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EVALUATION OF SUSTAINABLE CONCRETE PRODUCED WITH INDUSTRIAL HEMP FIBERS AND RECYCLED AGGREGATES USING MULTI-SCALE TESTING AND LIFE-CYCLE ANALYSIS

by
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ABSTRACT
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Title: Evaluation of sustainable concrete produced with industrial hemp and recycled aggregates using multi-scale testing and life-cycle analysis

Hemp and Recycled Aggregate Concrete (HRAC) is a sustainable concrete material prepared by partial 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 would solve socio-economic problems associated with the farming of hashish, the sister plant of Hemp, in Hermel-Bekaa (Lebanon) and elsewhere.

The proposed research was planned to be completed through tasks distributed across three phases. The objective of the first phase was to achieve a concrete mix that incorporates RCA and is reinforced with industrial hemp fibers while assuring that the designed mix meets the requirements of high-performance concrete including workability and durability. Tests on trial batches included plastic state slump; hardened state mechanical properties such as compressive strength, tensile splitting strength, modulus of elasticity, flexural strength of standard beams; and several durability tests. Results showed that while HRAC has considerably lower compressive strength and modulus of elasticity than plain concrete, the flexural strength and splitting tensile strength are not significantly affected. The durability tests indicated that whereas HRAC mixes have higher absorption than plain concrete, they have better thermal properties and their resistance to freeze–thaw cycles is comparable to plain concrete. All test results were not significantly affected by fiber length or fiber treatment.

The objective of the second phase was to assess the structural performance of reinforced concrete beams prepared using the HRAC's optimal batch achieved in the first phase. By investigating the difference in strength and behavior between conventional and HRAC structural concrete elements, the hypothesis to be tested was whether the substitution of natural aggregates with a combination of RCA and hemp fibers to produce HRAC would lead to reduction in the flexural, shear, and bond splitting characteristics of the structural

elements, or would affect the ductility of the mode of failure and the load-deflection history. The testing of large-scale specimens would serve as a validation study of the proposed mix. Test results of the second phase indicated that the HRAC beam with optimal combination of constituents, including hemp fibers and RCA, had a peak load comparable or higher than that of the control beam for the three tested mode of failures, despite the HRAC mix having a significantly lower compressive strength than the control mix.

The significance of the third phase was to conduct a life cycle analysis to quantitatively assess the benefits of HRAC over regular concrete from environmental aspects. The life-cycle assessment quantitively proved that HRAC is indeed a sustainable concrete, having better structural properties and lower environmental impact as compared to ordinary concrete.

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CHAPTER I

INTRODUCTION AND BACKGROUND

A. 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-environmentally friendly due to several concerns related to the depletion of natural resources, the high environmental impact of cement production, and the high energy consumption needed for the production of its other 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.

B. Recycled Concrete Aggregates

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.

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.

C. Fibers in Concrete

Using natural resources in concrete to make it more eco-friendly concrete is one of the main research interests in the construction field. Natural 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.

The agricultural sector in Lebanon usually struggles due to 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. Awwad et al. studied the effect of adding industrial hemp fibers on plain concrete. In order to assure sustainable and green concrete, natural fibers were added to the concrete mix to compensate for a reduction of the coarse aggregate quantity (Awwad et al. 2012a and 2012b). The hemp fibers were added in different volumetric percentiles 0.5%, 0.75%, and 1% of the concrete volume, with a coarse aggregate reduction 10%, 20%, and 30% of the concrete volume. A wide variety of tests were performed on all mixes including compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, thermal conductivity, density, and slump tests. Based on the standard cylinders test results, the compressive strength tended to decrease in the presence of hemp fibers. It was recommended not to use this material in pure compression members such as columns. The flexure results showed that the presence of hemp fibers allowed coarse aggregate reduction and resulted in a ductile behavior. The splitting tensile results were not affected by the presence of sufficient fibers. The results of the modulus of elasticity assured the ductility of the hemp concrete mixes and the thermal conductivity results showed the positive effect of hemp fibers in reducing the heat flow. Therefore, industrial hemps would increase the energy efficiency of structures. The slump results were affected by the hemp fibers water absorption. The density results were slightly decreased with the coarse aggregate reduction. Similar to the use of industrial fibers in reinforced concrete, such as steel, polypropylene, or others, the hemp fibers resulted in a ductile flexural behaviour that is favourable under dynamic and cyclic loading.

Awwad et al. used the results of their earlier research program and reported other studies performed to investigate the effect of adding industrial hemp fibers on structural behaviour of reinforced concrete beams (Awwad et al. 2014). For each of the three modes of failure (flexure, shear, and bond), three concrete beams were tested:

control with no fibers, 0.75%hemp-20%coarse aggregate reduction, and 1%hemp-20%coarse aggregate reduction mixes. In all beam types, it was commonly observed that the addition of the hemp fibers resulted in a ductile behavior after the peak load was reached. Although there was around 20% reduction in concrete compressive strength when hemp fibers were incorporated in the concrete mix, however the peak loads of the hemp fibers beams 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.

1. Fiber-reinforced concrete properties

Unreinforced concrete has a low tensile strength and a low strain capacity at fracture. These shortcomings are traditionally overcome by adding reinforcing bars or prestressing steel.

ACI 544 committee states that for structural applications, fiber reinforcement can be used in a supplementary role to reduce cracking, improve the resistance to impact and dynamic loading and resist material disintegration.

It’s important highlight that using fibers in concrete is not a substitute for conventional steel bars. Fibers and steel bars have different roles and should be used together in many applications. Conventional reinforcing bars are used to increase the load-bearing capacity of concrete while the fibers are used to achieve better crack control.

When concrete containing fibers starts to crack, fibers start functioning by stopping crack formation and propagation. Therefore, the main advantages of using fibers in concrete are the following:

- Increase of the tensile strength of the matrix, thereby improving the flexural strength of the concrete.
- The crack bridging mechanism of fibers and their tendency to redistribute stresses evenly throughout the matrix contributes to the post-cracking strength and restraining of the cracks in the concrete.
- Increase of the ductility of the concrete under both static and impact loads.

Fibers can also reduce the drying shrinkage of the concrete and reduce its permeability, thus improving its durability.

Other properties of concrete are affected by the addition of fibers, depending on the type of the used fibers and the percentage of the fibers by volume. Some of the properties affected include the slump, compressive and modulus of elasticity.

The failure of concrete beams with and without fibers is shown in Figure 1.1 (Ahad et al., 2015) and typical stress-strain curves of ordinary and FRC are shown in Figure 1.2 (Ongpeng, 2015).

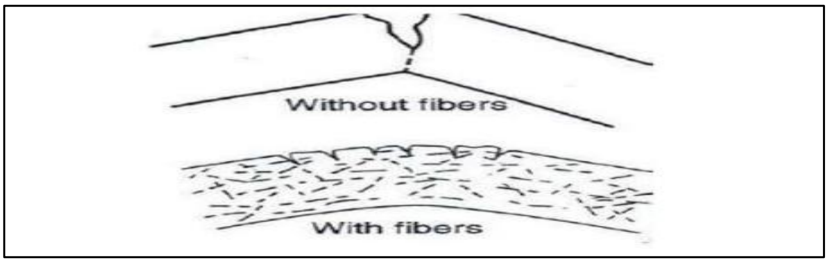

Figure 1.1 Failure of concrete with and without fibers (Ahad et al., 2015)

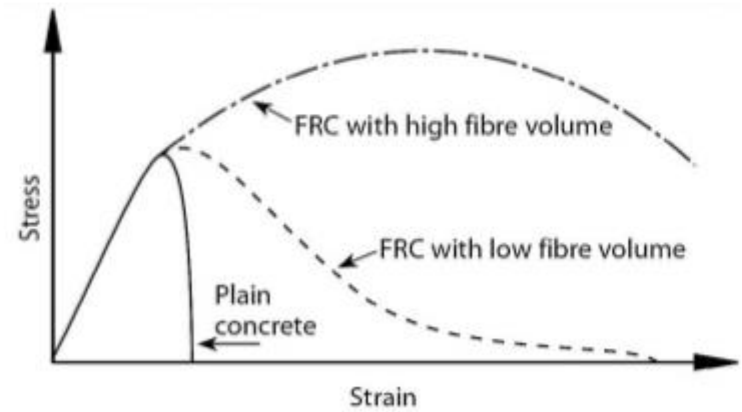

Figure 1.2 Stress-Strain curve of concrete with and without fibers (Ongpeng, 2015)

2. Type of fibers

Fibers used in concrete can be divided into three main types: steel fibers, synthetic fibers, and natural fibers. One of the main differences between the types of fibers is their elastic modulus.

Synthetic fibers have a low elastic modulus (less than 10 GPa): they improve the toughness of the concrete, but they don't have a significant effect on the tensile strength.

On other hand, steel fibers have a high elastic modulus (around 200 GPa) which allows improving the toughness and the tensile strength of the concrete.

The effect of natural fibers depend on their type as their elastic modulus can range from 9 GPa for sisal fibers to up to 70 GPa for hemp fibers. Natural Fibers with low tensile strength and low elastic modulus improve the dynamic properties of concrete but static strengths are not improved.

Some of the other differences between the different types of fibers are listed below:

- Steel fibers are the most commonly used fibers. They have better tensile strength and elastic modulus than other fibers which leads to better concrete properties, although they have a higher cost compared to other types of fibers. They are vulnerable to corroding and losing some of their strength, but investigations have shown that the corrosion of the fibers takes place only at the surface if the concrete is uncracked.

- Synthetic fibers are more durable and lightweight. They help to improve pumpability and keep concrete from spalling during impacts. Synthetic fibers help to prevent cracking as they do not expand in heat and contract in cold.
- Natural fibers are low-cost and more environmentally friendly than other types of fibers but they have a tendency to disintegrate in the alkaline environment of concrete if the proper measures weren't taken.

D. Research objectives

The advantages of using RCA and hemp fibers jointly in PCC will introduce HRAC as a new type of green PCC. The benefits of such a new technology prompted the initiation of the three-phased research program proposed herein.

The objective of the first phase is to achieve an optimum concrete mix that incorporates RCA and that is reinforced by industrial hemp fibers. This mix has to be designed such that it meets the requirements of high-performance concrete including workability and durability. Also, this study will take into consideration the fact that RCA and hemp fibers are non-conventional PCC components that are required to be further investigated to achieve a better understanding of its functionality. Therefore, a component level testing will be carried out in order to measure the fundamental properties of the materials to be used in this research. This set of testing will be carried out at the Civil Engineering Laboratory and the Central Research Science Laboratory at AUB.

In addition, this phase will aim at performing different trial batches of PCC at the Civil Engineering Materials Laboratory at AUB to investigate the compatibility of the NCA, RCA, and hemp fibers, in order to find an optimum mix that meets the requirements of high performance concrete as far as workability and durability.

Tests on trial batches 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. In addition, these tests will be used in order to determine the optimum of hemp fibers and thus the feasibility of using hemp fibers to increase the strength and ductility of PCC.

The second phase of this research will build on the results of the first phase where the HRAC's optimal batch will be used in order to assess the structural performance of reinforced concrete elements. By investigating the difference in strength and behavior between conventional and newly prepared HRAC structural concrete elements, the hypothesis to be tested is that partial substitution of natural aggregates with a combination of RCA and hemp fibers would not lead to reduction in the flexural, shear, and bond splitting and anchorage characteristics of the structural elements, in addition to having a ductile behavior. It is very significant to conduct a research program to determine the influence of HRAC on structural strength and behavior, and to get a better insight in the difference in strength and behavior of structural members with control PCC and HRAC. The testing of large scale specimens in this phase will serve as a validation study of the proposed mix.

In addition, results of the conducted tests along with the data available in the literature will be used to check the validity of the ACI 318 predictions and estimations of shear and flexural performance in terms of shear capacities, flexural capacities, cracking moments and modes of failure for structural members made with HRAC mixes.

The significance of the third phase is to investigate the durability of aged HRAC elements under long term condition and under aggressive environments. The results of this study will be used to conduct a life cycle analysis to quantitatively assess the benefits of HRAC over regular concrete from environmental aspects. The life cycle analysis will be done to compare conventional PCC and the designed HRAC mixes in this study. This analysis will take into account any changes in the proportions of cement, water, and virgin NCA. This will account for the environmental impact of HRAC as compared to the conventional PCC.

E. Research significance

The encouraging results of the previously reported research on RCA and on the use of natural hemp fibers in PCC triggered the proposal of a research program that builds on the previously conducted studies. This program combines the positive effects of RCA and hemp fibers into HRAC or Hemp and Recycled Aggregate Concrete.

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 local available recycled and natural materials will have a 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 the 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 neither in the flexural and shear strength of reinforced concrete elements and in the bond characteristics of reinforcing bars anchored in these elements.

There are no published papers in the literature on similar research which proves the novelty of the proposed research program. The research outcomes will be used to check the validity of the ACI 318 predictions and specifications for flexural and shear performance and capacities when applied to reinforced HRAC structural members.

Another indication of the significance of the proposed research is the investigation of the durability of the produced HRAC elements under long term condition. In addition, a life cycle analysis will be conducted to quantitatively assess the benefits of HRAC over regular concrete from environmental aspects.

CHAPTER II

LITERATURE REVIEW

A. International Research Related to the Mechanical Properties of RAC

Recycled aggregate concrete has been of interest for many researchers worldwide. The performance of recycled aggregate concrete can vary with different recycled aggregate demolishing source and with the substituted aggregate quality and quantity. Extensive international research is available due to the interest in recycled concrete in terms of the environmental impact concerns and sustainable development.

The ACI-555 committee considers the demolition techniques, the recycled aggregates preparation methods, and the recycled aggregate concrete mixes. The selection of the water cement ratio is the most critical part of controlling the concrete strength. There is an excellent correlation between water cement ratio and the compressive and flexural strengths. The water cement ratio is valid for recycled aggregate concrete as it is for concrete made with virgin material, but only the level of strength development would be reduced. To produce similar workability, 5% additional water was found to be required for a recycled coarse aggregate concrete. In other cases, approximately 15% additional water was needed to produce the same workability for both fine and coarse recycled aggregate concrete. The bleeding from recycled aggregate concrete was found to be slightly less than that of those using natural aggregates. Also, studies indicated that this coarseness and increased angularity are the reasons that concrete made with these materials tend to be somewhat harsh and unworkable. Thus, adding a portion of finer natural blending sand to the recycled sand can produce materials with suitable concrete making properties. Recycled aggregates generally had densities slightly less than the original materials used. Generally, variations in water-cement ratios of the concrete do not appear to have a significant impact on density. One main difference between recycled aggregates and natural aggregates is the higher water absorption, probably due to the absorption of the old cement mortar attached to the recycled aggregate particles. As for the Los Angeles Abrasion loss test, the RCA produced from all but the poorest quality recycled concrete can be expected to pass ASTM requirements. The compressive strength of recycled concrete depends on the strength of the original concrete and it is largely controlled by a combination of the water-cement ratio (w/c) of the original concrete and the w/c of the recycled concrete. The majority of researchers found that the compressive strengths for concrete manufactured from recycled coarse and fine aggregates were lower by 15 to 40% of strengths of concrete made with all naturally occurring materials.

Many studies are reported in the literature on research conducted on the mechanical properties and durability aspects of RAC as summarized in Table 2.1.

Table 2.1 Literature on mechanical properties of RAC

Study	Scope/Methodology	Results
Nagataki et al., 2000	Investigation of the effect of physical properties of RCA including the structure and amount of adhered mortar on the performance of RAC	All possible variations in the RCA properties should be taken into account in designing durable RAC mixes
Shayan and Xu, 2007	Developing techniques to improve the surface properties of RCA to provide better strength and durability of RAC	Similar durability aspects of RCA and natural aggregates.
Rahal, 2007	Conducting a comparative study of the mechanical properties of RAC and natural aggregate concrete made with the same mix proportions to achieve a nominal concrete strength between 25 and 30 MPa	The cube and cylinder compressive strength and the indirect shear strength of RAC were on the average 10% less than those of PCC with only natural aggregates. The reduction in the modulus of elasticity was only 3%
Etxeberria et al., 2007	Investigation of RAC with four different replacement percentages of NCA with RCA used in the wet unsaturated condition: 0, 25, 50 and 100%.	Lower modulus of Elasticity when RCA is used
Rao et al., 2007	Study of the properties of RCA and their effect on the fresh and hardened concrete properties.	The main factors negatively affecting the use of RAC in the industry were identified including lack of codes and specifications and absence of government support
Yang et al., 2008	Study of the influence of the type and percentage replacement of NCA with RCA on concrete properties	The fresh and hardened properties of RAC were dependent on the relative water absorption of the aggregates
Ahmed, 2012	Investigation of the effect of the use of RCA from CDW in West Australia on the properties of RAC	Increase in the mechanical properties of concrete made with 25% replacement of NCA with RCA

B. International Research Related to the Structural Performance of RAC

The large interest of research in investigating the properties of RAC in terms of compressive strength, splitting tensile strength, modulus of elasticity, indirect shear strength, resistance to freeze and thaw, and workability surpassed by big steps the rate of research in the field of structural behavior of specimens cast with RAC or the field of checking the current design specifications' validity with RCA structural members.

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 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. Also, 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.

C. Local Research Related to the Mechanical Properties and Structural Performance of RAC

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 fit the criteria of recycled aggregate concrete (RAC) as far as workability, homogeneity, and performance. Beside 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 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.

From an economical perspective, a brief analysis was conducted to compare the cost of producing one cubic meter of normal strength concrete using natural crushed limestone coarse aggregates normal strength concrete with 100% replacement of NCA with RCA. This analysis showed that the amount of cement and fine aggregates is the same. Fifty-one additional litres of water are required to produce one cubic meter of NSC with 100% replacement of NCA with RCA due to higher absorption capacity of RCA. As compared to the cost of producing the natural crushed limestone rocks in the natural quarries, there is no cost buying the tested concrete cylinders since they are a waste material at the batching plant. The crushing cost of natural limestone rocks in the natural quarries to the needed coarse aggregates size and sieving the products to the required standard ASTM requirements is assumed to be comparable to the crushing cost of the concrete cylinders and sieving the resulting recycled aggregates to the required standard sizes. Add to the above cutting the cost of collecting, transporting, and dumping the tested cylinders as waste material. Generally, it could be concluded that savings in the concrete construction industry are generated by replacing different portions of NCA by RCA.

D. International Research Related to the Mechanical Properties and Structural Performance of HRC

Substantial research work has been conducted on fiber reinforced concrete which is a concrete primarily made of a mix of hydraulic cement, aggregates, water, and reinforcing fibers. Fibers used are typically industrial such as steel, polypropylene, nylon, and fiberglass, or natural fibers such as sisal, jute, bamboo, and coconut (ACI 544, 1996). Adding such materials to concrete should result in a randomly, discrete, and discontinuous orientation of fibers whose main function is to bridge across cracks that develop in concrete, either as it is loaded or as it experiences environmental changes. Thus, fiber reinforced concrete is expected to satisfy the strength, ductility, and durability requirements of a high-performance concrete material. The first use of fibers in reinforced concrete has been dated back to 1870s. Since then, researchers around the world have been interested in improving the tensile properties of concrete by adding wood, iron, and other wastes (Naaman et al. 1990). Worldwide, natural organic and mineral fibers such as wood, sisal, jute, bamboo, coconut, asbestos, and rockwool have been also investigated and reported (Zhu 1994, A Rim 1999, Bilba 2007, and Savastano 2005).

Islam et al (2011) investigated the properties of fiber-reinforced composite concrete in a comparative manner for both normal-strength concrete (NSC) and high-strength concrete (HSC) .A total of 10 mix batches of NSC and HSC containing 0%, 0.5%, and 1.0% of coconut coir fiber volume dosage 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 et al. (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) and a new basalt concrete reinforcement product called minibars (MB) on mechanical properties of concrete. Concrete specimens having different length and dosages of fibers showed that fiber dosages beyond 12 kg/m3 and 40 kg/m3 of BF and MB, respectively, caused fiber balling and workability issues. In addition, flexural loading indicated that the increase of fiber dosage increased first-crack strength for both types but in case of MB the first crack was difficult to recognize because of the ductile failure .An optimum flexural behaviour was recorded for 50 mm and 12kg/m3 dosage for BF whereas 20 kg/m3 dosage was significant for MB.

Wasim Abbass et al. (2018) implemented a testing program investigating the mechanical behaviour 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 volume 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, a 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. (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 main component of fibers led to a change in its structure. Alkalization 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 a removal of hemicellulose and lignin from surface of fiber while silane had no effect. In addition, TGA of fibers 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 temperature.

Abdul Qadeer Dayo et al. (2018) 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 vol% silane treated fiber reinforced composites had a much better results compared with alkaline and ethanol washed fiber treatment.

Sepe et al. (2018) focused 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.

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 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 insulation properties of hemp. Moreover, the double treatment of amino alkaline treatment indicated an optimum behavior of the matrix.

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.

Ahmadi et al. (2017) 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.

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.

E. Local Research Related to the Mechanical Properties and Structural Performance of HRC

A full scale and multi-phase research has been conducted by Awwad et al. throughout four years 2012 to 2014 at AUB. In the first study and in order to assure a sustainable and green concrete, the 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 added in different volumetric percentages (0.5, 0.75 and 1%) of the concrete volume. Also, the coarse aggregate reduction was applied in different volumetric percentages (10, 20 and 30%) of the concrete volume. The compressive strength of cubes (70 mm) and standard cylinders (150x300 mm) were presented, in addition to the flexural strength of beam (50x50x200 mm) samples. Although the compressive strength was reduced, the presence of the hemp fibers when reducing coarse aggregate content resulted in a ductile flexural performance, instead of a brittle failure as in the case of plain concrete. The behavior of hemp fibers concrete is similar to the behaviors of concrete mixes with steel and polypropylene fibers. However, the hemp fibers are considered as a waste material and are cheaper than industrial fibers.

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 satisfactory ranging from 100 to 150 mm; whereas, with 1.0% hemp mixes, the slump reached the minimum allowable about 70 mm and 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 prepared and 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. For each of the three modes of failure investigated, three concrete beams were tested: control with no fibers, 0.75% hemp-20% coarse aggregate reduction, and 1% hemp-20% coarse aggregate reduction mixtures. Two large-scale replicate beams were considered for reliability and accuracy of results, and in total, 18 beams were tested. The selection of the hemp mixtures was based on the strength of the concrete mixture and the mixing workability. 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. Therefore, a more durable concrete might be produced while saving on natural resources. In all hemp-reinforced concrete mixtures, one adverse effect was that the compressive strength was reduced by 20 to 30%, which was expected because the removed coarse aggregates were replaced by the hemp fibers. Therefore, it was recommended not to use this material in pure compression members such as columns. In all beam types, it was commonly observed that the addition of the hemp fibers resulted in more 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 ductile behavior of the hemp fiber-reinforced beams was illustrated by the larger area under the load-deflection curves, in addition to the larger ratio of the deflection at failure to the deflection at maximum load. The ratio of deflections at failure load to maximum load was almost doubled or more 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. This was attributed to a better bond between concrete and reinforcing steel due to the presence of hemp fibers. For the tested 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, for the shear and bond beams, no ductility could be associated with the steel reinforcement. The shear and bond beams' ductility could be mainly attributed to the hemp-reinforced concrete rather than the main reinforcement.

CHAPTER III

MATERIALS CHARACTERIZATION

A. 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 incorporating hemp fibers and recycled concrete aggregates. Therefore, a multi-scale characterization of the newly incorporated materials in concrete is required for a better understanding of concrete's behavior, and to set a clear link between the concrete's properties and the properties of the materials used in the concrete mix. Material characterization includes microscopical, mineralogical, elemental and thermal techniques. Hemp microstructure is mainly studied to assess the effect of chemical treatments on the fiber's surface, to acknowledge its crystallinity characteristics and to investigate its thermal behavior. On the other side, physical properties of aggregates are factors determining the quality of aggregates.

In this chapter, a detailed description of the adopted materials in the experimental program is presented, including hemp fibers, recycled aggregates and natural aggregates, in addition to the tests performed to characterize these materials and determine their properties. Based on literature presented in Chapter 2, three different hemp fibers chemical treatments (Alkali, Silane, Acetyl), two different hemp lengths (20mm and 30mm), and two different maximum size aggregates MSA (10mm and 20mm) were used in this study.

B. Hemp fibers

Hemp fibers are natural fibers, widely available and are characterized by a high tensile strength and are capable of strengthening concrete by increasing its flexural and tensile properties, and its ductility. Moreover, hemp fibers prevent crack propagation at the early and hardened stages of concrete. Hemp fibers used in this study were imported from Hemp Traders, USA.

1. Hemp fibers treatment

As reported by Awwad et al. (2012a and 2012b), untreated fibers do not have a good bond with the cement matrix and their presence is consequently ineffective. Adding hemp to concrete requires a specific chemical treatment of the fibers to improve adhesion bond between fibers and the concrete matrix. Hemp fibers are mainly constituted of cellulose, hemicellulose, and lignin (Figure 1.1, Kabir et al., 2013). Cellulose surrounded by hemicellulose and lignin is considered the major component of hemp. Crystalline and amorphous regions are present 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 concrete incorporating hemp fibers, 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.

Therefore, hemp fibers in this study were subjected to three different chemical surface treatments, and the effect of each chemical treatment was studied.

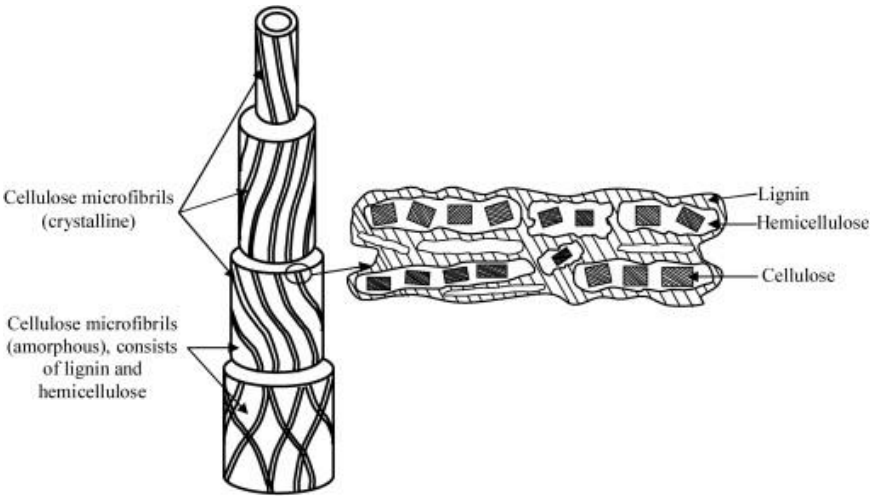

Figure 3.1 Structure of the hemp fiber (Kabir et al., 2013)

Based on the literature reported in chapter 2, the three chemical treatments most commonly used on natural fibers were tried in this study:

- Alkali treatment: Fibers are soaked in hydroxide sodium solution at 6% by weight for 48 hours (Figure 3.2). After 2 days, hemp fibers are removed from the solution and are washed with distilled water until the solution becomes clear. Then, the fibers are left to dry at room temperature.

- Silane treatment: the fibers are treated using a solution of glycidoxypropyltrimethoxysilane in water and ethanol solution in a 1:1 ratio. The pH of the solution was adjusted to 4 using 2% glacial acetic acid. The solution was stirred for 2 hours before the fibers were added. Then the fibers were washed with water and left to dry at room temperature.

- 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 H_2SO_4 for 5 minutes. Washed fibers are left to dry at room temperature.

Figure 3.2 Hemp fibers in the sodium hydroxide solution

2. *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 2 or 3 cm to ensure accurate cutting of the fibers. Finally, Fibers are cut to the lengths of 2 and 3 cm and ready to be used in concrete. Hemp fibers preparation steps are shown in Figure 3.3.

Figure 3.3 Hemp fibers preparation

3. Hemp fibers characterization

Each of the characterization tests was performed on untreated fibers, and after each chemical treatment, to evaluate the effect of these treatments on the fibers' properties.

a. 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), as shown in Figure 3.4. The top and bottom of the fiber were glued to cardboard to avoid direct contact with the grips of the testing machine. 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 3.4 Hemp fiber mounted in UTM machine

Five samples were tested for each set of fibers, and average values are reported in Table 3.1. 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 and it was the only treatment that increased the tensile strength of the fibers, while the silane treated fibers had the lowest strength. Cellulose, the crystalline part of the hemp fiber, is the part that gives it its strength. On the other hand, the outer amorphous parts of the fiber don’t contribute to its strength. When the fibers are treated and the outer amorphous parts are removed, the diameter of the fiber decreases without affecting its strength, therefore increasing its tensile strength.

A statistical analysis of the results was done through a one-way Analysis Of Variance (ANOVA) to compare the mean of each treatment with the untreated fibers using a Dunnett's t-test with a confidence level of 95%. Results showed that the silane treated fibers had a tensile strength significantly lower than the untreated fibers, while there wasn't a statistically significant difference between untreated fibers and alkali and silane treated fibers. The coefficients of variation are also presented in Table 3.1.

Table 3.1 Tensile strength results for different treatments

Treatment	Untreated	Alkali	Silane	Acetyl
Average tensile strength (MPa)	241.01	231.01	224.82	249.59
Coefficient of Variation	2.74	4.71	4.69	4.19

b. <u>Morphology</u>

Scanning Electron Microscopy (SEM) images were taken using a TESCAN MIRA3 LMU with OXFORD EDX detector. 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.

The fibers were coated with a 20 nm layer of gold to improve their conductivity and avoid charging to obtain clearer images. The images were taken at a slow scanning speed, at different magnifications ranging from 5 to 200 μm, and at an acceleration voltage speed of 8 KeV. The SEM images were used to study the morphology of the fibers' surface and the effect of treatments on it.

The microstructure of untreated fibers is shown in Figures 3.5.a and 3.5.b, while the microstructure of the fibers after each treatment is shown in Figures 3.5.c to 3.5.h. The images of untreated fibers show the presence of hemi-cellulose 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 (Figures 3.5.c, 3.5.d, 3.5.g, and 3.5.h), 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 (Figures 3.5.e and 3.5.f), some impurities were still present on the fibers surface. Silane particles that remained after the washing of the fibers were also noticed.

c. Crystallinity

An 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 to 45°. The fibers were chopped into fine particles then grinded to powder using a ball mill. The XRD analysis was performed to study the effect of each treatment on fiber crystallinity.

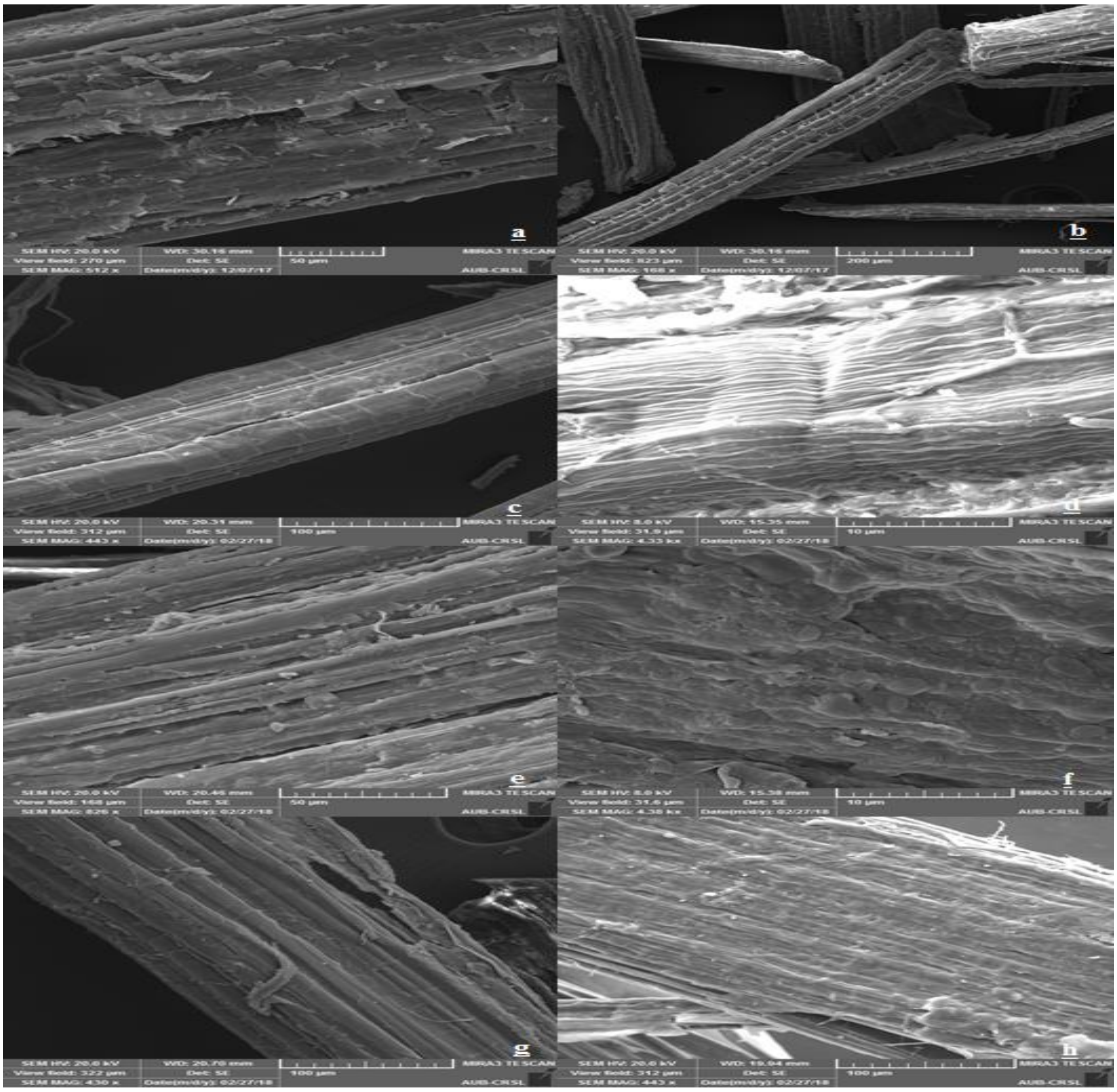

Figure 3.5 Figure 3.5 SEM images of the hemp
a-b: untreated; c-d: alkali; e-f: silane; g-h: acetyl

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 (refer to Figure 3.6). 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.

$$I_c = \left(\frac{I_{002} - I_{am}}{I_{002}}\right) \times 100 \quad (3.1)$$

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 3.2).

Table 3.2 Crystallinity index of fibers

	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

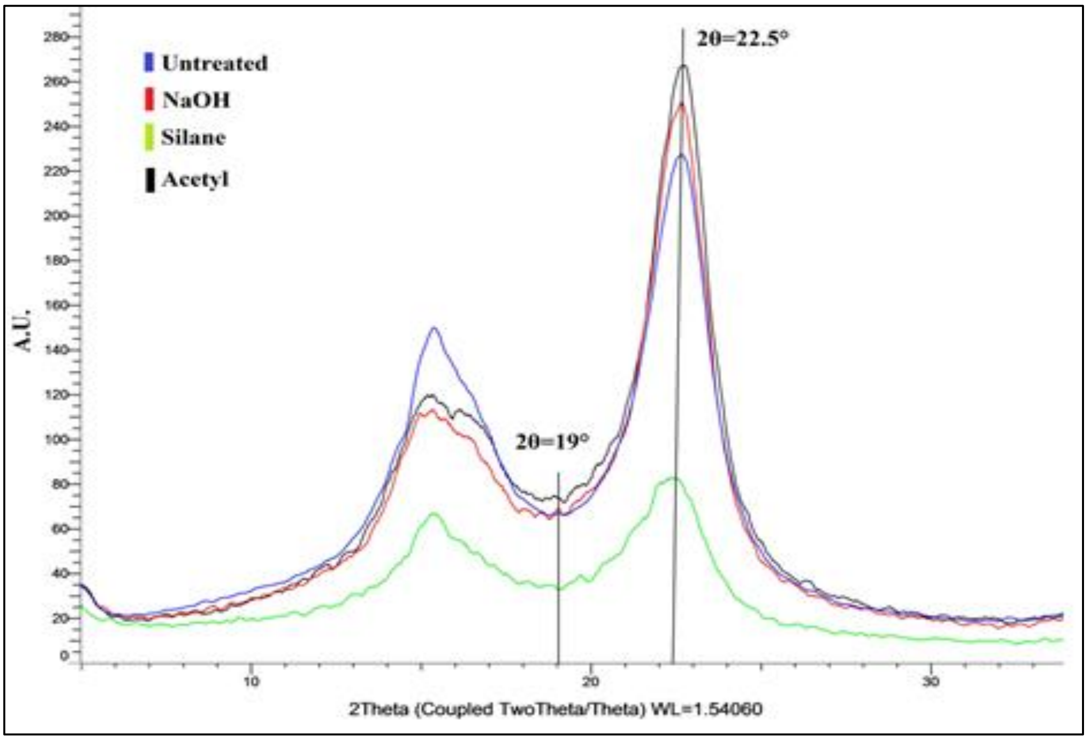

Figure 3.6 XRD diffractograms of the hemp fibers

d. Thermal Analysis

A thermogravimetric analysis (TGA) of the fibers was done using NETZSCH TG 209 F1 LIBRA. The temperature range was 30 to 550°C with a heating rate of 10°C/minute in a nitrogen atmosphere. TGA was used to study the thermal degradation of the untreated and treated fibers.

It can be observed from the TGA curves shown in Figure 3.7 that the hemp fibers decompose quickly after 250°C, and are completely decomposed at 370°C. The reason is that 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.

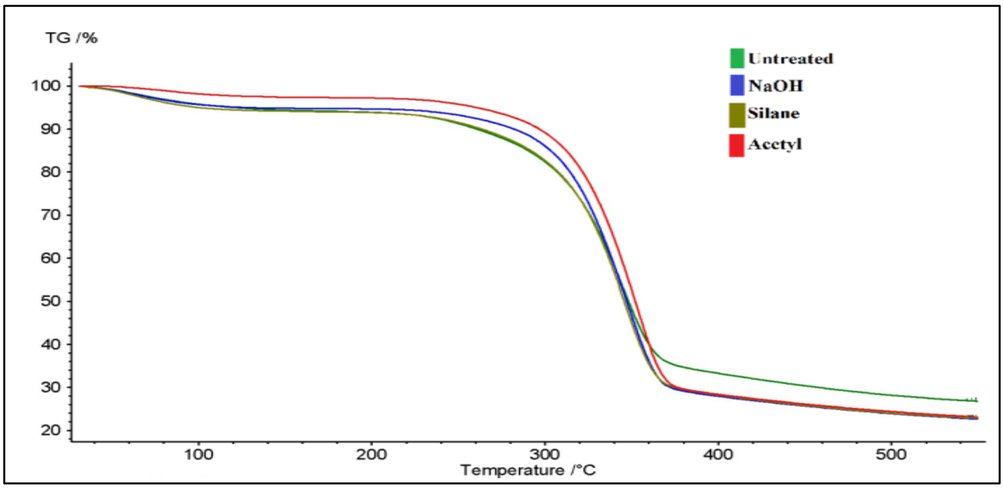

Figure 3.7 TGA results

C. Coarse aggregate

Coarse aggregates are defined as the aggregate retained on sieve No.4 (4.75 mm). Throughout this phase, natural and recycled aggregate having two different MSA (10mm and 20mm) were used. Natural aggregates (NA) were provided by ARACO ready-mix plant and recycled concrete aggregates (RCA) were obtained from the tested and crushed PCC cylinders in ARACO ready-mix plant. To identify the aggregates' properties and compare between NA and RCA, several characterization 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 the aggregates. 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 tests are shown in Figures 3.8, 3.9, 3.10, and 3.11.

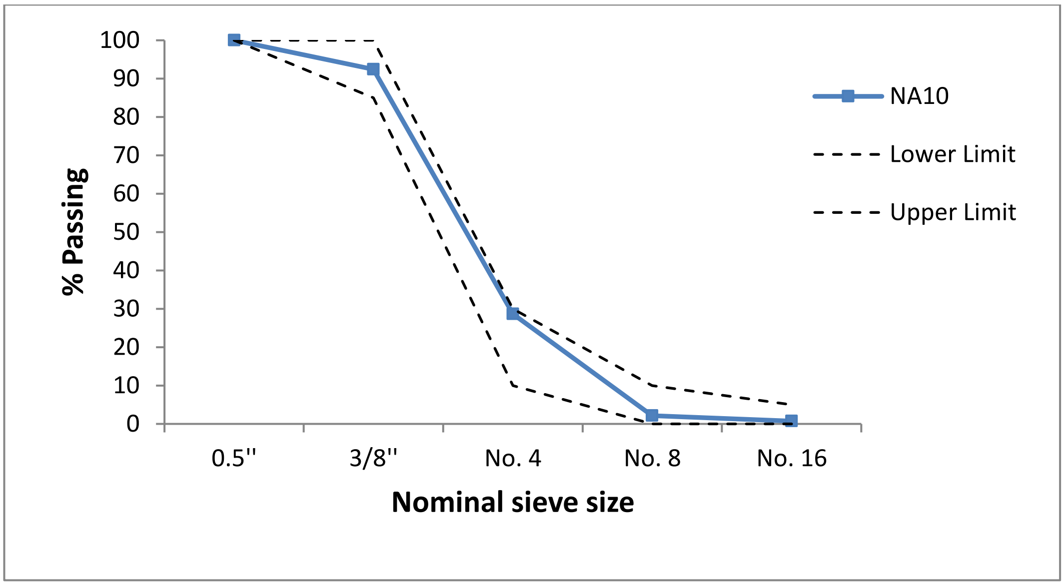

Figure 3.8 10mm natural coarse aggregates gradation

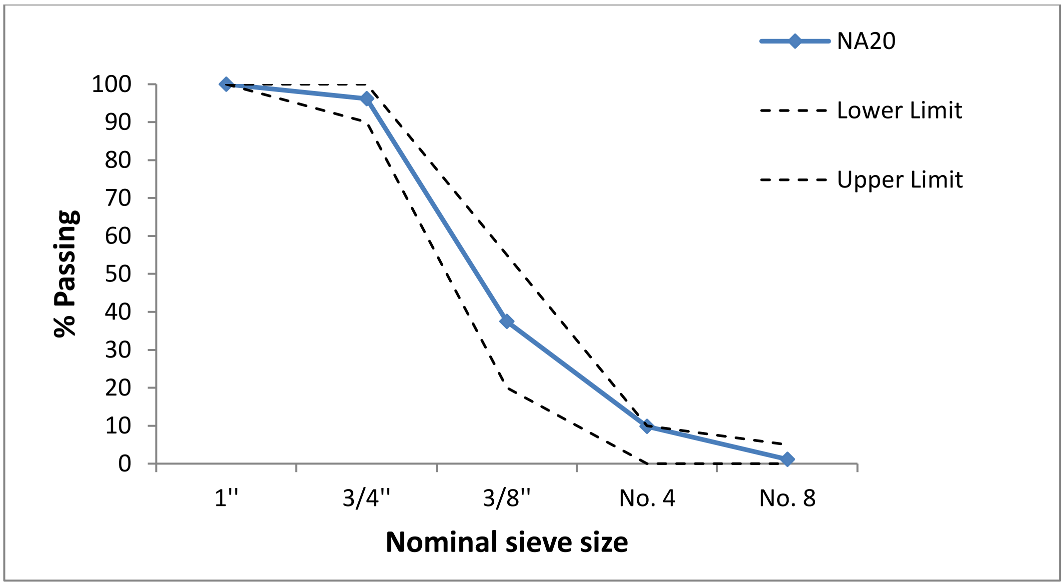

Figure 3.9 20mm natural coarse aggregates gradation

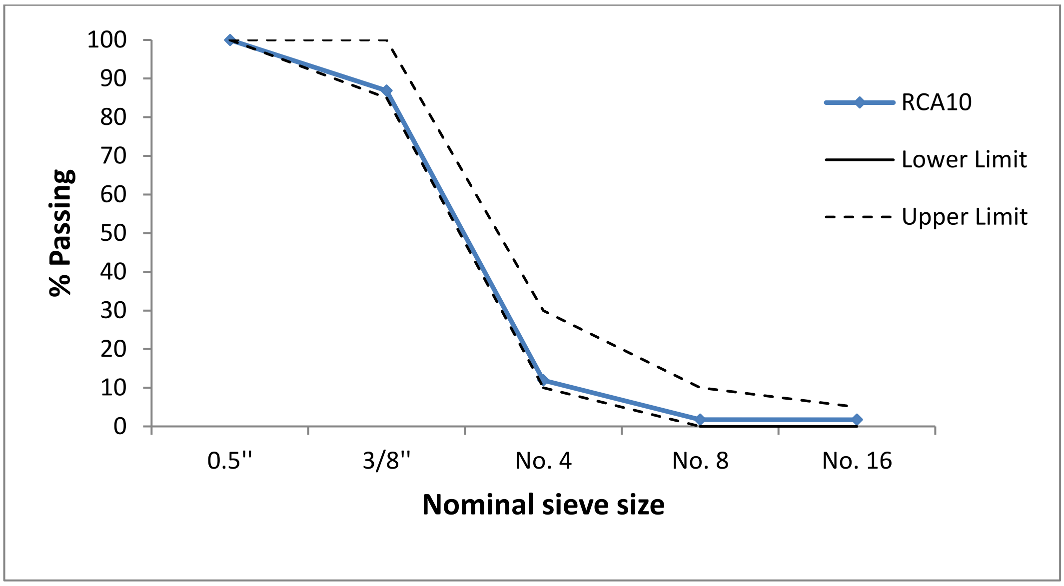

Figure 3.10 10mm coarse recycled aggregates gradation

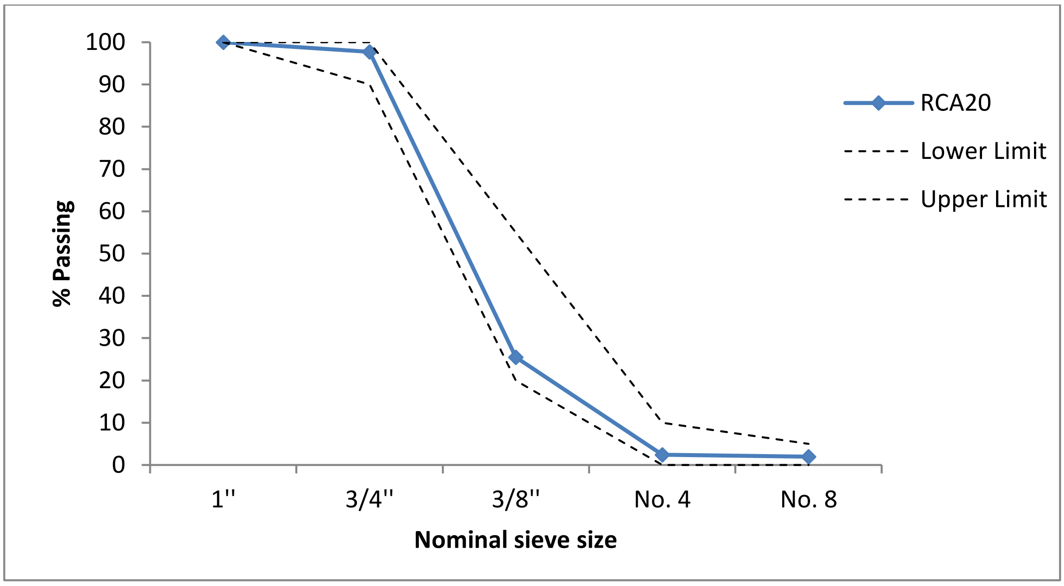

Figure 3.11 20mm coarse recycled aggregates gradation

Water absorption and bulk specific gravity are two important properties of coarse aggregates. Based on ASTM C127, a 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. 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). The specific gravity and the absorption are then calculated according to equations 3.2 and 3.3, respectively.

$$\text{Specific gravity} = \frac{A}{B-C} \quad (3.2)$$

$$\text{Absorption\%} = \left(\frac{B-A}{A}\right)*100 \quad (3.3)$$

To estimate the resistance to degradation of aggregates resulting from impacts and abrasions, 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. The machine was set to rotate 500 revolutions at 30 RPM. 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. The wear percentage is then calculated according to equation 3.4.

$$\text{Wear (\%)} = \left(\frac{C-Y}{C}\right)*100 \quad (3.4)$$

Table 3.3 Coarse aggregates properties

Aggregates Type	**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	

D. 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. It has a fineness modulus of 2.9 and a specific gravity of 2.64. Gradation results of the sand are presented in Figure 3.12.

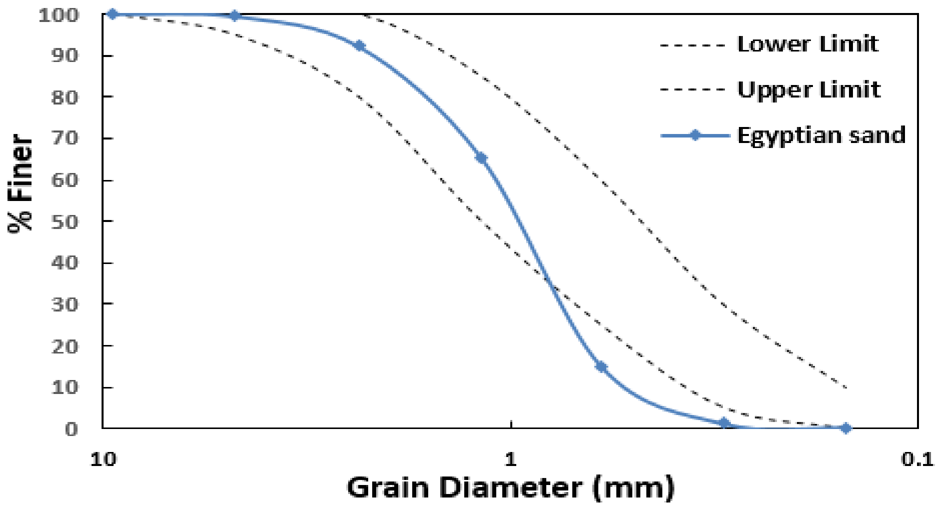

Figure 3.12 Sand gradation

E. Superplasticizer

Recycled aggregates holding adhered cement on their surface increase water absorption and consequently decrease the concrete workability. Moreover, the presence of hemp fibers, which have high water absorption, also affect the concrete's workability. Therefore, adding superplasticizer to the mixes was necessary to maintain an acceptable workability. Sikament NN was the adopted as superplasticizer in the concrete mixes. This product is a high range water-reducing, and it complies with ASTM C494 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. In this study, a dosage of 0.75% was used.

F. Conclusions

In this chapter, the materials in the experimental program were detailed, and results of tests performed to characterize these materials were presented. The tests were also used to compare between NA and RCA, and to study the effect of each of the chemical treatments done on the hemp fibers.

SEM results indicated that alkaline and acetyl treatments improved the hemp surface by removing the impurities while the silane treatment was ineffective. Alkaline and acetyl treatments increased the crystallinity index of fibers whereas the silane treatments had no significant effect on hemp. 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.

Based on these results, the silane treatment was proven ineffective, and only alkali and acetyl treatments were used in the later stages of this study.

CHAPTER IV

TRIAL MIXES, SMALL-SCALE TESTS, AND RESULTS

A. Introduction

In this chapter, different trial batches of PCC were performed to investigate the compatibility of the NCA, RCA, and hemp fibers, in order to find an optimum mix that meets the requirements of high-performance concrete as far as workability and mechanical properties.

Tests on trial batches 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.

In this research, in addition to studying the effect of the inclusion of RCA and hemp fibers in the concrete mix, several other variables were investigated including the maximum size aggregate (MSA) of the coarse aggregates, the length of the hemp fibers, and the surface treatment of the fibers.

B. Concrete Mixes

To study the effect of each of the variables on the concrete's properties, sixteen different mixes were prepared and are identified in Table 4.1. 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 used.

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 usually used in concrete mixes: 10mm and 20mm.

The mixes are divided into two groups: Group 1 with MSA of 10 mm and Group 2 with MSA of 20 mm. The control mixes with no hemp fibers and no coarse aggregate reduction are referred to as N10 (NCA with MSA = 10 mm) and N20 (NCA with MSA = 20 mm) and were designed to achieve a concrete compressive strength of 30 MPa. R10 and R20 are two mixes with 50 percent replacement of NCA with RCA, no hemp fibers, and also no reduction of coarse aggregate content.

The other twelve mixes with hemp fibers are identified by a three-part notation. The first part is N (100% NCA) or R (50% replacement of NCA with RCA) and 10 or 20 mm are the MSA. The second part of the notation refers to the length of the hemp fibers (H20 is 20 mm and H30 is 30 mm). The third part is the type of fiber treatment where T1 is alkali treatment and T2 is acetyl treatment. A total of 7 HRAC mixes were used.

Based on the reported studies of Awwad et al. (2012b), hemp fibers in mixes with fibers were added in a volumetric percentage of 0.75% of the volume of concrete. The weight of the fibers was then calculated based on the average density of the fibers determined to be 1,400 kg/m3. The weight of the coarse aggregates for these mixes was also reduced by 20% of the concrete volume. The batching weights for all 16 mixes are presented in Table 4.2.

It should be noted that tests done to determine the concrete volume yield of mixes with hemp fibers (with or without recycled aggregates) showed that when the quantity of coarse aggregates was reduced by 20% of the concrete volume and hemp fibers were added, the mix volume decreased by around 8%. To restore the 1 cubic meter concrete volume, the batching weights of the different constituents were slightly increased as shown in Table 4.2. As an example of the exercise done to restore the 1 cubic meter volume for mix N20-H20-T1:

a. Starting from the control mix N20, and after reducing the quantity of coarse aggregates by 20% of the concrete volume and adding the hemp fibers, the following weights are computed: cement: 400 kg; water: 216 kg; coarse aggregates: 603 kg; sand: 763 kg; and fibers: 10.5 kg.

b. Since the yield volume corresponding to the weights listed above is 0.92 m3, then to obtain a concrete volume of 1 m3, the weights are multiplied by a ratio of (1/0.92) to obtain the following weights listed in Table 3: cement: 434.78 kg; water: 234.78 kg; coarse aggregates: 630.43 kg; sand: 829.34 kg; and fibers: 11.41 kg.

A cost comparison of the three constituents (cement, NCA, and sand) for four representative mixes was done to assess the economical prospect of incorporating recycled aggregates and hemp fibers in concrete. The local costs per metric Ton were used: 150 USD for cement, 10 USD for NCA, and 16 USD for sand. Results presented in Table 4.3 show that the combined cost of cement, NCA, and sand of mixes incorporating recycled aggregates and hemp fibers is comparable to that of the control mix.

Although the cost is comparable, however the positive environmental impact of saving on natural resources and reusing waste materials, along with the positive socio-economic impact of promoting hemp cultivation, give the credibility to testing the newly proposed HRAC material.

C. Slump

The slump test of the fresh concrete mixes was made according to ASTM C143 (2015). The slump test was performed to evaluate the effect of the replacement of NCA by RCA and hemp fibers on the consistency of fresh concrete. Results presented in Table 4.5 and Figures 4.1 and 4.2 show that slump for the control mixes ranged between 20 and 23 cm whereas mixes with hemp fibers, with or without RCA replacements of NCA, had slump values ranging between 10 and 14 cm. The results remain in the acceptable range and the reduction is due to the fact that fibers absorb a significant quantity of the mix's water. Awwad et al. (2012b) observed similar reduction in slump for the mix with 0.75% fibers and 20% reduction in NCA as compared with the control mix.

Table 4.1 Identification of the concrete mixes

	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 4.2 Batching weights for all mixes in kg per cubic meter of concrete

	Mix ID	Cement	Water	NCA	RCA	Sand	Fibers
Group 1 MSA = 10 mm	N10 (Control10)	450	243	652	0	930	-
	R10	450	243	326	326	930	-
	N10-H20-T1	489.13	264.13	386.42	0	1010.87	11.41
	R10-H20-T1	489.13	264.13	193.21	193.21	1010.87	11.41
	R10-H20-T2	489.13	264.13	193.21	193.21	1010.87	11.41
	N10-H30-T1	489.13	264.13	386.42	0	1010.87	11.41
	R10-H30-T1	489.13	264.13	193.21	193.21	1010.87	11.41
Group 2 MSA = 20 mm	N20 (Control20)	400	216	905	0	763	-
	R20	400	216	452.5	452.5	763	-
	N20-H20-T1	434.78	234.78	630.43	0	829.34	11.41
	R20-H20-T1	434.78	234.78	315.22	315.22	829.34	11.41
	N20-H20-T2	434.78	234.78	630.43	0	829.34	11.41
	R20-H20-T2	434.78	234.78	315.22	315.22	829.34	11.41
	N20-H30-T1	434.78	234.78	630.43	0	829.34	11.41
	R20-H30-T1	434.78	234.78	315.22	315.22	829.34	11.41
	R20-H30-T2	434.78	234.78	315.22	315.22	829.34	11.41

Table 4.3 Cost of raw material of four representative mixes

MIX ID	Cement		NCA		Sand		Total Cost (USD)
	Weight (kg)	Cost (USD)	Weight (kg)	Cost (USD)	Weight (kg)	Cost (USD)	
N20	400	60.00	905	9.05	763	12.21	81.26
R20	400	60.00	452.5	4.53	763	12.21	76.73
N20-H20-T1	434.78	65.22	630.43	6.30	829.34	13.27	84.79
R20-H20-T1	434.78	65.22	315.22	3.15	829.34	13.27	81.64

D. Mechanical properties

For each of the sixteen mixes, 100x200 mm cylinders were tested at 28 days for compressive strength according to ASTM C39 (2018), for the modulus of elasticity according to ASTM C469 (2014), and for the splitting tensile strength according to ASTM C496 (2017). Also, 100x100x350 mm beams were tested for flexural strength or modulus of rupture (MOR) at 28 days according to ASTM C78 (2018). For each test, two replicate identical specimens were prepared, and the average value was reported, except for the compressive strength test, where three replicates were tested for each mix.

A statistical analysis of the results was done through a one-way Analysis Of Variance (ANOVA). To compare the mean of all the mixes with the control mix, a Dunnett’s t-test with a confidence level of 95% was used. To evaluate the effect of the other variables, a pairwise t-test with Bonferroni adjustment with a confidence level of 95% was used.

According to standards, the dimensions and materials used for each of the tests are presented in Table 4.4.

Views of the different test setups are shown in Figures 4.3, 4.4, and 4.5.

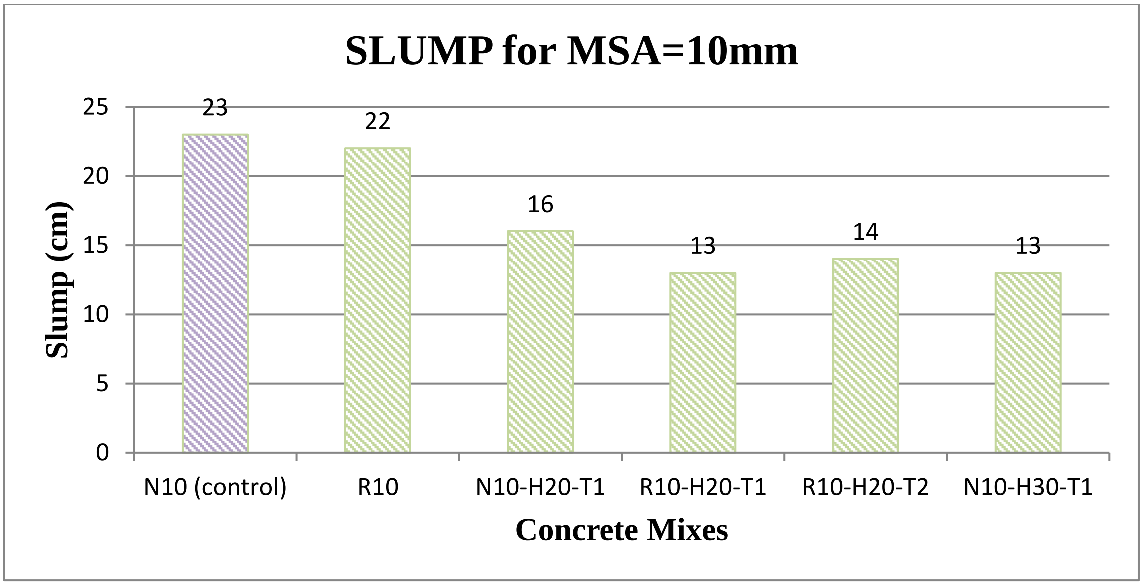

Figure 4.1 Slump of concrete mixes of group 1

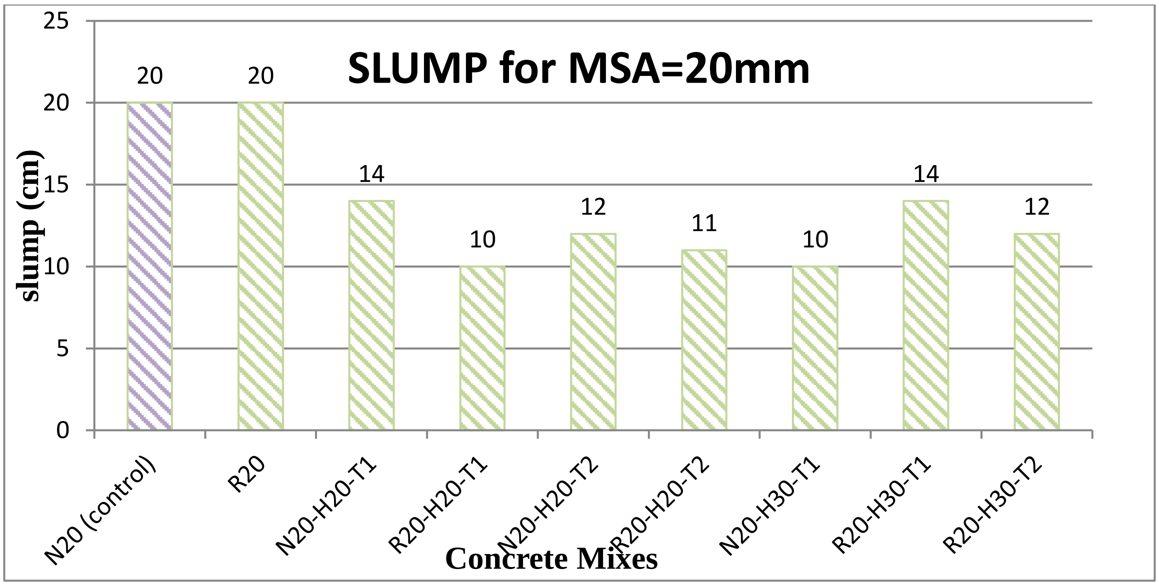

Figure 4.2 Slump of concrete mixes of group 2

Table 4.4 Molds specifications

Test	Mold dimensions (cm)	Mold Material
Compressive strength	10x20	PVC
Split tensile strength	10x20	PVC
Flexure beams	10x10x35	Plywood
Modulus of Elasticity	15x30	Steel

Figure 4.3 Compressive strength test

Figure 4.4 Flexural strength test

Figure 4.5 Tensile strength test

1. Compressive strength

Cylinder compressive strength test results at 28 days, presented in Table 4.5 and Figures 4.6 and 4.7, show that the replacement of 50% of NCA by RCA reduces the compressive strength of concrete by approximately 10%. 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 length and fiber treatment 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 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 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. Based on the above test results, it would not be advisable to use HRAC mixes in structural members subjected to compression forces like columns.

It is worth noting that in the study of Awwad et al. (2012b), the mix with 0.75% hemp fibers and 20% reduction in NCA but with no RCA recorded a 25% reduction in compressive strength relative to the control mix. Additionally, Hamad et al. (2017) reported an average reduction of 10% in compressive strength for mixes with different percentage replacement of NCA with RCA but with no fibers.

2. *Modulus of Elasticity*

Results of the modulus of elasticity test listed in Table 4.5 and Figures 4.8 and 4.9 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.

Table 4.5 Slump and mechanical properties of all mixes

	Mix ID	Slump	Compressive Strength		MOE		MOR		Splitting Tensile Strength	
		(cm)	Value (MPa)	Ratio*	Value (GPa)	Ratio*	Value (MPa)	Ratio*	Value (MPa)	Ratio*
Group 1 MSA = 10 mm	N10	23	38	-	30.8	-	5.1	-	2.24	-
	R10	22	34.25	0.90	28.8	0.94	4.8	0.94	2.21	0.99
	N10-H20-T1	16	23	0.61	22.2	0.72	4.95	0.97	2.08	0.93
	R10-H20-T1	13	24.5	0.64	22.8	0.74	4.35	0.85	2.10	0.94
	R10-H20-T2	14	24.5	0.64	22.9	0.74	4.2	0.82	2.14	0.96
	N10-H30-T1	13	24	0.63	22.7	0.74	4.8	0.94	1.94	0.87
	R10-H30-T1	13	24	0.63	22.5	0.73	4.2	0.82	1.99	0.89
Group 2 MSA = 20 mm	N20	20	39	-	33.2	-	5.25	-	2.64	-
	R20	20	35	0.90	31.4	0.95	4.57	0.87	2.53	0.96
	N20-H20-T1	14	28	0.72	26	0.78	5.1	0.97	2.51	0.95
	R20-H20-T1	10	25	0.64	23.7	0.71	4.65	0.89	2.31	0.88
	N20-H20-T2	12	27	0.69	24.9	0.75	4.65	0.89	2.55	0.97
	R20-H20-T2	11	25	0.64	23.4	0.70	4.5	0.86	2.52	0.95
	N20-H30-T1	14	32	0.82	27.2	0.82	4.95	0.94	2.3	0.87
	R20-H30-T1	10	26	0.67	24.3	0.73	4.5	0.86	2.1	0.80
	R20-H30-T2	12	25	0.64	23.7	0.71	4.5	0.86	2.4	0.91

*Ratio = Mechanical property value for the mix divided by that of the control mix N10 in Group 1 and by that of the control mix N20 in Group 2.

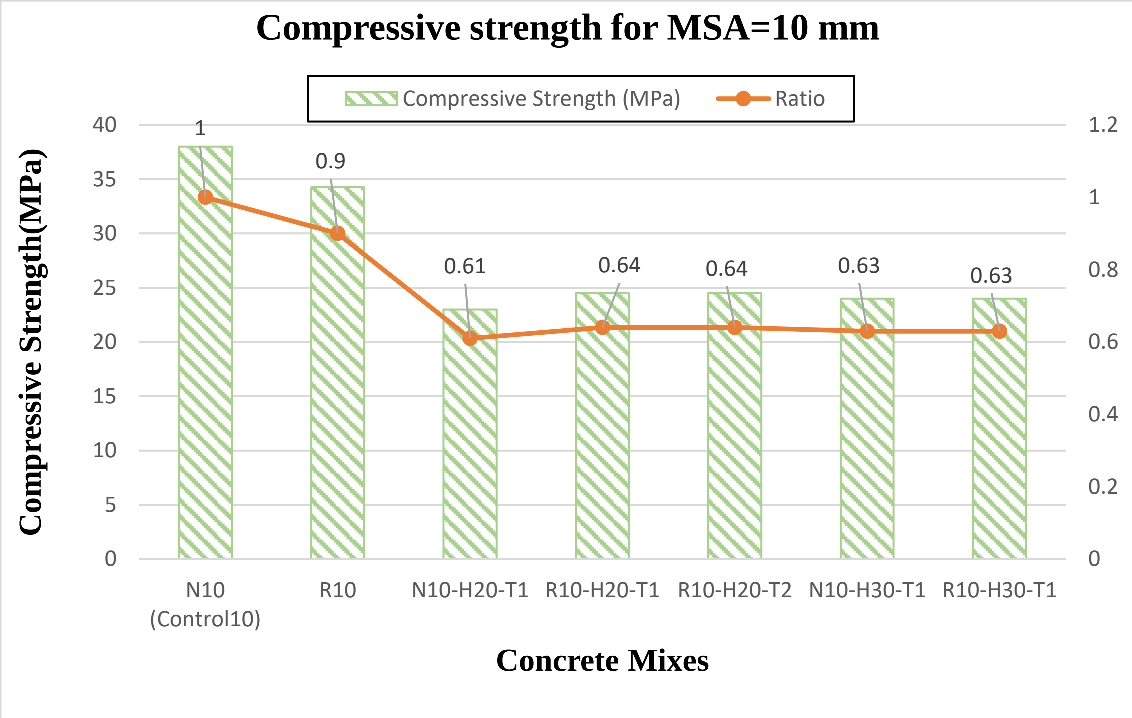

Figure 4.6 Compressive strengths and ratios to control for group 1

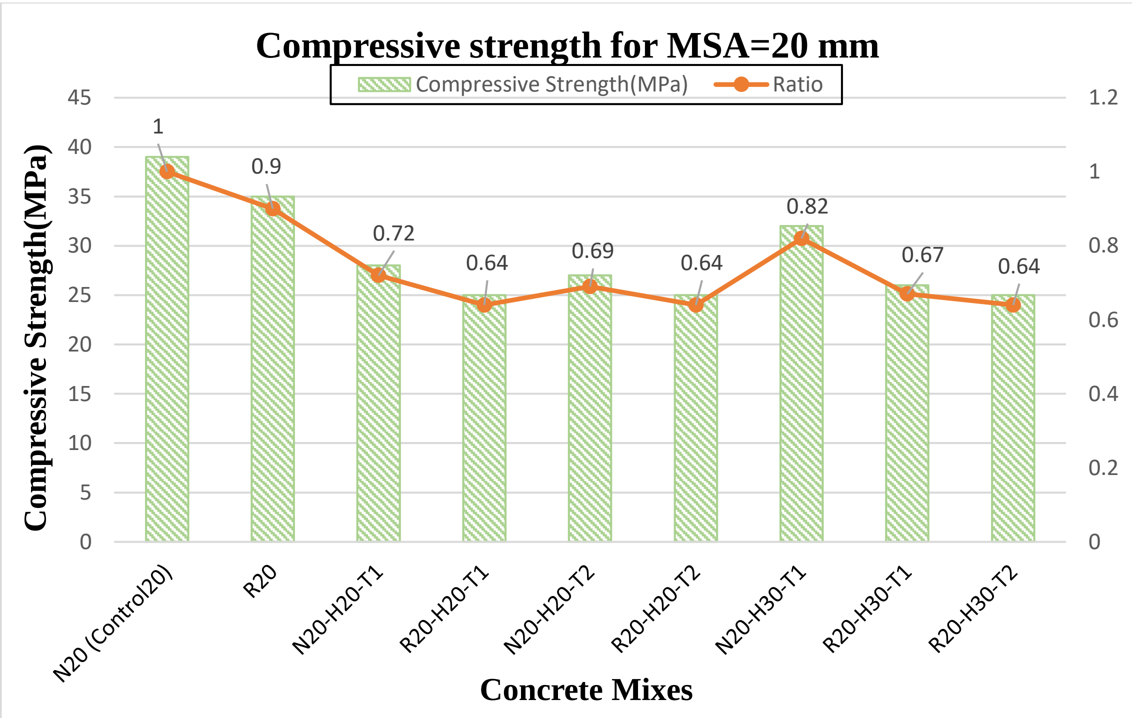

Figure 4.7 Compressive strengths values and ratios to control for group 2

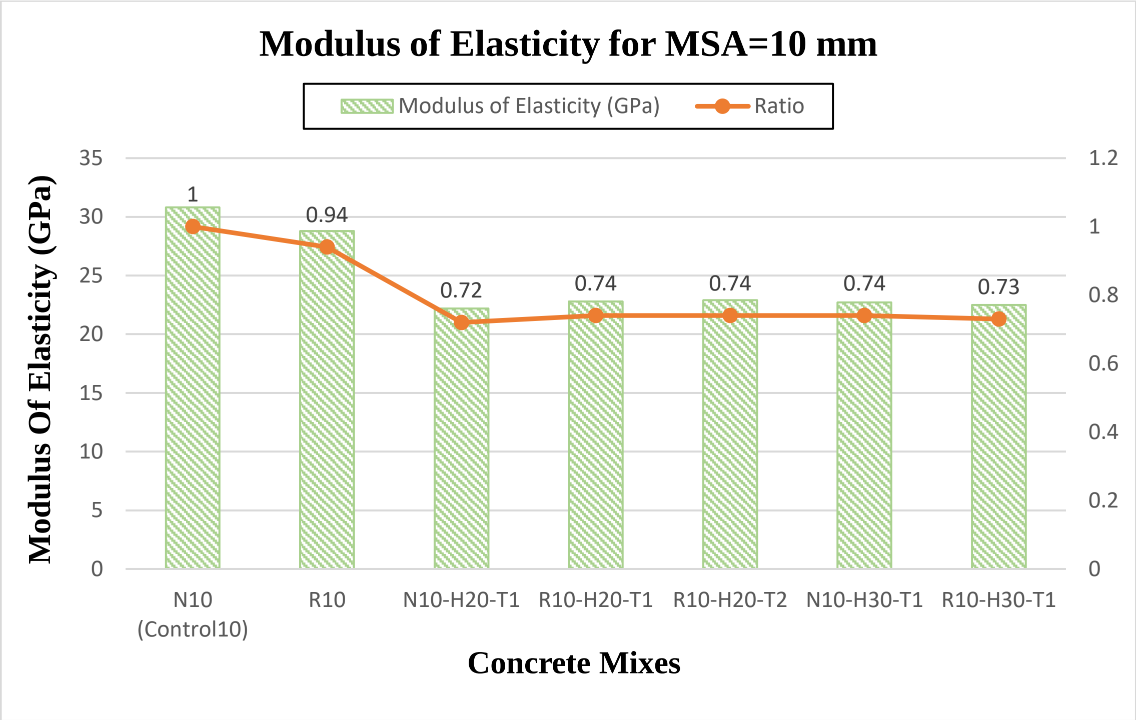

Figure 4.8 Modulus of Elasticity values and ratios to control for group 1

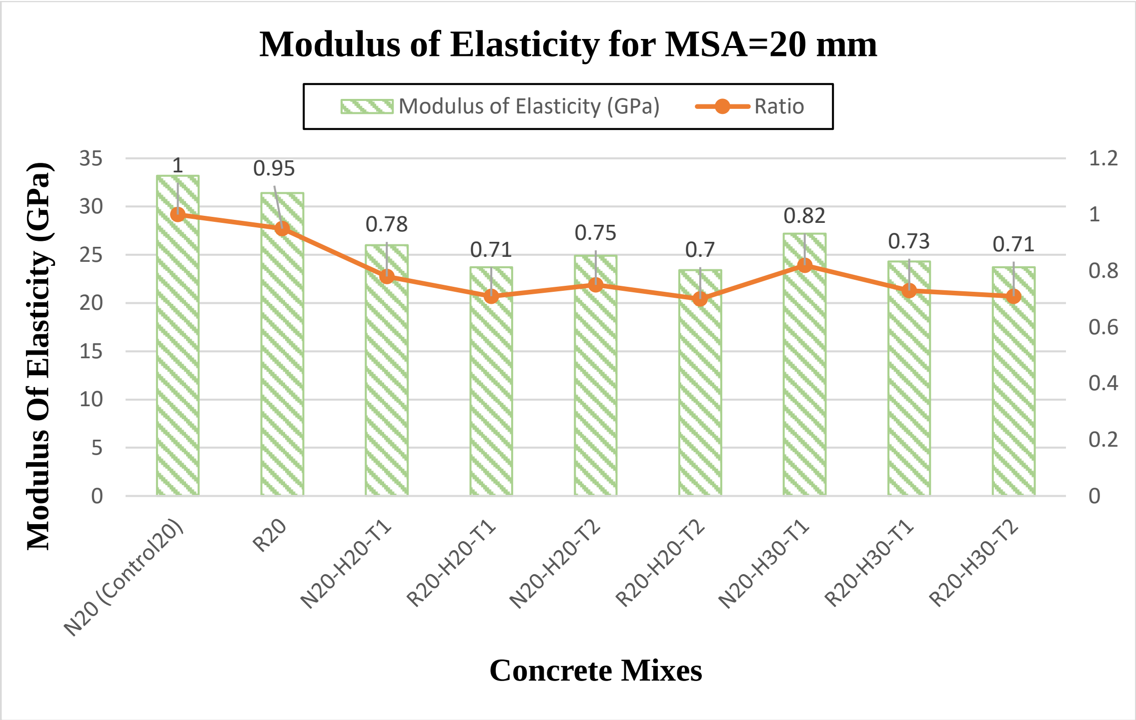

Figure 4.9 Modulus of Elasticity values and ratios to control for group 2

As compared to the reductions in the modulus of elasticity obtained in this study for the HRAC mixes, the study of Awwad et al (2012b) reported 13% reduction for the mix with 0.75% hemp fibers and 20% reduction in NCA but with no RCA and Hamad et al. (2017) reported an average 10% reduction for mixes with different percentage replacement of NCA with RCA but with no fibers.

3. *Flexural strength*

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 4.5 and Figures 4.10 and 4.11.

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 and the modulus of elasticity. Moreover, the fiber length (20 or 30 mm) and the fiber treatment (alkali or acetyl) did not affect the test results. The above reductions in the MOR are compared to the 24% reduction reported by Awwad et al (2012b) for the mix with 0.75% hemp fibers and 20% reduction in NCA but with no RCA, and to the average 10% reduction reported by Hamad et al. (2017) for mixes with different percentage replacement of NCA with RCA but with no fibers.

The load-deflection curves of the flexural beams are presented in Figure 4.12 for Group 1 of mixes with MSA of 10 mm and in Figure 4.13 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 hemp fiber mixes is demonstrated by the larger area under the load-deflection curves. According to Awwad et al. (2012b), the ductile behavior is directly related to the toughness of the composite material. When cracks start to appear in 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 would lead to an average of 15% reduction in flexural strength, however the load-deflection history becomes ductile.

To quantify the ductility of the tested specimens, the fracture energy was evaluated by calculating the area under the load-deflection curve from zero displacement up to the displacement corresponding to half the peak load (0.5 Pmax), or from zero displacement up to failure if failure occurs before the post-peak load reaches 0.5 Pmax as illustrated in Figure 4.14.

The ratio of fracture energy of the tested HRAC specimen to that of the control specimen was considered as a measure of ductility and is called the energy ductility index μ. Results presented in Table 4.6 show the positive impact of using fibers on load-deflection ductility with values of μ ranging between 1.95 and 3.53 in Group 1 of HRAC mixes (MSA = 10 mm) and between 2.07 and 3.46 in Group 2 of HRAC mixes (MSA = 20 mm).

4. Splitting tensile strength

Splitting tensile strength test results shown in Table 4.5 and Figures 4.15 and 4.16 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. Mixes with hemp fibers in both groups of different MSA 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 lead to a small reduction in the splitting tensile strength. Similar trends were reported by Awwad et al. (2012b) for hemp fiber mixes with reductions in NCA but with no RCA and by Hamad et al. (2017) for mixes with different percentage replacement of NCA by RCA but with no fibers. These results show that while the presence of fibers considerably increases the fracture energy, its effect on the tensile strength is less significant.

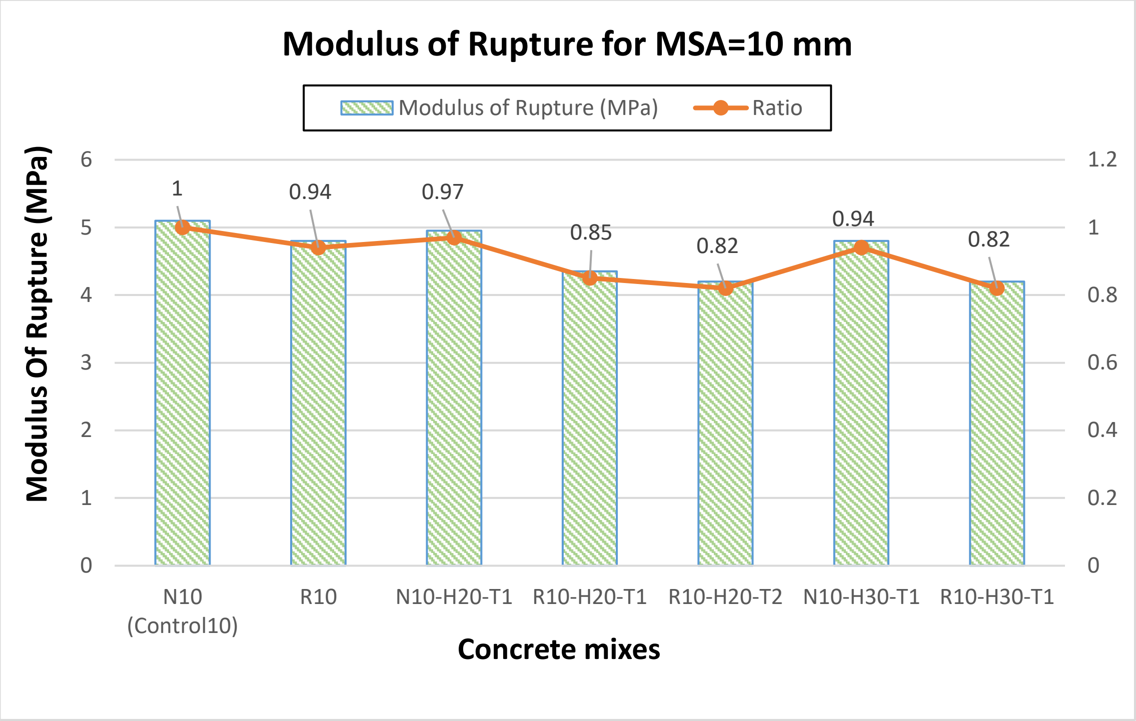

Figure 4.10 Modulus of rupture values and ratios to control for group 1

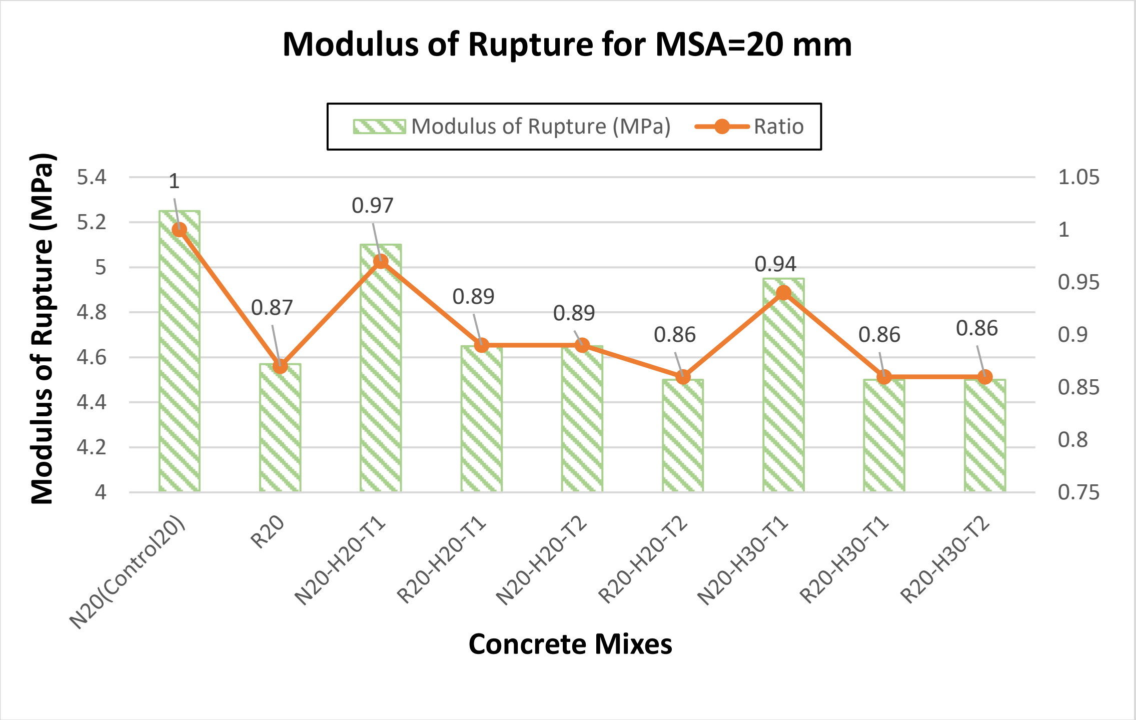

Figure 4.11 Modulus of rupture values and ratios to control for group 2

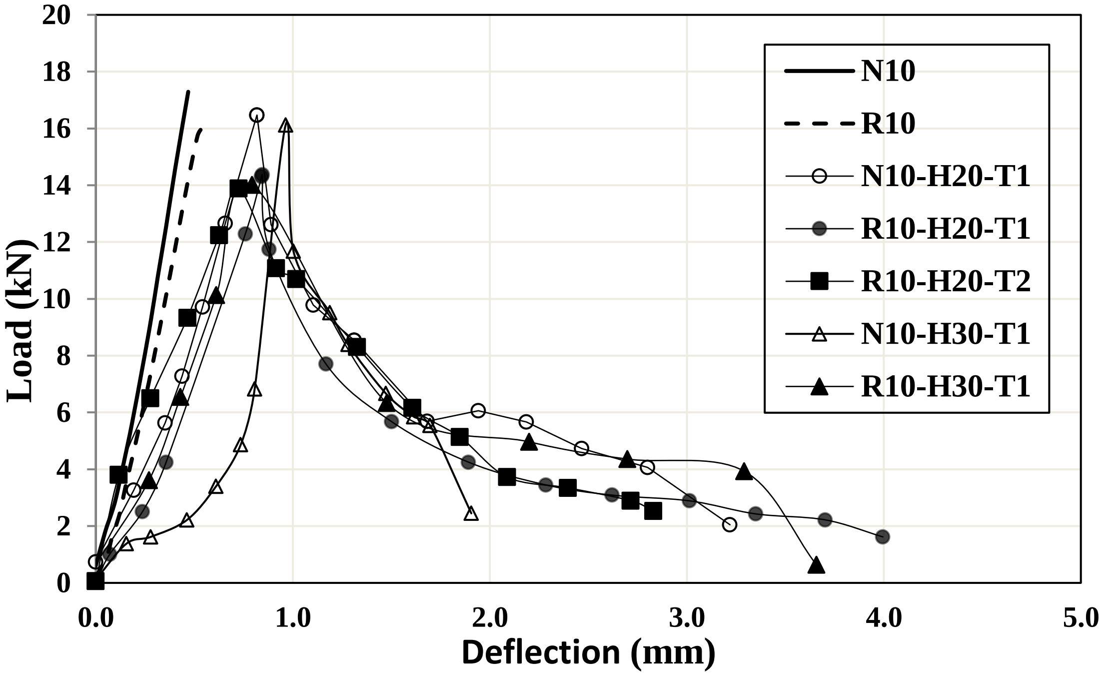

Figure 4.13 Load-deflection curves for group 1

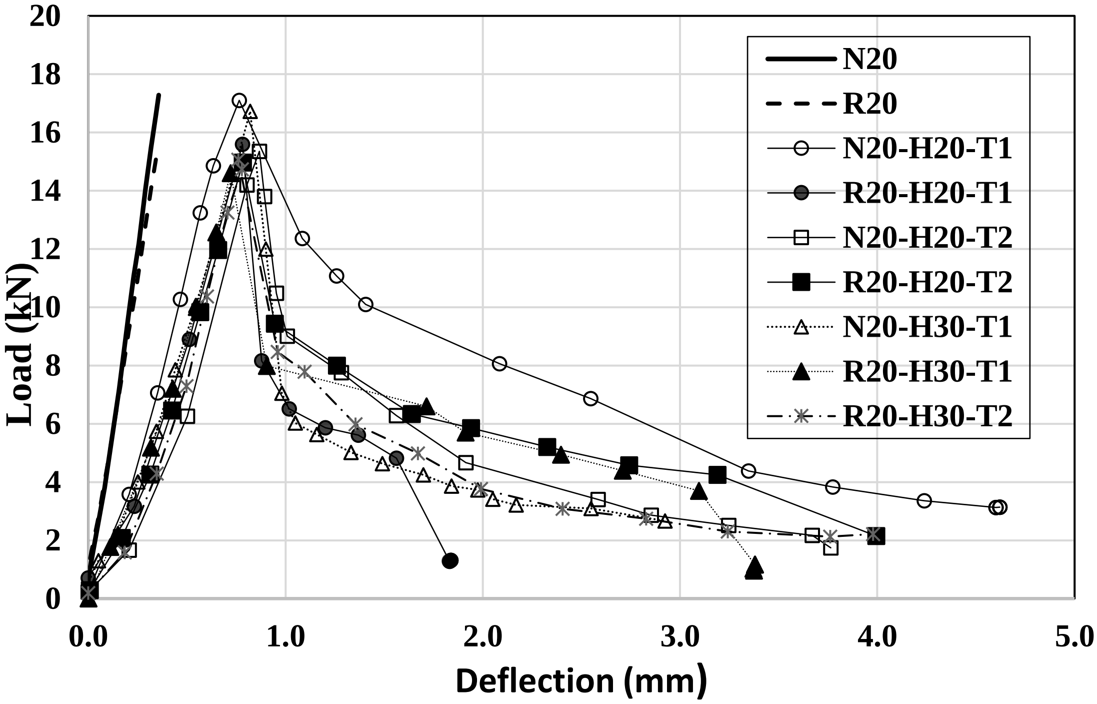

Figure 4.12 Load-deflection curves for group 2

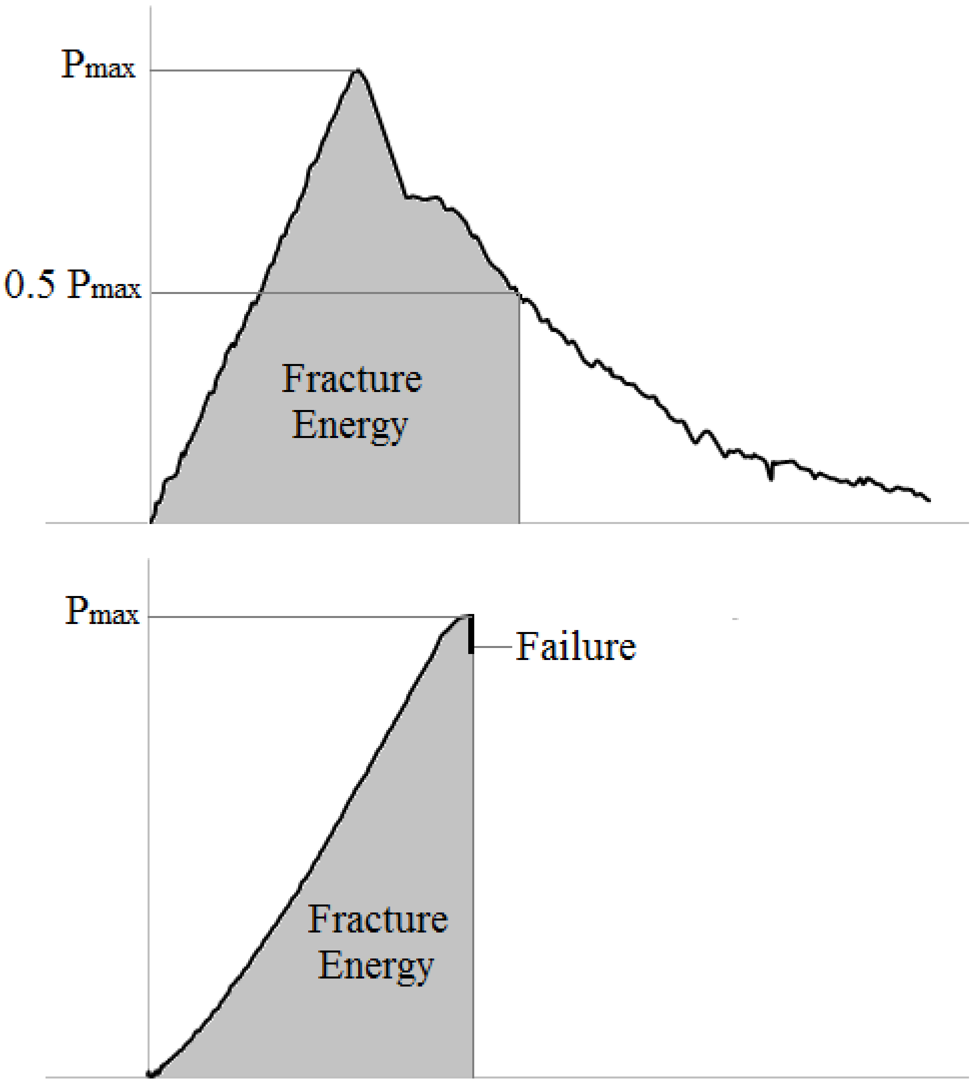

Figure 4.14 Schematic load-deflection curves to define the measured fracture energy.

Table 4.6 Fracture energy of all mixes

	Mix ID	Fracture Energy (kN-m)	μ*
Group 1 MSA = 10 mm	N10 (Control10)	3.77	-
	R10	4.04	1.07
	N10-H20-T1	11.52	3.06
	R10-H20-T1	8.53	2.26
	R10-H20-T2	13.29	3.53
	N10-H30-T1	7.37	1.95
	R10-H30-T1	9.22	2.45
Group 2 MSA = 20 mm	N20 (Control20)	3.21	-
	R20	2.71	0.84
	N20-H20-T1	18.02	5.61
	R20-H20-T1	6.66	2.07
	N20-H20-T2	9.09	2.83
	R20-H20-T2	10.47	3.26
	N20-H30-T1	8.18	2.55
	R20-H30-T1	11.11	3.46
	R20-H30-T2	8.63	2.69

*μ = Energy ductility index. It is the ratio of fracture energy of the tested specimen to that of the control mix N10 or N20.

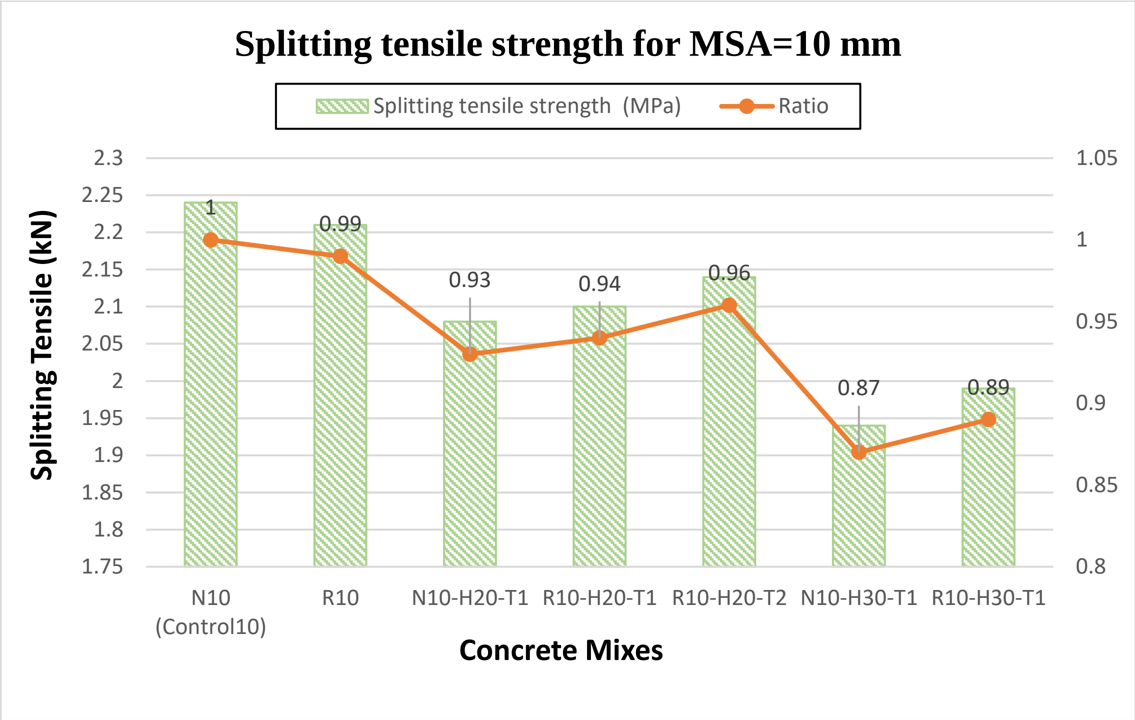

Figure 4.15 Tensile strength values and ratios to control for group 1

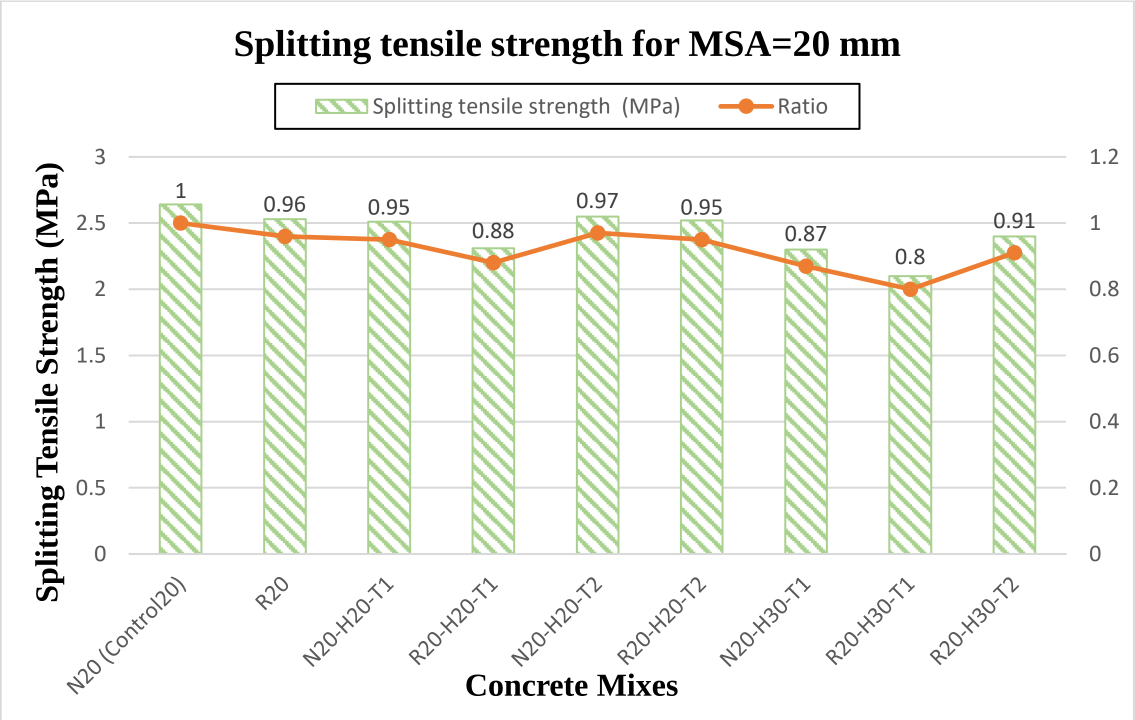

Figure 4.16 Tensile strength values and ratios to control for group 2

5. Statistical Analysis

A statistical analysis of the results was done using a one-way ANOVA test, the mean of all the mixes was compared to the control mix using a Dunnett's t-test with a confidence level of 95%. To evaluate the effect of the other variables, a pairwise t-test with Bonferroni adjustment with a confidence level of 95% was used.

a. <u>Compressive strength</u>

The statistical analysis of the compressive strength results showed that for group 1, all the mixes had a compressive strength significantly lower that the control mix N10. The pairwise t-tests showed that the compressive strength of all the mixes with hemp fibers is also significantly lower than the R10 mix, which shows that the hemp fiber incorporation is the main factor affecting the compressive strength. Furthermore, there was no statistical difference between mixes with different hemp length or different hemp treatment, which proves that these two variables don't affect the compressive strength of group 1 mixes.

For group 2, all the mixes had a compressive strength significantly lower that the control mix N20, except for the R20 mix, where the difference with control mix wasn't statistically significant. This confirms that 50% replacement of the NA by RCA doesn't significantly affect the compressive strength. Similar to group 1, the pairwise t-tests showed that the hemp length and treatment don't affect the compressive strength.

Moreover, pairwise t-tests between the two groups showed that the difference in the compressive strength between two corresponding mixes in the two groups (N10 and N20; R10 and R20; N10-H20-T1 and N20-H20-T1…) isn't statistically significant, which means that the MSA doesn't significantly affect the compressive strength.

b. Modulus of elasticity

The modulus of elasticity of all the mixes of group 1 was significantly lower than the control mix, except for the R10 mix. For group 2, the results were similar to the compressive strength, as all mixes had values significantly lower than the control mix except for the R20 mix.

Similar to the compressive strength, pairwise t-tests showed that the MSA, fiber length and fiber treatment don't affect the MOE significantly.

c. Flexural strength

For the flexural strength results of group 1, only R10-H20-T2 and R10-H30-T1 had a MOR significantly lower that the control mix N10, while the difference between the other mixes and the control mix wasn't statistically significant. Moreover, pairwise t-tests showed that the hemp fiber length and treatment didn't significantly affect the MOR for group 1.

For group 2, the difference between the MOR of N20-H20-T1 and N20-H30-T1 and the control mix N20 wasn't statistically significant, while all the other mixes had an MOR significantly lower than the control mix. Similar to group 1, pairwise t-tests showed that the hemp fiber length and treatment didn't significantly affect the MOR.

Moreover, pairwise t-tests between the two groups showed that the difference in the MOR between two corresponding mixes in the two groups isn't statistically significant, which means that the MSA doesn't significantly affect the flexural strength.

d. Tensile strength

For the tensile strength results, the difference between the control mix and the other mixes wasn't statistically significant for any of the mixes of both groups.

Moreover, pairwise t-tests between the two groups also showed no statistically significant difference.

e. <u>Summary</u>

These results confirm that the replacement 50% of NA by RCA for the most part doesn't significantly affect the mechanical properties of the concrete mix. On the other hand, when hemp fibers are added and the quantity of coarse aggregates is reduced, the compressive strength and the MOE are significantly reduced, while the flexural strength and tensile strength aren't significantly affected.

Moreover, the statistical analysis confirmed that the studied variables (MSA, fiber length and fiber treatment) didn't significantly affect any of the mechanical properties.

E. Summary and Conclusions

In this chapter, the effects of the different variables on the properties of HRAC were evaluated and compared with those of control mixes with no fibers or RCA.

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 and acetyl). The main conclusions are: (i) The incorporation of hemp fibers in the mix reduced the consistency of the mix but the value remained acceptable; (ii) The 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. 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 than 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. It would not be advisable to use HRAC mixes in structural members subjected to direct compression forces like columns; (iii) Although HRAC mixes had an average reduction of 15% in flexural strength relative to the control mixes, however load-deflection behavior became ductile with considerable history after reaching ultimate indicating high ductility and energy absorption of the hemp fiber mixes.

Concrete is of a three-phase system, comprising coarse aggregate, mortar matrix with fine aggregate, and interfacial zones (ITZ) between coarse aggregate and the mortar matrix. At a micro-level, the fibers increase the toughness and ductility of the concrete matrix by improving the stress transfer capability of the matrix. However, the effectivity of the fibers depends not only on the fibers' properties, but also on the matrix properties. Therefore, the presence and the properties of the coarse aggregates, which affects the fibers' distribution and bond with matrix, could affect the fibers' efficiency. RCA, due to the cement mortar remains and their high absorption, have a weaker ITZ. The same applies on fibers, which also have a high absorption and impurities on its surface and therefore a weaker ITZ. This explains the fact that concrete incorporating RCA and hemp fibers has a lower strength than normal concrete. On the other hand, when the fibers are present in the matrix, they improve concrete’s ductility by bridging over the formed cracks and transferring the stress to another location in the matrix.

CHAPTER V

DURABILITY AND THERMAL PERFORMANCE

A. Introduction

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 they project the lifetime of a concrete structure. A sustainable concrete should be also durable; therefore, it is important to study the effect of the incorporation of hemp fibers and RCA on the durability properties of concrete. Different approaches were used to evaluate HRAC's durability: the absorption capacity according to ASTM C642 (2013), resistance to freeze-thaw cycles according to ASTM C666/C666M-15 (2015), and long-term mechanical performance at an age of 2 years. In each of the two groups (MSA=10mm and MSA=20mm), normal and recycled aggregate mixes (N and R mixes) with or without hemp fibers and with different fiber lengths and fiber treatments were tested and compared. Furthermore, the thermal performance of the different mixes were evaluated by doing a thermal conductivity test according to ASTM C518 (2017)

B. Absorption

The percent absorption in hardened concrete test was conducted using ASTM C642 (2013) on all mixes that were covered in the slump and hardened mechanical properties tests. For each mix, three 100x200 mm cylindrical specimens were tested. The average of the three tested samples is presented for all mixes in Table 5.1. As expected, the presence of RCA leads to an increase in the absorption of the concrete mix since recycled aggregates have a higher absorption capacity as compared to natural aggregates due to

Table 5.1 Absorption values of the tested mixes

	Mix ID	Absorption	
		Value (%)	Ratio*
Group 1 MSA = 10 mm	N10 (Control10)	6.19	-
	R10	7.53	1.22
	N10-H20-T1	8.75	1.41
	R10-H20-T1	9.93	1.60
	R10-H20-T2	9.51	1.54
	N10-H30-T1	9.01	1.46
	R10-H30-T1	9.60	1.55
Group 2 MSA = 20 mm	N20 (Control20)	6.51	-
	R20	7.93	1.22
	N20-H20-T1	9.63	1.48
	R20-H20-T1	10.10	1.55
	N20-H20-T2	9.58	1.47
	R20-H20-T2	10.35	1.59
	N20-H30-T1	9.69	1.49
	R20-H30-T1	10.22	1.57
	R20-H30-T2	10.05	1.54

*Ratio = Absorption value for the mix divided by that of the control mix N10 in Group 1 and by that of the control mix N20 in Group 2.

their porous structure, which extends to the concrete matrix. The increase in the absorption of the mix with 50% replacement of NCA with RCA the control mix was by an average of 22% for both MSA of 10 (R10 as compared to N10) and 20 mm (R20 as compared to N20).

When hemp fibers were added to the mix, the hydrophilic nature of the fibers aggravated the absorption percentages as compared to the control mixes for either MSA. The increases in the absorption values for the hemp fiber mixes with no RCA, relative to the control mixes, ranged between 41 and 49%. For HRAC mixes with RCA and hemp fibers, the increases relative to the control mixes ranged between 54 and 60%. The fiber length and treatment type did not affect the absorption value of the concrete mix.

C. Thermal Conductivity

The thermal conductivity of the concrete mixes was determined according to ASTM C518 (2017). For every mix, one 300x300x30 mm block was tested. One test specimen was enough for each set of variables, since the thermal test determines the average thermal conductivity along the specimen surface. Each block was cured in water for 28 days then dried in the oven at 80 °C and finally cooled to room temperature before being tested. The thermal conductivity results are presented in Table 5.2.

Results show that for Group 1 (MSA = 10 mm) partial replacement of coarse aggregates by RCA (R10) increases the thermal conductivity of the mixes by 14% while for Group 2 (MSA = 20 mm) the replacement decreases the thermal conductivity by around 6% (R20 compared to N20). On the other hand, the incorporation of hemp fibers led to a decrease of the thermal conductivity for both groups. In Group 1 with MSA of

10 mm, reduction of hemp mix N10-H30-T1 without RCA relative to N10 was 19% and reduction of the HRAC mixes relative to N10 were 6 to 7%. For Group 2 with MSA of 20 mm, incorporation of hemp fibers led to decreases in thermal conductivity ranging between 13 and 22% relative to N20. It also should be noted that the type of the fiber treatment did not have a significant effect on the thermal conductivity of the concrete mix.

Table 5.2 Thermal conductivity of the tested mixes

	Mix ID	Thermal Conductivity	
		Value (Watt/meter. °kelvin)	Ratio*
Group 1 MSA = 10 mm	N10 (Control10)	1.728	-
	R10	1.977	1.14
	R10-H20-T1	1.605	0.93
	R10-H20-T2	1.622	0.94
	N10-H30-T1	1.401	0.81
Group 2 MSA = 20 mm	N20 (Control20)	1.939	-
	R20	1.821	0.94
	R20-H20-T1	1.513	0.78
	N20-H20-T2	1.691	0.87
	N20-H30-T1	1.575	0.81
	R20-H30-T2	1.544	0.80

*Ratio = Thermal conductivity for the mix divided by that of the control mix N10 in Group 1 and by that of the control mix N20 in Group 2.

Knowing that thermal resistance is inversely proportional to thermal conductivity, results of the thermal conductivity test show that HRAC mixes have superior thermal properties compared to normal concrete which makes HRAC more energy efficient than normal concrete by providing more insulation.

D. Resistance to Freeze-Thaw Cycles

The resistance of all mixes to rapid freezing and thawing was studied according to ASTM C666. Figure 5.1 shows specimens prepared for testing. For each mix, one prismatic specimen (75x100x405 mm) was cast and cured in water for 28 days. Each specimen was then brought to a temperature of -18 °C and tested for fundamental transverse frequency. Then, the specimens were exposed to 144 cycles of freezing and thawing. Each freezing-and-thawing cycle consisted of lowering the temperature of the specimens from 4 to -18 °C and raising it from -18 to 4 °C in a period of 4 hours and 40 minutes.

The specimens were tested for their fundamental transverse frequency each 36 cycles. The fundamental transverse frequency (n) was determined according to ASTM C215 (2008) using Humboldt HC-3177 Resonance Test Gauge. The relative dynamic modulus of elasticity (RDME) was then calculated according to equation 5.1.

$$P_c = \frac{n_1^2}{n^2} \times 100 \qquad (5.1)$$

where: P_c = Relative dynamic modulus of elasticity (RDME) after c cycles of freezing and thawing (%), n is the fundamental transverse frequency before proceeding freezing and thawing cycles, and n_1 is the fundamental transverse frequency after c cycles of freezing and thawing.

Figure 5.1 View of specimens prepared for freeze thaw cycles

Results of P_c or RDME after each 36 cycles of freezing and thawing are presented in Table 5.3. Views after 108 cycles of specimen R20 with the lowest P_c of 31.0 and specimen R10-H20-T1 with the second highest P_c of 88.5, are shown in Figure 5.2.

The results show that for Group 1 with MSA of 10 mm, all tested specimens showed good resistance to freeze-thaw cycles with Pc ranging from 77% to 90.4% after 144 cycles. Whereas Pc for the recycled aggregate mix R10 was 77 (the lowest in the group), values for all five mixes with hemp fibers ranged between 77 and 90.4, a value which is even higher than the control mix (83.5%).

Table 5.3 Relative dynamic modulus of elasticity (RDME) values of all mixes after each 36 cycles

	Mix ID	Relative Dynamic Modulus of Elasticity P_C (%)				
		c* = 0	c = 36	c = 72	c = 108	c = 144
Group 1 MSA = 10 mm	N10 (Control10)	100	94.1	90.2	86.2	83.5
	R10	100	98.2	89.5	87.5	77.0
	N10-H20-T1	100	93.8	87.2	81.6	77.0
	R10-H20-T1	100	90.5	90.5	90.5	88.5
	R10-H20-T2	100	90.2	88.5	83.7	79.5
	N10-H30-T1	100	95.2	93.0	93.0	90.4
	R10-H30-T1	100	95.2	93.0	90.4	90.4
Group 2 MSA = 20 mm	N20 (Control20)	100	93.2	79.2	62.4	51.0
	R20	100	92.7	70.2	57.8	31.0
	N20-H20-T1	100	88.1	79.2	70.8	42.0
	N20-H20-T2	100	83.2	75.3	63.7	55.5
	R20-H20-T2	100	85.8	78.3	69.5	53.2
	R20-H30-T1	100	87.7	77.2	70.5	56.5

*c = number of freeze-thaw cycles.

Figure 5.2 View of specimens R20 (top) and R10-H20-T1 (bottom) after 108 cycles.

For Group 2 mixes with MSA of 20 mm, the resistance to freeze-thaw cycles was much lower than that of Group 1 mixes, as P_c decreased intensively to reach values ranging between 31% to 56.5% after 144 cycles. As in Group 1 with MSA of 10 mm, the mix with 50% replacement of NCA with RCA but without hemp fibers (R20) had the lowest value of 31%. The low resistance of Group 2 to freeze-thaw cycles can be explained by the fact that when the MSA is increased from 10 to 20 mm, the cement matrix would contain less entrapped air bubbles. During the freezing phase of a cycle, the water present in the matrix freezes and expands causing pressure that may lead to cracks and to the deterioration of the concrete. The more entrapped air bubbles present in the 10-mm matrix relieves the pressure by providing more space for water to expand into when it freezes. As for the effect of incorporating hemp fibers in the mix, the four mixes with hemp fibers had values ranging between 42 and 56.5% as compared with 51% for the control mix N20.

It can be concluded that HRAC mixes had comparable resistance to freeze-thaw cycles as normal concrete mixes after 144 cycles for both maximum size aggregates, 10 and 20 mm. The resistance of the HRAC mixes was not affected by the type of the fiber length or fiber treatment.

E. Long-Term Mechanical Performance

To study the long-term mechanical performance of HRAC, compressive strength tests, flexural strength tests and modulus of elasticity tests were performed at an age of 2 years for 14 of the 16 mixes and the results were compared to the results at 28 days.

1. Compressive strength

Results of long-term compressive strength are presented in Table 5.4. In general, the results at the age of 2 years were consistent with results at the age of 28 days; when the hemp fibers are incorporated in the mix, the compressive strength decreases since aggregates which are the hardest elements in a concrete mix are replaced by fibers which are weak in compression. Furthermore, all mixes showed an improved compressive strength at the age of 2 years as compared to those at the age of 28 days (Figure 5.3). This increase ranges from 6 up to 31% for the HRAC mix R20-H30-T2.

Table 5.4 Long-term compressive strength test results

	Mix ID	28 days Compressive Strength		2 years Compressive Strength		Ratio (2 years /28 days)
		Value (MPa)	Ratio*	Value (MPa)	Ratio*	
Group 1; MSA = 10 mm	N10 (Control10)	38	-	42	1.00	1.11
	R10	34.25	0.9	37.75	0.90	1.10
	N10-H20-T1	23	0.61	29.5	0.70	1.28
	R10-H20-T1	24.5	0.64	29.25	0.70	1.19
	R10-H20-T2	24.5	0.64	26.5	0.63	1.08
	N10-H30-T1	24	0.63	26.25	0.63	1.09
	R10-H30-T1	24	0.63	27.5	0.65	1.15
Group 2; MSA = 20 mm	N20 (Control20)	39	-	44	1.00	1.13
	R20	35	0.9	38	0.86	1.09
	N20-H20-T1	28	0.72	34	0.77	1.21
	R20-H20-T1	25	0.64	31.5	0.72	1.26
	N20-H30-T1	32	0.82	34	0.77	1.06
	R20-H30-T1	26	0.67	31.25	0.71	1.20
	R20-H30-T2	25	0.64	32.75	0.74	1.31

*Ratio = Mechanical property value for the mix divided by that of the control mix N10 in Group 1 and by that of the control mix N20 in Group 2.

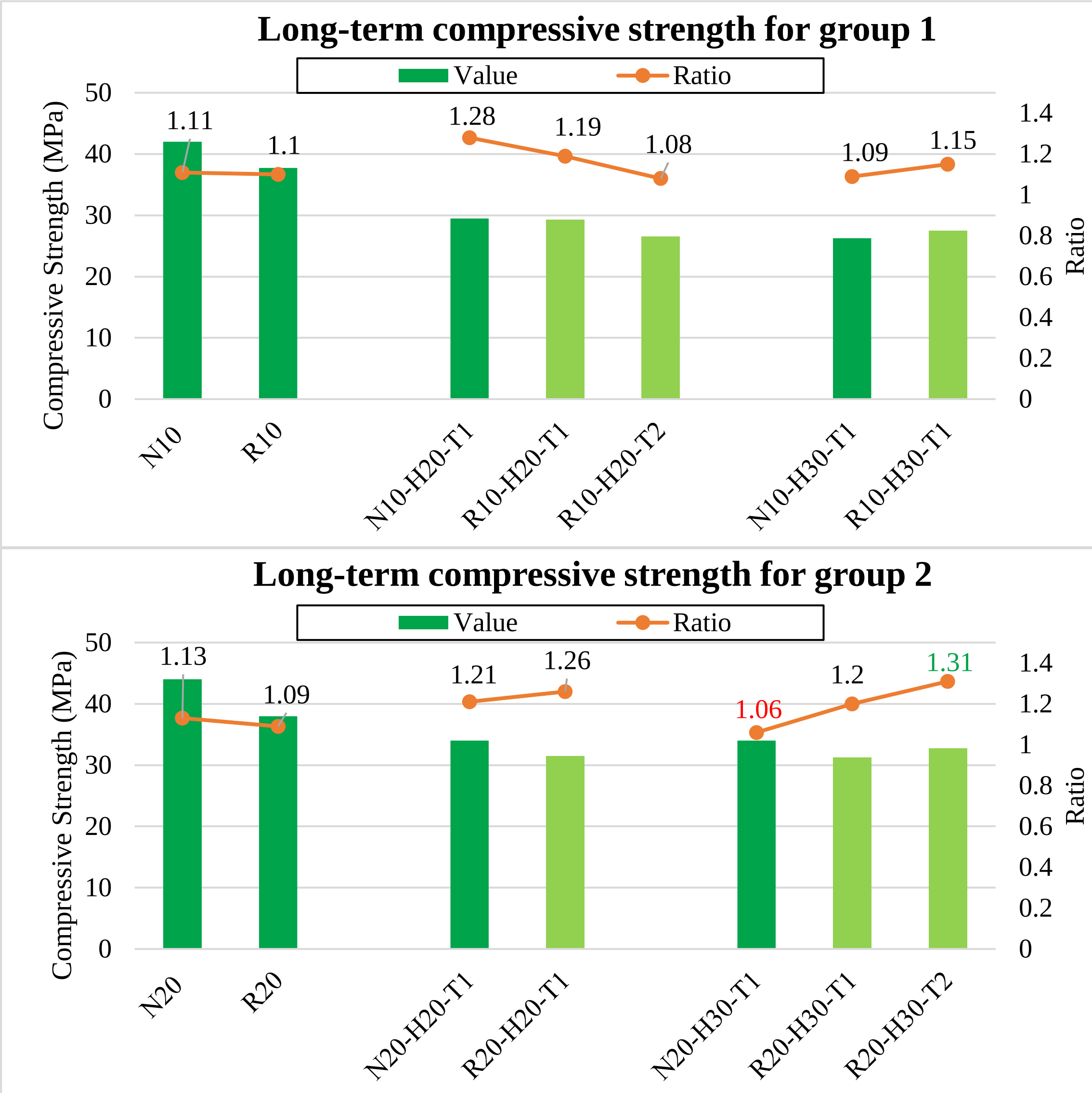

Figure 5.3 Values and ratio of compressive strength at 28 days and 2 years

2. Flexural strength

The results of the flexural strength test are presented in Table 5.5. The variation of the flexural strength at the age of 2 years is consistent with that at the 28 days; the incorporation of hemp fibers and recycled aggregates leads to lower flexural strength. However, this decrease is less significant as compared to that in the compressive strength as some HRAC mixes have a flexural strength of 94% compared to the that of the control mix at the age of 2 years. In addition, the flexural strength shows a significant increase at the age of 2 years with increases around 50% in some of the HRAC mixes (Figure 5.4).

Table 5.5 Long-term flexural strength test results

	Mix ID	28 days Modulus of Rupture		2 years Modulus of Rupture		Ratio (2 years /28 days)
		Value (MPa)	Ratio*	Value (MPa)	Ratio*	
Group 1; MSA = 10 mm	N10 (Control10)	5.1	-	6.87	-	1.35
	R10	4.8	0.94	6.78	0.99	1.41
	N10-H20-T1	4.95	0.97	5.75	0.84	1.16
	R10-H20-T1	4.35	0.85	5.43	0.79	1.25
	R10-H20-T2	4.2	0.82	6.07	0.88	1.45
	N10-H30-T1	4.8	0.94	6.71	0.98	1.40
	R10-H30-T1	4.2	0.82	6.43	0.94	1.53
Group 2; MSA = 20 mm	N20 (Control20)	5.25	-	7.71	-	1.47
	R20	4.57	0.87	7.30	0.95	1.60
	N20-H20-T1	5.1	0.97	6.05	0.78	1.19
	R20-H20-T1	4.65	0.89	5.77	0.75	1.24
	N20-H30-T1	4.95	0.94	6.71	0.87	1.35
	R20-H30-T1	4.5	0.86	6.68	0.87	1.48
	R20-H30-T2	4.5	0.86	6.19	0.80	1.38

*Ratio = Mechanical property value for the mix divided by that of the control mix N10 in Group 1 and by that of the control mix N20 in Group 2.

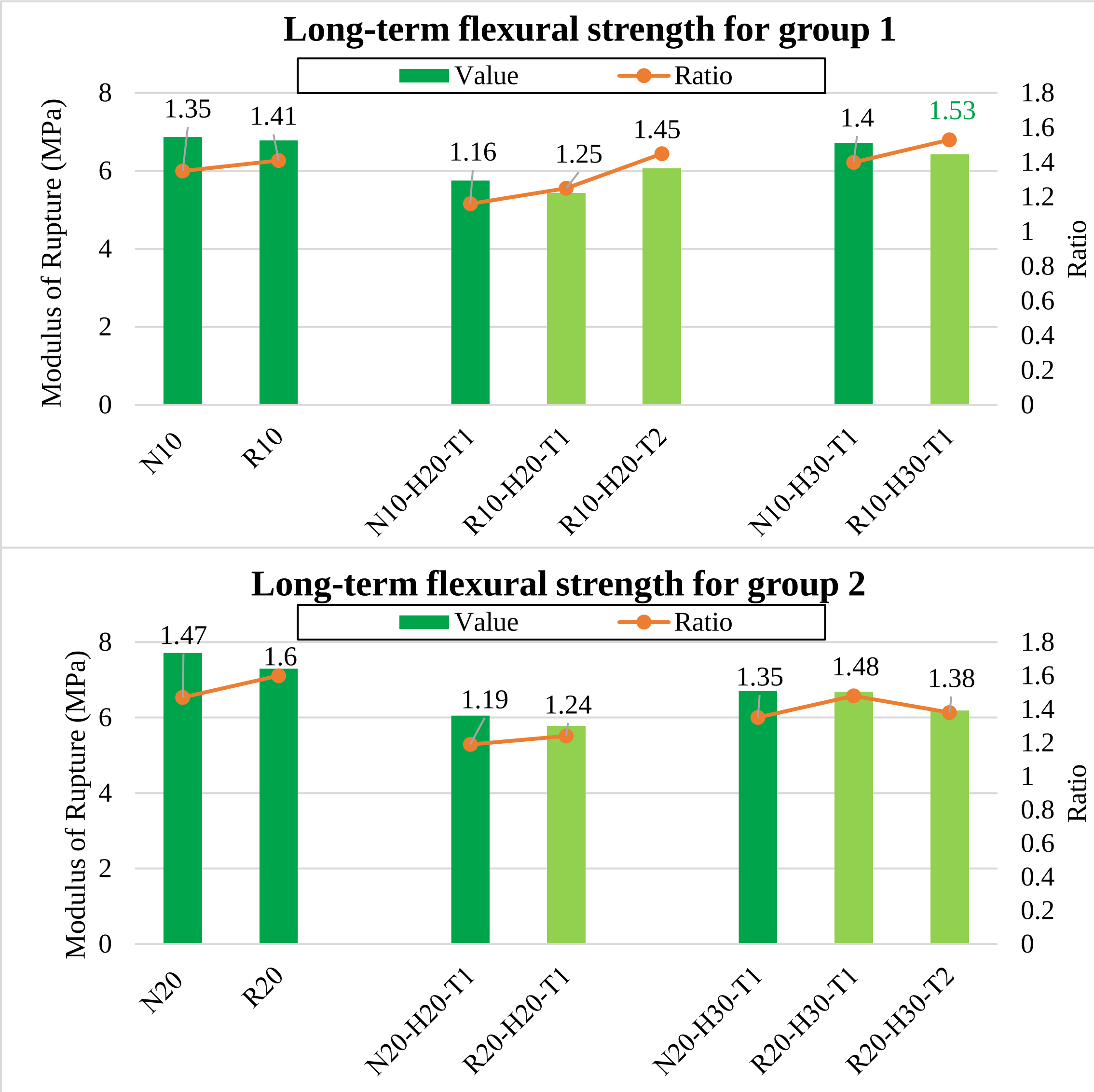

Figure 5.4 Values and ratio of compressive strength at 28 days and 2 years

3. Modulus of Elasticity

The results of the flexural strength test are presented in Table 5.6. Similar to the compressive strength, the MOE is also higher at the age of 2 years than at the age of 28 days. The increase ranges between 5 and 28% for HRAC mixes.

Table 5.6 Long-term modulus of elasticity test results

	Mix ID	28 days Modulus of Elasticity		2 years Modulus of Elasticity		Ratio (2 years /28 days)
		Value (MPa)	Ratio*	Value (MPa)	Ratio*	
Group 1; MSA = 10 mm	N10 (Control10)	34.2	1.00	30.8	1.00	1.11
	R10	34.1	0.94	28.8	1.00	1.18
	N10-H20-T1	28.6	0.72	22.2	0.84	1.29
	R10-H20-T1	27.7	0.74	22.8	0.81	1.21
	R10-H20-T2	26.8	0.74	22.9	0.78	1.17
	N10-H30-T1	28.3	0.74	22.7	0.83	1.25
	R10-H30-T1	28.8	0.73	22.5	0.84	1.28
Group 2; MSA = 20 mm	N20 (Control20)	36.3	1.00	33.2	1.00	1.09
	R20	34.5	0.95	31.4	0.95	1.10
	N20-H20-T1	30.3	0.78	26	0.83	1.17
	R20-H20-T1	28.9	0.71	23.7	0.80	1.22
	N20-H30-T1	28.6	0.82	27.2	0.79	1.05
	R20-H30-T1	25.5	0.73	24.3	0.70	1.05
	R20-H30-T2	25.7	0.71	23.7	0.71	1.08

*Ratio = Mechanical property value for the mix divided by that of the control mix N10 in Group 1 and by that of the control mix N20 in Group 2.

F. Summary and Conclusions

Durability tests that were performed on different mixes showed that HRAC mixes had increases in percentage absorption ranging between 54 and 60% relative to the control mixes, and had comparable resistance to freeze-thaw cycles as normal concrete mixes after 144 cycles. Variation of values was not significantly affected by fiber length or fiber treatment type.

Results also showed that at the age of 2 years, HRAC mixes have an improved mechanical performance as compared to the age of 28 days, The compressive strength, the flexural strength and the modulus of elasticity improved by up to 31%, 53% and 28%, respectively. The variation in the mechanical performance between HRAC mixes and control mixes was also consistent at the age of 28 days and the age of 2 years.

It was also concluded that had superior thermal properties as compared to normal concrete.

Based on these results, it can be concluded that HRAC, despite having a high absorption, is a durable concrete that has a reliable long-term mechanical performance, superior thermal properties compared to normal concrete, and can be used in cold climates as it has a freeze/thaw durability performance comparable to that of ordinary concrete mixes.

CHAPTER VI

STRUCTURAL BEHAVIOR OF HRAC REINFORCED BEAMS

A. Introduction

Results of the first phase of the research program where an optimal HRAC batch was determined, were used in the second phase presented in this chapter. It was very significant to conduct a research program to determine the influence of HRAC on structural strength and behavior, and to get a better insight in the difference in strength and behavior of structural members prepared with conventional PCC and those prepared using HRAC.

The hypothesis to be tested was that partial substitution of natural aggregates with a combination of RCA and hemp fibers would not lead to reduction in the flexural, shear, and bond splitting characteristics of the structural elements, and would have a positive impact on the ductile behavior. The testing of large-scale specimens in this phase serves as a validation study of the proposed HRAC mix.

The four mixes used in this phase were: the control mix (N20), the mix with 50% substitution of NA by RCA without hemp fibers (R20), the mix incorporating 20 mm hemp fibers treated in a sodium hydroxide solution (N20-H20-T1), and the HRAC mix with 20 mm hemp fibers treated in a sodium hydroxide solution with 50% substitution of NA by RCA (R20-H20-T1).

B. Experimental Program

Twenty-four full-scale normal strength concrete simply supported beam specimens were tested. For each set of variables, two companion identical beams were tested to check the reliability of the test setup and results. At each load increment, the deflection at mid-span was recorded and cracks were marked. The effect of HRAC was evaluated by comparing the performance of the companion PCC and HRAC specimens. Comparison was based on the mode of failure, ultimate load, crack patterns, and general load-deflection behavior.

The beams' reinforcing details were based on the required mode of failure and were according to the ACI Building Code (ACI 318-14). Different reinforcement details were considered to take into consideration flexure, shear, and bond failure modes. The beam specimen had a length of 200 cm length, a depth of 30 cm, and a width of 20 cm. The reinforcement consisted of two 20 mm bars on the tension side and two 12 mm bars on the top compression side. The clear side and bottom concrete covers were 3 cm resulting in an effective depth d of 25 cm for all tested beams. The transverse reinforcement was 8 mm bars. Two coupons of 20 mm and 8 mm bars were tested for yield strength and the average values were 5850 kg/cm^2 and 5210 kg/cm^2, respectively.

- Set 1: Flexure Beams

The first set of beams – the Flexure beams – were designed to fail under flexure. Therefore, adequate shear reinforcement was provided in the shear spans to avoid shear failure. Eight beams were prepared, 2 identical ones for each mix. For the shear reinforcement, 10 T8 stirrups were used on each side of the beam, with a spacing of 7.5 cm. Cracks were marked at each load increment, the midspan vertical deflection was measured using an LVDT sensor, and the elongation in the bottom reinforcement was recorded by installing a strain gauge in the middle of each longitudinal 20 mm bar.

- Set 2: Shear Beams

For the second set of beams – the Shear beams – the shear reinforcement was reduced to less than the required minimum by the ACI Building Code, to ensure a shear mode of failure. Similar to the first set, 8 beams were prepared, 2 identical ones for each mix. Only three 8 mm stirrups were used on each side of the beam, with a spacing of 60 cm. Cracks were marked, the midspan deflection was measured, and the steel elongation was recorded with strain gauges installed in the middle of each 20 mm bar.

- Set 3: Bond Beams

For the third set of beams – the Bond beams – the reinforcing bars on the tension zone were spliced at the beam center, with a splice length shorter than the recommended length by the ACI 318 Code, to insure a bond splitting failure. The bottom steel consisted of 2 pairs of 20 mm bars, and each pair of bars was spliced at midspan with a splice length of 30.5 cm (12 in.). The splice length was shorter than the required splice length according to the ACI 318 Code, which was calculated to be 67.2 cm. The top longitudinal reinforcement and the shear reinforcement were similar to the first set of beams. Cracks were marked, the midspan deflection was measured, and the steel elongation was recorded with strain gauges installed on the end of the splices of each 20 bar.

Figure 6.1 shows the typical reinforcement for each set of beams, Figure 6.2 shows a schematic presentation of the reinforcement details for each set of beams, and the 24 beams tested in this phase are identified in Table 6.1.

Figure 6.1 Typical reinforcement for each set of beams

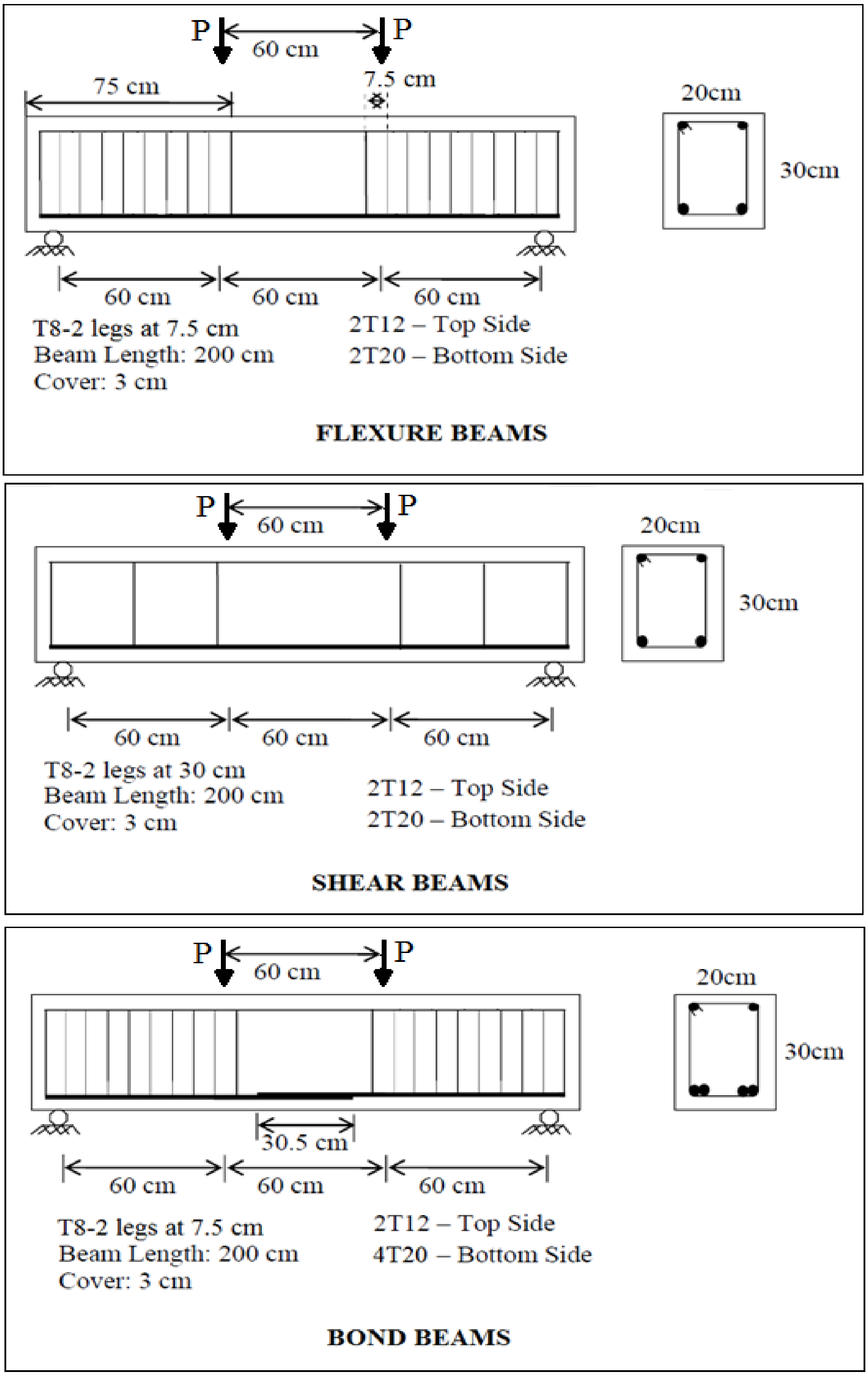

Figure 6.2 Reinforcement details for each set of beams

Table 6.1 Identification of the tested beams

Set	Beam Name	Concrete Mix	Mode of Failure
Set 1: Flexure Beams	F1-N20	N20	Flexure
	F2-N20	N20	Flexure
	F1-R20	R20	Flexure
	F2-R20	R20	Flexure
	F1-N20-H20	N20-H20-T1	Flexure
	F2-N20-H20	N20-H20-T1	Flexure
	F1-R20-H20	R20-H20-T1	Flexure
	F2-R20-H20	R20-H20-T1	Flexure
Set 2: Shear Beams	S1-N20	N20	Shear
	S2-N20	N20	Shear
	S1-R20	R20	Shear
	S2-R20	R20	Shear
	S1-N20-H20	N20-H20-T1	Shear
	S2-N20-H20	N20-H20-T1	Shear
	S1-R20-H20	R20-H20-T1	Shear
	S2-R20-H20	R20-H20-T1	Shear
Set 3: Bond Beams	B1-N20	N20	Bond Splitting
	B2-N20	N20	Bond Splitting
	B1-R20	R20	Bond Splitting
	B2-R20	R20	Bond Splitting
	B1-N20-H20	N20-H20-T1	Bond Splitting
	B2-N20-H20	N20-H20-T1	Bond Splitting
	B1-R20-H20	R20-H20-T1	Bond Splitting
	B2-R20-H20	R20-H20-T1	Bond Splitting

The 8 beams corresponding to each mix were cast using the same concrete batch, and 150x300 mm (6x12 in.) standard cylinders were also cast to determine the concrete's compressive strength (f'_c). After casting, the beams were covered with wet burlaps for three days to preserve moisture. After three days, the forms were removed, and the beams were continuously sprayed with water until they reached the age of 28 days.

The testing setup is illustrated in Figure 6.3. The beams were tested using the MTS (Material Testing System) closed loop servo-hydraulic machine with a dynamic actuator having a capacity of 1,000 kN. The distance between the supports was set at 180 cm and two loads P were applied simultaneously, at a distance of 60 cm from each support creating a constant moment and zero shear region in the central part of the beam. An actual view of the test setup is shown in Figure 6.4.

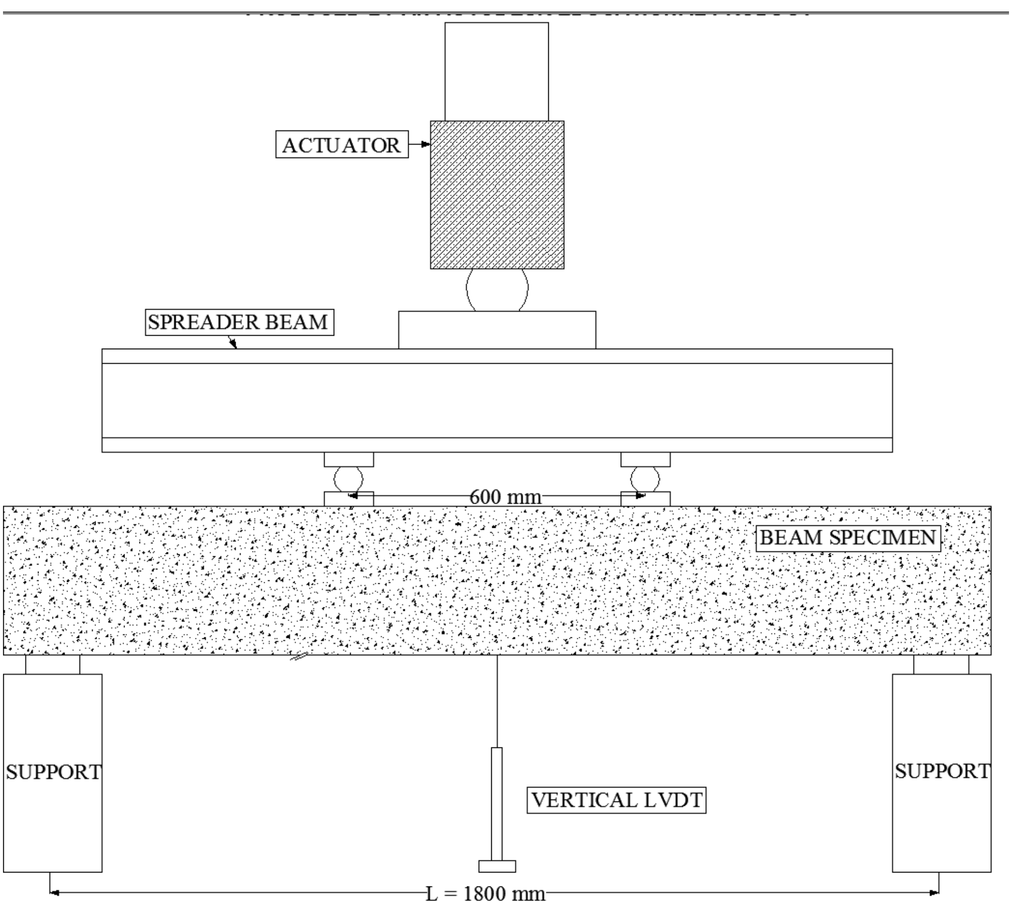

Figure 6.3 Test setup for the beam specimens

Figure 6.4 Actual view of the test setup for the beam specimens

C. Test Results

For each set of beams with a given mode of failure, test results will be displayed in a separate Table. The data includes the values of f'_c at the day of testing, Pmax, steel stress at ultimate load fs, load ratio or ratio of ultimate load of beam relative to the control beam N20, deflection δ_{max} at P_{max}, P_{ACI}, P_{max}/P_{ACI}, ductility index, and fracture energy.

The ductility index is defined as the ratio of the midspan deflection when the post-peak load reached 95% of P_{max} ($\delta_{0.95}$) to the midspan deflection at peak load (δ_{max}) (Ductility index = $\delta_{0.95}/\delta_{max}$). The fracture energy is defined as the area under the load-deflection curve for a midspan deflection ranging between 0 and 30 mm in the Flexure beams, between 0 and 15 mm in the Shear beams, and between 0 and 10 mm for Bond beams. This method was used to quantify the fracture energy because the objective was to compare between the fracture energy of the different mixes and the different mixes showed the same load-deflection curve pattern.

Figure 6.5 is a schematic load-deflection diagram used to define $\delta_{0.95}$, δ_{max}, and fracture energy.

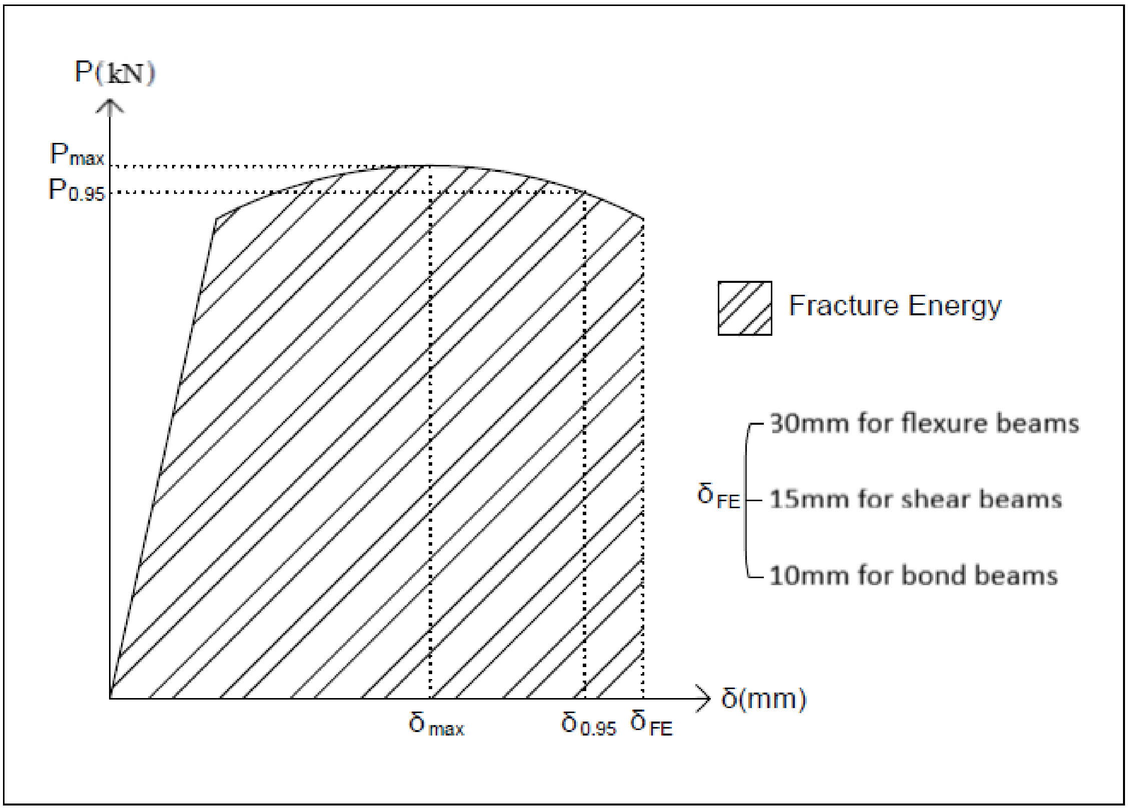

Figure 6.5 Schematic load deflection diagram

1. Flexure Beams

For this set of beams, data reporting was stopped when the midspan deflection reached a value of 30 mm. Test results are listed in Table 6.2. As shown in Figure 6.6, the load-deflection curves of all the tested Flexure beams were very similar: starting with a quasi-linear increase, followed by a slightly decreasing plateau after the steel reinforcement in the tension zone has yielded. Load-deflection curves of the replicate beams are presented in the Appendix.

Table 6.2 Test results of the flexure beams

Flexure Beam	f'c (MPa)	P_{max} (kN)	f_s (kg/cm^2)	Load ratio	δ_{max} (mm)	Ductility Index	Fracture Energy (kN.mm)
N20	42.67	107.68	6795.4	-	11.60	1.88	2886
R20	37.82	106.16	6862.6	0.99	13.88	1.29	2882
N20-H20	30.36	109.38	6641.6	1.02	9.48	2.89	2973
R20-H20	27.15	110.70	6829.25	1.03	9.62	2.27	2989

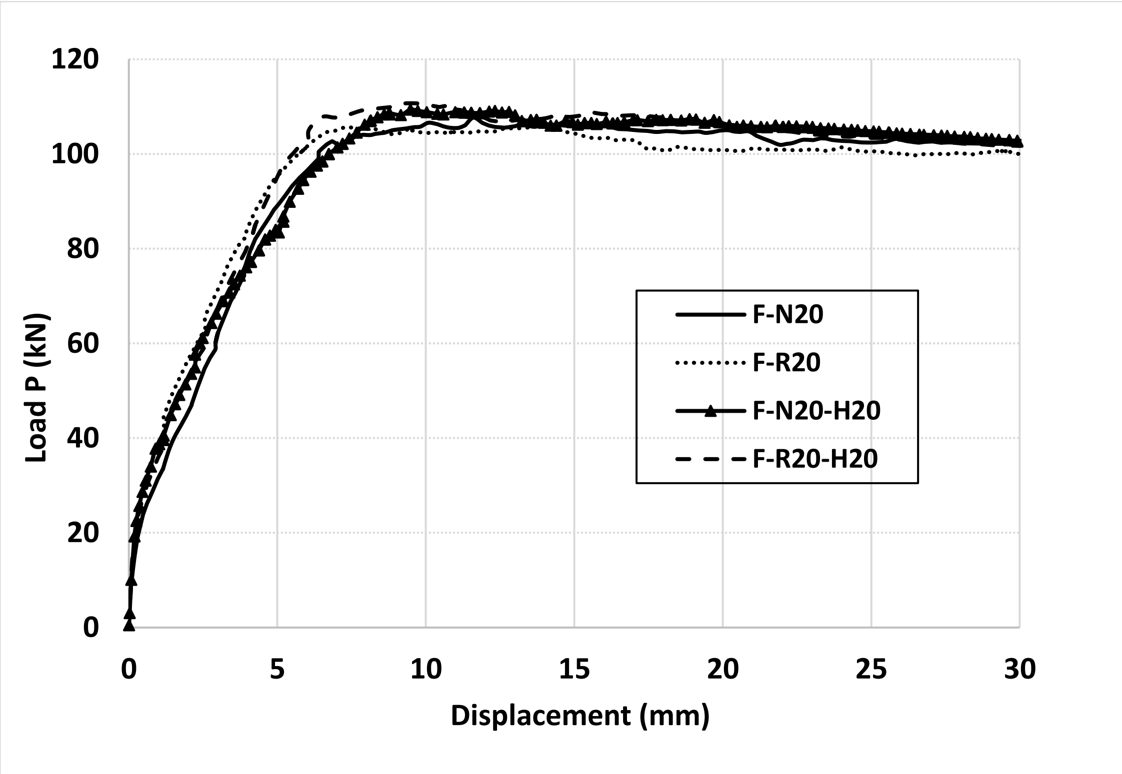

Figure 6.6 Typical load-deflection curves for the first set of beams (flexure beams)

The maximum load (P_{max}) for all the beams was in the same range (111.5 ± 2.5 kN), and beams incorporating hemp fibers resulted in a slightly higher maximum load (P_{max}).

These results indicate the positive role that the fibers play in mixes containing hemp fibers, increasing the flexural strength even though the fibers reduce the concrete compressive strength. Jabbour et al. (2020) stated that the additional confinement around the tension steel due to the crack-bridging capacity of the fibers present in the cement matrix plays an important role in enhancing the flexural strength of the beams. Values of the ductility index show a decrease of nearly 30% when NCA were partially replaced by RAC, but an increase by more than 50% when hemp fibers were used. The HRAC beam (R20-H20) had a ductility index 20.8% higher than the control mix. As for the fracture energy, values shown in Table 6.2 indicate almost identical values for the control beam N20 and the beam R20 with 50% replacement of NCA with RCA. Also, beams containing hemp fibers, N20-H20 and R20-H20, had comparable fracture energy values which were around 3.3% higher than beams with no fibers; the presence of RCA did not have an effect on fracture energy. The slight increase of fracture energy for the hemp fibers beams come in the same line as the increase of the ductility index confirming the role that these fibers play in providing a post-peak ductile behavior in the tested beams.

Schematic views of the crack patterns of the beam specimens are shown in Figure 6.7. On every crack line, the numbers represent the load (in kN) at which the crack has propagated to that level. Dashed lines represent post-peak cracks. As shown in Figure 6.7, all beams have similar crack patterns. The first cracks appeared on the tension side in the constant moment region in the middle part of the beam span. As the load increased, these cracks extended upwards into the beam's section and other cracks appeared along the beam's span. Beams containing fibers developed a larger number of cracks, with cracks generally having smaller width than beams with no fibers. This is due to the crack-bridging capacity of these fibers which stops the cracks from opening further and transfers the stresses to other locations, thus creating smaller crack widths. This phenomenon is behind the higher ductility of beams containing hemp fibers and is quantitatively reflected by the higher values of ductility index and fracture energy for the N20-H20 and R20-H20 beams when compared to the N20 and R20 beams.

The steel strain developed in the tension steel was measured by installing strain gauges at the center of each of the two 20 mm longitudinal bars. The steel stress (f_s) was then determined by multiplying the strain by the modulus of elasticity of steel and average values were reported in Table 6.2. The results confirm that the tension steel has yielded in all the beams, since all the reported values were higher than the yield strength of these bars (5850 kg/cm^2).

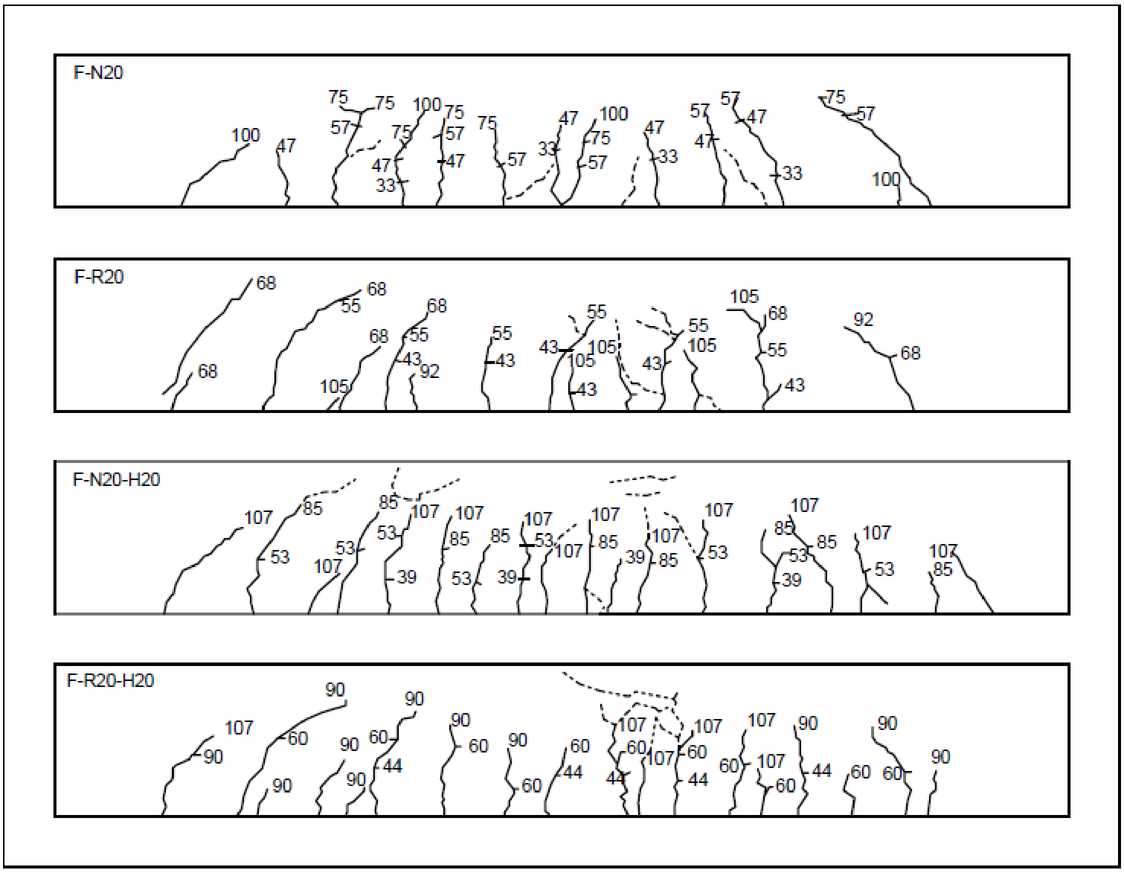

Figure 6.7 Schematic crack patterns for the flexure beams

2. *Shear Beams*

For this set of beams, data reporting was stopped when the midspan deflection reached a value of 15 mm. Test results are listed in Table 6.3. Typical load-deflection curves are shown in Figure 6.8. After reaching the maximum load (P_{max}), all curves show a gradual drop with a decreasing slope, until the curves become almost horizontal as the midspan deflection approaches the value of 15 mm. It can also be noticed that the drop is less significant for the beams containing fibers (N20-H20 and R20-H20). Load-deflection curves of the replicate beams are presented in the Appendix.

Table 6.3 Test results of the shear beams

Shear Beam	f'c MPa	P_{max} kN	f_s kg/cm^2	Load ratio	δ_{max} mm	P_{ACI} kN	P_{max}/ P_{ACI}	Ductility Index	Fracture Energy kN.mm
N20	42.67	79.98	3595.1	-	5.70	54.74	1.46	1.16	798
R20	37.82	74.42	3096.5	0.93	5.15	51.54	1.44	1.11	844
N20-H20	30.36	83.13	3579.4	1.04	6.27	46.17	1.80	1.21	925
R20-H20	27.15	81.58	3460.8	1.02	7.60	43.66	1.87	1.20	941

The maximum load (P_{max}) decreased by 7% when RAC were used. As in the case of the flexure beams, the incorporation of hemp fibers led to slight increase in the maximum shear capacity relative to the control Shear beam N20. The P_{max} value for the HRAC mix (81.58 kN) was 2% higher than that of the control mix (79.98 kN).

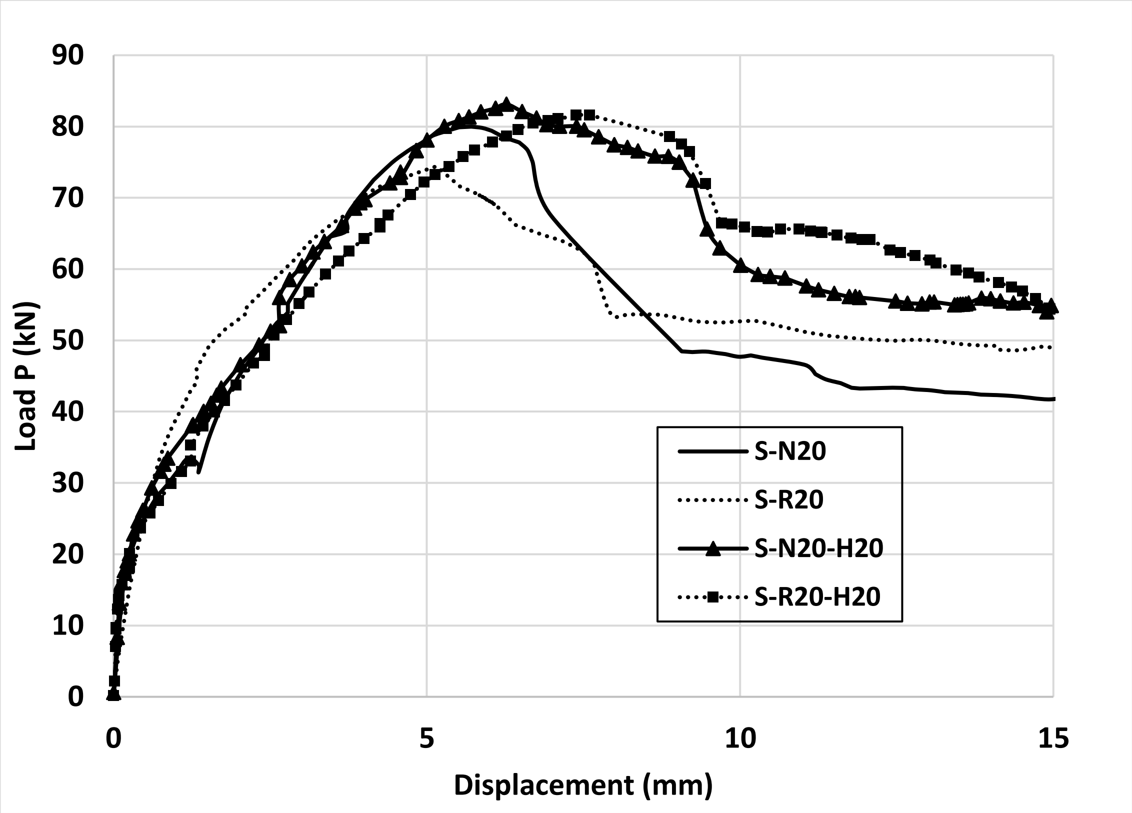

Figure 6.8 Typical load-deflection curves for the second set of beams (shear beams)

The experimental values of P_{max} were compared to the theoretical shear strength values calculated according to the ACI Building Code (ACI 318-14) using Equation 6.1:

$V_{ACI} = V_{concrete} = 0.53 * \sqrt{f_c'} * b * d$, and $V_{ACI} = P_{ACI}$ Eq. 6.1

Where: b is the beam width (cm) and d is the effective depth (cm).

The ratio of the experimental to theoretical ratio value (P_{max}/P_{ACI}) increased from an average of 1.45 for beams N20 and R20, not containing fibers, to 1.82 and 1.87 for N20-H20 and R20-H20, respectively. This increase is explained by the bridging effect of the fibers, which lead to a higher peak value despite the fact that mixes incorporating fibers had a low compressive strength.

The ductility index ($\delta_{0.95}/ \delta_{max}$) decreased from 1.16 for the control beam N20 to 1.11 for the RAC beam with no fibers R20. The drop is not as significant as the drop in the case of the Flexure beams indicating that the presence of RAC in the mix didn't significantly affect the ductility index when shear failure occurs. However, the index increased to 1.20 for the HRAC mix.

Similar to the Flexure beams, the presence of hemp fibers led to higher fracture energy, and the partial replacement of NCA by RAC did not affect the results. The HRAC mix R20-H20 had a fracture energy 17.9% higher than the control mix N20. The higher values of ductility index and fracture energy for the HRAC mix when compared with the control mix show that the presence of fibers led to a more ductile post-peak behavior even in the case of shear failure.

Schematic views of the crack patterns of the beam specimens are shown in Figure 6.9. On every crack line, the numbers represent the load in kN) at which the crack has propagated to that level. Dashed lines represent post-peak cracks. As shown in Figure 6.9, all beams have similar crack patterns. Similar to the Flexure beams, the first cracks appear in the flexure zone. But for this set of beams, as the load increases, shear cracks start to appear close to the support and propagate diagonally, eventually leading to the failure of the beams. Beams containing fibers also developed a larger number of fine width-cracks along the span of the beam than beams with no fibers, and this fact is again reflected by the higher values of ductility index and fracture energy for the N20-H20 and R20-H20 mixes when compared to the N20 and R20 mixes.

The steel strain developed in the tension steel was measured by installing strain gauges at mid-length of each of the two 20 mm tensile bars. The steel stress (f_s) was then determined by multiplying the strain by the modulus of elasticity of steel and average values were reported in Table 6.3. All the steel stresses are way below the yield strength of the bar (5,850 kg/cm^2), which is expected since these beams are under-reinforced in shear and shear failure occurs before that the bars in the tension zone reach the yield limit.

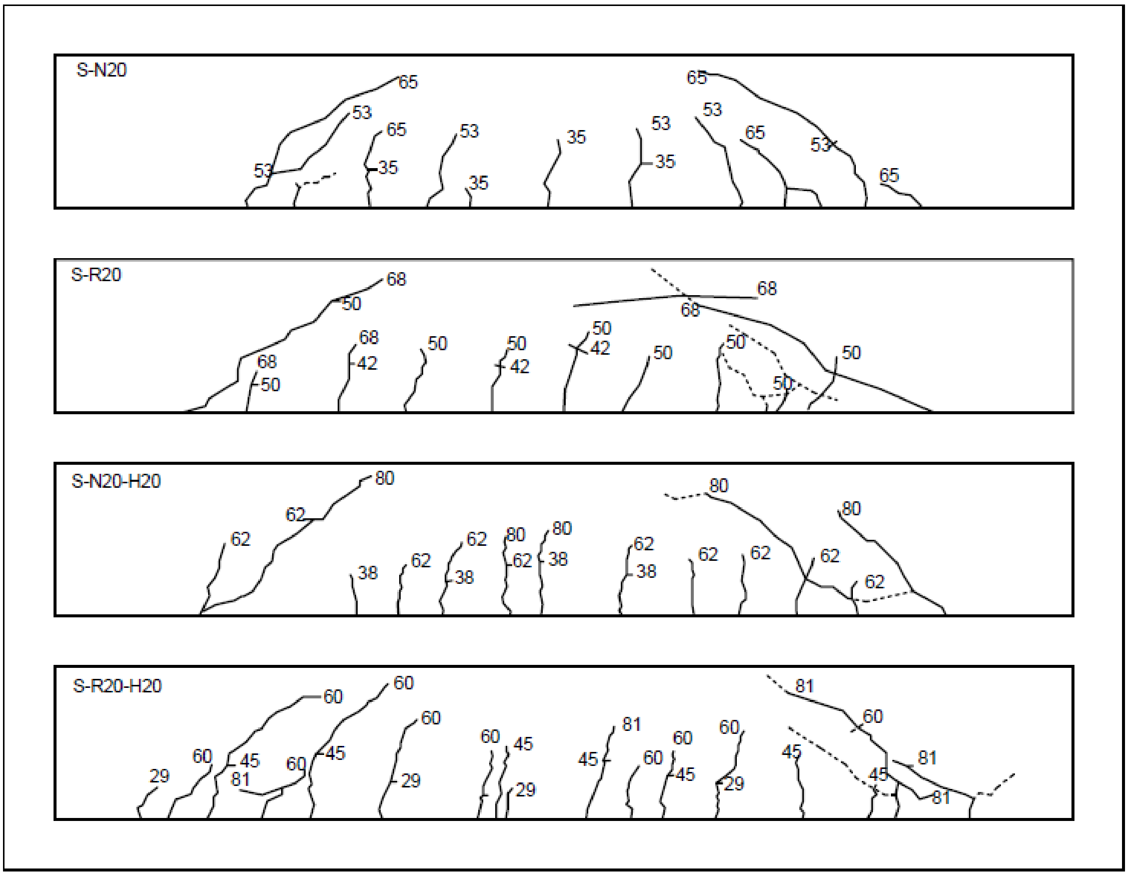

Figure 6.9 Schematic crack patterns for the shear beams

3. Bond Beams

For this set of beams, data reporting was stopped when the midspan deflection reached a value of 10 mm. Test results are shown in Table 6.4. Typical load-deflection curves are shown in Figure 6.10. After reaching the maximum load (P_{max}), all curves show a drop to around half the value of P_{max}, followed by a plateau until the midspan deflection reaches a value of 10 mm. Load-deflection curves of the replicate beams are presented in the Appendix.

Table 6.4 Test results of the bond beams

Bond Beam	**f'c (MPa)**	**P_{max} (kN)**	**u_t (MPa)**	**Bond ratio**	**Ductility Index**	**Fracture Energy (kN.mm)**
N20	42.67	63.81	4.52	-	1.06	369
R20	37.82	63.46	4.51	1.0	1.04	416
N20-H20	30.36	60.72	4.34	0.96	1.02	378
R20-H20	27.15	62.46	4.48	0.99	1.02	422

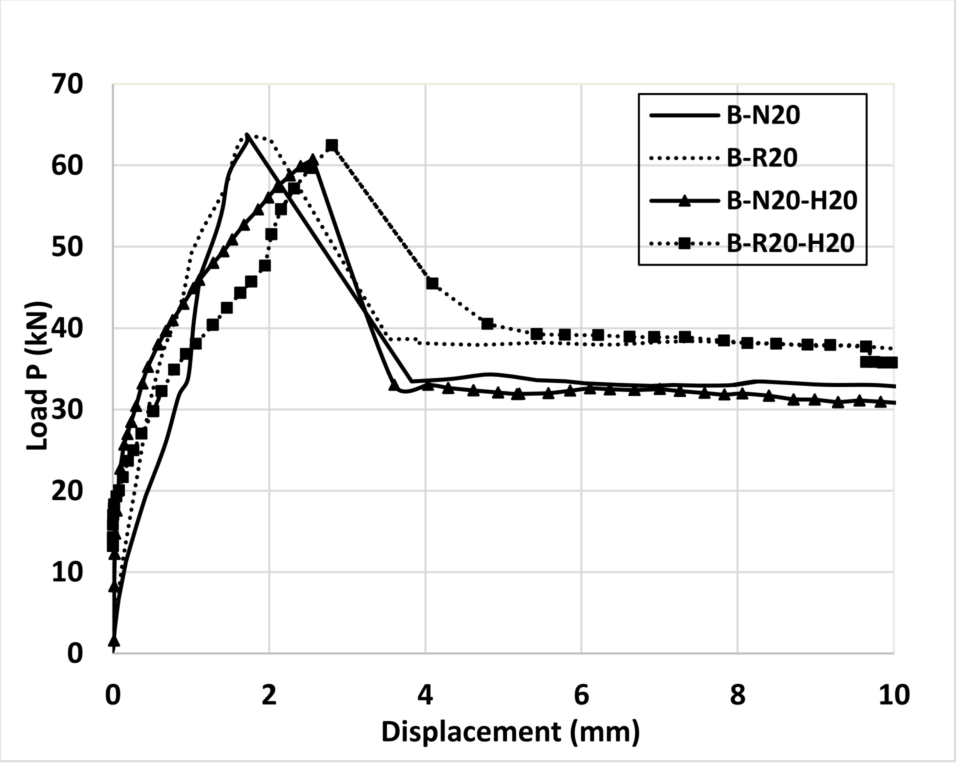

Figure 6.10 Typical load-deflection curves for the third set of beams (bond beams)

The maximum load (P_{max}) for all the beams was in the same range (62 ± 2 kN), which shows that the incorporation of RAC and hemp fibers did not negatively affect the bond strength between the steel and the cement matrix despite the fact that the mixes containing hemp fibers and RAC have a lower compressive strength. The difference in P_{max} between the control mix and the HRAC mix is only around 2%.

The average bond strength u_t was calculated by dividing the total force developed in the bar by the surface area of the bar over the splice length:

$$u_t = \frac{A_b * f_s}{\pi * d_b * l_s} \qquad \text{Eq. 6.2}$$

Where: A_b is the cross-sectional area of the bar, f_s is the ultimate steel stress, d_b is the diameter of the bar and l_s is the splice length. f_s was calculated based on the cracked section analysis of each beam when subjected to P_{max}. Average bond strength values for all the beams were in the same range (4.44 ± 0.1 MPa), which confirms that RCA does not have an adverse effect on the splitting bond strength of the beams, a conclusion previously made by Hamad et al. [xx], and that the incorporation of hemp fibers also does not negatively affect the bond strength, a conclusion reached beforehand by Awwad et al.

Schematic views of the crack patterns of the beam specimens are shown in Figure 6.11. On every crack line, the numbers represent the load (in KN) at which the crack has propagated to that level. Dashed lines represent post-peak cracks. For this set of beams, the view of the tension face of the beam after bond splitting was also shown. Similar to the previous sets of beams, the first cracks appear in the flexure zone. When the load reaches the value of P_{max}, several cracks appear in the midspan of the beam, where the two reinforcement bars are spliced, which indicates the failure of the bond.

The low values of the ductility index and the fracture energy are expected, and they reflect the brittle nature of the failure for the Bond beams.

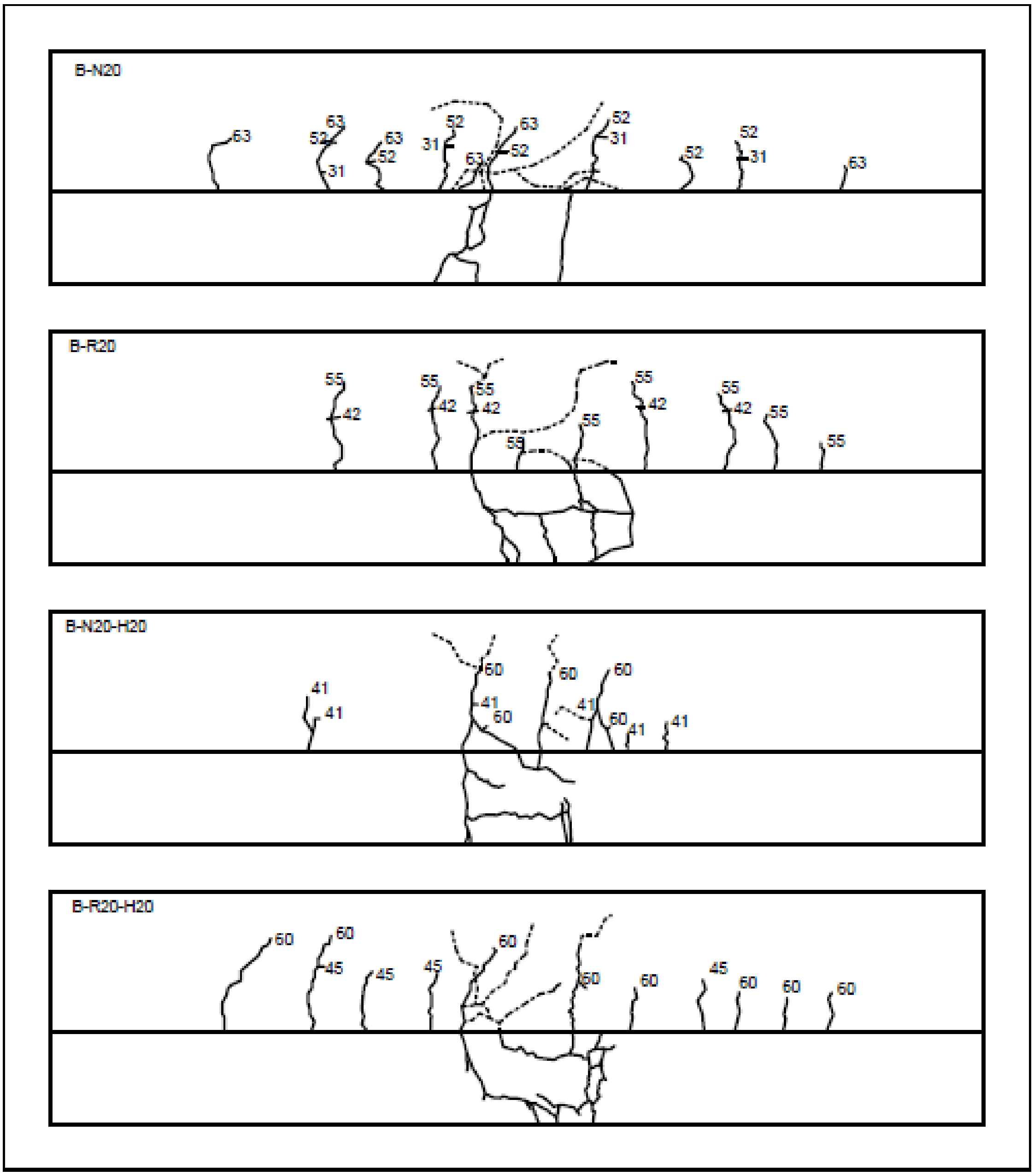

Figure 6.11 Schematic crack patterns on the side and bottom faces of the third set of beams (bond beams)

D. Summary and Conclusions

In this phase of the research program, the structural behavior of HRAC was investigated. The optimal HRAC mix R20-H20-T1 was used based on the previous phases of the research and its behavior was compared to three other mixes: N20, R20 and N20-H20-T1, to fully comprehend the effect of RAC and hemp fibers on the structural behavior of concrete. Twenty-four beams were tested under three modes of failure: flexure (Set 1 – 8 beams), shear (Set 2 – 8 beams) and bond splitting (Set 3 – 8 beams).

In all three modes of failure, the HRAC beam N20-H20-T1 had a peak load comparable or higher than that of the control beam N20, despite the HRAC mix having a significantly lower compressive strength than the control mix. Additionally, the HRAC beams showed a ductile behavior, especially for the flexure and shear modes of failure, which was reflected by higher ductility ratios and fracture energy values when compared to the control mix. This is mainly due to crack-bridging capacity of the hemp fibers, and this was manifested by the appearance of a higher number of cracks in tested beams incorporating hemp fibers.

The main conclusion from this phase is that it was possible to reduce the amount of NA used by more than 70% without affecting the maximum load that can be sustained by the structural beams under all three studied modes of failure, with the advantage of having more ductile behavior; hence having a better overall structural performance while saving on natural resources and using recycled material.

CHAPTER VII

LIFE-CYCLE ASSESSMENT OF HRAC REINFORCED BEAMS

A. Introduction

Since the main goal of this study is to produce a sustainable concrete, it’s essential to evaluate the environmental impact of HRAC and compare to that of ordinary concrete to confirm the benefits of using such concrete from the environmental aspect. This will serve as a validation for the experimental work done in the previous phases of this study and it will be used to quantitively prove that - in addition to minimizing the depletion of natural resources, finding a solution for CDW disposal, and incorporating renewable agricultural fibers in concrete - the use of HRAC is also beneficial environmentally.

The life-cycle assessment was done following the guidelines set by the International Organization for Standards (ISO 14040 and ISO 14044) which includes four main phases: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation of Results.

B. Goal and Scope

This phase consists of choosing the product, defining a functional unit, identifying the system boundaries, the impact category, and the type of analysis.

The goal is to study the effect of the partial replacement of natural aggregates (NA) by recycled concrete aggregates (RCA) and industrial hemp fibers on the environmental impact of the concrete mix, taking into consideration the structural performance of reinforced concrete beams in flexure, shear, and bond.

Since the main difference between the mixes is the constitution of the mix, the two main impacts taken into consideration were the impact of the raw materials and the carbon uptake of the concrete during its life. Thus, the system boundary includes cement manufacturing, aggregate production, aggregate recycling, admixture manufacturing, hemp fibers cultivation and processing, and the use phase of the concrete beam. Moreover, despite that in our research the hemp fibers were imported from the USA, the importation impact wasn't taken into consideration since the ultimate objective for HRAC is for hemp fibers to be planted locally.

The life-cycle stages of concrete are presented in Figure 7.1. Only stages represented by solid line boxes are included in this study, while stages represented by dashed line boxes are excluded since they don't include a significant difference between conventional concrete and HRAC.

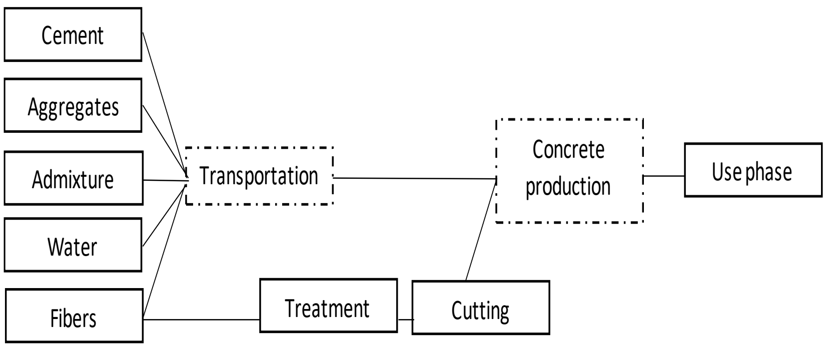

Figure 7.1 Concrete life-cycle stages

Defining a functional unit (FU) is essential to ensure the equivalence of the products being compared. To take into account the structural characteristics of a reinforced concrete beam (peak load it can support (P_{max}) and its ductility index (D.I.)), the FU considered is a 2 meters long reinforced concrete beam with a 200x300 mm section, used for structural testing.

The impact categories considered are:

- Global Warming Potential (GWP) (unit: kg CO_2 eq.): Gas emissions affect the absorption of heat radiations, which leads to an increase in Earth's temperature. This is known as the greenhouse effect. This characterization method considers the global warming potential for a 100-year time horizon for relevant emissions to air.
- Acidification Potential (AP) (unit: kg SO_2 eq.): Effects of acidifying pollutants, namely SOx and NOx, target numerous components such as: soil, surface and groundwater, and constructed structures. This affects human health, the surrounding environment, and natural resources.
- Abiotic Depletion Potential (ADP) (unit: kg Antimony (Sb) eq.): refers to the depletion of nonliving (abiotic) resources such as fossil fuels, minerals, clay, and peat. Abiotic depletion is measured in kilograms of Antimony (Sb) equivalents.
- Ozone Layer Depletion Potential (ODP) (unit: kg Trichlorofluoromethane (CFC-11) eq.): refers to the amount of degradation to the ozone layer.
- Photochemical Ozone Creation Potential (POCP) (unit: kg ethylene (C2H4) eq.): reactive compounds, namely O3, are formed when air pollutants, namely VOCs, are exposed to sunlight, in the presence of oxides, namely NOx. This is also known as the summer smog and affects human health, the surrounding environment, and natural resources. This characterization method considers relevant pollutants emitted to air.

Different methods can be used for each impact category, and each method leads to different results for the same data. The most suitable method for each category is called the baseline method. In this study, the CML-IA baseline method was used for all categories.

The sources of the data are summarized in Table 7.1.

Table 7.1 Data sources

Data	Source
Cement production	ecoinvent 3.7.1 database
Aggregate production	ecoinvent 3.7.1 database
Aggregate recycling	ecoinvent 3.7.1 database
Hemp fibers cultivation	Ministère de l'agriculture et de la pêche française (2006)
Fibers treatment	Based on the process followed in the laboratory + ecoinvent 3.7.1 database
Fibers cutting	Based on the process followed in the laboratory + ecoinvent 3.7.1 database
Water	ecoinvent 3.7.1 database
Superplasticizer	ecoinvent 3.7.1 database
Concrete CO2 uptake	Yang et al. (2014) + Pade et al. (2007) + Lagerblad (2005)

C. Inventory Analysis (LCI)

This phase consists of collecting the data required for the study according to the goal and scope.

For all data collected from the ecoinvent 3.7.1 database, openLCA 1.10.2 software was used to evaluate the data, and the location was set as 'Rest of the World', which represents the average of the data collected from countries all over the world.

For cement production, data was collected from the ecoinvent 3.7.1 database. The process in the database is called: “cement production, Portland”. The impact analysis for the production of 1kg of Portland cement is presented in Table 7.5.

For all types of aggregates used in the study, the data was also collected from the ecoinvent 3.7.1 database. The impact analysis of the process of mining gravel and crushing it to the required size and mining sand are presented in Table 7.5. The processes in the ecoinvent database are called, respectively, “gravel production, crushed”, and “gravel and sand quarry operation, sand”.

For RCA, the impact of the recycling process which includes dismantling, handling and crushing, is presented in Table 7.5. The process is named “treatment of waste concrete, not reinforced, recycling”.

A report made by the ministry of agriculture in France (2006), studied the impact of the whole process of hemp cultivation, including hemp fibers extraction. Results are presented in Table 7.5. For example, the process has a GWP of -1.7 kg CO_2 eq., which means the uptake of CO_2 by the hemp plant during this whole process is larger than the amount of CO_2 produced by 1.7 kg of CO_2 eq.

The process for sodium hydroxide production in the ecoinvent database is called “sodium hydroxide, without water, in 50% solution state”. The hemp fibers used in the concrete mixes were chemically treated in a 6% sodium hydroxide solution, and each kilogram of fibers was treated in a 5 liters solution. Therefore, 0.3 kg of sodium hydroxide was used to treat 1 kg of fibers, and consequently, the results of treating 1 kg of fibers are presented in Table 7.5.

Two different methods were used to cut the hemp fibers: cutting them manually using a blade or cutting them using a fiber cutting machine. For the purposes of this study, the second method was adapted. The used machine has power consumption of 250 Watts, and approximately 45 minutes were needed on average to cut 1 kg of fibers using the machine. The impact of 1 kWh of electricity produced was reported in the ecoinvent 3.7.1 database, and the impact of cutting 1 kg of fibers was calculated and presented in Table 7.5. The process for electricity production is called “electricity production, natural gas, conventional power plant”.

Moreover, according to the ecoinvent 3.7.1 database, the impact of tap water and superplasticizer, which were also used in the concrete mix, are presented in Table 7.5. The processes are called, respectively, “tap water production, conventional treatment” and “plasticizer production, for concrete”.

During its lifetime, concrete exposed to air absorbs CO_2 due to a process called carbonation, which is an intrinsic property for Portland cement-based concrete. Carbonation is usually considered a durability problem for concrete because when it happens, the pH of the concrete decrease which allows the electrochemical process that causes corrosion of steel to occur. On the other hand, this process can be beneficial environmentally since it absorbs CO_2 from air.

According to Pade et al. (2007), the depth of carbonation as a function of time can be described by Eq. (7.1)

$$d = k * t^{0.5} \qquad \text{Eq. (7.1)}$$

where d is the depth of carbonation, k is the rate constant, and t is time. In our case, the lifetime of concrete was assumed to be 50 years.

Lagerblad (2005) reported that the rate constant can be estimated according to the concrete’s compressive strength and exposure condition. In this study, half of the beam's surface was assumed to be indoors, and the other half was assumed as exposed. Based on the preceding and on the compressive strength of the concrete mixes, the rate constants were estimated and presented in Table 7.2.

Also according to Pade et al. (2007), the amount of CO2 absorbed per volume of carbonated concrete can be calculated from Eq. (7.2).

$$CO_2\, uptake\ (kg\ CO_2\ /m^3\ concrete) = 0.4875 * C * \frac{M_{CO_2}}{M_{CaO}} \quad (7.2)$$

where C is the mass of cement per meter cube of concrete, and M_{CO2} and M_{CaO} are the molar masses of CO_2 and CaO.

The results of CO_2 uptake for each concrete beam are presented in Table 7.2.

The quantities of raw materials needed to produce a beam for each studied mix is presented in Table 7.3, the structural characteristics of each mix are summarized in Table 7.4, and the inventory is presented in Table 7.5.

Table 7.2 CO_2 uptake per beam

Mix	Exposure condition	Rate constant k (mm/(year)$^{0.5}$)	Carbonation depth (mm)	Concrete Surface (m^2)	Carbonated concrete (m^3)	CO_2 uptake/m^3 carbonated concrete (kg CO_2/m^3)	CO_2 uptake (kg)	Total CO_2 uptake per beam (kg)
N20	Indoors	1	7.071	1.06	0.007	153.214	1.148	5.168
	Exposed	3.5	24.749	1.06	0.026	153.214	4.019	
R20	Indoors	1	7.071	1.06	0.007	153.214	1.148	5.168
	Exposed	3.5	24.749	1.06	0.026	153.214	4.019	
N20-H20	Indoors	1.5	10.607	1.06	0.011	166.536	1.872	9.362
	Exposed	6	42.426	1.06	0.045	166.536	7.489	
R20-H20	Indoors	1.5	10.607	1.06	0.011	166.536	1.872	9.362
	Exposed	6	42.426	1.06	0.045	166.536	7.489	

Table 7.3 Quantities of raw material per kg for each mix

Mix ID	Cement	Water	NCA	RCA	Sand	Fibers
N20 (Control20)	48.00	25.92	108.60	0.00	91.56	0.00
R20	48.00	25.92	54.30	54.30	91.56	0.00
N20-H20-T1	52.17	28.17	75.65	0.00	99.52	1.37
R20-H20-T1	52.17	28.17	37.83	37.83	99.52	1.37

Table 7.4 Structural properties of each mix

Mix ID	Flexure beams		Shear beams		Bond beams	
	P_{max} (kN)	D.I.	P_{max} (kN)	D.I.	P_{max} (kN)	D.I.
N20 (Control20)	107.68	1.88	79.98	1.16	63.81	1.06
R20	106.16	1.29	74.42	1.11	63.46	1.04
N20-H20-T1	109.38	2.89	83.13	1.21	60.72	1.02
R20-H20-T1	110.7	2.27	81.58	1.2	62.46	1.02

Table 7.5 Summary of LCI

Material/Process	GWP (kg CO2 eq.)/kg	AP (kg SO2 eq.) *E+05/kg	ADP (kg Sb eq.) *E+07/kg	ODP (kg CFC-11 eq.) *E+09/kg	POCP (kg C2H4 eq.) *E+06/kg
Cement production	0.84488	165	28.5	21.77	61.1
Coarse aggregate production	0.00819	4.06	0.75	0.547	2.66
Sand	0.00405	2.21	32.3	0.328	1.36
Coarse aggregate recycling	0.00396	2.97	0.0155	0.682	0.633
Water	0.00034	0.144	0.0211	0.0178	0.0642
Superplasticizer	1.28763	721	172	202	740
Hemp fibers cultivation	-1.7	190	1000	26	26
Fibers treatment	0.387	176.7	54.9	236.4	69
Fibers cutting	0.1122825	6	1.14375	5.8125	8.94375

D. Impact Assessment

The environmental impact is calculated from to the emissions of the products according to the data presented in the inventory analysis. Results are presented in Table 7.6 and Figure 7.2.

Table 7.6 Resulting impacts for each mix

Mix ID	**GWP (kg CO_2 eq.) *E-01**	**AP (kg SO_2 eq.) *E+01**	**ADP (kg Sb eq.) *E+03**	**ODP (kg CFC-11 eq.) *E+06**	**POCP (kg C_2H_4 eq.) *E+03**
N20 (Control20)	3.712	0.883	0.447	1.208	3.614
R20	3.689	0.877	0.443	1.215	3.504
N20-H20-T1	3.461	0.993	0.627	1.657	3.958
R20-H20-T1 (HRAC)	3.445	0.989	0.624	1.662	3.881

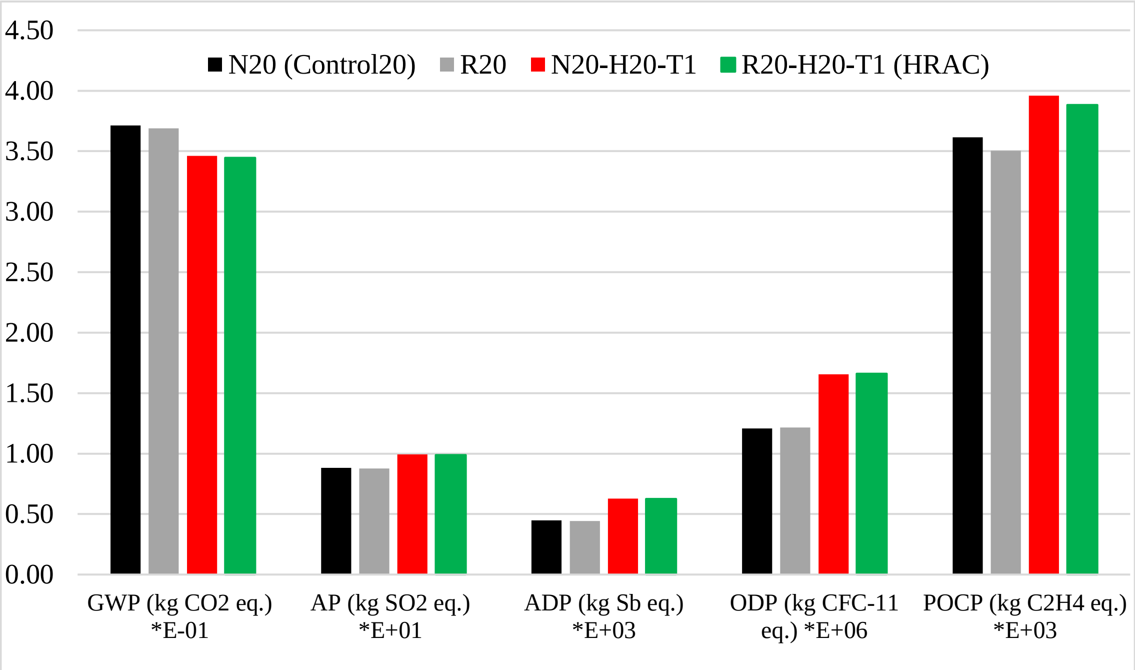

Figure 7.2 Impact factors values for each mix

To take into account the difference in the beams' ductility index between the different mixes, Figure 7.3 and Figure 7.4 show the ductility index versus GWP and the ductility index versus ODP trends for the different mixes and for the different sets of beams.

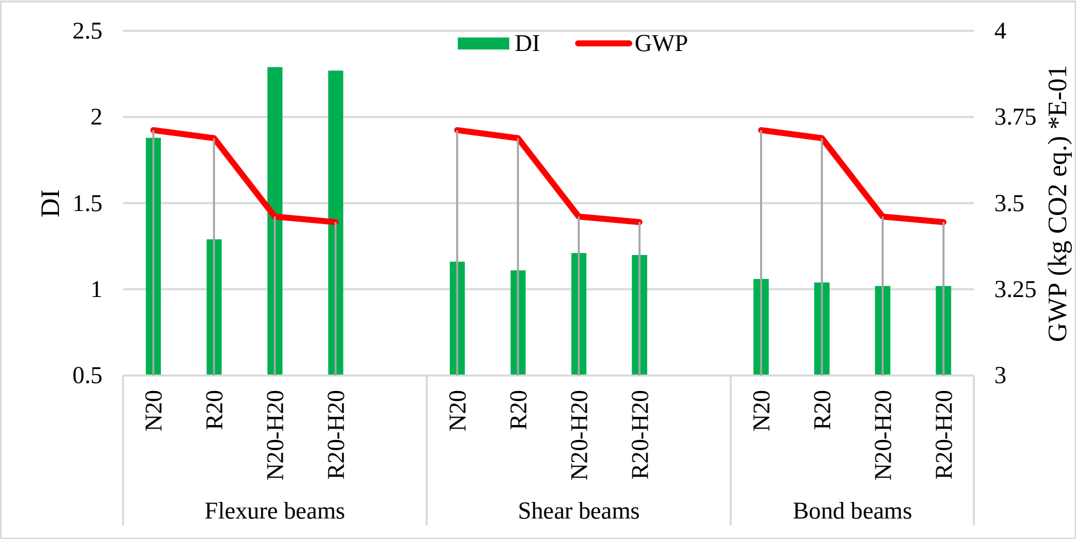

Figure 7.3 DI versus GWP trends for the different beams

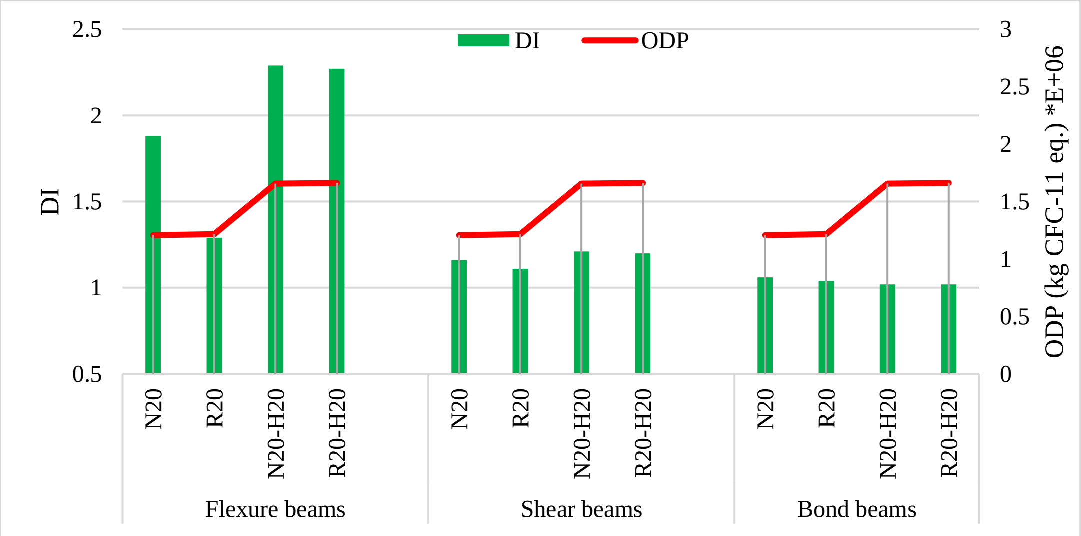

Figure 7.4 DI versus ODP trends for the different beams

E. Interpretation of Results

When RCA are incorporated in the concrete mix, the environmental impact of the mixes slightly decreases for all the impact categories, except for the ODP which slightly increases. This is due to the fact that recycling the aggregates and using them in the concrete mix has lower environmental impact that extracting, crushing and using natural aggregates.

The environmental impact of incorporating hemp fibers into the concrete mix depends on the impact category: mixes containing hemp fibers have a lower GWP than mixes without hemp fibers, while for almost all the other categories, including hemp fibers in the mix slightly increases the environmental impact. This is due to the fact that when hemp fibers are added, the aggregates volume is decreased, and to compensate for this decrease, the volume of other mix constituents is increased, including cement which has a very high environmental impact.

The positive impact of HRAC is more evident when the structural characteristics of the beams are taken into consideration, especially for the ductility index of the flexure and shear beams. As shown in Figure 7.3, the HRAC beams have a higher ductility index and lower GWP than ordinary concrete. Figure 7.4 displays the trend for the ODP, which is similar for the remaining categories. It shows that while the impact of the HRAC mix is higher, it has a higher ductility index for all beam categories. These trends are also valid if P_{max} is taken into consideration instead of the ductility index.

These results confirm that HRAC beams can have significantly better structural properties while having a lower or similar environmental impact as normal concrete.

This life-cycle assessment quantitively proves that HRAC is indeed a sustainable concrete, having better structural properties and adequate environmental impact when compared to ordinary concrete, with the additional advantages of minimizing the depletion of natural aggregates by more than 70%, solving the problem of CDW disposal, and incorporating renewable natural resources in concrete with the use of hemp fibers.

CHAPTER VIII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. Research Summary

In this research program, combines the objective is to combine the positive effects using of RCA and hemp fibers in concrete to develop HRAC or Hemp and Recycled Aggregate Concrete. HRAC would propose a potential solution for the depletion of natural resources and the disposal of construction waste material, by the partial substitution of natural aggregates with combination of RCA and industrial hemp fibers. Advantages and benefits of HRAC include:

- Saving on natural resources
- Alleviation of the demolished concrete waste disposal problem
- Use of renewable and agricultural products
- Production of a sustainable and green concrete material that satisfies the requirement of green codes and could help alleviate environmental impacts.

The benefits of such a new technology prompted the initiation of a three-phased research program.

The objective of the first phase was to achieve an optimum concrete mix that incorporates RCA and that is reinforced by industrial hemp fibers and that meets the requirements of high-performance concrete. Since RCA and hemp fibers are non-conventional concrete components, a component level testing will be carried out in order to measure the fundamental properties of these materials. In addition, this phase included performing different trial batches to investigate the compatibility of the NCA, RCA, and hemp fibers, in order to find an optimum mix. Tests on trial batches included plastic state slump and hardened state mechanical properties such as compressive strength, tensile splitting strength, modulus of elasticity, and flexural strength of standard beams. These tests were used in order to determine the feasibility of using hemp fibers to increase the strength and ductility of PCC.

The second phase of this research was based on the results of the first phase where the HRAC's optimal batch was used in order to assess the structural performance of reinforced concrete elements. By investigating the difference in strength and behavior between conventional and newly prepared HRAC structural concrete elements, the hypothesis that was tested is that partial substitution of natural aggregates with a combination of RCA and hemp fibers would not lead to reduction in the flexural, shear, and bond splitting and anchorage characteristics of the structural elements, in addition to having a ductile behavior. Two identical beams were prepared for every concrete mix and reinforcement beam type to ensure reliability and accuracy of results.

The third phase was to investigate the durability of aged HRAC elements under long term condition and under aggressive environments. The absorption capacity and thermal conductivity of HRAC mixes was also evaluated. In addition, a life cycle analysis was conducted to quantitatively assess the benefits of HRAC over regular concrete from environmental aspects. The life cycle analysis was be done to compare the conventional PCC and the designed HRAC mixes in this study.

B. Research Conclusions

The main conclusions of the study are the following:

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 and preparing it to be used in the concrete mix. Also, alkali and acetyl treatments have increased the crystallinity and thermal stability of the fibers while silane treatment decreased it.

2. Incorporation of hemp fibers and RCA in the concrete mix reduced the consistency of the mix but the values remained in the acceptable range.

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. 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 than 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. It would not be advisable to use

HRAC mixes in structural members subjected to direct compression forces like columns.

4. Although HRAC mixes had an average reduction of 15% in flexural strength relative to the control mixes, however load-deflection behavior became ductile with considerable history after reaching ultimate indicating high ductility and energy absorption of the hemp fiber mixes.

5. Durability tests that were performed on different mixes showed that HRAC mixes had increases in percentage absorption ranging between 54 and 60% relative to the control mixes, had superior thermal properties as compared to normal concrete, and had comparable resistance to freeze-thaw cycles as normal concrete mixes after 144 cycles. Variation of values was not significantly affected by fiber length or fiber treatment type.

6. Based on long-term mechanical test results, it was concluded that HRAC, is a durable concrete that has a reliable long-term mechanical performance.

7. Structural testing showed that it was possible to reduce the amount of NA used by more than 70% without affecting the maximum load that can be sustained by the structural beams under all three studied modes of failure (flexure, shear, and bond), with the advantage of having more ductile behavior; hence having a better overall structural performance while saving on natural resources and using recycled material.

8. The life-cycle assessment quantitively proved that HRAC is indeed a sustainable concrete, having better structural properties and lower environmental impact when compared to ordinary concrete.

In this research, it was proved that HRAC is a sustainable concrete that can be used in structural applications, mainly in flexural members, ensuring ductility and adequate flexural, shear, and bond splitting characteristics, while providing many environmental benefits.

It was also concluded that alkali-treated, 20mm hemp fiber and RCA with an MSA of 20mm can be used in HRAC while assuring that the designed mix meets the requirements of high-performance concrete.

It was also proved that HRAC is a durable concrete, having good resistance to weathering and adequate long-term mechanical performance. Also, results showed that HRAC has a better thermal performance than normal concrete.

C. Future Work

There are still many steps before HRAC could be applied on the construction field. First, more research and testing are needed to study other aspects and properties of HRAC, such as more extensive durability testing, internal curing potential, and plastering properties.

Also, it's essential to mention that the conclusions of this study, regarding the effect on RCA incorporation, depend on the source of the RCA. In this study, the RCA were provided from crushed concrete cylinders with an average compressive strength of 30 MPa. Other sources and properties of RCA could significantly affect the results and therefore should be studied.

Moreover, for more practical use of HRAC, mechanical equipment should be adapted to automate the process of preparing the hemp fibers to be used in the concrete mix: fibers processing, cutting to precise lengths, chemical treatment, cleaning and drying, and spreading.

Furthermore, HRAC could be important in high strength concrete, and earthquake resistant structures where ductility is required, and the possible benefits in such applications should be studied

Also, other possible uses of HRAC could be studied, such as in pavements, masonry blocks, and other non-structural uses.

To conclude, HRAC is a promising sustainable construction material with many benefits, and further research efforts should be invested in it.

APPENDIX

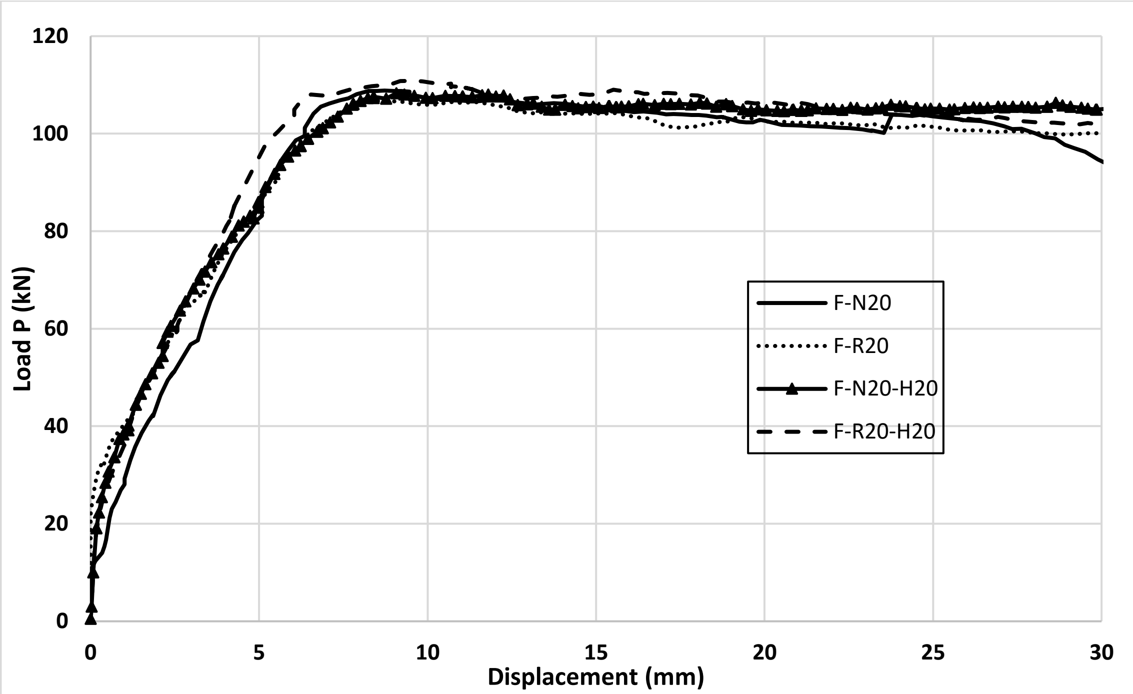

Figure 0.1 Load-deflection curves of replicate flexure beams

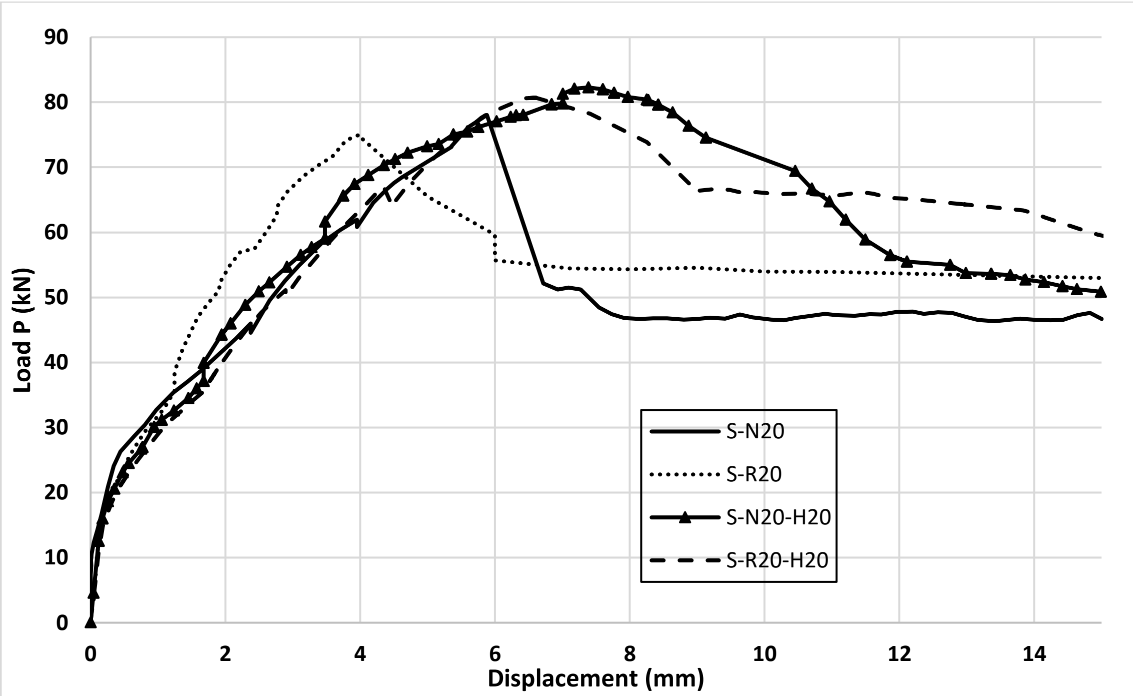

Figure 0.2 Load-deflection curves of replicate shear beams

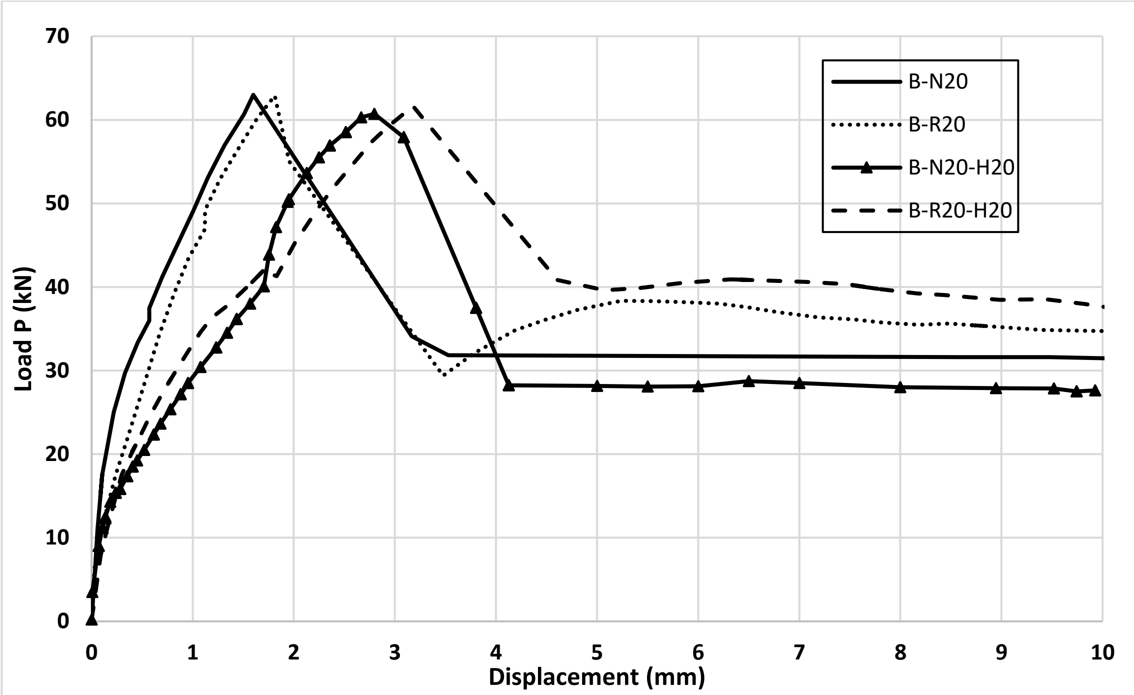

Figure 0.3 Load-deflection curves of replicate bond beams

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