

Hydro-Sieved Carbon-Rich Fly Ash: Procedure and Comparison to Coconut Shell Activated Biocarbon

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ABSTRACT: Crude fly ash collected from a Saudi desalination plant had high carbon content (79.91%) and was ranked as a carbon-rich fly ash (CRFA). Since this material had a wide range of particle size, separation it into homogeneous fractions, without distortion in its porous structure, may be essential for some recycling applications such as carbon foam. Utilization of the conventional methods for its graduation may reveal to either finer particles due to sample friability by shaking effect or coarser ones due to particles agglomeration. To overcome these shortages, sieving of CRFA in the presence of water (hydro-sieving) was used to separate it into different fractions. Particle size estimated from the standard sieves was coincided to that estimated from the analogous SEM micrograph among the seven separated fractions confirming, beside the intact porous structure, the method efficiency. Ash content was decreased from 7.03% to 3.42% for the crude CRFA and the fraction with particle size ranged between 63-88 μ m, respectively as a result of using water in the graduation process. Elemental composition of the CRFA fractions was investigated by proximate and ultimate analysis. The CRFA tends to agglomerate in spherical porous clusters having different sizes and pore diameters. Cluster diameter was directly related to the pore diameter and inversely related to the pore density. Anatomical structure of coconut shell-activated carbon was featured by sclerenchyma cells. The vessels possess two different types of border pits (single and scalariform) beside water steam-activated pores.

KEYWORDS: Carbon rich-fly ash; Proximate analysis; SEM; EDS; Particle size; Pore diameter

I. INTRODUCTION

Fly ash is a fine spherical powder with a glassy aspect having pozzolanic properties and consisting essentially of SiO₂ and Al₂O₃ [1]. It is produced during fuel combustion and transferring from the combustion chamber via exhaust gases and then collected by electrostatic or mechanical precipitators or fabric filters. Water desalination and power plants generate large quantity of fly ash daily [2] due to utilization of crude and heavy oils for heating processes [3]. Carbon rich-fly ash (CRFA) is a type of fly ash that contains high content of carbon. The CRFA is produced in Saudi Arabia in huge quantities and has not been utilized for any viable application [4]. The disposal of fly ash generated during municipal solid waste incineration may pose a significant risk to the environment due to the possible leaching of hazardous pollutants, such as toxic metals [5]. The danger of fly ash is due to its high toxic elemental content that can affect human health and causing genetic mutations [6,7,8,9,10,11]. Global production of coal fly ash is estimated to be 500 million tons annually with only 16% recycling activities [12] and the remainder amount is disposed of in landfills at significant costs [13,14,15]. The production of unburnt carbon in fly ash can be attributed to inefficient combustion conditions of fuel in the boilers or the use of low-NO_x burners to reduce power plant emission. [13]. The char particles remaining in the ash after the incomplete combustion of coal in the furnace essentially consist of carbon, free from volatile matter, often incorporating inorganic newly-formed components [16]. It is a critical to develop new

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technologies that will allow utilization of CRFA more efficiently as well as establishing environmental friendly and cost effective strategies for the use of these carbonaceous waste products [16].

Potential applications of fly ash have both environmental and industrial interests [17]. The high specific surface area makes fly ash a low cost adsorbent for coal fired flue gas and waste water treatment [12]. The higher carbon content makes fly ash a more efficient adsorbent for flue gas and waste water treatment [18,19,20,21] since the carbon contributes much of the surface area to fly ash. The Saudi CRFA contains about 80-90% of carbon, the remainder being oxides of silicon, iron, nickel, aluminum and vanadium [2,3]. The unburnt carbon has highly porous fragmented particle structure and visible as fused surface ash [13]. Fly ash with low carbon content is promising as a construction material due to its suitable geotechnical characteristics, especially specific gravity, permeability and consolidation [12]. The CRFA is not suitable for the cement industry since its carbon undesirably adsorbs the air entraining agents added to prevent cement crack formation [22]. Ashes differ in characteristics depending upon the type of coal burned, the process undergone by the coal before combustion as well as the operation conditions of the boiler. Accordingly, fly ash composition and its behavior change widely from case to case [16]. It was found that the carbon content of fly ash samples varied from 2.3 to 25.3% [23]. He indicated that the high the carbon content in fly ash the high the proportion of coarse char particles (in particular $> 10^6 \mu\text{m}^3$ particles). The size distribution of the fly ash has a major effect on its carbon content. The particle size of heavy oil fly ash (10 to 120 μm) are larger than those for carbon black and contains fine pores that may have formed during the combustion process [24]. The diversity of chemical, mineralogical and morphological characteristics of CRFA offers a chance to process it recovering various fractions with particular attributes [16].

Activated carbons have applications in various industrial processes including purification of water and gold adsorption from gold solutions. Materials commonly used for preparation of activated carbons include coal, wood and coconut shells [25,26,27]. For the carbon source, it is economically to use an available agricultural waste such as sugar cane husks, comcobs, cherry stones, macadamia nut shells, palm husks and coconut husks and shells. Since coconut [28,29]. The specific surface area of the coconut shells reached a maximum value of 795 m^2/g after 3.5 hours of activation. The maximum total pore and micropore volumes developed were about 0.42 cm^3/g [27].

CSAC produced by various chemical activation techniques and agents showed efficient and cost effective properties especially for sodium chloride agent in relation to adsorption capacity (Cobb et al, 2012). The activated carbon filtration has been using in municipal treatment facilities and for mitigation the critical health-related concerns due to pesticide and/or herbicide contamination [29].

High surface area activated carbons can be produced from coconut shells using physical activation (steam activation) by proper selections of carbonization temperature and activation time. [30]. The pore structure of the raw material has a direct bearing on the pore structure of corresponding sections of activated carbons [31].

The presence of permeable structure in lignocellulosic resources is very important to chemical reagents penetration during an industrial process. The openings of cavities and the amorphous region within the cell wall microfibrils exhibit the own permeable structure for such materials.

The diversity of chemical, mineralogical and morphological characteristics of CRFA offers a chance to process it recovering various fractions with particular attributes [16].

The objective of this investigation was to study the characteristics of a highly accumulated Saudi waste (CRFA) to ensure the possibility of using it as a substitute of CSAC in sorption and/or energy applications.

II. EXPERIMENTAL

The CRFA was collected from Al-Shaeaba desalination plant, about 50km south of Jeddah, Saudi Arabia. The CRFA sample was divided into two portions: a) The 1st was assigned for crude CRFA characterization and b) the second was allocated to particle size. The coconut shell-activated carbon (CSAC) samples were taken from the sewage water treatment station in Al-Taif, Saudi Arabia that used for the 3rd stage of treatment.

Hydro-sieving method

To overcome the agglomeration problem over sieves for CRFA particles and subsequently inaccurate sieving results, water was used as a novel tool to ease particle slipping and passing through sieve openings without fracture any part of

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the particles especially edges or disturbing their porous structure. Oven-dried crude CRFA portion was mechanically sieved at room temperature in a 100g batch by aim of water and separated into seven sieved particle size fractions (SPSF), namely more than 177 micron (μm), 149-177 μm , 125-149 μm , 105-125 μm , 88-105 μm , 63-88 μm and <63 μm . This was done by using six different standard US testing sieves (ASTM E-11 specification sieves no's 80, 100, 120, 140, 170, 230 with nominal openings of 177 μm , 149 μm , 125 μm , 105 μm , 88 μm and 63 μm , respectively) fixed on a mechanical shaker.

Characterization of Fly Ash

The traits studied were fraction yield (FY), fixed carbon content (FCC), volatile matter content (VMC), ash content (AC), moisture content (MC), elemental analysis by EDS (C%, O%, S%, Cu%, Sn%, Si% and Fe %), pore diameter (PD_i), pore density (PD_e) and cluster diameter (CD).

Determination of Fraction Yield (FY)

Each collected fraction was air dried, oven dried at $103 \pm 2^\circ\text{C}$ until constant weight. The FY was calculated based on the parent oven-dry weight of the crude CRFA (100g).

Proximate analysis

Fixed carbon content (FCC), volatile matter content (VMC), ash content (AC) and moisture content (MC) of the crude carbon rich-fly ash (CRFA) and its sieved particle size fractions (SPSF) as well as crude coconut shells-activated carbon (CSAC) were determined according to the ASTM [31] for proximate analysis of wood charcoal and as applied by [32]. The carbonaceous sample was oven-dried at $103 \pm 2^\circ\text{C}$ for 2 hours. The percentage of the MC was calculated as a percentage of the parent air-dry weight. The oven-dried carbonaceous sample was preheated in tube furnace at 300°C for 2 minutes, then, at 500°C for 3 minutes and at 950°C for 6 minutes. The percentage of the VMC It is calculated based on the parent oven-dry weight. The AC is determined by heating the carbonaceous sample at 750°C for 6 hours until all carbon is eliminated. Burning of the sample was repeated until a succeeding one hour period of heating results in a loss of less than 0.0005 g. It is calculated based on the parent oven-dry weight. The FCC content of the carbonaceous sample is calculated as a percentage by subtracting the sum of VMC, AC and MC from 100.

Elemental Analysis

This characterization was done only for the CRFA due to ash content is essential for effective fly ash applications [17]. Accordingly, elemental concentrations of C%, O%, S%, Cu%, Sn%, Si% and Fe % for SPSF as well as CRFA were determined by energy dispersive X-ray spectroscopy (EDS, Oxford Instruments, X-Max) mounted on the SEM device [33]. The standard reagent used for qualitative and quantitative elemental analysis were CaCO_3 (for carbon element), SiO_2 (for both oxygen and silicon elements), FeS_2 (for sulfur element), Cu (for copper element) and Sn (for tin element).

Scanning Electron Microscopy (SEM) Measurements

SEM study was used to measure the diameter of SPSF as well as CRFA-clusters and their pores as well as CSAC. These samples were placed on the double side carbon tape on Al-stub and dried in air. Before examination, all samples were sputtered with a 15 nm thick gold layer (JEOL JFC- 1600 Auto Fine Coater) in a vacuum chamber [34]. The imaging was done by Field Emission SEM device (JEOL, JSM-7600F). Pore Density (PD_e) and pore diameters (PD_i) of the SPSF as well as CRFA were measured with suitable software (Optika Vision Pro, TWAIN interface, SDK) from the SEM micrographs. The PD_e is the number of pores present in a suggested area ($1000\mu\text{m}^2$).

Statistical Design

Complete randomized block design with three replications was used in this investigation. Statistical analysis of the recorded data was done according to El-Nakhlawy [29] using the analysis of variance procedure and least significant difference test (LSD) at 0.05.

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III. RESULTS AND DISCUSSION

The studied traits for crude carbon rich-fly ash (CRFA) and sieved particle size fractions (SPSF) were fraction yield (FY), fixed carbon content (FCC), volatile matter content (VMC), ash content (AC) and moisture content (MC), elemental concentrations of C%, O%, S%, Cu%, Sn%, Si% and Fe %, cluster diameter (CD), pore diameter (PD_i) and pore density (PD_e). In addition, the traits for CSAC were diameters of microstructure elements of coconut shell-activated carbon

Evaluation of hydro-sieving method

It can be seen from Table 1 that the particle size of the CRFA ranged from less than 63±6.2µm to 177±4.1µm for the measurements estimated from the standard sieves. In addition, for the measurements estimated from the SEM micrographs, these values varied from 32.4±14.7µm to 188.2±3.2µm. However, these values were close to the particle size range of 10-20µm indicated by Kwon et al. [24]. Furthermore, the particles size from each SPSF estimated from each of standard sieves specifications (SSS) compared to those estimated from the SEM micrographs were found to be coincided among the seven SPSF's of the CRFA. This coinciding of particle diameters confirms the accurate results for our novel method for graduation of CRFA. Traditional sieving methods for dry CRFA may be resulted in either lower particles due to sample friability by shaking effect or higher particles due to particles agglomeration. Accordingly, the hydro-sieving of CRFA is more effective and accuracy than dry sieving.

Table 1. Mean values¹ of particle diameter (PD) of sieved particle size fractions (SPSF) estimated from each of standard sieves specifications (SSS) and scanning electron microscope (SEM) micrographs.

Sieves no.	PD of SPSF(µm)	
	SSS	SEM
80	>177±4.1	188.2±3.2
100	149-177±7.3	150.7±12.1
120	125-149±5.4	135.4±7.6
140	105-125±8.6	114.9±9.4
170	88-105±3.6	90.2±6.9
230	63-88±5.8	72.4±8.3
	<63±6.2	32.4±14.7

¹ Each value is an average of 10 observations. ± the standard deviation.

Fraction Yield (FY)

The FY of SPSF's and the proximate analysis of both SPSF and CRFA were presented in Table 2. Yield of SPSF differed significantly among the fractions with high values for the grades of 63-88 µm and 149-177 µm (31.99% and 149-177%, respectively). On the other hand, the fractions of SPSF, namely 88-105, >177 and 125-149 µm had the lowest yield (3.86, 1.56% and 1.45%, respectively). In between, the particle size of PSF that finer than 63 µm and that of 105-125 µm had yield values of 17.97% and 12.24%, respectively (Table 2).

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Table 2. Mean values^{1,2} of fraction yield (FY), fixed carbon content (FCC), ash content (AC) and volatile matter content (VMC) for crude and sieved particle size fractions (SPSF), carbon rich-fly ash (CRFA) as well as coconut shell activated carbon (CSAC).

SPSF, μm	FY, %	FCC, %	AC, %	VMC, %
>177	1.56 ^d	78.54 ^d	8.78 ^a	10.89 ^a
149-177	30.84 ^a	90.84 ^a	4.3 ^{cd}	4.17 ^{cd}
125-149	1.45 ^d	86.46 ^{bc}	4.89 ^{cd}	8.09 ^b
105-125	12.24 ^c	89.02 ^a	4.85 ^{cd}	4.53 ^{cd}
88-105	3.86 ^{cd}	87.22 ^b	5.37 ^{bc}	6.8 ^c
63-88	31.99 ^a	92.9 ^a	3.42 ^d	3.12 ^d
<63	17.97 ^b	85.51 ^{bc}	3.63 ^d	9.07 ^{ab}
CRFA	---	79.91 ^d	7.03 ^{ab}	5.83 ^c
CSAC	---	84.79 ^c	6.43 ^b	7.99 ^b

¹Means within the same column followed by the same letter are not significantly different according to LSD at 0.05

²As a percentage of the parent oven dry carbon precursor.

Chemical Characterization

Proximate Analysis

Fixed carbon content (FCC) of the PSF fractions of 63-88 μm , 149-177 μm and 105-125 μm was the highest (92.9%, 90.84% and 89.02%, respectively). The FCC of crude CRFA as well as particles with diameters higher than 177 μm was the lowest (78.54% and 79.91%, respectively). The remainder fractions of CRFA were statistically similar in their FCC and slightly higher than that for crude coconut shells-activated carbon (CSAC) as shown in Table 2.

Comparisons between fractions of CRFA in relation to ash content (AC) revealed that the highest value was found in the fraction with particle size coarser than 177 μm (8.78%) which comparable to that for the crude materials studied (CRFA and CSAC). In contrast, the other fractions of CRFA had less AC values ranged from 3.42% to 5.37%. The low AC in the CRFA fractions with particle size less than 177 μm may be attributed to the sorption trapping of more ash minerals within pores of the coarse particles (>177 μm). In addition, AC values of the later-mentioned fractions were lower than those for the crude materials (CRFA and CSAC) as presented in Table 2. This may be due to leaching out some salts by water meanwhile the hydro-sieving method used for graduation of the CRFA. Accordingly, washing CRFA by stream of water and consequent vacuum-filtration must be done to reduce its AC.

Higher VMC values were found to be 10.89%, 9.07%, 8.09 and 7.99% for the PSF of CRFA, namely >177 μm , <63 μm , 125-149 μm and crude CSAC. On the other hand, The lower values of VMC ranged from 6.8% to 3.12% for the fractions of 88-105 μm and 63-88 μm , respectively (Table 2). It can be noticed from Table 2 that some CRFA fractions have VMC values higher than that for crude CRFA meaning that washing them by water do not alter their VMC value. It is notable that increasing FCC and decreasing AC and VMC is the main principle for using CRFA in industrial applications. Materials with a high FCC are more purity than those with lower FCC that can produce more pure products and consuming less chemical reagents when used in synthesis process. Furthermore, high AC minerals and VMC arises many industrial problems such as producing byproducts that may interfere with chemical reagents and/or reduce quality of the final products.

Elemental analysis

Elemental concentrations of C%, O%, S%, Cu%, Sn%, Si% and Fe % for sieved particle size fractions (SPSF) of carbon rich-fly ash (CRFA) evaluated by EDS are presented in Figure 1 and Table 3. Qualitatively, it can be seen from Figure 1 that each band appears at a consistent kilo electron volt (KeV) value and corresponds to a specific element.

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For instance, C and O are adjacent and appeared at about 0.4KeV and 0.5KeV, respectively while Cu, Si, S, Sn and Fe appeared at the bands of 1KeV, 1.75 KeV, 2.5 KeV, 3.5 KeV and 6.5 KeV, respectively. It is clear that all the seven elements appeared together in the coarser SPSF fraction (>177 μ m). The following five finer fractions (149 μ m -177 μ m, 125 μ m -149 μ m, 105 μ m -125 μ m, 88 μ m -105 μ m and 63 μ m -88 μ m) contained C%, O%, S%, Cu% and Sn% with the absence of Si and Fe (Figure 1 and Table 3). In addition, the finer SPSF fraction was found to be free of Sn, Si and Fe.

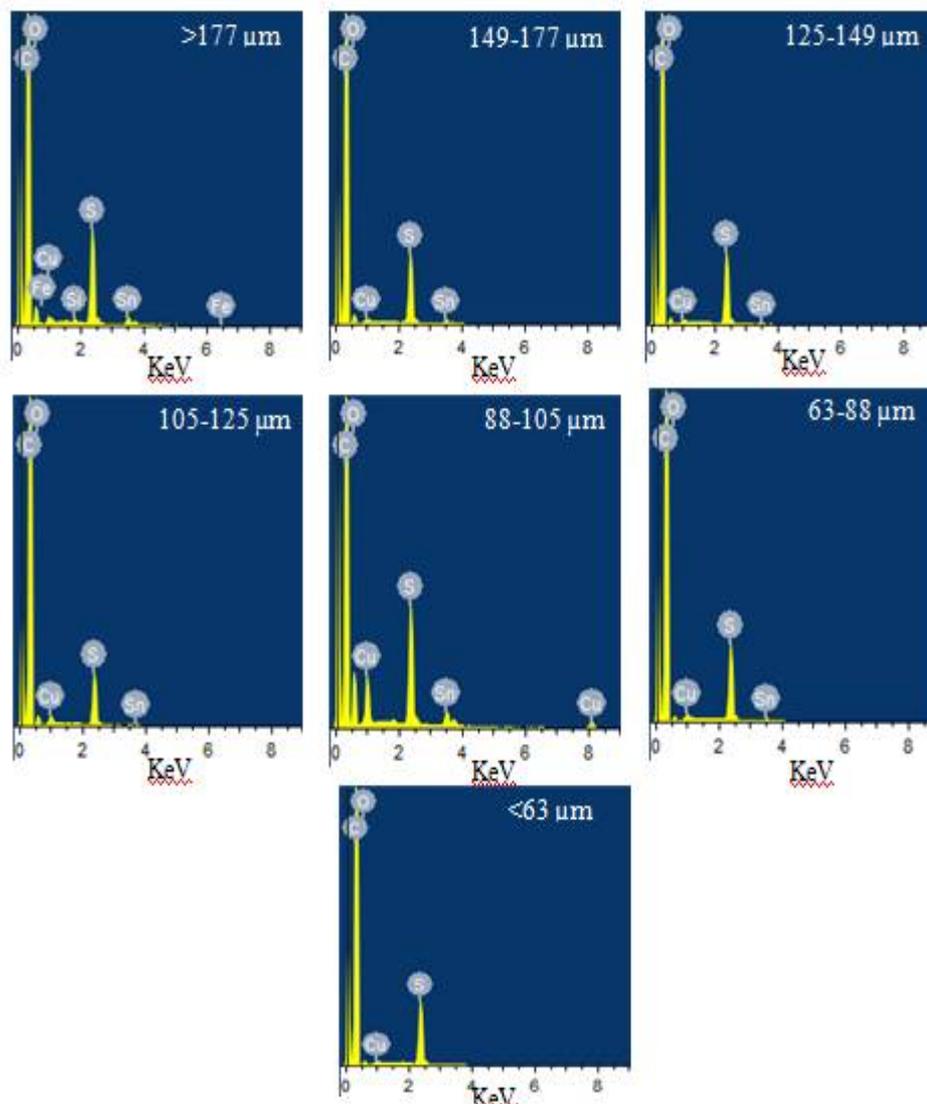


Figure 1. Qualitative and quantitative elemental analysis of sieved particle size fractions (SPSF) of carbon rich fly ash (CRFA) by energy dispersive X-ray spectroscopy (EDS)

Quantitatively, concentration of each element was estimated by measuring the area under its peak. Comparisons between elements revealed that carbon had the highest concentration (81.46%-94.93%) in all SPSF's. On the other hand, the lowest element concentrations were detected for Cu (0.07%-1.43%), Sn (0.11%-0.42%), Si (0.12%) and Fe

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(0.11%). Furthermore, comparisons between fractions within each element showed that there are notable differences between fractions in their contents of the elements studied. All the SPSF fractions with particle size less than 177 μm had high carbon concentration (more than 90%) except for the fraction of 88 μm -105 μm which had the lowest carbon content (81.46%). In between, the coarser fraction (>177 μm) had a moderate concentration of carbon (89.23%). The lower carbon content in the SPSF fractions (88 μm -105 μm and >177 μm) can be attributed to their high content of each of oxygen element (13.45% and 6.9%, respectively) and sulfur (3.23% and 3.24%, respectively). However, no consistent trend was observed for accumulation of the seven elements within the SPSF of CRFA (Figure 1 and Table 3).

Table 3. Elemental analysis of sieved particle size fractions (SPSF) of carbon rich fly ash (CRFA)

SPSF μm	C %	O %	S %	Cu %	Sn %	Si %	Fe %
>177	89.23 ^b	6.90 ^b	3.23 ^a	0.14 ^c	0.27 ^b	0.12	0.11
149-177	92.4 ^a	4.52 ^c	2.76 ^b	0.12 ^c	0.19 ^c	Nil	Nil
125-149	93.81 ^a	3.21 ^{de}	2.85 ^b	0.07 ^d	0.05 ^d	Nil	Nil
105-125	92.66 ^a	4.74 ^c	2.16 ^c	0.33 ^b	0.11 ^{cd}	Nil	Nil
88-105	81.46 ^c	13.45 ^a	3.24 ^a	1.43 ^a	0.42 ^a	Nil	Nil
63-88	94.22 ^a	2.63 ^{de}	2.83 ^b	0.17 ^c	0.14 ^{cd}	Nil	Nil
<63	94.93 ^a	2.11 ^e	2.88 ^b	0.08 ^d	Nil	Nil	Nil

¹Means within the same column followed by the same letter are not significantly different according to LSD at 0.05

²As a percentage of the parent oven dry carbon-rich fly ash.

Scanning Electron Microscopy (SEM)

It is clear from Figures 2 and 3 that CRFA tends to agglomerate in spherical porous particles having different sizes and variant pore diameters. It was found that the higher the particle diameter, the higher the pore diameter within it (Figure 5). A direct relationship was found between particle diameter and pore diameter ($R^2=0.905$) as shown in Table 4.

Pore density is a measure of pore number within a specific unity of area and was selected to be 1000 pores/ μm^2 in this study. As shown in Figure 6, pore density was low for coarser SPSF due to pores have wide diameters, so they found in a few number within the specified area and vice versa for the finer fractions. An inverse relationship was found between particle diameter and pore density ($R^2=0.837$) as presented in Table 4.

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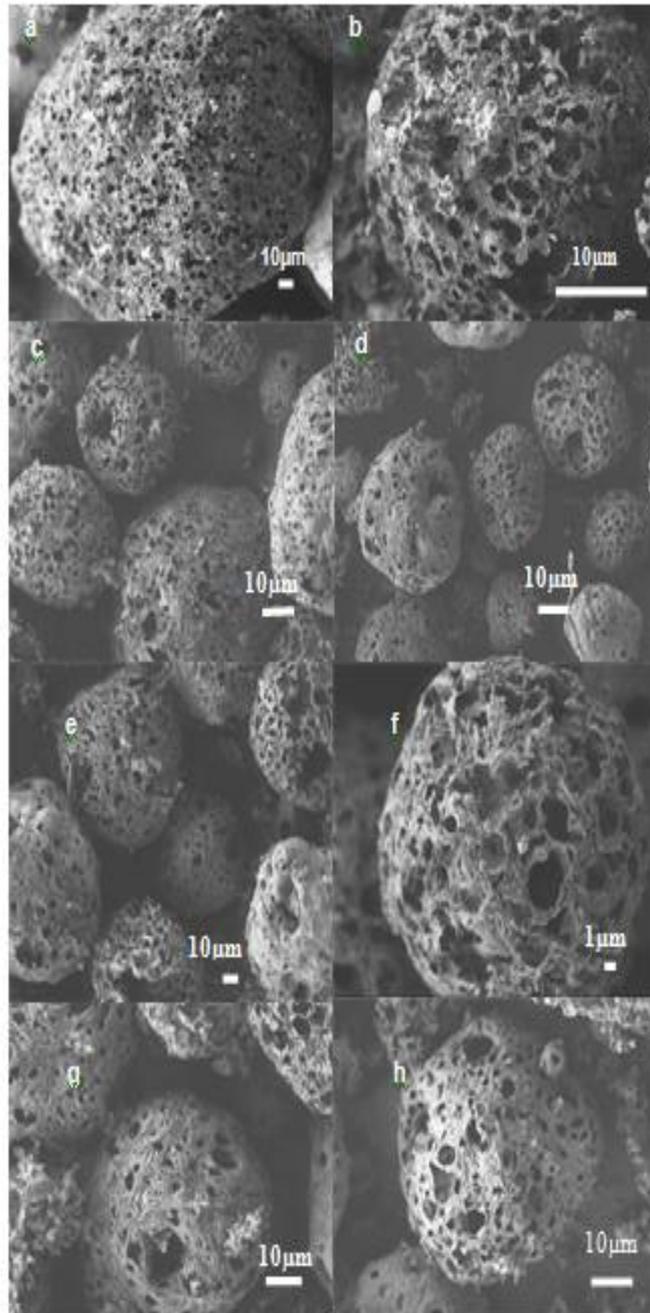


Figure 2. Particles of sieved particle size fractions (SPSF): a) $>177\mu\text{m}$, b) $149\text{-}177\mu\text{m}$, c) $125\text{-}149\mu\text{m}$, d) $105\text{-}125\mu\text{m}$, e) $88\text{-}105\mu\text{m}$, f) $63\text{-}88\mu\text{m}$ and g) $>63\mu\text{m}$ and h) crude carbon rich-fly ash (CRFA).

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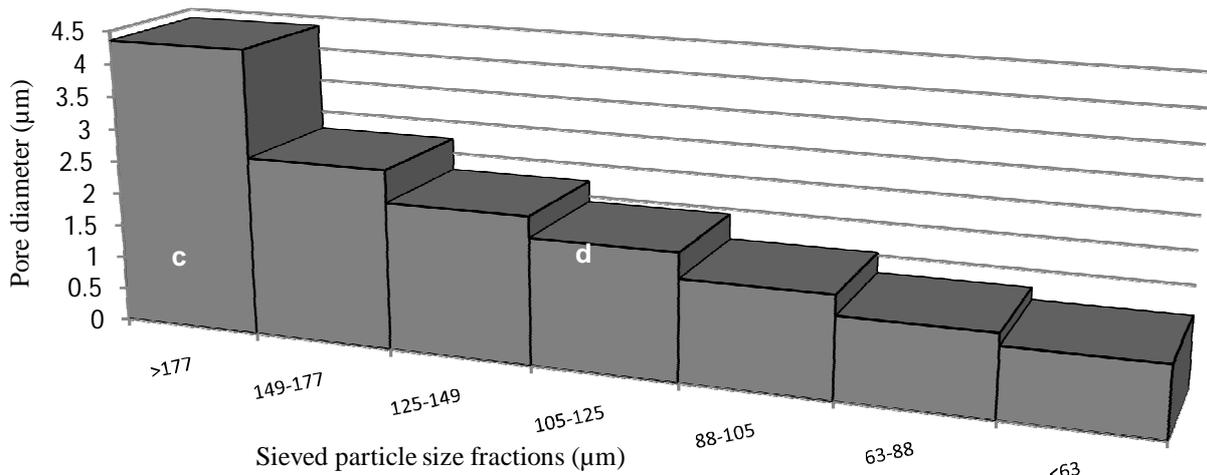


Figure 3. Pore diameter in particles of sieved particle size-fractions of carbon rich fly ash.

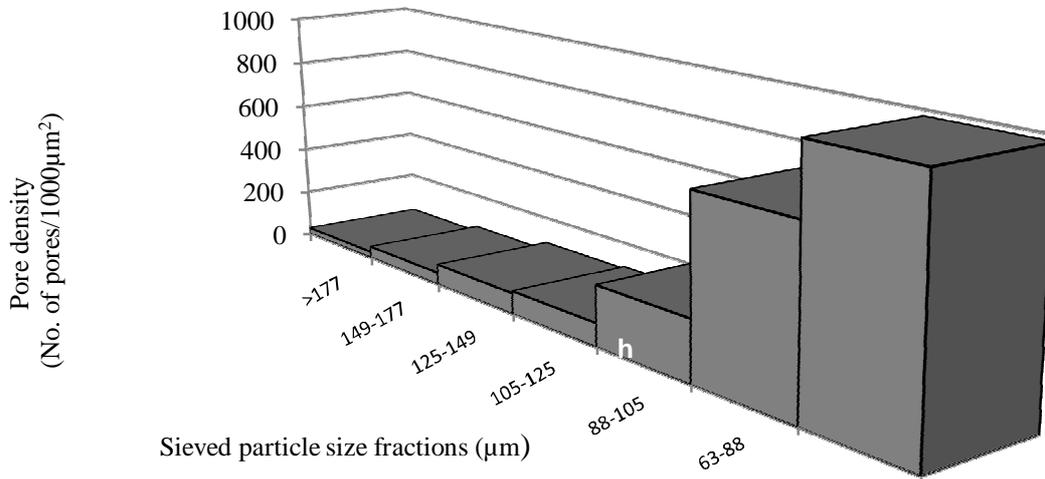


Figure 4. Pore density in particles of sieved particle size-fractions of carbon rich fly ash.

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Table 4. Relationship equations between particle diameter¹ (CD) and each of pore diameter¹ (PD_i) and pore density (PD_e) of the carbon rich fly ash.

Equation	R ²	N
PD _i =-0.399+0.024CD	0.905	35
PD _e =1076.5-7.076CD	0.837	35

¹ Measurements are in μm

Anatomical structure of coconut shell-activated carbon was found to be featured by sclerenchyma cells (longitudinal vessels) as shown in Figures 5 and 6. Their averages of transverse and longitudinal diameters were 29.32μm and 24.79μm, respectively (Table 5). The vessels possess three different types of pores:

1. Single border pits that align longitudinally often in the longitudinal radial section like a wood anatomical structure (Figures 5 and 6). Their averages of transverse and longitudinal diameters were 3.61μm and 1.47μm, respectively (Table 5).
2. Scalariform border pits are found in the longitudinal tangential section. Their averages of transverse and longitudinal diameters were 5.43μm and 1.21μm, respectively (Table 5).
3. Water steam activated pores are arisen when water steam strikes the carbonaceous skeleton (Figure 6). Their averages of transverse and longitudinal diameters were found to be 2.49μm and 2.32μm, respectively (Table 5).

Table 5. Mean values¹ of diameters of microstructure elements of coconut shell-activated carbon

Anatomical Element	Diameter (μm)	
	Transverse	Longitudinal
Vessel	29.32 ^a	24.79 ^a
Border pit	3.61 ^{bc}	1.47 ^b
Scalariform border pit	5.43 ^b	1.21 ^b
Water steam activated pores	2.49 ^c	2.32 ^b

¹ Means within the same column followed by the same letter are not significantly different according to LSD at 0.05

² Each value is an average of 10 observations.

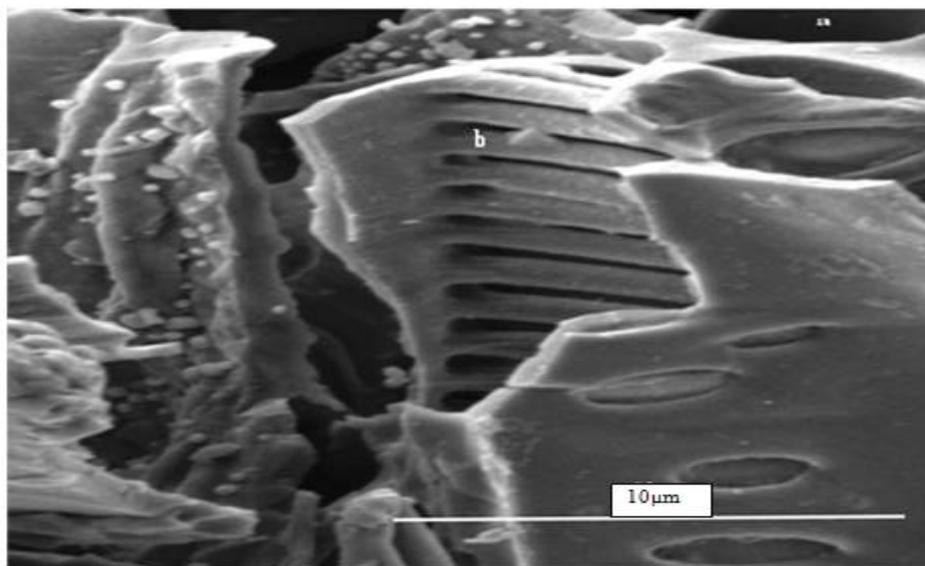


Figure 5. Porous structure of coconut shell-activated carbon; a) Pore vessel, b) Scalariform border pitting and c) Single border pit.

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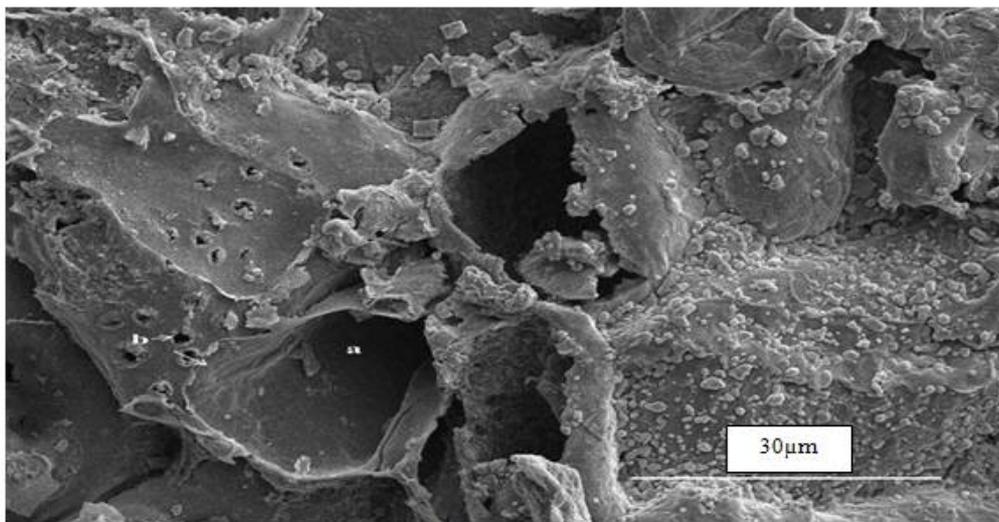


Figure 6. Porous structure of coconut shell-activated carbon: a) Natural pore vessel and b) A water steam activated-pore.

IV. CONCLUSIONS

- Sieving of CRFA in the presence of water (hydro-sieving) is effective and gives accurate data than dry sieving.
- Yield of sieved particle size fractions of carbon rich-fly ash differed significantly among the fractions.
- The highest fixed carbon content was found in the fractions of 63-88 μm , 149-177 μm and 105-125 μm . Fixed carbon contents of the crude carbon rich-fly ash as well as particles with diameters higher than 177 μm were the lowest. The reminder fractions were statistically similar in their FCC.
- The highest ash content was found in the fraction with particle size coarser than 177 μm which comparable to that for the crude materials. The ash content of the coarse particles exceeds on 177 μm) were lower than those for the crude material.
- Washing carbon rich-fly ash by water and consequent vacuum-filtration can be done to reduce its AC.
- Higher VMC values were obtained from the fractions of >177 μm , <63 μm , 125-149 μm and crude, while lower VMC were found in the fractions of 88-105 μm and 63-88 μm .
- Increasing fixed carbon and decreasing ash and volatile matter contents is the main principle for choosing carbon rich-fly ash for industrial applications. Materials with a high fixed carbon are more purity than those with lower one that can produce more pure products and consuming less chemical reagents when used in synthesis process.
- Seven elements (C%, O%, S%, Cu%, Sn%, Si% and Fe %) appeared together in the coarser SPSF fraction (>177 μm) of CRFA. The finer fractions (149 μm -177 μm , 125 μm -149 μm , 105 μm -125 μm , 88 μm -105 μm and 63 μm -88 μm) contained C%, O%, S%, Cu% and Sn% with the absence of Si and Fe In addition, the finer SPSF fraction was found to be free of Sn, Si and Fe.
- There are notable differences between fractions in their contents of the elements. Carbon had the highest concentration in all SPSF's of CRFA among the elements studied. The lowest element concentrations were detected for Cu, Sn, Si and Fe.
- All the SPSF of CRFA with particle size less than 177 μm had high carbon concentration except for the fraction of 88 μm -105 μm which had the lowest carbon content.
- No consistent trend was observed for accumulation of the seven elements within the SPSF of CRFA.
- CRFA tends to agglomerate in spherical porous particles having different sizes and variant pore diameters. It was found that the higher the particle diameter, the higher the pore diameter within it.

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- A direct relationship was found between particle diameter and pore diameter ($R^2=0.905$).
- Pore density was found to be low for coarser SPSF due to their pores have wide diameters, so they found in a few number within the specified area (1000 μ m) and vice versa for the finer fractions.
- An inverse relationship was found between particle diameter and pore density ($R^2=0.837$). Pore density was low for coarser SPSF due to pores have wide diameters, so they found in a few number within the specified area and vice versa for the finer fractions.
- Anatomical structure of coconut shell-activated carbon was found to be featured by sclerenchyma cells (longitudinal vessels). The vessels possess two different types of border pits (single and scalariform) beside water steam-activated pores.

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