Comparative Analysis of Different Fly Ash Percentage of Pozzolanic Cement

Busola D. Olagunju[1], Oludolapo A. Olanrewaju[2],
Department of Industrial Engineering
Faculty of Engineering and the Built Environment, Durban university of Technology,
Durban, South Africa
Olagunjubusola52@gmail.com[1], OludolapoO@dut.ac.za[2]

Abstract

The continuous increase in the environmental impacts of the cement industry is of great concern to the society as population increases. Several reports have established that high CO2 emission, resource consumption and high-energy consumption are the major environmental impacts of the cement industry. One of the prescribed means recommended to reduce these impacts is the incorporation of fly ash into cement as it is considered environmentally benign. We have compared Portland cement with cement containing 5-15%, 11-35% and 36-55% of fly ash. A p-value higher than the significant level obtained ratified the hypothesis of a lower environmental impact with higher percentage of fly ash

Keywords
Cement; Fly ash; Environmental impact; CO_2; Resource consumption; LCA.

1. Introduction
A sustainable environment having every necessary infrastructure is constantly required of the construction industry to accommodate the ever-increasing population. This sector is however faced with different environmental impact throughout its production cycle. In 2018, this sector accounted for a total of 36% of global energy use, 39% of CO_2 emissions and contributed to resource depletion (construction, 2019). Cement contributes significantly to the environmental impact faced by the construction industry as about a ton of cement is needed by every individual per year (Lippiatt & Ahmad, 2004). In the production of cement, the raw materials are extracted to the manufacturing plant where they are pulverized into the required quality after which they are preheated and finally transferred into a large kiln at 1450º C for the clinker production known as calcination (Pacheco-Torgal, Cabeza, Labrincha, & De Magalhaes, 2014). At this stage, the limestone ($CaCO_3$) is broken down into quicklime (CaO) and carbon dioxide (CO_2) (Feely et al., 2004; Stafford, Raupp-Pereira, Labrincha, & Hotza, 2016). Gypsum is added to the clinker after it is cooled for further treatment.

Different environmental impacts spans through the production process of cement and thereby require a life cycle assessment (LCA). The major impacts are: high resource consumption, high energy consumption and high Greenhouse gas (GHG) emission (Gursel, 2014; Huntzinger & Eatmon, 2009; Marinković, 2013; Stafford, Dias, Arroja, Labrincha, & Hotza, 2016; Stafford, Raupp-Pereira, et al., 2016; Van den Heede & De Belie, 2012). Calcination is the most energy consuming and greenhouse gas emitting stage (Summerbell, Khripko, Barlow, & Hesselbach, 2017; Young, Turnbull, & Russell, 2002). Several recommendations on the improvement of these factors include the use of best available techniques (BAT) which has to do with switching from dry to wet kiln; reduction of resources and CO_2 emission by replacing a particular percentage of limestone with natural or artificial pozzolana such as rice husk, fly ash, volcanic material. This study therefore intends to analyze the impact of pozzolanic cement with different percentage of fly ash and compare the outcome with that of ordinary Portland cement.

2. Fly Ash Pozzolan
Pozzolans are finely divided siliceous, or siliceous and aluminous material that in itself exhibit little or no cementitious properties but chemically reacts with slake lime [Calcium hydroxide, Ca $(OH)_2$] in the presence of moisture at standard temperatures to form compounds that have cementitious properties; this pozzolans can be natural or artificial. Fly ash also known as fine coal ash is an artificial pozzolan appropriate for use in cementitious system as it exhibits

cementitious properties without reaction with Ca $(OH)_2$ or hydraulic cement. It is a derivative that solidifies in the exhaust gases and is collected by filter bags or electrostatic precipitators usually from coal- fired power plant when coal is crushed and thereafter combusted (ACI). The pozzolanic properties of the fly ash is more of the particle size and mineral present in it than the chemistry as these properties are more influenced by the glass phase present in the fly ash. It contains more of SiO2 and falls under two classes (Class F and Class C); both classes are pozzolans but class F requires cement to react. When cement chemically reacts with water, calcium silicate hydrate is formed; this reaction is called hydraulic reaction. Unlike the hydraulic reaction, pozzolanic reaction starts later to form the same Calcium silicate hydrate (CaO and SiO2) but the hydrated cement paste in this case is of better strength and less permeable pore structure (Bremseth, 2009).

In recent time, fly ash is put in landfills or kept in power plants unlike in time past when it is commonly released into the atmosphere and thereby intoxicating it. The use of fly ash as partial substitute for clinker or direct addition will reduce the toxicity in the atmosphere and present a better ambience (A Bilodeau, Malhotra, & Seabrook, 2001). Also, there will be reduction in the CO2 emission from cement production and will also save energy when fly ash replaces some of the energy-intensive cement produced seeing that 0.7- 1.0 ton of CO2 is produced for every ton of cement produced (Bjerge & Brevik, 2014; García-Gusano, Garraín, Herrera, Cabal, & Lechón, 2015; Huntzinger & Eatmon, 2009; Marinković, 2013; Nigri, Rocha, & Romeiro Filho, 2017; Stafford, Raupp-Pereira, et al., 2016). Fly ash improves workability i.e. the ease to handle, place and finish a fresh concrete with reduced quantity of water required (ACI). While fly ash concrete is more receptive to vibration, rock pocket, segregation and void is even more reduced when compared to Portland cement due to increased cohesiveness and workability. The bleeding of high-volume (50-55%) fly ash concrete is as low as negligible due to its minimal water content (Malhotra & Mehta, 2002). The reduced water content of fly ash concrete is of great advantage as it helps reduce drying shrinkage (Alain Bilodeau & Malhotra, 2000). Table 1 below shows the summary of high-volume fly ash concrete with conventional Portland cement concrete (Malhotra & Mehta, 2002).

Fly ash reduce alkali aggregate reaction (AAR) which causes expansion, bleed channels, water demand, and increase cementitious properties which all contribute to the dense nature of the concrete made with it. It also produces higher comprehensive long-term strength in concrete which resist forces generated at very low temperatures. The conventional concrete strength reaches its peak value in 14-28 days while the fly ash cement takes over 90 days with higher strength value because of the pozzolanic reaction of fly ash (Malhotra & Mehta, 2002). It consumes the excess lime that reduce the risk of efflorescence (Sear). Also, concrete that incorporates fly ash is considered to be environmentally stable (Zhang, Blanchette, & Malhotra, 2001). As fly ash consumes the excess lime there is a reduced risk of efflorescence from the concrete. The concrete incorporating fly ash, is therefore, considered environmentally stable. The major demerit of high-volume fly ash is low strength development, which is due to the low cement to hydrate ratio, which influences the strength (slow reaction results to slow strength) but can be improved on by using finer fly ash, more reactive cement and also increasing the time needed for the pozzolanic cement for a better strength. This setback majorly affects concrete construction where swift stripping and turnaround is important (Seabrook & Campbell, 2000). Although both conventional concrete and fly ash concrete perform excellently at standard temperatures, they may however perform inaptly at very low temperatures due to reduced hydration rate. About 40-60% of fly ash incorporated in concrete can be successively used for standard structures (Thomas, Hopkins, Girn, Munro, & Muhl, 2002). The most important factor to be considered to enjoy the best of fly ash is to use it in its finest state and smallest particle size. This will further reduce the water requirement and further improve the strength of the concrete.

Table 1. Comparison of High-volume Fly Ash Concrete and Conventional Concrete (Malhotra & Mehta, 2002)

Characteristics	High-Volume fly ash concrete	Conventional Concrete
Flowability / Pumpability	High	Low
Workability	High	Low
Bleeding	Very low	Low
Finishing	Fast	Slow
Setting time	Slow up to 2 hours	Fast
Strength development: Early strength (up to 7 days) Ultimate strength (90 days +)	Slow Slow Higher	Fast Fast Slow (28 days)

Permeability	Slow	High
Crack resistance: Plastic shrinkage Thermal shrinkage Drying shrinkage	 High (if unprotected) Low Low	 Low High High
Air entraining	High	Low
Deicing salt scaling performance	Low	High
Resistance to penetration of chloride ions	Very high (after 90 days)	Low
Electrical resistivity	Very high	Low
Durability Resistance to sulphate attack Resistance to alkali-silica expansion (ASR/AAR) Resistance to reinforcement corrosion	Very high Very high Very high High	Low Low Low Low
Heat of hydration	Low	High
Abrasion resistance Endurance Limit	Same Same	Same Same
Cost: Materials Labour Life cycle	 Low Same Very low	 High Same High
Environmental friendliness with respect to CO_2 emission	Very high	Low
Energy saving due to less energy-intensive production	Very high	Low

3. Method

Life cycle assessment is a system-oriented tool used to analyze each and any environmental consequences in the production of a product or process. It gives a holistic information of a system by carrying out a step by step evaluation of the entire production cycle (Organization, 1997). The international standards organization (ISO) 14040 describes the four steps required when using this methodology which are: goal and scope, life cycle inventory (LCI), life cycle inventory assessment (LCIA) and Interpretation (Standardization, 2006). Goal and scope have to do with objectives, system boundaries, assumptions, functional units etc. of the assessment. It basically reveals the boundaries of the evaluation. LCI on the other hand involves all the input and output data which covers all environmental impacts of the product or process needed for the assessment (Arvanitoyannis, 2008). LCIA is a tool that analyzes every potential environmental implication because of production of the product or process under assessment. These impacts can thereafter be traced back to the particular inventory for proper recommendation. The last stage is interpretation which has to do with the outcome of the assessment (Ailleret, 2004; Curran, 1996). This study will make use of LCA methodology to assess Portland cement and pozzolanic cement with different percentage of fly ash via SimaPro 9 software (PRé & Mark Goedkoop, January 2016). This software incorporates EcoInvent database and was recommended as one of the best databases for construction industry (Meyer, 2009). Thus, all inventory in this assessment will be taken from EcoInvent (V3.5) (Ecoinvent, 2019).

4. Result and Discussion

The values obtained for the damage categories from the LCA of 1 kg Portland cement as well as pozzolanic cement containing 5-15%, 11-35% and 36-55% fly ash is summarized in Table 2. The damage on human health (DALY), ecosystem (species.yr) and resources (USD2013) significantly reduced as the percentage of fly ash increased for each kilogram of cement analyzed. The reduction observed for the impact on the ecosystem was higher than the human health for the different variation of pozzolanic cements with respect to Portland cement. The difference for human health was found to be 0.002e-6, 0.225e-6 and 0.503e-6 and that of ecosystem was 0.22e-9, 0.68e-9 and 1.39e-9 for

5-15%, 11-35% and 36-55% respectively. With 5-15% of fly ash, there was no change in the damage on resource but the damage decreased by 0.194 and 0.199 USD2013 for 11-35% and 36-55% respectively.

Table 2. Impact Assessment of 1kg Portland Cement and Pozzolanic Cement with Varying Percentage of Fly Ash

S/N	Damage category/unit	Name of product			
		Cement	Pozzolanic cement with 5-15% fly ash	Pozzolanic cement with 11-35% fly ash	Pozzolanic cement with 36-55% fly ash
1.	Human health (HH)/DALY	1.22e-6	1.218e-6	9.95e-7	7.17e-7
2.	Ecosystem (ES)/species.yr	3.19e-9	2.97e-9	2.51e-9	1.8e-9
3.	Resources (RE)/USD2013	0.0231	0.0231	0.0187	0.0135

The result obtained with the various percentages of fly ash for the damage categories aligned with our hypothesis which state that the higher the fly ash, the lower the impact. The p-value obtained from the hypothesis test is greater than the significant level, we therefore accepted the hypothesis. Each of this damage categories were critically analyzed by comparing the production processes and substances that make up the value of each damage categories lending credence to processes and substances with higher percentages. The specification to substance of human health presented in Table 3 shows a reduction in the CO2 as the volume of fly ash increased just as the clinker production stage decreased for the specification to process as shown in Table 4.

Table 3. Specific to Substance of Human Health

S/N	Human health	Name of product			
		Cement (%)	Pozzolanic cement with 5-15% fly ash (%)	Pozzolanic cement with 11-35% fly ash (%)	Pozzolanic cement with 36-55% fly ash (%)
1.	Carbon dioxide, fossil (air)	67.3	66.5	67	66.4
2.	Nitrogen oxides (air)	8.23	8.1	8.13	8.1
3.	Particulates, < 2.5 um (air)	9.01	9.8	9.53	9.89
4.	Sulphur oxide	12.2	12.3	12.1	12.3

Table 4. Specific to Production Process of Human Health

S/N	Human Health	Name of Product			
		Cement (%)	Pozzolanic Cement With 5-15% Fly Ash	Pozzolanic Cement With 11-35% Fly Ash	Pozzolanic Cement With 36-55% Fly Ash
1.	Clinker	70.1	68.5	69.6	68.4
2.	Electricity	12.6	12.2	10.9	12.1
3.	Coal	2.3	2.3	1.9	2.9
4.	Heat	1.9	1.9	2.5	2.5

The specific to substance of the ecosystem in Table 5 showed a minimal reduction in CO2 and nitrogen oxides. The reduction observed with the nitrogen oxides was uniform irrespective of the percentage of fly ash used. In the ecosystem damage category for the specific to process, the values obtained for the production of clinker was improved with the addition of different percentage of fly ash but with respect to electricity, the pozzolanic cement was higher than the Portland cement as shown in Table 6.

Table 5. Specific to Substance of Ecosystem

S/N	Ecosystem	Name of Product			
		Cement (%)	Pozzolanic Cement With 5-15% Fly Ash (%)	Pozzolanic Cement With 11-35% Fly Ash (%)	Pozzolanic Cement With 36-55% Fly Ash (%)
1.	Carbon Dioxide, Fossil	79.9	79.7	79.9	79.6
2.	Nitrogen Oxides	9.48	9.42	9.42	9.42

Table 6. Specific to Production Process of cement for Ecosystem damage category

S/N	Ecosystem	Name of Product			
		Cement (%)	Pozzolanic Cement With 5-15% Fly Ash (%)	Pozzolanic Cement With 11-35% Fly Ash (%)	Pozzolanic Cement With 36-55% Fly Ash (%)
1.	Clinker	77.8	76.8	77.7	76.7
2.	Electricity	7.5	8.2	8.1	7.7
3.	Coal	2.3	2.0	2.2	2.2
4.	Heat	2.1	2.2	2.0	2.1

With regards to the specification to substance and process for the damage made on resources, the highest percentage recorded was for oil and petroleum respectively. Pozzolanic cement with 5-15% and 36-55% fly ash was lower than 11-35% fly ash for oil and petroleum while the 36-55% fly ash was higher than 5-15% and 36-55% for natural gas and coal. The damage observed for the specific to substance for clay remained unchanged in all the percentage of fly ash used.

Table 7: Specific to Substance of Resources

S/N	Resource	Name of Product			
		Cement (%)	Pozzolanic Cement With 5-15% Fly Ash (%)	Pozzolanic Cement With 11-35% Fly Ash (%)	Pozzolanic Cement With 36-55% Fly Ash (%)
1.	Oil	67.9	67	67.7	67.1
2.	Natural Gas	16	16.9	16.3	16.9
3.	Coal	11.4	11.5	11.3	11.4
4.	Clay	4.2	4.1	4.1	4.1

Table 8: Specific to Process of Resources

S/N	Resource	Name of Product			
		Cement (%)	Pozzolanic Cement With 5-15% Fly Ash (%)	Pozzolanic Cement With 11-35% Fly Ash (%)	Pozzolanic Cement With 36-55% Fly Ash (%)
1.	Petroleum	68.7	66.5	66.8	67.6
2.	Natural Gas	12.6	13.9	13.3	14.1
3.	Coal	9.5	10	10.3	11
4.	Clay	4.7	4.1	4.2	4.1

5. Conclusion

A comparison of ordinary Portland cement with pozzolanic cement containing different percentages of fly ash has been analyzed using SimaPro 9 software containing Eco-invent database. Higher volume of fly ash in cement was found to be less energy intensive; improve cement properties and reduce the CO2 emitted. Hence, it is characterized as good workability, resistance to cracks and penetration of chloride ions, reduction of CO2, low energy consumption, reduced cost of material and labor among others. The values obtained from the analysis of pozzolanic cement with 5-15% and 36-55% fly ash are comparable despite the significant difference in the percentage of fly ash. This discrepancy arguably stems from the wide range (no specificity) of fly ash used, the secondary data employed in this assessment and several assumptions incorporated in the software.

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Biographies

Busola Dorcas Olagunju is currently a Masters student of the Department of Industrial Engineering, Durban University of Technology, South Africa. She earned her BSc degree with honours in Industrial and Production Engineering from the University of Ibadan, Nigeria. Her research interests are Energy/greenhouse gas analysis/management, Life cycle assessment, Ergonomics/human factor, Quality control management, Production planning and control, Operations research, Project management, Engineering management. She is a graduate member of Nigerian Society of Engineers (NSE).

Oludolapo Akanni Olanrewaju is currently a Senior Lecturer and Head of Department of Industrial Engineering, Durban University of Technology, South Africa. He earned his BSc in Electrical Electronics Engineering and MSc in Industrial Engineering from the University of Ibadan, Nigeria and his Doctorate in Industrial Engineering from the Tshwane University of Technology, South Africa. He has published journal and conference papers. His research interests are not limited to energy/greenhouse gas analysis/management, life cycle assessment, application of artificial intelligence techniques and 3D Modelling. He is an associate member of the Southern African Institute of Industrial Engineering (SAIIE) and NRF rated researcher in South Africa.