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RESEARCH

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Studies on Hemp and Recycled Aggregate Concrete

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Abstract

This paper reports on the first phase of a multi-phase research program conducted at the American University of Beirut (AUB) on "Hemp and Recycled Aggregates Concrete" (HRAC). HRAC is a new sustainable concrete material where hemp fibers are incorporated in the mix, the coarse aggregate content is reduced by 20% of the concrete volume, and 50% of the natural coarse aggregates (NCA) are replaced by recycled concrete aggregates (RCA), thus saving on natural resources and addressing the problem of waste material disposal. The effect of the new material on concrete consistency and hardened mechanical properties was studied. Also, few durability tests were conducted. Variables included percentage replacement of NCA by RCA (0 or 50%), maximum size aggregate (10 or 20 mm), hemp fiber length (20 or 30 mm), and hemp fiber treatment (alkali or silane or acetyl). Fiber characterization tests were conducted including morphology, crystallinity, and thermal analysis. The tests indicated that alkali and acetyl fiber treatments were better than the silane treatment in removing impurities on the fiber surface. Also, alkali and acetyl treatments have increased the crystallinity of the fibers while silane treatment decreased it. Results of mechanical properties tests showed that while HRAC has considerable lower compressive strength and modulus of elasticity than plain concrete, the flexural strength and splitting tensile strength are not significantly affected. The flexural stress–strain behavior of HRAC is ductile as compared to the brittle behavior of the plain concrete beams indicating positive impact on toughness and energy dissipation. 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.

Keywords: sustainable concrete materials, recycled aggregates, hemp fibers, mitigation of wastes, characterization, mechanical properties, durability

1 Introduction

Similar to other industries, the construction industry is trying nowadays to adapt sustainable practices where the main concern is to reduce the use of non-renewable natural resources. A more sustainable and environmentally friendly concrete material can be produced by reducing the use of natural coarse aggregates (NCA). This reduction can be compensated by the use of recycled materials and "green" construction materials like natural fibers. Construction and demolition wastes (CDW) are a mixture of left-over materials generated from the construction or the demolition of existing structures or from emergencies such as earthquakes and wars. Another source of CDW is quality control procedures in the construction industry such as laboratory testing of concrete cylinders. These CDW are increasingly becoming an environmental problem, specifically in countries where there are no mitigation plans for recycling them. Many practices involving the utilization of the cementitious portions of CDW as recycled concrete aggregates (RCA) have emerged in the recent years. Thus, the use of these wastes in concrete mixes has a dual purpose of solving the problem of their disposal and minimizing the depletion of natural resources.

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Significant amounts of CDW have been produced in Lebanon 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 are structurally defected. In addition, 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. However, according to Srour et al., Lebanon evidently lacks any guidelines on the reuse of RCA (Srour et al. 2012).

Another area that Lebanon is struggling with is the agricultural sector which is facing high production cost and minimal profit. Lately, the Ministry of Agriculture (MoA) and the United Nations Development Program (UNDP) implemented a project that monitors the farming of industrial hemp and its use in different activities such as construction (2010). However, hemp will not be easily adopted by farmers unless value-added processing is established in Lebanon. Hence, selling hemp as raw material (i.e. straw, seeds) will not generate sufficient revenue to attract famers. As such, a financially sound hemp processing business is the only mean for promoting hemp cultivation in Lebanon.

In line with the above, and to partially solve the socio-economic problems that farmers in Lebanon face, this study aims to investigate the feasibility of using industrial hemp fibers in concrete so that the public and private sectors would be more prone to invest in the cultivation of an industrial crop.

In the research reported in this paper, hemp and recycled aggregate concrete (HRAC) is introduced as a new sustainable concrete material prepared by reducing the coarse aggregate content (Reducing), partial substitution of NCA with NCA (reusing and recycling), and incorporating hemp fibers in the concrete mix (socio-economic impact). Several factors affecting the properties of HRAC are studied.

2 Background and Literature Review

2.1 Fiber-Reinforced Concrete

Over the past few decades, there has been a lot of development in fiber-reinforced cement composites. The main types of fibers that have been used in these composites are steel, glass, and synthetic fibers derived from organic polymers such as polyethylene and polypropylene fibers (ACI 544.1R 2009). Swamy (1975) presented a preview of the twentieth century early developments in different aspects of cement-based fibre-reinforced composites. Swamy stressed that whereas it is clear that fiber-reinforced materials resist cracking better than conventional materials, reliability of the use of fibers requires understanding their behavior, advantages, and limitations.

Qian and Stroeven (2000) investigated the mechanical properties of a high-strength and high-performance hybrid fiber concrete material made by adding fly ash and different combinations of polypropylene and steel fibers to the mix. Variables included the amount of fly ash and the type, amount, and size of the steel and polypropylene fibers used. Test results showed that the presence of the fly ash fine particles in the concrete matrix could help disperse the fibers homogeneously. Also, results indicated that the size of the fibers could have significant effect on the mechanical properties of the composite material.

When concrete containing fibers start to crack, fibers hinder crack propagation by bridging over cracks, thus improving stress transfer across the cracks and improving the post-crack behavior. Barros et al. (2005) conducted experimental and numerical research to investigate the post-cracking behavior of steel fiber-reinforced normal strength concrete. Usman et al. (2020) reported on an experimental study designed to study the effect of confinement of standard 150×300-mm cylinders cast with steel fiber-reinforced high-strength concrete on the axial-load behavior. Variables included steel fiber volume fraction and type of external confinement (steel tubes or carbon fiber-reinforced polymer). Results indicated the positive impact of the combined effect of steel fibers and external confinement on compressive strength, mode of failure (reducing the brittleness of high-strength concrete), and post-peak response.

Besides the research on steel, glass, and synthetic fiber-reinforced concrete, there has been a lot of reported research on the use of natural and vegetable fibers in the last few decades and this led to using natural fibers in cementitious products (Pacheo-Torgal and Jalali 2011; Xie et al. 2015; Alkbir et al. 2016; Onuaguluchi and Banthia 2016; Barros et al. 2017; and Lau at al. 2018). Cost of natural and vegetable fibers is significantly less than synthetic fibers made from raw materials since they are commonly considered as waste materials. This would contribute to saving on natural resources.

2.2 Previous Studies on Hemp Fibers

Sedan et al. (2008) investigated the influence of hemp fibers in reinforced cement on the setting time of cement. Results indicated a strong increase in the flexural strength for optimal fiber content and a decrease of the composite modulus of elasticity. Alkaline treatment improved the fiber strength and the fiber–matrix adhesion. Elfordy et al. (2008) conducted a research on concrete blocks made of a mixture of lime and hemp hurds. The block's thermal and mechanical properties were measured such as flexural and compressive strengths, and hardness. The thermal and mechanical properties were found to increase with the density of the concrete block. Pickering et al. (2007) investigated the performance of hemp fibers in a polypropylene matrix composite. The tests results showed that the strength of hemp fibers, treated in 10% (by weight) NaOH solution, was improved with a low lignin content and good fiber separation. The hemp fibers had an average tensile strength of 857 MPa and a Young's modulus of 58 GPa. Li et al. (2006) studied the mechanical and physical properties of hemp fiber-reinforced concrete. In the experimental program, the variables were the mixing method, the fiber content by weight, the aggregate size, and the fiber length. The compressive and flexural performances were determined, in addition to the specific gravity and water absorption ratio. The hemp properties used were specific gravity (1.5), water absorption (85–105%), tensile strength (900 MPa), and modulus of elasticity (34 GPa). It was found that the compressive strength, flexural strength, toughness, specific gravity, and water absorption were all affected by the aggregate size, fiber factors, and matrix initial mechanical properties.

In the past few years, many studies have been done at the American University of Beirut (AUB) to achieve sustainable concrete materials. Awwad et al. (2012a and 2012b) studied the effect of adding industrial hemp fibers to plain concrete accompanied by a reduction in the coarse aggregate content. The fibers were cut to a length of 30 mm and treated in a 6% solution of sodium hydroxide for 48 h. The hemp fibers were added in different volumetric percentages of the concrete volume (0.5, 0.75, or 1%), and with a coarse aggregate reduction equivalent to 10, 20, or 30% of the concrete volume. Several tests were done on all mixes including compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, density, and slump tests. Based on the test results, the compressive strength decreased by an average of 24% for mixes with different percentages of fibers and different coarse aggregate reductions. It was recommended not to use this material in pure compression members such as columns. Reduction in the flexural strength or the modulus of rupture (MOR) averaged 25%; however, the load–deflection behavior became more ductile after the peak load was reached. Moreover, the splitting tensile strength was slightly reduced, the modulus of elasticity tests showed a more ductile behavior, and the slump of fresh concrete tended to decrease when the fibers were added. Compared with the control mix with no fibers and no aggregate reduction, the best test results were achieved by the mix where the fibers were added in a volumetric percentage of 0.75 of the concrete volume with a coarse aggregate reduction of 20%.

Based on the above results, namely the ductile behavior induced by adding hemp fibers which is favorable for dynamic and impact loading applications, Awwad et al. (2014) reported on another study conducted at AUB to investigate the performance of the hemp-reinforced concrete mix in structural elements such as simply supported reinforced concrete beams. For each of the three modes of failure investigated (flexure, shear, and bond splitting), three concrete beams were tested: control with no fibers, 0.75% hemp–20% coarse aggregate reduction, and 1% hemp–20% coarse aggregate reduction mixes. Two large-scale replicate beams were considered for reliability and accuracy of results, and in total, 18 beams were tested. Test results showed that although the concrete compressive strength was reduced by almost 20%, the addition of the hemp fibers resulted in a ductile behavior after the peak load was reached. Besides, the peak loads of the hemp fibers beams were comparable to the control beams without fibers for each of the three investigated modes of failure while a 20% reduction in the coarse aggregates was possible. Thus, a more durable concrete subjected to dynamic loads may be produced while saving on natural resources.

2.3 Previous Studies on RCA

Many papers are reported in the literature on research conducted on the strength development, mechanical properties, and durability aspects of normal strength recycled aggregate concrete produced by replacing different percentages of NCA with RCA (Nagataki et al. 2000; Shayan and Xu 2003; Rahal 2007; Etxeberria et al. 2007; Rao et al. 2007 and Yang et al. 2008). Sources of the recycled aggregates were concrete construction and demolition wastes. Results indicated minor reductions in the various mechanical properties including compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity.

More recently, Hamad and Dawi (2017) studied the effect of replacing NCA with RCA obtained from crushing concrete cylinders in batching plants on the plastic and hardened mechanical properties of the produced normal and high-strength concrete mixes (NSC and HSC). Different percentage replacements of NCA with RCA (0, 20, 40, 60, 80 and 100 percent) were used. The compressive strength, splitting tensile strength, modulus of elasticity, and flexural strength values were all around 10% lower for mixes with RCA as compared with the control mix. In another study, Hamad et al. (2018) tested the hypothesis that partial or full substitution of natural aggregates with such recycled aggregates would not lead to negative effect on the structural behavior of reinforced concrete beams. Test results showed minimum difference in the peak load and load–deflection histories attributed to the percentage replacement of NCA with RCA.

3 Research Objectives

The encouraging results of the previously reported AUB research on the use of natural hemp fibers in concrete and on replacing portion of NCA with RCA triggered the significance of conducting a multi-phase research program which combines the positive effects of RCA and hemp fibers into HRAC or "Hemp and Recycled Aggregate Concrete". HRAC would be a potential solution for the depletion of natural resources and the disposal of construction waste material. This is achieved by the reduction of coarse aggregate content and the partial substitution of natural aggregates with combination of RCA and industrial hemp fibers. Advantages and benefits of HRAC would include saving on natural resources, alleviation of the demolished concrete waste disposal problem and reduction of its negative environmental impact, use of renewable and agricultural products, and the production of a sustainable and green concrete material. The objectives of the multi-phase program were to check the mechanical and durability properties of HRAC, assess the structural performance of reinforced concrete elements prepared using HRAC, and conduct a life cycle analysis to quantitatively assess the benefits of HRAC over regular concrete from socio-environmental aspects. This paper reports on the first phase of the program whose results will pave the way for the next phases.

4 Materials and Mixes

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.

4.1 Fibers

Hemp fibers shown in Fig. 1 were imported from Hemp Traders, USA, and were cut to the length of either 20 or 30 mm. The average tensile strength of the fibers was measured to be 241 MPa.

Fig. 1 Hemp fibers in their initial state.

4.1.1 Fiber 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. Therefore, hemp fibers in this study were subjected to three different chemical surface treatments:

a. Alkali treatment where the fibers were soaked in a 6% solution of sodium hydroxide for 48 h, then washed with water and left to dry.
b. Silane treatment where the fibers were 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 h before the fibers were added. Then the fibers were washed with water and left to dry.
c. Acetyl treatment where the alkaline-treated fibers were soaked in glacial acetic acid for 1 h and then soaked in acetic anhydride containing one drop of concentrated H_2SO_4 for 1 h.

4.1.2 Fiber Characterization

To study the effect of each fiber treatment, treated hemp fibers were subjected to several characterization tests:

a. Morphology: scanning electron microscopy (SEM) images were taken using a TESCAN MIRA3 LMU with OXFORD EDX detector. 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.

b. 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 ($\lambda = 1.54$ 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.
c. 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/min in a nitrogen atmosphere. TGA was used to study the thermal degradation of the untreated and treated fibers.

4.2 Coarse Aggregates

The NCA used were crushed limestone rock and the RCA were obtained by crushing the tested Portland Cement Concrete (PCC) cylinders in ready-mix plants. A view of the RCA used is shown in Fig. 2. Two MSA were considered: 10 and 20 mm. The properties of the NCA and RCA are presented in Table 1. As for the fine aggregates, natural sand with a fineness modulus of 2.9 and a specific gravity of 2.64 was used.

4.3 Concrete Mixes

Sixteen different mixes were prepared and are identified in Table 2. 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.

Fig. 2 Recycled coarse aggregates.

Table 1 Aggregate properties.

	NCA		RCA	
	N20	N10	R20	R10
Maximum size aggregate (MSA) (mm)	20	10	20	10
Specific gravity (oven-dry)	2.59	2.63	2.3	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	

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 seven 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/m^3. 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 3.

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 3. 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 m^3, to obtain a concrete vol-

Table 2 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 (control 10)	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 (control 20)	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 3 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 (control 10)	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 (control 20)	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

ume of 1 m^3, 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 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, the positive environmental impact of saving on natural resources and reusing waste materials, along with the positive socio-economic impact of promoting hemp cultivation, gives the credibility to testing the newly proposed HRAC material.

5 Test Results and Analysis

5.1 Fibers

5.1.1 Morphology

The microstructure of untreated fibers is shown in Fig. 3a, b, while the microstructure of the fibers after each treatment is shown in Fig. 3c–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 (Fig. 3c–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 (Fig. 3e, f), some impurities were still present on the fiber surface. Silane particles that remained after the washing of the fibers were also noticed.

5.1.2 Crystallinity

X-ray diffractograms of untreated and treated hemp fibers show a major crystalline peak that occurs around $2\theta = 22.5°$ which corresponds to the crystallographic plane of cellulose (refer to Fig. 4). 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.

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

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 5).

5.1.3 Thermal Analysis

It can be observed from the TGA curves shown in Fig. 5 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, hemi-cellulose, and lignin, have similar degradation temperatures. The small initial loss of weight is due to the moisture that exists in the fibers.

5.2 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 listed in Table 6 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.

5.3 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, $100 \times 100 \times 350$ 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

Table 4 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

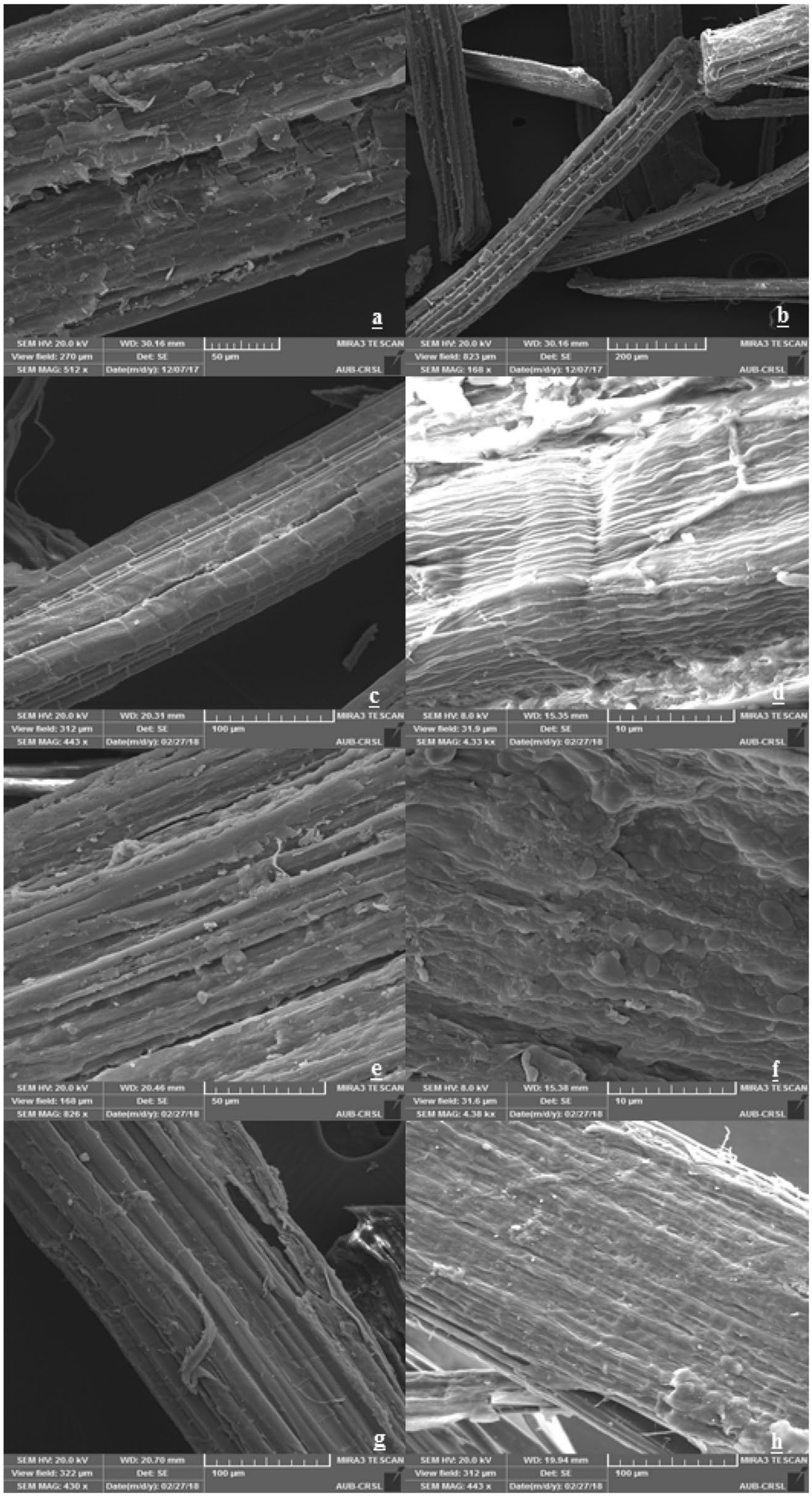

Fig. 3 SEM imges of the hemp fibers.

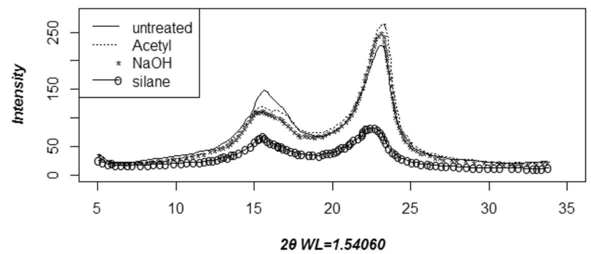

Fig. 4 XRD diffractograms of the hemp fibers.

Table 5 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

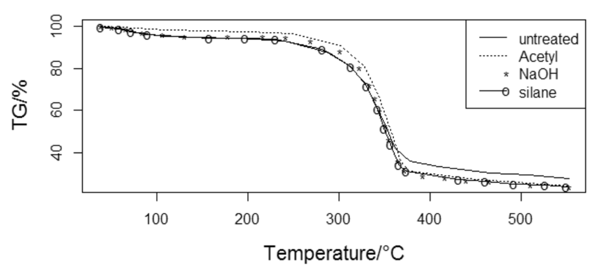

Fig. 5 TGA curves of the hemp fibers. **a** Compressive strength test. **b** Flexural strength test. **c** Splitting tensile strength test.

identical specimens were prepared and the average value was reported. Views of the different test setups are shown in Fig. 6.

5.3.1 Compressive Strength

Cylinder compressive strength test results at 28 days, presented in Table 6, 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.

5.3.2 Modulus of Elasticity

Results of the modulus of elasticity test listed in Table 6 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 five 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.

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.

5.3.3 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

Table 6 Slump and mechanical properties of all mixes.

Mix ID	Slump (cm)	Compressive strength		Modulus of elasticity		MOR		Splitting tensile strength	
		Value (MPa)	Ratio[a]	Value (GPa)	Ratio[a]	Value	Ratio[a]	Value	Ratio[a]
Group 1 MSA = 10 mm									
N10 (control 10)	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 (control 20)	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

[a] 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.

the ultimate flexural strength or modulus of rupture (MOR) are presented in Table 6.

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 Fig. 7 for Group 1 of mixes with MSA of 10 mm and in Fig. 8 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

a Compressive strength test.

b Flexural strength test.

c Splitting tensile strength test.

Fig. 6 Views of different test setups.

if failure occurs before the post-peak load reaches 0.5 Pmax as illustrated in Fig. 9. 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 7 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).

5.3.4 Splitting Tensile Strength

Splitting tensile strength test results shown in Table 6 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.

5.4 Durability Testing

Three different durability tests were conducted: the absorption capacity according to ASTM C642 (2013), the thermal conductivity test according to ASTM C518 (2017), and resistance to freeze–thaw cycles according to ASTM C666/C666M-15 (2015). For each test two groups of specimens were tested: Group 1 with MSA of 10 mm and Group 2 with MSA of 20 mm. In each group, 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.

5.4.1 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 8. 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 their porous structure, which extends to the concrete matrix. The increase in the absorption of the mix with 50% replacement of NCA with RCA relative to 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

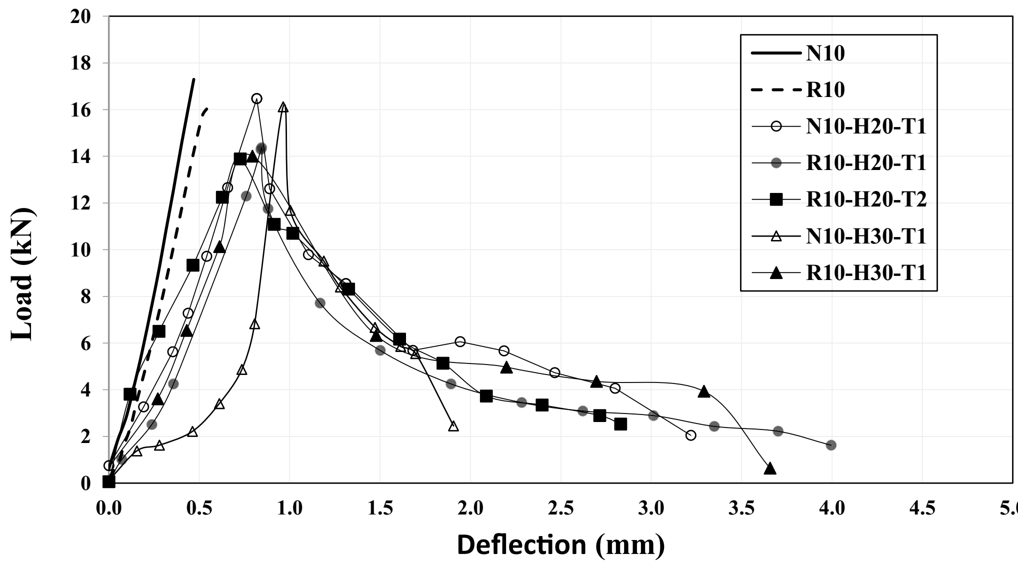

Fig. 7 Load–deflection curves of the standard beams; Group 1, MSA = 10 mm.

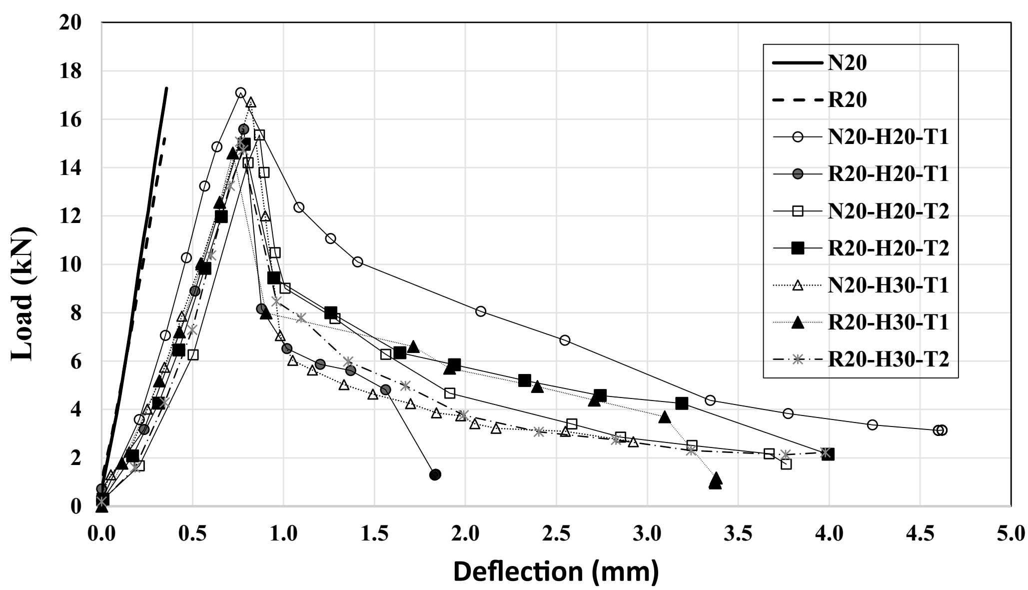

Fig. 8 Load-deflection curves of the standard beams; Group 2, MSA = 20 mm.

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.

5.4.2 Thermal Conductivity

The thermal conductivity of the concrete mixes was determined according to ASTM C518 (2017). For every mix, one 300 × 300 × 30-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

Table 7 Fracture energy of all mixes.

Mix ID	Fracture energy (kN-m)	μ[a]
Group 1 MSA = 10 mm		
N10 (control 10)	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 (control 20)	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

[a] μ energy ductility index. It is the ratio of fracture energy of the tested specimen to that of the control mix N10 or N20.

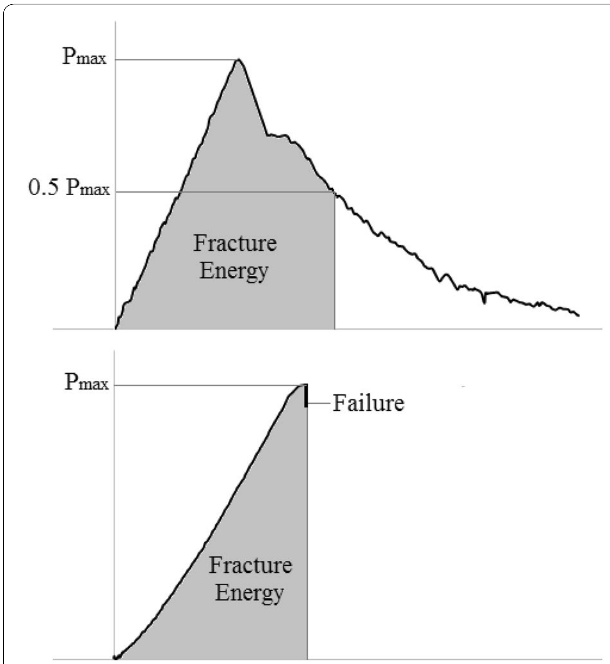

Fig. 9 Schematic load–deflection curves to define the measured fracture energy.

Table 8 Absorption values of the tested mixes.

Mix ID	Absorption	
	Value (%)	Ratio[a]
Group 1 MSA = 10 mm		
N10 (control 10)	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 (control 20)	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

[a] 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.

Table 9 Thermal conductivity of the tested mixes.

Mix ID	Thermal conductivity	
	Value (watt/meter. °Kelvin)	Ratio[a]
Group 1 MSA = 10 mm		
N10 (control 10)	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 (control 20)	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

[a] 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.

finally cooled to room temperature before being tested. The thermal conductivity results are presented in Table 9.

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.

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.

5.4.3 Resistance to Freeze–Thaw Cycles

The resistance of all mixes to rapid freezing and thawing was studied according to ASTM C666. Figure 10 shows specimens prepared for testing. For each mix, one prismatic specimen (75 × 100 × 405 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 h and 40 min.

The specimens were tested for their fundamental transverse frequency every 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 as follows:

Fig. 10 View of specimens prepared for freeze thaw cycles.

$$P_c = \frac{n_1^2}{n^2} \times 100,$$

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.

Results of P_c or RDME after each 36 cycles of freezing and thawing are presented in Table 10. 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 Fig. 11.

The results show that for Group 1 with MSA of 10 mm, all tested specimens showed good resistance to

Table 10 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[a]	*c* = 72	*c* = 108	*c* = 144
Group 1 MSA = 10 mm					
N10 (control 10)	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 (control 20)	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

[a] *c* number of freeze–thaw cycles.

Fig. 11 View of specimens R20 (top) and R10–H20–T1 (bottom) after 108 cycles.

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%).

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% and 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.

6 Conclusions

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

The main conclusions of the study are

a. Fiber characterization tests indicated that alkali and acetyl fiber treatments are better than the silane treatment in removing impurities on the surface of the fibers. Also, alkali and acetyl treatments have increased the crystallinity of the fibers while silane treatment decreased it.
b. Incorporation of hemp fibers in the mix reduced the consistency of the mix but the value remained acceptable.
c. 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.
d. Although HRAC mixes had an average reduction of 15% in flexural strength relative to the control mixes, load–deflection behavior became ductile with considerable history after reaching ultimate indicating high ductility and energy absorption of the hemp fiber mixes.
e. 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.

7 Future Research

A previous research paper on the use of recycled aggregates in structural concrete indicated that the reduction in concrete hardened mechanical properties due to replacement of 50% of NCA with RCA was not extended to the structural behavior of full-scale reinforced concrete beams designed to fail in flexure, shear, or bond splitting (Hamad et al. 2018). Experimental results showed minimum difference in the peak load and load–deflection histories of the tested beams attributed to the percentage replacement of NCA with RCA. Also, research reported on hemp–concrete beams prepared with hemp fibers and reduced natural coarse aggregate content indicated that the hemp beams had similar peak loads as the control beams without hemp fibers, and the hemp–concrete beams exhibited better load–deflection ductile behavior after the peak load (Awwad et al. 2014).

Therefore, it would be significant in the next phases of the AUB multi-research program to verify the hypothesis that reductions in the mechanical properties reported in this paper might not lead to inferior structural behavior of HRAC beams designed to fail in flexure, shear, or bond splitting modes of failure. It would be equally important to assess and quantify the impact of HRAC on load–displacement ductility and fracture energy of the tested beams. Also, there is need to conduct a life cycle analysis to quantitatively assess the benefits of HRAC over regular concrete from socio-environmental aspects.

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