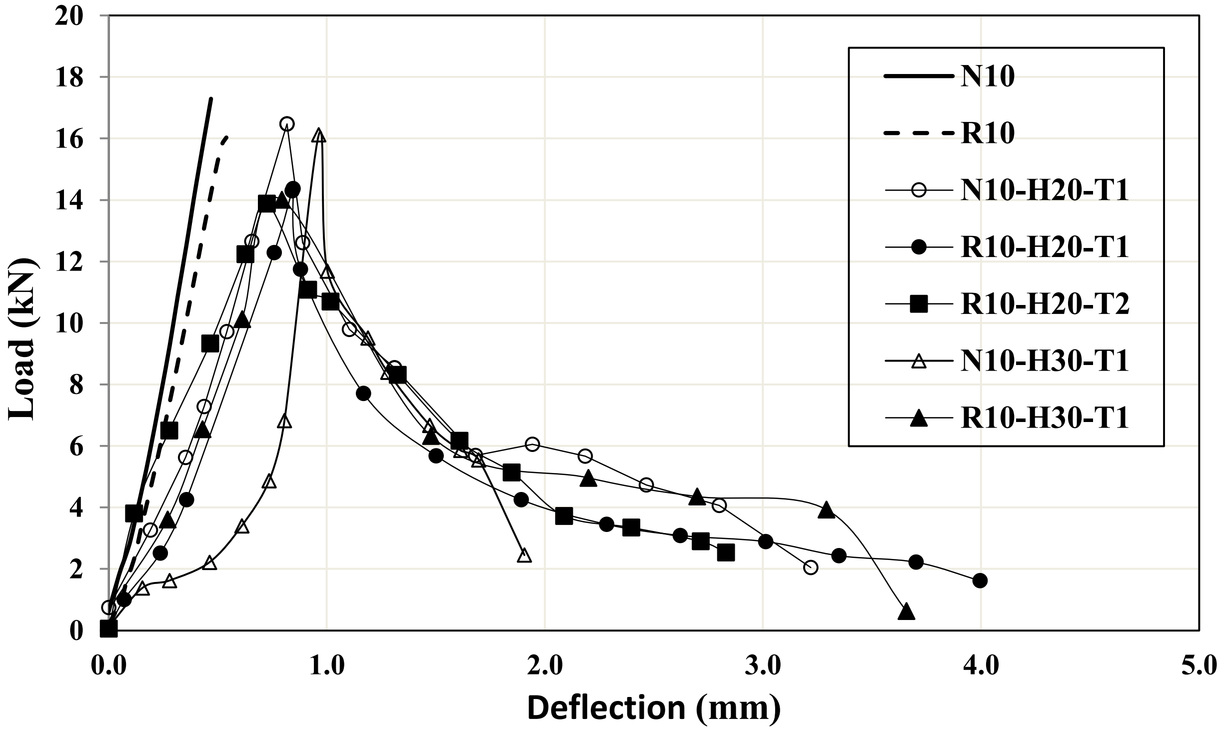



*Figure 60. Load deflection curves of concrete specimens for MSA of 10 mm.*

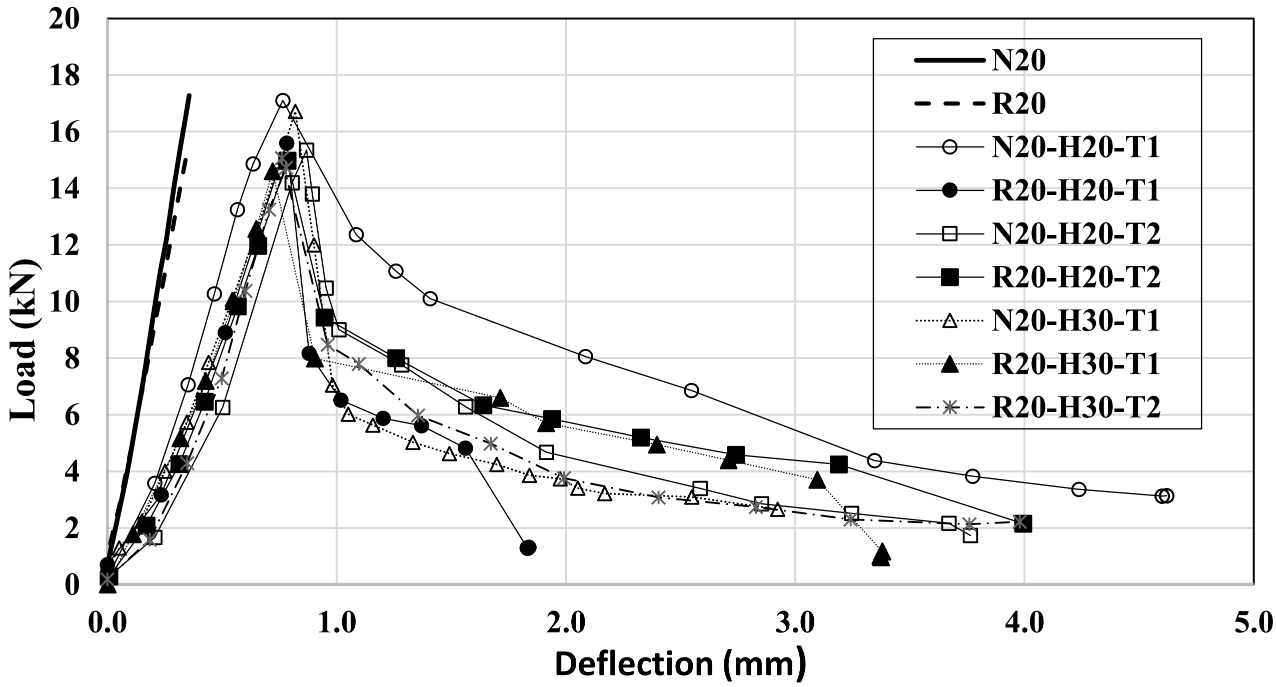



*Figure 61. Load deflection curves of concrete specimens for MSA of 20 mm.*

### *5.7.5 Modulus of Elasticity*

To measure concrete stiffness, the modulus of elasticity is tested in accordance per ASTM C469 (Figure 62). Modulus of elasticity is the ratio of the stress applied divided by the resulting strain within the elastic limit. To perform the test, the bearing surfaces are capped with sulfur as per ASTM C167 and then the wire strain gauges are atached, after ensuring the correct position.Then the sample in placed and centered in the universal testing machine .Then the strain gauges are connected to the strain indicator connected to the computer. The load is continuously applied at a rate of 250 kPa/s until it reaches 40% of the ultimate load of the specimen. Test results are listed in *Table 12* and are plotted in *Figure 63* and *Figure 64* for the groups with MSA of 10 and 20 mm, respectively.

*Figure 62.Modulus of Elasticity set-up*

*Table 12.Modulus of Elasticity results*

| | Mix ID | Modulus of Elasticity (GPa) | Ratio relative to N10 | | Mix ID | Modulus of Elasticity (GPa) | Ratio relative to N20 |
|---|---|---|---|---|---|---|---|
| **GROUP 1 MSA=10 mm** | N10 (Control10) | 30.8 | - | **GROUP 2 MSA=20 mm** | N20 (Control20) | 33.2 | - |
| | R10 | 28.8 | 0.94 | | R20 | 31.4 | 0.95 |
| | | | | | | | |
| | N10-H20-T1 | 22.2 | 0.72 | | N20-H20-T1 | 26 | 0.78 |
| | R10-H20-T1 | 22.8 | 0.74 | | R20-H20-T1 | 23.7 | 0.71 |
| | | | | | N20-H20-T2 | 24.9 | 0.75 |
| | R10-H20-T2 | 22.9 | 0.74 | | R20-H20-T2 | 23.4 | 0.7 |
| | | | | | | | |
| | N10-H30-T1 | 22.7 | 0.74 | | N20-H30-T1 | 27.2 | 0.82 |
| | R10-H30-T1 | 22.5 | 0.73 | | R20-H30-T1 | 24.3 | 0.73 |
| | | | | | R20-H30-T2 | 23.7 | 0.71 |

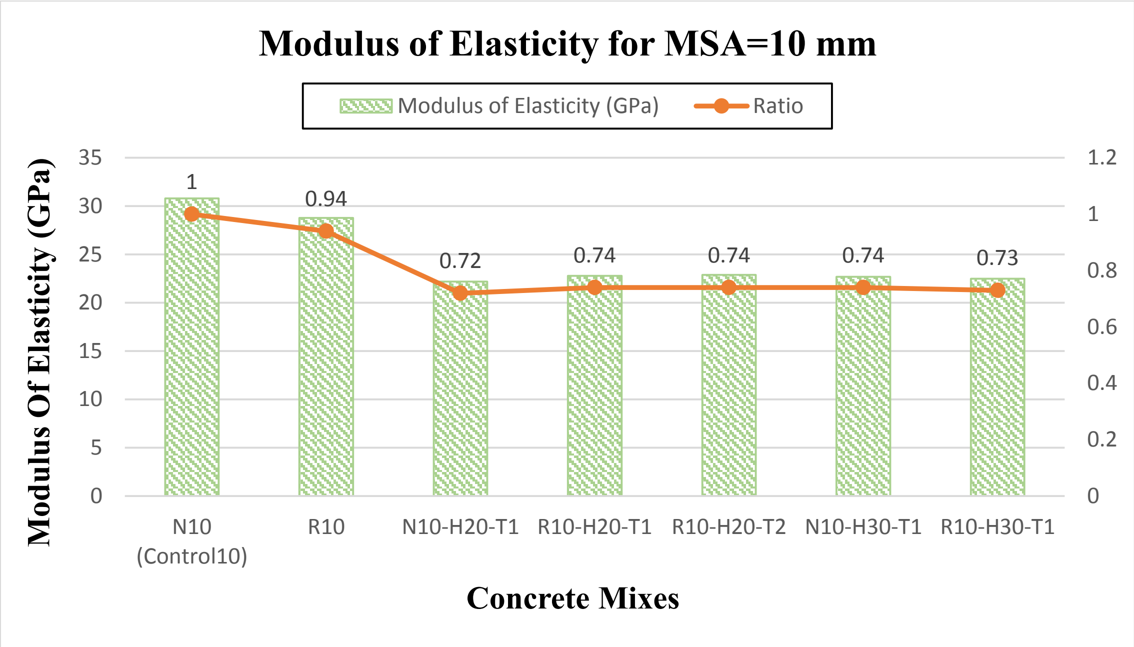



*Figure 63.Modulus of Elasticity values for concrete specimen with MSA=10 mm*

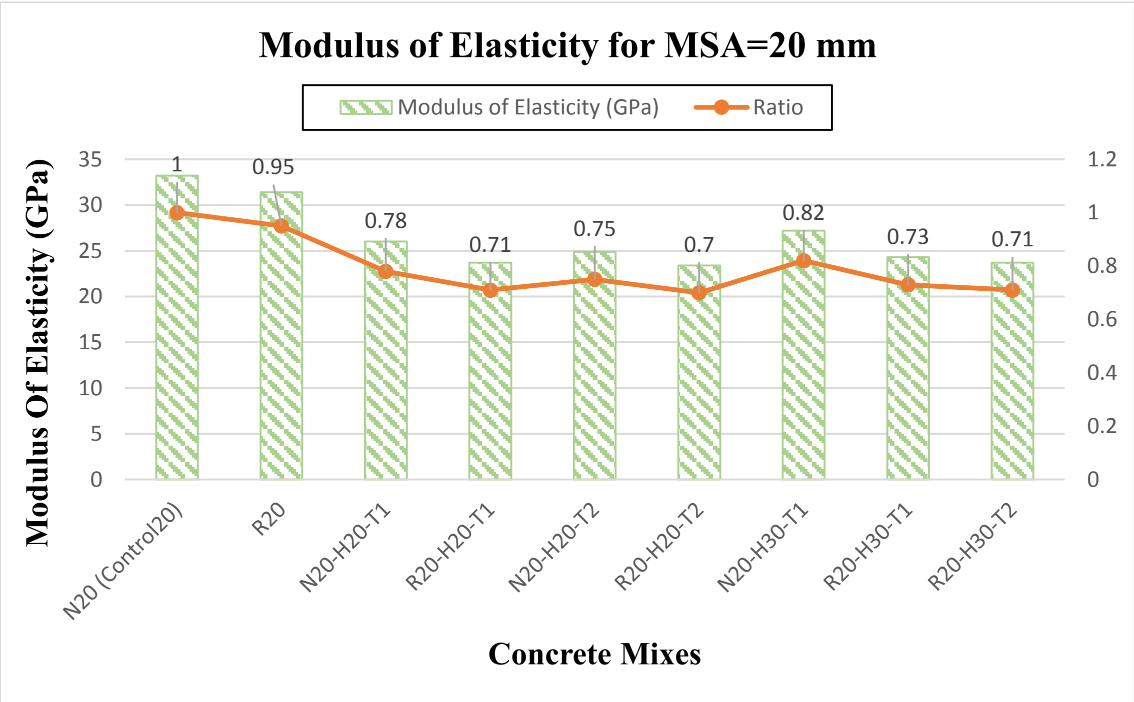



*Figure 64.Modulus of elasticity values for concrete specimens with MSA=20 mm*

Results of the modulus of elasticity test listed in Table 13 show that replacement of 50% of NCA with RCA reduces the modulus by 5 to 6% as compared with the 10% reduction in compressive strength. In Group 1 with MSA of 10 mm, the 5 mixes with hemp fibers showed a modulus reduction of 26 to 28% relative to the control mix N10 and the performance was similar whether RCA were included or not and was also similar for different fiber lengths and fiber treatments. In Group 2 with MSA of 20 mm, the reduction relative to the control mix N20 of mixes with hemp fibers ranged between 18 and 30% and mixes without RCA performed slightly better than the five HRAC mixes. Similar to the compressive strength test, incorporation of hemp fibers in the mix significantly reduced the modulus of elasticity and the MSA did not change the test values considerably.

## 5.8 Durability Testing

Durability of concrete is the capability of concrete to resist weathering, chemical attack and abrasion while preserving its anticipated engineering properties. Durability properties are equally important to mechanical properties and should not be underestimated because it projects the lifetime of the concrete structure. To estimate HRAC durability, durability tests on concrete such as thermal conductivity, freeze thaw and water absorption were performed.

### *5.8.1 Thermal Conductivity*

Thermal conductivity is the capability of material to absorb heat.The lesser the thermal conductivity of concrete, the solwer the rate at which heat is conducted, and hence the material is classified as insulator.Thermal conductivity of concrete is determined in accordance with ASTM C518. The 300x300x25 concrete specimen, conditioned at 23°C and 50% humidity, is placed in a calibrated rapid-k instrument between a cold plate and a hot plate (Figure 65). The heat flow meter provides a unidirectional constant heat flux between the cold and hot plates. After reaching thermal equilibrium measured by the transducer the test is carried out. In addition, a measurement of the millivot signal is recorded.The test setup is shown in Figure 65.

Thermal conductivity and thermal resistance are calculated using the Equations 5.3 and 5.4 ;

$k = \frac{q*L}{\Delta T}$ ………………………………………………………………… Equation (5.3)

$R = \frac{k}{L}$ …………………………………………………………… ……. Equation (5.4)

Where k is the termal conductivity (W/m.k) , L is the thickness of the specimen (m), T= temperature (K) , q is the heat flow rate ($W/m^2$) and R is the termal resistance ($m^2k/w$).

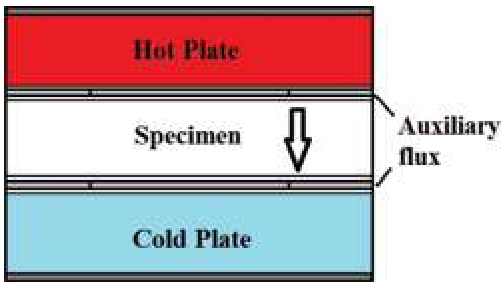



*Figure 65. Thermal conductivity concept*

Thermal conducivity and thermal resistance values are listes in *Table 13* and plotted in *Figure 66*.

*Table 13. Results of thermal conductivity and thermal resistance .*

| | Mix ID | Thermal conductivity (W/m.k) | Thermal Resistance ($m^2$.k/w) | | Mix ID | Thermal conductivity (W/m.k) | Ratio relative to N20 |
|---|---|---|---|---|---|---|---|
| GROUP 1 MSA=10 mm | N10 (Control10) | 1.728 | **0.14** | GROUP 2 MSA=20 mm | N20 (Control20) | 1.939 | 0.16 |
| | R10 | 2.072 | 0.12 | | R20 | 1.821 | 0.15 |
| | R10-H20-T1 | 1.605 | 0.13 | | R20-H20-T1 | 1.513 | 0.17 |
| | N10-H30-T1 | 1.401 | 0.14 | | N20-H30-T1 | 1.575 | 0.16 |
| | R10-H20-T2 | 1.691 | 0.18 | | R20-H30-T2 | 1.544 | 0.16 |

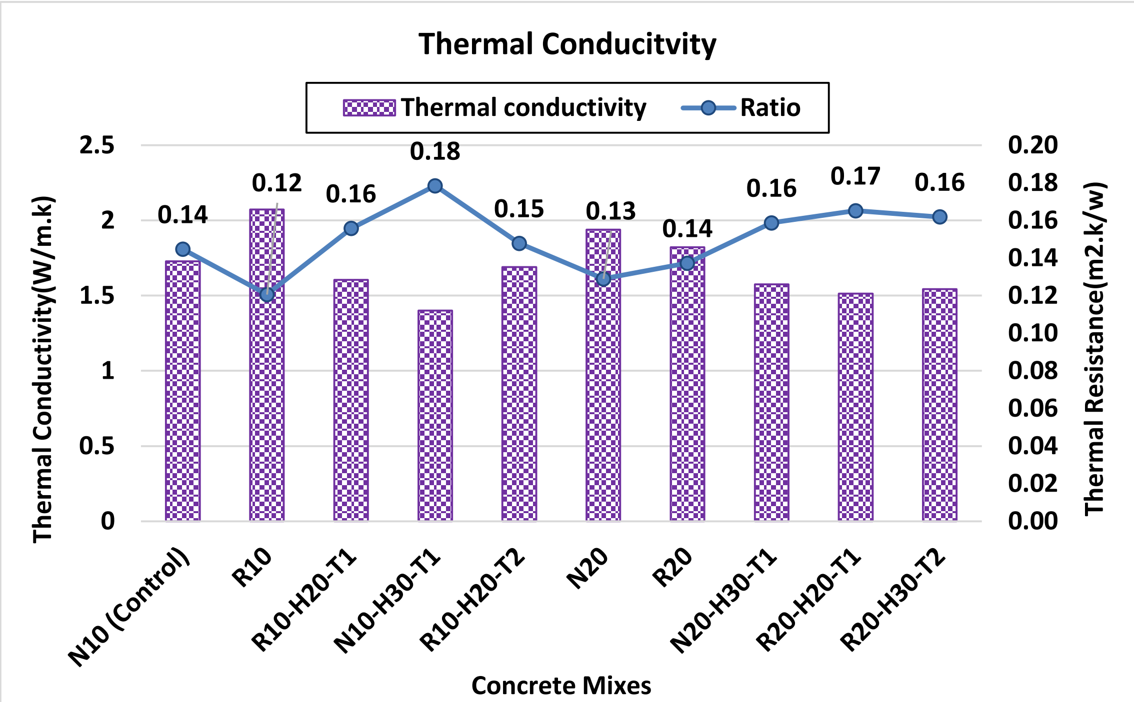



*Figure 66. Thermal conductivity result of concrete mixes*

Results indicate that the replacement of 50% of NCA with RCA increases the thermal conductivity of concrete mix with MSA = 10 mm by 19% and decreases the thermal resistance by whereas it decreases the thermal conductivity of mix with MSA = 20 mm by 6%. When hemp is introduced, a significant decrease is noticed for mixes with 10 natural aggregates along with 30 mm hemp treated with alkali by 23% while the other different mixes had a similar thermal behavior regardless of different variables with a reduction of an average of 8% with respect to the control mixes. Thermal resistance is inversely proportional to thermal conductivity, which explains a higher resistance of mixes having a lower thermal conductivity. This thermal conductivity decrease is due to the fact that hemp reinforced concrete with 20% reduction of aggregate volume has a lower density than the control mixes, thus a lower thermal conductivity and a higher thermal resistance.

### *5.8.2 Freeze and thaw*

One of the most significant concrete durability problem is the damage caused by the temperature fluctuation. Freeze-thaw is a procedure of erosion that takes place in cold areas. It is either classified based on the weight loss or on the loss of dynamic modulus of elasticity.When water freezes in the voids and cracks ,it expands about 9% .This volume change results in high tensile stress that, when exceeds the capacity of concrete it, causes cavity dilation. Successive freeze-thaw cycles generate expansion and cracking. Freeze-thaw testing was performed in compliance with ASTM C666.It consists of two procedures: Procedure A involves thawing the samples in water and Procedure B involves of thawing the samples in the air. Prior to testing, Beam specimens of dimensions 7.5x10x40.5 cm were left 14 days in the curing room. ASTM C666 limit the freeze-thaw cycle duration between 2 and 5 hours. In this experimental plan, the cycle duration was set at 2 hours, and 12 cycles are daily allowed. Each cycle consisted of two phases. Freeze phase, involved lowering the temperature from 4 to -18 ˚C and the Thaw phase involved rising the temperature 4 ˚C (Figure 67). Moreover, the relative dynamic modulus of elasticity was calculated based on ASTMC125. Specimens were hit with a hammer at their natural frequencies using a hammer, which provides impulse. Signals from the impact hammer and accelerometer, fixed on the top of specimen were acknowledged by the data acquisition system.The ratio of signals is referred to frequency response function. Views of different specimens after 108 and 144 cycles of freeze-thaw are shown in Figure 68 and Figure 69. Concrete specimen with 50% replacement of NCA by RCA and MSA of 20 mm (R20) showed a weaker resistance to freeze-thaw: The specimen exhibited a significant mass loss and spoiling of concrete after 144 cyles. Whereas, the specimens incorporating hemp fibers and recycled aggregates with MSA of 10 mm showed a better freeze-thaw resistance. The specimen did not show a significant change in shape.This is due to the good bond between hemp fibers and concrete matrix having aggregates with MSA of 10 mm.

*Figure 67. Freeze-thaw specimens placed in the container*

*Figure 68. R20 and R10-H20-T1 specimens after 108 cycles*

*Figure 69. R20 and R10-H20-T1 specimens after 144 cycles*

The relative Dynamic Modulus of elasticity (RDME) is defined as the ratio of stress so strain under vibratory conditions. RDME is calculated using Equation…

P=$\frac{fn}{f0}$ *100 ……………………………………………………………………**Equ.5.2**

- P is the dynamic modulus of elasticity
- $fn$ is the frequency at n freeze-thaw cycles
- $f0$ is the frequency before proceeding freeze-thaw

The calculated values for the RDME are listed inTable 14 and plotted in Figure 70 for specimen with MSA of 10 mm and in Figure 71 for specimens with MSA of 20 mm.

*Table 14. RDME values of concrete specimens after 36, 72, 108 and 144 cycles.*

| | Relative Dynamic Modulus of Elasticity (%) | | | | |
|---|---|---|---|---|---|
| Mix | 0 cycles | 36 cycles | 72 cycles | 108 cycles | 144 cycles |
| N10 | 100 | 95.4 | 63.7 | 50.25 | - |
| R10 | 100 | 98.25 | 89.5 | 87.5 | 77 |
| N10-H20-T1 | 100 | 93.8 | 87.25 | 81.6 | 77 |
| R10-H20-T1 | 100 | 90.5 | 90.5 | 90.5 | 88.5 |
| N10-H30-T1 | 100 | 95.2 | 93 | 93 | 90.4 |
| R10-H30-T1 | 100 | 95.2 | 93 | 93 | 90.4 |
| | | | | | |
| N20 | 100 | 93.25 | 79.2 | 62.4 | 51 |
| R20 | 100 | 92.75 | 70.2 | 57.85 | 31 |
| N20-H20-T1 | 100 | 88.1 | 79.2 | 70.8 | 42 |
| R20-H20-T1 | 100 | 73.1 | 59 | 48.7 | 25 |
| N20-H30-T1 | 100 | 83.5 | 70.3 | 53 | 20 |
| R20-H30-T1 | 100 | 86.1 | 73.2 | 47.25 | 30 |
| R10-H20-T2 | 100 | 77.15 | 66.8 | 48.35 | 32 |
| R20-H20-T2 | 100 | 76.85 | 58.8 | 40.4 | 21 |

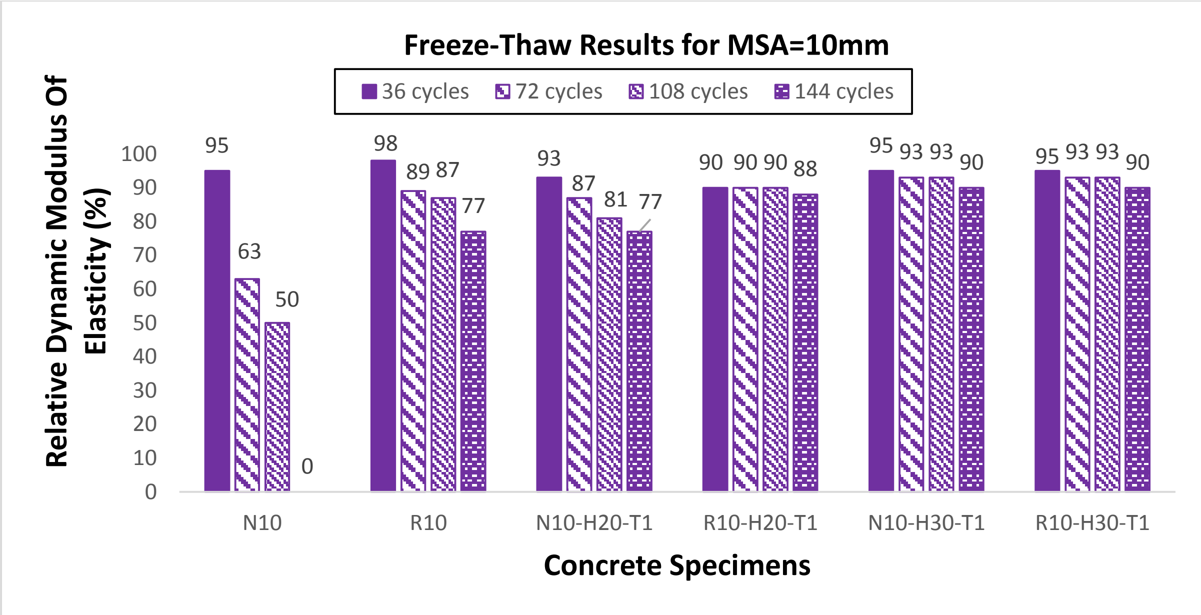



*Figure 70. Freeze-thaw results of concrete specimens with MSA of 10 mm after 36, 72, 108 and 144 cycles*

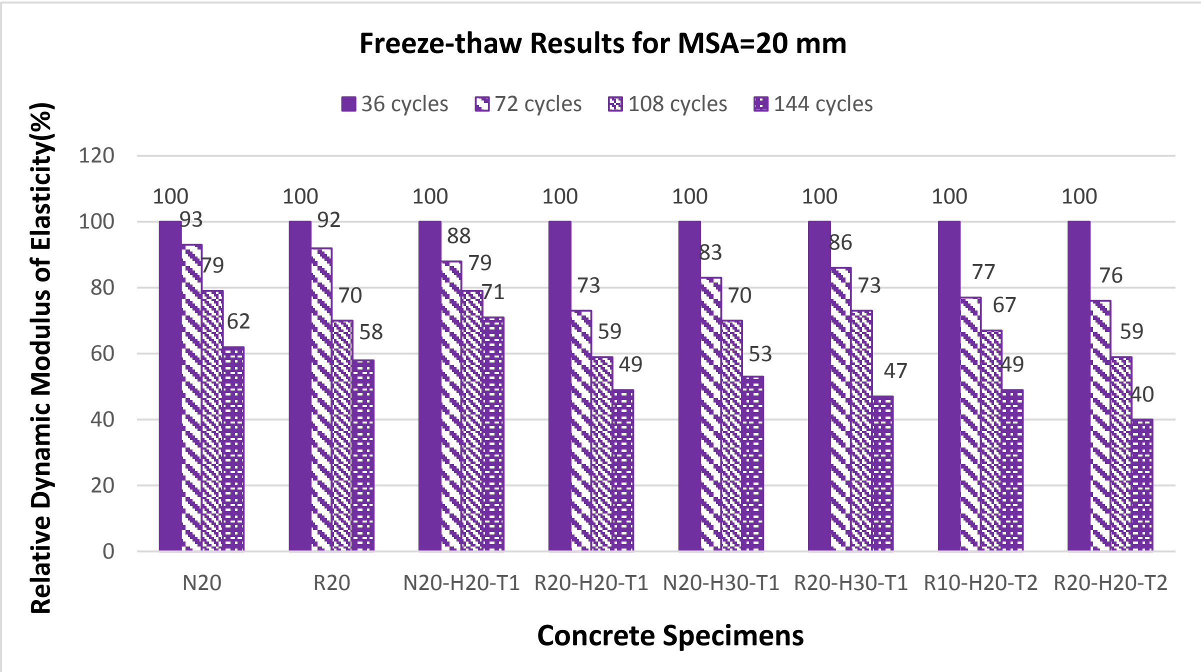



*Figure 71. Freeze-thaw results of concrete specimens with MSA of 20 mm after 36, 72, 108 and 144 cycles*

Freeze-thaw test results indicate that the control specimen with MSA = 10 mm degraded totally after 144 cycles. The specimen with 50% replacement of NCA by RCA (R10) showed a better freeze-thaw resistance reaching an RDME of 77% after 144 cycles. Introducing hemp fibers in the concrete mixes of MSA=10 mm increased the RDME to a value ranging between 77% and 90% after 144 cycles. On the other hand, concrete specimens with MSA=20 mm revealed relatively weaker resistance to freeze-thaw cycles. Whereas the control specimen with MSA =20 mm (N20) degraded to a value of 62% after 144 cycles, the value for R20 (no fibers) had a value of 31% and all specimens with fibers had values ranging between 21 and 42%.

Results are clearly indicate by the fact that the concrete specimens with MSA=10 mm have a better resistance to freeze-thaw cycles.

### *5.8.3 Water Absorption*

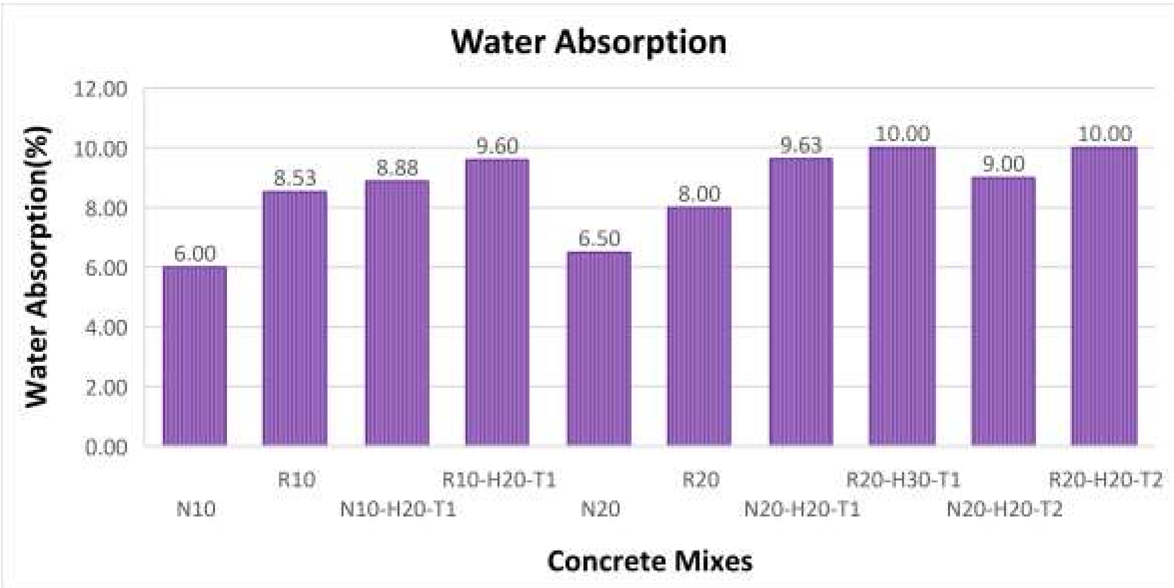
Water absorption is an important factor for a high performance concrete. Low water absorption concrete enhances the durability of concrete. To study the absorption effect of hemp fibers and recycled aggregate on the total concrete specimen, the absorption test was conducted with compliance with ASTM C140. To perform the test, 10x20 cylindrical concrete specimens were over-dried to a constant weight then weighed. These specimens werethen immersed in water for 48 hours and then weighed. The difference in weight is expressed as water absorption.

Water absorption test results listed in Table 15 and plotted in *Figure 72* indicates that control mixes of MSA=10 (N10) and 20 mm (N20) demonstrates the lower water absorption of 6.19% and 6.51% respectively. However, the replacement of 50% of NCA by RCA increases the water absorption of concrete to a value of 8.53% for MSA=10 mm and 8% for MSA=20 mm. Moreover, the addition of hemp fibers along with recycled aggregate in concrete mixes for both MSA increased the water absorption to a values ranging between 8.53% to 9.6% for MSA=10 mm and 8% to 10% for MSA=20 mm. This major increase in water absorption refers to the high water absorption of recycled aggregates and hemp fibers.

*Table 15. Water absorption result of different concrete specimens*

| | **Mix ID** | **Water Absorption (%)** | | **Mix ID** | **Water Absorption (%)** |
|---|---|---|---|---|---|
| **GROUP 1 MSA=10 mm** | N10 (Control10) | 1.728 | **GROUP 2 MSA=20 mm** | N20 (Control20) | 1.939 |
| | R10 | 2.072 | | R20 | 1.821 |
| | R10-H20-T1 | 1.605 | | R20-H20-T1 | 1.513 |
| | N10-H30-T1 | 1.401 | | N20-H30-T1 | 1.575 |
| | R10-H20-T2 | 1.691 | | R20-H30-T2 | 1.544 |

*Figure 72. Water absorption for concrete specimens*



# Chapter 6

# CONCLUSION

## 6.1 Introduction

The paper reports on preliminary studies which were conducted on Hemp and Recycled Aggregates Concrete (HRAC) which is a new sustainable concrete material where hemp fibers are incorporated in the mix, the coarse aggregate content is reduced by 20% of the concrete volume, and 50% of the natural coarse aggregates are replaced by recycled concrete aggregates. Variables included percentage replacement of NCA with RCA (0 or 50%), maximum size aggregate (10 and 20 mm), hemp fiber length (20 and 30 mm), and fiber surface treatment (alkali, silane, and acetyl). The effects of the different variables on the properties of HRAC were evaluated and compared with those of control mixes with no fibers.

## 6.2 Summary of the findings

The main conclusions of the study are:

1. Fibers characterization tests indicated that alkali and acetyl fiber treatments are better than the silane treatment in removing impurities on the surface of the fibers. Also, alkali and acetyl treatments have increased the crystallinity of the fibers while silane treatment decreased it.
2. Incorporation of hemp fibers in the mix reduced the consistency of the mix but the value remained acceptable.
3. Replacement of 50% of NCA with RCA reduced the tested mechanical properties by 1 to 10% when MSA was 10 mm and by 4 to 13% when MSA was 20 mm. Reduction in the splitting tensile strength was negligible. When fibers were incorporated in the mix and the coarse aggregate content was reduced by 20%, the reductions relative to the control specimen N10 with MSA of 10 mm were on the average 37, 26.6, 12, and 8.2% in the compressive strength, the modulus of elasticity, modulus of rupture, and the splitting tensile strength, respectively. When the MSA was 20 mm, the average reductions relative to the control mix N20 were 31.1, 25.7, 10.4, and 9.6%, respectively. The reductions were more significant for the compressive strength and the modulus of elasticity values than in the modulus of rupture and tensile strength values. The values corresponding to the HRAC mixes were slightly lower that the companion fiber mixes with no replacement of NCA with RCA. Fiber length (20 or 30 mm) and fiber treatment (alkali or acetyl) did not significantly affect the measured properties.

4. Although HRAC mixes had an average reduction of 15% in flexural strength relative to the control mixes with no fibers and no RAC replacement for the different variables (MSA, fiber length, and fiber treatment), however load-deflection behavior became ductile with considerable history after reaching ultimate.

5. Durability tests indicate that the 50% replacement of NCA by RCA increased the thermal conductivity by 20% when MSA was 10 mm (R10), whereas it decreased the thermal conductivity of MSA=20 mm (R20) by 6% when compared with control mixes. Freeze thaw results indicated a better resistance of R10 compared to R20 by 31% after 144 cycles. Water absorption increased similarly for R10 and R20 by 8% with respect to control mixes. When Hemp fibers were introduced to the concrete mixes, RDME increased for specimen with MSA of 10 mm to a values ranging between 77 and 90% while decreased to a values ranging between 40 and 53% for MSA of 20 mm unless for N20-H20-T1 reaching an RDME value of 77%. Whereas, water absorption increased to a values ranging between 8.53% and 9.6% for MSA=10 mm and 8% and 10% for MSA=20 m.

Based on the results of the research reported in this paper, the investigated HRAC material could be a promising sustainable construction materials, however more experimental work is needed to investigate the effect of HRAC on durability of concrete and on the structural performance of full-scale reinforced concrete members.

## 6.3 Future work

The implementation of HRAC in industrial companies requires further concrete testing and analysis. It includes the study of the structural behavior and a life cycle analysis of HRAC.

### *6.3.1 Structural Elements*

A full-scale reinforced concrete structural element is essential to study the behavior of HRAC. Hemp Length, MSA, and treatment selection will be done based on the mechanical and durability properties of concrete discussed throughout this thesis. Shear flexure, bond, first crack width and load-deflection tests will be carried on the concrete specimens.

### 6.3.2 *Life Cycle assessment*

Life cycle analysis will be conducted to quantitatively assess the benefits of HRAC over regular concrete from socio-environmental aspects.

# BIBLIOGRAPHY


Saidani, M., Saraireh, D., & Gerges, M. (2016). Behaviour of different types of fibre reinforced concrete without admixture. Engineering Structures, 113, 328–334.

Terpáková, E., Kidalová, L., Eštoková, A., Čigášová, J., & Števulová, N. (2012). Chemical Modification of Hemp Shives and their Characterization. Procedia Engineering, 42, 931–941.

Netinger Grubeša, I., Marković, B., Gojević, A., & Brdarić, J. (2018). Effect of hemp fibers on fire resistance of concrete. Construction and Building Materials, 184, 473–484.

Sair, S., Oushabi, A., Kammouni, A., Tanane, O., Abboud, Y., Oudrhiri Hassani, F., El Bouari, A. (2017). Effect of surface modification on morphological, mechanical and thermal conductivity of hemp fiber: Characterization of the interface of hemp –Polyurethane composite. Case Studies in Thermal Engineering, 10, 550–559.

Kabir, M. M., Wang, H., Lau, K. T., & Cardona, F. (2013). Effects of chemical treatments on hemp fibre structure. Applied Surface Science, 276, 13–23.

Sepe, R., Bollino, F., Boccarusso, L., & Caputo, F. (2018). Influence of chemical treatments on mechanical properties of hemp fiber reinforced composites. Composites Part B: Engineering, 133, 210–217.

Islam, M. S., & Ahmed, S. J. (2018). Influence of jute fiber on concrete properties. Construction and Building Materials, 189, 768–776.

Dayo, A. Q., Zegaoui, A., Nizamani, A. A., Kiran, S., Wang, J., Derradji, M., … Liu, W. (2018). The influence of different chemical treatments on the hemp fiber/polybenzoxazine based green composites: Mechanical, thermal and water absorption properties. Materials Chemistry and Physics, 217, 270–277.

Angulo, S. C., Ulsen, C., John, V. M., Kahn, H., & Cincotto, M. A. (2009). Chemical–mineralogical characterization of C&D waste recycled aggregates from São Paulo, Brazil. Waste Management, 29(2), 721–730.

Limbachiya, M. C., Marrocchino, E., & Koulouris, A. (2007). Chemical–mineralogical characterisation of coarse recycled concrete aggregate. Waste Management, 27(2), 201–208.

Evangelista, L., Guedes, M., de Brito, J., Ferro, A. C., & Pereira, M. F. (2015). Physical, chemical and mineralogical properties of fine recycled aggregates made from concrete waste. Construction and Building Materials, 86, 178–188.

Ahmed, S.F.U., “Properties of concrete containing construction and demolition wastes and fly ash,” ASCE Journal of Materials in Civil Engineering, December 2012, 25 (12), pp. 1864-1870.

Al Hassanieh, D.Z., Kassem, H.A., Chehab, G.R., and Abiad, M.G., “Use of fine aggregates recycled from cementitious constituents of construction demolition waste in HMA,” paper presented in Transportation Research Board 94th Annual Meeting, January 2015, Paper No. 15-4393.

Al Rim K., Ledhem A., Douzane O., Dheilly R.M., and Queneudec M., “Influence of the proportion of wood on the thermal and mechanical performances of clay–cement–wood composites,” Cement and Concrete Composites, Elsevier, August 1999, 21(4), pp. 269–76.

ACI Committee 318, Building Code Requirements for Reinforced Concrete and Commentary (ACI-318-11/ACI-318R-11), American Concrete Institute, Farmington Hills, Michigan, 2011.

ACI Report 544.1R-96, “Fiber-reinforced concrete,” ACI Committee 544, American Concrete Institute, Farmington Hills, Michigan, 1996 (Reapproved in 2009).

ACI Report 555R-01, “Removal and reuse of hardened concrete,” ACI Committee 555, American Concrete Institute, Farmington Hills, Michigan, 2001.

Awwad E., Hamad B., Mabsout M., and Khatib H., “Sustainable concrete using hemp fibers,” Proceedings of the ICE (Institution of Civil Engineers) - Construction Materials Journal, June 2012, 166(1), pp. 45-53.

Awwad, E., Mabsout, M., Hamad, B., Farran, M., and Khatib, H. “Studies on fiber-reinforced concrete using industrial hemp fibers,” The Construction and Building Materials Journal, Elsevier, October 2012, V. 35, pp. 710-717.

Awwad, E., Hamad, B., Mabsout, M., and Khatib, H., “Structural behavior of simply supported beams cast with hemp-reinforced concrete,” ACI Structural Journal, November/December 2014, 111(6), pp. 1307-1316.

Bilba K., Arsene M.A., Ouensanga A., “Study of banana and coconut fibers botanical composition, thermal degradation and textural observations,” Bioresource Technology, Elsevier, February 2007; 98(1), pp. 58-68.

Cheng J.C.P., and Ma L.I.H., “A BIM-based system for demolition and renovation waste estimation and planning,” Waste Management, Elsevier, June 2013, 33(6), pp. 1539-1551.

Dawi, A., “Sustainable Concrete Using Recycled Aggregates,” Unpublished Thesis, American University of Beirut, Beirut, Lebanon, May 2015.

Etxeberria, M., Vázquez, E., Marí A., and Barra M., “Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete,” Cement and Concrete Research, May 2007, 37(5), pp. 735–742.

Farran. M. T., G. W. Barbour, and N. K. Usayran, “Nutritional value, performance, and egg quality of laying hens fed diets containing industrial hemp (Cannabis sativa L.) seed,” Book of Abstract, World’s Poultry Science, 2014, p. 32.

Gholamreza, F., Razaqpur, A.G., Isgor, O.B., Abbas, A., Fournier, B., and Foo, S., “Flexural performance of steel-reinforced recycled concrete beam,” ACI Structural Journal, November/December 2009, 106(6), pp. 858-867.

Hamad, B. S.; Dawi, A. H.; Daou, A.; Chehab, G. R. Studies of the Effect of Recycled Aggregates on Flexural, Shear, and Bond Splitting Beam Structural Behavior. Case Studies in Construction Materials 2018, 9

Han B.C., Yun H.D., and Chung S.Y., “Shear capacity of reinforced concrete beams made with recycled-aggregate,” ACI Special Publication SP 200, American Concrete Institute, Farmington Hills, Michigan, 2001, pp. 503-516.

Hassanieh, D.Z.A., Chehab, G.R., Srour, I., and Kassem, H.A. (2016). “Recycling cementitious constituents of construction demolition waste in asphalt mixes: the case of Lebanon,” International Journal of Sustainable Society, 2016, 8(2), pp. 109-125.

House, J.D., Neufeld, J., and Leson, G., "Evaluating the quality of protein from hemp seed (Cannabis sativa L.) products through the use of the protein digestibility-corrected amino acid score method," Journal of Agricultural and Food Chemistry, October 2010, 58(22), pp.11801-11807.

Kim, S.W., and Yun, H.D., "Influence of recycled coarse aggregates on the bond behavior of deformed bars in concrete," Engineering Structures, March 2013, V. 48, pp. 133-143.

Ministry of Agriculture – Food and Agriculture Organization, "Agricultural census in Lebanon," Lebanon, 2010/2011.

Naaman A. and Harajli M., "Mechanical properties of high performance fiber concretes, a state-of-the-art report," Report No. SHRP-c/wp-90-004, Strategic Highway Research Program, National Research Council, Washington D.C., 1990, 194 p.

Nagataki, S., Gokce, A., and Saeki, T. "Effects of recycled aggregate characteristics on performance parameters of recycled aggregate concrete," ACI SP 192, American Concrete Institute, Farmington Hills, Michigan, 2000, pp. 53-72.

Rahal, K., "Mechanical properties of concrete with recycled coarse aggregate," Building and Environment, Elsevier, January 2007, 42(1), pp. 407-415.

Rao, A., Jha, K., and Misra, S., "Use of aggregates from recycled construction and demolition waste in concrete," *Resources, Conservation and Recycling*, March 2007, 50(1), pp. 71-81.

Savastano H. Jr., Warden P.G., and Coutts .S.P., "Microstructure and mechanical properties of waste fibre-cement composites," *Cement and Concrete Composites, Elsevier*, May 2005, 27(5), pp. 583-592.

Shayan, A. and Xu, A., "Performance and properties of structural concrete made with recycled concrete aggregate," *ACI Materials Journal*. September/October 2003, 100 (5), pp. 371-380.

Srour, I.M., Chehab, G.R., El-Fadel, M., and Tamraz, S., "Pilot-based assessment of the economics of recycling construction demolition waste," *Waste Management & Research*, November 2013, 31(11), pp. 1170-1179.

Srour, I.M., Chehab, G.R., and Gharib, N., "Recycling construction materials in a developing country: four case studies," *International Journal of Engineering Management and Economics*, 2012, 3(1-2), pp. 135-151.

Tamraz, S.N., "A framework for proper management of construction demolition waste," Unpublished Thesis, American University of Beirut, Beirut, Lebanon, 2011.

Yang, K.H., Chung, H.S., andAshour, A.F., "Influence of type and replacement level of recycled aggregates on concrete properties," *ACI Materials Journal*, May/June 2008, 105 (3), pp. 289-296.

Zhu W.H. and Tobias B.C., "Air-cured banana-fibre-reinforced cement composites," *Cement and Concrete Composites, Elsevier*, 1994, 16(1), pp. 3-8.