EFFECT OF PALM OIL FUEL ASH ON SELF-COMPACTING CONCRETE SHORT COLUMNS SUBJECTED TO FIRE

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DEDICATION

This thesis is dedicated to my lovely late parents, Rasaki Mujedu and Taibat Mujedu, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my adopted late father, Chief Isamosta Okesola Ashiru, who taught me that even the largest task can be accomplished if it is done one step at a time and to my wife and children.

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ABSTRACT

There have been quite a significant research and development activities in producing self-compacting concrete (SCC) through the use of palm oil fuel ash (POFA) since 2011. POFA was used as a partial replacement to Portland cement since it improves strength and durability properties of SCC. However, the study on the application of self-compacting POFA concrete to structural members that exposed to elevated temperatures as in the case of fire is quite limited. This research, therefore, focuses on the effect of POFA on self-compacting concrete short columns subjected to fire. Assessment of the microstructure, physical and chemical characteristics of the binders were carried out for characterization. Mechanical properties and microstructure of SCC produced with POFA at elevated temperatures were also carried out. For this purpose, two mixes of SCC containing 0% and 15% of POFA were prepared. The variables considered in the study include the percentage of POFA which is 0 and 15%, the concrete cover of 25 and 35 mm and the longitudinal steel reinforcement ratios of 2% and 3%. The columns produced were made of normal strength and had 600 mm height and 150 mm square cross – section. Twenty four columns were cast altogether. Eight columns out of these columns were un-heated and serve as a control while the remaining sixteen columns were heated in an automatic electric furnace to 750 °C and this temperature was maintained for 2 and 4 hours exposure time. After cooling down, all the columns were tested under axial compression load up to failure. Furthermore, POFA self-compacting concrete standard specimens were fabricated and tested for mechanical properties in 27 – 1000 °C temperature range at 28 days. Various techniques which include the use of scanning electronic microscope and X-ray diffraction were used to study the microstructure of the hardened SCC in 27 – 1000 °C temperature range at 28 days. Results from characterization confirmed that POFA was a good pozzolanic material and satisfied the specified physical and chemical properties requirements. Results from elevated temperature mechanical property tests revealed that there was an increment in residual compressive and gradual loss in the residual flexural, splitting tensile strengths and modulus of elasticity for SCC produced with and without POFA at 400 °C temperature. The loss in residual modulus of elasticity, splitting tensile, compressive and flexural strengths fluctuated sharply at 400 – 600 °C, 600 – 800 °C and 800 – 1000 °C temperatures. However, residual mechanical properties of SCC produced with POFA reduced at faster rate than SCC produced without POFA at 800 - 1000 °C temperatures. Results from elevated temperature microstructures showed that the transformation of calcium silicate hydrate (C-S-H) gel into distinctive phases and formation of micro-cracks, voids and pores were noticed on the hardened SCC at temperature above 600 °C. Results from ultimate axial capacity tests showed that all the unheated columns produced with POFA were improved on strength at 28 days. The residual axial capacity tests also showed that all the columns exhibited similar non-linear reduction trends with time of exposure. Heating the columns at 750 °C caused a severe reduction in the strength of all the columns. However, irrespective of concrete covers and percentage of steel reinforcements used, the loss in residual strength was high in the columns produced with POFA than the columns produced without POFA for 2 and 4 hours exposure time. The residual strength loss is in the range of 51% - 63% and 47% - 59% for columns produced with and without POFA. The performance of SCC containing POFA does not significantly improve the concrete performance in resisting fire. However, further research needs to be carried out on POFA so as to improve this short coming.

ABSTRAK

Terdapat banyak aktiviti penyelidikan dan pengembangan dalam menghasilkan konkrit pemadatan sendiri (SCC) melalui penggunaan abu bahan bakar kelapa sawit (POFA) sejak 2011. POFA digunakan sebagai pengganti separa kepada simen Portland kerana ia meningkatkan sifat kekuatan dan ketahanan SCC. Walau bagaimanapun, kajian mengenai penggunaan konkrit POFA pemadatan diri pada anggota struktur yang terdedah kepada suhu tinggi seperti kebakaran agak terhad. Oleh itu, penyelidikan ini memfokuskan pada kesan POFA pada tiang pendek konkrit pemadatan sendiri yang mengalami kebakaran. Penilaian struktur mikro, fizikal dan kimia pengikat dilakukan untuk pencirian. Sifat mekanikal dan struktur mikro SCC yang dihasilkan dengan POFA pada suhu tinggi juga dilakukan. Untuk tujuan ini, dua campuran SCC yang mengandungi 0% dan 15% POFA disediakan. Pemboleh ubah yang dipertimbangkan dalam kajian merangkumi peratusan POFA iaitu 0 dan 15%, penutup konkrit 25 dan 35 mm dan nisbah tetulang keluli membujur 2% dan 3%. Tiang yang dihasilkan terbuat dari kekuatan normal dan mempunyai ketinggian 600 mm ketinggian dan 150 mm persegi keratan rentas. Dua puluh empat lajur dilemparkan sama sekali. Lapan lajur dari lajur ini tidak dipanaskan dan berfungsi sebagai kawalan sementara enam belas lajur dipanaskan dalam relau elektrik automatik hingga 750 ° C dan suhu ini dikekalkan selama 2 dan 4 jam waktu pendedahan. Setelah sejuk, semua tiang diuji di bawah beban mampatan paksi hingga gagal. Selanjutnya, spesimen standard konkrit pemadatan sendiri POFA dibuat dan diuji untuk sifat mekanikal dalam julat suhu 27 - 1000 ° C pada 28 hari. Pelbagai teknik yang merangkumi penggunaan mikroskop elektronik pengimbasan dan difraksi sinar-X digunakan untuk mengkaji struktur mikro SCC yang mengeras dalam lingkungan suhu 27 – 1000 °C pada 28 hari. Hasil dari pencirian mengesahkan bahawa POFA adalah seorang bahan pozzolanic yang baik dan memenuhi syarat sifat fizikal dan kimia yang ditentukan. Hasil dari ujian sifat mekanikal pada suhu tinggi menunjukkan bahawa terdapat peningkatan kehilangan mampatan dan penurunan secara beransur-ansur dalam lenturan sisa, kekuatan tegangan pemisah dan modulus keanjalan bagi SCC dihasilkan dengan dan tanpa POFA pada suhu 400 ° C. Kehilangan modulus keanjalan baki, kekuatan tegangan perpecahan, mampatan dan lenturan turun naik secara mendadak pada suhu 400 - 600 ° C, 600 - 800 ° C dan 800 - 1000 ° C. Walau bagaimanapun, sifat mekanikal SCC yang dihasilkan dengan POFA dikurangkan pada kadar yang lebih cepat daripada SCC yang dihasilkan tanpa POFA pada suhu 800 – 1000 °C. Hasil dari struktur mikro pada suhu tinggi menunjukkan transformasi gel kalsium silikat hidrat (C-S-H) pada fasa khas dan pembentukan retakan mikro, lompang dan liang-liang diperhatikan pada spesimen SCC pada suhu di atas 600 °C. Hasil dari ujian keupayaan paksi utama menunjukkan bahawa semua tiang yang tidak dipanaskan yang dihasilkan dengan POFA bertambah baik pada kekuatan pada 28 hari. Ujian kapasiti paksi baki juga menunjukkan bahawa semua tiang menunjukkan tren pengurangan tak linier yang serupa dengan masa pendedahan. Memanaskan tiang pada suhu 750 °C menyebabkan penurunan kekuatan semua tiang yang teruk. Walau bagaimanapun, tanpa mengira penutup konkrit dan peratusan tetulang keluli yang digunakan, kehilangan kekuatan baki adalah tinggi pada tiang yang dihasilkan dengan POFA daripada tiang yang dihasilkan tanpa POFA selama 2 dan 4 jam waktu pendedahan. Kehilangan kekuatan baki adalah dalam ligkungan 51% - 63% dan 47% - 59% untuk tiang yang dihasilkan dengan dan tanpa POFA. Prestasi SCC yang mengandungi POFA tidak meningkatkan prestasi konkrit secara signifikan dalam menahan kebakaran. Walau bagaimanapun, penyelidikan lebih lanjut perlu dilakukan di POFA untuk memperbaiki jangka pendek ini.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACI	-	American Concrete Institute
ASTM	-	American Standard for Testing of Materials
BP	-	Basalt Powder
BET	-	Brunauer Emmet and Teller
BFS	-	Blast Furnace Slag
BSI	-	British Standards Institution
COL-POFA	-	Column Produced with Palm Oil Fuel Ash
COL-OPC	-	Column Produced without Palm Oil Fuel Ash
CCOL1	-	Un-heated Column Produced without Palm Oil Fuel Ash with 25 mm concrete cover and 2% steel reinforcement ratio
CCOL2	-	Un-heated Column Produced without Palm Oil Fuel Ash with 35 mm concrete cover and 2% steel reinforcement ratio
CCOL3	-	Un-heated Column Produced without Palm Oil Fuel Ash with 25 mm concrete cover and 3% steel reinforcement ratio
CCOL4	-	Un-heated Column Produced without Palm Oil Fuel Ash with 35 mm concrete cover and 3% steel reinforcement ratio
CCOL5	-	Column Produced without Palm Oil Fuel Ash with 25 mm concrete cover and 2% steel reinforcement ratio heated at 750 °C for 2 hours exposure time
CCOL6	-	Column Produced without Palm Oil Fuel Ash with 35 mm concrete cover and 2% steel reinforcement ratio heated at 750 °C for 2 hours exposure time
CCOL7	-	Column Produced without Palm Oil Fuel Ash with 25 mm concrete cover and 3% steel reinforcement ratio heated at 750 °C for 2 hours exposure time
CCOL8	-	Column Produced without Palm Oil Fuel Ash with 35 mm concrete cover and 3% steel reinforcement ratio heated at 750 °C for 2 hours exposure time

CCOL9	-	Column Produced without Palm Oil Fuel Ash with 25 mm concrete cover and 2% steel reinforcement ratio heated at 750 °C for 4 hours exposure time
CCOL10	-	Column Produced without Palm Oil Fuel Ash with 35 mm concrete cover and 2% steel reinforcement ratio heated at 750 °C for 4 hours exposure time
CCOL11	-	Column Produced without Palm Oil Fuel Ash with 25 mm concrete cover and 3% steel reinforcement ratio heated at 750 °C for 4 hours exposure time
CCOL12	-	Column Produced without Palm Oil Fuel Ash with 35 mm concrete cover and 3% steel reinforcement ratio heated at 750 °C for 4 hours exposure time
DSC	-	Differential Scanning Calorimetry
DTA	-	Differential Thermal Analyzer
EDX	-	Energy Dispersive X-ray
FA	-	Fly Ash
GPa	-	Giga Pascal
GGBFS	-	Ground Granulated Blast Furnace Slag
HPC	-	High Performance Concrete
HRWR	-	High Range Water Reducer
HSC	-	High Strength Concrete
HSSCC	-	High Strength Self-Compacting Concrete
IS	-	Indian Standard
ITZ	-	Interfacial Transition Zone
JF	-	J-Ring Flow
JRMCA	-	Japanese Ready-Mixed Concrete Association
JSCE	-	Japanese Society of Civil Engineers
LP	-	Limestone Powder
LVDT	-	Linear Variable Differential Transducers
LOI	-	Loss on Ignition
MP	-	Marble Powder
MPa	-	Mega Pascal
MK	-	Metakaolin

MT-POFA	-	Modified Treated Palm Oil Fuel Ash
NSC	-	Normal Strength Concrete
NSSCC	-	Normal Strength Self-Compacting Concrete
NVC	-	Normal Vibrated Concrete
OPF	-	Optimum Packing Factor
OPV	-	Optimum Paste Volume
OPC	-	Ordinary Portland Cement
PA	-	Passing Ability
PF	-	Packing Factor
POFA	-	Palm Oil Fuel Ash
PCOL1	-	Un-heated Column Produced with Palm Oil Fuel Ash with 25 mm concrete cover and 2% steel reinforcement ratio
PCOL2	-	Un-heated Column Produced with Palm Oil Fuel Ash with 35 mm concrete cover and 2% steel reinforcement ratio
PCOL3	-	Un-heated Column Produced with Palm Oil Fuel Ash with 25 mm concrete cover and 3% steel reinforcement ratio
PCOL4	-	Un-heated Column Produced with Palm Oil Fuel Ash with 35 mm concrete cover and 3% steel reinforcement ratio
PCOL5	-	Column Produced with Palm Oil Fuel Ash with 25 mm concrete cover and 2% steel reinforcement ratio heated at 750 °C for 2 hours exposure time
PCOL6	-	Column Produced with Palm Oil Fuel Ash with 35 mm concrete cover and 2% steel reinforcement ratio heated at 750 °C for 2 hours exposure time
PCOL7	-	Column Produced with Palm Oil Fuel Ash with 25 mm concrete cover and 3% steel reinforcement ratio heated at 750 °C for 2 hours exposure time
PCOL8	-	Column Produced with Palm Oil Fuel Ash with 35 mm concrete cover and 3% steel reinforcement ratio heated at 750 °C for 2 hours exposure time
PCOL9	-	Column Produced with Palm Oil Fuel Ash with 25 mm concrete cover and 2% steel reinforcement ratio heated at 750 °C for 4 hours exposure time

PCOL10	-	Column Produced with Palm Oil Fuel Ash with 35 mm concrete cover and 2% steel reinforcement ratio heated at 750 °C for 4 hours exposure time
PCOL11	-	Column Produced with Palm Oil Fuel Ash with 25 mm concrete cover and 3% steel reinforcement ratio heated at 750 °C for 4 hours exposure time
PCOL12	-	Column Produced with Palm Oil Fuel Ash with 35 mm concrete cover and 3% steel reinforcement ratio heated at 750 °C for 4 hours exposure time
PR	-	Passing Ratio
PFA	-	Pulverized Fly Ash
QDP	-	Quarry Dust Powder
RPC	-	Reactive Powder Concrete
RC	-	Reinforced Concrete
RHA	-	Rice Husk Ash
RILEM	-	International Union of Testing and Research Laboratory for Materials and Structures
SEM	-	Scanning Electron Micrograpy
SCC	-	Self-Compacting Concrete
SCLC	-	Self-Compacting Lightweight Concrete
SCLCPFF	-	Self-Compacting Lightweight Concrete with Polypropylene Fibres
SCC-H	-	Self-Compacting Concrete Contains Combination of Polypropylene and Steel Fibres
SCC-P	-	Self-Compacting Concrete Contains Polypropylene Fibres
SCC-S	-	Self-Compacting Concrete Contains Steel Fibres
POFA-SCC	-	Self-Compacting Concrete Produced with Palm Oil Fuel Ash
OPC-SCC	-	Self-Compacting Concrete Produced without Palm Oil Fuel Ash
SCHPC	-	Self-Consolidating High Performance Concrete
SCHSC	-	Self-Consolidating High Strength Concrete
SSA	-	Sewage Sludge Ash
SF	-	Silica Fume

SSP	-	Steel Slag Powder
SBA	-	Sugarcane Bagasse Ash
SP	-	Superplasticizers
SCM	-	Supplementary Cementitious Materials
TC	-	Thermocouple
TMA	-	Thermo Mechanical Analysis
TPS	-	Transient Plane Source
UHSC	-	Ultra High Strength Concrete
UPV	-	Ultrasonic Pulse Velocity
UTM	-	Universal Testing Machine
UTM	-	Universiti Teknologi Malaysia
VPSEM	-	Variable Pressure Scanning Electron Microscopy
VMA	-	Viscosity Modifying Admixture
VEA	-	Viscosity Enhancing Admixture
W/B	-	Water-to-Binder Ratio
WSA	-	Wheat Straw Ash
XRD	-	X-Ray Diffraction
XRF	-	X-Ray Fluorescence

LIST OF SYMBOLS

A_c	-	Design air content (%)
Al	-	Aluminium
Al_2O_3	-	Aluminium oxide (Alumina)
Ca	-	Calcium
$CaCO_3$	-	Calcium carbonate
$Ca(OH)_2$	-	Calcium hydroxide
CaO	-	Calcium oxide
Ca_2SiO_4	-	Larnite
$Ca_6Si_6O_{17}(OH)_2$	-	Xonotlite
$Ca_5Si_6O_{16}(OH)_2.4H_2O$	-	Tobermorite
C_4AF	-	Calcium aluminoferrite
C_2S	-	Dicalcium silicate
C_3Al	-	Tricalcium aluminate
C_3S	-	Tricalcium silicate
C-S-H	-	Calcium silicate hydrate
C_2SH	-	Dicalcium silicate hydrate
C_2S_3H	-	Gyrolite
$C_7S_{12}H_3$	-	Truscottite
$C_7S_6CH_2$	-	Scawtite
C	-	Carbon
CO_2	-	Carbon dioxide
C_p	-	Heat capacity
E_s	-	Modulus of Elasticity
$E_{m,T}$	-	Modulus of elasticity at required temperature
Fe	-	Iron
Fe_2O_3	-	Iron oxide
f_c	-	Compressive Strength
f_f	-	Flexural Strength
f_t	-	Splitting Tensile Strength
$f_{c,T}$	-	Compressive strength at required temperature

$f_{f,T}$	-	Flexural strength at required temperature
$f_{t,T}$	-	Splitting tensile strength at required temperature
K	-	Potassium
K_2O	-	Potassium oxide
k	-	Thermal conductivity
Mg	-	Magnesium
NO_x	-	Nitrogen oxide
Na	-	Sodium
$NaCa_2Si_3O_8(OH)$	-	Pectolite
O	-	Oxygen
P_{pofa}	-	POFA content (% of binder by weight)
R^2	-	Correlation coefficient
S/A	-	Sand to aggregate ratio
Si	-	Silicon
SiO_2	-	Silicon dioxide or Silica
SO_2	-	Sulphur dioxide
SO_3	-	Sulphur trioxide
SG_c	-	Specific gravity of cement
SG_{ca}	-	Specific gravity of coarse aggregate
SG_{fa}	-	Specific gravity of fine aggregate
SG_{pofa}	-	Specific gravity of POFA
T	-	Temperature (°C)
T_{500}	-	500 mm slump flow time
T_V	-	V-funnel flow time
V_{ca}	-	Volume of coarse aggregate
V_p	-	Paste volume (m^3/m^3)
W/B	-	Water to binder ratio (by weight)
W_b	-	Weight of binder (Cement plus POFA) (kg/m^3)
W_c	-	Weight of cement (kg/m^3)
W_{ca}	-	Weight of coarse aggregate (kg/m^3)
W_{fa}	-	Weight of fine aggregate (kg/m^3)
W_{pofa}	-	Weight of POFA (kg/m^3)
W_w	-	Weight of water (kg/m^3)

ρ	-	Density
ρ_w	-	Density of water (kg/m^3)
α	-	Thermal diffusivity
δ_T	-	Strength reduction coefficient ratio

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General

All constituent materials utilized in the production of concrete are indispensable; cement is definitely the most significant constituent due to the fact that it is generally the delicate connection in the chain (Li, 2011). However, in the cement manufacturing industry, gases such as carbon (iv) oxide (CO_2), Sulphur (iv) oxide (SO_2) and nitrogen oxide (NO_x) are released into the atmosphere. All these gases caused acid rain and greenhouse effect. The major confronts facing the industries that are producing cement is how to reduce all these gases. However, the utilization of supplementary cementitious materials (SCM) have been supported to be a feasible solution to this problem (Ismail and Waliuddin, 1996; Shannag, 2000; Dinakar *et al.*, 2008). In between these years, the utilization of both artificial and natural pozzolanic materials such as metakaolin (MK), rice husk ash (RHA), sugarcane bagasse ash (SCBA), corn cob ash (CCA), palm oil fuel ash (POFA), wheat straw ash (WSA), ground granulated blast furnace slag (GGBFS), silica fume (SF), pulverized fuel ash (PFA), ground glass powder (GGP) and fly ash (FA) have been examined to partially replaced cement. All these materials are predominantly utilized in the form of wastes which are classified into municipal wastes, agricultural wastes and industrial wastes.

A major confronts facing the construction industry nowadays is how to reduce the cost of cement utilized in the production of concrete. Since concrete is the major materials used for building, it is necessary to look for alternative material to substitute for cement. This can be achieved by making use of ecologically friendly materials that are produced at inexpensive cost (Hassan, 2015). Numerous studies on the use of wastes as SCM such as MK, GGBFS, FA, CCA, RHA, SCBA, POFA, etc., have established that the incorporating of such wastes in the production of concrete has the prospective of enhancing fresh as well as hardened properties of concrete and at the same time make the construction cost to be reduced (Khatib and Hibbert, 2005; Şahmaran *et al.*, 2006; Chindaprasirt *et al.*, 2007; Dinakar *et al.*, 2008; Adesanya and Raheem, 2009; Givi *et al.*, 2010; Bahurudeen *et al.*, 2015).

Apart from the fact that the professionals in the construction industry put efforts to effectively substitute in whole or in part, the cement with waste materials, the confronts of confirming that the green concrete produced functions up to the targeted expectancy has been the main attention of numerous researches. The concrete structural element durability problem was the most important topic of concern and interest in many countries like Japan, France, Canada, Australia, Sweden, Britain, Netherlands and India as far back as early 1980's. This concern brought about the gradual reduction in the numeral of skilled personnel, which result to the diminution in the quality of work executed. The term self-compacting concrete (SCC) was then introduced by Prof. Okamura in the year 1986 and later developed by Ozawa and Maekawa together with their team at the University of Tokyo in Japan to solve the problem aforementioned above (Okamura and Ouchi, 2003). Since that time up till now, a lot of different researches have been investigated to overcome the important issues that deals with the workability, rheology, mechanical as well as durability properties of self-compacting concrete (Schwartzentruber *et al.*, 2006; Sukumar *et al.*, 2008; Dehwah, 2012; Khushnood *et al.*, 2014; Nagaratnam *et al.*, 2016; Sasanipour *et al.*, 2019; Vaidevi *et al.*, 2020).

POFA is used in this research as SCM due to the fact that it is produced in large quantity as waste material in countries like Malaysia, Indonesia and Thailand who are the major producers of palm oil and palm products in the world. In the 21st century, POFA is still considered a nuisance to the environment and is usually disposed of without any profitable returns compared to other by-products of palm oil. Since Malaysia, Indonesia and Thailand continue increasing the production of palm oil, a lot of POFA will be produced and failure to find alternative solution in making utilization of this waste will continue creating environmental problems (Kabir, 2012). A lot of research has been investigated on the materials properties of SCC produced with POFA at ambient temperature. However, the use of POFA to produce reinforced SCC columns exposed to elevated temperature as in the case of fire is scarce in the literatures. Column is selected for the study because it is strong and failure of it is delayed due to different concrete covers when exposed to fire. The use of SCC to produce reinforced concrete columns is chosen in this research due to many benefits such as self-compaction performance, durability performance, highly congested reinforcement problem, higher load capacity, reduction in labour cost, improved constructability and delay heating to steel reinforcement.

Palm oil fuel ash (POFA) is normally categorized as an agricultural waste. It is obtained from the burning of residues, such as palm oil fibers (POF), palm kernel shell (PKS) and empty fruit bunches (EFB) from a palm oil and used as fuel in the power plants of a palm oil factories to produce electricity. Only in Malaysia, approximately 10×10^6 tons of POFA are generated yearly and this production rate is forecast to upsurge due to an increased plantation of oil palm trees (Khankhaje *et al.*, 2016). For instance, as at 2019, the total oil palm tree plantation area in Malaysia covers 5.90 million hectares compared to 2016, 2017 and 2018 which were 5,74, 5.81 and 5.85 million hectares, respectively (MPOB, 2020). POFA generated in the factories where palm oil is produced, is normally dumped in the surrounding of the factories, thereby causes environmental pollution and health hazards that can results into lung and bronchi diseases (Tay and Show, 1995). A lot of researches carried out have shown many advantages of properties with partial replacing of Portland cement with POFA to produce normal and high strength self-compacting fresh and hardened concrete and the durability. The researchers have observed that ground POFA can be used as a SCM to produce SCC up to the level of 30% by weight of cement. However, the optimum POFA content is 10 – 20% (Salam *et al.*, 2013, 2015; Alsubari *et al.*, 2014a; Safiuddin *et al.*, 2014; Ranjbar *et al.*, 2016). POFA that is treated up to percentage content of 70% can be utilized to produce SCC. Nonetheless, the optimum content of treated POFA is 50 - 60% (Alsubari *et al.*, 2016, 2018). All these studies were carried out at ambient temperature. In contrast, the utilization of POFA to produce SCC when exposed to elevated temperatures has not been investigated. Likewise, the use of POFA to produced reinforced self-compacting concrete columns when exposed to elevated temperatures has not been investigated.

When the reinforced concrete members produced with self-compacting concrete exposed to fire, the temperature of the concrete mass will be increased. This increase in temperature theatrically decreases the mechanical properties of steel and concrete (Youssef and Moftah, 2007; El-Fitiany and Youssef, 2009). Concrete itself undergoes a series of changes in its physical structure and chemical composition. These changes happen mainly in the hardened cement paste starting from the disintegration of calcium hydroxide at 530 °C temperature, and carry on until the complete devastation of the calcium silicate hydrate at 900 °C temperature. Due to all these changes, concrete progressively and sometimes suddenly loses its mechanical strength and durability (Poon *et al.*, 2001a). However, Ünlüoğlu *et al.* (2007) observed that at temperature close to 500 °C, the specimens of steel reinforcement with concrete cover had similar values of tensile strength and yield strength with that of the steel reinforcements without exposure to elevated temperature. Notwithstanding, when the temperature is increased beyond 500 °C, the strength capacities of the steel reinforcement with concrete cover reduced significantly. Moreover, the bond strength between the steel and concrete reduces with increasing temperature. The extent of the loss depends on the type of concrete used and the surface's condition of the steel bar (deformed, smooth, degree of rusting). At elevated temperatures, deformed or plain bars with corroded surfaces display higher bond strengths than smooth or plain bars (Youssef and Moftah, 2007). Furthermore, fire temperatures inspire new thermal, transient creep and strains. In addition, explosive spalling of concrete member's surface might occur (El-Fitiany and Youssef, 2009). On the other hand, Ünlüoğlu *et al.* (2007) reported that heat resistance of the reinforced concrete structures depend on the factors like thermal disparity that occurs between aggregate and cement paste during heating, vicissitudes in cement paste, the pressure of evaporating water and chemical structure in the aggregates.

A reinforced concrete column which is an important element in reinforced concrete structures support and transfer the loads from the structure to the foundation. Any failure or damage takes place within the column may result in a complete or partial failure of the structure possibly by chain action (Sakai and Sheikh, 1989). The behaviour of reinforced concrete columns in fires is complex as thermal and load induced stresses are combined, however the most apparent effect of a fire is the changes in material properties of concrete and the reinforcing steel. The reductions in elastic modulus and yield strength lessen the overall strength of the column. When the strength of the column reduces lower than the load applied, the column will tend to fail either by means of crushing or with the aid of flexural buckling (Alkafaji, 2015).

The most significant procedure in calculating the reduction that occur in the strength of any types of specimens when exposed to fire as in the case of elevated temperatures is through the help of heat transfer from the surrounding of the specimens through the specimen's cross-section. The heat transfer analysis normally used when the specimens exposed to elevated temperatures consists of the three mechanisms of heat transmission namely radiation, convection and conduction. Radiation and convection will occur between the hot light/gases surrounding the specimen and the specimen surface. Radiation can also occur between the specimen and other boundaries in the area, like the ceiling, floor and walls. Conduction will occur within the specimen itself. When the boundary layer of the specimen get heated by the radiation and convection, conduction will then transfer the thermal energy throughout the cross section of the specimen from the regions of higher temperature to the lower temperature (Emberley, 2013).

1.2 Statement of the Problem

Pouring the concrete into formworks together with its durability necessitates sufficient compaction to be performed by experienced labour. Compaction of concrete is important in order to remove entrapped air in fresh concrete which produce a homogeneous mix without honeycomb. If the air in the concrete is not fully removed, its strength will be losing significantly. Likewise, when the compaction of concrete is not done fully, both its strength and durability will be affected and nowadays, durability turns out to be more important than the strength (Shetty, 2005). Nowadays, normal vibrated concrete (NVC) has compaction problem and have a tendency to display certain drawbacks for example cavities, voids as well as microstructural cracks, which expedites the concrete to deteriorate due to access of harmful agents for instance acids, carbonation and chlorides. The presence of transporting agent such as gas or liquid makes the deterioration of concrete to be possible (Hassan, 2015). In addition, the machines used for the compaction usually produce a noise which is not good for the health of the people. It has been established that the utilization of SCC has the potentials to solve all the aforementioned drawbacks above associated with NVC (Li, 2011).

To produce NVC, it involves skilled labour that will handle the vibrator machine used for compaction of the concrete. This increases the cost of the labour to be used and at the same time, the time to be used on the construction will be increased. Improper compaction can lead to inferior surface finishes and when this one happens; it is going to increase the maintenance cost of a structural members. It has been established that the use of SCC has the advantages of making the construction time together with labour cost to be reduced and at the same time produces superb surface finishes which can reduce the maintenance cost (Khayat *et al.*, 1999).

One of the elemental ways out towards accomplishing better - quality concrete properties both in the fresh as well as hardened state is the introduction of self-compacting concrete. These types of concrete benefit structural engineers and architects, and eventually the building users. The new kinds of structural components, which were difficult to cast with NVC, can be produced by making use of SCC. Such components include different kinds of steel-concrete structural components with more multifaceted shapes, which are thinner with a much weightier reinforced cross – section (Li, 2011). Self-compacting Concrete (SCC) is a modern and innovative class of concrete that does not need vibration for placement and compaction. It is extremely consistent and highly flowable, without the loss of stability, and furthermore it can flow due to its own weight, fill the formwork completely and attaining complete compaction even when the reinforcements are fully congested (EFNARC, 2005). SCC is gradually gaining popularity due to the advantages it has over NVC. These advantages include reduction in labour cost and construction time, improved constructability and structural integrity, solving highly congested reinforcement problem, bond to reinforcing steel, produces superior surface finishes, superior strength and durability and fast placement without vibration. However, producing self-compacting concrete with high fluidity and good strength necessitates a lot of cement content and this make the cost of production to be high together with higher carbon dioxide (CO_2) emissions. These situations prompt the attention of the researchers to look into viable and cheaper materials that can be used to replace Portland cement in order to reduce its production cost. Agricultural wastes such as POFA, RHA, SCBA, CCA and WSA that are produced in large quantity have been used in that direction by researchers. Most of the researches examined with the utilization of POFA to substitute Portland cement in SCC production are performed at ambient temperature. Hence there is need to investigate the performance of the SCC incorporating POFA at elevated temperature.

Apart from these advantages in which SCC has over NVC, many of the structures produced with such type of concrete are often required to expose to severe ecological conditions, as in case of fire. Many researches have been carried out on the behaviour of SCC when exposed to elevated temperatures (Persson, 2004; Noumowé *et al.*, 2006; Sideris, 2007; Fares *et al.*, 2009; Tao *et al.*, 2010; Khaliq and Kodur, 2011; Bamonte and Gambarova, 2012). There are conflicting results on compressive strength of SCC at temperature below 400 °C. Fares *et al.* (2009) observed compressive strength gain of about 12% at temperature range of 150 and 300 °C. Likewise, the increase in strength of about 16% between 100 and 200 °C was examined by Khaliq and Kodur (2011). However, Persson (2004), Sideris (2007) and Tao *et al.* (2010) observed loss in compressive strength within these temperatures. Nevertheless, at temperature above 400 °C, there are significance losses in compressive strength of SCC. There is gradual decrease in splitting tensile strength which is almost linear between 20 and 400 °C and later there is sharp decrease in its value up to 600 or 800 °C. There is significance loss in flexural strength from 300 °C up to 600 °C or 900 °C. Increase in temperature leads to too much loss of modulus of elasticity of SCC.

Comprehensive researches have been investigated on the effects of high temperatures on the normal vibrated concrete properties produced with POFA (Ismail *et al.*, 2011; Awal and Shehu, 2015; Awal *et al.*, 2015; Mohammadhosseini and Yatim, 2017). However, all the authors were concerned only on concrete residual compressive strength and the cube specimens cast were exposed to the maximum temperature of 800 °C. The other properties like modulus of elasticity, flexural strength and splitting tensile strength which are also important under the mechanical properties are not investigated. It has been established that incorporation of POFA content to produce SCC enhances the strength as well as durability properties up to the percentage's ranges of 10 - 20% replacement. However, any addition which is more than 20% makes the strength to be reduced progressively and at the same times induces bleeding and segregation (Salam *et al.*, 2013; Alsubari *et al.*, 2014a; Ranjbar *et al.*, 2016). All these studies were done on material properties by fabricating standard specimens such as cubes, prisms and cylinders at ambient temperature. When this type of concrete exposed to elevated temperature, as in a case of fire, it undergoes a series of changes in its physical and chemical characteristics. The effect of high temperatures on properties of SCC produced with POFA is very limited in the literatures. It was only Alsubari *et al*. (2018) that extends part of their research to the residual compressive strength of SCC made with POFA and the cubes cast were exposed to the maximum temperature of 600 °C. The temperature of concrete may reach a value of 1350 °C especially in building, reactor vessel, tunnel and nuclear plant during fire under extreme occasions like impact or blast loading condition (Awal and Shehu, 2015). Most of the researchers that carried out a research on residual compressive strength of POFA concrete exposed the cube specimens to 800 °C. Therefore, it is necessary to expose the standard specimens to exceed this temperature. It is for these reasons very important to examine the impact of POFA on the residual mechanical properties of SCC at elevated temperature up to 1000 °C**.**

The basic parameter for the determination of concrete performance either at ambient temperature or elevated temperatures by the engineering profession is the use of strength. However, researchers are busy nowadays try to search for the remote causes of deterioration and failure of the concrete elements. Therefore, the current practice focuses on the combination of microstructure and strength of the material to assess its performance and durability when exposed to high temperatures. The impact of high temperatures on the microstructures of either NVC or SCC produced with POFA is very limited in the literatures. It was only Mohammadhosseini and Yatim (2017) that extends part of their investigation on the microstructure of green concrete produced with POFA using waste carpet as fibres. The research on the microstructure carried out by the authors was performed at 200 and 800 °C using scanning electron microscopy (SEM), thermogravimetric analysis (TGA) and differential thermal analysis (DTA). However, X-ray diffraction (XRD) tool which is also important for the study of phase transformations is not investigated. Therefore, there is need to investigate the microstructure of SCC produced with POFA at different elevated temperatures up to 1000 °C.

A lot of research have been investigated on the use of FA (Khaliq and Kodur, 2013; Sunayana and Barai, 2018; Sunayana and Barai, 2019; Hashmi *et al.*, 2020) and GGBFS (Sangeetha and Joanna, 2014; Hawiley *et al.*, 2017; Lokeshwaran *et al.*, 2017) to partially replace cement to cast reinforced concrete structural members. However, the use of POFA to cast reinforced concrete structural members is very limited in the literatures. It was only Andalib *et al.* (2014) that used combination of POFA and FA to cast geo-polymer concrete beams. POFA is an agricultural waste material that is produced in large quantity from the palm oil industries in the country like Indonesia, Malaysia, Thailand, Colombia and Nigeria etc. It is obtained from the burning of residues, such as palm oil fibers, palm kernel shell and empty fruit bunches from a palm oil industry and used as fuel in the power plants of a palm oil factories to produce electricity (Ranjbar *et al.*, 2016). On the other hand, fly ash (FA) is an industrial waste that is generated in furnaces as a result of burning coal in power plants. It consists of predominantly very fine spherical glassy particles obtained in the dust collection systems from the exhaust gases of fossil fuel power plants (Nagaratnam *et al.*, 2016). The main threat to modern buildings nowadays is fire. With the recent extensive research on the utilization of POFA in SCC and the upsurge in fire incidents in recent years, an in-depth understanding of the effect of fire on POFA SCC structural element is urgently needed. When using POFA to produce SCC columns, it must satisfy fire safety requirements specified in building codes. After the incidence of fire on the SCC columns produced with POFA, the residual axial capacity of the SCC columns needs to be carried out. This is due to the fact that failure of an individual column member could probably activate a progressive collapse of the whole building structure (Li *et al.*, 2012). The evaluation of the residual axial capacity of fire-damaged reinforced self-compacting POFA concrete columns becomes important in order to know the capacity of the columns after fire. This will help in understanding if the columns should be repaired instead of demolishing and rebuilding it and to repair will be more economical.

1.3 Aim and Objective of the Research

The aim of this research is to investigate the residual axial capacity of self-compacting POFA concrete columns exposed to fire.

1.3.1 Research Objectives

The objectives of the research are:

(a) To characterize the physical properties of collected POFA.

(b) To determine the mechanical properties of self-compacting concrete produced with POFA at elevated temperatures.

(c) To assess the microstructure of self-compacting concrete produced with POFA at elevated temperatures.

(d) To evaluate residual axial capacity of self-compacting POFA concrete columns under fire.

1.4 Research Questions

The research seeks to address the following questions:

1. What effect does the POFA have on the mechanical properties of SCC at elevated temperature?
2. What effect does the POFA have on the microstructure characteristics of SCC at elevated temperature?
3. What effect does the POFA have on the residual axial capacity of SCC columns?

4. What effect does the concrete cover have on the residual axial capacity of self-compacting POFA concrete columns?

5. What effect does the longitudinal percentage ratio have on the residual axial capacity of self-compacting POFA concrete columns?

1.5 Scope of the Research

The research work focuses on the residual axial capacity of self-compacting palm oil fuel ash concrete columns exposed to fire. POFA was used basically as partial replacement of ordinary Portland cement with the percentages of 15% to produce SCC. Analytic properties of the constituent materials used to produce the concrete together with their microstructural characteristic were investigated. The fresh properties in terms of flowing ability and passing ability of the POFA self - compacting concrete were investigated.

The first phase deals with the preparation as well as testing of the standard size specimens containing POFA and without POFA at ambient and elevated temperatures. All the tests were carried out after 28 days of curing. All the specimens to be tested at elevated temperatures were heated in a regulated electric furnace to required temperature which varying from 200 to 1000 °C at an intermission of 200 °C. Each peak temperature was sustained for duration of 2 hours with heating rate of 2.7 °C/min. After the heating, the specimens were then allowed to cool naturally inside the electric furnace to ambient temperature before residual mechanical properties such as compressive strength, splitting tensile strength, flexural strength and modulus of elasticity were determined.

The second phase deals with testing for microstructure of hardened self – compacting concrete containing POFA and without POFA at ambient and elevated temperatures.

The third phase deals with the preparation and testing for residual axial capacity of twenty - four self - compacting concrete columns containing POFA and without POFA. The variables considered were 25 mm and 35 mm concrete cover, and 2% and 3% longitudinal reinforcement ratios. All the columns were 150 x 150 x 600 mm cross – section with longitudinal bars of 12 mm diameter and the size of the stirrups were 6 mm diameter. All the columns cast were tested after 28 days of curing. Parts of the columns cast were subjected to heat in an automatic electrical furnace. The test electrical furnace is designed to produce conditions such as temperature and heat transfer to which a column might be exposed to during a fire. A peak temperature of 750 ºC was chosen for the electrical furnace in order to assess the effect of thermal damage on the performance of self – compacting POFA concrete columns. When the electrical furnace reached the desired temperature of 750 ºC, this temperature was maintained for 2 hours and 4 hours so as to ensure uniform heating throughout the SCC column. After the heating, the columns were then allowed to cool naturally inside the electrical furnace to ambient temperature before residual ultimate axial load test were performed.

1.6 Significance of Study

1. High quantity of Portland cement is needed to produce SCC, therefore, the utilization of certain percentage of POFA to replace cement will make the quantity of waste produced from Palm oil factory to be reduced.

2. When replacing the quantity of cement with certain percentage of POFA, mechanical properties of SCC could be significantly enhanced.

3. By using POFA to partially replace cement in the SCC production, the gases like CO_2, SO_2 and NO_x emission which causes acid rain and greenhouse effect would be reduced.

4. POFA is an agricultural waste material that usually obtained at reasonable minimal cost; their usage will significantly reduce the overall cost of construction.

5. Structural Engineers and researchers will have a better understanding of the performance of self-compacting POFA concrete columns exposed to fire.

1.7 Thesis Organization

The research was prepared and documented in line with the provisions specified in the UTM thesis manual, June 2019. Therefore, the thesis was designed to cover eight chapters.

Chapter 1 presents the introduction of the area study thereby provides a summary of the problem background to support the problem statements. The chapter also highlights the aim and the objectives of the research. The scope and the limitation together with the significant contribution of the research were stated.

Chapter 2 provides a critical review of the literature relevant to the behaviour of SCC materials at elevated temperatures and SCC columns exposed to fire. This chapter also pinpoints the gaps in current knowledge to establish the originality of the research.

Chapter 3 provides in detail the experimental studies on material property of the self-compacting concrete with and without POFA exposed to elevated temperatures. The chapter also presents in detail the procedure of columns preparation, heating of the columns and testing of the columns after heating.

Chapter 4 presents the characterisation of the constituent materials which include the chemical composition, physical properties as well as the microstructural characteristics. The chapter also describes the mix design of the self-compacting concrete (SCC).

Chapter 5 focuses on the assessment of the mechanical properties of the self-compacting concrete produced with and without POFA exposed to elevated temperatures.

Chapter 6 describes the assessment of the microstructures of the self-compacting concrete produced with and without POFA exposed to elevated temperatures.

Chapter 7 presents the residual axial capacity of self-compacting POFA concrete columns exposed to elevated temperatures.

Chapter 8 focuses on the conclusions, contributions and recommendations for future work based on the findings of the research.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Mujedu, K. A.**, Ab-kadir, M. A. and Ismail, M. (2020) 'A review on self-compacting concrete incorporating palm oil fuel ash as a cement replacement', *Construction and Building Materials*, 258, p. 119541. https://doi.org/10.1016/j.conbuildmat.2020.119541. **(Q1, IF: 4.419)**

2. **Mujedu, K. A.**, Ab-kadir, M. A., Sarbini, N. N. and Ismail, M. (2021) 'Microstructure and compressive strength of self-compacting concrete incorporating palm oil fuel ash exposed to elevated temperatures', *Construction and Building Materials*, 274, p. 122025. https://doi.org/10.1016/j.conbuildmat.2020.122025. **(Q1, IF: 4.419)**

Indexed Conference Proceedings

1. **Mujedu, K. A.**, Ab-kadir, M. A. and Ismail, M. (2020) 'Effect of high temperatures on physical and compressive strength properties of self-compacting concrete incorporating palm oil fuel ash', *IOP Conference Series: Materials Science and Engineering*, 849, pp. 1–11. https://doi.org/10.1088/1757-899X/849/1/012040. **(Indexed by SCOPUS)**

2. **Mujedu, K. A.**, Ab-kadir, M. A., Ismail, M., Mohamad Ali Mastor, M. N., Zuhan, N., Aluko, O. G. and Abou Sif, M. T. M. (2021) 'Structural Performance of Reinforced Self-compacting Concrete Columns Produced with Palm Oil Fuel Ash', *IOP Conference Series: Materials Science and Engineering.* 1153, pp. 1-9. https://doi.org/10.1088/1757-899X/1153/1/012006. **(Indexed by SCOPUS)**