

# Fate of Metals in Coal Fly Ash Ponds

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**Abstract**—The coal fly ashes contain toxic metals much higher concentrations than soil background levels that can be released into the environment through coal combustion processes. Disposal of coal fly ash in open and unlined ash ponds causes serious adverse environmental impacts to its elevated metals concentration and leaching into soils and groundwater. In the present research work, the water columns above the settled ash were sampled and cores of ash were collected over the course of 11 months from one class C and two class F ashes containing laboratory scale ash ponds. Samples were analysed for pH and metals. The arsenic, chromium were found to increase with aging of ash ponds containing class F ash while the concentration of all metals deceased in ash pond with class C ash. However, the free water column metals concentration was above 150 pbb, way above drinking water standard.

**Index terms**—Ash pond, fly ash, metals, leaching, thermal power plant.

## I. INTRODUCTION

A thermal power plant generates large amounts of fly ashes which contain toxic metals and environmental risks associated with these coal fly during wet storage in the ash ponds [1]. The disposal of coal fly ash subjects these metal rich materials to conditions that may result in further sequestration of the metals or to their release to the environment [2]. The release and transport of trace metals from coal fly ash material is an area of environment concern because of the wet storage in the ash ponds. The volatilization, melting, decomposition and the formation of new materials and oxidation are the main mechanisms to transfers the metals from coal to fly ash [3]. The major potential impacts of fly ash disposal either in ash pond or reused in the cement industry leads to leaching of potentially toxic substances into soils, surface water and groundwater. Environmental concerns regarding the potential contamination of soil, surface and ground water due to the presence of soluble metal species in the ash pond leachate is of great concern [4]. The soluble salt content in ashes is closely related to the coal properties and the age of the fly ash and also to the pH and other environmental conditions [5]. When fly ash interacts with water the principal process

affecting the leaching process are dissolution of primary solids and precipitation of secondary solids as well as redox conditions, sorption and hydrolysis reactions [6]. Leaching tests are used as tools to estimate the release potential of constituents from fly ash over a range of possible waste management activities, including during recycling or reuse, for assessing the efficacy of waste treatment processes, and after disposal [7]. The wet disposal of the fly ash into the ash ponds caused leaching of constituents from fly ash due to weathering. Some metals concentration is increased due to leaching of constituents from fly ash particles [8]. The continuous long term leaching experiments were carried out with the 3.4 kg of fly ash was suspended in 17 L of deionised water to simulate the ash ponding environment [9]. An 18 month survey was done to assess the environmental impacts of the Tennessee Valley Authority (TVA) coal ash spill in Kingston, Tennessee in 2008 to demonstrated the leaching experiments on the spilled TVA coal ash which revealed that leachable coal ash contaminants, particularly arsenic, selenium, boron, strontium and barium had different effects on the quality of impacted environments and the EPA has proposed regulations to manage coal ash disposal [10-12].

Ash pond releases are an environmental concern due to the potential leaching of toxic metals and metalloids from the ash to the water and the subsequent discharge of waters from the ponds. Numerous studies have examined the leaching potential of Se and As from fly ash due to their solubility and toxicity [13-15]. Metal mobility is controlled by the dissolution of primary solids and precipitation/sorption reactions. Class C fly ash has high calcium content and therefore alkaline conditions, which for adsorption reactions favor arsenic and selenium release from the fly ash [15-17]. Chemical characterization of solid waste can be determined using sequential extraction procedures. Such experiments have shown that arsenic and selenium leaching from alkaline fly ash was controlled by a calcium phase [16-18].

More than 65000 acre of land in India is occupied for storage of fly ash in ash storage ponds which is leading to the wide spread contamination of soil as well as surface and groundwater [19]. The purpose of characterization of the ash basins waters of the thermal power plants can help identify constituents of concern from an environmental perspective [20]. Purpose of the laboratory scale simulated ash ponds is to examine the long term aging/ weathering of fly ashes in poorly mixed, high solid to liquid ratio mixture to accurately model true ash ponds used in thermal power plants.

The objective of the research work was to assess the leaching potential coal fly ash in rain water environment and to study the mobility of metals within the settled ash layers from the ash ponds that store coal fly ash and the changes in the mineralogy of the fly ash during wet storage aging under static conditions.

Manuscript received January 23, 2012; revised February 4, 2012. This work was supported in part by the McDonnell Academy of Clean Coal Utilization, Washington University, Saint Louis, USA and Indian Institute of Technology Bombay, India.

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## II. MATERIAL AND METHODS

### A. Materials

Three coal fly ash materials, named as FA-1, FA-2 and FA-3, were collected from dust hoppers of electrostatic precipitators of three full-scale Indian power plants in and around Maharashtra, India. The power plants are using bituminous and sub-bituminous coals from India and from imported Indonesia. The ash content of FA-2 is about 1.9% while that of FA-1 and FA-3 were 25% and 38% respectively. Coal fly ashes are classified based on their calcium oxide contents. Coal fly ash FA-2 is class C ash being calcium-rich with greater than 10% calcium oxide while FA-1 and FA-2 are silica-rich class F ash having less than 10% calcium oxide.

Ultra pure water produced by Seimens Water Kit (TWF EDI UV TM, Singapore) was used for washing of glassware and preparation of reagents. Ammonium nitrate, acetic acid, sodium dithionite, sodium citrate, sodium bicarbonate, concentrated nitric and hydrochloric acids were used to prepare extractants for the sequential extraction experiments. The acetic acid, nitric and hydrochloric acids were trace metal grades. All chemicals were purchased from Merck chemical (Mumbai, India). The 25 element aqueous custom standard in 5% HNO<sub>3</sub> (ZOASIS 1004) from VHG Labs, Manchester, USA was used for calibration of ICP-AES. An aliquot of the standard was also used as control for the extraction tests.

### B. Methods

Experimental ash ponds were designed to explore metal leaching from fly ash in poorly mixed environments. The ash ponds of 20 L capacities were prepared in perplex sheets. The ashes were mixed with rain water of pH 5.9 at a 1:1 ratio by mass and then added to the ponds to an ash depth of 20 cm. The total depth of the free water column above the ash pond was maintained at 10 cm. The actual setup of the ash ponds are shown in the Fig. 1.

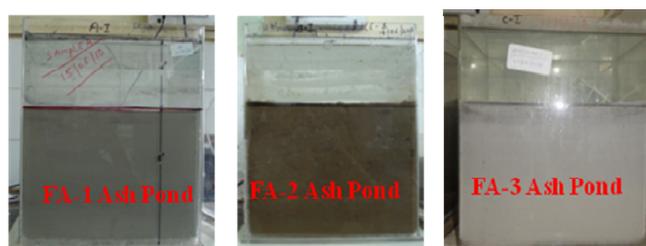


Fig. 1. Laboratory scale coal fly ash ponds.

50 mL free water samples were drawn from the each ash pond at a depth of 2.5 cm above the surface of the settled ash layer every month and were analysed pH. 10 mL samples were filtered with 0.2 µm PTFE filter and acidified by 2% by mass with concentrated HNO<sub>3</sub> and were analyzed for major and minor metals. Solid core fly ash samples were taken every month by cutting a sample core of 0.6 cm diameter core cutter. Samples were weighed and dried in oven over 24 hours at 105°C to get the water content of the samples. The oven dried samples were used for sequential extraction procedure (SEP) and XRD. The sampling process is shown in the Fig. 2.

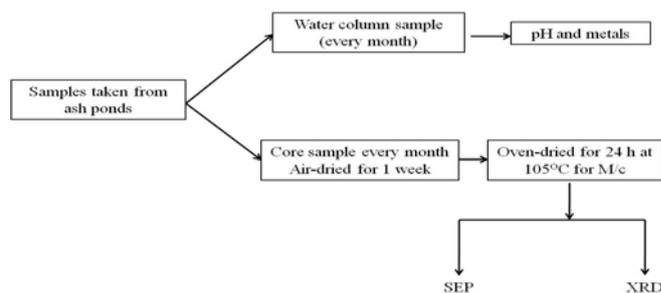


Fig. 2. Sampling process in coal fly ash ponds.

A five step SEP adopted is as follows: (1) ultrapure water was used to extract water soluble metals; (2) 1.0 M NH<sub>4</sub>NO<sub>3</sub> was used to remove ion exchangeable metals; (3) 0.11 M acetic acid targeted acid soluble metals; (4) a solution of 0.128 M sodium dithionite, 0.3 M sodium citrate, and 0.1 M NaHCO<sub>3</sub> (DCB) was used to remove reducible metals; and (5) finally a 4:1 mixture of concentrated HNO<sub>3</sub> and HCl in a microwave acid digestion to dissolved the remaining solids. Based on the optimization of the procedure in preliminary tests, a solid to liquid ratio of 0.5 g ash/50 mL (10 g/L) extractant was used. Agitation times of 24 h were used for the acid soluble and reducible steps, and 4 h was used for the other steps. The ash was mixed with the extractant for the prescribed time, and then the suspension was centrifuged for 10 minutes at 10000 rpm. Nearly all of the supernatant was decanted, filtered with a 0.2 µm PTFE filter and then acidified to 2% (by mass) nitric acid in preparation for ICP-AES analysis.

The elemental composition of the coal fly ash samples was obtained with the help of Philips X-Ray Fluorescence Spectrometer (XRF) (2404, Netherlands), which determined all major oxides present in the sample. 4 g of oven-dried, finely ground coal fly ash sample and 1 g of micro crystalline methyl cellulose were mixed uniformly with isopropyl alcohol and kept for slow drying under a 200 W infrared lamp. This dried sample was made as a pellet by filling in an aluminium dish and was compressed under a load of 1-2 ton for 1 minute with the help of a hydraulic jack. The compressed pallet was run in the XRF setup for computing the composition as oxides of elements as percentage by weight of the ash sample.

Mineralogical investigations of coal fly ashes were carried out by Rigaku Geigerflex powder X Ray Diffractions (XRD) (Japan), coupled with PW 1729 X-ray generator using CuKα radiation. All samples were run at a tube voltage 20 kV and 30 mA. The goniometer and chart speed were maintained at 0.05 mm/2θ and 10 mm/2θ, respectively. All samples were dried at 110°C before analysis.

### C. Quantification of Metals Concentration

Concentrations of trace metals in samples from free water column and those from SEP were obtained using Jobin Yvon Horib ICP-AES (ULTIMA 2000, France). Prior to analysis the samples were diluted with 2% nitric acid solution. Samples from the SEP were diluted 1:2 for the water soluble step, 1:10 for the acid soluble step, and 1:20 for the other three steps. Calibration standards were analyzed in the same matrices as the samples and the extraction for SEP was carried out in duplicate.

The operating conditions of ICP-AES are shown in Table I.

TABLE I: ICP-AES INSTRUMENTAL AND OPERATIONAL CONDITIONS

Parameters	Value/Type
RF generator power	1.0 kW
RF frequency	40 MHz
Plasma	12.0 L/minutes
Auxillary	0.75 L/minutes
Nebulizer type	V-type
Nebulizer make	Glass concentric
Nebulizer pressure	2.90 bars
Nebulizer flow rate	0.85 L/min
Spectrometer	Monochromator
Analyzer	PMT
Integration time	3 Seconds
Replicates	2

pH were regularly monitored for each sample using Thermo Scientific pH meter (Orion 3 star, Singapore).

#### D. Quality Control and Quality Assurance

The quality control (QC) samples were analysed as part of the ICP-AES analytical runs to check for instrument drift, accuracy and precision. Spiked blanks of the multi element custom standard (ZOASIS 1004) were used as control for ICP-AES during the experiments. Secondary standards were also used frequently to check the accuracy. SEP involved the extraction and analysis of blank samples and standard reference fly ash material (NIST 1633b). All analytical and sampling experiments were carried out in duplicates.

### III. RESULTS AND DISCUSSIONS

The results obtained by the experiments mentioned in previous section are discussed below.

#### A. Composition of Coal Fly Ashes

The ash samples were characterized with respect to the various physical properties and compositions of coal fly ashes are provided in Table II.

TABLE II: ICP-AES INSTRUMENTAL AND OPERATIONAL CONDITIONS

Parameters	FA-1	FA-2	FA-3
Mean particle size ( $\mu\text{m}$ )	17.03	3.25	2.14
Specific surface area ( $\text{m}^2/\text{g}$ )	0.65	1.2	0.97
pH	9.77	11.54	9.75
Major oxides (wt %)			
SiO <sub>2</sub>	61.00	35.32	62.00
CaO	2.18	18.81	1.03
Al <sub>2</sub> O <sub>3</sub>	23.67	27.82	26.3
Fe <sub>2</sub> O <sub>3</sub>	7.51	10.64	5.50
MgO	1.02	3.00	0.75
Na <sub>2</sub> O	0.17	1.03	0.10
P <sub>2</sub> O <sub>5</sub>	0.25	0.14	0.35
TiO <sub>2</sub>	1.66	0.72	1.61
K <sub>2</sub> O	0.65	0.63	0.41
BaO	0.08	0.12	0.06
SrO	0.12	0.12	0.13
MnO	0.04	0.08	0.05
SO <sub>3</sub>	0.25	0.47	0.11
LOI <sup>a</sup>	1.40	1.10	1.60
Total	100.00	100.00	100.00

<sup>a</sup>LOI is Loss on Ignition, which represents the unburnt carbon content in the fly ash sample

Particle size analysis of fly ashes was carried using

Beckman Coulter Particle Size Analyser (LS 13 320, Japan) which relies on the fact that particles passing through a laser beam will scatter light at an angle that is directly related to their size. Surface area of various fly ash samples was determined using the Brunauer-Emmet-Teller (BET) Specific Area Analyzer (Smart Instruments, India).

The pH of the fly ash samples was measured using Thermo Scientific pH Meter (Orion 3 Star, Singapore) within 10 min of the initial mixing of the fly ash solids with ultrapure water using a 1:20 solid/solution ratio in orbital shaker (Trishul Equipment, India) at 180 rpm. Total major elemental composition was determined with the help of X-ray Fluorescence Spectrometer for all the ashes.

#### B. Variation of pH

The variation of pH in various ash ponds for 11 months is shown in Fig. 3. The results show that pond water pH initially increased to 5.9 to 11.5 for FA-2 ash and 9.8 and 9.7 for FA-1 and FA-3 ashes respectively.

This increase in pH with to the aging was due to the dissolution of CaO and Al<sub>2</sub>O<sub>3</sub> in the solid phase. After that, the pH decreased slowly over the course of the experiment as the ash pond free water column took up CO<sub>2</sub> from the atmosphere and CaCO<sub>3</sub> precipitated.

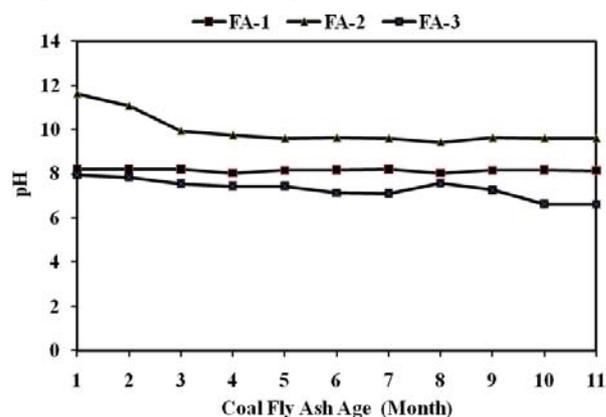


Fig. 3. Variation of pH with respect to aging of ash ponds.

#### C. Metals in Free Water Column

The concentrations of toxic metals contents in water columns of various ash ponds for 11 months have been analyzed so far. The changes in the toxic metals concentrations with respect to the aging time of coal fly ash are shown in the Fig. 4.

Arsenic, selenium, chromium, zinc, lead, and barium were the main toxic metals detectible in the free water columns of all three ash pond as shown in Fig. 4 (a), (b) and (c). The amount of arsenic and chromium metal concentrations increased with aging time for the silica rich coal fly ashes FA-1 and FA-3 coal whereas these decreased in concentration for the calcium rich coal fly ash FA-2. The selenium, zinc, lead and barium concentrations were seen to be decreasing in all the three coal fly ash ponds. The arsenic concentration also increased over time in the FA-2 ash pond, with a slow increase from an initial concentration of 120  $\mu\text{g}/\text{L}$  to a concentration of 193  $\mu\text{g}/\text{L}$  after 11 months. The FA-1 and FA-2 ash ponds had high initial selenium concentrations that decreased throughout the duration of the experiment, low initial chromium concentrations that

increased with the duration, and the arsenic concentrations increased over the 1-year duration of the experiments.

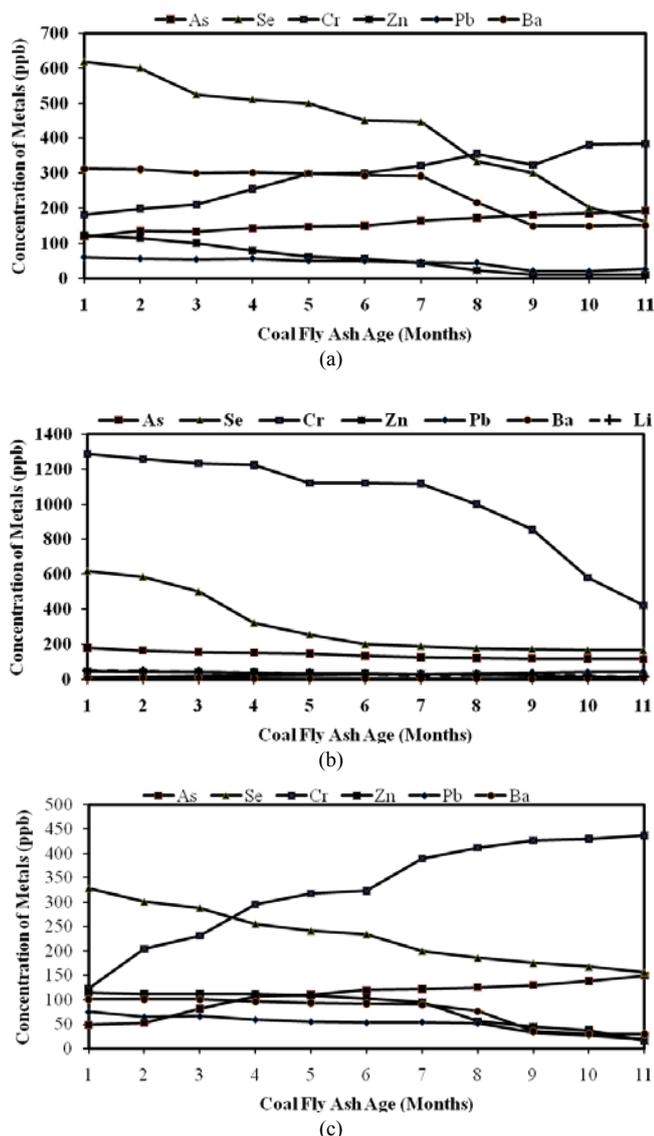


Fig. 4. Dissolved concentrations of metals in free water columns of ash ponds for (a) FA-1, (b) FA-2 and (c) FA-3 coal fly ashes.

#### D. Metals in Solid Phase

Most of the metals present in the solid phase were quantified using SEP and are shown in the Fig. 5.

The arsenic remaining in solid phase after first month aging of ash pond containing FA-1 fly ash was 19.26  $\mu\text{g/g}$  of ash which decreased in the 11 months to 15.21  $\mu\text{g/g}$ . FA-2 ash pond had 54.90  $\mu\text{g/g}$  of arsenic concentration in the first month but with the aging over the course time, it decreased to 43  $\mu\text{g/g}$ . The concentration of arsenic in the FA-3 ash pond was 11.17  $\mu\text{g/g}$  in the first month and the concentration after the 11 month became 10.90  $\mu\text{g/g}$  and is shown in the Fig. 5 (a).

The chromium concentration in the 5-step SEP in the solid phase ash pond core samples was the maximum concentration in the first month of the ash pond FA-1 was 49.56  $\mu\text{g/g}$  of ash and over the course of time the concentration was decreased to 31.99 because of the initial dissolution of the silica and aluminum oxides into the free water column. The similar trends were observed in the other

two ash ponds. The initial first month Cr concentration of ash pond FA-2 was 109.89  $\mu\text{g/g}$  of ash where as the 11 months concentration of Cr was 93.62  $\mu\text{g/g}$  of ash. Where as the FA-3 were 32.62  $\mu\text{g/g}$  of ash in the initial first month where as 25.74  $\mu\text{g/g}$  of ash. The selenium of concentration of the first month of FA-1 was 44.23  $\mu\text{g/g}$  of ash and is decreased to 39.74  $\mu\text{g/g}$  of ash where as in the FA-2 was 42.98  $\mu\text{g/g}$  of ash to 30.40  $\mu\text{g/g}$  of ash and FA-3 was 40.45  $\mu\text{g/g}$  of ash to 26.4  $\mu\text{g/g}$  of ash.

The zinc concentration was ranged between 78.9 to 66.5  $\mu\text{g/g}$  in FA-1, 206.89 to 165.65  $\mu\text{g/g}$  and 69.45 to 63.56  $\mu\text{g/g}$ .

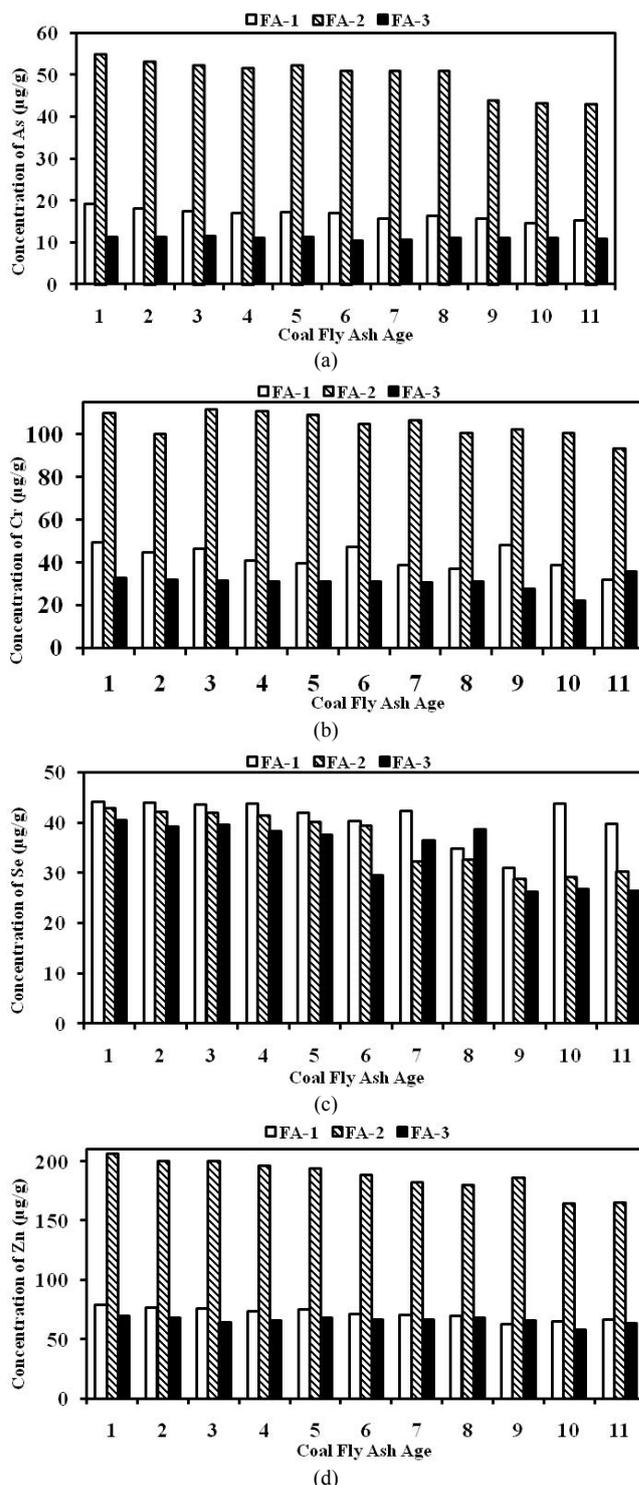


Fig. 5. Variation of (a) As, (b) Cr, (c) Se and (d) Zn in the solid phase of coal fly ash ponds.

### E. Mineralogical Transformations

The changes in the mineralogical transformations with aging of coal fly ashes were examined using X-ray diffraction shown in Fig. 6. Patterns were collected from  $5^\circ$  to  $45^\circ$  ( $2\theta$ ) with a step spacing of  $0.04^\circ$  and a dwell time of 4 s per point, and the low-angle background was subtracted.

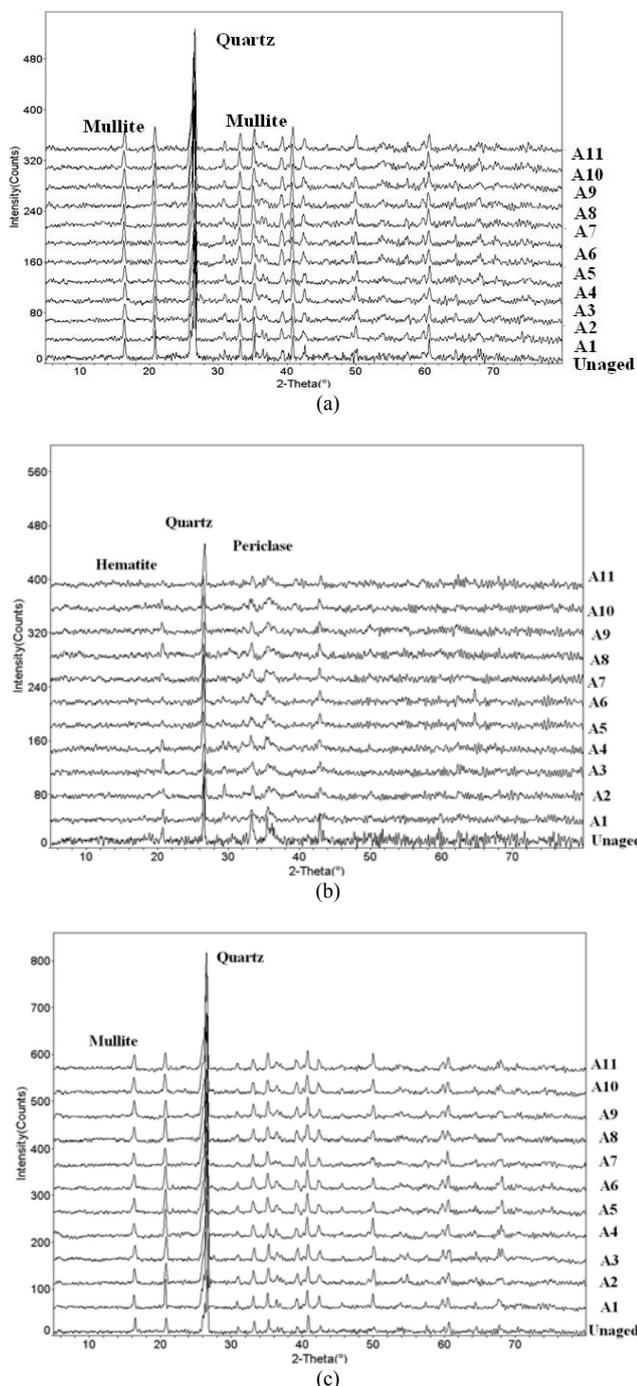


Fig. 6. Variation of XRD patterns over the course of 11 months ageing of (a) FA-1, (b) FA-2, (c) FA-3 coal fly ash ponds.

The unaged coal fly ashes were composed of quartz, mullite and iron oxides. The long term dissolution of the calcium aluminium silicate glass phase has taken place in all the class of ashes. In the case of silica-rich coal fly ashes, a minor changes has been taken place over the period of time since the breaking the alumino-silica bond took the longer time (Fig. 6 a and c). In case of calcium-rich coal fly ash,

there was immediate dissolution of anhydrite and the long term formation of the calcite in response to  $\text{CO}_2$  uptake. For this reason, there was a change in the pattern of XRD. Over the course of time, periclase and hematite disappeared as can be seen in Fig. 6(b).

### IV. CONCLUSIONS

The FA-1, FA-2 and FA-3 ash ponds had initially high pH and calcium concentrations that declined as the water column took up  $\text{CO}_2$  and discharge from silica-rich namely FA-1 and FA-3 coal fly ash ponds could contribute to leaching of arsenic and chromium to surface water and groundwater in addition to contaminating the nearby soils. Though concentrations of other metals leached from ash ponds reduced with time in Ca-rich ash namely FA-2, still it was above  $150 \mu\text{g/L}$  in most of the cases. The practice of disposal fly ash in unlined ash ponds could be considered as environmental unsafe. The concentrations of the trace elements exceeded drinking water standards, but higher levels may be acceptable for discharge permits. Sequential extraction procedure for core samples of ash ponds from the FA-1, FA-2 and FA-3 provided complementary information to the water column composition. Changes in the mineralogy of the ash indicate the formation of calcite with time as well as the production of a clay mineral and a zeolite, which may be related to the increased resistance of the ash arsenic and chromium to extraction in the ash ponds FA-1 and FA-3.

### ACKNOWLEDGMENT

The authors are grateful to the Centre for Environmental Science and Engineering, Indian Institute of Technology Bombay, India for providing the facilities for this project. The authors are thankful to management and staff of Thermal Power Plants in Maharashtra, India for providing the fly ash samples used in this research and scholars of Professor Dikshit Research Group for their help and cooperation to complete these experiments.

### REFERENCES

- [1] B. Lokeshappa, A. K. Dikshit, D. E. Giammar, Y. Luo, and J. G. Catalano, "Metals in Indian fly ash: a preliminary investigation," presented at the 3rd International Symposium on Global Energy Futures, Washington University, Saint Louis, USA, October 1-4, 2010.
- [2] B. Lokeshappa, and A. K. Dikshit, "Metals and their leachings in coal fly ash ponds," presented at the National Conference on Environmental Perspectives and Challenges for the 21st Century (EPC-2011), Andhra University, Visakhapatnam, June 28-29, 2011.
- [3] A. G. Kim, "Leaching methods applied to cub: standard, regulatory and other," in *Proc. 15th International Symposium on Management and Use of Coal combustion Products*, St. Petersburg, FL, 2003, pp. 1-12.
- [4] T. Praharaj, M. A. Powell, B. R. Hart, and S. Tripathy, "Leachability of elements from sub bituminous coal fly ash from India," *Environmental International*, vol. 27, pp. 609-615, 2002.
- [5] J. Jankowski, C. R. Ward, D. French, and S. Groves, "Mobility of trace elements from selected Australian fly ashes and its potential impacts on aquatic ecosystems," *Journal of Fuel*, vol. 85, pp. 243-256, 2006.
- [6] C. Brunori, S. Balzamo, and R. Morabito, "Comparison between different leaching tests for the evaluation of metal release from fly ash," *Fresenius Journal of Analytical Chemistry*, vol. 371, pp. 843-848, 2001.
- [7] D. S. Kosson, H. A. Vander Sloot, F. Sanchez, and A. C. Garrabrants, "An integrated frame work for evaluating leaching in waste management and utilization of secondary materials," *Environmental Engineering Science*, vol. 19 (3), pp. 159-204, 2002.
- [8] A. Ugurlu, "Leaching characteristics of fly ash," *Environmental Geology*, vol. 46, pp. 890-895, 2004.

- [9] W. R. Roy, R. A. Griffin, D. R. Dickerson, and R. M. Schuller, "Illinois basin coal fly ashes. 1. chemical characterization and solubility," *Journal of Environmental Science Technology*, vol. 18, pp. 734-745, 1984.
- [10] L. Ruhl, A. Vengosh, G. S. Dwyer, H. Hsu-Kim, and A. Deonarine, "Environmental impacts of the coal ash spill in Kingston, Tennessee: An 18-month survey," *Environmental Science & Technology*, vol. 44, pp. 9272-9278, 2010.
- [11] USEPA. (December 2010). Coal Combustion Residuals – Proposed Rule. Available: <http://www.epa.gov/wastes/nonhaz/industrial/special/fossil/ccr-rule/index.htm>.
- [12] USEPA. (December 2010). National Primary Drinking Water Regulations: Maximum Contaminant Levels. Available: <http://www.epa.gov/safewater/contaminants/index.html>.
- [13] F. E. Huggins, C. L. Senior, P. Chu, K. Ladwig, and G. P. Huffman, "Selenium and arsenic speciation in fly ash from full-scale coal-burning utility plants," *Environmental Science and Technology*, vol. 41(9), pp. 3284-3289, 2007.
- [14] A. P. Khodadoust, P. Naithani, T. L. Theis, and I. P. Murarka, "Leaching characteristics of arsenic from aged alkaline coal fly ash using column and sequential batch leaching," *Industrial & Engineering Chemistry Research*, vol. 50(4), pp. 2204-2213, 2011.
- [15] T. Wang, J. Wang, Y. Tang, H. Shi and K. Ladwig, "Leaching characteristics of arsenic and selenium from coal fly ash: role of calcium," *Energy & Fuels*, vol. 23(6), pp. 2959-66, 2009.
- [16] C. L. Rowe, W. A. Hopkins, and J. D. Congdon, "Ecotoxicological implications of aquatic disposal of coal combustion residues in the United States: A review," *Environmental Monitoring and Assessment*, vol. 80(3), pp. 207-276, 2002.
- [17] S. R. Al-Abed, G. Jegadeesan, J. Purandare, D. Allen, "Arsenic release from iron rich mineral processing waste: influence of pH and redox potential," *Chemosphere*, vol. 66(4), pp. 775-782, 2007.
- [18] A. G. Kim, "The effect of alkalinity of class F PC fly ash on metal release," *Fuel*, vol. 85(10-11), pp. 1403-1410, 2006.
- [19] V. C. Pandey, J. S. Singh, R. P. Singh, N. Singh, and M. Yunus, "Arsenic hazards in coal fly ash and its fate in Indian scenario," *Resources, Conservation and Recycling*, vol. 55, pp. 819-835, 2011.
- [20] L. Dorman, J. H. Rogers, and J. W. Castle, "Characterization of ash basin waters from a risk based perspective," *Water Air Pollution*, vol. 206, pp. 175-185, 2010.



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