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To cite this article: P S Matheu *et al* 2015 *IOP Conf. Ser.: Mater. Sci. Eng.* **96** 012080

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Comparing the Environmental Impacts of Alkali Activated Mortar and Traditional Portland Cement Mortar using Life Cycle Assessment

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Abstract. Since the year 1908 there has been research into the use alkali activated materials (AAM) in order to develop cementitious materials with similar properties to Ordinary Portland Cement. AAMs are considered green materials since their production and synthesis is not energy intensive. Even though AAMs have a high compressive strength, the average cost of production among other issues limits its feasibility. Previous research by the authors yielded a low cost AAM that uses mine tailings, wollastonite and ground granulated blast furnace slag (GGBFS). This mortar has an average compressive strength of 50MPa after 28 days of curing. In this paper the software SimaPro was used to create a product base cradle to gate Life Cycle Assessment (LCA). This compared the environmental impact of the AAM mortar to an Ordinary Portland Cement mortar (PCHM) with similar compressive strength. The main motivation for this research is the environmental impact of producing Ordinary Portland Cement as compared to alkali activated slag materials. The results of this LCA show that the Alkali Activated Material has a lower environmental impact than traditional Portland cement hydraulic mortar, in 10 out of 12 categories including Global Warming Potential, Ecotoxicity, and Smog. Areas of improvement and possible future work were also discovered with this analysis.

1. Introduction

The production of traditional Portland cement is harmful to the environment due to the high energy consumption and CO₂ emissions. On average 0.81kg CO₂ is released to the environment for every kilogram of Portland cement produced [1]. Most of the environmental impact is generated during the

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clinker production. In order to manufacture clinker, a mixture of raw materials has to be slowly heated to approximately 1450°C then quickly cooled to a range of 100 to 200°C. This process requires a large amount of energy. In 2012, 3700 million cubic meters of Portland cement were produced around the world [2]. The demand for this product is growing, causing an increased risk to the environment.

Due to the environmental impacts of Portland cement it is important to find a viable, cost effective replacement for this product. A promising alternative to this issue are Alkali Activated Materials (AAMs). These types of materials are an emerging technology that utilizes industrial by-products such as fly ash or blast furnace slag to produce cementitious materials. The process involves the reaction of the by-product with an alkali solution at low temperature. The resulting binder has high early compressive strength, resistance to chemical attack and high thermal stability among other properties [3]. The energy requirement to produce these products is significantly lower than the requirement for the traditional Portland cement manufacture.

The cost of AAMs is normally higher than ordinary Portland cement, hindering their commercial application. However, previous research performed by the authors yielded a cost effective AAM. This design mix consisted of a mixture of Ground Granulated Blast Furnace Slag (GGBFS), mine tailings, and wollastonite activated with a potassium based alkali solution. Most of the components are by-products of different industrial processes [4]. The Alkali solution contains potassium hydroxide, amorphous silica, and water.

It was found that the current literature lacks quantitative research on the environmental impacts of these AAMs compared to those of Portland cement. This paper will focus on this gap by comparing the environmental impacts of a traditional Portland cement and the design mix AAM previously research by the authors [4]. A Life Cycle Assessment (LCA) using SimaPro was used in order to quantifiably compare the environmental effects of Portland cement and the design mix. According to the United States Environmental Protection Agency, an LCA is a methodology to assess the environmental impacts associated with a process, product, or service from cradle to grave [5]. This methodology uses data to analyse all of the environmental impact of every production stage from raw material acquisition to disposal. This methodology helps to easily find opportunities to reduce the overall environmental impact. This will not only give a comparison of the total environmental impacts of both products but also the impact of each component, which will help to find future areas for improvements.

2. Analysis

The preparation of the AAM has been previously discussed by the authors [4]. This cementitious material was obtained by the use of a Potassium base solution which reacted with a mixture of blast furnace slag, mine tailings and Wollastonite. The resultant slurry was cured at room temperature, enhancing the workability. It is common for similar LCA analysis to not take into consideration any environmental impact caused by the by-products used. However, in this analysis the impact for grinding the GGBFS and the amorphous silica manufacture was included in the inventory.

In order to perform the LCA, it was necessary to determine the precise ingredients that go into a typical Portland cement hydraulic mortar. The ingredients for the analysis in this study were taken from a paper by Mahyuddin Ramli [6]. Both the AAM mix and the Portland cement mix had a compressive strength of 50 Mpa after 28 days of curing. The materials needed to produce one cubic meter of the AAM and the Portland cement hydraulic mortar were calculated and input into SimaPro to perform the analysis. The mix composition and percentage content can be seen in the tables below.

Table 1. AAM mix composition per cubic meter.

Material	Kg	%
45% KOH	83.95	4.37
Amorphous Silica	20.14	1.05
Water	251.85	13.10
Slag	711.91	37.04
20% NYAD G	142.38	7.41
Mining Tails	711.91	37.04

Table 2. Traditional portland cement hydraulic mortar mix composition per cubic meter.

Material	Kg	%
Lime (CaO)	387.84	17.32
Silica (SiO ₂)	127.68	5.704
Alumina (Al ₂ O ₃)	33.6	1.501
Iron Oxid (Fe ₂ O ₃)	20.16	0.901
Magnesia (MgO)	12.36	0.552
Sulphur Trioxide (SO ₃)	12.84	0.574
N ₂ O	0.3	0.013
Loss of Ignition	3.84	0.172
Water	240	10.72
Sand	1400	62.54

The LCA was performed as outlined by the ISO 14040 guidelines. The functional unit was a cubic meter of hydraulic mortar with an average compressive strength of 50 MPa after 28 days of curing. The scope of this LCA study focused on cradle to gate analysis. More specifically, the raw material acquisition, processing and manufacturing of both materials were studied. The packaging, use and disposal were not considered in this study. The AAM design mix has never been created in quantities equal to that of the functional unit, so the design mix materials were scaled up assuming a linear relationship.

Another major area of impact in the LCA is the transportation of materials. In this study Rochester Institute of Technology (RIT), Rochester, NY was used as the end point of all materials. When the exact starting location of materials was unknown, an average of all locations in the area was used. Given the location of the end point, it was decided to use the Building for Environmental and Economic Sustainability (BEES) method to compare the environmental impact of both mortars. This method was developed by the National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce. It was developed to measure the environmental impact of building materials specifically [7]. However, not all of the commonly used categories are calculated with this method. Due to this lack of categories and to verify the results, a sensitivity analysis using different methods was performed.

3. Results and discussion

The Life Cycle Assessment using the BEES method compares the impact of each material in thirteen different categories: Global Warming Potential, Acidification, Human Health: Cancer, Human Health: Non-Cancer, Human Health: Criteria Air Pollutants, Eutrophication, Ecotoxicity, Smog, Natural Resource Depletion, Indoor Air Quality, Habitat Alteration, Water Intake, and Ozone Depletion. As presented in table 3, in ten categories the AAM had less impact than Portland cement. In seven categories the Alkali-activated design mix had less than 40% of impact compared to the traditional Portland cement hydraulic mortar. The Indoor Air Quality category was excluded from the analysis because neither had a discernible impact. This was due to the fact that the use and disposal phase of the life cycle were not considered in this study. The two categories in which the traditional Portland cement mortar performed better, Eutrophication and Habitat Alteration, it had 97% and 38% of the impact of the AAM respectively. In an attempt to determine the cause of the higher AAM impact in the categories of Eutrophication and Habitat Alteration further analysis was done in these two categories.

Table 3. Comparing MT12 (AAM) with traditional portland cement hydraulic mortar BEES method.

Impact Category	Unit	MT12 (AAM)	PCHM	MT12/PCHM
Acidification	H ⁺ moles eq	60609.15	143637.49	0.42
Ecotoxicity	g 2,4-D eq	500.53	2479.10	0.20
Eutrophication	g N eq	271.60	215.24	1.26
Global warming	g CO ₂ eq	200309.50	790558.51	0.25
Habitat alteration	T&E count	8.00E-12	2.71E-12	2.95
HH cancer	g C ₆ H ₆ eq	317.48	1226.27	0.26
HH criteria air pollutants	microDALYs	30.30	31.24	0.97
HH noncancer	g C ₇ H ₇ eq	647311.80	2391701.70	0.27
Natural resource depletion	MJ surplus	266.25	686.17	0.39
Ozone depletion	g CFC-11 eq	0.002	0.011	0.22
Smog	g NO _x eq	881.0962	3293.5687	0.27
Water intake	liters	588273.7	904118.08	0.65

The Eutrophication category refers to the amount of nutrients that a particular material emits into the surrounding waterways. Table 4 shows the main process contributions for the Eutrophication category. As can be seen, potassium hydroxide is the main contributor for the AAM design mix. For this analysis the potassium hydroxide is manufactured by the electrolysis of potassium chloride brine in an electrolytic cell, all information is based on industry data in the US.

Looking into the Habitat Alteration category, it is visible that the production of potassium hydroxide is again the largest contributor. However, as it can be seen in table 5 the total amount of T&E count, damage of Threatened and Endangered Species, is 8×10^{12} . This number shows that even though the Alkali Activated Material has a larger impact, it is so small that it is not a priority compared to other categories.

Table 4. Process contribution eutrophication BEES method.

Process	Unit	MT12	PCHM
Total of all processes	g N eq	271.60	215.24
Remaining processes	g N eq	1.83	3.69
Crude oil, at production/RNA	g N eq	1.47	6.58
Diesel, at refinery/US	g N eq	0.50	2.24
Electricity, high voltage, at grid/US S	g N eq	32.10	x
Electricity, low voltage, at grid/US S	g N eq	72.75	11.20
Operation, transoceanic freight ship/OCE S	g N eq	1.53	x
Portland cement, strength class Z 42.5, at plant/CH S	g N eq	x	105.47
Potassium hydroxide, at regional storage/RER S	g N eq	143.40	x
Sand, at mine/CH S	g N eq	x	5.45
Transport, combination truck, diesel powered/US	g N eq	16.59	74.25
Transport, ocean freighter, residual fuel oil powered/US	g N eq	1.42	6.36

Table 5. Habitat alteration comparing AAM to traditional portland cement hydraulic Mortar BEES Method.

Process	Unit	MT12	PCHM
Total of all processes	T&E count	8.00E-12	2.71E-12
Remaining processes	T&E count	2.51E-14	2.54E-12
Potassium hydroxide, at regional storage/RER S	T&E count	6.17E-12	x
Electricity, low voltage, at grid/US S	T&E count	1.12E-12	1.73E-13
Electricity, high voltage, at grid/US S	T&E count	5.99E-13	x
Operation, transoceanic freight ship/OCE S	T&E count	8.83E-14	x
Total of all processes	T&E count	8.00E-12	2.71E-12
Remaining processes	T&E count	2.51E-14	2.54E-12
Potassium hydroxide, at regional storage/RER S	T&E count	6.17E-12	x
Electricity, low voltage, at grid/US S	T&E count	1.12E-12	1.73E-13
Electricity, high voltage, at grid/US S	T&E count	5.99E-13	x
Operation, transoceanic freight ship/OCE S	T&E count	8.83E-14	x

4. Sensitivity analysis

ReCiPe model offers three different perspectives, the individualist perspective is based in a short term interest, and it assumes that the technological advances are going to help reduce the impact in the long run. This is contrary to Egalitarian which is the most precautionary perspective out of the three [8]. The hierarchist viewpoint is representative of the midpoint between the Individualist and Egalitarian, it is often considered to be the default model for ReCiPe. It was created with European normalisation in order to collaborate the results found by the BEES method, it was decided to compare both mortars using the ReCiPe midpoint hierarchist method.

Table 6. Comparing MT12 (AAM) with traditional portland cement hydraulic mortar ReCiPe method.

Impact Category	Unit	MT12 (AAM)	PCHM	MT12/PCHM
Climate change	kg CO ₂ eq	201.34	792.23	0.25
Ozone depletion	kg CFC-11 eq	0.00	0.00	0.55
Terrestrial acidification	kg SO ₂ eq	1.02	2.23	0.46
Freshwater eutrophication	kg P eq	0.01	0.00	3.00
Marine eutrophication	kg N eq	0.03	0.11	0.28
Human toxicity	kg 1,4-DB eq	41.98	162.83	0.26
Photochemical oxidant formation	kg NMVOC	0.84	3.05	0.27
Particulate matter formation	kg PM ₁₀ eq	0.38	0.83	0.46
Terrestrial ecotoxicity	kg 1,4-DB eq	0.01	0.01	1.26
Freshwater ecotoxicity	kg 1,4-DB eq	0.36	1.01	0.36
Marine ecotoxicity	kg 1,4-DB eq	0.35	1.06	0.33
Ionising radiation	kg U235 eq	12.09	16.50	0.73
Agricultural land occupation	m ² a	2.29	2.61	0.88
Urban land occupation	m ² a	1.28	1.47	0.88
Natural land transformation	m ²	0.01	0.03	0.36
Water depletion	m ³	1.07	3.83	0.28
Metal depletion	kg Fe eq	6.09	4.35	1.40
Fossil depletion	kg oil eq	58.87	131.59	0.45

As it can be seen in table 6, 18 categories are studied in this model. Similar to the other model, the AAM material has significantly lower environmental impact in most categories. The traditional Portland cement hydraulic mortar only has a lower impact in Freshwater Eutrophication, Terrestrial Ecotoxicity and Metal Depletion. Freshwater Eutrophication occurs when there is a discharge of nutrients into freshwater that create an increase in the nutrients level of the freshwater [9]. A simple definition for Terrestrial Ecotoxicity is the impact of chemicals on the terrestrial ecosystem. The last category with less impact created by traditional Portland cement, Metal Depletion, refers to the use of virgin metals.

After reviewing the main contributors to the environmental impacts of the AAM design mix, it was found that the main contributor for all of the categories in which the AAM had a higher impact was the potassium hydroxide production. However, it can be seen the effects from Freshwater Eutrophication and Terrestrial Ecotoxicity are minimal. For Metal Depletion, the kg FE equivalent for the potassium hydroxide is 4.56, the next contributor is the energy used for mixing the raw materials. The use of renewable energy sources, for example wind energy, will help to reduce the overall impact of the AAM making it an even more sustainable viable replacement.

5. Conclusions

Both methods used in this study demonstrate that the Alkali-Activated Material (MT12) has a significantly lower environmental impact in most categories. This suggests that AAMs would be a viable and much less impactful alternative to Portland cement hydraulic mortar. An important category for these materials is the Global Warming Potential, Climate Change in ReCiPe method, tables 3 and 6 show that the AAM has approximately 25% of the Portland cement hydraulic mortar impact. It was also demonstrated that the potassium hydroxide used in the activating solution is the main cause of environmental impact. Further work will search for a replacement to the potassium hydroxide activator as this would alleviate many of the environmental impacts of Alkali Activated Mortar. Another area for future research will be the possibility to reactivate or recycle this AAM making it an even more sustainable material.

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