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Thermal activation effect on palm oil clinker properties and their influence on strength development in cement mortar

Mohammad Razaul Karim, Huzaifa Hashim, Hashim Abdul Razak *

StrucHMRS Group, Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

HIGHLIGHTS

- Thermal activation reduces the content of organic carbon in palm oil clinker powder.
- The percentage of inorganic oxides content increases in palm oil clinker through thermal activation process.
- Compressive strength is developed in thermally activated palm oil clinker powder blended cement mortar.

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ABSTRACT

Compressive strength of mortar and concrete is an important consideration when incorporating waste as supplementary materials. Palm oil clinker (POC) is a waste material produced as result of incomplete burning of palm oil shells and mesocarp fibres as fuel to run steam turbines in palm oil mills. The current practice is to dump the waste in open land or landfill sites, which leads to environmental problems. Thermal activation was carried out to investigate the effects of applied heat energy on changes in chemical composition, physical properties, organic carbon content, morphology and crystalline structure of the mineral in palm oil clinker powder (POCP), and their influence on compressive strength development. The effects were investigated using TGA, XRF, TOC analyzer, SEM and XRD. Thermal activation was carried out in a programmable electrical furnace at 300 °C, 580 °C and 650 °C temperatures for 3 h. The right condition for thermal activation effect on POCP was found to be at 580 °C for 3 h, where the compressive strength of mortar was significantly increased.

1. Introduction

In recent decades, environmental issues have motivated researchers to focus on finding new supplementary cementitious materials from wastes and enhanced the quality of waste materials, especially intended for use in cement-based applications [1,2]. Problems associated with the utilization of traditional supplementary materials such as fly ash (FA), granulated blast furnace slag (GBFS), silica fume (SF), etc. are due to limited availability locally and higher transport cost of imported from elsewhere [2]. Palm oil produces abundant agricultural waste in Malaysia. The palm oil industry generates nearly 80% of waste materials such as fruit bunches and shells which create serious problem to the environment [3]. This waste has been used as substitute for fuel [4] to run turbines for electricity generation in palm oil mills. After combustion process, the remaining residues are either dumped into the soil or left in open land. This waste material leads to environmental pollution, contaminate ground water [5] and change the natural composition of the soil. Moreover, the addition of waste as a supplementary material in concrete or mortar reduces the compressive strength as result of lowering the concentration of portlandite due to the dilution effect [6–8]. The effect of thermal activation on POCP properties i.e. physical, chemical, morphology and structural change of minerals and their influence on compressive strength development is a motivation for this study.

Several significant studies have focused on optimization of thermal activation process and effect of heat energy on waste properties i.e. unburned carbon content, morphology, chemical composition, crystalline state of minerals and their influence on cement-based application. Table 1 presents the thermal activation effect on properties of waste and their influence on cement-based applications. Palm oil fuel ash (POFA) is another form of waste produced in a similar way as POC. The technical suitability of this waste to be used in cement-based application has been proven. The heat of hydration of POFA blended cement was lower

* Corresponding author.
E-mail address: hashim@um.edu.my (H. Abdul Razak).

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Table 1
Thermal activation effect on properties of waste and their influence on cement-based applications.

Name of waste	Condition for thermal activation	Major change occurred	Main influence on cement-based applications	Refs.
POFA	500 °C for 1hour	Reduced unburned carbon content	Fluidity& compressive strength increased	[9]
POFA	500 °C for 1.5 h	Particle size become smaller, removed unburned carbon and increased the glassy phases	Long-term compressive strength was significantly increased	[10]
Clayey waste of Art paper sludge	600–650 °C for 2 h	$Ca(OH)_2 \rightarrow CaO + H_2O$ $CaCO_3 \rightarrow CaO + CO_2$	Normal consistency for water and compressive strength increase and decreases the setting times	[6]
Paper de-ink sludge	700 °C for 2 h	Kaolin converted to metakaolin and decomposition of calcite & talc	Increase compressive strength slightly after 7 days	[11]
Clay	600 °C for 3 h	Kaolinite was converted to metakaolinite	20% replacement show optimum result on strength development, corrosion and chloride resistivity	[12]
Kaolin containing mica	700 °C and 750 °C for 3 h	Partial kaolinite and complete mica phase amorphization	Pozzolanic activity increased	[13]
Natural kaolinitic clay	800 °C for two hours	Structural disorder happened and increased pozzolanic activity	Good compressive strength at 25% replacement	[2]
Honeycomb briquette ash	Froth flotation	Remove unburned carbon	Compressive strength of the geopolymer body increased to 65.6 MPa	[8]
Fly ash	900 °C for 1 h	Remove unburned carbon	Suffered severe corrosion, when the carbon level in fly ash was increased	[14]

compared with OPC [15] and also exhibit good pozzolanic properties [16]. Moreover, unburned carbon in POFA (6.01%) causes problems in the fluidity and the development of compressive strength because the absorption capability of unburned carbon for super plasticizer (SP) is higher compared to other ingredients of cement-based materials. Secondly, this organic carbon has a negative effect on the compressive strength by increasing the porosity of the cement matrix [9,17]. Mechanical activation method was used to reduce the particle size of POFA such that it increased compressive strength significantly [18]. FA and steel slag are being used for blended cement production which not only reduces carbon footprint but also the costs [19,20]. Thermally activated FA was used to increase the fluidity, sulfate and chloride resistivity of mortar [14]. Clay and paper sludge contain significant amount of calcite and kaolin. These wastes were decomposed using heat energy to increase the content of existing oxides which positively influences the strength development [2,11,12].

The performance of waste materials in concrete or mortar also depends on the microstructure change through thermal activation. The thermal activation method reduces unburned carbon with morphological change of POFA [10]. The fine particles of POFA accumulate near the aggregate-paste matrix interface resulting in improvement of internal bonding energy and also modify the particle packing density of the matrix [21]. The microstructure investigation found that POFA which is free of carbon together with nano silica increased the density of mortar matrix. As a result the compressive strength significantly increased [1]. Organic carbon free honeycomb briquette ash was found to increase the compressive strength of geopolymeric bodies up to 65.6 MPa [8]. Utilization of fly ash having a high loss of ignition increases water demand that ultimately decreases compressive strength [22]. Additionally, unburned carbon in supplementary materials is responsible for turning the grey color of the OPC into black [23].

A numbers of researchers has been used TGA, TOC, XRF, XRD and SEM techniques for investigation of the change on waste properties through thermal activation [9,11,16,24]. Thermal activation was carried out at relatively low temperature of 500 °C for 1 h and the organic carbon was found to decrease from 6.01% to 0.07% of POFA [16] determined using TOC analyzer. The XRD technique was used to observe the effect of heat energy on crystalline structure of minerals of any waste. If molecules in the crystal lattice are disordered, it has a positive influence on pozzolanic activity [6,24]. The crystalline structure of clay minerals becomes disordered through thermal activation at 800 °C leading to increase pozzolanic activity. This crystalline structure change causes increase in the compressive strength by activating the alumina and silica to react with $Ca(OH)_2$ of cement [11,24]. Al atom plays an important role in improving the structural and mechanical performance by occupying in between the defected C-S-H layers to form C-A-S-H gel [25]. The content of SiO_2, Fe_2O_3 and Al_2O_3 oxides are increased in fly ash, paper sludge and POFA through the activation process was observed using XRF. This is mainly due to the unburned reduction, removes water as well as other impurities but most of the inorganic oxide still remains in the waste material. Previous investigation demonstrated that the percentage of main cementing inorganic oxide such as SiO_2, Fe_2O_3 and Al_2O_3 could be increased by thermal treatment [9,24].

The objective of this study is to investigate the effect of thermal activation on physical properties, chemical composition, morphology, TOC (total organic carbon) content and crystalline structural of minerals of POCP and their influences in compressive strength development of cement mortar.

2. Materials and methods

2.1. Materials

The POC is collected from palm oil mill, located in Dengkil in Kuala Lumpur, Malaysia. Fig. 1 presents a large chuck of POC. It contains 1–3% of moisture, and oven dried prior to crushing at temperature of 100 ± 5 °C for half an hour. Initially the large size chunks of POC were crushed using a jaw crusher. The smaller pieces after crushing were then grounded in a ball mill for 3 h at 150 RPM to produce POCP. This powder was sieved through 150 μm and the material passing 150 μm was used for thermal activation. The average particles retained for POCP on 150 μm sieve was 0.23%. The OPC (CEM I 42.5N) was obtained from a local cement factory. Blaine specific surface area (SSA) and loss on ignition (LOI) was measured using Blaine apparatus and furnaces, respectively. The LOI was measured according ASTM C114 [26]. Specific gravity was determined by hydrostatic weighing of powder in non-reactive liquid (kerosene). SSA, LOI, specific gravity of cement used was 365 m^2/kg, 1.21% and 3.15 g/cm^3, respectively.

2.2. Thermogravimetric analysis (TGA)

TGA is used to determine the thermal stability of POCP. This measurement is carried out using 16.348 mg samples at inert atmosphere using N_2 gas with a flow of 100 ml/minute. The