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Characteristics of Fly ash Produced at Power and Water Desalination Plants Firing Fuel Oil

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ABSTRACT: Plants firing fuel oil produce huge quantities of fly ash as solid waste, which needs to be characterized prior to its proper management. It is worth mentioning that the published literature lack comprehensive information on the characteristics of such fly ash. Characteristics of fuel oil fly ash produced at selected power (PP) and water desalination (DP) plants were determined. The results showed that grain size of the DP fly ash (66.87 μm) is slightly larger than that of PP fly ash (63.09 μm). The PP fly ash is mostly carbon while DP has a larger percent of metal oxide ashes. Ash content in PP and DP fly ash were 4.8 and 43.3 percent, respectively. Moreover, metal concentrations are higher in DP fly ash than that in PP fly ash. As an example, average vanadium concentrations were 15619 and 40879 mg/kg in PP and DP fly ash samples, respectively. Generally, fly ash samples produced at the two plants are different in their physical and chemical characteristics, which could be attributed to the different fuels and additives being used at the two plants.

Key words: Fly ash, Fuel Oil, Characteristics, Metals

INTRODUCTION

Fly ash is a powdery residue generated by plants that use oil as the source of fuel. Fuel oil fly ash contains relatively high heavy metal content, particularly V and Ni. In addition, the residual carbon level in the fly ash is relatively high (Kwon *et al.,* 2005). Typical fuel oils contain Fe, Ni, V, and Zn, in addition to Al, Ca, Mg, Si, and Na. Transition metals (Fe, Mn, and Co) and alkaline-earth metals (Ba, Ca, and Mg) may also be added for the suppression of soot or for corrosion control (Bulewics *et al.,* 1974; Feldman, 1982). The chemical characteristics of the fuel oil fly ash generated at a power plant differ significantly from that of coal fly ash. The carbon content of heavy fuel oil fly ash is about 95 percent while coal fly ash contains 20 and 50 percent carbon. Blinova et al. (2012) characterized oil shale combustion fly ash. They reported that fly ash proved potentially hazardous for tested aquatic organisms and high alkalinity of the leachates (pH > 10) is apparently the key factor determining its toxicity. Pihu et al. (2012) studied the cementation of circulating fluidized bed combustion (CFBC) oil shale ash in a large-scale field experiment. Compared to pulverized fuel (PF) combustion oil shale ashes, they reported that the CFBC process ashes have lower cementation properties due to their different phase composition. Al-Ghouti et al. (2011) reported that large amounts of metals (V, Ni, Fe, Ca, Mg, Na, and K) were easily leached from FA under acidic, basic, and neutral conditions, while Miao et al (2011) reported an optimal extraction efficiency of 89.71 percent for Al. Velts et al. (2011) elucidated a method for converting lime-containing oil shale waste ash into precipitated calcium carbonate (PCC). The results showed that high brightness PCC with mean particle sizes ranging from 4 to 10 μm was obtained under the conditions studied.

Xiao et al. (2010) studied metal recovery from a selected waste mixture. Two waste ash residues of steelmaking flue dust and petroleum fly ash were used as raw materials, and the residue carbon from the fly ash was used as reducing agent. They reported that the ferrovanadium with about 20 weight percent vanadium was obtained. Lin and Yeh (2010) examined the effects of operational parameters in a fluidized-bed combustion process to understand the distribution of heavy metals in bottom ash after agglomeration/defluidization. The study showed that heavy metal concentrations increased when the bottom ash size was smaller than 0.59 mm and larger than 0.84 mm. The concentrations of heavy metals in the bottom ash after Ca addition were higher than of those without Na or with Na only. Sippula et al. (2009) studied flue gas emissions of wood and heavy fuel oil

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(HFO) fired district heating units of size range 4–15 MW. The results showed that the fine particles from HFO combustion contained varying transient metals and Na that originate from the fuel, sulphuric acid, elemental carbon and organic material. Pattanaik et al. 2007 evaluated the effect of fuel compositions and combustion conditions on the amount, form, and distribution of sulfur and nickel in size-fractionated fuel oil fly ash particles. They reported that sulfate is abundant in all particles. However, depending upon the combustion conditions, lesser amounts of thiophenic sulfur, metal sulfide, and elemental sulfur may also be observed.

Reddy et al. 2005 studied emissions of As, Cd, Co, Cr, Cu, Hg, Fe, Mn, Ni, Pb, Se, and Zn from a 220-MW coal-fired power plant and 6-MW oil fired-power plant. Simultaneous sampling of coal, fuel oil, oil waste, bottom ash, fly ash, flue gases, and particles associated with the gas phase has been performed. The results indicated that trace metals emissions were higher in coal-based power plant than that in the fuel oil-fired power plant.Galbreath et al. 2005 collected representative duplicate fly ash samples from the stacks of 400- and 385-MW utility boilers as they burned 0.9 and 0.3 weight percent S residual oils. They found that total Ni concentrations in the ash samples were similar, ranging from 1.3-1.5 weight percent. Chang et al. 2004 measured particle size distribution from different combustion sources burning various fuels at a nominal heat input rate of 160 kW/h and 3 percent excess oxygen. The results showed that the measured particle size distributions showed peaks of particle number concentrations for medium sulfur bituminous coal, fuel oil, and natural gas at 40-50 nm, 70-100 nm, and 15-25 nm, respectively.Abu-Rizaiza 2004 investigated the characterization of fly ash from residual oil combustion at an electric power plant. He concluded that the results indicated high content of metals and heavy metals. Moreover, 82 percent of the fly ash was carbon and the loss on ignition was 95 percent.Lai 2010 investigated ferrovanadium production from heavy fuel oil fly ash. He reported that the fly ash is mainly V (27 percent), S (12 percent), Ni (6 percent), Mg (3 percent), Ca (1 percent), Fe (1 percent) and C (37 percent). More work on the characteristics of oil fuel fly ash can be cited in Sholkovitz et al. (2009), Chen et al. 2004, Gonzalez et al. 2004, Teinemaa et al. 2002, Hsieh et al. 2001, Huffman et al. 2000, Yagasaki and Ujiie 2000, Kevin et al. 1998, Galbreath et al. 1998a,b and Lin and Sheu 1997. The literature survey clearly demonstrates that there is a lack of comprehensive data with respect to the characteristics of fuel oil fly ash. Based on that, the main objective of the current study is to investigate the physical and chemical characteristics of fly ash generated at two selected power and desalination plants firing fuel oil in the Kingdom of Saudi Arabia.

MATERIALS & METHODS

A comprehensive characterization of heavy fuel oil fly ash from Rabigh power plant (PP fly ash) and Shuaiba desalination plant (DP fly ash) was carried out. Fly ash samples were collected once every two months from each of the selected plants.The characterization included determining the physical and chemical characteristics of the fly ash samples. Table 1 summarizes the details of the different parameters that were analyzed together with the analytical methods used.The importance of the chemical and physical parameters stems from the fact that they have a direct effect on the alternative disposal and/or reuse schemes that can thereafter be implemented. Also, the concentration of heavy metals in the fly ash depends, among other factors, on the pH. As the pH decreases, the concentration of heavy metals may decrease due to the fact that at lower pH, heavy metals are more soluble and tend to concentrate in the fly ash samples. Therefore, the physical and chemical characteristics of fly ash are essential to decide on its fate. Standard methods were used for sample analysis. Each sample was analyzed in triplicates. Table 1 shows the different physical and chemical parameters of the fly ash that were investigated together with the test methods and instruments that were used throughout the project. It is worth to mention that, in case where any of the proposed method was not well recognized by laboratory technicians, alternative standard method was implemented. As mentioned previously, two power and water desalination plants utilizing crude oil or heavy fuel oil were selected for the current study. Six fuel oil fly ash samples were collected from each of the selected power and desalination plants over a period of one year. Samples from both plants were collected from one location, which is prior to disposal activity. Collection of fly ash samples, from the selected power and desalination plants, was carried out once every two months. Therefore, by the end of the collection period 12 fly ash samples (6 from each plant) were collected and subjected to analysis.

RESULTS & DISCUSSION

Fly ash samples from the two selected plants were collected for the purpose of determining the general characteristics of the produced fuel oil fly ash.The maximum, minimum and average values of physical characteristics are shown in Table 2.

In addition to the parameters in Table 2, it should be noted that the PP fly ash was black in color, while the DP fly ash was gray in color. True Density is the density of a porous solid defined as the ratio of its

Table 1. Summary of the Physical and Chemical Parameters Investigated

Parameter	Method	Remarks
Particle Size	D2862-97	Standard Test Method for Particle Size Distribution of Granular Activated Carbon
Moisture Content	ASTM D- 4643-00	Weigh in oven at 105^{o}C after drying
Bulk Density	ASTM D 6683-01	
True Density	ASTM D1817-05	Standard Test Method for Rubber Chemicals—Density
Porosity	ASTM D 4222-98	Standard Test Method for Determination of Nitrogen Adsorption and Desorption Isotherms of Catalysts By Static Volumetric Measurements
S, C, O, N		Elemental Analyzer
Residue Ash	ASTM D1506-99	Standard Test Methods for Carbon Black-Ash Content
	ASTM D2866-94	Standard Test Method for Total Ash Content of Activated Carbon
pH	ASTM D1512-05	Standard Test Methods for Carbon Black-pH Value
	ASTM D3838-05	Standard Test Method for pH of Activated Carbon
Heavy Metals	ASTM D 3682-91	Using AAS
	ASTM D 3683-94	Using AAS
	EPA 6020-B	Using ICAP / ICPMS
Metal Oxides		Using X-Ray Diffraction

Table 2. Physical Parameters of Flyash Samples

Constituent	PP Flyash			DP Flyash		
	Max	Min	Average	Max	Min	Average
Bulk Density (by gas), (g/cm^3)	0.36	0.31	0.34	0.55	0.42	0.48
Bulk Density (by water), (g/cm^3)	1.93	1.51	1.67	2.19	1.84	2.03
True Density (by water), (g/ cm^3)	2.23	1.84	1.98	2.45	2.09	2.30
Specific Gravity (٢), Ww/Ws	0.37	0.31	0.34	0.55	0.42	0.49
Grain Size (μm)	68.76	57.74	63.09	79.87	58.24	66.87
Porosity (by helium gas), (%)	85.45	79.68	82.85	78.61	69.13	75.81
Porosity (by water), (%)	24.31	20.05	22.03	20.38	17.87	18.93

mass to its true volume. Bulk Density, on the other hand, is the mass of dry soil per unit bulk volume (solids plus pores) expressed in gram per cubic centimeter. Bulk density is used mostly in trade and transportation but both characteristics indicate differences in fly ash composition. The bulk density data in the table shows higher density of DP fly ash than that of the PP fly ash. Although grain sizes are slightly higher in fly ash collected from desalination plant, which means they do not compact as well as in fly ash collected from the power plant, but metal oxide ashes are several folds heavier than carbon which is prevalent in the PP fly ash samples. Grain size data show that fly ash collected from desalination plant is slightly larger than that of power plant fly ash. This is to be expected because PP fly ash is mostly carbon while DP fly ash has a larger percentage of metal oxide ashes. Moisture and ash contents were measured in fly ash samples and Table 3 shows the results. The data were obtained by following a standards method that is mentioned in Table 1.

The loss of ignition data indicated that carbon makes most (95.2 percent) of the PP fly ash while it makes 56.7 percent of DP fly ash. So, ash content of power plant fly ash is only 4.8 percent by weight while

Table 3. Moisture and Ash Contents in Flyash Samples

Constituent	PP Flyash			DP Flyash		
	Test 1	Test 2	Average	Test 1	Test 2	Average
Moisture Content (%)	0.9	0.9	0.9	3.2	3.0	3.1
Loss on Ignition (%)	94.4	96.0	95.2	54.6	58.8	56.7
Ash Content (%)	5.6	4.0	4.8	45.4	41.2	43.3

ash content of desalination plant fly ash was 43.3 percent. Moisture content in DP fly ash was 3.1 percent while in PP fly ash it was 0.9 percent. This was also to be expected since DP fly ash contains more ash and ash is known to be a better absorbent of moisture than carbon.

Individual metal concentrations were determined for fly ash samples using method EPA 3050-B and ICAP analysis. Hydride generation system was used with ICAP to determine arsenic and selenium. Data of metal concentrations is presented in Table 4.Metal concentrations are higher in DP fly ash than in PP fly ash, which explains the reason for having higher ash content in the water plant fly ash. The table clearly shows the high concentrations of nickel and vanadium in the collected fly ash samples, which is attributed to the fuel oil and additives being used in the two selected plants. Vanadium concentrations were 9072 and 31044 mg/kg in PP and DP fly ash samples, respectively. On the other hand, nickel concentrations were 2382 and 13633 mg/kg in PP and DP fly ash samples, respectively.

Table 4. Metal Concentrations in Flyash Samples

Constituent	PP Flyash			DP Flyash		
	Average (mg/kg)	Min (mg/kg)	Max (mg/kg)	Average (mg/kg)	Min (mg/kg)	Max (mg/kg)
Silver	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Aluminum	354.1	275.1	406.2	1041.8	539.4	1555.4
Arsenic	2.54	2.34	2.90	18.46	4.93	37.69
Barium	7.42	1.05	14.65	49.68	5.96	123.52
Calcium	582.3	403.7	736.7	4121.2	3475.9	4671.1
Cadmium	1.65	0.30	3.58	3.70	1.79	5.81
Cobalt	2.88	0.00	6.95	12.33	0.79	34.38
Chromium	36.79	11.52	63.88	113.09	64.47	168.83
Copper	10.44	3.29	17.58	50.40	20.07	81.66
Iron	7210	277	20225	8771	3527	17909
Magnesium	6971	2584	12622	94608	42159	175353
Manganese	23.90	6.98	48.84	149.26	81.39	295.10
Sodium	1395	1151	1689	7555	4669	12932
Nickel	2382	741	4334	13633	6760	22730
Lead	17.09	2.79	46.70	13.94	3.28	28.07
Selenium	< 1.0	< 1.0	< 1.0	6.81	< 1.0	9.16
Vanadium	9072	3103	15619	31044	22954	40879
Zinc	21.92	13.19	34.19	118.0	28.3	202.4

Calcium, magnesium nand sodium are not toxic and their environmental impact is minimal. Concentrations of Ca, Na, and Mg clearly indicate the respective ash content in fly ash samples. The ratio of ash percentage in the DP fly ash is several times higher than that in the PP fly ash. The same trend is obviously shown for concentrations of major elements in both fly ash samples.

The sum of the concentrations of these three major elements in fly ash does not add up to the percentage of ash contents, which can be attributed to several reasons. One reason is that some other metals contribute to the ash contents in large proportions. Among these are nickel and vanadium. Table 5 lists ash contents for DP fly ash and PP fly ash samples and the respective concentrations of major elements plus nickel and vanadium.Another reason why metal concentration does not add up to ash content is that ash is not made of pure metals but made of their oxides. Tables 6 and 7 list the metal oxide concentrations in fly ash samples. A third reason is the presence of non-metal constituents in the ash such as silica and silicate compounds.

The table shows that ash contents are higher in DP fly ash than PP fly ash and the same is true for metal concentrations in the fly ash samples. The results can be attributed to the same reasons given before.

Metals are present in fly ash in the form of metal oxides. Table 6 presents metal oxide concentrations in PP and DP fly ash samples. It is obvious that the results presented in the table are having similar trends as those presented in Table 4.

Beside metals and their compounds, fly ash samples contain high percentages of other metals. Fly ash samples have been analyzed for carbon, sulfur, nitrogen and hydrogen. Table 7 shows the results of elemental contents in the collected fly ash samples.

As indicated before, it should be noted that PP fly ash was black in color, which indicates the high level of carbon content. On the other hand, DP fly ash was grey in color, which indicates that the ash content is high. Moreover, Table 7 and the previous tables clearly demonstrate that fly ash samples produced at the two plants are different in their physical and chemical characteristics. This could be attributed to different fuels being used at the two plants. Another reason for the differences could be attributed to the use of chemical additives for the purpose of improving the combustion process and corrosion control. The selected power plant (PP) fires residual fuel oil (RFO) which has the specifications shown in Table 8. On the other hand, the selected desalination plant (DP) fires two types of fuels, namely, light Arabian crude (LAC) fuel oil and heavy Arabia crude (HAC) fuel oil, which have the characteristics shown in Tales 10. The data in Table 8 was obtained from Saudi Aramco through personal communication.The table clearly demonstrates that ash content in the three types of fuel oil varies. As an example, the Light Arabian Crude (LAC) contains the lowest ash content while the Heavy Arabian Crude (HAC) contains the highest.With respect vanadium, lead and nickel contents in the fuel oils, only data related to HAC was provided. There is no data provided with respect to the heavy metal content in the other two fuel oils. Sodium content in LAC is higher than that in the HAC, while no data was provided with respect to RFO. Data related to calcium content was provided for HAC only. Data provided in Table 8 shows the difficulty of making a proper comparison between the three fuel oils in terms of their contents.

While there is an abundance of literature about coal fly ash, very limited resources reporting fuel oil fly ash characteristics have been published in the literature. Saisuwan 1998 described the particle size distribution of fuel oil fly ash from Bang Pakong thermal power plant in Thailand. He reported that the particle size varies from less than 75μm to more than 250 μm, however, 65 percent of the particles have a size that is between 150 and 250 μm.

Compared to the fly ash under investigation, the PP fly ash samples seem more homogeneous since particle sizes ranges between 57.7 and 68.7 μm. Moreover, DP fly ash showed a similarly narrow range of distribution, where particle sizes range between 69.1 and 79.9 μm. This may be due to the different types of fuel oil being used at the selected power and desalination plants. Chemical composition and other chemical properties of the Thailand fly ash are listed in Table 9, which indicates that they exhibit the same trend of high carbon content. The Table shows that carbon makes 80.61 percent of fly ash weight in Bang Pakong thermal power plant in Thailand. In comparison, PP fly ash has an average of 92.0 percent carbon, while DP fly ash has an average 27.64 percent carbon.The difference in carbon content in fly ash samples could be attributed to the same justifications given before.

Reddy et al. 2005 provided comparison between chemical characteristics of coal fly ash and heavy oil fly ash, as shown in Table 10. It is worth to mention that the listed values are based on average of three samples. It can be noted from the table that moisture and ash contents are higher in the coal fly ash than that in the fuel oil fly ash. It has been already observed in the case of DP and PP fly ash samples that higher ash content means also higher moisture content since

Table 5. Summary of Ash Contents and Major Element Contents in Flyash Samples

Constituent	Ash Content %	Calcium (mg/kg)	Magnesium (mg/kg)	Sodium (mg/kg)	Nickel (mg/kg)	Vanadium (mg/kg)
PP flyash	4.8 %	582.3	6971	1395	2382	9072
DP flyash	43.3 %	4121.2	94608	7555	13633	31044

Table 6. Metal Oxide Concentrations in PP Flyash Samples

Constituent	PP Flyash Samples			DP Flyash Samples		
	Average	Min	Max	Average	Min	Max
	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
(Ag_2O)	< 0.107	< 0.107	< 0.107	< 0.107	< 0.107	< 0.107
(Al_2O_3)	669.8	519.8	767.5	1968	1019	2939
(As_2O_5)	3.90	3.59	4.45	28.32	7.56	57.81
(BaO)	8.28	1.172	16.36	55.47	6.65	137.9
(CaO)	739.2	564.9	1030	5766	4863	6536
(CdO)	1.885	0.343	4.09	4.227	2.045	6.637
(CoO)	3.662	< 0.076	8.84	15.68	1.004	43.71
(Cr_2O_3)	53.77	16.84	93.36	165.29	94.23	246.8
(CuO)	13.07	4.118	22.01	63.01	25.12	102.2
(Fe_2O_3)	10308	396.0	28916	12540	5042	25605
(MgO)	11559	4285	20929	156875	69907	290764
(MnO)	37.82	11.05	77.29	236.2	128.8	467.0
(Na_2O)	1880	1551	2276	10182	6293	17430
(NiO)	3031	943.0	5516	17350	8603	28927
(PbO)	19.73	3.221	53.91	16.09	3.787	32.41
(SeO_2)	< 1.41	< 1.41	< 1.41	9.570	< 1.41	12.87
(V_2O_5)	16196	5379	27884	55421	40978	72979
(ZnO)	27.28	16.42	42.56	146.9	35.23	251.9

Table 7. Elemental Analysis of PP and DP Flyash Samples

Constituent	PP Flyash			DP Flyash		
	Average	Min	Max	Average	Min	Max
	(%)	(%)	(%)	(%)	(%)	(%)
Carbon	90.56	89.10	92.01	25.77	23.89	27.64
Sulfur	7.774	7.708	7.839	17.18	16.54	17.82
Nitrogen	0.0	0.0	0.0	0.189	0.163	0.215
Hydrogen	0.074	0.059	0.089	0.082	0.080	0.080
Total	98.41	97.03	99.78	43.21	41.95	44.47

Table 8. Design Specifications of RFO, LAC and HAC (Saudi Aramco)

Property	Units	RFO	LAC		HAC	
		Average	Min	Max	Min	Max
Carbon, C	% by weight	83.9	82	86	82	86
Sulfur, S	% by weight	3.7	1.75	2	2.9	3.1
Hydrogen, H_2	% by weight	11.0	11	15	10	14
Nitrogen, N_2	% by weight	0.7	0.2	0.6	0	1
Oxygen, O_2	% by weight	0.7	0	1	0	1
Ash	% by weight	0.1	0	0.01	0	1
Carbon Residue	% by weight	11.0	3.5	5	5	10
Sediment and Water	% by volume	0.5	**ND**	**ND**	0	0.1
Water, H_2O	% by volume	0.5	**ND**	**ND**	**ND**	**ND**
Gross Heating Value	kJ per kg	43,031	**ND**	**ND**	43380	44357
Kinematics Viscosity, 40° C	cSt	1.83	**ND**	**ND**	16.9	21.9
Specific Gravity, 15° C	-	0.9792	**ND**	**ND**	0.87	0.92
Pour Point	° C	0	**ND**	**ND**	-29	-15
Flash Point	° C	66	**ND**	**ND**	**ND**	**ND**
Fire Point	° C	93	**ND**	**ND**	**ND**	**ND**
Asphaltines	% by weight	**NA**	7	12	**ND**	**ND**
H2S	ppm	**NA**	10	70	**ND**	**ND**
NaCl	ptb	**ND**	0	10	0	1
Total Ash	ppm	**ND**	50	81	39	180
Na	ppm	**ND**	0	10	2	5
K	ppm	**ND**	**ND**	**ND**	0	1
V	ppm	**ND**	**ND**	**ND**	32	117
Ca	ppm	**ND**	**ND**	**ND**	0	10
Pb	ppm	**ND**	**ND**	**ND**	0	10
Ni	ppm	**ND**	**ND**	**ND**	0	10
Wax	% by volume	**ND**	**ND**	**ND**	1.6	2.7

RFO = Residual Fuel Oil; LAC = Light Arabian Crude; HAC = Heavy Arabian Crude; ND = No Data

ash is better absorbent of moisture than carbon particles.

A comparison of heavy oil fly ash generated from a power plant in Korea with the characteristics of carbon black revealed that the particle sizes of heavy oil fly ash (as confirmed by SEM micrographs) range from 10 to 120 µm, with an average of 45 µm. This is larger than that of carbon black where the average particle size is around 6 µm (Kwon et al.2005).

Chemical characterization of the same heavy oil fly ash shows that it consists of inorganic substances such as SiO_2, Fe_2O_3, and Al_2O_3 with 70-80 percent of unburned carbon. The heavy oil fly ash also contains heavy metals (e.g. vanadium and nickel) which existed in the crude petroleum at the outset and they were found to increase during the process of incineration. Table 11 compares between physical and chemical characteristics of both heavy oil fly ash and carbon black.

Table 9. Chemical Properties of Fuel Oil Ash Produced at Bang Pakong Thermal Power Plant

Constituents	% (By Weight)
Carbon	80.61
Hydrogen	0.62
Nitrogen	0.97
Magnesium	0.02
Vanadium (as V)	0.44
Sulfur (as S)	3.5-5.16
Non-soluble in acid	84.79
pH 1 % solution	2.30
Ash	2.87-4.5
Residual moisture	7-9
Volatile matter	11.01

Table 10. Characteristics Comparison Between Coal Fly Ash and Heavy Oil Flay Ash [4]

Constituents	Coal Fly Ash	Heavy Oil Fly Ash
Moisture content (%)	8.0	0.05
Ash (wt %)	34.5	0.031
Carbon (wt %)	40.2	87.8
Hydrogen (wt %)	3.44	2.5
Nitrogen (wt %)	0.85	0.41
Sulfur (wt %)	0.72	0.37
Oxygen (wt %)	10.4	7.38
Arsenic (mg kg^{-1})	172.3	25.8
Cadmium (mg kg^{-1})	1.57	0.84
Cobalt (mg kg^{-1})	0.31	2
Chromium (mg kg^{-1})	13.4	7
Copper (mg kg^{-1})	328.4	148.3
Iron (mg kg^{-1})	54326	4300
Mercury , total (mg kg^{-1})	0.29	0.42
Manganese (mg kg^{-1})	4.5	124.5
Nickel (mg kg^{-1})	73.9	94.2
Lead (mg kg^{-1})	266.1	342.2
Selenium (mg kg^{-1})	32.4	3.8
Zinc (mg kg^{-1})	465	72.5

Table 11. Chemical and physical Characteristics of Heavy Oil Flyash and Carbon Black [19]

Constituents	Heavy Oil Flyash	Carbon Black
Carbon (wt %)	76.13	97.87
Sulfur (wt %)	3.26	0.79
Oxygen (wt %)	1.92	1.25
Nitrogen (wt %)	1.24	0.92
Residue ash (wt %)	19.85	0.8
Moisture content (wt %)	11.54	14.77
Bulk density (g cm^{-3})	0.52	1.28
True density (g cm^{-3})	2.15	1.98
Porosity (%)	10.31	18.52
Average particle size (µm)	45	6

Table 12. Physical Characteristics of Oil Fuel Flyash Produced from the Current Study and Other Different Power Plants [4, 16 and 19]

Constituent	PP Flyash	DP Flyash	[16]	[4]	[17]
	Average	Average	Average	Average	Average
Bulk Density (by gas), (g/cm^3)	0.34	0.48	0.52	**ND**	**ND**
Bulk Density (by water), (g/cm^3)	1.67	2.03	**ND**	**ND**	**ND**
True Density (by water), (g/ cm^3)	1.98	2.30	2.15	**ND**	**ND**
Specific Gravity (٣), Ww/Ws	0.34	0.49	**ND**	**ND**	**ND**
Grain Size (µm)	63.09	66.87	45	**ND**	**ND**
Porosity (by helium gas), (%)	82.85	75.81	10.31	**ND**	**ND**
Porosity (by water), (%)	22.03	18.93	**ND**	**ND**	**ND**
Moisture Content (%)	0.9	3.1	**ND**	**ND**	**ND**
Loss on Ignition (%)	95.2	56.7	**ND**	**ND**	**ND**
Ash Content (%)	4.8	43.3	**ND**	2.87 – 4.5	0.031

ND = NO DATA

As indicated in the table, heavy oil fly ash is mainly composed of carbon, sulfur and residue ash, whereas carbon is the dominant element of carbon black. Comparing with carbon black sample, heavy oil fly ash contains lower carbon content and higher amount of sulfur and residual ash. Compiling all available data, Table 12 shows physical characteristics of oil fuel ash obtained from the current study and studies published in the literature, while Table 13 compares the chemical characteristics. Proper comparison between the results obtained from the current investigation and those published in the literature cannot be achieved due to the lack of enough information in the published literature.

Fly ash samples collected from the selected power and desalination plants contained considerably higher sulfur concentrations. Power plant fly ash contains an average of 7.8 percent sulfur, while desalination plant fly ash contains an average of 17.2 percent.

Table 13. Chemical Characteristics of Oil Fuel Fly Ash Produced from the Current Study and Other Different Power Plants [4, 18 and 19]

Constituent	PP Flyash	DP Flyash	[16]	[4]	[17]
	Average	Average	Average	Average	Average
Silver (mg/kg)	< 0.10	< 0.10	ND	ND	ND
Aluminum (mg/kg)	354.1	1041.8	ND	ND	ND
Arsenic (mg/kg)	2.54	18.46	ND	ND	25.8
Barium (mg/kg)	7.42	49.68	ND	ND	ND
Calcium (mg/kg)	582.3	4121.2	ND	ND	ND
Cadmium (mg/kg)	1.65	3.70	ND	ND	0.84
Cobalt (mg/kg)	2.88	12.33	ND	ND	2
Chromium (mg/kg)	36.79	113.09	ND	ND	7
Copper (mg/kg)	10.44	50.40	ND	ND	148.3
Iron (mg/kg)	7210	8771	ND	ND	4300
Magnesium (mg/kg)	6971	94608	ND	0.02	ND
Manganese (mg/kg)	23.90	149.26	ND	ND	142.5
Sodium (mg/kg)	1395	7555	ND	ND	ND
Nickel (mg/kg)	2382	13633	ND	ND	94.2
Lead (mg/kg)	17.09	13.94	ND	ND	342.2
Selenium (mg/kg)	< 1.0	6.81	ND	ND	3.8
Vanadium (mg/kg)	9072	31044	ND	0.44 %	ND
Zinc (mg/kg)	21.92	118.0	ND	ND	72.5
Nitrogen (%)	0.0	0.189	1.24	0.97	0.41
Carbon (%)	90.56	25.77	76.13	80.61	87.8
Hydrogen (%)	0.074	0.0823	ND	0.62	2.5
Sulfur (%)	7.774	17.18	3.26	3.5 – 5.16	0.37
Oxygen (%)	ND	ND	1.92	ND	7.38

ND = NO DATA

CONCLUSION

Grain size data showed that DP fly ash is slightly larger than that of PP fly ash. This was expected because PP fly ash is mostly carbon while DP has a larger percent of metal oxide ashes. Metal concentrations are higher in DP fly ash than in PP fly ash due to the higher ash contents in DP fly ash which consists mostly of metal compounds. Moreover, fly ash samples produced at the two plants are different in their physical characteristics and chemical contents. This could be attributed to different fuels and additives being used at the two plants. Chemical characterization of the same heavy oil fly ash shows that it consists of inorganic substances such as SiO_2, Fe_2O_3, and Al_2O_3 with 70-80 percent of unburned carbon. The heavy oil fly ash also contains heavy metals (e.g. vanadium and nickel). The elemental analysis of the fly ash samples indicated that heavy oil fly ash is mainly composed of carbon, sulfur and residue ash. The results of the current study provide very important information with respect to the characteristics of fuel oil fly ash. Based on the provided information, more investigation needs to be carried out to look into the issues of utilization of the fuel oil fly ash.

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