The Influence of the Alkaline Activator on the Life Cycle Assessment of Alkaline Activated Natural Pozzolan Geopolymers Concrete

تأثير المحفز القلوي على تقييم دورة الحياة لخرسانة بوزولان البوليمرات الجيولوجية الطبيعية المحفزة قلوياً

by

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Abstract

This paper studies the effectiveness of replacing cement in concrete with natural pozzolan, originated from Saudi Arabia, on the reduction of the harmful gasses, carbon dioxide equivalent gases, during the production process of the concrete. Life cycle assessment is done on the alkaline activated natural pozzolan geopolymer concrete, global warming potential of 100 years GWP100 category. The life cycle assessment exercise was also done on alkaline activated natural pozzolan geopolymers where the natural pozzolan was activated with different types of alkaline activator to reduce the GWP100 of the geopolymer concrete even further. The results of the study showed that the geopolymer with natural pozzolan activated by sodium hydroxide and sodium silicate have the lowest GWP100 of 106 kg.CO^2.eq, which is lower than that of the PC concrete by 72%. Also, it is found that the alkaline activator is responsible for the largest amount of the carbon dioxide equivalent gases produced during the production of 1 m^3 of the geopolymer concrete. Two further life cycle assessment exercises were done to replace the sodium silicate alkaline activator with sodium hydroxide and silica extracted from rice husk ash. The results of the life cycle assessment, GWP100 category, showed that both geopolymer concretes have higher GWP100 than that of the natural pozzolan activated with sodium hydroxide and sodium silicate. The GWP100 of the natural pozzolan alkaline activated by sodium hydroxide geopolymer and natural pozzolan activated by sodium hydroxide and silica extracted from rice husk ash are 114 kg.CO^2.eq and 197 kg.CO^2.eq respectively. However, all of the alkaline activated natural pozzolan geopolymer concrete showed GWP100 less than that of the PC concrete by at least 48%. The results of the life assessment exercise are then compared to life cycle assessment exercises done by other researchers on alkaline activated natural pozzolan geopolymer concrete as well as other types of geopolymer concretes.

The recommendations of this study is that further research needs to be conducted to study the properties of the alkaline activated natural pozzolan geopolymer concrete and further life cycle assessments need to be conducted on different mix design option on both raw and calcinated natural pozzolan to encourage the consultants and contractors to replace cement with more sustainable and durable material like the natural pozzolan.

نبذة مختصرة

تدرس هذه الورقة فعالية استبدال الأسمنت في الخرسانة بالبوزولان الطبيعي المستخرج من المملكة العربية السعودية، الحد من الغازات الضارة والغازات المماثلة لثاني أكسيد الكربون أثناء عملية إنتاج الخرسانة. يتم تقييم دورة الحياة على خرسانة البوليمرات الجيولوجية البوزولانية الطبيعية المحفزة قلوياً، وإمكانية الاحترار العالمي لفئة 100 سنة (GWP100).

تم إجراء إختبارات لتقييم دورة الحياة على البوليمرات الجيولوجية البوزولانية الطبيعية المحفزة قلوياً، حيث تم تنشيط البوزولان الطبيعي مع أنواع مختلفة من المحفزات القلوية لتقليل إمكانية الاحترار العالمي لفئة 100 سنة (GWP100) من خرسانة البوليمرات الجيولوجية بشكل أكبر. أظهرت نتائج الدراسة أن مادة البوليمرات الجيولوجية مع البوزولان الطبيعي التي يتم تنشيطها بواسطة هيدروكسيد الصوديوم وسيليكات الصوديوم قيم أقل لإمكانية الاحترار العالمي لفئة 100 سنة (GWP100) ما يكافئ 106 كجم من ثاني أكسيد الكربون، والذي يعتبر اقل من تلك المنبعثة من خرسانة الإسمنت البورتلاندي بنسبة 72%.

أيضا، وجد أن المحفز القلوي مسؤول عن أكبر إنتاج كميات أكبر من الغازات الممالثلة لثاني أكسيد الكربون أثناء إنتاج 1 متر مكعب من الخرسانة البوليمرات الجيولوجية. تم إجراء تمرينين آخرين لتقييم دورة الحياة لاستبدال المحفز القلوي للسيليكات الصوديوم بهيدروكسيد الصوديوم والسيليكا المستخرجة من رماد قشر الأرز. أظهرت نتائج تقييم دورة الحياة لفئة إمكانية الاحترار العالمي لفئة 100 سنة (GWP100)، أن كلا من خرسانة البوليمرات الجيولوجية لديها قيمة إمكانية الاحترار العالمي لفئة 100 سنة (GWP100) أعلى من البوزولان الطبيعي المحفز بهيدروكسيد الصوديوم وسيليكات الصوديوم من القلويات البوزولانية الطبيعية المحفز بواسطة جيوبوليمر هيدروكسيد الصوديوم والبوزولان الطبيعي المحفز بواسطة هيدروكسيد الصوديوم والسيليكا المستخرجة من رماد قشر الأرز ما يكافئ 114 كجم من ثاني أكسيد الكربون و197 كجم من ثاني أكسيد الكربون على التوالي. ومع ذلك، أظهرت خرسانة البوليمرات الجيولوجية الطبيعية المحفزة قلوياً إمكانية الاحترار العالمي لفئة 100 سنة (GWP100) أقل من خرسانة الإسمنت البورتلاندي بنسبة 48% على الأقل. في حين قام باحثون آخرون بمقارنة نتائج تجارب تقييم الحياة مع تجارب تقييم دورة الحياة على خرسانة البوليمرات الجيولوجية الطبيعية المحفزة قلوياً وكذلك أنواع أخرى من خرسانة البوليمرات .أظهرت مراجعة المادة الواردة في هذه الدراسة أن خرسانة البوليمرات الجيولوجية الطبيعية المحفزة قلوياً لها خصائص مقبولة. ومع ذلك ، فإن نوع المحفز القلوي وتركيزه هو احد المؤثرين الرئيسيين على خصائص خرسانة بوزولان البوليمرات الجيولوجية الطبيعية الطبيعية المحفزة قلوياً.

توصيات هذه الدراسة هي أن هناك حاجة إلى إجراء مزيد من البحوث لدراسة خصائص خرسانة بوزولان البوليمرات الجيولوجية الطبيعية المحفزة قلوياً، ويجب إجراء تقييمات أخرى لدورة الحياة على خيارات مختلفة من الخلطات المستحدثة على كل من البوزولان الطبيعي الخام والمتكلس لتشجيع الاستشاريين والمقاولين لاستبدال الأسمنت بمواد أكثر استدامة ودائمة مثل البوزولان الطبيعي.

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Table of Contents

Table of Figures

Table of Tables

1.0 Introduction

1.1 Purpose of the Research

Concrete is material that is made of varying sizes of aggregates, binding material, water and admixtures as needed. The widely spread binding materials around the world is Cement. It is used as structural material in buildings, roads bridges and dams for its benefits which includes its raw materials availability around the world, high strength, low maintenance requirement and has a long life. The main drawback with cement is the CO_2 emission during the manufacturing process where the raw materials including Lime, shell, Calcium, Silicon, iron and other ingredients are fed into a kilns and heated up to 1,400 C^0. This process is called calcination which produce Calcium Oxide (Lime) and Carbon Dioxide to the air as a biproduct. The process does both, producing harmful gasses as a biproduct that stays in the atmosphere and absorbs energy from the earth causing an increase in temperature as a biproduct and requires a large amount of energy to produce the heat needed for the production process. According to (Shen et al., 2017) the cement production is one of the main contributors to greenhouse gases that are produced to the environment. Cement industry is also responsible for 8% of the Carbon Dioxide emission into the environment and it is the second largest CO_2 emission. The manufacturing process of cement is also energy intensive, it is responsible for consuming up to 15% of the industry energy (Galvez-Martos, J. and Schoenberger, H., 2014). Greenhouse gases are responsible for global warming and reducing them would save the environment. As the world population increase, the need for improved infrastructure and construction increase, thus the need for concrete increases as well.

Another concern about concrete is its durability, studies have shown that concrete age and deteriorate. The rate of deterioration of concrete depend on the mix design and environment it is built in. In general, traditional concrete life is less than what is required, (Najimi, Ghafoori and Sharbaf, 2018) stated that the traditional concrete had frequently showed failure in concrete infrastructures caused by aging and deterioration.

Many researches were conducted to find an alternative to the traditional concrete or the Portland Cement Concrete. Some studies showed the potential of replacing the cement partially in the concrete mix to reduce the greenhouses gases emission and to improve its sustainability while other studies found alternative materials to replace the cement completely in the concrete.

Despite the research conducted so far and the encouragement to use alternatives to cement in concrete, countries and companies are still producing it and using it in construction in large amounts. The main reasons would be because PC concrete still have superior properties that encourage its usage. We need an alternative material with similar, if not better, properties of the cement to be able to produce good strength and sustainable concrete. This paper presents the studies that were previously done to study the substitution of cement with natural pozzolans in concrete. In addition to an evaluation of the properties of alkaline activated natural pozzolans geopolymer, its strengths, weakness as a construction material and it's the sustainability will be compared to the traditional concrete.

This research focus on the evaluation of the environmental impact of the alkaline activated natural pozzolan geopolymers through conducting a life cycle assessment and studies the effect of substituting the types of the alkaline activators on the environment.

Life cycle assessment is done to assess the environmental impact of a certain product on the environment through its life cycle. The life cycle stages consist of raw material, processing, transportation, retail and use phase and waste. In case of natural pozzolan concrete, the raw materials would be extraction, transportation to the factory and preparation of the natural pozzolan, manufacturing of the alkaline activator and the extraction and the preparation of the sand and gravel. The processing will include the mixing in case of the fresh concrete and mixing and curing in case of the pre-cast concrete. Also, it will include the power and fuel required through the production process. The transportation phase will include transporting the concrete from the factory to the targeted site. The use phase will include the energy required for placing and maintenance through its life. Finally, the waste phase includes demolishing the structure. However, in some cases the materials of the concrete are recycled.

The assessment can be done on some or all the stages stated. For example, cradle to gate will start from the first stage until it leaves the gate of the factory. Which means transportation, in use and waste will not be included in the assessment. Cradle to grave assessment will include all the stages from the raw material until waste. Cradle to cradle will include all the stages including recycle of the materials. finally, gate to gate will include the assessment during the production process, which means the assessment once it enters from the factory gate until it leaves the factory after the production.

The assessment that will be done in this study will be gate to gate to make it more general and will make the comparison more accurate and limited to the production process because the distance from the resource to the factory may vary from country to country, the same applied to the distance from the factory to the site. Gate to gate assessment is sufficient to decide which type of concrete has less harmful impact on the environment.

1.2 The Material – Natural Pozzolans

Natural pozzolans are materials that that contain reactive silica and alumina (Maria, S., 2016) and according to ASTMC593 natural pozzolans are siliceous or alumino-siliceous materials. Natural pozzolans are used in construction in ancient civilization before the cement was introduced. They were discovered in Italy and were used by the Romans in construction. Natural pozzolans as a raw material do not have cementitious properties but when they react with alkaline in presence of moist they form a compound, calcium silicate hydrates and calcium aluminum hydrates, which have cementitious properties (Maria, S., 2016). They can react with alkaline at ambient room temperature to form a solid rock.

Some types of Natural Pozzolans include the products of volcanic ashes and natural minerals like clay and shale. Volcanic ash are more famous Natural Pozzolans in today's world due to their pozzolanic behavior; unlike natural mineral which may need heat treatment to show pozzolanic behavior (Maria, S., 2016). Thus, volcanic ash is sometimes called ‘’true natural pozzolans’’ or ‘’raw natural pozzolans’’ because they have pozzolanic properties in the raw form and doesn't need any treatment. While the clay or shale natural pozzolans are called ‘’calcinated natural pozzolans’’. The pozzolanic properties of different types of natural pozzolans also depend on the amount of reactive Silicon Oxide and Aluminum Oxide that is available in them, the higher Silicon Oxide and Aluminum Oxide they contain the better properties they have. The Calcium Oxide amount in natural pozzolans also influence natural pozzolans properties.

Table 1 shows the chemical composition of some types of volcanic natural pozzolans. It clearly shows the high amount of Silicon Oxide and Aluminum Oxide available in them. The varying amount of chemicals in each type of the natural pozzolans shown in the table depend on the type of the magma that erupted them. Chemical composition of the magma, temperature and humidity conditions produce natural pozzolans with different chemical compositions (Firdous, R., Stephan,

D. and Djobo, J., 2018). In addition, some types of natural pozzolans contain clay minerals. High amount of loss in ignition can show that the natural pozzolans contain dissolved gases like Carbon Dioxide and water in glassy form which indicated the presence of carbonates and clay minerals in them (Firdous, R., Stephan, D. and Djobo, J., 2018).

According to ASTM C618, the particle size of two-third of natural pozzolans are less than 45 micrometers, and the finer the particles the higher reactivity they have. Natural pozzolans properties will depend on their composition, their composition will vary from place to place (from county to country) thus their properties. The products of natural pozzolans reaction with water and Calcium Hydroxide are CH and CSH. CSH provide the strength to the concrete and make it more sustainable due to its high density.

Many researchers have introduced natural pozzolans as a partial substitution to cement to improve the PC concrete characteristics. However, others conducted researches introduced natural pozzolans as a complete substitution to cement because of its outstanding properties. Also, because it eliminates the two main problems with PC concrete which are sustainability and durability.

The manufacturing of concrete with Natural pozzolans are less energy intensive and emits less CO_2 to the environment. Studies have shown that the production of concrete with natural pozzolan emits less CO_2 by 22% to 72% than the production of PC concrete (Bondar, D., Lynsdale, C. J. and Milestone, N. B., 2013). The lower percentage difference in the CO_2 emission, 22%, would be for the concrete with calcinated natural pozzolan because it still needs heat treatment process. While the raw natural pozzolan concrete would even emit less CO_2 to the environment which can be 72% less than that of the PC concrete production. Another study showed even higher percentage difference in the CO_2 emission between PC concrete and natural pozzolan concrete. according to (Firdous, R., Stephan, D. and Djobo, J. N. Y., 2018), compared to Ordinary Portland Cement, the CO_2 emission is less by 80%.

Other strong properties of alkaline activated natural pozzolans paste forms a denser structure thus more durable concrete, high resistance and longer age. The low reactivity of natural pozzolan can be both an advantage and disadvantage. The low reactivity means low heat of hydration in mass concreting, but it also elongates the setting time of the concrete.

The main drawbacks of natural pozzolan concrete might be lower compressive strength in some cases, higher drying shrinkage and lower early strength than PC concrete.

Table 1: chemical compositions of some volcanic ashes around the world (Firdous, R., Stephan, D. and Djobo, J., 2018)

Source	SiO_2	Al_2O_3	CaO	Fe_2O	K_2O	Na_2O	MgO	TiO_2	MnO	P_2O_5	LOI	Total
Saudi Arabia	46.48	14.74	8.78	12.16	1.27	3.39	8.73	2.31	0.19	0.629	1.324	98.68
South East, Iran	61.7	15.9	8.0	4.3	2.1	3.2	2.0	0.4			1.9	97.7
Jordan cement factories Lafarge, Jordan	40.2	13.9	9.7	15.2	1.5	3.7	9.6				4.8	93.7
Bayburt Stone waste, Turkey	68.9	12.0	3.9	0.3	2.4	0.2	1.3				10.1	89.2
Mt. Shinmoe, Southern, Japan	54.9	16.4	8.8	10.9	1.7	2.8	3.3	0.8	0.2			99.9
North West, Iran	70.1	11.1	2.5	1.3	2.3	1.0	0.9	0.1			10.3	89.4
North West, Iran	64.7	11.9	6.8	3.0	4.3	2.3	1.1	0.5			5.2	94.5
South East. Iran	68.5	11.8	2.9	3.7	3.2	1.6	1.4	0.4			6.1	93.6
South East, Iran	68.3	12.6	3.9	2.7	3.3	2.4	1.4	0.3			4.4	94.8
Chihuahua, Mexico	59.5	9.4	8.0	2.3							14.3	79.3
Foumbot West Region, Cameroon	44.2	14.1	10.4	13.2	1.5	3.7	9.7	2.7	0.2	0.6	-0.6	100.3
Foumbot West Region, Cameroon	43.4	15.3	11.1	12.5	1.7	4.5	6.8	2.9	0.2	0.9		99.3
Djoungo, Littoral Region, Cameroon	46.3	15.4	9.1	13.3		3.9	6.7	2.8	0.2	0.6	-0.4	98.4
Djoungo, Littoral Region, Cameroon	44.0	15.3	9.3	12.8	1.4	5.6	7.0	2.9	0.2	0.5	1.1	98.9
Loum. Littoral Region, Cameroon	47.7	15.4	8.3	12.9	1.1	3.6	6.5	2.8	0.2	0.5	0.7	98.9
Galim, West Region, Cameroon	41.4	15.4	7.9	12.9	1.0	2.2	6.5	3.0	0.2	0.5	9.3	90.9
Rhine Land, Germany	58.6	17.7	4.7	6.2	5.1	3.4	2.4					98.0
Yellow Tull Italy	54.7	17.7	3.7	3.8	6.4	3.4	0.9				9.1	99.7
Bacoli, Italy	53.1	17.9	9.0	4.3	7.6	3.1	1.2	0.3			3.0	99.5
Bartle, Italy	44.1	19.2	9.0	4.3	7.6	3.1	12	0.3			3.0	91.8
Coastal Region, Ecuador	68.2	113	3.7	4.1			1.0					88.5
Coastal Region, Ecuador	66.0	11.0	4.7	3.9			15					87.1

1.3 Volcanic Ash Natural Pozzolans Availability

Natural pozzolan is redundant around the world. In Saudi Arabia Natural Pozzolan is found at the red sea coast covering 100,000 km^2 of the western region of Saudi Arabia (Firdous, R., Stephan, D. and Djobo, J., 2018).

In Jordan, the volcanic tuff reserve is 2000 million tons in the Jordanian desert and throughout north-eastern Jordan at Tel-Alremah (Haddad, R. and Alshbuol, O., 2016).

In Algeria, it is found over a distance of 160 km between the Algerian and Moroccan borders, and it is also found in Sahel of Oran (Kamal, n.d., 2016). The Algerian natural pozzolans is the true natural pozzolan because it shows the pozzolanic behavior without ant treatment process. According to (Kamal, n.d., 2016), the physical properties of natural pozzolan brought from Sahel of Oran are: bulk density, 0.98 g/cm3; density, 2.75; Pozzolanicity, 85 (%); absorption, 58.70%; and index of activity is 0.67.

In Nigeria, Natural Pozzolan (kaolin clay) is found in the south-west Nigeria along Abeokuta-Ajebo Road, it is found nine meters under the ground level. This type of natural pozzolan need heat treatment to become calcinated natural pozzolan (Adekitan, O. and Ayininuola, G., 2017).

In Iran, there are five types of natural pozzolans produced by the factories there. They are Shahindej dacite which contains 70% of Silicon Oxide, 11% of Aluminum Oxide and 2.5% of Carbon Oxide; Sahand dacite that contains 64% of Silicon Oxidem, 11% of Aluminum Oxide and 7% of Calicium Oxide; Sirjan dacite that contains 68.5% of Silicon Oxide, 11.8% of Aluminum Oxide and 2.9% of Calcium Oxide, Rafsanjan dacite 68% of Silicon Oxide, 12.6% of Aluminum Oxide and 3.8% Calcium Oxide and Taftan andesite which contains 61.7% of Silicon Oxide, 15.9% of Aluminum Oxide and 8% of Calcium Oxide. The first two types are from northwest of Iran and the latest three are from southwest of Iran (Bondar, D., Lynsdale, C. J. and Milestone, N. B., 2013). It is also found that these types have high loss of ignition and they contain zeolites and clays material. Such types need heat treatment to improve their pozzolanic properties.

Natural Pozzolans is also found in Island of Nisyros in Greece, its chemical composition is 49.6% of Silicon Oxide, 9.8% of Aluminum Oxide and 15% of Calcium Oxide. The mean particle size of a sample was found to be 11.6 micrometer and its pozzolanic index is 10.5 MPa (Robayo-Salazar, R., Mejía-Arcila, J., Mejía de Gutiérrez, R. and Martínez, E., 2018). The are other two types of natural pozzolans available in the Greek market, type A and type B, originated from the area of Cyclades. Type A has 50.6% if Silicon Oxide, 9.8% of Aluminum Oxide, 15% of Calcium Oxide, and a specific gravity of 2.4. While type B has 49% of Silicon Oxide, 8.8% of Aluminum Oxide, 17.9% Calcium Oxide and a specific gravity 2.17. The particle size of type A is larger than that of type B (Maria, S., 2016).

In Colombia, the available natural pozzolan has 62% Silicon Oxide, 15.5% Aluminum Oxide and 5.2% of Calcium Oxide (Robayo-Salazar, R., de Gutiérrez, M. and Puertas, F., 2017), (Mfinanga, D. and Kamuhabwa, M., 2008).

In Tanzania, the available the natural pozzolans are Esilalei pozzolan from Monduli district, Oldonyo Sambu pozzolan from Arumeru district and Kilimatembo pozzolan from Karatu district. The first one has a chemical composition of 57.3% of Silicon Oxide, 10.3% of Aluminum Oxide and 5.5% of Calcium Oxide. The second one has 34.8% of Silicon Oxide, 8.8% of Aluminum Oxide and 6% of Calcium Oxide. The last one contains 51.9% of Silicon Oxide, 8.2% of

Aluminum Oxide and 11.7% of Calcium Oxide (Kalina, R., Al-Shmaisani, S., Ferron, R. and Juenger, M., 2019).

In Cameroon, the natural pozzolan is found in Littoral region in Djoungo located N 04 340 57.400 and altitude 129m. its composition is 46.3% of Silicon Oxide, 15.4% of Aluminum Oxide and Calcium Oxide of 9% (D. Bondar, C.J. Lynsdale, N.B. Milestone, N. Hassani, 2012).

According to the natural pozzolan association, there are worldwide suppliers who supply natural pozzolans with chemical compositions that serves the purpose of construction.

1.4 ASTM C618

ASTM C618 is standard specification that defines the requirement for raw and calcinated natural pozzolans. The below tables show the chemical requirements and physical requirements of the natural pozzolans as advised by ASTM official website.

Table 2: Chemical Requirements of natural pozzolan - ASTM

	Class		
	Class N	Class F	Class C
Silicon dioxide (SiO_2) + aluminum oxide (Al_2O_3) + iron oxide(Fe_2O_3) - Min	70%	70%	50%
Sulfur trioxide (SO_3) - Max	4%	5%	5%
Moisture content - Max	3%	3%	3%
Loss on ignition - Max	10%	6%	6%

Table 3: Physical Requirements of natural pozzolan - ASTM

	Class		
	Class N	Class F	Class C
Fineness:			
Amount retained when wet-sieved on 45 µm (No. 325) sieve, max, %	34	34	34
Strength activity index:			
With portland cement, at 7 days, min, percent of control	75	75	75
With portland cement, at 28 days, min, percent of control	75	75	75
Water requirement, max, percent of control	115	105	105
Soundness:			
Autoclave expansion or contraction, max, %	0.8	0.8	0.8
Uniformity requirements:			
The density and fineness of individual samples shall not vary from the average established by the ten preceding tests, or by all preceding tests if the number is less than ten, by more than:			
Density, max variation from average, %	5	5	5
Percent retained on 45-µm (No. 325), max variation, percentage points from average	5	5	5

2.0 Research Methodology

The purpose of this research is to evaluate if the replacement of cement in concrete with natural pozzolan, volcanic ash, will reduce the environment impact of the concrete production industry and to what limit. The following steps were done during the research:

- Natural pozzolan were introduced and the specific type of that natural pozzolan was defined, volcanic ash – natural pozzolan, which is the concentration of this research.
- The chemical compositions of some volcanic ashes available around the world was presented
- The locations of the availability of the natural pozzolan in some counties were identifies. The countries include Saudi Arabia, Algeria, Jordan and Iran from the middle east and includes other countries in Africa and around the globe.
- The international standard from ASTM (American Society for Testing Materials) of the natural pozzolan chemical and physical requirement were presented.
- The properties of geopolymers concrete or paste based on volcanic ashes were studied. This section included research that were conducted on geopolymers were cement was completely replaced by volcanic ash. Volcanic ashes were used from around the world including Saudi Arabia, Jordan, Algerian and Iran. It evaluates the geopolymer properties and identify the factors that influence them. However, this section shows that there is a lack of research on specific properties on the alkaline activated natural pozzolan geopolymers.
- Based on the literature review, a mix design was selected of alkaline activated natural pozzolan geopolymer concrete based on volcanic ash from Saudi Arabia and a life cycle assessment was carried out to assess the global warming potential of 100 years of the geopolymer concrete production. The life cycle assessment carried out on three types of alkaline activated natural pozzolan concrete which had the same mix design except of changing the alkaline activator to study its influence on the life cycle assessment of the geopolymer concrete.
- Life cycle assessment was done on traditional concrete to use it as a benchmark.

- The results on the life cycle assessment exercise of the alkaline activated natural pozzolan geopolymer concrete was compared to that of the traditional PC concrete. Also, it was compared to one another while changing the type of the alkaline activator.
- The literature review of the life cycle assessment was presented and compared to the study. However, since there is only one life cycle assessment done on geopolymers based on volcanic ash by other researchers, other life cycle assessment bashed on other supplementary cementitious materials was considered to compare it to the outcome of this study.

3.0 Research Significance

This research conducts a life cycle assessment exercise on alkaline activated geopolymers based on completely volcanic ash natural pozzolan, specially originated from the Middle East. This research reviews the available research regarding similar geopolymer types and draw a conclusion about the expected properties of the alkaline activated natural pozzolan which may encourage using them instead of the PC concrete in our structures and infrastructure.

This study highlights the gaps of the research conducted on the alkaline activated natural pozzolan geopolymer concrete and identify the areas where further research is needed.

The life cycle assessment exercise done in this study considers the use silica extracted from rice rusk ash which wasn't considered with the volcanic ash natural pozzolan in previous published papers.

4.0 Review of the Properties of Geopolymers Concrete Based on Volcanic Ash Natural Pozzolans

Previous studies were done to study the possibility of completely replacing the cement in the concrete with other materials. One of these materials is volcanic ash natural pozzolan due to its availability in many countries around the world, cheap extraction, its pozzolanic properties and its low environmental impact.

This section presents and discusses the previous tests and studies that were done on volcanic ash based geopolymers where cement is not used. The tests were done on volcanic ashes from different parts of the world were their chemical composition varies. Also, the chemical composition of the natural pozzolan sometimes vary in the same country. Previous tests will be presented with their results and the mix designs used will be evaluated and will be compared with other research. The outcome of this study will answer the possibility of replacing cement completely with natural pozzolan in construction.

4.1 Compressive Strength of Geopolymer Concrete Based on Volcanic Ash Natural Pozzolan

The compressive strength is the material ability to resist loads. The compressive strength of PC Concrete depends on the purpose of construction. According to the construction organization the residential concrete compressive strength is 17 MPa and the compressive strength for bigger structures is around 30 MPa, the latest compressive strength is the common one use in United Arab Emirates. The compressive strength can even reach a range from 70 MPa to 120 MPa for the high strength concrete. High compressive strength is mainly used in high rise buildings and bridges. The PC Concrete gain 65% of its compressive strength during the first 7 days and 90% of its final strength during the initial 14 days. The compressive strength is an essential property to decide if the Natural Pozzolans can be used in structural element like PC concrete uses.

Same as PC Concrete, the pozzolans fresh and hardened concrete properties depend on the input, or the mix design. The main factors that significantly impact the properties of the natural pozzolans concrete includes the type of the pozzolans, its composition and its pozzolanic activity, the alkaline solution used to activate it, the curing temperature, curing duration and water/binder (w/b) ratio.

The inputs will have an effect on the strength of natural pozzolan concrete, its workability in the fresh state, its setting time and its durability.

4.1.1 Alkaline Activator

A high alkaline solution is needed to activate the silicon and aluminum ions in the natural pozzolan to form a paste, and this is why it is called alkali activated natural pozzolan paste or concrete. Alkaline solutions include sodium hydroxide, sodium carbonate and sodium silicate were used to activate natural pozzolans. Although using potassium hydroxide as an alkaline activator produce higher strength paste with lower setting time (Hanjitsuwan, S., Hunpratub, S., Thongbai, P., Maensiri, S., Sata, V. and Chindaprasirt, P., 2014); but due to its lack of availability and price the other alkaline solutions are more often used to activate natural pozzolans. Previous studies have shown that the type of the alkaline activation and its concentration affect the properties of the alkaline activated natural pozzolans including its compressive strength, its early age strength and it can change the curing duration and temperature requirement.

According to a research that was conducted by (Moon et al., 2014) to study the properties of natural pozzolans concrete properties, achieving close compressive strength to that of the PC concrete is possible. In the study, a natural pozzolan from Saudi Arabia was used (chemical composition of aluminum oxide: 14.7%, silicon oxide: 46.5% and calcium carbonate: 8.78%). Two mixes were prepared, The first mix was prepared with sodium hydroxide solution as the alkaline activator and the second mix was prepared with sodium silicate (water-glass) in addition to the sodium hydroxide as the alkaline activator. Both samples were cured at 80 C^0 for 30 days and the solution/binder ratio was 0.45. The results showed that the compressive strength was found to be 33 MPa of the first mix, which is natural pozzolan geopolymer with alkaline activator of Sodium Hydroxide, and 47 MPa of the second mix, Natural Pozzolan geopolymer with alkaline activator of sodium hydroxide and glass-water.

The achieved compressive strength shows that natural pozzolans are suitable to use instead of PC concrete in different applications. However, the temperature used to cure the natural pozzolans concrete to produce such strength is high and the duration of the curing is also long. The addition of sodium silicate solution in addition to the sodium hydroxide produced a higher compressive strength. This benefit can be used to lower the curing temperature and shorten the curing duration as needed. To demonstrate, after four days of curing the first mix had a compressive strength of 18 MPa while the second mix, which was prepared with water-glass in addition to the sodium hydroxide, had a compressive strength of 30 MPa. At the seventh curing day, the compressive strength of the first mix was 22 MPa and the compressive strength of the second mix was 40 MPa. This means achieving a natural pozzolan concrete of compressive strength of 30 MPa can be achieved after 7 days of curing but at a lower temperature if glass water is used with the alkaline solution.

The BSE image showed that the mix done with sodium hydroxide alone as the alkaline activator had a micro-size porosity of 8% while the micro-size porosity of the mix that was mixed with glass-water and sodium hydroxide as the alkaline activator was 4%. This means that the addition of glass-water increases the durability of the concrete because it produced denser concrete structure. This also explains the reason why the compressive strength of the first mix was lower than the second mix.

Another study conducted by (Hanjitsuwan et al., 2014) has also showed that using a combination of sodium hydroxide and sodium silicate produce denser and more durable paste. The study reported that using solution activator of sodium hydroxide and sodium silicate produced an improved paste with higher amount of C-S-H, it also produced higher compressive strength by 40% that the paste with sodium hydroxide only used as the alkaline activator.

The soluble silicate in the glass-water increases the speed of reaction. It also reduces the energy required for the initial geopolymerization. Thus, it increases the compressive strength of the natural pozzolan concrete in addition to increasing it early age compressive strength (Li, N., Shi, C., Wang, Q., Zhang, Z. and Ou, Z., 2017). However, according to (Bondar, Lynsdale and Milestone, 2012), if the silicate ratio increases beyond a certain limit, it will negatively influence the fresh and the hardened properties of the alkali activated natural pozzolans, so the compressive strength will decrease.

On the other hand, having a sodium silicate as the alkaline activator alone without the sodium hydroxide is not sufficient and will produce lower compressive strength of alkali activated natural pozzolan paste. According to (Tanakorn Phoo-ngernkhama, M. Akihiro, M. Naoki, H. Shigemitsu, Prinya Chindaprasirtd, 2015), using both sodium hydroxide and sodium silicate as the activator solution will lead to double the compressive strength compared to when using the sodium silicate alone as the activator solution at the 28th day of curing.

An experiment was conducted by (Jafari Nadoushan and Ramezanianpour, 2016) to study the Alkaline activator composition effect on the alkali activated natural pozzolan mechanical properties, in particular the compressive strength. The researchers used natural pozzolans from Saudi Arabia to prepare four mix designs of concrete; the alkaline activated solution were sodium silicate and sodium hydroxide. The silica modulus was 3.3 and the sodium hydroxide concentration was 14M and the ratio of sodium silicate/sodium hydroxide were 2, 2.25, 2.5 and 2.75 while other constitutes materials were kept constant. The compressive strength was measured at 0.5 day, 1 day, 3 days. 7 days, 14 days and 28 days. The results showed that when sodium hydroxide concentration was 14M and sodium silicate/sodium hydroxide ratio was 2.5, with seven days of curing lead to the highest compressive strength of 38 MPa.

In addition, another two samples were prepared with constant sodium silicate/sodium hydroxide ratio with varying concentration. The sodium silicate/sodium hydroxide ratio was 2.5 and the concentration of sodium hydroxide were 8M and 12M; the other constitutes materials were kept constant. The results showed that as the curing duration increased from seven days to fourteen days and then to twenty-eight days, the compressive strength decreased to 37 MPa and 35 MPa respectively. At sodium silicate/sodium hydroxide ratio of 2 and 2.25 the compressive strength showed similar pattern to sodium silicate/sodium hydroxide ratio at 2.5 with slightly lower values. The compressive strength increased as the curing duration increased to read 33 MPa and 34 MPa respectively at the seventh curing day then the compressive strength decreased as the curing duration increased. For sodium silicate/sodium hydroxide ratio of 2.75, the compressive strength at curing of half a day, one day and seven days were significantly lower than the other sodium silicate/sodium hydroxide ratios. However, at the fourteenth curing day the compressive strength reached its peak at 37 MPa then it decreased again at curing day twenty-eight. This shows that the highest compressive strength of 38 MPa was at sodium silicate/sodium hydroxide ratio of 2.5 by weight with sodium hydroxide concentration of 14M and curing duration of seven days. The other conclusion is that the compressive strength at sodium silicate/sodium hydroxide ratio of 2.5 after one day of curing showed a high compressive strength gain of 24 MPa, which is around 63% of the ultimate strength.

The above studies prove that suitable combination of alkaline activators with a suitable concentration and ration can result in better mechanical properties of alkali activated natural pozzolan geopolymer than that of PC concrete, such as the compressive strength and the durability. It also can reduce the curing duration which will reduce the cost and the time for construction.

In addition, the decrease in the compressive strength as the curing duration increases can be due to the weakening of the microstructure and the development of microcracks within the specimen. On the other hand, a lower concentration of sodium hydroxide caused a lower compressive strength. The compressive strength of the specimen with sodium hydroxide of 8M showed a lower compressive strength at all the curing duration. While a specimen with 12M and 14M of Sodium Hydroxide showed close compressive strength at the beginning of the curing but as the curing duration increased that gap between the two compressive strength increase and the specimen with the higher concentration of sodium hydroxide, 14M, showed the higher compressive strength with difference around 25%. To summarize, the highest compressive strength was achieved by a concentration of sodium hydroxide of 14M and sodium silicate/sodium hydroxide ratio of 2.5 and curing period of seven days.

Another study done by (Najimi, Ghafoori and Sharbaf, 2018) also proved that a 25% of sodium silicate to be present in the alkaline activator leads to an increased compressive strength. The compressive strength was measured at an age of one day, three days, seven days, twenty-eight days and ninety days. The samples were cured for seven days. The results showed that as the sodium silicate increases from 20% to 25%, and as the sodium silicate/sodium hydroxide ratio increase from 2 to 2.5, the compressive strength increased. Also, the researchers stated that when sodium silicate is present in the alkaline solution the microstructure of the sample was more homogenous which might be the reason for higher compressive strength than when the activated alkaline solution is only sodium hydroxide.

According to (Haddad, R. H. and Alshbuol, O., 2016) who studies the natural pozzolan paste mix design and properties by using natural pozzolan from Jordan states that regardless of the sodium silicate/sodium hydroxide ratio, the compressive strength increased as the concentration of the sodium hydroxide increases. The authors stated that a concentration of 14M of sodium hydroxide led to the highest compressive strength. Also, the authors stated that the specimen with concentration of 14M was denser and had less pores and lower percentage of unreacted natural pozzolan that the specimens with lower concentrations of sodium hydroxide as shown by SEM image. However, a higher concentration of sodium hydroxide led to much lower workability and inconsistency and was inappropriate to prepare a specimen with.

The authors also studied the sodium silicate/sodium hydroxide ratio that leads to the highest compressive strength. Four specimens were prepared with sodium silicate/sodium hydroxide ratio varied from 0.5 to 3, a ratio of 2.5 gave the highest compressive strength. Also, a higher sodium silicate/sodium hydroxide ratio led to low workability and inconsistency in the specimen. An SEM images showed that the specimen with sodium silicate/sodium hydroxide ratio of 2.5 have lower pores and consistent structure than the other sodium silicate/sodium hydroxide ratios. Although addition of superplasticizer increased the Jordanian Natural Pozzolan Geopolymers, but it caused a severe decrease in the compressive strength. It is advised that if the use of superplasticizer is necessary, it should be at a maximum of 4%. A 6% of superplasticizer caused a 28% reduction in compressive strength at age of seven days and a 26% reduction in the compressive strength at age twenty-eight days (Najimi, M., Ghafoori, N. and Sharbaf, M., 2018).

The alkaline activator used in the mix design for the alkaline activated natural pozzolan geopolymer affects the properties on the geopolymer. The compressive strength depends on the type and concentration of the solution that is used to activate the natural pozzolan. Previous studies found that activating the natural pozzolan with sodium hydroxide will result in acceptable compressive strength and durability but activating it with sodium hydroxide and sodium silicate will result in higher compressive strength and higher durability. In contrast, it was found that using sodium silicate alone to activate the natural pozzolan will result in compressive strength less than that activated by sodium hydroxide and sodium silicate by half. The optimum alkaline activator concentration and ratio that led to the highest compressive strength and high early age compressive strength is sodium hydroxide concentration of 14M and a ration of 2.5 of sodium hydroxide/sodium silicate.

4.1.2 Volcanic Ash Natural Pozzolan Composition

The chemical composition of the natural pozzolan influence its pozzolanic behaviors thus it influences the mechanical properties of the natural pozzolan geopolymer concrete. There are different types of natural pozzolans, and they have different compositions, hence the concrete that is made with each type of natural pozzolan will vary. The chemical composition of the natural pozzolans includes alkali percentage, activity index, which is its solubility in alkaline solution, L.O.I (loss of ignition) and the quartz percentage.

The activity index is the ratio of (aluminum oxide + calcium oxide + iron oxide + magnesium oxide) over the silicon oxide. The alkaline percentage can be found by X-ray fluorescence analysis. The alkali solubility index is the ratio of (silicon oxide + aluminum oxide + calcium oxide) in solution from the (silicon oxide + aluminum oxide + calcium oxide) in mineral. The compressive strength of the natural pozzolan paste decrease as the alkali percentage increase and it increases as the alkali solubility increase. The quartz is hard mineral and its bonding start to rapture starting at 2000 C^0, as its percentage in the composition of the natural pozzolan increase, the compressive strength of the alkali activated paste for that natural pozzolan increases (Shi, C. and Day, R., 2001). The loss of ignition is a test that measures the difference in the mass of a material before and after 'igniting' it.

In general, the calcium oxide content in the natural pozzolan have positive effect on the natural pozzolan concrete., such as the compressive strength and the setting time of the concrete. The Si-Al ratio also have positive effect on the natural pozzolan concrete. The hardness of the of the material, natural pozzolan, increases the compressive strength of the natural pozzolan concrete of the alkali activated natural pozzolan. On the other hand, as the percentage of the Potassium Oxide increase, the properties are negatively affected (Shi, C. and Day, R., 2001).

The chemical composition of the natural pozzolan is important because it determine its pozzolanic activity; and the pozzolanic activity of the natural pozzolans influence the mechanical properties of the natural pozzolans concrete. The more reactive the natural pozzolan is, the better mechanical properties its concrete is. Beside the natural pozzolan composition, other factors may affect the natural pozzolan reactivity including specific surface, pozzolana ratio of the mix, w/b ratio, curing time and curing temperature (Shi, C. and Day, R., 2001),(Jafari Nadoushan, M. and Ramezanianpour, A., 2016).

In addition, a one way to test the reactivity of a natural pozzolan is to conduct a compressive strength test for the alkaline activated paste. However, there is chemical test to determine the natural pozzolan reactivity ‘’pozzolanic activity index’’ as well, which is by finding the amount of silica or silica and alumina in an alkaline of acid solution (Shi, C. and Day, R., 2001),(Jafari Nadoushan, M. and Ramezanianpour, A., 2016).

Reference to the relationship between the natural pozzolans composition and the resulting mechanical properties of its concrete or past, a model was developed by (Bondar, Lynsdale and Milestone, 2012) to predict the compressive strength of natural pozzolan from its chemical composition. The model is done for alkali activated natural pozzolan that are cured for 28 day with curing temperature of 40 C^0, 60 C^0 and 80 C^0. According to the authors, the benefit of this model is to predict the compressive strength of alkali activated natural pozzolans with less time and resources; the model also is applicable for both raw natural pozzolan and calcinated/treated natural pozzolans.

Two models were created to predict the compressive strength of alkali activated natural pozzolan, a linear model and non-linear model. The predicted compressive strength was compared to that of the real one after testing and it was found that both models can be used, however, the non-linear model is more accurate than the linear model and it has higher correlation.

The linear model equation is:

Y = b_0 + b_1Sol + b_2 $(1.77 - 0.01\,T^{1.05})^{-1}$ + b_3 $(1.77 - 0.001\,T^{1.06})^{-1}$ Sol + b_4A + b_5 $(0.166 - 0.01\,T^{1.05})^{-1}$A + $b_6\,K_{ax}$ + b_7 (-437.84 + 10.36T - 0.12T^2) + b_8 (-437.84 + 10.36T - 0.12T^2) K_{ax}. (Jafari Nadoushan, M. and Ramezanianpour, A., 2016).

Where Y = compressive strength (MPa), Sol = alkali solubility index, A = alkali percentage, K_{ax} = activity index, T = curing temperature (C^0) and b_0 to b_8 are coefficient that are determined by least square technique.

The above model was further developed by the authors to a non-linear model and they have also included more parameters like loss of ignition (L.O.I), ratio of dissolution, and the quarts percentage.

The non-linear equations are as follows:

At 40 C^0, Y_{40} = b_0 + b_1Sol + b_2A + b_3 (192.73 - 1005.99K_{ax} + 1358.41 ${K_{ax}}^2$) +b_4 $2.72^{L.O.I}$ $(L.O.I)^{-3.81}$

+ b_5 $e^{0.02Q}$ +b_6 / (0.03+ l866.18 K_{alr} - 8.77x$10^6{K_{alr}}^2$). (Jafari Nadoushan, M. and Ramezanianpour, A., 2016).

At 60 C^0, Y_{60} = b_0 + b_1Sol + b_2A + b_3 (263.3 - 144.22K_{ax} + 2064.93 ${K_{ax}}^2$) +b_4 $1.72^{L.O.I}$ $(L.O.I)^{-2.42}$

+ b_5 $e^{0.04Q}$ +b_6 / (-1.15 + 60050.58 K_{alr} – 17.65x$10^6{K_{alr}}^2$). (Jafari Nadoushan, M. and Ramezanianpour, A., 2016).

At 80 C^0, Y_{80} = b_0 + b_1Sol + b_2A + b_3 (357.49 – 1921.36K_{ax} + 2639.98 ${K_{ax}}^2$) +b_4 $2.02^{L.O.I}$ $(L.O.I)^{-3.0}$

+ b_5 $e^{0.04Q}$ + b_6 / (-1.15 + 60050.58 K_{alr} – 6.25x$10^8{K_{alr}}^2$). (Jafari Nadoushan, M. and Ramezanianpour, A., 2016).

Where L.O.I = loss of ignition, Q = quartz percentage and K_{alr} = the ratio of solving main elements measured from leaching test.

The two above models are accurate and showed high correlation between the predicted compressive strengths and the tested one. However, the non-linear model was more accurate, and it showed a higher correlation. The authors have used the models to predict the compressive strength of the alkali activated natural pozzolan in Iran but we can use it to predict the compressive strength of alkali activated natural pozzolan around the world because it would be very beneficial and time saving to know if a specific type of natural pozzolan is suitable for the purpose of construction or not.

The two models show that the main external factor that affect the outcome, the compressive strength, with the same natural pozzolan composition is the curing temperature. So, the same pozzolan with the same composition can lead to a varying compressive strength if the curing temperature alters. It also shows that increasing the curing temperature may not necessary leads to a higher compressive strength, but the optimum curing temperature that results the maximum compressive strength depends on the composition of that natural pozzolan. For example, the optimum curing temperature for Shahindej alkali activated natural pozzolan was 80 C^0 and it showed lower compressive strength at lower curing temperature while the optimum curing temperature for Sirjan alkali activated natural pozzolan was at 60 C^0 and its compressive strength was lower at a higher curing temperature.

4.1.3 Curing Temperature and Duration

Another variable that affect the Natural Pozzolan Geopolymers is the curing time and temperature. Curing is the process of keeping the moisture in concrete with a proper temperature in order for the components of concrete to react to form strong solid and prevents the concrete from high drying shrinkage and cracking. In case of the alkaline activated natural pozzolan geopolymer concrete curing temperature and duration is very important to increase the rate of the reaction of the natural pozzolan with the alkaline activator and to achieve acceptable early age compressive strength because one its negative properties is its slow reaction, low reactivity, thus long setting which causes long duration during construction and it is also not favorable properties in cast of pre-cast concrete.

One of the main drawbacks of geopolymers based on volcanic ash natural pozzolan is to achieve high compressive strength and reasonable setting time it requires high curing temperature done on long duration. High curing temperature and duration has many drawbacks including high cost and safety concerns in construction sites. However, it might be achievable in the precast factories. To study the influence of the curing temperature on the properties of the alkaline activated natural pozzolan geopolymer, (Haddad, R. H. and Alshbuol, O., 2016) prepared two specimens of Jordanian natural pozzolan pastes were cured for one and two days at temperatures of 40, 80 and 120 C^0. The compressive strength tests showed that the compressive strength of curing for two days is higher than the curing for one day at all the curing temperatures. Also, it shows that the highest compressive strength at curing temperature of 80 C^0 and it declines sharply at higher curing temperatures.

In addition, the SEM image at curing temperature of 80 C^0 showed a dense structure and aluminosilicate gel was formed with limited cracks which means the curing temperature was sufficient to activate the natural pozzolan to react with the alkaline activator and form a strong gel. This does not only increase the compressive strength but also reduce connected pores in the geopolymer concrete which leads to high durability.

At curing temperature of 40 C^0 the SEM image showed holes and crisps which means less durable paste than the paste cured at 80 C^0. It also means that we can expect higher proportion of unreacted volcanic ash natural pozzolan in the paste.

Nevertheless, at curing temperature of 120 C^0 the SEM image showed large crystals with cracks and holes. This SEM image tells that the curing temperature was very high which cause a high rate of reaction between the natural pozzolan and the alkaline activator. However, this is a disadvantage because the high temperature caused cracks in the paste and lead to less durable geopolymer concrete and also cause a sharp reduction in compressive. The holes and the cracks that was formed because of the high curing temperature caused the structure to be weaker.

At curing temperature of 40 C^0, the reason for the holes and cracks might be because the Natural Pozzolan did not react well with the alkaline so no enough gel was formed to fill the holes and form dense structure. Finally, at curing temperature of 80 C^0 the geopolymer had the highest compressive strength because of the gel that was formed and filled the gaps and holes and resulted in a stronger compressive strength. On the other hand, in the above study the specimens were cured at three temperatures only and there was a gap between 80 and 120 C^0 and the authors assumed that the compressive strength will start dropping after 80 C^0. However, the compressive strength might still increase after 80 C^0 and then start dropping at higher temperature, the study didn't cover enough curing temperatures and the temperature increment was high.

Other studies also cured alkaline activated natural pozzolan geopolymer at 80 C^0. However, it is obvious from previous studies done by other researchers that there is a possibility to reduce the curing temperature or the curing duration and compensate it by the use of alkaline activator type and concentration. To demonstrate, according to (Moon et al., 2014), when using sodium hydroxide and sodium silicate to activate the natural pozzolan, the compressive strength was higher than the geopolymer when sodium hydroxide was used to activate the natural pozzolan. This means that the type of alkaline activator can increase the rate of reaction thus we can use the alkaline activator to compensate the reduction in curing temperature or duration when required. However, there are no researches that studies the possibility of reducing the curing temperature or duration and compensate it by the alkaline activator.

4.2 Drying Shrinkage

Drying shrinkage is the change in volume of the concrete as it hydrates. The volume reduction is the result of the loss of water when the concrete changes from the liquid to the solid state. The shrinkage causes stress in the concrete and might cause cracks as well. According to (Bondar, D., Lynsdale, C. J. and Milestone, N. B. 2013) the drying shrinkage of the alkaline activated natural pozzolans is ‘’extremely small’’ and it is lower than that of the traditional PC concrete. Their explanation of the reason of the small amount of the drying shrinkage is that alkaline activated natural pozzolan form zeolite-type phase, where the volume it unaffected by the loss of water. According to the research, the w/b ratio also influences the drying shrinkage. However, the higher the solution to binder ratio, the lower the drying shrinkage which contradicts the solution to binder ratio influence on the PC concrete. According to the (Bondar, D., Lynsdale, C. J. and Milestone, N. B., 2013), the reason might be because of the crosslinking (Si-O-Al or Si-O-Si bonding) made because of water evaporation by the high temperature. The paper only discusses the findings regarding the drying shrinkage of the alkaline activated natural pozzolan geopolymer, but it does not explain the experiment, nor the materials used in it.

(Najimi, Ghafoori and Sharbaf, 2018) conducted experiment to study the drying shrinkage of the alkaline activated natural pozzolan geopolymer. However, the ash that was used depends only partially on volcanic ash and the other component was slag. The mortars were made from 30%, 50% and 70% of slag and 30%, 50% and 70% of volcanic ash natural pozzolan. The mortars were activated with sodium hydroxide and sodium silicate. The drying shrinkage test was in accordance with ASTM C596, the samples were cured for seven days and the drying shrinkage was tested on a duration of five months. In contrast with the results that was found by (Bondar, D., Lynsdale, C. J. and Milestone, N. B., 2013), this study found that as the natural pozzolan decrease the drying shrinkage decrease as well. It was also found that the drying shrinkage of the alkaline activated geopolymer based on slag and natural pozzolan is higher than that of the PC concrete.

In addition, the study found that as the quantity of sodium hydroxide increases, and the quantity of sodium silicate increases the drying shrinkage decreases. Also, as the silica in content in the sodium silicate increases, the drying shrinkage increases. The increase in drying shrinkage when sodium silicate is used as part of the alkaline activator can be explained by the fast that the rate of reaction is faster when the natural pozzolan is activated by both sodium hydroxide and sodium silicate which will consume the hydration content in the paste and leads to higher drying shrinkage. The study also finds that as the solution to binder ratio increases, the drying shrinkage increases. This trend is expected because there is larger amount of water willing to evaporate when the solution to binder ratio is higher thus it causes a bigger change in volume.

The findings of the two studies done by (Bondar, D., Lynsdale, C. J. and Milestone, N. B. 2013) and (Najimi, Ghafoori and Sharbaf, 2018) report different results. Although the later study used slay in addition to the natural pozzolan but al least they should have similar or close trends. The two studies reported different trend of drying shrinkage in comparison to the PC concrete where the first study done by (Bondar, D., Lynsdale, C. J. and Milestone, N. B. 2013) states that the drying shrinkage of the alkaline activated natural pozzolan geopolymer is lower than that of the PC concrete while the study done by and (Najimi, Ghafoori and Sharbaf, 2018) concluded that the drying shrinkage of alkaline activated geopolymer based on 70% of volcanic ash and 30% of slag have higher drying shrinkage than that of the PC concrete. Also, the first study reported that as the solution to binder ration increases the drying shrinkage decreases while the later study reported that as the solution to binder increases the drying shrinkage increases.

There are no enough studies that tests the drying shrinkage of the alkaline activated natural pozzolan geopolymer to draw a conclusion in comparison with the PC concrete. However, the results reported by (Bondar, D., Lynsdale, C. J. and Milestone, N. B. 2013) are based geopolymers that contain 100% natural pozzolan.

4.3 Setting Time

Setting time of concrete is the required duration for the paste to gain strength and move from the liquid state. There are two thresholds for the setting time, initial setting time and final setting time. The initial setting time is the time when the paste starts to harden and lose its plasticity, so a needle can penetrate 1 mm but cannot penetrate 5 mm of the paste. The mixing and placing of concrete have to be done before the initial setting of concrete. The final setting time is when the concrete gains its final strength and lose its plasticity completely, moves in the solid state. Concrete with short setting time is an advantage in cold weather, fast construction and pre-cast factories and concrete with long setting time is an advantage in hot weather.

According (Bondar, D., Lynsdale, C. J. and Milestone, N. B. 2013) the setting time of the natural pozzolans geopolymers is influenced by curing temperature, alkaline activator type and the composition of the pozzolanic material. Volcanic ash natural pozzolan types that have high content of silicate and aluminate will cause longer setting time of the alkaline activated natural pozzolan paste. Also, According to Hardjito et al. who studied the setting time of the alkaline activated natural pozzolan geopolymer concluded that the calcium oxide content in the natural pozzolan impacts the setting time of the alkaline activated natural pozzolan. So, as the calcium oxide content in the natural pozzolan increase, the setting time increases as well. However, if the natural pozzolan contains minerals for example, opal, it increases the reactivity with the alkaline solution and reduces the setting time (Bondar, D., Lynsdale, C. J. and Milestone, N. B., 2013).

The finesse of the natural pozzolan also influence the setting time because it impacts the reactivity of the natural pozzolan thus the rate of reaction between the natural pozzolan and the alkaline activator. According to (Hardjito, D.; Wallah, S. E.; Sumajouw, D. M. J.; and Rangan, B. V., 2003), the smaller the surface area the longer the setting time of the alkaline activated natural pozzolan geopolymer. Also, the same study reported that the setting time of the alkaline activated natural pozzolan geopolymer showed that the fresh geopolymer starts the initial setting after 120 minutes. An experiment was done by P.N. Lemougna, K.J.D. MacKenzie, U.C. Melo to study the effect of the natural pozzolan fineness on the setting time, it was found that when the natural pozzolans were milled for 30 minutes, the initial setting time of the alkaline activated natural pozzolan geopolymer was over 600 minutes, when the milling time was 60 minutes, the initial setting time was 150 minutes, while when the natural pozzolans were milled for 90 minutes the initial setting time decreased to 15 minutes. The authors found that the fineness of the natural pozzolans does not affect the physical properties of the geopolymers based on alkaline activated volcanic ash natural pozzolan.

The setting time of the alkaline activated natural pozzolan geopolymer is affected by the type of the alkaline activator and its concentration. (Firdous, R., Stephan, D. and Djobo, J. N. Y., 2018) found that the concentration of the sodium silicate, in case it is part of the alkaline activator, affects the setting time of the alkaline activated natural pozzolan geopolymer. The authors concluded that as the concentration of the sodium silicate increase the setting time of the alkaline activated natural pozzolan geopolymer reduces.

Finally, the setting time also depends on the curing temperature and duration. According to (Bondar, D., Lynsdale, C. J. and Milestone, N. B., 2013), the setting time decreases as the curing temperature and duration increases, this trend is similar to that of the PC concrete.

Similar to other properties, the setting time of the alkaline activated natural pozzolan geopolymer is affected the geopolymer parameters which includes the chemical composition of the natural pozzolan and its finesse, the type of the alkaline activator and its concentration and curing temperature and duration. The affect of the curing temperature and duration on the alkaline activated natural pozzolan geopolymer is similar to its effect on the traditional PC concrete.

4.4 Workability

The workability of the concrete is its flowability when its in the liquid state. The workability of the concrete determines how easy to place to the concrete and to compact it. In general, as the solution to binder ration increases, the water content in concrete increases, the workability of the concrete increase. However, the compressive strength decreases. There are tests to measure the workability of the concrete but the most used one is the slump cone test and the flow test table. So, as the slump of the concrete increases, its means that the concrete is more workable. There are chemical additives, like superplasticizer, that can increase the workability of the concrete without compromising the compressive strength, which means higher concrete workability can be achieved without increasing the water to binder ratio.

(Najimi, Ghafoori and Sharbaf, 2018) studied the workability of the alkaline activated natural pozzolan geopolymer. The authors found that the combination of the alkaline activator affect the workability of the alkaline activated natural pozzolan concrete, so, when the amount of the sodium silicate increases in the alkaline activator and the sodium hydroxide increases, the workability of the geopolymer increases. The workability of the alkaline activated natural pozzolan geopolymer increased when the concentration of sodium hydroxide increased from 0.5M to 1M. However, when the concentration of sodium hydroxide solution increased from 1M to 2M the workability of the geopolymers decreased. Also, when the concentration of sodium hydroxide increased from 0.5M to 1M, the workability of the alkaline activated natural pozzolan paste samples increased by 1.7, 3.5 and 1.9 cm. Furthermore, as the concentration of sodium hydroxide increased from 1 to 2M, the workability of the samples decreases by 3.3 and 1.5 cm for different mix designs. Based on this, the authors concluded that the workability decreased by 11% for each increase of content by 5% of the sodium hydroxide solution. However, the decrease in workability might not necessary be due to the type of the alkaline activator but it might be due that the solution to binder ration when sodium hydroxide is higher than when the sodium silicate is used.

Similar to PC concrete, the workability of alkaline activated natural pozzolans geopolymer increased when the solution to binder ratio increases. The workability decreased around 20% when the solution to binder ratio decreased from 0.60 to 0.56 and 0.56 to 0.52 (Najimi, M., Ghafoori, N. and Sharbaf, M., 2018).

The workability of the alkaline activated natural pozzolan geopolymer trend is similar to that of the PC concrete so as the solution to binder ration increases, the workability increases as well. Based on previous studies presented in this paper, the solution to binder ratio used for the mix design of such geopolymers is 0.45. Finally, the alkaline activator type affects the workability of the alkaline activated solution. Such that when sodium hydroxide is used alone to activate the natural pozzolan, it results in lower workability than when the natural pozzolan is activated by sodium hydroxide and sodium silicate. However, other types of the alkaline activator affect on the workability is not studied.

4.5 Durability

Durability of concrete is its ability to resist the environmental factors that may cause deterioration in the reinforcement or causes defects in the binder that's leads to cracks, in addition to water leaching and sulphate attack. The more durable the concrete is the longer it is able to survive and the longer our structures will last. Like other mechanical properties of alkali activated natural pozzolan there are factors that determine how durable the concrete is, such as the alkaline activator type, the curing temperature and duration and the w/b ratio.

The concrete durability depends on its permeability, which is the how much pores there are in the concrete and whether they are connected with each other. The higher the percentage of pores, the higher ability of the concrete to absorb contaminants from the environment; and the when the pores are connected, the contaminants will be able to travel and diffuse through the concrete deeper. There are tests to measure the concrete durability which are absorption test, rapid chloride permeability test and water permeability test.

Another way to measure the durability of concrete is to immerse concrete cubes in water with high concentration of dissolved sulphate. Sulphate attack will cause the concrete sweating, spalling and cracking. high permeability concrete is less resistance to sulphate attacks and to severe environmental conditions than the low permeability concrete. A study that was conducted by (Bondar, D., Lynsdale, C., Milestone, N. and Hassani, N., 2014) to study the sulphate resistance of alkali activated natural pozzolan concrete where two types of Iranian Pozzolans concrete samples were immersed in water and sulphate solution for 180 days. The samples were cured with two different techniques, some were cured with fogging and others were cured with sealing. The study result showed that the absorption for all of the samples in both tap water and sulphate solution varied between 5% to 7%. The absorption in the samples that were cured by fogging had higher absorption than the samples cured by sealing. The reduction of compressive strength after two years of immersing was 8% to 20%. The maximum expansion was 0.074% after six months immersions.

The maximum percentage of expansion acceptable by ASTM C1012 for PC concrete is less than 0.1%; the maximum expansion of natural pozzolan concrete was 0.074%. The loss of strength of PC concrete with the same regime was up to 38% (Bondar, D., Lynsdale, C., Milestone, N. and

Hassani, N., 2014). The reason for high absorption for samples that were cured with fog may be cause by the absorption of the fog which caused a porous concrete.

A study that was conducted by (Yankwa Djobo, Elimbi, Kouamo Tchakouté and Kumar, 2016) to study the sulphate resistance of the natural pozzolan concrete. Natural pozzolan was used from region of Cameroon. The alkaline activator used was sodium silicate and sodium hydroxide with the ratio of sodium silicate to sodium hydroxide is 1.4; The concentration of the sodium hydroxide is 12M; the w/b ratio is 0.45. All the samples were mixed in similar manner except for the curing. Some samples were left at room temperature at 27 C^0, and others were cured in the over at 80 C^0 for 24 hours. To perform the sulphate resistance test, the samples were immersed into sulphate solution for 180 days.

The results show that the initial compressive strength is 20 MPa for the sample cured at 27 C^0 and 30 MPa for the sample that was cured at 80 C^0. After 90 days of immersion in sulphate solution the compressive strength was 20 MPa and 27 MPa respectively; and the weight loss was 3% and 1.5% respectively; the depth of the sulfuric acid penetration was 5 mm and 10 mm respectively. After 180 days of immersion, the compressive strength was 16 MPa and 12 MPa respectively; and the weight loss was 3.5% and 3% respectively. Both samples didn't have any surface degradation until the 180 day but the samples show change in color, became lighter.

The results show that although the high curing temperature lead to a higher compressive strength, but it negatively affected the sulphate resistance, thus the durability of the paste that was cured at high curing temperature, 80 C^0. The sample that was cured at room temperature didn't lose compressive strength for the first 90 days although there was a weight reduction by 3% in the sample. This means that it had fewer pores, connected pores, than the specimen that was cured at 80 C^0. A possible reason for the less durable sample that was cured at high curing temperature is the loss of water from the sample which left a connected pore in the samples that leaded to high compressive strength but less durable paste. The change in color of the samples is probably due to the reaction with the sulfuric acid.

The researchers conclude that a possible reason for the high sulphate resistance of the sample that was cured at 27 C^0. Might be because of the unreacted sodium, sodium gel, availability in the sample, which reacted with the sulfuric acid and became neutral.

Although high curing temperature increase the alkali activated natural pozzolan compressive strength and it can reduce the setting time as well, but it may also reduce its sulphate resistance. However, there are structures where the durability is required but high compressive strength is not essential. On the other hand, if both samples are compared to PC cement durability, the PC cement would destroy totally after four months of exposure to the same acid solution (D. Bondar, C.J. Lynsdale, N.B. Milestone, N. Hassani, 2012). So both samples are more durable than the PC concrete. Another conclusion is that the curing temperature increment is high. Other studies have shown that optimum curing temperature of the alkali activated natural pozzolan ranges between 40 C^0 and 60 C^0. So, a lower curing temperature may have led to a more sulfuric resistance alkaline activated natural pozzolan paste.

An experiment was conducted by (Yankwa Djobo, Elimbi, Tchakouté and Kumar, 2016), using natural pozzolan from region of Cameroon to test the effect of the curing temperature on the water absorption of the alkali activated natural pozzolan pastes. The samples were cured at 27 C^0, room temperature, and 80 C^0 in the oven. For the water absorption test, the specimen were dried in an oven and the then were immersed in water. The weight was measured before and after the water immersion. The percentage difference in weight is equal to the water absorption. The water absorption was measured on the 7, 28, 90, 120 and 180 days.

The results shows that initially, in the 7th day, the two samples absorbed the same amount of water which was 4.5%. However, after the 7th day until the end of the duration, the sample that was cured at 27 C^0 absorbed more water. The maximum absorption of the two samples was at the 28th day; the maximum water absorption of the sample that was cured at 27 C^0 was 7% and the sample that was cured at 80 C^0 was 6%. The water absorption of both samples was constant until the 180 day.

This shows that the sample that was cured at 27 C^0 has higher porosity than the sample which was cured at 80 C^0. The results of the water absorption conflict the results of the sulfuric acid resistance, although the similar type of natural pozzolan was used and similar mis design. The sulfuric acid resistance test showed that the sample that was cured at 27 C^0 had higher resistance. So, the assumption made was that the sample that was cured at 80 C^0 have more connected pores and less durable.

(Bondar, Lynsdale, Milestone and Hassani, 2014) found that the oxygen permeability of the alkaline activated natural pozzolan concrete is similar to that of the ordinary Portland cement concrete and as the water/binder ratio decreases so does the oxygen permeability. However, a reduction in the water/binder ratio in the activated alkaline natural pozzolan concrete caused a reduced permeability by 20% compared to the PC concrete because water causes open microstructure in activated alkaline natural pozzolans concrete which causes higher permeability (Bondar, D., Lynsdale, C. J. and Milestone, N. B., 2013). The permeability of the Natural Pozzolan geopolymers showed 10%-30% lower Oxygen permeability than Ordinary Portland Cement.

On another hand, (Moon et al., 2014) shows that when a mixture of 80% mass of Sodium Hydroxide, at a concentration of 10M, and 20% mass of Sodium Silicate solution is used to activate the Natural Pozzolan instead of Sodium Hydroxide only, it resulted in less porous paste and leaded to more durable alkaline activated natural pozzolan paste. The natural pozzolan used in the experiment is from Saudi Arabia. When sodium hydroxide alone is used as the alkaline activator, the porosity of the paste was found to be 8.2%; and the porosity of the paste when both sodium hydroxide and sodium silicate was used to activate the natural pozzolan was 6%.

The concentration of the alkaline activator influences the durability of the alkaline activated natural pozzolans. The effect of the concentration of the alkaline activator on the alkaline activated natural pozzolan paste is similar of its effect on the compressive strength. Thus, as the concentration of the alkaline solution increase, the permeability of the paste will decrease producing a more durable paste (Yankwa Djobo, J., Elimbi, A., Kouamo Tchakouté, H. and Kumar, S., 2016). Using a suitable alkaline activator with the optimum concentration increase the amount of C-S-H (calcium – silica – hydrates) which increases the density of the paste thus increases its durability and reduces its permeability.

The reason why the natural pozzolan is expected to be more durable than the PC concrete is because it forms higher quantity of C-S-H (Calcium Silica Hydrates) thus a reduced number of calcium because of the pozzolanic reaction. The C-S-H makes the paste denser, stronger and more durable. Similar to PC concrete lower w/b ratio causes higher permeability which leads to less durable concrete. This is also in agreement with a study that was conducted by D. (Bondar, C.J. Lynsdale, N.B. Milestone, N. Hassani, 2012), to test the oxygen permeability for Iranian (Tafan) alkaline activated natural pozzolan which shows that the alkali activated natural pozzolan have higher permeability with w/b of 0.45 than the mix with w/b ratio of 0.55. The study also tested three types of Iranian natural pozzolan which are Tafan with w/b ratio of 0.45 and 0.55, raw Shahendij with w/b ratio of 0.43 and calcinated Shahendij with w/b ratio of 0.42, in addition to PC cements with w/b ratio of 0.45 and 0.55 as a control mixes. The results shows that all alkali activated natural pozzolans paste have lower oxygen permeability than both PC cement paste, the permeability was at least less by half than that of the PC cement. The lowest oxygen permeability was for Tafan with w/b ratio of 0.45 and the calcinated Shahendij at age of 90 days. The oxygen permeability of both was around 2x10^{-7} m^2. The oxygen permeability at early age of both mixes of alkali activated Shahendij was more than the double of that of the PC cement. However, both of the alkali activated Tafan had similar permeability of the PC cement at an early age.

The oxygen permeability of the alkali activated natural pozzolan is showing similar manner of the compressive strength where it is low at an early age and increases with time. The difference in permeability in alkali activated Tafan with w/b ratio of 0.45 and w/b ratio of 0.55 shows a higher permeability difference than that of PC cement of w/b ratio 0.45 and w/b ratio of 0.55. So, we can conclude that the effect of w/b ratio on the alkali activated natural pozzolan is more than its effect on PC cement. The study also shows that the mixes which were cured at 40 C^0 by both sealing and fogging had lower permeability that the mixes which were cured at 20 C^0.

The same study that is conducted by (D. Bondar, C.J. Lynsdale, N.B. Milestone, N. Hassani 2012), also examines the chloride penetration of alkali activated natural pozzolans. In this study, and in agreement to the study that was conducted by J.N.Y. Djobo, A. Elimbi, H. Kouamo Tchakouté, S. Kumar, the researchers conducted that the Rapid Chloride Permeability Test is not applicable on the alkaline activated natural pozzolan paste. The alkaline activator that is part of the paste makes the paste more conductive and allows to pass higher charges and caused over heating to the system. The chloride penetration was tested by bulk diffusion test, the samples were exposed to chloride solution for 90 days. The result showed that the lowest chloride penetration was for the alkaline activated Tafan with w/b ratio of 0.45 which was around 0.05% of the weight of concrete. The alkaline activated Tafan with w/b ratio of 0.55 has a chloride penetration of 0.1% of the weight of concrete. So, as the w/b ratio decrease the chloride permeability decreases. The chloride penetration of alkaline activated raw Shahendij is almost similar to the alkaline activated Tafan with w/b of 0.55. While, the chloride alkaline activated calcinated Shahendij had a similar chloride penetration to alkaline activated Tafan with w/b of 0.45. All the alkaline activated natural pozzolans samples had higher chloride permeability at an early age and then as the samples age the permeability decreases.

The chloride permeability of alkaline activated Tafan with w/b ratio of 0.55 was the lowest when cured by sealing at of 40 C^0. However, the chloride permeability of alkaline activated Tafan with w/b ratio of 0.45 was the lowest when cured by sealing by 60 C^0. In addition, the reason why the chloride permeability of alkaline activated calcinated Shahendij was lower that the alkaline activated raw Shahedij might be because the former was treated by sealing at 60 C^0 while the latest was tested by sealing at 20 C^0. So the chloride permeability depend of both the w/b ratio and the curing temperature.

The durability of the alkaline activated natural pozzolans needs further research, considering the different types of natural pozzolans available around the world. There are only few published papers regarding the alkali activated natural pozzolan sulfuric acid resistance, oxygen permeability, chloride permeability and water absorption.

In addition, the corrosion of the steel reinforcement is expected to be reduced since the binder is alkaline with a PH of 10 or higher. However, there are no published papers that studied this aspect.

5.0 Life Cycle Assessment of Alkali Activated Natural Pozzolan

Life cycle analysis is the impact of an activity on the environment. The life cycle assessment of a material includes the energy needed for extraction from the natural resource, transportation to the factory, the emission and wastes produced during the production process. Depending on the life cycle assessment approach, it can also include the energy required for the transportation from the factory to the user and the energy required through the material's life for maintenance, in addition to the energy required to dispose the material at its end life.

While the world is aware that the production process of cement in the traditional concrete, PC Concrete, is responsible for producing a large amount of global warming gases to the environment yet we still need to produce large amount of the concrete to develop our infrastructure and buildings. Since the reduction in producing PC Concrete is not a practical solution, researchers proposed multiple ideas to substitute the cement in the concrete partially or replace it completely with other materials.

To substitute the traditional concrete in the market we need to achieve similar, or better, properties of the traditional concrete and to reduce the impact of the production on the environment.

In this section the life cycle assessment of alkaline activated natural pozzolan geopolymer will be studied and the results will be compared to the traditional concrete as well as other geopolymers that were previously proposed by other researches to examine if the alkaline activated natural pozzolan geopolymer have lower negative impact on the environment by producing lower amount of global warming gases.

The assessment will be limited to the production process only, which is gate-to-gate. It will not assess the extraction, transportation, distribution, pacing, curing, maintenance and disposal because this will differ from country to country and may depend on the location of the resource and the location of the factory. The life cycle assessment exercise will cover Global Warming Potential (GWP100) category, expressed as CO_2-equivalent (kg).

Greenhouse gases have a long life, which means they can stay in the atmosphere for many years before they decay, some of the gases stay in the atmosphere for thousands of years one of them is carbon dioxide (CO_2). Such gases increase the temperature of the earth and causes global warming by absorbing the earth's energy and prevent it from escaping the atmosphere. The duration of the gases can stay in the atmosphere before they decay, their residence time, differ from one type of gas to another. In Global Warming Potential, carbon dioxide is used as the reference gas and all the other gasses are compared to it in 100 years.

5.1 Life Cycle Assessment - Exercise 1

5.1.1 Goal and Scope

The goal of this life cycle assessment exercise is to evaluate the Global Warming Potential GWP100 produced during the production process of the alkaline activated natural pozzolan geopolymer concrete using a natural pozzolan from Saudi Arabia. The mix design of the alkaline activated paste is obtained from a previous research done by (Moon et al., 2014) and the mix design of 1 m^3 of the alkaline activated concrete is obtained by the absolute volume method.

The natural pozzolan from Saudi Arabia that was used didn't need a heat treatment to be activated because it shows the pozzolanic properties. However, crushing, drying and grinding is usually done to the natural pozzolan to increase its activity and make it consistent. The process of natural pozzolan production is shown in figure 1.

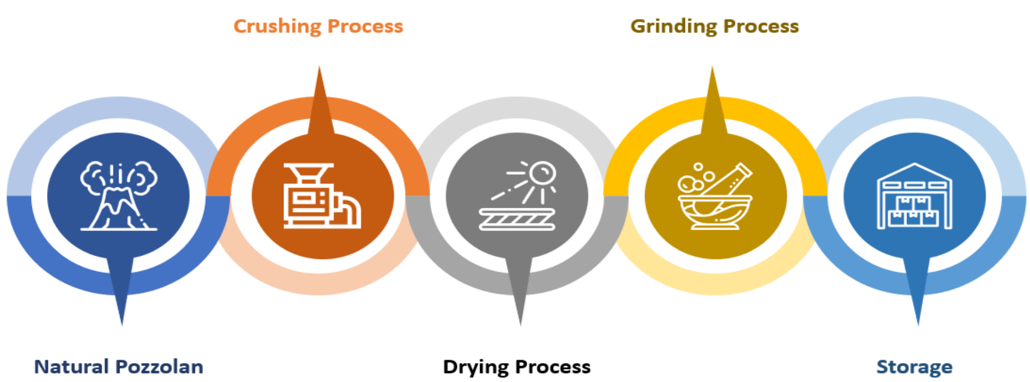

Figure 1: Preparation of Natural Pozzolan

To obtain a concrete with a compressive strength of 47 MPa, a 400 kg of Natural Pozzolan was used with a composition of aluminum oxide of 14.74%, calcium oxide of 8.78% and loss of ignition of 1.324. To activate the natural pozzolan, sodium hydroxide and sodium silicate were used. The water-binder ratio is 0.45. the samples were cured at 80 C^0 for 28 days. However, the curing is not included in the life cycle assessment.

5.1.2 Inventory Analysis for Alkaline Activated Saudi Natural Pozzolan Concrete Activated with Sodium Hydroxide and Sodium Silicate

To produce 1 m^3 of Alkaline Activated Natural Pozzolan Concrete, the following materials will be used:

Natural pozzolan from Saudi Arabia = 400 Kg,
Sodium hydroxide solution = 144 Kg, 10M - sodium hydroxide dry weight = 58 kg
Sodium Silicate Solution = 36 Kg, Ms = 3.22 - sodium silicate dry weight = 14 kg
Gravel = 940 Kg
Sand = 770 Kg

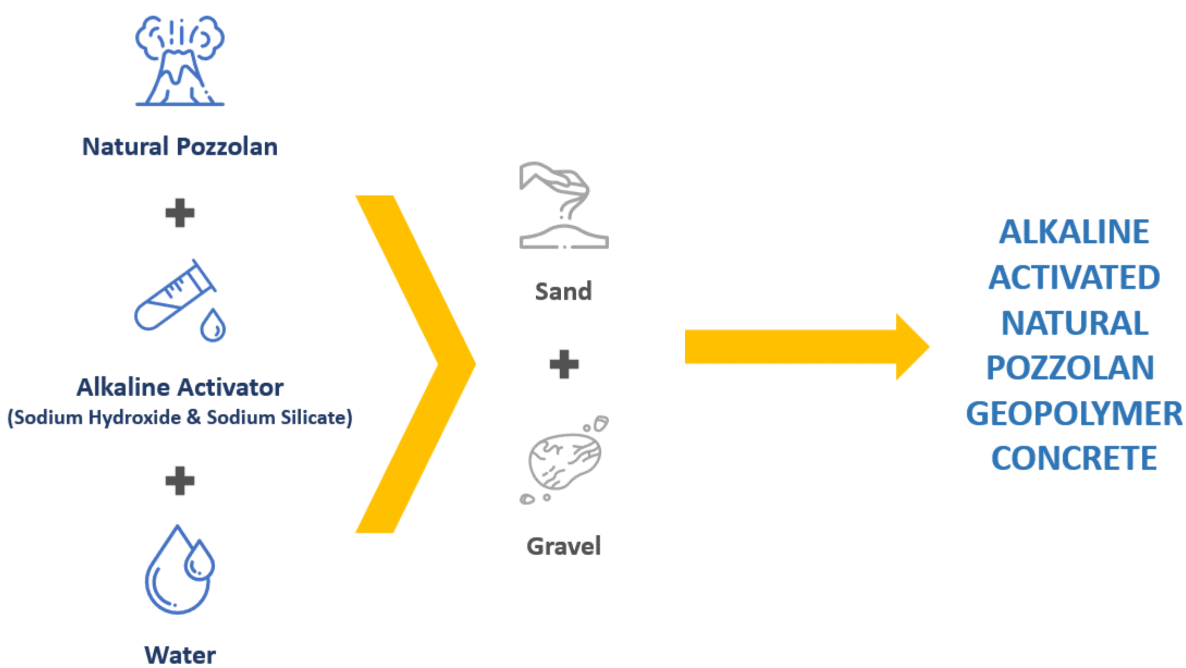

Figure 2: Production Process of Alkaline Activated Natural Pozzolan Geopolymer Concrete

5.1.3 Impact Assessment

Table 4: Alkaline Activated Natural Pozzolan Concrete GWP100

Material	**Dry Weight (Kg)**	**GWP100 (kg·CO_2 ·eq)/Kg**	**Total (kg·CO_2 ·eq)**	**Source**
natural pozzolan	400	0.009312	3.7248	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
sodium hydroxide	58	1.359	78.822	Thannimalay,L.,Yusoff, S. Zawawi, N. (2013)
sodium silicate	14	0.7925	11.095	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
water	180	0.0004288	0.077184	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
sand	940	0.004473	4.20462	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
gravel	770	0.0108	8.316	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
Total	**2,362**		**106.24**	

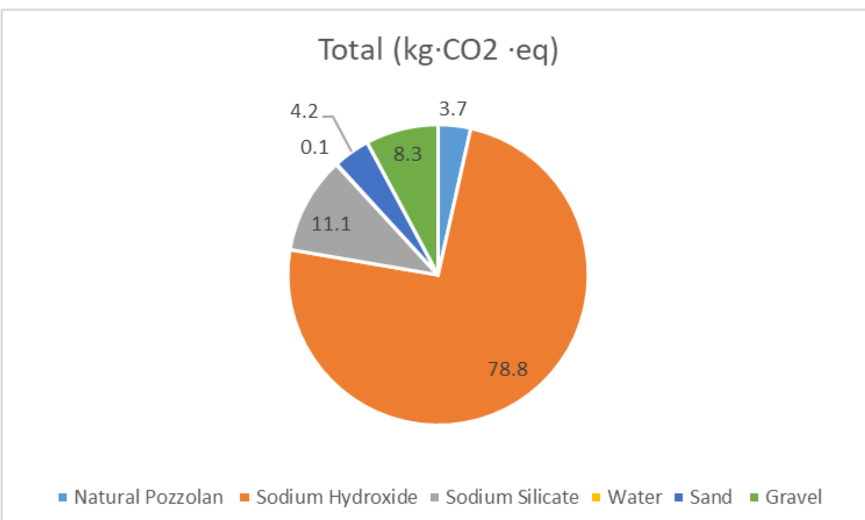

Figure 3:GWP100 of Alkaline Activated Natural Pozzolan Geopolymer Concrete

5.1.4 Discussion of the Results

The gate-to-gate life cycle assessment of the alkaline activated natural pozzolan shows that the global warming potential of 100 years is 106 kg·CO_2·eq. The assessment does not include the global warming potential during curing the concrete. Figure 3 shows that the alkaline activators, sodium hydroxide and sodium silicate, produce the highest amount of carbon dioxide equivalent gases with 78 kg·CO_2·eq and 11 kg·CO_2·eq respectively. This means that the alkaline activator is responsible for 83% of the carbon dioxide equivalent gases in producing 1 m^3 of alkaline activated natural pozzolan. The natural pozzolan is responsible for producing 3.7 kg·CO_2·eq which is 3.5% of the carbon dioxide equivalent gases in producing 1 m^3 of the geopolymer. The water, sand and gravel global warming potential are similar to that of the traditional concrete given the same mix design of the concrete.

5.2 Life Cycle Assessment – Exercise 2

5.2.1 Goal and Scope

This life cycle assessment exercise will be done for alkaline activated natural pozzolan similar to exercise 1 but the alkaline activator that will be used is only sodium hydroxide instead of a mixture of sodium hydroxide and sodium silicate. The compressive strength tested by (Moon et al., 2014) is 31 MPa after 28 days of curing at 80 C^0. Since only sodium hydroxide was used as the alkaline activator the compressive strength was lower than when both sodium hydroxide and sodium silicate was used as the alkaline activator. Also, the pores percentage was higher when using sodium hydroxide alone as the alkaline activator. Thus, using both sodium hydroxide and sodium silicate to activate the natural pozzolan lead to a more durable geopolymer concrete.

5.2.2 Inventory Analysis for Alkaline Activated Saudi Natural Pozzolan Concrete Activated with Sodium Hydroxide

The mix design to produce 1 m^3 of Alkaline Activated Natural Pozzolan Concrete is as follows:

Natural pozzolan from Saudi Arabia = 400 kg,
Sodium hydroxide solution = 180 kg, 10M - sodium hydroxide dry weight = 72 kg
Gravel = 940 kg
Sand = 770 kg

5.2.3 Impact Assessment

Table 5: Alkaline Activated Natural Pozzolan Concrete GWP100Activated with Sodium Hydroxide

Material	Dry Weight (Kg)	GWP100 (kg·CO_2 ·eq)/Kg	Total (kg·CO_2 ·eq)	Source
natural pozzolan	400	0.009312	3.7248	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
sodium hydroxide	72	1.359	97.848	Thannimalay,L.,Yusoff, S. Zawawi, N. (2013)
water	180	0.0004288	0.077184	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
sand	940	0.004473	4.20462	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)

gravel	770	0.0108	8.316	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
Total	**2,362**		**114.17**	

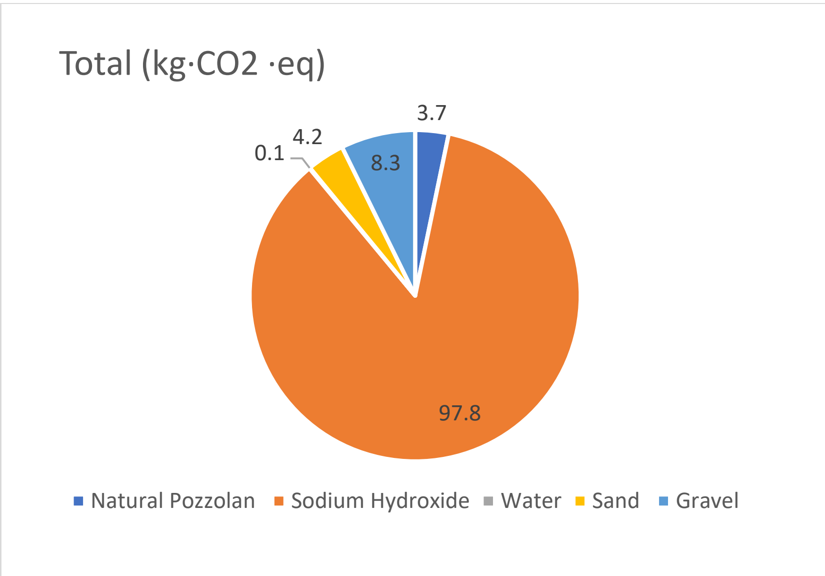

Figure 4: : Alkaline Activated Natural Pozzolan Concrete GWP100 Activated with Sodium Hydroxide

5.2.4 Discussion of the Results

The assessment shows that the total carbon dioxide produced is 114 kg·CO_2·eq. The main producer of the global warming potential gases was the sodium hydroxide which produced 97.7 kg·CO_2 ·eq, it is responsible for 86% of the total produced gases. The results show that using sodium hydroxide and sodium silicate as the alkaline activator causes an increase in the compressive strength, results in more durable geopolymer concrete and produce less global warming potential gases.

5.3 Life Cycle Assessment – Exercise 3

5.3.1 Goal and Scope

The aim of this life cycle assessment is to examine the global warming potential of alkaline activated natural pozzolan concrete using sodium hydroxide and rice husk ash as the alkaline activator. Since the alkaline activators were the main producers of the global warming potential gases, rice husk ash will be used instead of sodium silicate as an alkaline activator. The silica is extracted from the rice husk ash by alkaline digestion method. The process involves calcination, filtration and Sulphur acid treatment. It is then added to the sodium hydroxide as a source of silica. The rice husk ash is a waste material, so it is assumed that there is no GWP100 emitted by its production. The GWP100 of extracting the silica from the rice husk ash is considered in the life cycle assessment. According to (Joglekar, Kharkar, Mandavgane and Kulkarni, 2018) the GWP100 is 7.26 kg·CO_2 ·eq per each kilogram of silica extracted.

5.3.2 Inventory Analysis for Alkaline Activated Saudi Natural Pozzolan Concrete Activated with Sodium Hydroxide and Rice Husk Ash

To produce 1 m^3 of Alkaline Activated Natural Pozzolan Concrete, the following materials will be used:

Natural pozzolan from Saudi Arabia = 400 Kg,
Sodium hydroxide solution = 144 Kg, 10M - sodium hydroxide dry weight = 58 kg
Silica from rice husk ash dry weight = 14 kg
Gravel = 940 Kg
Sand = 770 Kg

5.3.3 Impact Assessment

Table 6: Alkaline Activated Natural Pozzolan Concrete GWP100Activated with Sodium Hydroxide and Rice Husk Ash

Material	**Dry Weight (kg)**	**GWP100 (kg·CO_2 ·eq)/kg**	**Total (kg·CO_2 ·eq)**	**Source**
natural pozzolan	400	0.009312	3.7248	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
sodium hydroxide	58	1.359	78.822	Thannimalay,L.,Yusoff, S. Zawawi, N. (2013)
silica from rice husk ash	14	7.26	101.64	(Joglekar, Kharkar, Mandavgane and Kulkarni, 2018)
water	180	0.0004288	0.077184	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
sand	940	0.004473	4.20462	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
gravel	770	0.0108	8.316	(Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018)
Total	**2,362**		**196.78**	

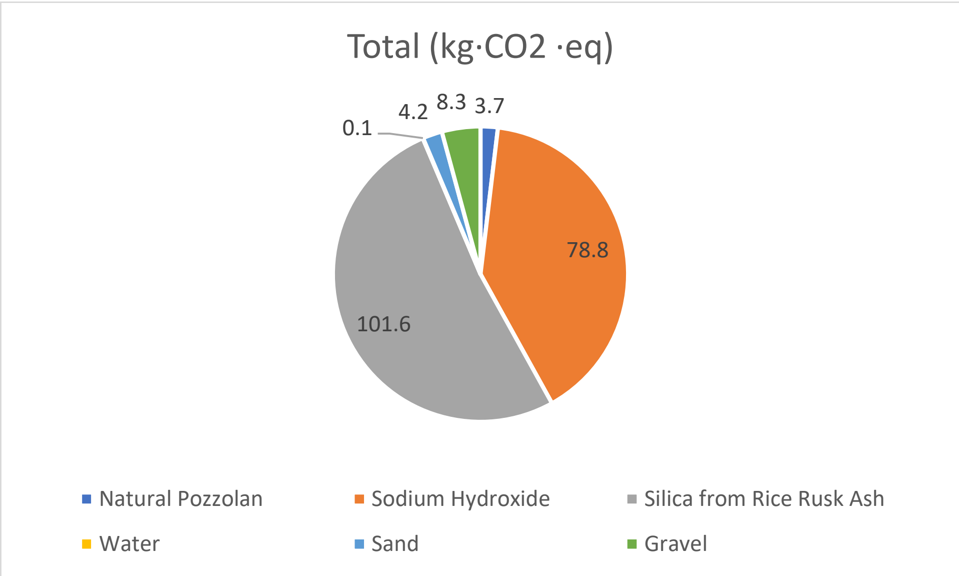

Figure 5: Alkaline Activated Natural Pozzolan Concrete GWP100 Activated with Sodium Hydroxide and Rice Husk Ash

5.3.4 Discussion of the Results

Although the commercial glass water, sodium silicate, is replaced by replaced by silica extracted from a waste material, but the extraction process is energy intensive and resulted in higher GWP100 than when the commercial sodium silicate was used. The replacement of sodium silicate by a waste material increased the global warming potential by 46%. The total global warming potential of 100 years of alkaline activated natural pozzolan activated by sodium hydroxide and silica extracted from rice husk ash is 196 kg·CO_2 ·eq. The alkaline activator is still main producer of the global warming potential gases which is 95% of the total carbon dioxide equivalent gases. However, further research needs to be done to study the affect of replacing the sodium silicate with silica extracted from rice husk ash on the geopolymer concrete properties including the compressive strength and the durability.

5.4 Life cycle assessment – Exercise 4

5.4.1 Goal and Scope

The purpose of this life cycle assessment exercise is to find the life cycle assessment of the traditional PC concrete to examine if geopolymer concrete have harmful impact on the environment and by how much. The results of this life cycle assessment will be a benchmark to the other life cycle assessment exercises.

5.4.2 Inventory Analysis for PC Concrete

To produce 1 m^3 of PC Concrete, the following materials will be used:

Cement = 400 Kg
Water = 200 Kg
Gravel = 940 Kg
Sand = 770 Kg

5.4.3 Impact Assessment

Table 7: PC Concrete GWP100

Material	Dry Weight (kg)	GWP100 (kg·CO_2 ·eq) / kg	Total (kg·CO_2 ·eq)
Cement	400	0.9097	363.88
Water	180	0.0004288	0.077184
Sand	940	0.004473	4.20462
Gravel	770	0.0108	8.316
Total	**2,290**		**376.48**

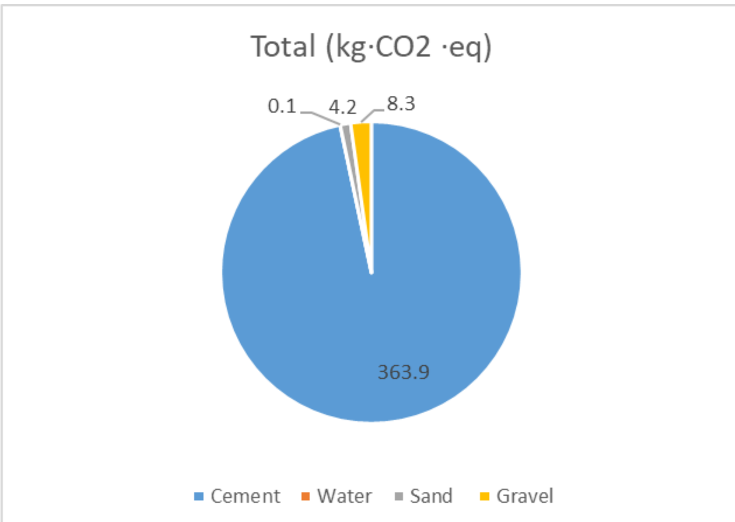

Figure 6: GWP100 of Portland Cement Concrete

5.4.4 Discussion of the Results

The assessment is done on concrete design with cement only without any addition of supplementary cementitious materials nor chemical additives. The results show that the main producer of global worming potential gases of 100 years id the cement by 97%. The compressive strength of this PC concrete is 38 MPa after 28 days of curing.

5.5 Interpretation of the Life Cycle Assessment Exercises

The mix design for the alkaline activated natural pozzolan geopolymer paste in exercise one and two is from previous experiment that was done by (Moon et al., 2014). Natural pozzolan from Saudi Arabia was used, it has a chemical composition that is presented in table 9. To Prepare the natural pozzolan for usage, it should pass through crushing, drying and grinding to make it finer in order to increase its pozzolanic activity this process will produce around 0.009 kg·CO_2·eq per one kilogram. In the life cycle assessment exercises a raw natural pozzolan was used, thus, heating to activate the natural pozzolan to show its pozzolanic activity is not required. In the first life cycle assessment exercise sodium hydroxide and the sodium silicate were used as the alkaline activators to activate the natural pozzolan. Sodium hydroxide and sodium silicate (glass water) are melted in water and mixed with the natural pozzolan to form the paste. As shown in table 5, the required amount of sodium hydroxide and sodium silicate to produce 1 m^3 of the geopolymer concrete are 58 kg and 14 kg respectively. The water-binder ratio is 0.45 and the amound of sand and gravel used were 940 kg and 770 kg respectively. The absolute volume method was used to estimate the geopolymer concrete mix design. The paste samples were tested by (Moon et al., 2014) after curing at 80 C^0 for 28 days. According to (Moon et al., 2014). The compressive strength was 47 MPa at the 28th day, and it showed low porosity. So, the paste is highly durable compared to traditional concrete. The addition of sodium silicate improved the reaction of the alkaline solution with the natural pozzolan and lead to lower amount of unreacted natural pozzolan in the paste, less connected pores, higher compressive strength and higher durability than using sodium hydroxide alone as the alkaline activator.

The life cycle assessment shows that the global warming potential of 100 years (GWP100) produced by the production of 1 m^3 of alkaline activated natural pozzolan geopolymer concrete activated by sodium hydroxide and sodium silicate is 106 kg·CO_2·eq. The highest quantity of global warming potential gases produced is by sodium hydroxide which is about 73% of the total quantity produced. The natural pozzolan preparation produce 372 kg·CO_2·eq. Compared to the traditional PC concrete in exercise 4, producing 1 m^3 of alkaline activated natural pozzolan geopolymer concrete activated by sodium hydroxide and sodium silicate has less GWP100 by 72%. The results of life cycle assessment in exercise one concludes that replacing the cement with natural pozzolan will increase the durability of the concrete, will have similar compressive strength and will produce less harmful gases to the environment.

The second life cycle assessment exercise examine the global warming potential of 100 years (GWP100) in case sodium hydroxide is used as the alkaline activator to activate the natural pozzolan. The reason why this option is preferred on using sodium hydroxide and sodium silicate together is because sodium silicate is expensive. In the mix, the quantities of the natural pozzolan, sand and gravel were kept that same. However, the quantity of the sodium silicate is compensated by the sodium hydroxide. The results of the life cycle assessment exercise show that the global warming potential of 100 years is 114 kg·CO_2 ·eq. The GWP100 of the natural pozzolan geopolymer concrete activated with sodium hydroxide is more than that of the natural pozzolan geopolymer concrete activated with sodium hydroxide and sodium silicate by 7% with slightly lower compressive strength and less durable. The compressive strength of the natural pozzolan activated with sodium hydroxide at the 28th day of curing is 33MPa, so the compressive strength is less that in the case were sodium hydroxide and sodium silicate were used as the alkaline activator by 30%.

Although the second mix were the natural pozzolan was activated by sodium hydroxide showed higher GWP100 and lower compressive strength and durability compared to the first case were the natural pozzolan is activated by sodium hydroxide and sodium silicate, its GWP100 is lower than that of the PC concrete by 69%. Also, it showed acceptable compressive strength and acceptable porosity, thus it is a durable geopolymer concrete mix and its production cost is lower than the first mix.

In the first and second exercise the alkaline activators were the main producers of the global warming potential gasses by 81% of the total produced gases in the first case and 85% of the total produced gasses in the second case. So, the global warming potential of 100 years of the alkaline activated natural pozzolan geopolymer concrete can be further reduced if it is possible to replace of reduce the amount of the sodium hydroxide and sodium silicate without compromising the properties of the geopolymer concrete. One possible solution is to replace the sodium silicate (commercial glass-water) by silica extracted from rice husk ash. The process of producing the sodium silicate required heating at high temperature and the use of chemicals so it produce large amount GWP100, while rice husk ash is a waste material from the rice milling industry so recycling it is beneficial for the environment because small portion of it is used in agriculture while the majority of the portion is a landfill. The silica can be extracted from the rice husk ash by alkaline digestion method. However, the process of extracting the silica from the rice husk ash is energy intensive and includes calcination at 700 C^0. It was found that using silica extracted from rice husk ash will produce higher global warming potential gases than using the commercial sodium silicate. The life cycle assessment shows that the GWP100 when using silica extracted from a waste material is higher than the GWP100 when using commercial sodium silicate by 46%. However, this will still have the benefit of reusing a waste material. A more efficient way needs to be found to extract the silica from the rice husk ash to reduce its global warming potential to make it possible to use it as a recycled material. Also, the effect of replacing the commercial glass-water with silica extracted from rice husk ash on the properties on the alkaline activated natural pozzolan needs to be further studied.

The fourth life cycle assessment exercise was conducted to check if replacing the cement by the natural pozzolan is actually efficient and will produce less harmful gases to the environment. The main producer of GWP100 gasses in case of PC concrete is the production of the cement which represent 96% of the total produced global warming potential gases. Figure 6 shows that traditional PC concrete has the highest GWP100 that all the other three alkaline activated natural pozzolan at least by 48%. So, all the proposed mixed achieved the target by lowering the GWP100 of the concrete. However, the best solution the alkaline activated natural pozzolan activated by sodium hydroxide and sodium silicate. It also achieves a high compressive strength and high durability.

Table 8: Chemical composition of natural pozzolan from Saudi Arabia

Oxide	SiO_2	Al_2O_3	CaO	Fe_2O	K_2O	Na_2O	MgO	TiO_2	MnO	P_2O_5	LOI	Total
	46.48	14.74	8.78	12.16	1.27	3.39	8.73	2.31	0.19	0.629	1.324	98.68

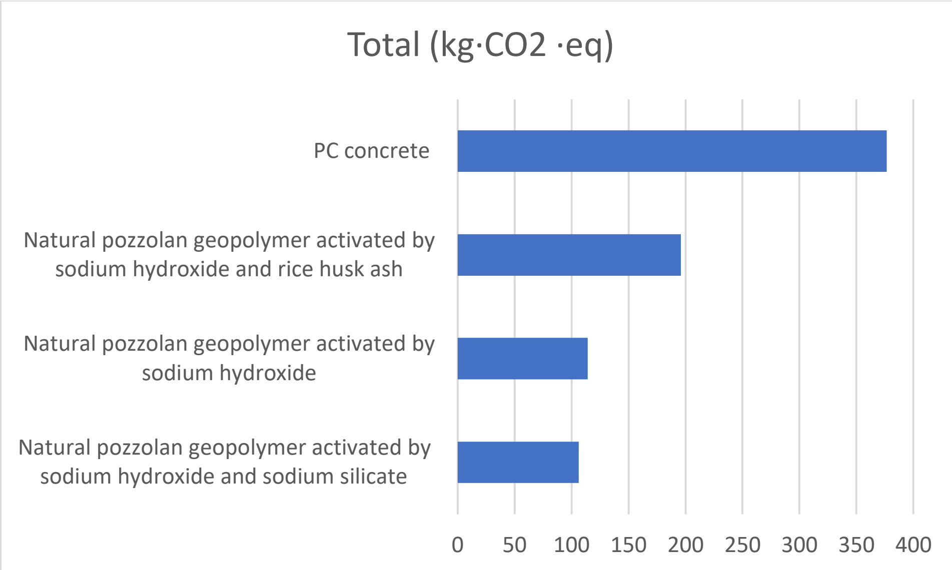

Figure 7: GWP100 produced by four different types of concrete

The results achieve above are also stands better that the results achieved by (Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018) were it is found that the GWP100 of a geopolymer consisted of natural pozzolan by 70% and ground granulated blast furnace slag by 30% is 210 kg·CO_2·eq and it is found that it is lower than that of the PC concrete by 47%. The natural pozzolan was activated by sodium hydroxide and sodium silicate and the natural pozzolan used was from Colombia.

(Turner, L. K. and Collins, F. G., 2013) conducted a life cycle assessment on geopolymer concrete where fly-ash was used instead of cement and superplasticizer was used as well. The finding was the GWP100 is 320 kg·CO_2·eq including batching and curing. However, the GWP100 if it was done gate-to-gate would be 259 kg·CO_2·eq. The highest global warming potential gasses producer was the sodium silicate by 156 kg·CO_2·eq, which is 60% of the total produced gases, and both of the alkaline activators, sodium hydroxide and sodium silicate produced 190 kg·CO_2·eq. The fly-ash produced 11 kg·CO_2·eq. However, the results reported compared to the literature review in their paper are not in agreement where the other researched who conducted life cycle assessment on similar geopolymer reported lower GWP100.

(Salas et al., 2018) replaced the cement with natural zeolite to obtain geopolymer paste at compressive strength of 15 MPa. Sodium hydroxide and sodium silicate was used as the alkaline activators. It was reported a GWP100 of 110 kg·CO_2·eq compared to 302 kg·CO_2·eq when using cement. (Teh, Wiedmann, Castel and de Burgh, 2017) reported GPW100 of 310 kg·CO_2·eq of fly-ash based geopolymer, ground granulated blast furnace slag was also part of the mix, the mix was activated by sodium hydroxide and sodium silicate. The compressive strength of the geopolymer was 40 MPa.

(Bajpai, R., Choudhary, K., Srivastava, A., Sangwan, K. and Singh, M., 2020) conducted life cycle assessment exercise on three types of geopolymers, first type consist of fly ash activated by sodium hydroxide and sodium silicate, the second type consist of fly ash and silica fumes activated by an equal amount sodium hydroxide and sodium silicate and the third type consist of fly ash activated by sodium hydroxide only. The compressive strength of the three geopolymers were 35 MPa, 38 MPa and 34 MPa respectively and the GWP100 of the three geopolymers were 148 kg·CO_2·eq, 136 kg·CO_2·eq and 134 kg·CO_2·eq. The GWP100 results are contrasting with the life cycle assessment results in exercise one and two in this study were the GWP100 when using sodium hydroxide alone as the alkaline activator was higher than when using both sodium hydroxide and sodium silicate.

(Kastiukas, Ruan, Liang and Zhou, 2020) conducted a research and life cycle assessment exercise on a geopolymer consist of fly ash and ground granulated blast furnace slag and was activated by sodium hydroxide and silica extracted from rice husk ash, similar to the alkaline activator used in life cycle assessment exercise three in this study. The global warming potential was 100 kg·CO_2·eq and the compressive strength was 34 MPa. The largest amount of global warming potential gasses was produced by the alkaline activator. (Passuello et al., 2017) studied the global warming potential of a geopolymer consisted of a kaolin sludge residue from the Brazilian mining industry and the alkaline activator was sodium hydroxide and sodium silicate (commercial water glass) in one mix and sodium hydroxide and silica extracted from rice husk ash in another mix. The reported a reduction of 70% of GWP100 when replacing the cement by kaolin sludge. In contract to this study, the geopolymer with silica extracted from rice husk ash reported lower GWP100 than when sodium silica was used. However, details about the extraction of the silica from the rice husk ash is not explained. The compressive strength of the geopolymers varied from 40 MPa to 60 MPa.

The previous studies do not report a life cycle assessment exercise on alkaline activated natural pozzolan based completely geopolymer concrete. However, single life cycle assessment exercise was done on a geopolymer based on natural pozzolan of 70% and the ground granulated blast furnace slag of 30% conducted by (Robayo-Salazar, Mejía-Arcila, Mejía de Gutiérrez and Martínez, 2018), he reported a GWP100 slightly higher than that reported in the study which might be due to the use of the ground granulated blast furnace. The replacement of cement with zeolite and ground granulated blast furnace activated by sodium hydroxide and sodium silicate reported close GWP100 to that of the alkaline activated natural pozzolan activated by sodium hydroxide and sodium silicate in this study.

Although exercise one and two in this study reported that the GWP100 of geopolymer concrete activated by sodium silicate and sodium hydroxide is lower than the GWP100 of geopolymer concrete activated by sodium hydroxide but the results conflicts the life cycle assessment that was done by Bajpai, R., Choudhary, K., Srivastava, A., Sangwan, K. and Singh, M., 2020), where it is reported that fly ash geopolymer concrete activated with sodium hydroxide have lower GWP100 than the geopolymer concrete activated with sodium hydroxide only. Another conflict that was found with the previous life cycle assessment was the GWP100 of replacing the sodium silicate with silica extracted from rice husk ash, which was done by (Kastiukas, Ruan, Liang and Zhou, 2020). However, the author does not report the method of extraction of silica from the rice husk ash nor the carbon dioxide equivalent gases produced per one kilogram. In exercise three in this study, the carbon dioxide equivalent gases produced during the extraction of silica from the rice husk ash used was from previous research done by (Joglekar, Kharkar, Mandavgane and Kulkarni, 2018) and according to the author, the extraction of silica method was the alkaline digestion method.

There are no enough studies that considers alternatives to the sodium hydroxide and sodium silicate as the alkaline activator solutions and the impact of replacing the alkaline activator on the properties of the geopolymer concrete.

To conclude, the previous life cycle assessment exercises done on geopolymer concrete show GWP100 in a rage close to that done in this study. This shows that reducing the environmental impact of geopolymer concrete where cement is replaced by other cementitious materials is possible while still having acceptable properties of the concrete.

6.0 Conclusion

- Geopolymer concrete where the cement is completely replaced by volcanic ash natural pozzolan has less harmful impact on the environment. The Global Warming Potential of 100 years (GWP100) for the alkaline activated natural pozzolan is lower than the GWP100 of the traditional PC concrete by 48%-72%.
- The alkaline activator is responsible for the highest portion of the GWP100 of the alkaline activated natural pozzolan geopolymer.
- Geopolymer based on natural pozzolan activated by sodium hydroxide and sodium silicate showed a GWP100 of 106 kg.CO_2.eq. The test that were conducted on the paste showed high compressive strength of 47 MPa and the BSE image showed low porous structure thus high durability. The GWP100 is lower than the GWP100 of the PC concrete by 72%.
- Geopolymer based on natural pozzolan activated by sodium hydroxide showed a GWP100 of 114 kg.CO_2.eq. The compressive strength was 34 MPa, it is lower than the geopolymer activated by sodium hydroxide and sodium silicate and the BSE image showed unreacted natural pozzolan and more porous structure thus less durable. The GWP100 is lower than the GWP100 of the PC concrete by 70%.
- Geopolymer based on natural pozzolan activated by silica extracted from rice husk ash and sodium hydroxide showed a GWP100 of 196 kg.CO_2.eq. Further research needs to be done on the properties of this geopolymer type. The GWP100 is lower than the GWP100 of the PC concrete by 48%.
- Alkaline activated natural pozzolan geopolymer concrete have similar or lower GWP100 to the other types geopolymer concretes GWP100 including geopolymers based on fly-ash, zeolite and ground granulated blast furnace.
- The properties of the alkaline activated natural pozzolan geopolymer depends on the natural pozzolan chemical composition, alkaline activator and curing duration and temperature.
- Alkaline activated natural pozzolan geopolymer have higher sulphate resistance than the tradition PC concrete.

- Alkaline activated natural pozzolan geopolymer have higher compressive strength but lower sulphate resistance when cured at high temperatures compared to when cured at room temperature.
- Oxygen permeability of alkaline activated natural pozzolan geopolymer is lower than that of the traditional PC concrete
- Alkaline activated natural pozzolan geopolymer have lower permeability when activated by sodium hydroxide and sodium silicate compared to when activated by sodium hydroxide only.
- Higher concentration of the alkaline activator causes lower permeability of the alkaline activated natural pozzolan geopolymer
- Rapid Chloride Permeability Test is not applicable on alkaline activated natural pozzolan paste because of the presence of the alkaline activator.
- Because of high PH of alkaline activated natural pozzolan geopolymer it is expected that the corrosion of the reinforcement is less and at a lower speed rate than that of the traditional concrete.
- Alkaline activated natural pozzolan geopolymer activated with sodium hydroxide and sodium silicate have lower workability than when activated by sodium hydroxide only.
- The workability of the alkaline activated natural pozzolan geopolymer as the concentration of the alkaline activator increases to some limit, then the workability starts to decrease as the concentration of the alkaline activator increases after that limit.
- The workability of the alkaline activated natural pozzolan geopolymer concrete increases when the solution to binder ratio increases.
- The setting time of the alkaline activated natural pozzolan increases as the percentage of silica and alumina in the natural pozzolan increases.
- The setting time of the alkaline activated natural pozzolan increases as the content of the calcium oxide in the natural pozzolan increases.
- The setting time of the alkaline activated natural pozzolan geopolymer decreases when it is cured at elevated temperatures.
- The setting time of the alkaline activated natural pozzolan geopolymer increases as the finesse of the natural pozzolan increases.

- The drying shrinkage of the alkaline activated natural pozzolan geopolymer is smaller than that in PC concrete.
- In contract to PC concrete, the increase in water-binder ratio causes lower drying shrinkage in alkaline activated natural pozzolan geopolymer.
- The combination and the concentration of the alkaline activator influence the compressive strength of the alkaline activated natural pozzolan geopolymer

7.0 Areas of Limited Research

- Replacement of sodium silicate with silica extracted from rice husk ash effect on the properties of the alkaline activated natural pozzolan geopolymer concrete.
- Influence of replacing alkaline activator with alternatives with lower environmental impact on the properties of the alkaline activated natural pozzolan geopolymer concrete.
- The rate of corrosion of the reinforcement of alkaline activated volcanic ash natural pozzolan geopolymer concrete.
- Drying shrinkage of alkaline activated volcanic ash natural pozzolan geopolymer.
- Effect of chemical additives, including superplasticizer and setting time accelerator, on the alkaline activated volcanic ash natural pozzolan geopolymer concrete.
- The possibility of reducing curing temperature and duration of the alkaline activated volcanic ash natural pozzolan geopolymer concrete.
- The workability of the alkaline activated volcanic ash natural pozzolan geopolymer concrete.
- Types of natural pozzolan available in the United Arab Emirates, if exists.

8.0 Resources

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