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# Durability Evaluation of Hemp Fibers and Recycled Aggregates Concrete

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**Abstract.** *Hemp and Recycled Aggregates Concrete (HRAC) is a sustainable concrete where coarse aggregates are partially replaced with industrial hemp fibers and recycled concrete aggregates (RCA). This replacement has two main benefits: it saves on natural resources and it recycles and reuses waste material. Previous studies showed that the mechanical performance of HRAC is satisfactory. On the other hand, concrete's durability is also an important criterion to evaluate concrete's performance and HRAC's durability can be affected by the presence of both RCA and hemp fibers in the concrete's alkaline environment. This paper aims at investigating the durability of HRAC concrete mixes by comparing the mechanical performance of HRAC specimens at the ages of 2 and 28 days. Furthermore, the performance of HRAC under freeze/thaw cycles is evaluated and compared to that of regular concrete. Results showed that the mechanical performance of HRAC improves at older age and the resistance of HRAC mixes to freeze-thaw cycles is similar to that of control mixes***.**

**Keywords:** *Sustainable Concrete Materials, Recycled Aggregates, Hemp Fibers, Durability, Mechanical Properties.*

## 1 Introduction and Background

Sustainability has become an essential issue on a global scale in the recent years. Therefore, construction, among other sectors, is reviewing its practices to make them more environmentally friendly and reduce their negative effect on the planet as a whole.

Concrete production consumes large quantities of natural aggregates causing significant damage to the environment. To reduce the amount of natural aggregates used in concrete HRAC is proposed. This is a concrete mix where hemp fibers are incorporated in the mix, the amount of natural coarse aggregates (NCA) is reduced by 20%, and where 50% of NCA are replaced by RCA.

HRAC also helps in reducing the problem of construction and demolition wastes (CDW) which are a mixture of surplus materials generated during new construction, renovation, and demolition of buildings, roads, bridges, and other structures (Cheng *et al.*, 2013)

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.

Ramli *et al.* (2013) studied the durability of coconut-fiber-reinforced concrete in aggressive environments. Results showed that the damaging effects of aggressive environments on concrete can be lowered with fiber-reinforced concrete since the fibers play a role in restraining the development of cracks. Awwad *et al.* (2014) investigated the long-term behavior of concrete incorporating hemp fibers and concluded that at an age of 1.5 years hemp fibers did not have a negative effect on concrete strength. Vázquez et al. (2014) found that the presence of RCA in concrete can improve the resistance to chloride penetration since C-S-H gels that exist in higher amounts in RCA assist in chloride binding. Also, the resistance of high-performance concrete with RCA to freezing can be similar to that of normal concrete (Ajdukiewicz *et al.*, 2002). The carbonation depth increases with the increase of RCA replacement ratio, but Lei *et al.* (2008) found that when the percentage replacement of NCA with RCA was higher than 70%, the carbonation depth decreased, which may be due to the adhered mortar on the RCA which increases the total cement content and slows down the carbonation rate.

In this paper, the durability of the proposed HRAC is investigated by evaluating its mechanical performance at the age of 2 years and by studying its resistance to freeze-thaw cycles.

## 2 Materials and Experimental Procedures

Sixteen different mixes were prepared and are identified in Table 1. 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.* (2014), 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.

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 presented in previous studies (Ghosn *et al.*, 2019). The tests were done according to ASTM C39 (2017), ASTM C78 (2016) and ASTM C469 (2014) respectively. For each test, 2 replicates were made for each mix.

The resistance to freeze-thaw cycles was conducted according to ASTM C666 (2015). 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.

**Table 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 |

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 as follows:

$$P_c = \frac{n_1^2}{n^2} \times 100 \quad (1)$$

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.

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.

# 3 Results and Discussion

## 3.1 Long-Term Mechanical Performance

### *3.1.1 Compressive strength*

The results of the compressive strength test are presented in Table 2.

**Table 2**. Compressive strength test results.

| | Mix ID | 28 days Compressive Strength Value (MPa) | 28 days Compressive Strength Ratio* | 2 years Compressive Strength Value (MPa) | 2 years Compressive Strength Ratio* | Ratio (2 years /28 days) |
|---|---|---|---|---|---|---|
| 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.*

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. This increase ranges from 6 up to 31% for the HRAC mix R20-H30-T2.

### *3.1.1 Flexural strength*

The results of the flexural strength test are presented in Table 3.

**Table 3**. 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.*

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.

### 3.1.1 Modulus of Elasticity

The results of the flexural strength test are presented in Table 4.

**Table 4**. 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.*

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.

### 3.1 Resistance to Freeze/Thaw Cycles

Results of Pc or RDME after each 36 cycles of freezing and thawing are presented in Table 5. Group 1 with MSA of 10 mm, had a good resistance to freeze-thaw cycles for all tested specimens with Pc ranging from 77% to 90.4% after 144 cycles. While Pc for the recycled aggregate mix R10 was the lowest in the group (77%), mixes with hemp fibers had a Pc ranging between 77 and 90.4, a value which is even higher than the control mix (83.5%).

Group 2 mixes with MSA of 20 mm, had a lower resistance to freeze-thaw cycles than that of Group 1 mixes. Pc decreased more quickly to reach values ranging between 31% and 56.5% after 144 cycles. Similar to Group 1, 50% replacement of NCA with RCA but without hemp fibers incorporation (R20) led to the lowest value of Pc after 144 cycles (31%). This poor resistance of Group 2 to freeze-thaw cycles can be due to the fact that when the MSA increases from 10 to 20 mm, the cement matrix contains 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.

**Table 5**. 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.*

## 4 Conclusion

This paper studies the durability and long-term performance of HRAC, a “green” concrete material where natural aggregates are partially replaced by recycled concrete aggregates and industrial hemp fibers. Results 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. Furthermore, the resistance to freeze-thaw cycles of HRAC was similar to that of normal concrete mixes after 144 cycles.

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

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