

## **Pollution potential of beneficial uses of bottom coal ash** **(e.g. roadbases, structural fills, and agriculture)**

Dr. Yaacov Nathan and Yoetz Deutsch  
Geological Survey of Israel  
2004

### **Abstract**

Bottom ash is one of the two main Coal Combustion Byproducts (~ 10 % of CCB's). It represents the coarser part of the inorganic residues, which falls to the bottom of the combustion chamber. Characterization tests (leaching) carried out on bottom ash produced by Israeli power plants showed that it belongs to the "inert waste" class as defined by the Council Working Party of Environment of the European Communities decision [1]. Furthermore, it causes no other environmental problems; it has negligible radioactivity, and practically, causes no atmospheric pollution.

### **Introduction**

Fly ash (~ 80-85 %) and Bottom ash (~ 10 % of CCB's) are the two main Coal Combustion Byproducts (CCB's). Both are mainly the inorganic residues after the burning of coal. Fly ash represents the finer (lighter) fraction, which is carried from the combustion boiler by the flue gases and is separated by the electrostatic precipitators. Bottom ash is the coarser (heavier) fraction, which falls to the bottom of the combustion chamber. Technically, coal ash may be defined as a waste, still it is also correct to view it as a by-product of the energy produced by coal-fired power plants.

Obviously it is better to use coal ash than to dispose of it as waste. Nevertheless, its use must be done in such a way that it does not pollute the environment. Three main environmental problems may arise when coal ash is used: I) radioactivity; II) leaching out of toxic elements which will eventually pollute the groundwater. This is an acute problem in Israel where groundwater is the main water supply; III) polluting the atmosphere through dust emission when coal ash is used without any cover or stored in open (uncovered) piles.

The United States EPA preliminarily concluded in March 1999 that fossil fuel combustion wastes (FFCW), not covered under Subtitle C of the Resource Conservation and Recovery Act (RCRA), do not warrant federal hazardous waste regulation. Environmental groups attacked this preliminary conclusion, citing public health concerns, hazardous environmental effects, and poor state regulation enforcement. A final decision was delayed several times, and at the beginning of

2000, USEPA appeared ready to push for a hazardous designation. However, in May 2000, USEPA determined that “regulation of fossil fuel combustion waste (FFCW) under subtitle C is not warranted” [2]. However, the Agency (USEPA) has determined that national non-hazardous wastes regulations under RCRA Subtitle D are needed for coal combustion wastes disposed in surface impoundments and landfills and used as minefilling. The Agency also concluded that beneficial uses of these wastes, other than minefilling, pose no significant risk and no additional national regulations are needed. This landmark decision cleared the way for continued progress in the beneficial reuse of CCBs in the U.S.

The Council Working Party of Environment of the European Communities adopted the decision of establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 and Annex II of the Council Directive 199/31/EC on the landfill of waste (Landfill Directive) on December 19, 2002. This decision was published in the Official Journal of the European Communities on January 16, 2003 - L11/27 [1]. The decision lays down, among others, the following which are relevant to this report:

- 1) The procedures for characterizing waste, checking compliance of the waste with the acceptance criteria and the on-site verification that the waste arriving at the landfill is identical to the waste described in the documents;
- 2) Acceptance criteria and limit values for inert waste, for certain non-hazardous waste, for stable non-reactive hazardous waste accepted at landfills for non-hazardous waste, for hazardous waste and for underground storage.

The present report deals mainly with the pollution potential of bottom ash, first regarding groundwater and then atmosphere (dust emission). The radioactivity of bottom ash in Israel has been measured and most of the results have been summarized in two reports: “Evaluation of exposure to radiation due to the use of Bottom Ash in agriculture” by J. Koch [3]; and “Environmental conditions for the use of Coal Ash in infrastructures” by O. Peled et al., [4]. Both reports conclude that the concentrations of radionuclides in bottom ash are very low and that the yearly exposure to the radiation is minimal for an exposure of 500 hours per year (2.5 – 3 mrem). See also references [5], [6] and [7] quoted from these reports. The U.S.G.S. Fact Sheet FS-163-97 [8] gives a wealth of information on radioactive elements in coal and fly ash.

#### **D) Groundwater pollution potential:**

Table 1 compares the concentration range of major chemical constituents found in fly ash and bottom ash from Israeli power plants.

Table 1  
Major elements (results in %)

	Fly ash		Bottom ash	
	Low	High	Low	High
SiO <sub>2</sub>	38	70	40	65
Al <sub>2</sub> O <sub>3</sub>	17	35	18	30
Fe <sub>2</sub> O <sub>3</sub>	2	16	3	14
TiO <sub>2</sub>	0.04	1.6	0.3	0.7
CaO	0.6	13	1	6
MgO	0.4	5	0.4	3
Na <sub>2</sub> O	0.1	2	0.2	1.3
K <sub>2</sub> O	0.5	3	0.7	1.6
SO <sub>3</sub>	0.4	5	0.5	4

It can be seen that there are no significant differences in the major element constituents of fly and bottom ash. Table 2 gives the average composition of trace elements of fly and bottom ash produced in Israel and compares them to average compositions of soils and some common sediments. The data given for the averages was taken mainly from Wedepol's Handbook of Geochemistry [9].

Table 2  
Trace elements (results in ppm)

Element/ Sample	Fly ash <sup>1</sup>	Bottom Ash <sup>2</sup>	I	II <sup>3</sup>	III <sup>3</sup>	IV <sup>3</sup>	V <sup>3</sup>
Ag	6	2	<1	0.05	0.1	0.1	-
As	23	6	3	0.5	10	2	15
B	225	100	10	20	130	12	40
Ba	1777	1560	25	150	600	500	900
Cd	0.9	0.2	8	0.1	0.3	0.2	0.2
Co	45	31	<10	2	20	25	6
Cr	147	144	135	15	90	100	200
Cu	77	43	40	5	60	55	20
Hg	0.2	0.2	n.d.	0.04	0.4	3	-
Mn	540	350	155	300	800	950	500
Mo	13	4	7	0.4	2	1.5	6
Ni	100	69	40	8	70	75	50
Pb	67	18	1.5	8	25	13	20
Se	7	3	<2	0.4	0.5	0.05	1
V	197	127	60	20	120	135	80
Zn	114	47	270	30	150	70	72

- 1 – Average of some 200 samples (except for Ag), including many 6 monthly composite samples collected at the power stations (IEC reports).
- 2 – Average of 22, 6 monthly composite samples collected at the power stations (IEC report from 25/12/02) and 2 samples from the bottom ash used in Zikim.
- I – Analysis of a phosphate-rich rock from the Negev
- 3 – The world averages of II, III, IV and V are compiled from the literature [9].
- II – Average of soils.
- III – Average of sedimentary rocks.
- IV – Average of clay-rich shales.
- V – Average of limestones.
- n.d. – not determined.

As can be seen from Table 2, the trace element concentrations of bottom ash are significantly lower than those of fly ash, contrary to the major element concentrations, Table 1, which are rather similar. The concentration of trace elements in coal fly ash relatively to coal is due to the fact that practically all the trace elements, which were bound to the organic fraction of the coal and many of the trace elements associated with the inorganic fraction of the coal are volatilized during combustion and later precipitate in the cooler upper regions of the boiler on the fly ash particles transported in the flue gas. The bottom ash particles precipitate in the boiler and do not reach the upper cooler regions. This explains the big differences in trace element concentrations between fly ash and bottom ash and partly explain the lower leachability of trace elements (Table 3). The big differences in grain size distribution between fly ash and bottom ash (see Tables 4 and 5) and the consequent differences in surface areas also explain why the leachability of the trace elements is much lower in bottom ash compared to fly ash. As a result it can be observed that the average concentrations of trace elements in bottom ash (Table 2) and their leachability (Table 3) are comparable to those of sedimentary rocks.

Table 3 compares the results of various leachates to environmental standards.

Table 3  
Average of analyses of fly and bottom ash leachates  
Results are in microgram/litre (ppb).  
The results are compared with various standards

Sample Element	Fly Ash 1	Bott. Ash 1	Fly Ash 2	Bott. Ash 2	Bott. Ash 3	Bott. Ash 4	Bott. Ash 5	I	II	III	IV
Ag	1	0.7	0.3	0.1	0.4	0.7	0.6	0.3	10	-	5000
As	176	14	3	2.5	5	2.5	26	3	50	2000	5000
B	7466	773	3810	260	420	700	2700	155	-	-	-
Ba	3808	733	1230	77	226	436	625	120	1000	-	100,000
Cd	1.3	0.4	0.3	0.02	0.04	0.08	0.3	55	5	100	1000
Co	24	8.9	8	<8	<8	<8	<8	<10	-	-	-
Cr	453	8.8	128	14	20	20	60	25	50	2000	5000
Cu	15	7.8	5	n.a.	n.a.	n.a.	n.a.	40	1400*	-	-
Hg	0.7	<0.3	0.6	<0.3	0.1	n.a.	0.04	<0.3	1	25	200
Mn	273	496	5	n.a.	40	n.a.	110	730	500	5000	-
Mo	268	11	190	9.	15	n.a.	140	1.5	-	2000	-
Ni	140	30	<10	<10	<10	<10	10	35	50	-	-
Pb	3.4	3.8	3.4	0.02	0.4	0.6	1.2	0.8	10	150	5000
Se	83	5.5	52	2	2	5	10	2	10	700	1000
V	766	23	135	n.a.	100	n.a.	135	60	-	5000	-
Zn	65	173	278	n.a.	55	n.a.	80	550	5000*	-	-

\* Drinking water limits are for human consumption and have taken into account the situation with copper distribution lines and Zn containing materials in piping. This implies that for judgment of groundwater impact these numbers are not acceptable. In the EU water framework directive, much lower values for Cu and Zn have been used to assess impact from waste disposal.

Bott. Ash = Bottom Ash

1 = TCLP leachate (l/s ratio 20:1)

2 = Water leachate (l/s ratio 20:1)

3 = Water leachate (l/s ratio 10:1)

4 = Water leachate (l/s ratio 5:1)

5 = Water leachate (l/s ratio 2:1)

I= TCLP leachate (l/s ratio 20:1) of the phosphate-rich rock whose analysis is given in table 2

II = Primary Drinking Water Standard

III = Proposed Israeli Standard for using ash

IV = USEPA Criterion for Toxicity

n.a. = not analysed

It can be seen from Table 3 that both distilled water and TCLP (acetic acid) leachates of bottom ash have low concentrations of trace elements and are comparable to a rock TCLP leachate.

Table 4  
Comparison of bottom ash leachates with EU criteria  
The results are given in mg of the element leached from 1 kg ash

Element	Bottom ash l/s 2:1	EU Inert criteria l/s 2:1	Bottom ash l/s S 10:1	EU Inert criteria l/s 10:1
	mg/kg dry weight	mg/kg dry weight	mg/kg dry weight	mg/kg dry weight
As	0.052	0.1	0.05	0.5
Ba	1.25	7	2.26	20
Cd	0.0006	0.03	0.0004	0.04
Cr total	0.12	0.2	0.2	0.5
Cu	-	0.9	-	2
Hg	0.00008	0.003	0.001	0.01
Mo	0.28	0.3	0.15	0.5
Ni	0.02	0.2	<0.1	0.4
Pb	0.0024	0.2	0.004	0.5
Sb	n.a.	0.02	n.a.	0.06
Se	0.02	0.06	0.02	0.1
Zn	0.16	2	0.55	4

Table 4 compares the results of the water leachates (L/S 2:1 and 10:1) to the EU criteria for inert wastes and it can be seen that according to these criteria, coal bottom ash produced by Israeli power plants can be classified as inert waste. In fact the results are much better than those given in table 4. The reason is that a considerable amount of water (the leaching agent) is adsorbed by the ash, some 20% per weight of the ash, even when the ash is wet. At high l/s ratios this effect is negligible but at low ones such as 2:1, it is considerable (10%). In actual localities with the rainfall in Israel, the ratio is very much lower such as l/s 1:30.

Some 50,000 tons of bottom ash were used for a structural fill (under building foundations) in Zikim. Since this locality is very near (less than the protection radius C, 120m) to an operating well, Erez-Shikma 6 (drinking water), it was decided to monitor the quality of water from this well and two adjacent ones (Erez-Shikma 5 and 7). The results for the first two years are presented in Table 5 and they do not show any pollution related to the ash. It is intended to continue the monitoring for at least 4 more years.

Table 5  
Analyses of waters from three wells in Erez-Shikma  
(results are in µg/l)

7			6						5						Well
22.10. 2002	11.7. 2002	26.6. 1995	3.7. 2003	15.12. 2002	7.10. 2002	11.7. 2002	11.10. 2001	25.6. 1995	3.7. 2003	15.12. 2002	6.10. 2002	11.7. 2002	11.3. 2002	16.6. 1996	Date
1	2	1	2	2	1	2	1	1	2	2	1	2	1	1	Lab./ Element
<1	<0.1	-	<0.1	<0.1	<1	<0.1	<1	-	<0.1	<0.1	1	<0.1	<1	-	Ag
<1	2	2	2	2.5	<1	2	1	3	2.5	3	<1	2	2	<1	As
-	100	1150	90	120	130	110	130	-	140	150	170	150	180	350	B
290	285	244	210	250	186	200	174	109	220	200	165	175	153	137	Ba
<0.2	<0.02	<0.2	<0.05	<0.1	<0.2	<0.02	<0.2	<0.2	<0.05	<0.1	<0.2	<0.02	<0.2	<0.2	Cd
-	-	<5	-	-	<3	-	<3	<5	-	-	<3	-	<3	<5	Cn
<3	<10	-	<10	<10	<3	<10	-	-	<10	<10	<3	<10	-	-	Co
7	10	9	<10	<10	9	10	10	10	<10	<10	11	15	12	17	Cr
3	<10	4	<10	<10	<3	<10	3	10	<10	<10	<3	<10	<3	<3	Cu
67	<20	92	<10	<10	8	<20	16	62	<10	<10	8	<20	29	56	Fe
-	0.09	<0.1	<0.05		<0.1	0.02	<0.1	<0.1	<0.05	-	<0.1	0.06	<0.1	<0.2	Hg
3	<2	14	<2	<2	<3	<2	<3	14	<2	<2	<3	<2	<3	8	Mn
<3	1.5	-	2.5	3	3	3	-	-	2.5	2	3	2	-	-	Mo
<3	<10	-	20	<10	<3	<10	<3	-	<10	<10	<3	<10	<3	-	Ni
<2	0.14	<3	0.16	<0.1	<2	0.12	<2	<3	<0.05	<0.1	<2	0.13	<2	<3	Pb
8	9	5	4.5	6	2	3	1	<1	3.5	4	<1	2	<1	<1	Se
-	<30	-	<30	<20	-	<30	-	-	<30	<20	-	<30	-	-	V
16	9	62	12	<10	10	8	16	42	5	<10	12	12	13	44	Zn

Lab. – Laboratory, 1 – Mekorot; 2 – Geological Survey of Israel.  
- not analysed

It can be concluded that there is no danger of chemical pollution (leaching of toxic elements to the groundwater) deriving from the utilization of bottom ash in roadbases or structural fills. This is true in all cases in the short run (as indicated by the water leachates). In the long run (as indicated by the TCLP leachates), there might be a problem with boron, not for drinking water, but for irrigation waters. Concentrations above 300 ppb B in the irrigation waters hinder the growth of certain agricultural crops (e.g. citrus). In these localities the quantity of bottom ash used and the B concentrations in the groundwater have to be taken into account, before using bottom ash in roadbases or structural fills.

## **II) Atmosphere pollution potential:**

The use of container media (soil-less culture) in agriculture is widespread in Israel, especially in greenhouses. Recently a study has shown that coarse bottom ash may be used, very successfully, in container media instead of tuff. Coarse bottom ash is bottom ash from which the fraction smaller than two millimeters has been removed. It should be noted that this separation is far from perfect and some 10 to 15% of the fraction smaller than two millimeters remains in the “coarse” bottom ash. Since both fly and bottom ash contain some 5% of quartz (free crystalline  $\text{SiO}_2$ ), and the coarse bottom ash is used without any cover in this particular use, two questions were raised: will dust derived from coarse bottom ash raise the amount of dust in the air to intolerable concentrations and will the concentration of quartz in the air become dangerous?

Table 4 and 5 give the grain size distribution of typical fly ash and bottom ash respectively. The analyses were carried out for fly ash by sieves from 45  $\mu\text{m}$  up, and for 45  $\mu\text{m}$  down by a “Mastersizer” produced by Malvern Instruments (average of two measurements made in two different laboratories); for bottom ash, the analyses were carried out by sieves from 45  $\mu\text{m}$  up, and for 45  $\mu\text{m}$  down by hydrometer (average of 11 sieve analyses). Figure 1 shows the cumulative grain size distribution.



Table 4  
Grain size distribution of a coal  
fly ash

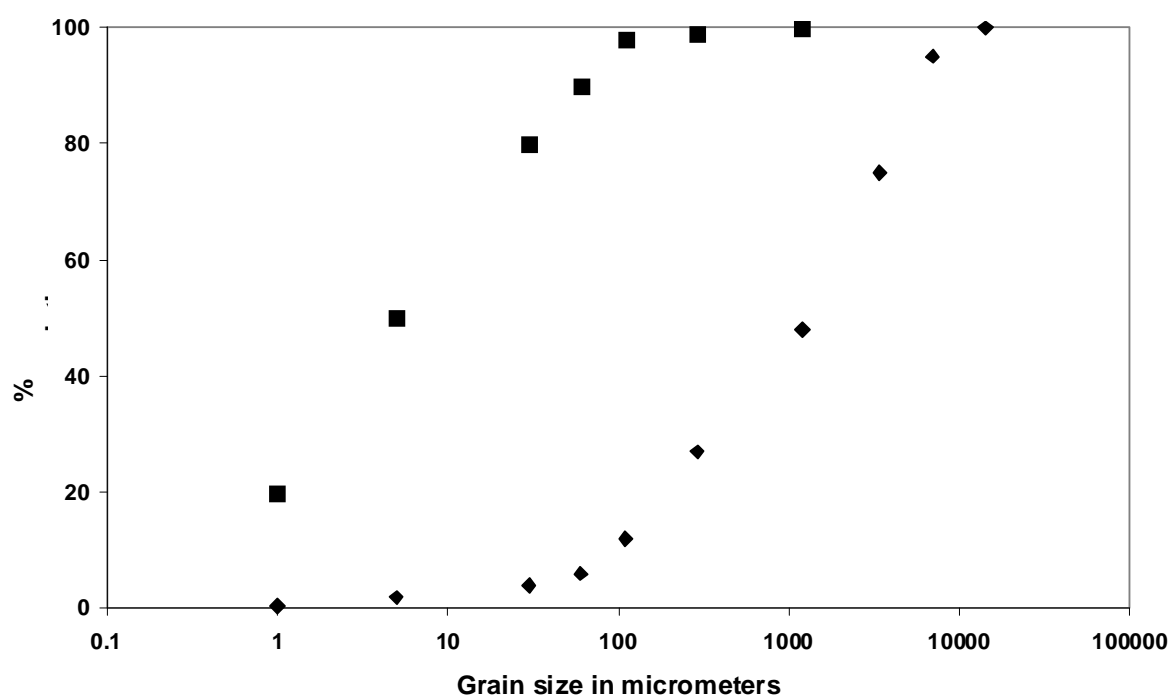
Fraction size in $\mu\text{m}$	%
425 - 2000	1
150 - 425	1
75 - 150	8
45 - 75	10
10 - 45	30
1 - 10	30
<1	20

Table 5  
Grain size distribution of a coal  
bottom ash

Fraction size in $\mu\text{m}$	%
9500 - 19000	5
4750 - 9500	47
2000 - 4750	21
425 - 2000	15
150 - 425	6
75 - 150	2
45 - 75	2
10 - 45	1.6
1 - 10	0.4

Figure 1

Cumulative distribution of grain size for fly and bottom ash



Squares represent fly ash and diamonds bottom ash.

Figs. 2 – 4 give the X-ray diffractograms of three fractions of bottom ash, > 40 microns; from 10 to 40 microns; < 10 microns. It can be seen that the presence of quartz in the respirable fraction (less than 10 microns) is barely noticeable and its concentration is very low

(less than 0.5%). The reason for the large difference in quartz concentrations between the coarse fraction ( $> 40$  microns),  $\sim 7\%$ , and the very fine fraction ( $< 10$  microns)  $\sim 0.5\%$ , is that quartz in coal ash is residual, it is quartz which was originally in the coal and has not reacted, e.g. with CaO to form Ca-silicates. Small grained-sized quartz is much more reactive than coarse particles.

If we take into consideration that the amount of coarse bottom ash used per  $1000\text{ m}^2$  of container media is 50 tons, and the amount of ash with grain size smaller than 10 microns is less than half of what is found in untreated bottom ash. This makes the percentage of this fraction in coarse bottom ash at most 0.2% instead of 0.4% in regular bottom ash. Therefore the amount of bottom ash particles smaller than 10 microns in an area of  $1000\text{ m}^2$  is 100 kg and the amount of quartz is less than 500 grams. Taking into account that only the surface can supply particles to the atmosphere and that the ash is irrigated between two to six times daily, these quantities are negligible. Since the irrigation water is reused after purification and addition of nutrients, there is no danger of pollution from this water.

Our results agree with those of studies abroad, in the Netherlands, Kema, one of the leading research centers in the field, started a research project [10] to determine the quartz content in coal and the corresponding PFA (Pulverized Fly Ash), they found that, “the amount of the total alpha-quartz in the respirable fraction of the ashes studied is less than 0.2%, so probably the Dutch occupational quartz standard of  $0.075\text{ mg/m}^3$  will not be exceeded”. Their conclusion is that “in spite of the presence of quartz, coal fly ash can be considered as a nuisance or inert dust”.

In spite of the fact that coal has been used as a fuel in electricity production for more than 100 years (the first coal-fired electric power plant was built in New York in 1882), very few cases have been reported of damage to workers because of exposure to coal ash. Cho et. al. [11] report about such a case in 1994 and specify “To our knowledge, this is the first case report described in the medical literature of acute lung disease developing after fly ash exposure.”

Recently studies have been carried in power stations to evaluate health hazards to workers exposed to ash. The main conclusions of three studies are given here. A - “The exposure to fly-ash during cleanout does not appear to have resulted in pulmonary disease” [12]. B - “All personal coal dust, fly ash, crystalline silica, nitrogen-dioxide, and nitric-oxide, were below the lowest current criterion level. The authors conclude that a health hazard

existed only for employees exposed to sulfur-dioxide and noise” [13]. C – “The highest fly ash concentration in personal samples was 0.26 mg/m<sup>3</sup>. The authors conclude that a hazard existed for some workers exposed to sulfur-dioxide, and that a potential hazard existed due to boiler leaks” [14].

## Conclusions

It should be stressed that practically all the literature, included what is quoted in this report, relates to fly ash; because fly ash is the main CCB. It can be seen from the short literature review and from the data given here that even coal fly ash is a non-hazardous waste. Still because of the problematic state of the groundwater in Israel and because of its grain size distribution, there is a need for regulations even for the beneficial uses of fly ash (similar to the ones, earlier proposed by the Ministry of Environment). For bottom ash, the subject of this report, which falls under inert wastes even according to the more stringent European criteria, there is no danger whatsoever of groundwater or atmosphere pollution when using it, except for the leaching of Boron. My recommendation is to regard it as an inert waste also in Israel without any need for regulations (except for boron).

## Acknowledgements

I thank Dr. Ariel Metzger (Israel Electric Co.), Omri Lulav (National Coal Ash Board) Dr. Rami Keren (Institute of Soils and Water, Volcani Center), Yoetz Deutsch and Dr. Henri Foner, last but certainly not least (Geological Survey of Israel) for their comments and data. I also thank Dr. Greg Goldstein (World Health Organization) and Prof. Tee L. Guidotti (The Georges Washington University Medical Center) for introducing me to the field of Environmental and Occupational Health. Special thanks are due to Faye L. Rice (National Institute for Occupational Safety and Health) who generously put at my disposal her extensive bibliography. Special thanks are also due to Drs. Bob Finkelman (USGS), Jack Groppo (CAER) and Hans van der Sloot (ECN) for their careful reviewing of this report and their constructive criticisms.

## References

- 1 - Council Working Party of Environment of the European Communities decision. Official Journal of the European Communities, January 16, 2003 - L11/27.
- 2 – Federal Regulation of U.S.E.P.A. (May 2000). 40 CFR part 261, Regulatory Determination on Wastes from the combustion of Fossil Fuels; Final rule, Part III.
- 3 –Koch J. (2002) Evaluation of exposure to radiation due to the use of bottom ash in agriculture. In Hebrew, Internal report, Soreq Nuclear Center, 4p.
- 4 – Peled O., S. Seroya and O. German. (2002) Environmental conditions for the use of Coal Ash in infrastructures. In Hebrew, Internal report, Israel Atomic Energy Commission, 12 p.
- 5 – Rogbeck, J. (1996) Coal bottom ash as fill material in construction. Waste Management, 16: 125-128.
- 6 – ICRP (1999) Protection of the public in situations of prolonged radiation exposure, ICRP Publication 77. Annals of the ICRP 27 (Supplement), Pergamon Press, Oxford, UK.
- 7 – Tso, M. W. (1996) Radiological impact of coal ash from the power plants in Hong-Kong. J. Environmental Radioactivity, 30(1): 1-14.
- 8 - Zielinski, R.A., and Finkelman, R.B. (1997) Radioactive Elements in Coal and Fly Ash: Abundance, Forms, and Environmental Significance. U.S. Geological Survey Fact Sheet FS-163-97.
- 9 – Wedepohl, K.H.; Ed., Handbook of Geochemistry, Vol. I (1969); Vol. II/1-5; Elements H to U, Berlin, Springer.
- 10 - Meij R; Nagengast S, and te Winkel H. The Occurrence of Quartz in Coal Fly Ash Particles. Inhalation Toxicology. 2000; 12(Suppl 3):109-116.
- 11 - Cho K; Yoon JC; Shrivastava DK, and Kapre SS. Acute lung disease after exposure to fly ash. CHEST, 1994, 106(1):309-311.
- 12 - Gunter BJ; Pryor P, and Thoburn TW. Health Hazard Evaluation Report, No. HETA 81 338 1070, Public Services Company of Colorado, Pueblo, Colorado. Hazard Evaluations and Technical Assistance Branch, NIOSH, Cincinnati, Ohio, 12 Pages, 5 References. 1982.
- 13 - Zey JN and Aw, T. C. Health Hazard Evaluation Report No. HETA 82 093 1453, Southwest Power Station, City Utilities, Springfield, Missouri. Hazard Evaluations and Technical Assistance Branch, NIOSH, U.S. Department of Health and Human Services, Cincinnati, Ohio, Report No. HETA-82-093-1453, 42 Pages, 30 References. 1984.
- 14 - Zey JN and Donohue, MT. Health Hazard Evaluation Report No. HETA 81 112 1372, Culley Generating Station, Yankeetown, Indiana. Hazard Evaluations and Technical Assistance Branch, NIOSH, U.S. Department of Health and Human Services, Cincinnati, Ohio, Report No. HETA-81-112-1372, 36 Pages, 17 References. 1983.

Caption for figures

Fig. 1 - Cumulative distribution of grain size for fly and bottom ash

Fig. 2 – X-ray diffractogram of bottom ash fraction  $> 40$  microns.

Fig. 3 – X-ray diffractogram of bottom ash fraction from 10 to 40 microns.

Fig .4 – X-ray diffractogram of bottom ash fraction  $< 10$  microns.

