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Environmental assessment of utilizing date palm ash as partial replacement of cement in mortar

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ABSTRACT

Saudi Arabia's date palm industry generates date palm ash (DPA) from the thermal processing of palm oil fibers and shells. This waste material has potential to be used as partial replacement of cement in structural mortar. However, no studies to date have examined its pollution potential. DPA was used as a cement replacement in Portland cement mortar (PCM) using a 10% and 100% replacement rate and then compared to an ordinary PCM control sample. Total elemental analysis, the toxicity characteristic leaching procedure (TCLP) and monolith leaching tests were conducted. Elemental analysis revealed a standard elemental profile similar to data for the comparably used wood ash. Aluminum (Al) and iron (Fe) were elements with the greatest abundance in DPA but no element exceeded regulatory thresholds. Leachability testing revealed that while concentrations of Al and Fe may appear high in DPA, they experience relatively low mobility when encapsulated in PCM matrices as indicated by their calculated leachability index. The results presented in this paper indicate that DPA poses no environmental risk to human health when used as cement replacement in PCM.

1. Introduction

Beneficial use is the recycling of waste materials as ingredients for novel products or for use in manufacturing processes. Research has shown how waste material produced in large quantities such as bio solids, coal ash, or water treatment sludge is repurposed for profitable use in a variety of applications across the United States of America [1]. The environmentally friendly reuse of waste in this manner reduces landfilling and eliminates harmful manufacturing footprints. A variety of industrial waste materials are suitably explored in a number of applications around the world [2]. For example, Waste to Energy (WTE) bottom ash is beneficially used across the Eastern Hemisphere, perhaps most notably in the Netherlands and Denmark, where over 90% of WTE bottom ash is recycled [3]. Much of this ash is utilized in road construction applications as a coarse base material which provides structural support under roadways [4]. A potential target for such productive use is in the Saudi Arabian date palm industry which generates more than 200,000 tons of waste annually [5]. The waste is generated in palm oil mills and includes date palm (DP) ash, a by-product of burning extracted palm oil fibers and shells. Currently, date palm ash is not being commercially utilized in any reuse applications but it's potential for reuse has received some recent attention [6].

Research on the chemical properties of DPA, as observed in beneficial use opportunities, is limited. Additionally, with the exception of work done by [6], no research studies have examined the factors affecting DPA's performance in reuse scenarios [7]. This lack of information coupled with uncertainty in the DPA market, due to fluctuating volumes of DPA, results in a lower than nominal amount of recycling for this waste material [6]. A key to alleviating the scientific uncertainty in DPA's reuse is dependent upon its physical properties and how well it performs in environmental tests. As citizens across the globe grow increasingly more aware of the human impact on the environment governments have responded with initiatives, as is the case in Saudi Arabia, to investigate the effective utilization of solid waste materials in an effort to decrease landfilling [8]. A potential application of DPA that has been examined in the past is its utilization as partial cement replacement, in different construction applications [9,10]. For example, Khellou et al. [11] investigated the mechanical properties of construction pavement containing DPA (4–12%) mixed gypsum-calcareous material. The author concluded from the findings that 8% DPA replacement substantially increase the compressive strength and bearing index. Additionally, W. Al-Kutti et al [7] evaluated the compressive strength development in concrete and mortar using (10 to 30) % DPA Type I cement replacement at different curing period. The author reported that 10% DPA in concrete and mortar showed significant improvement in compressive strength development in 28 to 360 days as compared to pure PCM and reached to maximum value of 85.5 MPa in 360-days. Recently, Gunarani and Chakkravarthy [12] investigated the effect of using date palm seed ash (DPSA) (4–12) % as partial replacement of conventional cement on strength, water absorption,

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alkalinity and soprtivity. They found that using 4% DPSA replacement to PCC showed higher compressive strength while 2% and 8% replacement level can be effectively applied for construction requiring higher acid resistance and bond strength, respectively. Similar behavior was observed in our previous study [6] at 10% DPA as cement replacement in mortar.

Palm tree signifies an important national status. Production of palm waste and ash deserves its usage as a raw supplement material in building industry. An advocate for usage of the material demands such kind of environmental assessment study to reassure its health safety issues. Therefore, in order to justify the use of DPA in PCM, multiple environmental impact assessments have to be conducted. The environmental risk a beneficially used waste material poses is assessed by examining two exposure pathways: direct human exposure and leaching to water supplies [13]. Direct human exposure is commonly evaluated by comparing total element concentrations (mg/kg) to risk thresholds based on toxicity data and exposure assumptions [14]. Leaching risk is assessed using standardized tests that are commonly used for both hazardous waste determinations and beneficial use determinations [13]. Hazardous waste determination is assessed in the United States using the Environmental Protection Agency's (EPA) Toxicity Characteristic Leaching Procedure (TCLP), a method designed to simulate leaching conditions resulting from disposal with municipal solid waste [15]. Leaching test results are then compared to toxicity characteristic (TC) limits to evaluate whether a material should be designated as hazardous waste.

Batch and monolithic leaching tests assess the pollution potential of leachate originating from size-reduced waste materials used as aggregate replacements in semi-impermeable monoliths [1]. These tests measure the mobilization of trace elements as a function of time and allow for the calculation of observed elemental diffusivity [16]. When waste materials are incorporated into media, such as PCC, or when treated with solidification and stabilization (S/S) for disposal purposes, the mobility of pollutants out of contaminated media is governed by diffusion [18]. Further background information on the protocols used during these leaching tests was outlined by [17] in a review of the methods as presented in the EPA's Leaching Environmental Assessment Framework (LEAF).

Current research on DPA used as a cement replacement in profitable application, has evaluated its civil engineering properties. However little other work has examined its pollution potential in either un-encapsulated or encapsulated forms [18]. While some research has evaluated pollutant leaching from un-encapsulated DPA no work has attempted to evaluate the concentration of trace elements originating from beneficially used DPA in its encapsulated form. This information is necessary to assess the environmental risk recycled DPA poses and to serve as a basis by which applicable waste management practices can be recommended in any future uses of the waste as a cement replacement in PCM. The work presented in this paper evaluates the environmental risk associated with pollutants leaching from DPA in its un-encapsulated and encapsulated forms. Laboratory-scale leaching experiments, using standardized EPA methodologies, quantified the pollution potential of DPA used as replacement material in PCM. Results obtained from leaching tests were compared to Florida's Soil Cleanup Target Levels (SCTL) to evaluate whether ash amended samples should be characterized as posing a hazardous risk to humans.

Batch test results from the DPA evaluated relative leaching risk of ash amended samples and were used, subsequently, to determine proper disposal methods of the waste if it was not suited for reuse. Monolithic leaching tests, conducted under diffusion control scenarios, evaluated the mobility of trace elements in encapsulated, DPA amended monoliths which simulate mortar blocks and sidewalks. Leachability index (LI) and observed elemental diffusivity were then calculated for the monoliths to quantify trace element mobility. These tests provide insight into the environmental impact of DPA reuse and can be used by stakeholders to make informed decisions regarding the productive and cost effective use of DPA in Portland cement.

2. Methods

2.1. Facility description and sample collection

DPA samples were collected from a date palm recycling facility located in Saudi Arabia's Eastern Province. The facility utilizes desiccated palm fronds in the production of coal and firewood with a maximum capacity of 2 tons per day. The facility first grinds and then thermally processes the desiccated material which produces DPA. Sampling trips consisted of collecting 40 kg sub-samples in sealed containers. Samples were then homogenized, and stored in sealed polypropylene plastic containers until analyzed. In order to preserve sample consistency particle size requirements, as outlined in EPA method 1311, were achieved by passing DPA through a 425 μm US sieve. Particle distribution of the DPA and mix design is referenced in [6]. Mortar specimens for Method 1315 test were produced using a mix design with three replacements (control, 10%, and 100% replacement) and aged for 28 days and mix design composition is listed in Section S1. The structural data such as workability, density, compressive strength, approx. setting time and chemical composition of OPC and DPA is demonstrated in section S2 (A–E).

2.2. Total concentration

Total elemental analysis was conducted using the total environmentally available procedure outlined in EPA method 3050b at a constant temperature of 95 ± 5 °C [19]. Prior to conducting the procedure, DPA was ground to a powder using a ceramic ball mill. Throughout the course of this study, samples were analyzed in triplicate. Quality control protocols were used for all laboratory analysis in this research.

2.3. Leaching tests

All leachate generated from leaching experiments were digested in accordance to EPA Method 3010 A. Batch leaching test Toxicity Characteristic Leaching Procedure (TCLP) was conducted on DPA and control samples as outlined by EPA Method 1311 [20]. TCLP extraction fluid was determined using the final pH of DPA samples after preliminary testing was completed (EPA method 1311). Extraction Fluid #2 was used because pH was > 5.0. TCLP test Fluid #2 is an acetic acid, sodium hydroxide solution with a pH of 4.93 ± 0.05 [20]. The TCLP test utilizes a liquid to solid (L/S) ratio of 20:1 mL reagent water/g-dry sample and an extraction period of 18 ± 2 h at 28 rpm. Following extraction, samples were filtered using borosilicate glass fiber filter. Some samples were centrifuged at 4000 ± 100 rpm for 10 min when high suspended solid content was observed.

Triplicate monolith testing was conducted on PAA (100% DPA replacement), PAAO (10% DPA replacement) and PCM (100% Portland cement) samples as outlined by EPA method 1315. Cylindrical samples were submerged in reagent water and measured 10.1 cm in diameter and ranged in height from 10.3 to 10.6 cm. Reagent water was renewed after 0.08, 1.0, 2.0, 7.0, 14, 28 42, 49, and 63 days [21] using a liquid to exposed surface area ratio of 9 ± 1 mL reagent water/cm^2 of sample area. Equations for calculating cumulative mass release from monolith testing are included by [14]. Leachability Index is calculated by taking the –log10 (D_i^{obs}) and has units of cm^2/s. High mobility waste has an LI < 6.5 while moderate and limited mobility is understood as 6.5 < LI < 8.0 and LI > 8.0, respectively [22].

2.4. Trace elemental analysis

Total elemental analysis for arsenic, cadmium, iron, lead, selenium, silver, and vanadium was evaluated using Inductively Coupled Plasma-