3rd International Conference on Bio-based Building Materials

June 26th - 28th 2019
Belfast, UK

THE EFFECT OF LONG TERM WEATHERING AND CARBONATION ON HEMP AND RAPESEED STRAW CONCRETE

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Abstract

In recent decades sustainability, carbon footprint and pollution have become significant issues on a global scale. It is widely recognised that the carbon footprint of the construction industry is something that can be reduced and this has led to sustainable materials being used more and more widely to meet emissions targets. The most widely researched bio-aggregate to date is hemp shiv; which is used in this study as well as chopped rapeseed straw which is an alternative bio-aggregate widely available in the UK. Bio-concretes are made of, in this case, hemp or rapeseed straw as well as water and a binder. The binder used in this study is *Vicat* prompt natural cement as well as a viscosity modifying agent (VMA) as a mixture additive. Most of the research into this area has revolved around the material properties in the relative short term and considerably less research has been conducted into the long term durability of these materials. This study investigates the effect of long term weathering and carbonation on rapeseed and hemp concrete with and without a VMA as an additive.

Keywords:

Hemp; rapeseed straw; viscosity modifying agent; weathering; carbonation.

1 INTRODUCTION

Due to the significant issues of sustainability, carbon footprint and pollution that have recently come to the forefront of global public concern sustainable materials and a greener future have become a large focus for research. It is widely recognised that the human race needs to revise its stance on these key sustainability issues as areas such as industry, construction and energy and transport cause degradation to the environment and the planet as a whole.

Energy use in the building sector can and needs to also be reduced and has led to a focus in research on more sustainable building materials. Energy use in buildings can be greatly reduced simply by better insulation. It is reported by Eurostat [2018] that 25.7% of all energy used in the European Union in 2013 was in households, slightly ahead of industry (25%) and behind only transport (33.2%). It is reported by the UK Department of Energy & Climate Change that in the UK the amount of household energy that is used in heating space amounted to 62% [Palmer and Cooper 2013]. Thus, based on these figures roughly 15.9% of all energy used was in the heating of space, this is a number that has potential to be reduced by the use of new and improved building materials that are both sustainable to produce and also provide excellent levels of insulation. Both of these energy sectors need to be improved and their carbon footprint reduced if the EU is to attain its global emissions targets of a reduction in greenhouse gas emissions of 40% for 2030 and 80% for horizon 2050 compared to the 1990 level.

One such material that that can help reach these goals is bio-based building materials [Amziane & Sonebi 2016]. This bio-concrete is most commonly made up of chopped hemp shiv, a lime binder and water. However, this paper also presents an alternative aggregate for comparison in the form of chopped rapeseed straw. Hemp is already well known to be a great insulator [Amziane & Sonebi 2015]. And initial testing indicates that the same can be said for rapeseed concrete [Laidoudi et al. 2015; Sheridan et al. 2017].

Considerable research has been conducted into bio-based building materials however the long-term durability of vegetal concretes is something that still needs to be investigated in depth. Several durability mechanisms have been studied thus far; from biological aging [Marceau et al. 2015; Hellebois et al. 2013], fire exposure [Grelat 2004], wetting and drying with variable humidity cycles [Delannoy et al. 2018; Hellebois et al. 2013], salt exposure and freeze-thaw [Walker, Pavía, and Mitchell 2014].

Limited studies have also been conducted on weathering [Hellebois 2013; Sonebi et al. 2015; Yoann, Amziane, and Sonebi 2017; Sentenac, Sonebi, and

Amziane 2017] as well as carbonation [Chabannes et al. 2015; Sentenac, Sonebi, and Amziane 2017b], however for both of these mechanisms more research is needed. Despite the investigations being a good start the total experiment length as well as the actual cycle lengths are not long enough to adequately investigate the effect of both weathering and carbonation on vegetal concretes.

The mixes used in this investigation were developed at Queen's University Belfast in a previous investigation by Sheridan et al. [2017] and so a polyacrylic acid admixture is again used and its resistance to long term weathering and carbonation will also be studied simultaneously

2 MATERIALS, METHODS AND EXPERIMENTAL PROCEDURES

2.1 Materials

As mentioned above the two aggregates that were used in this investigation were hemp shiv and chopped rapeseed straw. The hemp shiv is grown and packed in Driffield, East Yorkshire in the UK and the rapeseed straw is chopped and packed in Co. Kildare in Ireland. The binder that was used was Vicat Prompt Natural Cement which is a lime binder mined from a seam of argillaceous limestone in Grenobles, France. The VMA that was used was a polyacrylic acid VMA from Larsen, UK.

2.2 Methodology

2.3 Experimental Procedure

Weathering Testing – Cycle Lengths

In order to evaluate the weathering resistance of hemp and rapeseed straw concrete a test was devised in QUB to investigate this property in the long term. It was decided that in order to this samples had to be submerged in water for a length of time that would allow them to fully saturate; and then similarly to desaturate and dry completely. These 2 processes formed a single cycle and obviously these cycles had to repeated numerous times in order to investigate long term durability.

Initially these saturation/desaturation times had to be established in order to form the cycle lengths that were going to be used. To do this the samples were submerged in water and each day were weighed after being placed on a steel grid for 30 mins to allow any free water to escape. If the mass of the sample was within 0.1% of the previous day's mass, then saturation was assumed to have been reached and the previous day was taken to be the length of that wetting or drying cycle. Similarly, for drying the samples were placed in an oven at 50°C and day-by-day were weighed until desaturation had been reached and the length of the cycle found. This was done for each of the four mixes and the cycle lengths were found to be; 11 days for both hemp and rapeseed untreated (5 days wetting and 6 days drying) and 13 days for hemp and rapeseed VMA (7 days wetting and 6 days drying). It was decided that the test would be a long term test and so 20 cycles were conducted meaning a total test time of 220 days for untreated samples and 260 days for VMA samples.

Weathering Testing – Full Immersion

Once the cycle lengths had been evaluated the testing could begin. Large plastic boxes were used and filled with water to submerge the samples and the cycles were adhered to (Figure 1).

Figure 70 – Rapeseed VMA samples during a full immersion weathering test

After each cycle had been completely the samples were weighed and measured for height, width and depth using digital callipers. This was done after the samples had been removed from the oven as well as removed from the water in order to measure any effect of the saturation/desaturation cycles, in particular swelling. Any changes in amount of water absorbed were also noted by observing the differences in mass that the samples were producing. In order to investigate the effect the submersion was having after 5, 10, 15 and the full 20 cycles were completed samples were removed for compressive strength testing as well as fourier-transfer infrared spectroscopy (FTIR) on fibre samples.

Weathering Testing – Partial Immersion

As well as simply considering full immersion of the samples it was decided also that partial immersion would be taken in to account. The reason for this is because full immersion, although a necessary and valid parameter for this durability test, is an extreme case that would be relatively rare in a real life situation. The only situation where this full immersion for the material would occur would be during a flood. Thus it was necessary to study a less extreme case of wetting and drying that would more closely imitate the conditions of a building in a real life.

Figure 71 – Samples partially submerged during a partial immersion test

Regarding the actual experiment, to allow for comparison between the two immersion methods, the same cycle lengths were used for partial as were used in the full immersion experiment. That is to say 13 days for the hemp and rapeseed mixes and 11 days for the untreated mixes. The samples were sat upon a steel grid in the water to allow vertical absorption of water via capillary suction (Figure 2). Again at the end of each wetting and drying cycle the samples were weighed and measured with digital callipers and after 5, 10, 15 and

20 cycles samples were removed for compressive strength testing.

Compressive Strength

1. Weigh the sample and measure the height, width and thickness to be able to calculate the density.
2. Position the sample in the Zwick machine and lower the crosshead until the compression pad is in contact with the top surface of the sample.
3. The loading rate was set to 0.6 N/s and the samples were tested up to 20% strain.
4. The resultant maximum force was divided by the cross-sectional area to obtain the compressive strength (MPa)

Carbonation

As part of the durability aspect of this study long term carbonation of bio-based building materials were studied in detail. The samples were stored in laboratory conditions for an initial 28 days to allow the internal relative humidity of the samples to stabilise. Then the samples were placed in the chamber and the total test length of the accelerated carbonation experiment would be 6 months. Thus the samples were placed in a carbonation chamber with an atmospheric carbon dioxide level of 5%, temperature of 20°C and relative humidity of 55% (Figure 3). The atmospheric carbon dioxide level was decided upon in accordance with BS 1881-210:2013 (2013), the British standard for the accelerated carbonation method.

Figure 72 – Carbonation Chamber

Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR was used in conjunction with attenuated total reflectance (ATR) on a *Jasco FT/IR-4100* machine (Figure 4) to determine the chemical makeup of numerous bio-aggregates before and after various tests. The testing was conducted by studying the vibratory sequences of the samples in the range of 650 – 4000 cm^{-1} with a 4 cm^{-1} scan resolution.

Figure 73 – Jasco FT/IR-4100 Machine

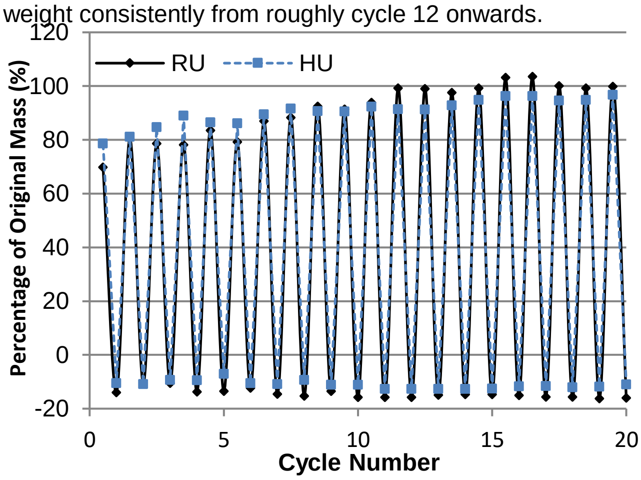
3 RESULTS AND DISCUSSION

3.1 Weathering

Mass Gain

The full immersion test was conducted over a period of 9 months (depending on the cycle lengths discussed in section 2.3). The changes in mass were recorded as the tests progressed and the comparative results for the aggregate types are presented in Figure 5 below.

As can be seen for both cases (untreated as well as with the VMA additive) the results are very close. As a percentage of the original mass recorded at the start of the test the hemp samples initially seem to gain the most mass however towards the end of the test the rapeseed samples begin to gain similar amounts of water and indeed for the untreated samples gain more weight consistently from roughly cycle 12 onwards.



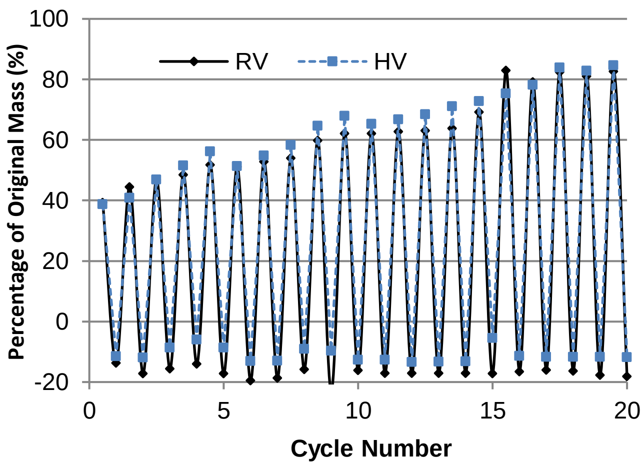


Figure 74 – Effect of aggregate type on mass change per cycle over time with regards to full immersion weathering

Figure 5 illustrates the differences in the microstructure of the two concrete types (hemp untreated and rapeseed untreated). It can be seen that considerable damage has been caused to the microstructure and a lot of the binder has been washed away in both cases, however this effect is more severe for the rapeseed samples.

Next the effect of the VMA on the samples were compared. Here the pattern is much clearer; for both aggregate types it is clear that the use of a VMA reduces the amount of mass gained. The reason for this is the same reason for the reduction in water absorption of the concrete samples observed by Sheridan et al. [2017]. Although, it should be noted that in both cases the VMA samples increase the amount of weight gained as the test progressed at a much faster rate than the untreated samples. A conclusion that could be drawn is that the VMA samples are more susceptible to the pore widening effect discussed above.

However, even with this alarming rise in weight gained per sample as the strength data will illustrate later in this section the untreated samples had almost failed by the end of the test. Thus, the increase by the VMA samples is less of a concern because they still held their compressive strength better in the final round of strength testing. The reason for this increase in amount of water absorbed and the sharp increase with time observed with the VMA samples is explained by a washing away effect that has been hypothesised. Testing is ongoing at present to highlight high levels of mineral leaching of vegetal concretes during immersion and drying experiments. This leaching increases the porosity of the bio-concrete and results in the sample absorbing more water with over time.

Sample Swelling

In addition to taking the mass of each sample before every wetting and drying cycle, the volume was taken. Presented are the results of the changes in cross-sectional area of the samples as the test progressed. It should be noted the results in the z axis are not presented as the top of the sample was obviously not flat and it was the exposed face during casting. This made the height an unreliable measurement as it varied slightly across the sample. Thus the swelling was considered only for the flat-edged cross-sectional area only.

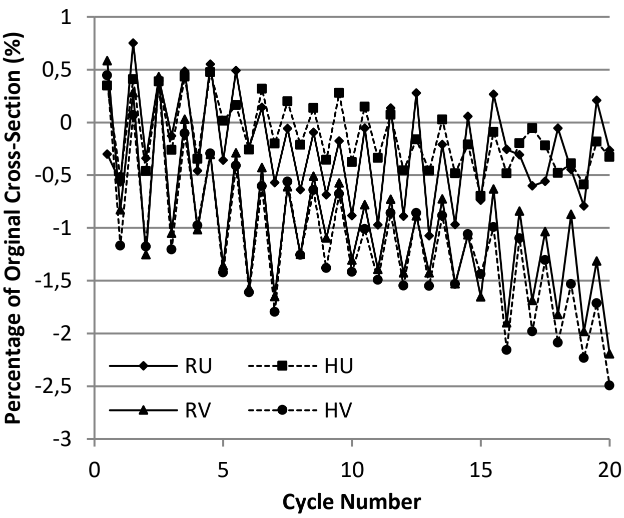


Figure 75 – Effect of VMA and Aggregate Type on Cross-Sectional Swelling of Concrete Samples

Figure 6 shows the cross-sectional changes due to weathering over time. The first thing to notice is that overall all the sample mixes lost area. Even if the changes were only small (in the range of 0.25 to 2.5% which is equal to 25 – 250 mm²) for a 100 mm³ cube if this is scaled up to a real life application of a house, a problem could arise. It is conceivable that an element of any of the studied samples could be fixed or glued between 2 other elements and shrinking like this could cause the build-up of internal stresses as the element shrinks and tries to pull away from its fixings. This potential concern would be more for the VMA samples compared to the untreated samples which reduced in area more. Again, though, it should be kept in mind that this 2.5% loss of area was the end product of an extreme test over a long period of time with a high severity, so the size of this concern could potentially be studied further and adjusted accordingly.

Also it can be seen that differences between the two aggregate types was relatively small nonetheless, the rapeseed samples shrank less than the hemp samples in both the untreated and VMA samples. Finally, it can be seen that towards the end of the test the untreated samples started to become extremely soft, which impacted on the swelling measurements. From cycle 16 onwards the defined structure of swelling during the wetting stage and contraction during the drying stage was lost, or at least much less defined. In contrast the rigid swelling and contraction remained throughout the end of the test for the VMA samples, also partially illustrating their partial resistance to weathering.

Strength Degradation

Finally, the strength degradation of the samples were monitored at periods throughout the experiment to determine the effect of the weathering upon the mix types and are presented in Figure 7.

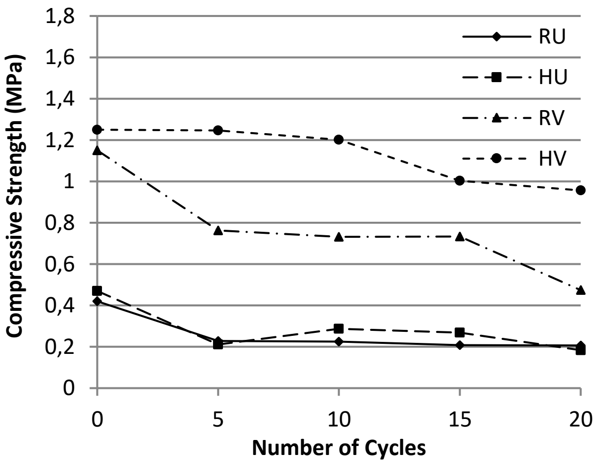


Figure 76 – Compressive Strength Development of Concrete Mixes During the Weathering Test

It can be seen that as the experiment progresses the strength of the VMA samples degrade however it does not with the untreated samples. This is reflective of the mass gain results discussed in section 3.1 where the increase in mass gain of the untreated samples does not really increase however for the VMA samples the mass gain progressively increases throughout the test. Again as discussed in the mass gain results this is because of the weakening of the ITZ, propagation of cracks in the microstructure and increase in the material porosity caused by the leaching and washing away of the binder in the bio-concrete matrix.

3.2 Carbonation

Finally, the effect of carbonation on the strength of the mixes was investigated, plotted in Figure 8 are the overall results of the development of the material's strength as the test progressed.

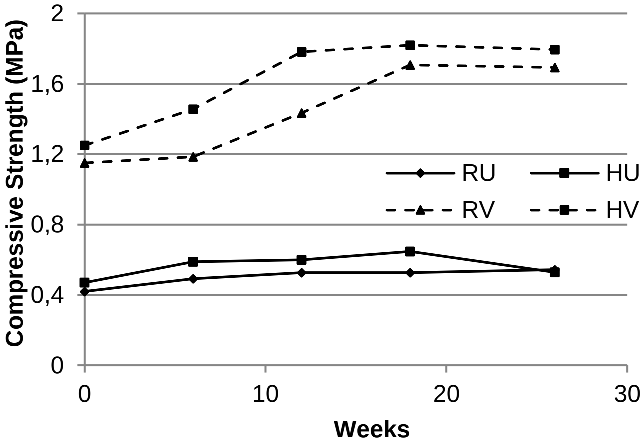


Figure 77 – The Effect of Carbonation on Compressive Strength of All Mixes

As can be seen, overall carbonation had a positive impact on the compressive strength on the mixes. The strength of the VMA samples especially improved dramatically.

However, despite the fact that on the surface it looks as if carbonation has aided the compressive strength of the untreated mixes it actually has inhibited the strength development when considering the strength development of the control samples. This is an interesting result and contradicts the common knowledge that carbonated concretes are stronger than uncarbonated bio-concretes [Chabannes et al. 2015]. This is confirmed when the difference in the results of the compressive tests between the tested and control samples are plotted as a percentage (Figure 9).

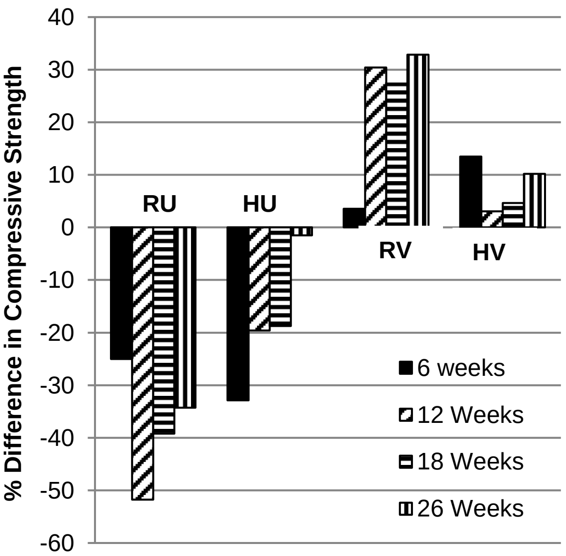


Figure 78 – Percentage Difference in Compressive Strength Between Tested and Control Samples for all Mixes

Figure 9 clearly shows that the carbonation chamber improved the compressive strength of the VMA samples compared to their equivalently aged control samples however the trend is reversed for the untreated samples. This is a peculiar result that needs to be investigated further.

4 CONCLUSION

The weathering testing revealed that initially the changes in mass with each cycle was very close between the hemp and rapeseed samples. It can be concluded that the hemp samples initially absorb more water during the weathering however over time with the increased propagation of cracks and damage to the ITZ it is the rapeseed samples that gain more mass from absorbed water.

Analysing the effect of adding a VMA it can be seen that with the drastic reduction in porosity the amount of mass gained from absorbing water is also drastically reduced because of the increase in density and reduction of porosity [Sheridan et al. 2017].

When investigating the swelling of the samples during this testing it can be concluded that all of the vegetal concrete mixes lost cross-sectional area over time; however, the VMA samples lost it at an increased rate when compared with the untreated samples. It could also be seen by the swelling patterns of the samples that by the end of the testing the untreated samples were starting to fail. However, the differences between the two aggregate types were negligible.

Overall, the compressive strength of all the samples was reduced as the test progressed; with the VMA samples experiencing the biggest weakening in strength compared to the untreated samples; although they had much more strength to lose to begin with.

The effect of carbonation on the compressive strength of vegetal concretes yielded mixed results. Overall all of the samples gained strength as the experiment progressed however when the strength results were compared with those of the control samples it was observed for both the hemp and rapeseed samples that the compressive strength of the carbonated samples was actually inhibited by carbonation and gained more strength when left to mature in indoor laboratory conditions with normal atmospheric carbon dioxide levels.

Conversely the hemp and rapeseed VMA samples both gained strength at an increased rate when compared with the control samples. With the rapeseed VMA samples gaining 32% more compressive strength compared to their control counterparts by the end of the experiment. Thus, it can also be concluded that the addition of a VMA into the vegetal mix increases the positive effect of carbonation on the concrete's strength gain. Whereas in the untreated mix carbonation has a negative effect on the strength gain of hemp and rapeseed concretes. This phenomenon needs to be studied further.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge Vicat for supplying the binder in this investigation and Larsen Building Products for supplying the VMA admixture.

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