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A Study on the Effect of Saturated Hemp Shives on the Compressive Strength of Concrete

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Abstract

Bio-based materials are often used in concrete production to increase the sustainability of the product. Key sustainable usages include carbon sequestration, lessening natural aggregate extraction, and easier decomposition after demolition. In addition to the sustainability factor, appropriate usage of bio-based aggregates that include plant fibres, husks and chips can improve concrete properties. Current research explores the possibility of utilising the superior water absorption capacity of porous hemp shives to increase the concrete compressive strength through optimising the cement hydration process. A systemic study has been conducted with varying hemp shive particle (1.18 to 2.36 mm) percent inclusion (3%, 2% and 1% mass of binder content). The resulting compressive strengths at 1, 3, 7 and 28 days curing age were recorded and obtained results suggest that hemp shives positively impact concrete curing. Furthermore, the difference between sealed and unsealed early-age curing conditions was minimal.

Keywords: hemp shive, concrete, compressive strength, curing, water absorption.

1. INTRODUCTION

In recent years scientists have explored the possibilities of hemp as a 'green' substitute/addition to concrete (Jami, Karade, & Singh, 2019). Hemp exhibits three useful properties, namely, its superior thermal insulation capacity, high acoustic resistance and low density that make it particularly favourable as a construction element. Its first use in construction dates back to the nineties as a bio-based concrete known as 'hempcrete' (Sassoni, Manzi, Motori, Montecchi, & Canti, 2014). While hempcrete is highly favourable from acoustic and thermal insulation aspects, it is reported to offer low mechanical compressive and flexural strength (0.12 to 2 MPa and 0.06 to 1.21 MPa, respectively) compared to ordinary concrete which limits its applicability as a structural building element (Arnaud & Gourlay, 2012; Elfordy, Lucas, Tancret, Scudeller, & Goudet, 2008; Walker, Pavia, & Mitchell, 2014). The low mechanical strength is often considered as a result of the highly porous structure of hemp shives (Sáez-Pérez, Brümmer, & Durán-Suárez, 2020), poor bonding between the shive and the concrete matrix (Balčiūnas, Vėjelis, Vaitkus, & Kairytė, 2013) and substitution of a hard element within the mix (aggregate) with a relatively 'softer' material (Awwad, Mabsout, Hamad, Farran, & Khatib, 2012). While used in hempcrete, hemp shives are used as the main aggregate and mixed with a binder as lime or cement. However, the porous structure of hemp shives could also be utilised as an internal source of water if that's added partially, on a saturated state within the normal concrete. These saturated hemp shives could supply water to the concrete mass and assist in aged hydration. A technique often termed as 'internal curing. Common internal curing agents (ICA) found in the construction industry are light-weight aggregates (LWA) and super-absorbent polymer (SAP), and recycled concrete aggregates (RCA) (Li, Liu, Xiao, & Zhong, 2020). Additionally, some natural sources of ICAs were also used as eucalyptus pulp fiber (Passarin Jongvisuttisun & Kimberly) and kenaf fiber (Gwon, Choi, & Shin, 2022). The utilisation of hemp shives as internal curing is yet to be found in the existing literature.

Thus, current research explores the possibility of using saturated porous hemp shives as an additive to the cement matrix. When added to a concrete mix in saturated conditions, it is expected that the shives will dissipate their absorbed water gradually as the concrete experiences self-desiccation due to evaporation. This additional internal water supply will aid in concrete hydration to offset the water loss due to evaporation resulting in an increased strength gain of the final concrete product. Within this research, a concrete mix will be prepared where hemp shives shall be added in varying amounts. Concrete cylinders will be produced using the mix and tested for compressive strength to observe the effect of hemp addition on concrete strength.

2. EXPERIMENTAL DETAILS

Hemp shives have been added by pre-saturated mass (3%, 2% and 1%) of binder content to concrete samples which were cured under sealed and unsealed conditions. Compressive strength testing was conducted at 1, 3, 7 and 28 days of curing to monitor the effect of evaporation and performance of the hemp shive when compared to a traditional (non-hemp) concrete control mix.

2.1. Hemp shives

Hemp shives, produced and processed in Victoria, Australia, were supplied by Australian Hemp Manufacturing Company, a subsidiary of Developing Sustainable Direction Pty Ltd (DSD). The particle size of the raw shives was widely variable between 30 mm to 0.5 mm. The mean size of the particles used in this study lies in the range of 1.18 mm to 2.36 mm, as classified by a combination of sieve analysis followed by image analysis techniques. The bulk density of the particles was 86.76 kg/m^3 with an initial water content of 8.75%. The water absorption capacity of washed samples was 335% of its own weight. Desorption was measured as 96% of its absorbed moisture at a relative humidity drop to 90% (from saturated conditions) (Nazmul, Garcez, Ashraf, & Sainsbury, 2022).

2.2. Mixture and composite preparation

A control mix was prepared according to ASTM C192/C192M (ASTM C192/C192M, 2019). The mix included Type I Ordinary Portland cement, 10 mm coarse aggregate, sand, and water with a target compressive strength of 50 MPa. The water-cement ratio was selected at 0.45 to represent a standard concrete mix. Hemp shives of predetermined lengths were added to the mix under Saturated Surface Dry (SSD) conditions at the specified dosage summarised in Table 1. The amount of binder and aggregates used to prepare each mix with varying hemp shive content. This was done to observe the effect of varying saturated hemp shives on the same concrete mass. A photograph of the batch mixing process is presented in Figure 1.

Table 1. Mixture proportion with hemp shive sizes and dosage

Mix ID	Sample Repeats	Curing Time (Days)	Hemp shive sizes	Hemp (% mass of binder)	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Water (l/m^3)
Control Mix (CM)	3	1,3,7,28	-	-	556	729	806	203.26
Non-cured Mix (NC)	3	1,3,7,28	-	-	556	729	806	203.26
MHS-3P	6	1,3,7,28	1.18	3.0%	556	729	806	203.26
MHS-2P	6	1,3,7,28	to	2.0%	556	729	806	203.26
MHS-1P	6	1,3,7,28	2.36mm	1.0%	556	729	806	203.26

Figure 1 Batch mixing hemp-concrete composite

Cylinders (100 × 200 mm) were prepared for each of the mix IDs and were kept at room temperature for 24 hours prior to demoulding. Upon demoulding, samples were then subjected to three different curing scenarios.

1. Control Mix (CM) samples were cured according to ASTM C192 / C192M-19 (2019).
2. No Curing (NC) samples were cured in 'air' at room temperature.
3. Sealed (S) samples were covered in plastic wrap to ensure minimum moisture loss. Samples were cured at room temperature.

Half of the samples that included hemp shives (MHS-3P, MHS-2P and MHS-1P) were subjected to NC conditions and half were subjected to S conditions to determine the effect of curing on the mechanical strength response. The hemp shives were saturated in water for 48 hours and then dried with paper towels to bring to SSD condition prior to including in the mix. The change in mass was recorded to estimate the additional water added to the concrete mix for curing.

3. RESULTS AND DISCUSSION

The compressive strengths of each of the batch mixes and curing conditions were tested following ASTM C39/C39M (2021) after 1 day, 3 days, 7 days, and 28 days. It was observed that the compressive strength of concrete with hemp as an additive varies with both hemp dosage and curing conditions. Obtained results are presented in Table 2.

Table 2. Density and compressive strength of composites

Mix ID	Curing condition	Density (kg/m3)	Compressive strength 28 days (MPa)	Comparison to CM at 28 days
Control Mix (CM)	Water	2505.31	48.12	0%
Non-cured Mix (NC)	Air	2435.24	41.78	-13.18%
MHS-3p	Sealed	2256.90	35.71	-25.79%
	Unsealed	2339.70	31.81	-33.89%
MHS-2p	Sealed	2305.73	44.31	-7.92%
	Unsealed	2388.54	39.33	-18.27%
MHS-1p	Sealed	2307.86	51.49	+7.00%
	Unsealed	2356.69	45.46	-5.53%

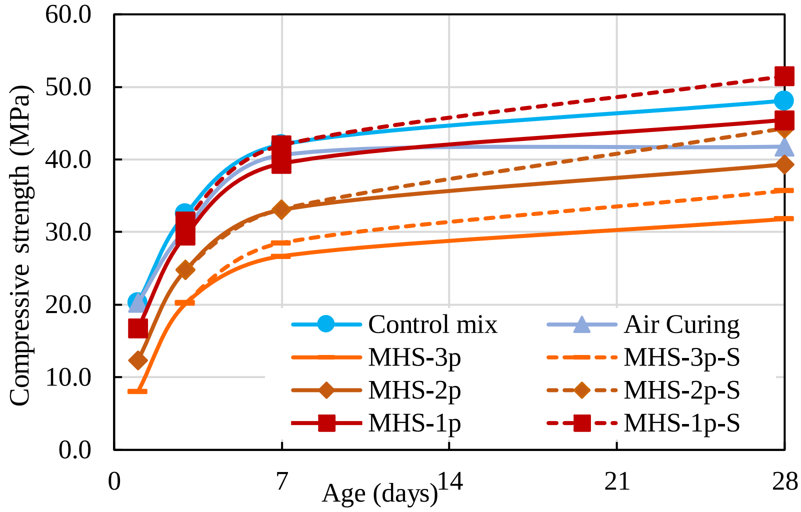

Figure 2 Compressive strength of hemp-concrete mixes under sealed and unsealed condition

The time-dependent strength gain for all samples is presented in Figure 2. There is a gradual decrease in the compressive strength of NC (air-cured) samples when compared to that of water-cured (CM) samples. This difference was initially low and increased with curing age. Thus, it can be confirmed that in the absence of proper curing, the mechanical strength may be reduced by about 13.18% after 28 days. In this case, seemingly evaporation in the absence of curing water limits the concrete from gaining its maximum strength.

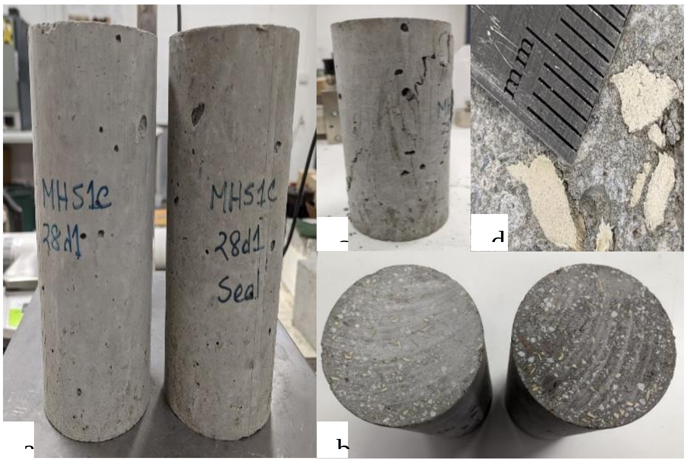

Figure 3 Image of a) Unsealed and Sealed hemp-concrete samples b) top view of sealed and unsealed samples c) cracked sample on 28 days d) magnified image of hemp shives in concrete

In the current experimental study, sealed conditions represent the case where the total water supplied by the hemp shives should be available for the hydration of self-desiccating concrete. Whereas in the unsealed condition samples, the effect of evaporation is observed on the available water for hydration. Therefore, the significant amount of water that can be supplied by porous hemp shives is more than sufficient to meet the need for both evaporation and cement hydration. This could also be observed in Figure 3 where the sealed specimen demonstrates to have a darker appearance compared to the unsealed specimen, which has dried to the exposure to air. Thus, it was observed for a particular percentage of hemp shives, the compressive strength of the sealed sample was higher than the unsealed cylinders.

As the proportion of saturated hemp shives was increased from 1 to 3% by mass into the concrete mix, there was a clear reduction in compressive strength, respectively 5.53-33.89% less than the control mix. It should be noted that the mass-wise increase of hemp shives proportionally increases the volume percentage of hemp shives with respect to the total concrete volume. Thus, the strength reduction could be attributed to the volume wise increase of hemp shives containing porous and soft intrinsic structure. The porous hemp shives replace stronger concrete elements and leave a negative effect on concrete compressive strength. Nevertheless, this effect can be optimised, as seen from the results of the mixes with 1% hemp shives. In this mix, the strength of the concrete is not undermined by excessive hemp inclusion. Rather the hemp inclusion promotes full uniform hydration of the cement providing a stronger product when compared to the control mix under ideal curing conditions.

Of note, in the test results, the 1% shive mix that was cured under sealed conditions reported a result that is 7% higher than the 28 days strength of the control mix. It can be observed in Figure 3 that the strength gain of the mix MHS-1p (when cured under sealed conditions) is far greater than the air-cured samples without shives. This can be simply explained as the relative humidity inside self-desiccating concrete drops below 93%, and self-desiccation starts to take place (presumably sometime after 3-7 days). The hemp shives release their absorbed moisture and aid in internal curing. Considering that no admixtures were used in these mixes, the reduction in relative humidity was natural – possibly due to self-evaporation and/or concrete hydration.

Seemingly, the internal curing water supplied by the soaked hemp shives was more beneficial at later stages of curing (7-28 days) for concrete hydration. However, in the early stages (i.e., 3 days - 7 days) it may be that due to the presence of sufficient water in the samples already, it is assumed that hemp shive could not release their absorbed water. Instead, the hemp left a negative effect on concrete compressive strength since their poor mechanical properties were only mobilised and not their hydration superpower.

It should be noted that this experimental program could not identify the optimum percentage of hemp shives which could maximise the compressive strength of concrete by supplying internal curing water. As the lowest percentage of hemp shives by mass was 1% of binder mass, it is possible that the inclusion of hemp shives at a lower percentage might yield a higher strength of concrete by internal curing yet maintaining a stronger structure of the concrete mass.

4. CONCLUSION

The research documents the effect of curing cementitious materials dosed with various volumes of saturated hemp shives. The followings findings are reported from the study.

1. The compressive strength of hemp-concrete composites decreases with an increase in hemp dosage.

2. Water stored in hemp shives aids in developing concrete compressive strength and is shown to be more effective with increased curing ages (e.g., 7-day +).

3. Restricting the effect of evaporation positively contributes to the compressive strength development of concrete by retaining the available moisture. Therefore, sealed cured samples perform better in compressive stress than unsealed samples.

4. At 1% dosage of hemp shives, under sealed conditions, the strength reduction due to the inclusion of the porous hemp structure is minimised to such an extent that the compressive strength is compensated by the effect of internal curing/hydration. In fact, in this case, at 29-days the sealed 1% hemp inclusion samples exceeded the compressive strength of the control mix by 7%.

These preliminary results suggest that a small, distributed volume of hemp shives in cement mixes provides positive strength benefits when long-term (28-day+) strength are considered.

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