Waste and Biomass Valorization

Hemp waste valorization as biofuel and cement replacement in cement and concrete production

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Abstract:	The growing interest in industrial applications of the hemp plant requires alternative solutions for disposing of hemp waste. At the same time, the concrete industry is seeking ways to reduce its environmental impact, which could be realized by partially replacing Portland cement with more sustainable materials. In this study, a two-step valorization strategy of hemp waste is explored, including the use of hemp waste as biofuel and the addition to concrete of the biofuel by-product, hemp ash, as partial cement replacement. Hemp waste was incinerated in a muffle furnace at different combustion regimes and the residual hemp ash was analyzed before being added to some concrete mixes. Concretes with different hemp ash replacements (5-25% by cement weight) were tested for compression strength, air content, workability, and water absorption. Results showed that hemp ash has the potential to be added to concrete as a filler to reduce environmental impact and costs at 5% cement replacement.
Response to Reviewers:	The authors would like to thank the reviewers for their constructive feedback. All comments have been addressed as detailed below. Changes to the manuscript are highlighted in yellow. 1)Add physical characterization data - particle size distribution and specific surface area Tests were done, data was generated, compiled and is now presented in the manuscript.(Page 4, lines 112-114; Page 10, Lines 226-232, and Figure 4) 2)Add a discussion (or warning) on the introduction of potentially harmful chemical

	elements in concrete, mainly alkalis (K and Na) and Cl. Discussion on the introduction of these elements has now been included in the manuscript. (Page 4, Lines 87-90; Page 7, Lines 183-186) 3)Update data on legalization of cannabis for recreational purposes (Canada) A statement updating the status of cannabis in Canada has been included, along with up to date cultivation data. (Page 2, Lines 51-53) 4)Figure 1 - Add scale to photos Scale has been added to the figure. (Page 6, Figure 1) 5)Figure 6 lacks clarity (lack of resolution) The resolution of the figure has been improved, and the numbering of the figure has been changed (following introduction of Fig. 4 so as to address a comment above). (Page 15, Figure 7) 6)It should be clear in the abstract that the material acts as a filler. The abstract has been revised to clarify this point. (Page 1, Lines 22-23)

Hemp waste valorization as biofuel and cement replacement in cement and concrete production

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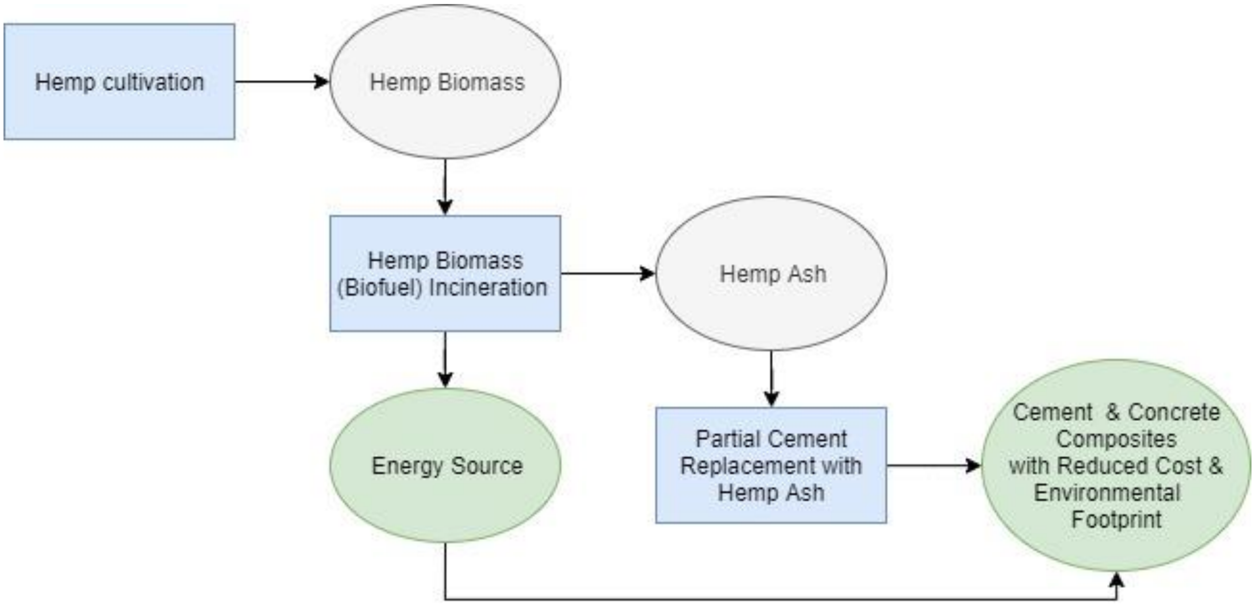
Abstract:

The growing interest in industrial applications of the hemp plant requires alternative solutions for disposing of hemp waste. At the same time, the concrete industry is seeking ways to reduce its environmental impact, which could be realized by partially replacing Portland cement with more sustainable materials. In this study, a two-step valorization strategy of hemp waste is explored, including the use of hemp waste as biofuel and the addition to concrete of the biofuel by-product, hemp ash, as partial cement replacement.

Hemp waste was incinerated in a muffle furnace at different combustion regimes and the residual hemp ash was analyzed before being added to some concrete mixes. Concretes with different hemp ash replacements (5-25% by cement weight) were tested for compression strength, air content, workability, and water absorption. Results showed that hemp ash has the potential to be added to concrete as a filler to reduce environmental impact and costs at 5% cement replacement.

Keywords: Hemp biomass; Biofuel; Hemp Ash; Supplementary cementing materials; Cement; Concrete; Incineration

Graphical abstract:



Statement of novelty: The main novel contributions of this study is the suggestion to use hemp ash as a partial cement replacement that can reduce concrete environmental footprint and costs. This solution can also help address the management of hemp ash, a by-product of using hemp waste as biofuel. Information available on hemp as biofuel and especially on the characteristics of the resulting hemp ash is limited and this publication helps shed some light on the physical and chemical properties of hemp ash.

1 Introduction and background

Industrial hemp cultivation is growing globally under restrictive laws and regulations [1, 2, 3]. Industrial hemp is cultivated mostly for production of seed and fiber and it contains extremely low amounts of the psychoactive cannabinoid **Δ** 9-tetrahydrocannabinol (THC). Cannabis plant which contains less than 0.3% THC is defined as hemp. Legality of hemp cultivation varies worldwide. In Canada, hemp cultivation has been allowed since 1998 and is regulated by Health Canada as per Bill C-45 (2018) [4], otherwise known as the Cannabis Act. Legal cannabis production for medicinal purposes increased approximately 8 times [5] and is expected to considerably increase with the legalization of cannabis for reactional purposes. Canada legalized recreational cannabis in October 2018, and as of November 2019, the data for licensed indoor and outdoor cultivation areas stands at 1,415,869 m^2 and 185 ha [6]. In the United States, hemp cultivation was legalized in 2018 as per the Agriculture Improvement Act (2018) [7], also known as the Farm Bill, removing it from the list of controlled substances.

One of the major difficulties of hemp production is the large amount of biomass and waste generated from the harvest of the plant. Hemp has large dry matter yield (about 10 tons per ha) [8] with relatively low moisture content after drying in the field (about 20%) [9]. The growth of the hemp plant in about 4 months produces 4–5 times more biomass than that of a forest with the same extension in a year [10, 11, 12]. While the leaves, flowers and seeds are of primary interest in the production of medical cannabis products, disposal of the remaining waste product is an issue to consider. Hemp waste is defined as the hemp stalk without leaves, flower and seeds, which currently is deposited in landfills. The worldwide increase in hemp production requires alternative solutions for sustainable waste management.

The net calorific value of hemp (13.4 MJ/Kg) is higher than that of other biomass, such as wood residue (10 MJ/kg) and starch (13 MJ/Kg), so higher heat is released when a unit quantity of the hemp is burned [13, 8, 9]. Hence, the hemp waste is a potentially highly effective biomass and energy-yielding crop for biofuel applications [14]. However, this solution has been rarely reported, partly due to some unfavorable hemp properties such as low bulk density [15] and the additional energy required for handling, transporting, and processing the residual ash [16]. Hemp waste minerals include calcium (Ca), potassium (K), phosphorus (P) and magnesium (Mg), but limited information is available on the chemo-physical properties of the hemp ash [17, 18, 19].

The large availability of hemp biomass as an industrial by-product can help address the pressing demand for the concrete and cement industry to reduce their environmental impact. Concrete is the most widely used material on earth apart from water, with annual cement production now approaching 4 billion tons. Amongst the main challenges currently facing the cement industry, lie the need to reduce the embodied energy and CO_2 emissions of cement manufacturing. Studies reported that Portland cement production is responsible for 2-3% of global primary energy use [20] and ~5% of man-made CO_2 emissions [21].

Introducing hemp biomass in the cement manufacturing process could partially address both of the described challenges, while solving the problem of reducing waste accumulation by the hemp industry. There is a history of recycling ashes & mineral powders collected from other manufacturing process and use them as partial cement replacement (e.g. fly ash, silica fume, or ground granulated blast furnace slag) to reduce costs and environmental impact of concrete and/or to improve some concrete properties. In addition, ash from other types of local and largely available organic materials is used as SCM worldwide (e.g. rice husk [19], banana leaf [22] and bamboo leaf [23]). In this regard, the influence of ash constituents on the concrete properties is important. For example, the high amorphous silica content is beneficial for the Pozzolanic reactivity of the ash, but constituents such as alkalis (Na, K), chloride and sulfate can negatively affect the concrete properties [24]. While hemp hurds mixed with lime have limited use in the production of non-structural construction materials such as hempcrete [25], the use of the waste hemp ash in structural concrete is an as-yet non-researched topic.

In the following study, the authors suggest the hypothesis that hemp biomass can be used as a biofuel and, moreover, it is hypothesized that the by-product of the hemp biofuel, that is, hemp ash, can be employed as a partial replacement of common Portland cement in concrete, thereby reducing the overall cement content in concrete and, hence, concrete's embodied energy, CO_2 emissions, and cost. The study is subdivided into two main stages as follows: (i) analysis of the incineration process and its influence on the final characteristics of hemp ash and (ii) assessment of the effect of the ash addition on the main engineering properties of concrete. A discussion on the overall CO_2 emissions embodied in the process follows.

2 Experimental materials and methods

2.1 Hemp ash characterization

The physico-chemical properties of hemp ash depend on the temperature and the duration of the thermal treatment, i.e. the combustion regime. For the sake of higher efficiency, a low firing temperature and a short retention period to produce an ash with a low carbon content and a high surface area are preferred [26, 27, 28]. The hemp waste as raw air-dried "stalk" was provided by Next Leaf Solutions Ltd. The muffle furnace was used for incineration at different temperatures (500°C, 600°C, 800°C) and durations (1 hour, 4 hours, and 6 hours). The produced ash morphology, chemistry and composition were analyzed by using x-ray diffraction (XRD), x-ray fluorescence (XRF) and scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS) analysis [28]. The selected hemp ash for use in concrete was further analyzed for particle size distribution and specific surface area by using laser diffraction and BET nitrogen absorption methods, respectively [25, 26, 27].

2.2 Concrete specimens

To assess the behavior of hemp ash in concrete, concrete specimens were prepared with the mixture designs shown in Table 1. Two mixtures with water to binder ratios (w/b) of 0.5 and 0.55 were prepared. The binder was modified by varying the levels of cement replacement with hemp ash in the amounts of 5%, 15%, and 25%. Hence, the cement content was changed slightly in order to maintain a constant binder fraction (Table 1). The maximum size of the coarse aggregate was 12mm. Commercially available polycarboxylate-ether based superplasticizer (Sika ViscoCrete 2110) was added when necessary to maintain the workability of the concrete mixtures. 75x100 mm concrete cylinders were cast as per CSA A23.2-3C. Cylinders were demolded 24 hours after casting and placed in a controlled curing environment with the standard temperature of 23 ± 2°C and 95% relative humidity until the time of testing. For each concrete mixture, compressive strength was measured at different maturity levels (i.e. 3, 7, 14, and 28 days) following the standard methodology recommended by CSAA23.2-9C [29]. Final water absorption [30], as an indication of the apparent porosity [31, 32], was also determined after 56-day curing, when the concrete microstructure can be considered stabilized. Three replicates were employed for each species and test. Standard tests on the fresh properties of concrete during placement were conducted throughout the program (density, air content, and slump test as an indication of the concrete workability [29]).

Table 1: Concrete mixture proportions with different water binder (w/b) ratios and hemp ash replacements

Material (kg/m^3)	w/b=0.5				w/b=0.55			
	Hemp Ash Percentage				Hemp Ash Percentage			
	0	5	15	25	0	5	15	25
General Use Portland Cement	430	408.5	365.5	322.5	420	399	357	315
Hemp Ash	-	21.5	64.5	107.5	-	21	63	105
Coarse Aggregate	920	915	910	910	900	900	890	880
Fine Aggregate	665	665	660	650	855	855	650	650
Water	215	215	215	215	231	231	231	231
Superplasticizer	-	0.25	0.3	1	-	0.25	0.5	1.75

3 Hemp incineration and hemp ash characterization

3.1 Combustion regimes, by-products, and macroscopic observation

Samples of hemp waste were incinerated in a muffle furnace at different combustion regimes. Combustion at lower temperatures and shorter times is preferred in the interests of energy economy. The ashes produced at different combustion regimes are shown in Fig. 1.

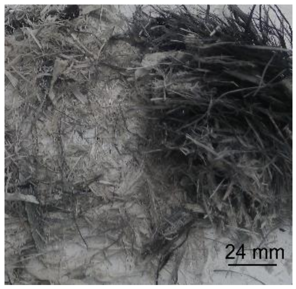
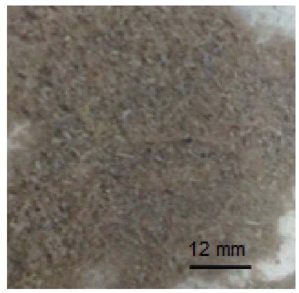
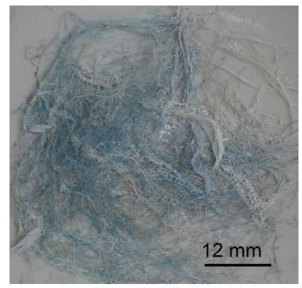
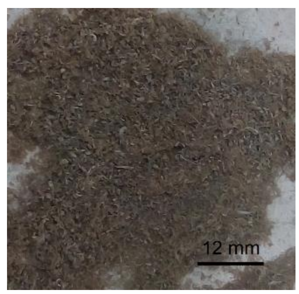
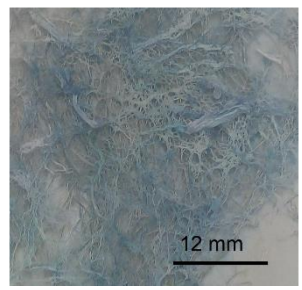
Combustion Regimes			
Temperature- Hour	500°C-1h	600°C-4h	800°C-4h
Produced Ash			
Temperature- Hour	500°C-4h	600°C-6h	800°C-6h
Produced Ash			

Figure 1: By-products of hemp waste incineration at different combinations of temperature (500°C, 600°C, and 800°C) and time (1h, 4h, and 6h).

The minimum combustion temperature and time were 500°C and 1 hour, respectively. The presence of unburned and dark wood pieces indicates an incomplete process of incineration (Fig. 1, 500°C-1h). The increase in combustion time from 1 hour to 4 hours produced a more uniform white ash (500°C-1h vs 500°C-4h, Fig. 1). This subsequently decreased the ash content from 8% by weight in 500°C-1h to 4% in 500°C-4h. The lower weight of the incineration by-product at 500°C-4h compared to 500°C-1h was due to evaporation of more impurities at a longer combustion time (i.e. 4h). One-hour combustion was insufficient for removing impurities, and hence, longer combustion times of 4 and 6 hours were selected for the subsequent stages of the research, at higher combustion temperatures (600°C and 800°C). The incineration at 600°C changed the ash color to more brownish (Fig. 1, 600°C-4h, 600°C-6h) with 3-4% by-product by weight. The combustion at 800°C changed the ash color to white (Fig. 1, 800°C-4h, 800°C-6h) with strips of greenish-blue and decreased the ash production to ~1% by the original weight of hemp waste with moisture content of lower than 20% by weight. At both temperatures (600°C and 800°C), the increase in combustion time from 4 to 6 hours had an insignificant influence not only on the ash production and color but also on its morphology. The ash produced at 800°C was somewhat coagulated, however, it could be dispersed with a rather minimal force. This is important to consider because the slagging and fouling tendency of the ash can be detrimental to the functioning and life span of a furnace [24].

3.2 Microanalysis of hemp ash composition and morphology

The morphology of the hemp ash obtained from the 500°C-4h regime is shown in Figure 2. The particles' rough surface and the porous structure could be beneficial to its reactivity as supplementary cementitious material (SCM) in concrete but, may increase the concrete's water demand thereby impacting workability, strength, and overall porosity. This observation is consistent with the need to use more superplasticizer in the concrete mixtures with larger hemp ash replacement during the second stage of the research (see Table 1 and Chapter 4.1). The XRF analysis of the ash produced at different combustion regimes indicated low silicon (Si) and high potassium (K) contents and a large amount of light elements (Table 2). Pozzolanic reactivity of the ash would be desirable to enhance the composite microstructure and engineering performance (e.g. strength and durability). However, a significant presence of amorphous silica (>50% of SiO_2 content) would be required [24], thereby suggesting that the hemp ash may act primarily as a filler with possibly a low or negligible pozzolanic reactivity within the cement composite. It must be noted that the use of low-reactive or non-reactive fillers for various reasons (including economic and environmental reasons or the need to control the heat of hydration) is not new to concrete technology and practice [33, 34, 35]. A high amount of alkalis in concrete (from different sources such as cement or additives) should be avoided as they can react with certain aggregates to produce an expansive gel (known as the alkali-silica reaction) which subsequently induces cracking in concrete structures [24]. The high alkali (K) content in the biomass also reduces the fusion point of the ash, while increasing the fouling and slagging tendencies [36]. The slagging tendency of the hemp ash was observed at the higher temperature (as discussed previously). The crystalline compounds of the hemp ash are explored in the next paragraph and can help clarify the alteration in the ash composition at different combustion regimes.

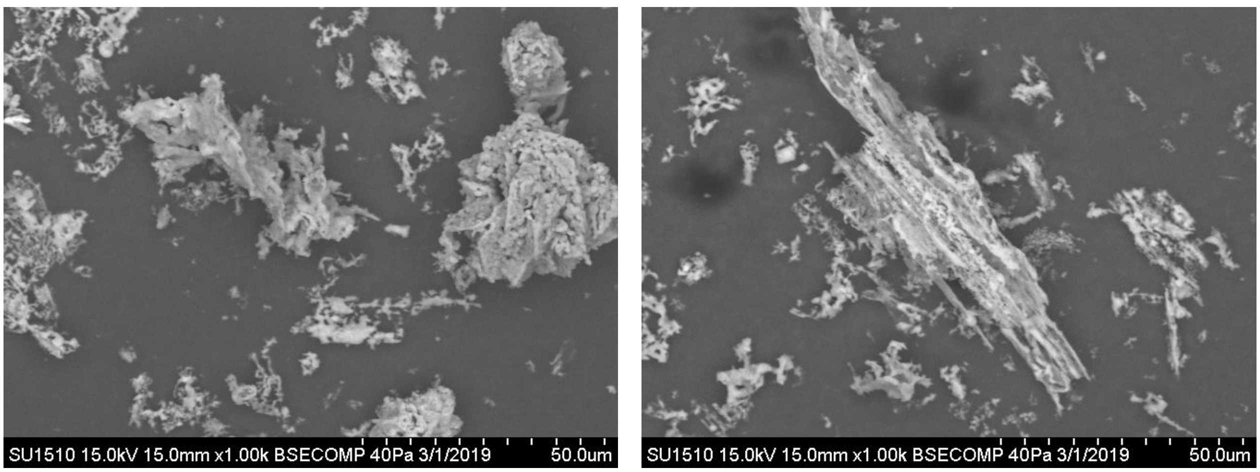


Figure 2: SEM/EDS micrograph of the produced ash at combustion regime of 500°C- 4h (see Fig. 1)

Table 2: Oxide composition of hemp ash at different combustion regimes (see Fig. 1)

Code	Ca (%)	Si (%)	P (%)	S (%)	Mg (%)	Al (%)	K (%)	Mn (%)	Fe (%)	Sr (%)	LE* (%)
500C-4h	15.73	1.17	0.59	0.82	0.23	-	22.94	0.15	0.18	0.13	58.06
600C-4h	11.63	0.76	0.24	0.55	0.25	0.38	24.04	0.09	0.11	0.10	61.85
600C-6h	11.53	0.66	0.13	0.41	-	0.25	22.12	0.06	0.11	0.10	64.63
800C-4h	21.39	0.95	0.40	0.54	-	0.22	15.45	0.16	0.33	0.17	60.39
800C-6h	30.28	0.79	0.49	0.62	-	0.20	10.04	0.20	0.26	0.28	56.84

*Light element (LE) are the elements with atomic weights lower than Mg in the periodic table, (e.g. B, N, Na, etc.)

The XRD patterns of hemp ash from different combustion regimes are presented in Fig. 3. The diffraction peaks in the XRD patterns were analyzed by means of the DIFFRAC.EVA software to identify the crystalline phases in the sample. A compound is detected in a sample when 2θ of the main peaks of that compound (derived from DIFFRAC.EVA database) match the XRD pattern. The peaks for calcite ($CaCO_3$), strontium chloride hydroxide hydrate ($Sr_2Cl_2(OH)_2)8H_2O$) and fairchildite ($K_2Ca(CO_3)_2$) were obviously found in 500°C-4h sample (Fig. 3). The absence of such well-pronounced peaks in other patterns (Fig. 3) is due to the evaporation of impurities from the sample as a result of the higher temperatures employed (600°C, 800°C) and the ensuing formation of new compounds. Therefore, strong peaks of Calcium oxide (CaO), Zeolite ($Na_{12}(Al_{12}Si_{12}O_{48})27H_2O$), Potassium chloride (KCl) and Magnesia (MgO) in addition to other potassium and magnesium-containing compounds were detected at higher temperatures (Fig. 3, 600°C-4h, 600°C-6h, 800°C-4h, 800°C-6h). The most intensive combustion regime - at the highest temperature (800°C) and longest duration (6 hours) - weakened the peaks of impurities such as KCl and Zeolite, while making CaO peaks stronger (Fig. 3, 800°C-6h).

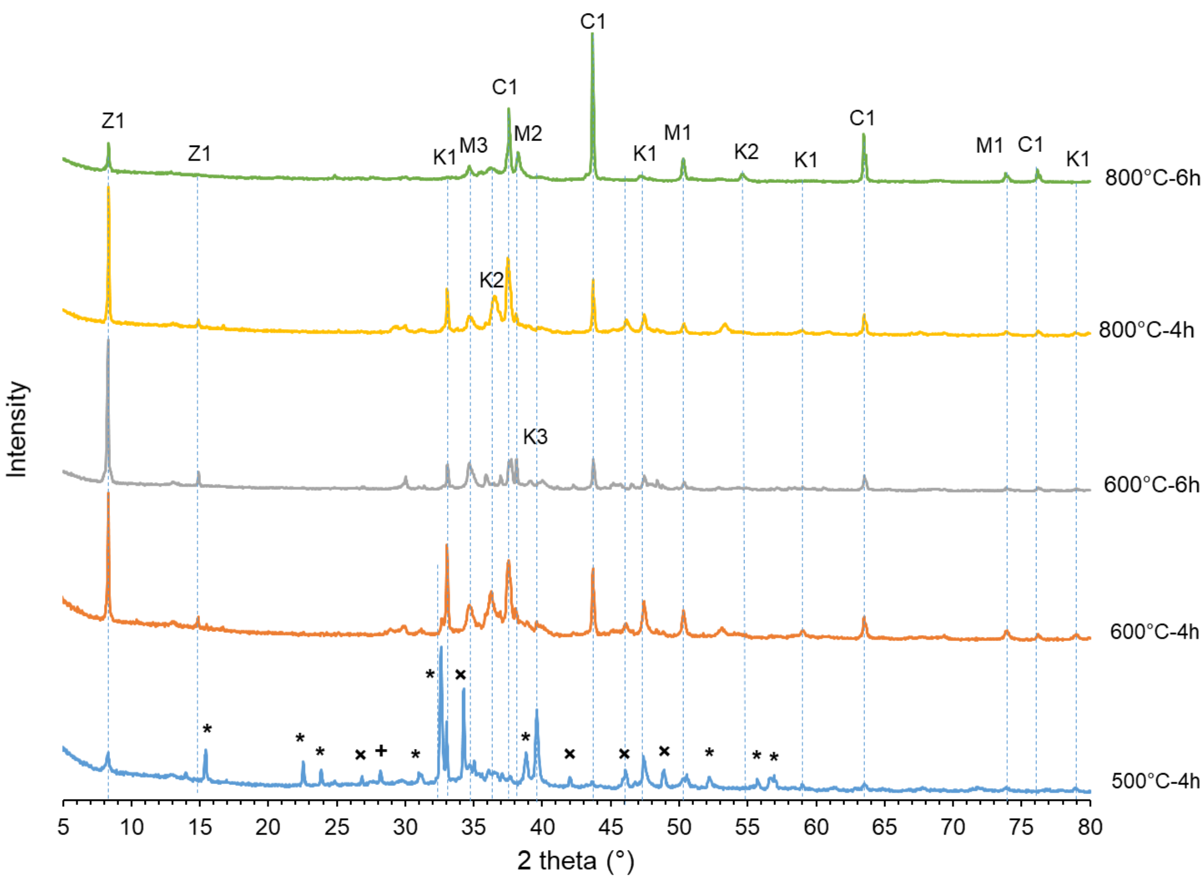


Figure 3: XRD pattern of hemp ash after incineration at different combustion regime; M1=Magnesia (MgO), M2=Magnesium carbonate ($MgCO_3$), M3=Magnesium calcite ($MgCa(CO_3)_2$), K1=Potassium chloride (KCl), K2=Dipotassium phosphate (K_2HPO_4), C1=Calcium oxide (CaO),

Z1=Zeolite ($Na_{12}(Al_{12}Si_{12}O_{48})27H_2O$), "+" Strontium chloride hydroxide hydrate ($(Sr_2Cl_2(OH)_2)8H_2O$), "×" Calcite ($CaCO_3$), "*" Fairchildite ($K_2Ca(CO_3)_2$)

4 Addition of hemp ash to concrete

The XRF and SEM analysis indicated that the probability of pozzolanic reactivity of the hemp ash was quite low. Thereafter, hemp ash could be added to concrete as a non-reactive cement replacement (or filler). The performance of hemp ash in concrete was studied after open field burning with relatively low temperature and uncontrolled burning process [24], followed by oven combustion of the collected ash at 250°C for 2 hours. The effect of the ash on concrete properties is dependent upon its physical parameters, i.e., particle size distribution and surface area. Therefore, the particle size distribution of the used hemp ash in concrete is shown in Fig. 4. The particle size distribution and the mean particle size of hemp ash were determined by laser diffraction [27]. The mean particle size of hemp ash is 215.5 µm (2-1000 µm range, hence larger than cement grains ~7-200 µm). The corresponding specific surface area determined by the BET nitrogen absorption method is 2.51 m^2/g.

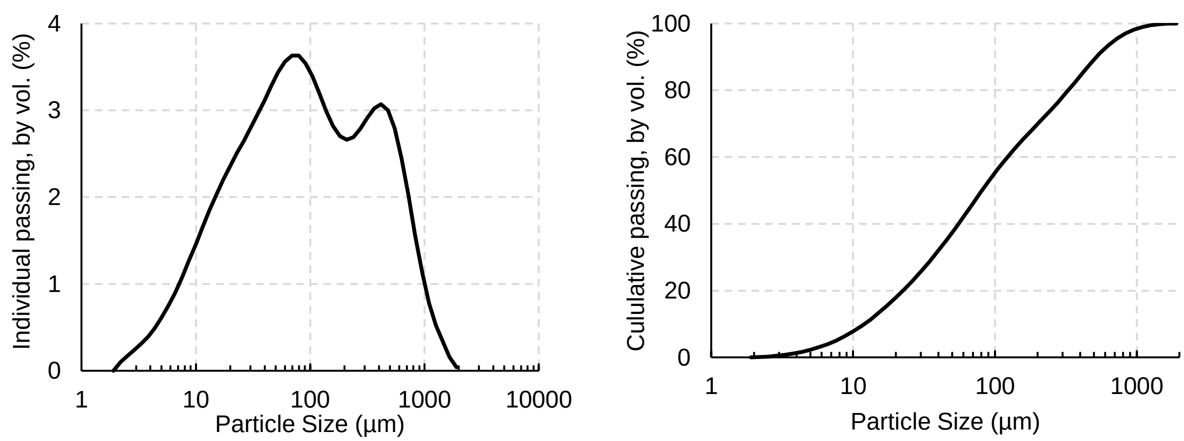


Figure 4: Particle size distribution of hemp ash used in concrete.

4.1 Fresh properties

The fresh concrete test results are summarized in Table 3. There appears to be no relation between the ash content and density/air content of the mixtures. The density of the mixtures varied in between 2321 to 2401 kg/m^3 with 1.4-2.6% air content (except the control case of w/b=0.5 with 4% air content). Superplasticizer was added to the mixes as necessary to try and maintain a workable mix while avoiding segregation. Despite greater volumes of superplasticizer being added to the mixtures with higher ash content (from 0 kg/m^3 in control case to 1-1.75 kg/m^3 in the 25% hemp ash mixture as shown Table 1), the workability was significantly reduced (Table 3). This trend was consistent in both w/b ratios. Hence, the measured slump decreased from 210-250 mm for the control cases to 0-35 mm in the mixtures with hemp ash (Table 3). The mixtures with w/b=0.5 containing 15-25% hemp ash and 0.3-1 kg/m^3 superplasticizer had extremely dry consistency with zero slump (see Table 3). Similarly, the slump of the mixture with w/b=0.55 containing 25% hemp ash and 1.75 kg/m^3 superplasticizer was very low (35 mm). The lower workability of the mixtures containing ash is likely due to the rough and porous structure of hemp ash (see Fig. 2) as discussed in Chapter 3.1. The rough surface of the ash increases the friction between the particles, while the porous structure increases the absorption of free mix water [32, 37]. Therefore, external consolidation using a vibrating table was necessary to achieve satisfactory concrete compaction into the molds. These mixtures would require an even higher amount of plasticizer and/or water to achieve similar slump values to those of the respective control mixes. As a result, mixtures with 15-25% of hemp ash replacement are considered economically and practically unfavorable.

Table 3: Fresh concrete properties of different mixtures (see Table 1)

Fresh concrete properties	w/b=0.5				w/b=0.55			
	Hemp Ash Percentage				Hemp Ash Percentage			
	control	5	15	25	control	5	15	25
Density (kg/m^3)	2347	2369	2351	2356	2401	2352	2327	2321
Air (%)	4	2.6	1.7	2	1.4	2.2	2.3	2.2
Slump (mm)	210	85	0	0	250	220	190	35

4.2 Compressive strength

Compressive strength test results are summarized in Fig. 5. A minimum of three cylinders was tested for each mixture at each stage of testing. Hence, the given results are average values with corresponding standard deviations. There is a common trend between the mixtures with w/b ratios of 0.5 (Fig. 5a) and 0.55 (Fig. 5b) at different hemp ash contents. The compressive strength decreased with increasing the ash replacement in the mixes. For instance, an increase in ash content from 5% to 25% caused an increase in the 28-day compressive strength loss by a factor of 8% to 42%. The compressive strength loss is a macroscopic indication of the negligible beneficial reactivity discussed in section 3.2 and maybe emphasized by the particles' water absorption, which will affect compaction and hydration at higher replacement levels. The minimum reduction in compressive strength for mixtures with 5% hemp ash indicates that the hemp ash is viable filler in concrete when applied at low percentages for economic and environmental reasons.

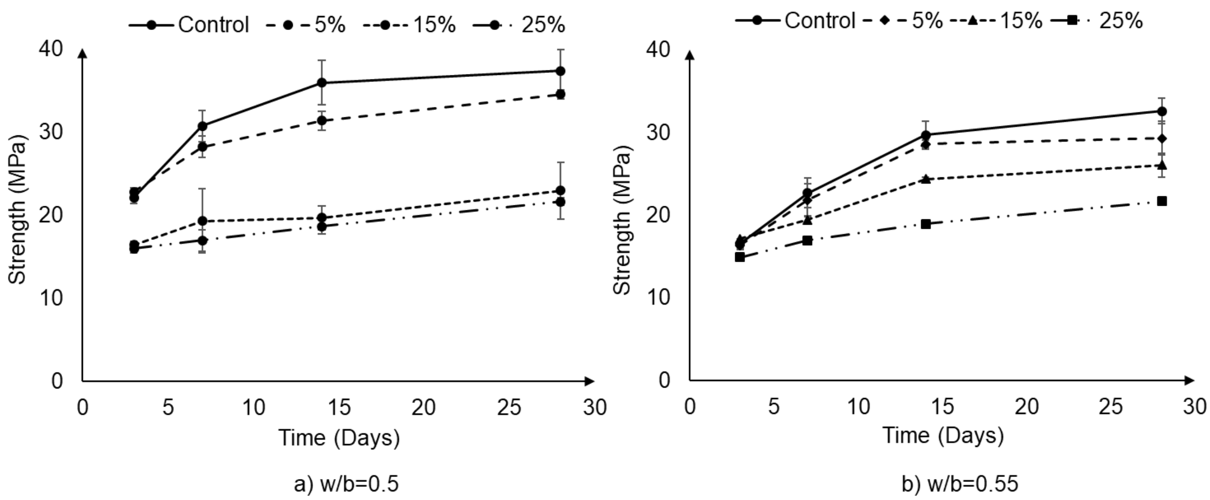


Figure 5: Average compressive strength and the standard deviation of mixtures with different percentage of hemp ash replacement (control, 5%, 15%, 25%); a) w/b=0.5, b) w/b=0.55

4.3 Water absorption

As expected, and similar to what reported for fresh properties and compressive strength, water absorption and porosity of concrete were affected by the hemp ash proportion in the mixture. The water absorption increased with the increase in the amount of hemp ash in the mixes (see Fig. 6). The water absorption was 5.3-7% in control case, increasing to 6.9-7.6% in 5% hemp ash content, 7.8-8.2% in 15% hemp ash and 8.1-8.8% in 25% hemp ash content. The higher water absorption of 15-25% hemp ash content is consistent with the previous discussion on the side effect of higher hemp ash replacements on densification of the binder matrix. Entrapping of water-filled pores between ash particles during the mixing of concrete ingredients can subsequently turn into voids. This, combined with the porous structure of the hemp ash particles (Fig. 2), justify the higher water absorption at 15-25% hemp ash.

Compatibly with the conclusions drawn from compressive strength and workability data, water absorption results suggest that, while 15-25% replacements may not be recommendable, the use of 5% hemp ash as supplementary cementing material has a minimal side-effect, which can be accepted at the benefit of lower cost and environmental impact.

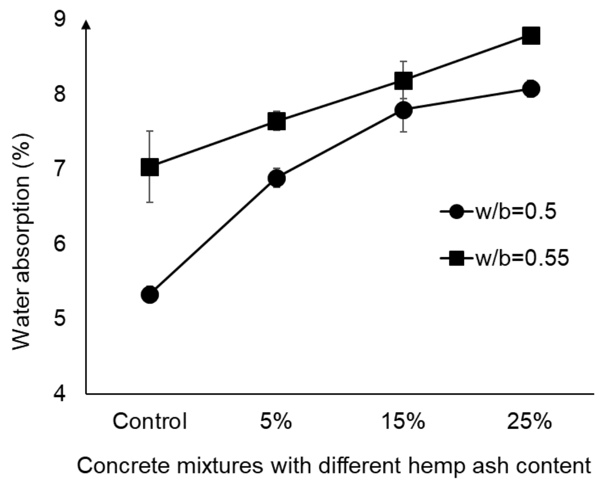


Figure 6: Average water absorption and the standard deviation of mixtures with different w/b ratio and percentage of hemp ash

5 Carbon Footprint and Environmental Impacts

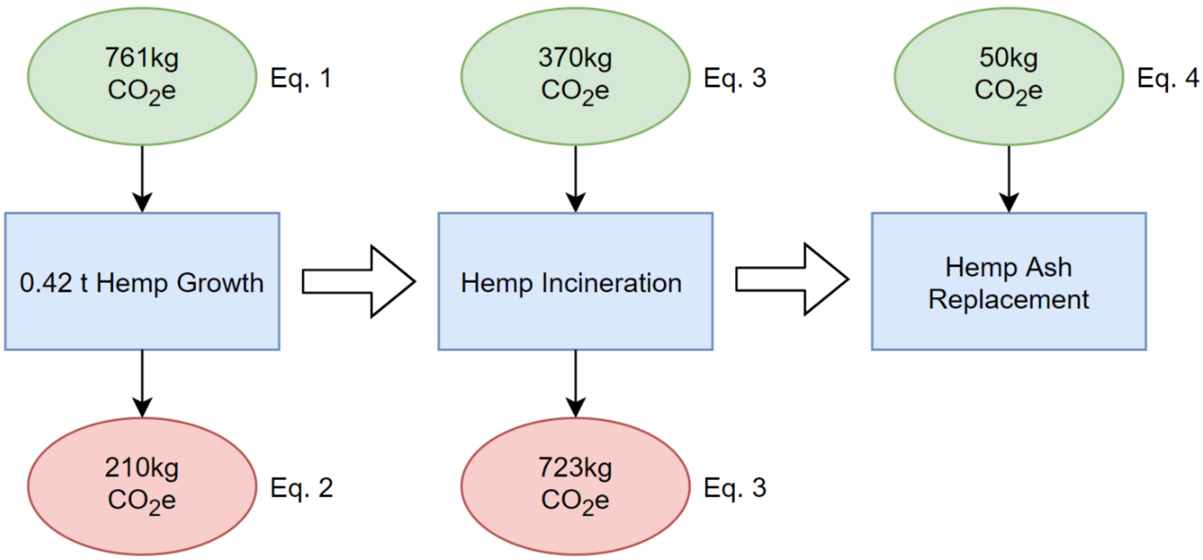
Research into the energy and carbon balance of hemp grown to be used as a biofuel is presently being carried out. This section is not meant to be a comprehensive examination of the topic, but meant to provide some insight into its potential feasibility for use as a source to power a cement kiln. Moreover, some preliminary numbers are presented attempting to quantify the carbon footprint and potential environmental benefits by using hemp in the cement production process, and incorporating the ash into a conventional concrete mix design.

With regards to the carbon footprint related to the incineration of hemp for use as a biofuel, there is some debate. Because most types of biomass are less energy-intensive than fossil fuels, the use of biomass to substitute for fossil fuels will nearly always initially increase emissions to the atmosphere. Indeed, it should be noted that the full environmental benefits of using a biofuel such as hemp can only be met when the crop is regrown which may take years. The preference in the absence of re-growing biomass is to use a residual crop which would otherwise decompose and emit CO_2 to the atmosphere on its own if not otherwise used for energy recapture. This assumption is used in the discussion in this section.

Industrial hemp has been scientifically proven to absorb more CO_{2eq} per hectare than any forest or commercial crop, and therefore is potentially, a very potent carbon sink (-). Vosper [38] estimated that 1630 kg CO_{2eq}/t were absorbed by hemp straw. The cultivation and harvest of hemp, however, have carbon emissions associated with it (+). Barth and Carus [39] calculated the emissions associated with cultivation and harvest of hemp varied depending on the type of fertilizer used, between 450-600 kg CO_{2eq}/t of hemp straw produced. Using data from Andreae and Merlet [40], and assuming a 90% conversion rate of hemp straw into biomass, we can calculate the approximate CO_{2eq}/t emitted during the incineration of hemp straw, to be approximately 1722 kg CO_{2eq}/t. This is much less than the 2176 kg CO_{2eq}/t emitted during the incineration of a fossil fuel such as bituminous coal [41].

Broadly speaking, the literature suggests net energy yields per hectare and energy output-to-input ratios of hemp are above average in most applications, and are highest for use of hemp as solid biofuel [42, 43, 9]. Several factors affect the net energy yield of the crop, including, but not limited to growing locations, climate, and time of year the crop is harvested [44]. Prade [42] calculated the net energy yield of hemp harvested for use as a solid biofuel to be approximately 65 GJ/Ha. The yield of hemp will depend heavily on the location and soil conditions. As per Prade [42] for this discussion, an average yield of 5.8 t/Ha is assumed, meaning the net energy yield of 1 t of hemp is 11.2 GJ/t.

Depending on the type of kiln used, the energy consumed in the production of cement clinker in Canada varied, between 3.6-6.0 GJ/t [45]. Average energy consumption was 4.69 GJ/t. Therefore, as per the information in the previous paragraph, assuming the use of an energy-efficient kiln, we can assume approximately 0.42 t of hemp is required to produce 1 T of cement clinker. In comparison, assuming an energy yield of 28 GJ/t for coal [45], it would require 0.17 t of coal to produce an equivalent amount of cement clinker.



Eq.	Description	Calculation	Net (kg $CO2_{eq}$)	Ref.
Eq. 1	Sequestration of Atmospheric CO_2 as Hemp is grown in a field	1630 kg CO_{2eq}/t x 0.42t x 0.9^{-1}	-761	[38]
Eq. 2	CO_2 generated during the cultivation of Hemp	450 kg CO_{2eq}/t x 0.42t x 0.9^{-1}	210	[39]
Eq. 3	Replacement of Coal in Cement Kiln with Hemp Biomass	2176 kg CO_{2eq}/t x 0.17 t	-370	[41]
Eq. 4	CO_2 emitted during the incineration of Hemp Biomass (assuming 90% conversion)	1550 kg CO_{2eq}/t x 0.42t x 0.9^{-1}	723	[40]
Eq. 5	Replacement of 100% cement with 95%/5% Cement/Hemp Ash blend	1000 kg CO_{2eq}/t x 0.05 t	-50	[45]
			-248	

Figure 7: CO_{2eq} generation and reduction due to use of Hemp Biomass in Cement production

A hypothetical scenario was devised which involve the following:

1. The growth of a quantity of hemp straw in an outdoor environment to be used as a biofuel to heat a cement kiln to produce 1 t of clinker.
2. Incineration of the hemp, and use the heat generated to fire a cement kiln (biofuel).
3. Use of the ash byproduct from hemp incineration to replace a portion of the cement used (5%) in a conventional concrete mix.

The schematic in Fig. 7 shows the net CO_{2eq} emissions generated in this scenario. Note that there is assumed to be a reduction in CO_{2eq} generated as emissions from 0.17 t of coal are replaced by 0.42 t of hemp biomass. Moreover, it is assumed that there will be a 5% reduction in the amount of clinker required by replacing it with the waste ash generated from the hemp incineration process.

Overall, the net balance indicates a net reduction in CO_{2eq} of 248 kg /t of clinker produced. We recognize that there is not entire consensus in some of the numbers used in this analysis, and moreover, there will be variability depending on several factors (yield of hemp, efficiency of cement kiln, type of fuel used to power the kiln in the absence of hemp), but the rudimentary analysis seems to suggest that the concept has some merit and is worth investigating further.

6 Conclusions

A study was conducted to investigate the hypothesis that hemp waste can be recycled as a biofuel for cement manufacturing and that the by-product of the incineration process can be further employed as a cement replacement in concrete technology. The feasibility of this technology was assessed with experiments on the incineration process, the by-product composition, microstructure, and morphology, as well as the engineering properties of concrete including different amounts of hemp ash as cement replacement. The following conclusions can be drawn:

1- The increase in combustion temperature from 500°C to 800°C significantly reduced the by-product weight (by weight of hemp waste) from 8% to 1% due to increasing evaporation of impurities, accompanied by formation of new compounds, changes in the ash color, and an unfavorable increase in slagging and fouling tendencies. Combustion time had a minimal impact beyond a 4-hour duration.

2- The hemp ash had low silica content and high percentages of potassium, calcium and impurities. Although the impurities decreased with higher temperature, the silica content was independent of the combustion regime

3- Higher replacements of hemp ash in concrete (15% and 25% by weight of cement) significantly decreased the workability and compressive strength while increasing water absorption of the mixtures. On the other hand, lower replacements (5% by weight of cement) had minimal adverse effects on the mechanical and durability properties of concrete, thereby suggesting that a low percentage of hemp ash (5% by weight of cement) can be used as a filler in concrete for economic and environmental reasons.

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The authors would like to thank the reviewers for their constructive feedback. All comments have been addressed as detailed below. Changes to the manuscript are highlighted in yellow.

Comment from Reviewer	Response from Authors	Change in Manuscript
Add physical characterization data - particle size distribution and specific surface area	Tests were done, data was generated, compiled and is now presented in the manuscript.	Page 4, lines 112-114 Page 10, Lines 226-232, and Figure 4
Add a discussion (or warning) on the introduction of potentially harmful chemical elements in concrete, mainly alkalis (K and Na) and Cl.	Discussion on the introduction of these elements has now been included in the manuscript.	Page 4, Lines 87-90 Page 7, Lines 183-186
Update data on legalization of cannabis for recreational purposes (Canada)	A statement updating the status of cannabis in Canada has been included, along with up to date cultivation data.	Page 2, Lines 51-53
Figure 1 - Add scale to photos	Scale has been added to the figure.	Page 6, Figure 1
Figure 6 lacks clarity (lack of resolution)	The resolution of the figure has been improved, and the numbering of the figure has been changed (following introduction of Fig. 4 so as to address a comment above).	Page 15, Figure 7
It should be clear in the abstract that the material acts as a filler.	The abstract has been revised to clarify this point.	Page 1, Lines 22-23