

THE REPUBLIC OF TURKEY
MUĞLA SITKI KOÇMAN UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED
SCIENCES

DEPARTMENT OF MINING ENGINEERING

REJECTION OF TRACE ELEMENTS IN MUĞLA,
SALİHPAŞA COAL USING HEAVY MEDIUM
SEPARATION

MASTER OF SCIENCE

ERCAN POLAT

DECEMBER 2014

MUĞLA

MUĞLA SITKI KOÇMAN ÜNİVERSİTESİ
Fen Bilimleri Enstitüsü

TEZ ONAYI

ERCAN POLAT tarafından hazırlanan 'REJECTION OF TRACE ELEMENTS IN MUĞLA, SALIHPAŞA COAL USING HEAVY MEDIUM SEPARATION' başlıklı tezinin, 30/12/2014 tarihinde aşağıdaki jüri tarafından Maden Mühendisliği Anabilim Dalı'nda yüksek lisans derecesi için gerekli şartları sağladığı oybirliği/oyçokluğu ile kabul edilmiştir.

TEZ SINAV JÜRİSİ

Prof.Dr. Taki GÜLER

Başkan, Maden Mühendisliği Anabilim Dalı,
Muğla Sıtkı Koçman Üniversitesi, Muğla

İmza:



Prof. Dr. Murat GÜL

Üye, Jeoloji Mühendisliği Anabilim Dalı,
Muğla Sıtkı Koçman Üniversitesi, Muğla

İmza:



Doç. Dr. Naci Emre ALTUN

Danışman, Maden Mühendisliği Anabilim Dalı,
Orta Doğu Teknik Üniversitesi, Ankara

İmza:



ANA BİLİM DALI BAŞKANLIĞI ONAYI

Prof.Dr. Osman Zeki HEKİMOĞLU

Maden Mühendisliği Anabilim Dalı Başkanı,
Muğla Sıtkı Koçman Üniversitesi, Muğla

İmza:



Doç. Dr. Naci Emre ALTUN

Danışman, Maden Mühendisliği Anabilim Dalı,
Muğla Sıtkı Koçman Üniversitesi, Muğla

İmza:



Savunma Tarihi: 30/12/2014

DECLARATION

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

ERCAN POLAT

30/12/2014

ABSTRACT

REJECTION OF TRACE ELEMENTS IN MUĞLA, SALİHPAŞA COAL USING HEAVY MEDIUM SEPARATION

Ercan Polat

Master of Science (M.Sc.)

Graduate School of Natural and Applied Sciences

Department of Mining Engineering

Supervisor: Assoc. Prof. Dr. Naci Emre ALTUN

December 2014, 89 pages

Large scale coal consumption is the source of several environmental concerns. These concerns should be eliminated as much as possible to sustain eco-friendly utilization of coal. Post consumption products from coal such as fly ash, CO_x, SO_x, NO_x and particularly some hazardous trace elements (TEs) emitted from coal-fired power plants as stack gases, arsenic (As), chromium (Cr), mercury (Hg), manganese (Mn), nickel (Ni), selenium (Se), zinc (Zn) and lead (Pb) which have direct impacts on environment, are major problems.

Evaluation of trace elements in Salihpaşa run-of-mine coal from Muğla, Turkey, with respect to their extents and rejections through heavy medium separation (HMS) are the backbones of the study. Studied trace elements are as following: Arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), uranium (U), vanadium (V) and zinc (Zn). In this respect, sink and float tests were applied at various industrial sizes (+50 mm, -50+18 mm, -18+9.5 mm and -9.5+0.5 mm) and at different separation specific gravities fractions to evaluate the possibility of removal of trace elements.

All trace elements, except Ni, revealed variation in amount with respect to coal particle size and cleaning by HMS (Heavy Medium Separation). As, Ba, Cu, Hg, Mn, Mo, Pb and Zn showed enrichment with increasing the fineness of Salihpaşa Coal, while Cd, Cr, Sb, Se, U and V were reversely related with decreasing particle size. Also, As, Ba, Cu, Hg, Mn, Mo, Pb, and Zn were positively correlated with ash and showed inorganic association. This is an indication of the linkage of the above mentioned trace elements with ash making minerals. In contrast Cd, Cr, Sb, Se, U and V were found mainly associated with organic matter in coal. Ni was found to be an exception, revealing no meaningful correlation with inorganic and/or organic matter in Salihpaşa coal.

HMS could remove much of trace elements via rejection of ash making minerals in Salihpaşa Coal. As, Ba, Cu, Hg, Mn, Mo, Pb, and Zn could be removed effectively, while other TEs concentrated in the cleaner products. For HMS tests, Ni was again an exception and Ni content showed fluctuating behavior with respect to separation specific gravity rather than a tendency towards cleaned and/or reject products.

Keywords: Coal, Trace Elements, Sink and Float Tests, Heavy Medium Separation

ÖZET

SALİHPAŞA/MUĞLA KÖMÜRÜNDEKİ ESER ELEMENTLERİN AĞIR ORTAM AYIRMA YÖNTEMİ İLE TEMİZLENMESİ

Ercan Polat

Yüksek Lisans Tezi

Fen Bilimleri Enstitüsü

Maden Mühendisliği Anabilim Dalı

Danışman: Doç. Dr. Naci Emre ALTUN

Aralık 2014, 89 pages

Büyük ölçüde kömür tüketimi birçok çevresel endişelerin ana kaynaklarından. Kömürün çevreci kullanımı için bu kaygılar mümkün olduğu ölçüde giderilmelidir. Kömür tüketimi sonucunda ortaya çıkan uçucu kül, CO_x, SO_x, NO_x gibi gazlar ve özellikle termik santrallerden yayılan arsenik, krom, civa manganez, nikel, selenyum, çinko ve kurşun gibi bazı tehlikeli eser elementler, çevreye doğrudan etkilerinin olması sebebiyle büyük problemler oluşturmaktadırlar.

Salihpaşa kömüründeki eser elementlerin dağılımları ve yoğunluğa bağlı geleneksel ayırma yöntemleri ile uzaklaştırılabilme olanaklarının değerlendirilmesi bu çalışmanın temellerini oluşturmaktadır. Arsenik (As), baryum (Ba), kadmiyum (Cd), krom (Cr), bakır (Cu), civa (Hg), mangan (Mn), molibden (Mo), nikel (Ni), kurşun (Pb), antimuan (Sb), selenyum (Se), uranyum (U), çinko (V) ve bakır (Zn) bu çalışmada incelenen eser elementlerdir. Yoğunluğa bağlı ayırma yöntemi olan yüzdürme-batırma testleri endüstriyel boyutlarda (+50 mm, -50+18 mm, -18+9.5 mm and -9.5+0.5 mm) sınıflandırılan kömür boyutlarında ve farklı ağır ortam özgül ağırlıklarında eser elementlerin uzaklaştırılabilme olanakları açısından Salihpaşa kömürüne uygulanmıştır.

Nikel haricindeki bütün elementler miktarsal olarak kömür boyutundaki değişim ve ağır ortam ayırmasına bağlı olarak değişim göstermişlerdir. As, Ba, Cu, Hg, Mn, Mo, Pb ve Zn kömür boyutundaki küçülmeye bağlı olarak zenginleşmişlerdir, öte yandan Cd, Cr, Sb, Se, U ve V tersi yönde bir eğilim göstermiştir. Benzer şekilde, As, Ba, Cu, Hg, Mn, Mo, Pb ve Zn gibi eser elementler kül ile pozitif ilişkili ve inorganik bağlılık göstermişlerdir. Bu durum, adı geçen eser elementler ile kül yapıcı mineraller arasında bir bağ olduğunun göstergesidir. Tersine olarak ise Cd, Cr, Sb, Se, U and V ise daha çok organik kısım ile ilişkili oldukları belirlenmiştir. Bir istisna olarak Nikel, ne organik ne de inorganik kısım ile anlamlı/tutarlı bir ilişki göstermiştir.

Yoğunluğa bağlı ayırma birçok eser elementin kül yapıcı mineraller üzerinden uzaklaştırılmalarını sağlamıştır. As, Ba, Cu, Hg, Mn, Mo, Pb ve Zn verimli şekilde Salihpaşa kömüründen uzaklaştırılabilmelerine karşın geri kalanlar temiz kömür parçalarında zenginleşmişlerdir. Nikelin kömürdeki kararsız dağılımı temizleme işlemlerinde belli bir kısımda yoğunlaşmasını engellemiştir.

Anahtar Kelimeler: Kömür, Eser Element, Yüzdürme Batırma Testleri, Ağır Ortam Ayırması.

To my family and my lovely girlfriend, who supports me in all conditions

ACKNOWLEDGMENTS

My supervisor, Assoc. Prof. Dr. Naci EMRE ALTUN will never be forgotten with his great help and support for the study.

I also would like to thank to Assoc. Prof. Dr. Taki GÜLER and Assoc. Prof. Dr. Murat Gül for their supports and positive contributions during my works for study.

Finally, thanks a lot to my parents, Zeynel and Hüsniye and my lovely girlfriend, Nazan who always meets me with a smile on her face.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	vii
TABLE OF CONTENTS.....	viii
LIST OF TABLES	ix
LIST OF FIGURES	xi
LIST OF ABBREVIATIONS	xiii
1. INTRODUCTION	1
2. TRACE ELEMENTS IN COAL	3
2.1 Definition.....	3
2.2 Classification of Trace Elements in Coal	3
2.3 Mode of Occurrence of Trace Elements.....	4
2.4. Hazardous Effects of Some Trace Elements on Human Body.....	9
3. LITERATURE REVIEW	12
4. MATERIALS AND METHODS	18
4.1. Coal Sample and its Characterization	18
4.2. Size Fractionation and Sink and Float Tests	20
4.3. Pearson's Correlation Coefficient	23
5. RESULTS AND DISCUSSION	24
5.1. Relationship Between Trace Element Contents and Size Fractions.....	25
5.2. Removal of Trace Elements by Heavy Media Separation	40
6. CONCLUSION	74
REFERENCES.....	76
APPENDIX	82
Appendix A. Contents and Distributions of Trace Element and Ash in Coal Sizes.	82
CURRICULUM VITAE.....	89

LIST OF TABLES

Table 2.1. Classification of trace elements according to level of concern.....	4
Table 2.2. Association of trace elements (Firth and Dale, 1998).....	4
Table 2.3. Modes of occurrence of trace elements (Finkelman, 1995).	6
Table 2.4. Association of some trace elements in world coals (Boyd, 2004)	9
Table 4.1. Proximate Analysis of Salihpaşa Coal	19
Table 4.2. Ultimate Analysis of Salihpaşa Coal	19
Table 4.3. Distribution of Salihpaşa ROM coal with respect to size fractions	21
Table 5.1. Trace Element Contents of some World and Turkish Coals with Salihpaşa ROM coal.....	24
Table 5.2. Distributions of As, Ba, Cd with respect to size fractions of Salihpaşa ROM Coal.....	25
Table 5.3. Distributions of Cr, Cu, Hg with respect to size fractions of Salihpaşa ROM Coal.....	28
Table 5.4. Distributions of Mo, Mn, Ni with respect to size fractions of Salihpaşa ROM Coal.....	31
Table 5.5. Distributions of Pb, Se with respect to size fractions of Salihpaşa ROM Coal.....	34
Table 5.6. Distributions of Sb and U with respect to size fractions of Salihpaşa ROM Coal.....	35
Table 5.7. Distributions of V and Zn with respect to size fractions of Salihpaşa ROM Coal.....	37
Table 5.8. Pearson correlation coefficients between trace element and ash contents with respect to coal size fractions	40
Table 5.9. Arsenic content of sink and float products at different coal size fractions	41
Table 5.10. Barium content of sink and float products at different coal size fractions	45
Table 5.11. Cadmium content of sink and float products at different coal size fractions.....	47
Table 5.12. Chromium content of sink and float products at different coal size fractions.....	49
Table 5.13. Copper content of sink and float products at different coal size fractions	51
Table 5.14. Mercury content of sink and float products at different coal size fractions	53

Table 5.15. Manganese content of sink and float products at different coal size fractions.....	55
Table 5.16. Molybdenum content of sink and float products at different coal size fractions.....	57
Table 5.17. Nickel content of sink and float products at coal size fractions.....	59
Table 5.18. Lead content of sink and float products at coal size fractions	61
Table 5.19. Antimony content of sink and float products at coal size fractions	63
Table 5.20. Selenium content of sink and float products at coal size fractions	65
Table 5.21. Uranium content of sink and float products at coal size fractions.....	67
Table 5.22 Vanadium content of sink and float products at coal size fractions.....	69
Table 5.23 Zinc content of sink and float products at coal size fractions.....	71
Table 5.24. Total rejection of trace elements at separation specific gravities of 1.5-1.8.....	72

LIST OF FIGURES

Fig. 2.1. Trace Element Associations in Coal (Swaine, 1990).	5
Fig. 2.2. Me-Hg cycle (Lockwood et.al., 2009).	11
Fig. 4.1. XRD Spectrum of Salihpaşa Coal (Q = quartz, P = pyrite, C = calcite, D = dolomite).	20
Fig. 5.1. Arsenic content vs. size fractions of Salihpaşa ROM Coal	26
Fig. 5.2. Barium content vs. size fractions of Salihpaşa ROM Coal.....	26
Fig. 5.3. Cadmium content vs. size fractions of Salihpaşa ROM Coal.....	27
Fig. 5.4. Chromium content vs. size fractions of Salihpaşa ROM Coal	28
Fig. 5.5. Copper content vs. size fractions of Salihpaşa ROM Coal.....	29
Fig. 5.6. Mercury content vs. size fractions of Salihpaşa ROM Coal.....	30
Fig. 5.7. Molybdenum content vs. size fractions of Salihpaşa ROM Coal.....	31
Fig. 5.8. Manganese content vs. size fractions of Salihpaşa ROM Coal	32
Fig. 5.9. Nickel content vs. size fractions of Salihpaşa ROM Coal.....	32
Fig. 5.10. Lead content vs. size fractions of Salihpaşa ROM Coal.....	33
Fig. 5.11. Selenium content vs. size fractions of Salihpaşa ROM Coal	34
Fig. 5.12. Antimony content vs. size fractions of Salihpaşa ROM Coal	35
Fig. 5.13. Uranium content vs. size fractions of Salihpaşa ROM Coal	36
Fig. 5.14. Vanadium content vs. size fractions of Salihpaşa ROM Coal.....	37
Fig. 5.15. Zinc content vs. size fractions of Salihpaşa ROM Coal	38
Fig. 5.16. Arsenic content vs. ash % of sink and float products at different coal size fractions	43
Fig. 5.17. Barium content vs. ash % of sink and float products at different coal size fractions	44
Fig. 5.18. Cadmium content vs. ash % of sink and float products at different coal size fractions	46
Fig. 5.19. Chromium content vs. ash % of sink and float products at different coal size fractions	48
Fig. 5.20. Copper content vs. ash % of sink and float products at different coal size fractions	50
Fig. 5.21. Mercury content vs. ash % of sink and float products at different coal size fractions	52
Fig. 5.22. Manganese content vs. ash % of sink and float products at different coal size fractions	54

Fig. 5.23. Molybdenum content vs. ash % of sink and float products at coal size fractions	56
Fig. 5.24. Nickel content vs. ash % of sink and float products at coal size fractions	58
Fig. 5.25. Lead content vs. ash % of sink and float products at coal size fractions...	60
Fig. 5.26. Antimony content vs. ash % of sink and float products at coal size fractions	62
Fig. 5.27. Selenium content vs. ash % of sink and float products at coal size fractions	64
Fig. 5.28. Uranium content vs. ash % of sink and float products at coal size fractions	66
Fig. 5.29. Vanadium content vs. ash % of sink and float products at coal size fractions	68
Fig. 5.30. Zinc content vs. ash % of sink and float products at coal size fractions ...	70

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
EGS	Enhanced Gravity Separator
HAPs	Hazardous Air Pollutants
HMS	Heavy Medium Separation
ICP-MS	Inductively Coupled Plasma - Mass Spectrometry
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry
Pearson's r	Pearson's Correlation Coefficient
ROM	Run-of-Mine
TEs	Trace Elements
XRD	X-Ray Diffraction
USA	United States of America
USGS	United States Geological Survey

1. INTRODUCTION

Human activity, aiming to satisfy expanding global energy demand, have direct impacts on environment. Growing demand for energy, particularly for electricity, has been continuously increasing parallel to the economic and social development. Electricity production, which is also an indication for modernization, strongly relies on the use of non-renewable fossil fuels. Among these sources, coal will sustain its importance in the long term, being reliable, abundant, securely suppliable and cost-effective.

Coal fired power plants meet more than 40% of total global electricity production (Ozbayoglu, 2011; Vejahati et al., 2009; Vardar and Yumurtaci, 2009). This production rate for electricity is even higher for some countries such as South Africa (93%), Poland (92%), China (79%), India (69%). According to current consumption figures, the use of coal is anticipated to increase by more than 50% by 2030. Developing countries will be responsible for 97% of this increase, primarily for electricity production by power plants (Vardar and Yumurtaci 2009).

Civilization/modern world is addicted on coal. The coal is the backbone/bedrock for energy supply despite its negative impacts due to the following:

Coal is reliable; All energy sources, significantly non-renewables, are essential for sustainable modern life. Coal, which is one of those, will continue playing a key role until environment-friendly technologies become more efficient and reliable for energy production.

Supply does not depend on seasonal conditions; Renewable energy sources such as solar, wind and hydro-power are affected by daily and seasonal weather conditions. Presence of abundant coal beds can satisfy energy demand for certain time periods in a stable way.

Coal is widely distributed; Because coal can be found almost any where on earth, it preserves its importance, especially for developing and well developed countries.

Coal is abundant; Approximately, there are over 860 billion tonnes of proven coal reserves in the globe which is in 70 countries. Coal can therefore meet world energy demand for more than 118 years at current consumption rates (Vejahati et al., 2009).

The requirement for transportation and security is relatively less; Gas and oil need more secure and relatively expensive transfer routes between the source and final destination of usage. Additionally, storage is easier, safe and cheaper as compared to other fossil based resources.

It is clear that addiction on coal will continue as compared to other fossil resources until more cleaner/re-newable energy production methods are suitable to support human civilization. Continuing demand for coal makes some negative footprints. Increased usage of coal on a global scale has led to particularly environmental issues (emission of trace elements, release of particulate matter, acid rains, green house effect) and health problems. Therefore the use of clean coal has become a necessity in today's world. Using coal more efficiently is one of the most important steps towards this goal. In order to reduce these problems to tolerable levels, some developments have been achieved and applied on raw coals to obtain a cleaner fuel resource. Today, clean coal is demanded more than ever, especially in power generation to sustain eco-friendly perspective.

1.1 Objective

Main objectives of this study can be summarized as: To determine the amount and distribution of trace elements in Salihpaşa run-of-mine coal, a major lignite source supplying Yatağan thermal power plant of Yatağan/Muğla. In addition, the partitioning behavior of trace elements with respect to commercially accepted particle size fractions and separation densities were identified so as to estimate the possibility of trace element rejection from Salihpaşa Coal by the industrially applied Heavy Medium Separation (HMS) method.

2. TRACE ELEMENTS IN COAL

2.1 Definition

Definition of ‘Trace’ is used for concentration of elements less than 1000 ppm (Firth and Dale, 1998; Boyd, 2004) for most coals in the world, with some exceptions. Swaine (1990) reported that the amounts of trace elements (TEs) in coal are not more than 1% by weight.

2.2 Classification of Trace Elements in Coal

Swaine and Goodarzi (1995) classified trace elements in three major groups according to their environmental impacts. These groups are prime environmental interest elements (also known as environmentally sensitive elements), environmental interest elements, and finally, least environmental interest elements.

1. Prime environmental interest elements (toxic substances): As, Cd, Hg, and Se.
2. Environmental interest elements: B, Be, Cu, F, Mo, Ni, Pb, Th, U, V, and Zn.
3. Least harmful elements: Ba, Co, Sb, Sn, and Tl.

U.S National Committee for Geochemistry reported a study about the trace elements which have potential adverse effects during mining of coal and its utilization (National Research Council, 1980). Three groups were identified as follows:

1. Greatest concern; As, B, Cd, Pb, Hg, Mo and Se,
2. Moderately concern; V, Cr, Ni, Cu, Zn and F,
3. Trace elements with minor concern; Li, Na, Sr, Ba, Mn, Co, Ge, Cl, Br, Ra, Po, Rn, Th and U.

Both US National Research Council (1980) and US Clean Air Act (1990) classified trace elements below, according to level of concern/adverse effect. US Clean Air Act classified some trace elements as hazardous air pollutants. These are given in italic and bold characters in Table 2.1.

Table 2.1. Classification of trace elements according to level of concern.

High	Medium	Minor	Radioactive	Low Levels
Arsenic	Chromium	Antimony	Polonium	Beryllium
Boron	Copper	Barium	Radium	Tellurium
Cadmium	Nickel	Cobalt	Radon	Thallium
Lead	Vanadium	Germanium	Thorium	Tin
Mercury	Zinc	Lithium	Uranium	
Molybdenum		Manganese		
Selenium		Strontium		

Trace elements are found associated both organically and inorganically in coal. Their modes of occurrence vary during coal formation in swamp environment. Trace element associations in coal have been separated into four groups (Table 2.2.).

Table 2.2. Association of trace elements (Firth and Dale, 1998).

Organic association in coal	Organic affinity in coal	Inorganic association in coal	Inorganic affinity in coal
B	Sb	As	Co
Be	Ce	Cd	Cr
Ge	Ga	Cu	Ni
Sc	P	Hg	Se
U	Ti	Mn	
	V	Mo	
		Pb	
		Zn	
		Zr	

2.3 Mode of Occurrence of Trace Elements

Total trace element content of coal is the sum of trace elements in organic and inorganic matter (Fig. 2.1.). Discrete minerals, which is part of the mineral matter, are most important components of coal body because of being a main host for many trace/toxic elements. Trace elements associate with organic part in coal via

carboxylic acid/carboxyl (-COOH), mercapto (-SH), imino (=NH) and phenolic hydroxyl (-OH) (Swaine 1990; 1992; Swaine 1997).

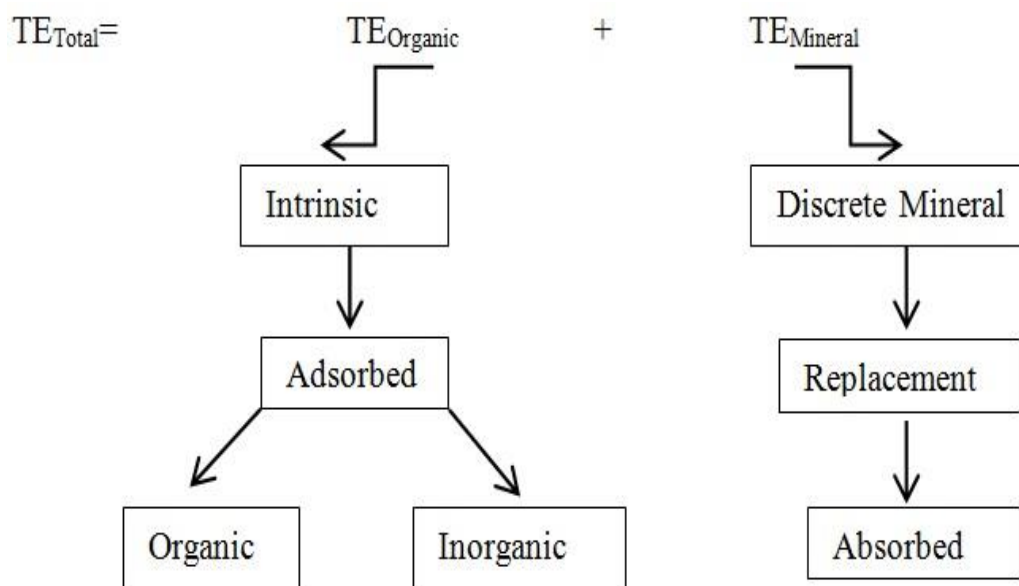


Fig. 2.1. Trace Element Associations in Coal (Swaine, 1990).

Modes of occurrence of twenty five trace elements found in coal are well explained by Finkelman (1995). They are tabulated with their modes of occurrence in Table 2.3 (bold elements are included in EPA's list of hazardous air pollutants). In the table 10 corresponds to the highest level of confidence and 1 indicates no confidence regarding the association of trace elements.

Antimony (Sb): Finkelman (1994) reported no particular indication to support any specific mode of occurrence of antimony in coal but stated that Sb may be found as solid solution in pyrite or as minute accessory sulfides distributed in the organic constituents of coal. In another study, antimony was found organically bound in the coal matrix (Gluskoter et al. 1977; Swaine, 1990). The antimony content of most coals changes between 0.05 - 10 ppm (Swaine, 1990).

Arsenic (As): Both direct and indirect evidence exist for the association of arsenic with the sulfides (especially pyrite) in the coal matrix (Finkelman, 1994). Arsenic is mostly concentrated in the mineral matter. Organically associated arsenic may also be present in small amounts (Swaine, 1990). Finkelman (1995) stated that arsenic is found as associated with pyrite for most U.S. coals with a confidence level of 8 (Table 2.3.). Gluskoter et al. (1977) also states that arsenic showed inorganic

association. Arsenic was also concentrated in the ash of coals from Çan basin from Turkey (Gürdal, 2011). A wide range applies for the amount of arsenic in coal (0.5–80) ppm (Swaine, 1990).

Table 2.3. Modes of occurrence of trace elements (Finkelman, 1995).

Element	Mode of Occurrence	Level of Confidence
Antimony	In pyrite and accessory sulfides	4
Arsenic	In pyrite	8
Barium	Barite and other Ba-bearing minerals	6
Beryllium	Organic association	4
Boron	Organic association	6
Cadmium	In sphalerite	8
Chlorine	Chloride ions in pore water or adsorbed onto macerals	6
Chromium	Organic or clay association	2
Cobalt	In pyrite, some in accessory sulfides	4
Copper	Chalcopyrite	8
Fluorine	Various minerals	5
Lead	In galena	8
Mercury	In pyrite	6
Manganese	In carbonates, siderite and ankerite	8
Molybdenum	Probably sulfides	2
Nickel	Unclear	2
Phosphorus	Phosphates	6
Selenium	Organic association, in pyrite and accessory sulfides and selenides	8
Silver	Various sulfides	4
Thallium	Associated with pyrite	4
Thorium	Monazite with lower concentrations in xenotime and zircon	8
Tin	Sn oxides and Sn sulfides	6
Vanadium	In clays and organic association	3
Uranium	Organically associated, some in zircon	7
Zinc	Sphalerite	8

Cadmium (Cd): Cadmium is found mostly associated with the mineral constituents in coal matrix, and particularly with sphalerite (Swaine, 1990). Similar results were reported by Finkelman (1994). Gluskoter et al. (1977) showed that cadmium was strongly associated with inorganic matter in coal. Similarly, Gürdal (2011) reported for Çan basin from Turkey that Cd was associated with the ash making minerals. Cadmium content is generally found to vary in the range of 0.1 - 3 ppm for different coals (Swaine, 1990).

Chromium (Cr): Organic or clay association may be present for Chromium in coals, however relying on very low confidence levels as shown in Table 2.3 (Finkelman, 1995). Swaine (1990) attributed this non-clarity to the presence of insufficient data and the need for more detailed investigations. Finkelman (1994) assumed that

chromium might be present in coal either as associated with the organic matter or with in the clays. Rimmer (1991) found strong evidences that chromium was associated with the inorganic constituents in coal, particularly with the clays on a study on the Lower Kittanning seam from USA. In contrast, Mukherjee et al. (1988) found for coal seams in India that chromium was mostly linked with organic constituents. Gluskoter et al. (1977) classified chromium as it was neither strongly associated with the organic or inorganic material in coal. Most coals show chromium presence in the range of 0.5-60 ppm (Swaine, 1990).

Lead (Pb): Finkelman (1994) stated that lead occurs mainly as sulfides or as strongly associated with sulfide minerals. It was also added that means galena is the most common form of lead that can be found in coal. Gürdal (2011) calculated positive correlation coefficient with ash content which means inorganic association of lead for Çan coals from Çanakkale, Turkey. Organic linkage may also be anticipated. As reported in literature, the extent of lead possibly varies in the range of 2-80 ppm for most coals (Swaine, 1990).

Manganese (Mn): Swaine (1990) reported that major modes of occurrence for manganese in coal are as associations both with carbonate minerals and clays. Similarly statements were made by Finkelman (1994), as manganese might occur in bituminous coal in the form of solid solution within the carbonate minerals such as siderite and ankerite. A confidence level of 8 was reported by Finkelman (1994) for findings related to manganese linkage to carbonate minerals in coal. In addition, both researchers agreed that manganese is organically linked in low rank coals. Mukherjee et al. (1988) found that Manganese is merely linked with the inorganic constituents of coal. For the extent of manganese in coals, a range of 5-300 ppm was reported for most coals (Swaine, 1990).

Mercury (Hg): Swaine (1990) reported that a variety of mercury forms (mercury sulfide-HgS, metallic mercury, organic mercury) are mainly found in Russian coals near areas of mercury mineralization. Swaine (1990) also added that mercury was associated with metallic sulphides such as pyrite and sometimes with sphalerite. Finkelman (1994) also agreed that mercury is found in solid solution with pyrite and also concluded that epigenetic pyrite probably has more mercury than syngenetic pyrite. The existence of Hg in USA coal deposits has been evaluated by the US Geological Survey (Tewalt et al., 2001). One obstacle in determining the modes of

Hg occurrence in coals is its low quantity and difficulties in analyses. Yudovich and Ketris (2005) reviewed the geochemistry of Hg in coals from different regions in the world and suggested that Hg might be associated with the clays (silicates), organic matter and sulphides. For Çan coals in Turkey, however, Gürdal (2011) reported that no meaningful correlation between Hg quantities and the inorganic matter could be suggested. The quantity of Hg in most coals varies between 0.02-1. ppm (Swaine, 1990).

Nickel (Ni): The existence of nickel in coal is not very well established and insufficient data exists for the modes of occurrence of Nickel in coal. Nickel may be either organically bound or associated with sulphides. Finkelman (1994) found that a big portion of Nickel in coal, is organically associated. Mukherjee et al. (1988) found that Nickel is present as organic chelates. However, Swaine (1990), reported Nickel may be inorganically linked with sulfide minerals inside the coal matrix. Content of Nickel in most coals is 0.5-50 ppm (Swaine, 1990).

Selenium (Se): Several modes of occurrence were reported for selenium in coals (Swaine, 1990). Finkelman (1994) indicated that bulk of the selenium in most coals is organically associated. Some selenium was also found associated with sulfide minerals in coal, mainly with pyrite and these findings were also supported by Gürdal (2011). Gürdal reported positive correlation of selenium with sulfur content and pyrite was anticipated as the source of selenium. Selenium quantity in most coals ranges between 0.2-10 ppm (Swaine, 1990).

An extended survey on trace elements in several coals from different regions of the world is listed in Table 2.4. (Boyd, 2004). According to the Table 2.4, most of As, Pb, Hg, Mo, Ni, Se, Th, Tin and Zn were found associated with sulfides, which is known as the most environmentally important mineral category due to being host for most trace elements (number of papers reporting the encountered modes in coal).

Table 2.4. Association of some trace elements in world coals (Boyd, 2004)

Element	Organic	Inorganic	Sulphide	Clays	Carbonate	Others
Antimony	13	41	36	-	-	10
Arsenic	15	14	69	1	-	1
Barium	21	19	-	21	35	4
Beryllium	75	-	-	25	-	-
Boron	81	-	-	-	-	19
Cadmium	-	-	32	-	-	68
Chlorine	61	-	-	-	-	39
Chromium	22	28	-	30	-	20
Cobalt	33	19	23	14	6	5
Copper	22	20	38	13	-	7
Lead	5	13	65	-	-	17
Manganese	18	19	10	-	37	16
Mercury	-	8	78	-	-	14
Molybdenum	34	6	49	-	-	11
Nickel	23	11	36	-	-	31
Phosphorus	6	-	-	-	-	94
Selenium	25	7	43	-	-	24
Thallium	-	-	83	-	-	17
Thorium	1	40	-	-	-	59
Tin	9	30	33	-	-	28
Uranium	39	32	-	22	-	7
Vanadium	30	25	-	35	-	10
Zinc	7	16	35	-	-	42

2.4. Hazardous Effects of Some Trace Elements on Human Body

Trace elements (TEs) in coal, especially those in the group of great environmental concern such as As, Se, and Hg have profound effects on human body, vegetation and animal life. The problem starts when their concentrations are above the optimal level of the body and of the nature.

Coal combustion from coal-fired power plants have adverse effects on life (Finkelman, 1999). The impact is proportional with distance to the power plants. Particulates and trace element emissions are sources of some major health problems. For instance, in China, people use coals with hazardous TEs, for drying food and heating without adequate ventilation (Kang et al., 2011; Finkelman et al., 1995; Belkin et al., 2008).

Mercury emissions are the greatest concern compared to other hazardous pollutants for human health and also for wildlife in nature (Pavlish et al., 2003). It has three types in environment and one type of mercury called methyl-mercury (Me-Hg), which is more important for human and wildlife. Major effect of Hg is associated with the nervous system. Hg harms/damages the learning ability and reduces IQ level, especially for children under the age of 14.

The form of Me-Hg is much more important for human life and health. This type of form is produced/converted by micro-organisms from other types of Hg sources. More interaction of Hg with aqueous media leads to the enrichment of Hg and some series of chemical reactions by micro-organisms further increase the Me-Hg concentration. The increase of Me-Hg in water streams and lakes results in accumulation in tissues of fish and shell fish, forming the basic bio-accumulation in aqueous ambient. Larger predators usually have more Me-Hg concentrations in their bodies. Due to this, mammals and fish eating birds can easily be affected more vigorously owing to ingestion of high Me-Hg containing food from contaminated lakes, rivers and other water sources. Rapid developing countries such as China and India have increasing contribution of Hg due to a large number of coal-fired power plants.

Me-Hg affects human life in every stage of lifetime. Consumption of Me-Hg containing food negatively affects pregnant-nursing women, infants, developing fetus and overall the humans at all ages (Fig. 2.2.).

Arsenic is a well known carcinogen element to humans (ATSDR, 2000; 2007; Ng et al., 2003). Consumption of As rich coals for drying food especially in rural regions of India, China and South Africa leads to adverse effects on human life (USGS 2006; Finkelman et al., 2002). Arsenic poisoning may lead to damages of internal organs of digestive, respiratory, circulatory, renal and neural systems (ATSDR, 2000; Finkelman et al., 2002; Boyd, 2004). Chronic arsenic poisoning, arsenosis, was reported well by Belkin et al. (2008), including all its possible forms and effects. Arsenic poisoning was reported to lead to hearing loss, birth anomalies while presence of intentional poisoning was observed for adults (Belkin et al., 2008). Main indications of arsenism was briefly explained as pigmentary skin changes and hyperkeratosis of the palm, along with indications of the nervous system and the

digestive system. The impairment is mainly shown as non-inflammatory hepatomegaly (Zheng et al., 1998).

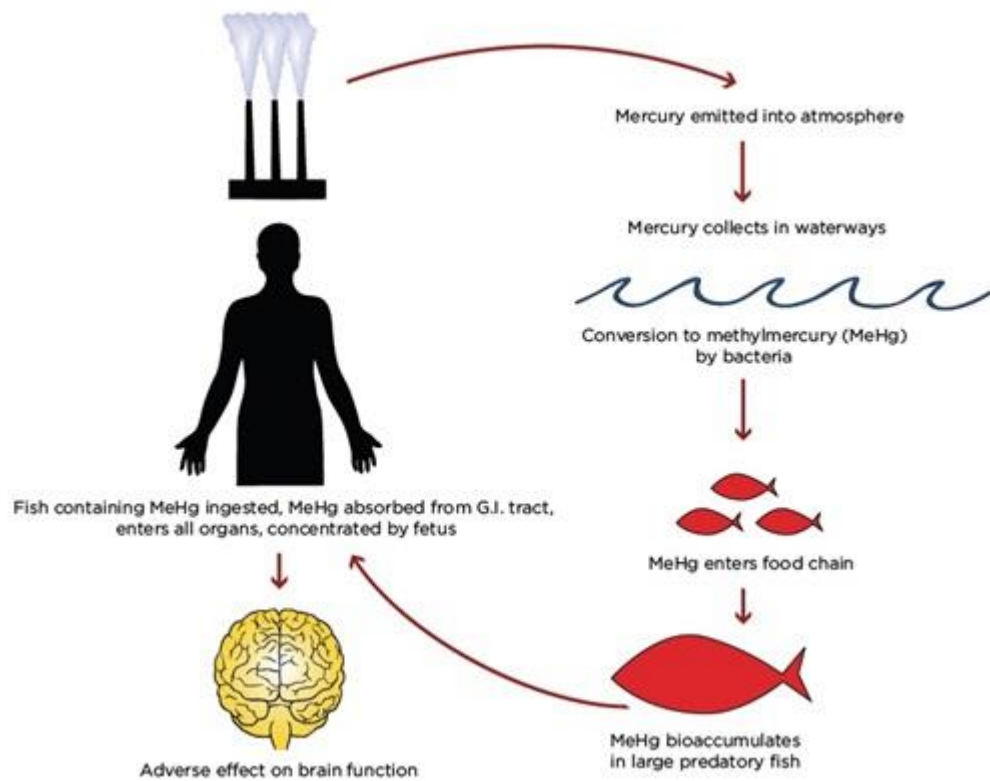


Fig. 2.2. Me-Hg cycle (Lockwood et.al., 2009).

3. LITERATURE REVIEW

In this section, some studies on trace elements for various coals in the world were briefly assessed on the basis of trace element associations and bonding in coal, their partitioning behavior and rejection possibilities, especially using conventional cleaning methods.

Karayigit et al. (2000) studied major and trace elements in coals from ten coal-fired power plants from Turkey. The studied coal samples had ash values ranging between 23% to 64% on air-dried basis. It was shown that the amount of As, Co, Cu, Ga, Mn, Li, Sc, Sn, Ta, Tl and some rare earth elements exceeded the world averages. The amounts of Ba, Bi, Ga, Nb, Pb, Rb, Sc, Ta, La, Ce, Pr, Nd, Sm, Eu and Gd were positively correlated with the ash yield, which is an indicator of association with mineral constituents. The rest were linked mostly on organic matter of coal. The amounts of As, B, Cr, Ni and Zr were higher in Cayirhan coals. Cr, Ni, and U which were considered as hazardous air pollutants (HAPs), had higher quantities in raw coals as compared to the world averages. The amount of As exceeded the world average only in Cayirhan coals, and it was shown that As association was inorganic. Other HAPs, such as Be and Pb were in the world range, while Mn and Co exceeded the limits in coals.

Baba (2002) studied coals from Yatagan Basin from Turkey for 30 volatile elements. The results showed that heavy trace metal contents in the coal were below the world averages. Hazardous effects of heavy trace metals especially after their transportations to the distance locations via fly ash is the biggest problem for environment. It was also reported that trace metal contents were higher in fly and bottom ashes compared with the coal.

Özbayoğlu (2010) applied sink-float tests for Soma coal on three size fractions, (+50, 50-18, and -18+0.5 mm). The amounts of Sr, Y, Ba, Pb, and Th of 1.80 and 1.90 sp.gr. sink were higher than content of the feed, while V, Cr, As, Rb, and U were lower than the feed. Trace elements, indicating strong affinity to organic matter such as U and V were enriched in coal and could not be removed with the removal of ash.

More than 50% of Cu, Pb, Th, Sr, and Y could be rejected from Soma coal at 1.80 specific gravity.

Gürdal (2011) studied abundances and modes of occurrence of trace elements in 81 coal samples from the Çan basin of northwestern Turkey. Twenty trace elements; As, B, Ba, Be, Cd, Cu, Co, F, Hg, Mo, Ni, Pb, Sb, Se, Sn, Th, Tl, U, V, and Zn were evaluated. As, Cd, Hg, Se, Cu, Mo, Ni, and Zn were associated with pyrite, while Se, B, and Mo were found associated both with organic and inorganic matter. The amounts of As, B, Cu, Co, Mo, Pb, Th, U, V and Zn exceeded world averages. Except B, Mo, U, and V all trace elements were positively correlated with ash content, showing their linkages mostly to mineral matter in coal. Inorganic matter rich coal samples were remarkably enriched in As, Ba, Cu, Co, F, Pb, Sn, Th, U, and V.

Ozbayoglu (2011) also applied partitioning of major and trace elements on Soma coal. It was found that the amounts of Ni, Se, Zr, Nb, and Nd showed affinity to the inorganic matter and concentrated in the sink product of +1.90 specific gravity. However Sb, Co and Bi tended to decrease in the sink (particularly in the fine sizes), when compared to the feed. Rejections at mediums with 1.80 and 1.90 specific gravities were also compared. It was seen that removal of trace elements is higher for all elements at 1.80 specific gravity. Mo, Nb, Nd, W, Hg and Zr removals were more than 70%, while Co, Sb and Bi removals remained were relatively lower (from 37 to 50%) due to organic affinity. The decrease in ash contents were 18.42% at 1.8 specific gravity and 22.58% at +1.9 specific gravity.

Ozbayoglu (2013) studied the quantities of twelve hazardous trace elements; As, Cd, Co, Cr, Hg, Mn, Ni, Pb, Se, Th and U in a coal preparation plant (Turkey). The run-of-mine (ROM) coal was separated into industrially used and accepted size fractions. Cleaned coals were obtained using Drewboy at a separation density of 1.55 g/cm³. Fine particles were separated and removed at 0.5 mm. The trace elements of As, Cd, Cr, Mn, Se, Th, U and V within the ROM coal were found to exceed the world averages. Cd, Mn, Th, V and Hg were found higher than the Turkish coal averages. Cd, Cr, Hg, Mn, Pb and Th were associated with the inorganic constituents of coal and could be removed through ash rejections (ash rejection in a range of 51.8% to 77.4 % was obtained). Removal of As, Co, Ni and Se remained relatively less (from

35.1% to 44.2%). U and V were found not rejected at higher extents due to their organic affinities with coal (within a range of 15.8% and 25%, respectively).

Luttrell et al. (1999) applied conventional and advanced precombustion cleaning technics on coals from Pittsburgh, Illinois and Coalburg (USA) to remove hazardous air pollutants. It was shown that HAPs (Hazardous Air Pollutants) rejections of 50–80% could be achieved by means of conventional cleaning processes. Advanced processes could enhance extent of rejection especially for trace elements linked with pyrite. Cadmium and mercury rejections were around 50%, and chromium, cobalt, lead and manganese rejections were around 70%.

Wenfeng et al. (2004) studied 43 elements in ROM coals obtained from northern Ordos basin and Shanxi Province (China). It was found that Br and Ba showed a strong affinity to the organic constituents and Cs, Cd, Pb, Zn and Hg were partially linked to the organic matter. The rest of trace elements were mainly associated with the mineral matter in coal. As and Hg were removed with extents of more than 60%, corresponding to a relatively successfull rejection process. Sb, S, Pb and Cd were found partly associated with the ash making minerals, so their rejections remained relatively less (around 30%). Se and Mo rejections could be improved if a further reduction in size was applied on ROM coal. S, Pb, Cd and Hg with partial bonding with the organic constituents could be decreased using different routes such as blending of ROM coal with other coals of relatively lower trace element contents.

Wenfeng et al. (2009) showed that hazardous trace elements could be removed via rejection of ash and sulfur bearing minerals by conventional cleaning. Such a cleaning process could be further improved using advanced cleaning techniques, such as froth flotation. Heavy medium separation on Antaibao coals from China were not adequately useful on the contents of U, Se, Br, Be and Cl owing to the affinity of these elements with organic constituents. Pb, Ba, V, Cr, Co, As, Hg, Cd, Fe, S yielded higher extent of removal by HMS. This was due to associations of these elements with inorganic portions. P, Mn, Zn, Cu, Br, U, Mo, Be and Cl were almost impossible to be removed by HMS. It was concluded that elements having affinity to the organic matter in coal could be enriched in the cleaned products after physical treatment.

Bergh et al. (2010) studied reduction of trace elements via dense medium separation and froth flotation for Witbank Coalfield No. 4 coal seam in South Africa. Reduction of the trace elements by froth flotation was lower as compared to dense medium separation. Reduction for trace elements via pyrite (As, Hg, Mo, Pb, Se, Mo, Cu, Ni and Cd) by flotation was not remarkable due to similar surface behavior of pyrite with coal. Mn removal was higher due to its association with carbonate minerals and clays. According to sink-float results, maximum As and Hg limits were determined at the lightest sepcific gravity products, corresponding to possible organic bonding of these trace elements.

Firth and Dale (1998) analyzed coal samples from different washeries in Australia with respect to the presence of trace elements. The coals were cleaned before exporting by gravitational methods as well as by flotation for -0.5 mm fractions. Ash content varied between 10-35% for raw coals and between 5-15% for the cleaned products. Some trace elements including titanium, vanadium and copper were removed effectively with the rejection of ash. Chronium, manganese, zinc and arsenic removals were relatively variable. The investigated coal samples showed that the amounts of the studied trace elements were less in Australian thermal coals as compared with world averages.

Mohanty et al. (1997) investigated coal samples from Illinois No. 6 coal seam (USA) which was crushed and ground to -250 micron size in order to apply advanced physical methods including enhanced gravity separator (EGS) and column flotation. Mentioned methods were found successful at removing ash, total sulfur and TEs. Ash making minerals were the hosts for Se, Hg and Cr, but Cr was moderately associated. 83% of pyritic sulfur and 84% of ash making parts could be rejected using the EGS-Column Flotation circuit. Content of Cr, Hg and Se were decreased by 62%, 86% and 80%, respectively. According to the study, suggested methodology were found highly effective and succesful in the removal of mentioned TEs with the inorganic part of the coal.

Akers and Raleigh (1998) reported that most of HAPs could be removed partially or fully via mineral matter rejections, i.e. higher removal of ash results in greater removal of most TEs. Factors affecting HAPs removal were explained in main categories as degree of liberation of host minerals for TEs, the relative intensity of cleaning (described as reduction of ash content), mode of occurrence and the

cleaning method. Northern Appalachian coals from USA were used for the tests in the work. Hg rejection was about 35% for uncrushed cleaned coal, but crushed and ground coals which were reduced to -100 mesh provided almost 50% Hg reduction. Higher reductions were obtained for As, Cr, Hg, ash and sulfur after sink and float application. Over 70% of Cr was found associated with clays. Illite was found as the major host for Cr. It was also found that As content increased with the increase in the grain size of pyrite. Pyrite was found as the main host mineral for As. According to the results physical cleaning methods, such as sink-float, could reduce much of As content, especially when pyrite particles were relatively larger. Hg was linked predominantly with pyrite and was suitable for removal by sink and float tests. However, due to similar surface properties of pyrite and organic matter of coal, froth flotation was not effective for Hg removal.

Davidson (1997) compiled an extensive survey about trace elements and their removals by conventional and alternative cleaning methods. The investigations for different coals showed that most of the trace elements were associated with ash making part of the coal and were available for removal by cleaning.

Hower et al. (1998) studied coal samples from Eastern Kentucky and Virginia coal preparation plants from USA. Many trace element contents including Cr, V, Zn, Ga, As, Zr, Nb, Pb, Mn and Rb were decreased, approximately with an extent of 90% as compared to the raw coal. Reduction of trace elements depended on the mode of occurrence of the host mineral and the size of the coal. Rejection of most trace elements by removal of inorganic matter was related with the degree of the fineness.

Demir (1998) studied Illinois coals using flotation and sink and float tests at -250 micron size to seek for the opportunity of trace elements rejection. Average decreases after sink-float tests at 55% ash removal were determined as follows; As 67%, Cd 78%, Hg 73%, Mn 71%, P 66%, Co 31%, Cr 27%, F 39%, Ni 25%, Pb 50%, S 28%, Sb 20%, Se 39%, Th 32%, U 8%. Only Be was enriched to some degree in the cleaned product. Sink and float tests were found to be more effective compared to flotation. B, Be, Ge, Ni, Sb, U and V were bound with the organic part of the coal, or might be finely disseminated in macerals, meaning that these elements were not available for an effective rejection through the removal of mineral matter heavy medium separation. Rejection of As, Cd, Hg, Mn, and P exceeded the extent

of ash rejection. This implied strong association of these elements with the ash making constituents and these elements were available for removal by ash rejection.

4. MATERIALS AND METHODS

4.1. Coal Sample and its Characterization

In this study, coal sample obtained from Salihpaşa-Merdivenli seam from Yatağan, Muğla, Turkey was used. The main motivation for selecting this seam was that this seam has recently been the main supply of lignite to Yatağan Thermal Power Plant and it is likely that it will preserve its importance as a source supplying this thermal plant within the next decades. Results of the proximate and ultimate analysis of Salihpaşa coal are presented in Table 4.1. and Table 4.2, respectively. Representative sampling was done on the belt conveyor which transfers the coal to the stock area of the power plant at certain intervals. By sampling, run-of-mine (ROM) Salihpaşa coal was collected and immediately put to air-tight plastic bags to preserve the original features of the coal. In the laboratory, ROM coal was further divided representatively into smaller portions using coning and quartering and using riffles, where necessary. Following these procedures, representative portions were prepared for analysis, characterization, size partitioning and laboratory scale sink and float testing.

Also, where necessary size of the ROM coal was reduced using laboratory scale jaw crusher, rod mill and ring mill, sequentially. For size-partitioning of the ROM coal, Tyler-scale laboratory sieves (Retsch) were used. Details about sink and float tests and size-partitioning are further described in the following sections.

Table 4.1. Proximate Analysis of Salihpaşa Coal

	As Received	Dry	Dry, Ash Free
Moisture, %	10.55	-	-
Ash, %	40.27	45.02	-
Volatile Matter, %	30.80	34.44	62.63
Fixed Carbon, %	18.38	20.54	37.37
Total	100	100	100

Table 4.2. Ultimate Analysis of Salihpaşa Coal

	%
C	30.02
H	1.92
N	0.96
S	2.05
O*	65.05

* by difference

Evaluated trace elements are Arsenic (As), Barium (Ba), Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Lead (Pb), Antimony (Sb), Selenium (Se), Uranium (U), Vanadium (V) and Zinc (Zn). These trace elements are in the list of potential environmental hazardous elements. Hence, in order to evaluate their contents, representative sampling applied on feed coal from Yatağan power plant played a crucial role, as being the primary step. The amount of mercury was determined using cold-vapor atomic adsorption analysis. The extent of all other studied trace elements were determined by ICP-MS (inductively coupled mass spectrometry) and ICP-AES (inductively coupled atomic emission spectrometry). Low temperature ashing at approximately 450 °C, was followed by acid digestion was applied to prepare representative coal samples for ICP-MS and ICP-AES.

To have a qualitative understanding about the mineralogical characteristics and major inorganic constituents of Salihpaşa lignite, XRD analysis was performed. The XRD spectrum of the sample, presented in Fig. 4.1, was obtained in the 5 – 100° range at a scan rate of 0.02°/min. In the figure, significant peak positions are shown

and labeled. According to the spectrum, the inorganic content of Salihpaşa coal is comprised mainly of carbonate minerals (calcite and dolomite), quartz and pyrite. It should be noted that the carbonate minerals in the coal are dominated by calcite and the amount of dolomite is relatively less. Presence and amount of pyrite is remarkable, as revealed by several peaks with apparent peak intensities. Pyrite presence in Salihpaşa coal is critical as it is likely to be the source of sulphur related pollution as well as pyrite may be the host of and/or associated to various trace elements. Despite peaks with relatively weaker intensities, presence of quartz should also be noted (Figure 4.1.).

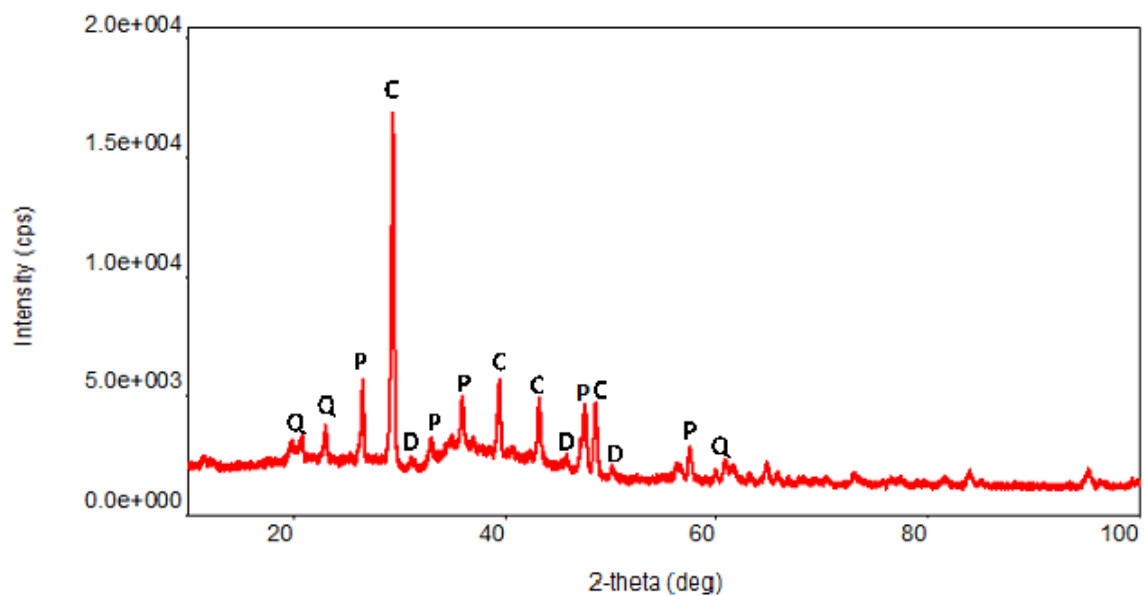


Fig. 4.1. XRD Spectrum of Salihpaşa Coal (Q = quartz, P = pyrite, C = calcite, D = dolomite).

4.2. Size Fractionation and Sink and Float Tests

Following characterization, Salihpaşa coal was divided into five size fractions of +50 mm, -50+18 mm, -18+9.5 mm, -9.5+0.5 mm and -0.5 mm. The abundance of each size fractions in the Salihpaşa run-of-mine coal is presented in Table 4.3. These certain size fractions were determined considering industrial acceptance, specifications and applications. Size fractionation was done to serve two objectives:

Table 4.3. Distribution of Salihpaşa ROM coal with respect to size fractions

Size fraction (mm)	Weight (g)	Weight (%)
+50	31323.15	19.49
-50+18	51888.05	32.28
-18+9.5	23074.49	14.36
-9.5+0.5	46969.94	29.22
-0.5	7475.37	4.65
Total	160731.00	100.00

The first goal was to analyze and assess each size fraction with respect to the presence of trace elements concerned. This would provide a detailed picture of the distribution of trace elements with respect to particle size and to determine whether a specific correlation between the fineness of coal particles and concerned trace element exists.

This correlation would also be a viable indication between a possible ash-trace element link or vice versa, in case an observable correlation between particle fineness and the extent of ash could be identified. In this respect, ash content of each size fraction was also determined.

Secondly, size fractionation was performed to apply sink and float tests on Salihpaşa coal in a detailed way so as to see the effectiveness of separation with respect to specific particle size fractions, i.e. to have an idea about the performance and success of a possible heavy medium based cleaning scenario as a function of size fractions. In this regard, trace element assays in the sink and float products of each size fraction were determined and evaluated in addition to the ash content of these products. This directly provided the opportunity to identify the extent of rejection achievable for the trace elements concerned in case of a potential heavy medium separation procedure on Salihpaşa coal.

Sink and float tests in laboratory scale represent the gravity-based and widely used process known as dense medium separation (DMS) or heavy medium separation (HMS). It is a proven and widely used method especially to investigate the liability of a particular coal type to cleaning or de-ashing and desulphurization.

For sink and float tests on Salihpaşa coal, a series of heavy liquids with specific gravities ranging between 1.3-1.9 were prepared at 0.1 specific gravity increments. The specific gravity of the heavy liquid was adjusted using and dissolving zinc chloride (ZnCl_2) salt. The reasons for using ZnCl_2 , rather than organic materials and/or solutions, in preparing the heavy liquids were; ZnCl_2 , is a relatively safer, less harmful and much cheaper chemical as compared to the organic chemicals available for this purpose. Separate series of sink and float tests were conducted at four distinct coal size fractions of +50 mm, -50+18 mm, -18+9.5 mm and -9.5+0.5 mm. Here, it should be noted that the -0.5 mm was not subjected to sink and float testing and directly discarded and characterized as reject material. It was seen that the extent of ash in the -0.5 mm fraction was relatively high whereas the total weight of this fraction in the entire mass was quite small (Table 4.3). Based on these, it could be anticipated that the -0.5 mm fraction of Salihpaşa coal is available for direct rejection as a pre-concentration strategy in the possible cleaning of Salihpaşa coal by HMS. For sink and float tests on the remaining four size fractions, seven vessels, involving the heavy medium at pre-determined specific gravities were prepared and used. The specific gravity of the heavy liquids were adjusted using hydrometers and by gradually dissolving ZnCl_2 , until each targeted specific gravity level is achieved. The test procedure applied in accordance with the ASTM standards is briefly, as follows (ASTM, 2012);

Approximate portions of coal was introduced into the densest medium at the desired specific gravity level. In this study, this corresponds to the medium at a specific gravity of 1.9. The mass in the vessel is gently stirred in order to allow all the coal mass be subjected to the separation specific gravity. Sufficient time is also allowed for the stabilization of the particles in the vessel, i.e. for a complete separation to occur. Next, the float product was gently and smoothly removed using a simple wire mesh strainer. This float product is the feed for the second densest bath in the series, i.e. the vessel with the 1.8 specific gravity medium. The sink product of 1.9 specific gravity was later removed from the vessel, left to drain in a pan/tray. After draining, the product is rinsed several times to assure removal of ZnCl_2 remains on coal particles. This basic procedure was repeated until the entire coal sample at the distinct size fractions were subjected to separation at all mediums with subsequent specific gravities from 1.9 to 1.3.

4.3. Pearson's Correlation Coefficient

Pearson's Correlation Coefficient (r), a.k.a Pearson's product moment, is denoted by “ r ”. Pearson's r is unitless and ranges between -1 and +1. Linear association between two variables can be measured by Pearson's Correlation Coefficient (Weinberg and Abramowitz, 2002; Le Blanc, 2003).

A value of +1 corresponds to a scatter plot where all the points fall on a straight line with a positive slope, defined as perfect positive association. In contrast, a value of -1 corresponds to a scatter plot where all the data points fall on a straight line with a negative slope. Such a relation is termed as perfect negative association. A correlation value of zero indicates that there is no association between the variable of the concerned parameters. For this study, a r value greater than zero (showing positive correlation) indicates that as the ash increases the fineness of coal also increases. On the contrary, a negative r value corresponds to an inverse relation between ash and fineness of Salihpaşa coal.

Preliminary/supporting informations of association of trace elements on inorganic or organic matter in coal were also determined by calculating the Pearson's r values (Gürdal, 2011; Dai et al., 2005).

5. RESULTS AND DISCUSSION

The extent of the studied elements in Salihpaşa ROM coal and their comparison with average values of trace element contents of Turkish and world coals are presented in Table 5.1. It is remarkable that only Hg amount of Salihpaşa ROM coal (1.1 ppm) was found higher as compared to Turkish coals and also slightly higher than the maximum Hg extent in world coals. In addition, Cr, Mo and U exceeded the world range. The remaining TEs were in the range of both Turkish and the world coals (Table 5.1).

Table 5.1. Trace Element Contents of some World and Turkish Coals with Salihpaşa ROM coal

Trace Element	Trace Element Content (ppm)		
	World Coals ^a	Turkish Coals ^b	Salihpaşa Coal ^c
As	0.5–80	1.8–620	62.6
Ba	20–1000	15–590	151.8
Cd	0.1–30	No Data	1.2
Cr	0.5–60	3.7–540	61
Cu	0.5–50	1.5–100	43.2
Hg	0.02–1	0.03–0.66	1.1
Mo	0.1–10	0.43–69	13.6
Mn	5–300	13–650	124.1
Ni	0.5–50	3.1–1600	33
Pb	2–80	0.95–58	10.9
Se	0.2–10	0.045–24	2.4
Sb	0.05–10	0.12–41	5.1
U	0.5–10	0.32–140	18
V	2–100	5.5–270	57
Zn	5–300	5.8–260	48

^a Swaine (1990); ^b Palmer et al. (2004); ^c Run-of-mine

5.1. Relationship Between Trace Element Contents and Size Fractions

It was seen that the amount of As increased with decreasing coal size (Table 5.2, Fig. 5.1.). In the coarsest fraction, +50 mm, As content was 36.20 ppm whereas in the finest fraction the extent of As was almost three times higher, corresponding to an amount of 105.00 ppm. This has shown that As was liable to disintegrate and liberate with comminution and fragmentation of coal. It should also be noted that the ash content of Salihpasa coal tends to increase with decrease in particle size (Table 5.2, Fig. 5.1.), i.e. the finer size fractions became richer in terms of inorganic, ash making constituents whereas the coarser fractions such as +50 mm and -50+18 mm were relatively dominated by the organic content. It can be implied that As existence is in direct relationship with the ash making constituents. In other words it has an affinity towards the inorganic fraction in Salihpasa coal. The typical range of As in various world coals is 0.5 – 80 ppm (Swaine, 1990). There is direct evidence and a substantial amount of indirect evidence for the association of As with pyrite from most U.S. coals (Finkelman, 1994). As is mainly associated with the mineral constituents, with small portions that may be organically linked (Swaine, 1990). Overall, several studies showed that As was generally associated with the mineral matter and especially with sulfides. Pyrite is the most common host mineral for As content (Finkelman, 1994; 1995; Gluskoter et al., 1977; Goodarzi, 2002). The findings in this study are also in agreement with previous findings in literature regarding the association of As mainly with the mineral matter in coals.

Table 5.2. Distributions of As, Ba, Cd with respect to size fractions of Salihpaşa ROM Coal

Size (mm)	Weight (g)	Weight (%)	Ash (%)	Arsenic, As		Barium, Ba		Cadmium, Cd	
				Assay (ppm)	Dist. (%)	Assay (ppm)	Dist. (%)	Amount (ppm)	Dist. (%)
+50	31323.15	19.49	39.78	36.2	11.28	72.60	9.28	1.4	22.74
-50+18	51888.05	32.28	43.15	45.72	23.59	92.60	19.60	1.3	34.97
-18+9.5	23074.49	14.36	46.55	61.32	14.07	134.00	12.61	1.1	13.16
-9.5+0.5	46969.94	29.22	57.08	92.6	43.25	262.20	50.24	1	24.35
-0.5	7475.37	4.65	69.56	105	7.81	270.80	8.26	1.2	4.65
Total	160731	100.00		62.56	100.00	152.50	100.00	1.2	99.87

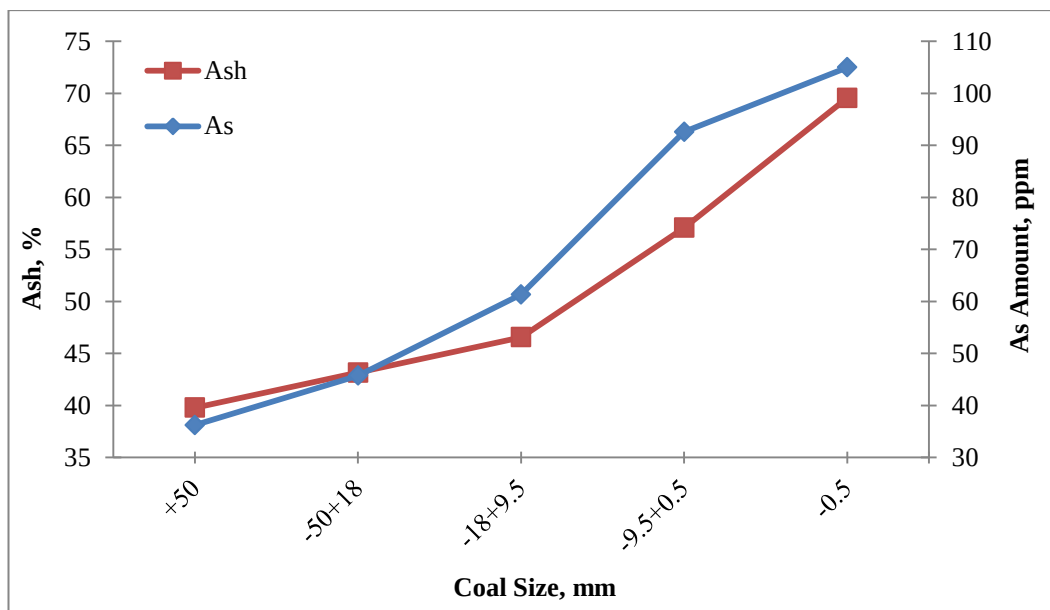


Fig. 5.1. Arsenic content vs. size fractions of Salihpaşa ROM Coal

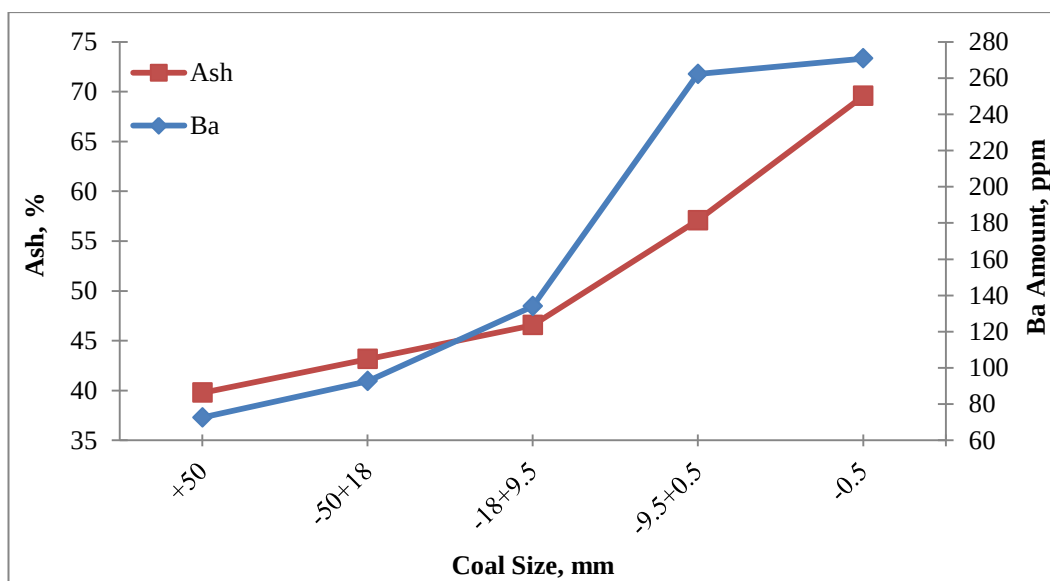


Fig. 5.2. Barium content vs. size fractions of Salihpaşa ROM Coal

The amount of Barium (Ba) increased with fineness of coal size (Table 5.2, Fig. 5.2.). The coarsest fraction, +50 mm, had minimum Ba which is 72.60 ppm. The finest fraction (-0.5 mm) had the highest extent of Ba (270.80 ppm) which was 3.7 times higher than that of +50 mm size fraction. This showed that Ba was liable to disintegrate and liberate with comminution and fragmentation of coal. Ba amount followed a similar trend with the tendency of ash w.r.t particle size (Table 5.2, Fig. 5.2.), that is the indicator for strong association between Ba and inorganic matter. Ba

is mainly associated with the inorganic part in coal and mineral matter and barite is the main host mineral for Ba in the coal. Gürdal (2011) investigated Çan coal and also found possible inorganic linkage of Ba, supporting the findings for Salihpaşa coal.

Cadmium (Cd) content in Salihpaşa coal followed a decreasing trend from +50 mm to -9.5+0.5 mm but an increase in Cd amount was observed at -0.5 mm size fraction (Table 5.2, Fig. 5.3.). Content of Cd was inversely proportional with the ash content of district size fractions except -0.5 mm. Cd was mostly associated with the organic matter, on the other hand Cd was also reported to be bonded with the mineral matter in coal and particularly with sphalerite (Gluskoter et al., 1977; Swaine, 1990; Finkelman, 1994). However, possible organic association was claimed by Goodarzi (2002).

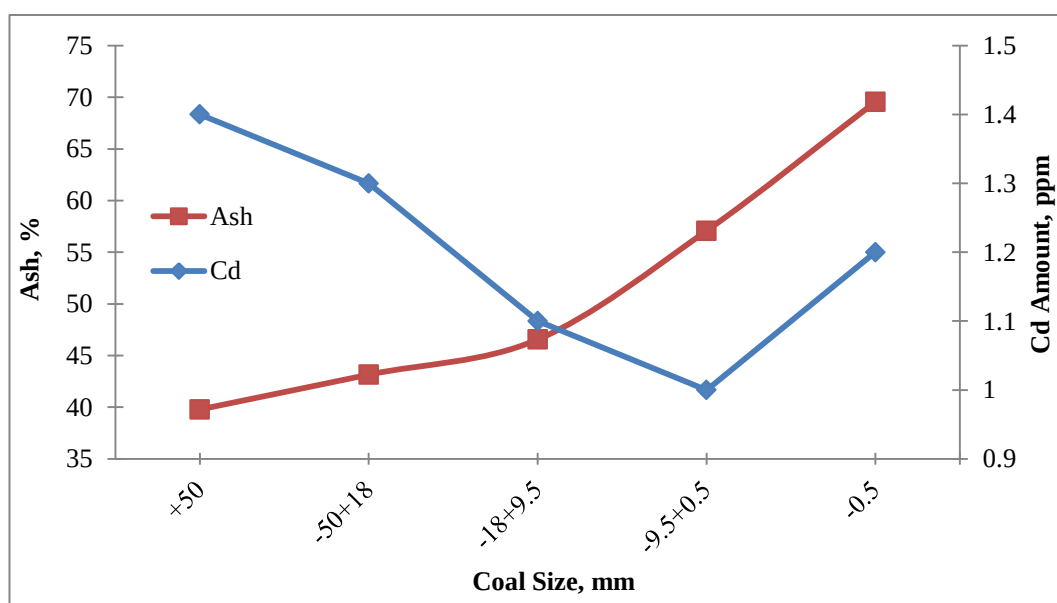


Fig. 5.3. Cadmium content vs. size fractions of Salihpaşa ROM Coal

Chromium (Cr) amount tended to decrease with fineness in coal and was in an inverse relationship with the ash (Table 5.3, Fig. 5.4.). Cr content was almost reduced by 50% from the coarsest to the finest fraction (Table 5.3.). This has shown that Cr was not liable to disintegrate and liberate with comminution of coal, which indicates organic linkage of chromium in Salihpaşa coal. Similar findings were also reported for Canadian and USA coals (Goodarzi, 2002).

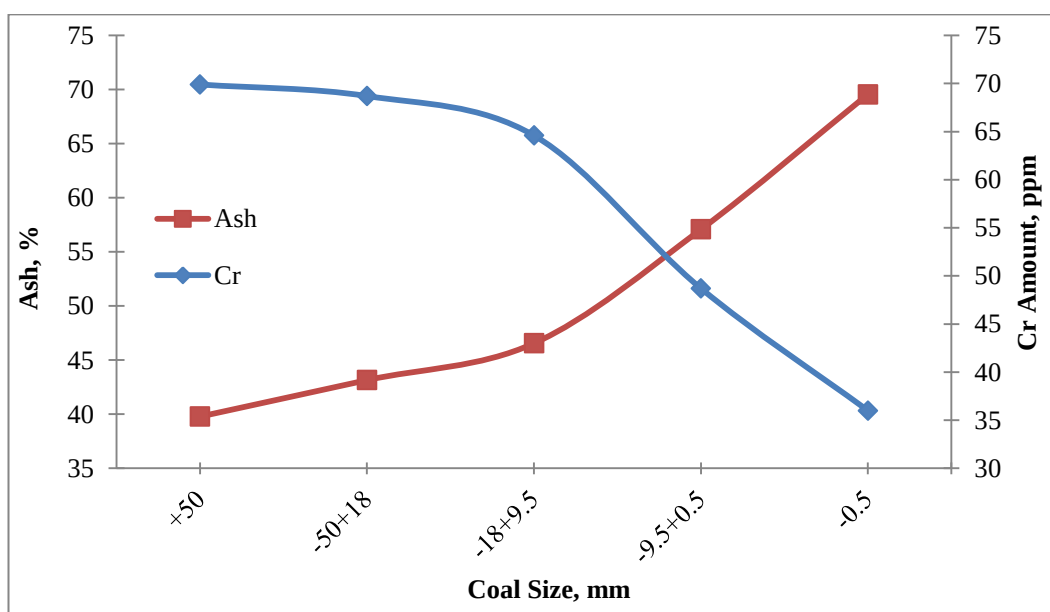


Fig. 5.4. Chromium content vs. size fractions of Salihpaşa ROM Coal

Table 5.3. Distributions of Cr, Cu, Hg with respect to size fractions of Salihpaşa ROM Coal

Size (mm)	Weight (g)	Weight (%)	Ash (%)	Chromium, Cr		Copper, Cu		Mercury, Hg	
				Assay (ppm)	Dist. (%)	Assay (ppm)	Dist. (%)	Assay (ppm)	Dist. (%)
+50	31323.15	19.49	39.78	69.9	22.33	32.2	14.52	0.9	15.94
-50+18	51888.05	32.28	43.15	68.7	36.36	38.2	28.53	0.9	26.41
-18+9.5	23074.49	14.36	46.55	64.6	15.2	46.2	15.34	1.1	14.36
-9.5+0.5	46969.94	29.22	57.08	48.7	23.33	51.8	35.02	1.4	37.19
-0.5	7475.37	4.65	69.56	36	2.74	62.8	6.76	1.7	7.19
Total	160731	100.00		60.98	99.97	43.30	100	1.11	100

Copper (Cu) amount increased with increase in ash content and decrease in coal size. (Table 5.3, Fig. 5.5.). Content of Cu was almost doubled from +50 to -0.5 mm fraction. Linear relationship between Cu content and ash yield showed that a strong linkage existed amongst ash making constituents and Cu content. Findings in literature point to Cu association with both organic and inorganic matter in coal. A definite conclusion on the the mode of occurrence of Cu in coal has not been drawn yet (Swaine, 1990; Finkelman, 1994). Swaine (1990) reported that Cu could be associated with inorganic constituents (sulphides). On the other hand Finkelman (1994) stated that Cu was either associated with organic part or with inorganic matter

(clays) in the coal matrix. For Lower Kittanning seam (USA), Rimmer (1991) found strong indications that Cu was associated with clays. Gürdal (2011) statistically showed that there was a strong relationship between Cu and ash making part in Çan coal from Turkey. In addition, Cu was found in association with sulphides (pyrite) in Etili (Turkey) region. In contrast, Mukherjee et al. (1988) found for coal seams in India that Cu was predominantly associated with the organic matter. Gluskoter et al. (1977) classified Cu as an intermediate mineral, which means it is neither strongly associated with the organic matter in coal nor with the inorganic constituents.

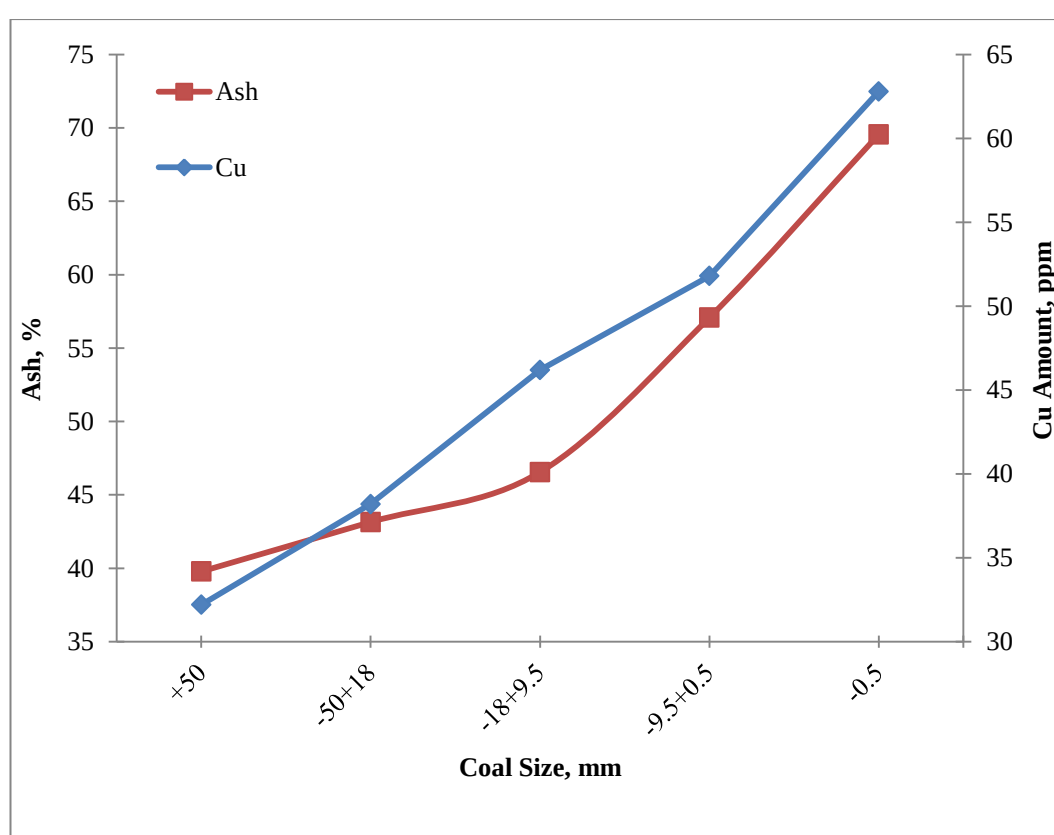


Fig. 5.5. Copper content vs. size fractions of Salihpaşa ROM Coal

For Mercury (Hg), the content was constant in the two coarsest fractions and there was an increase in the amount of Hg with decrease in coal size. This showed the liability of Hg to disintegration and liberation with comminution of coal, particularly for the sizes finer than -50+18 mm (Table 5.3., Fig. 5.6.). Higher Hg content (especially at -18+9.5 mm and finer fractions) with increase in ash showed that Hg was mostly associated with the inorganic matter in Salihpaşa coal. Swaine (1990) concluded that Hg was mainly associated with pyrite and with sphalerite. Finkelman

(1994) also agreed that Hg was mainly as associated with found in pyrite in coal. The occurrence of Hg in USA coals has been studied by the US Geological Survey (Tewalt et al., 2001), and it was concluded that due to low quantity of Hg, it was particularly difficult to determine the exact modes of mercury occurrence in USA coals. Yudovich and Ketris (2005) reviewed the geochemistry of Hg in various world coals and suggested that Hg might be associated with the clays (silicates), organic matter and sulphides.

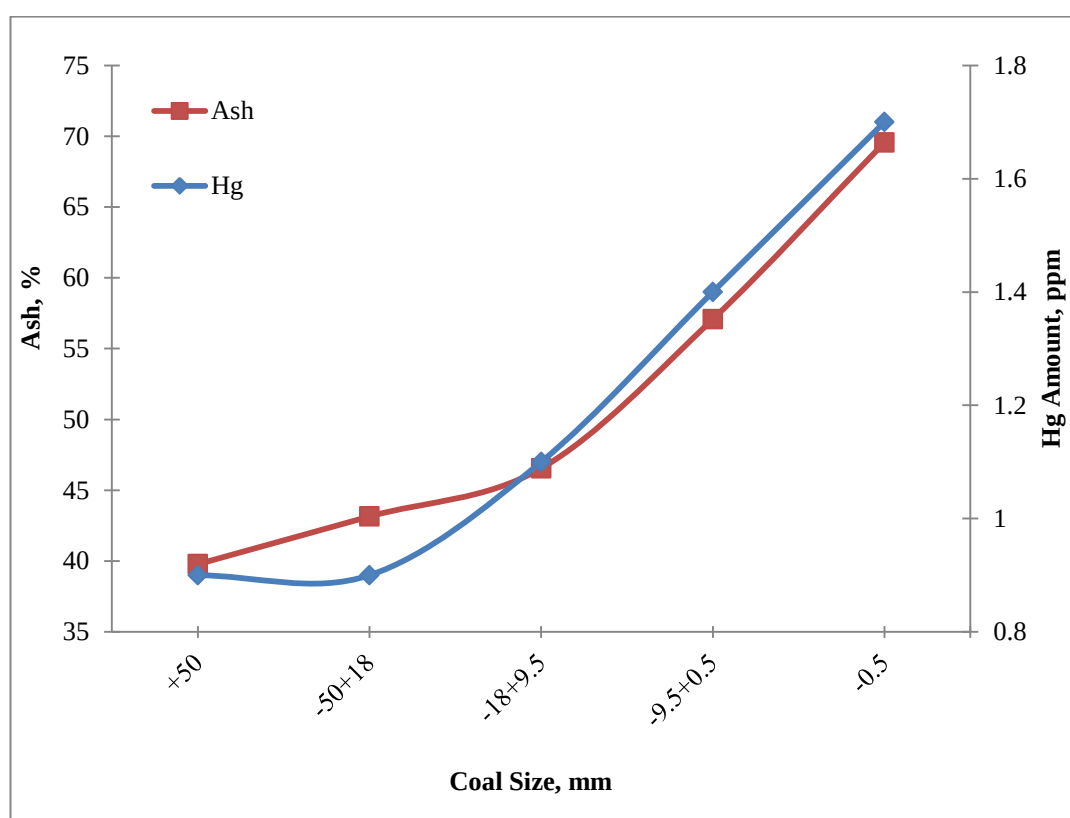


Fig. 5.6. Mercury content vs. size fractions of Salihpaşa ROM Coal

The amount of Molybdenum (Mo) increased with decrease in particle size, which is an indicator for being liable to liberation with comminution of coal. Maximum amount of Mo (32 ppm) was obtained at -0.5 mm fraction, and was more than 4.5 times of the minimum amount of 6.9 ppm obtained at +50 mm fraction. In addition, there was a sharp increase in Mo from -9.5+0.5 mm size fraction to -0.5 mm, from 19.10 ppm to 32 ppm (Table 5.4, Fig. 5.7.). Mo content had direct proportional relationship with increasing ash yield, most probably due to having strong affinity to ash making inorganic constituents. Mo was found associated with the inorganic part of coal

(Goodarzi, 2002). Also, Gürdal (2011) found that there was a direct relationship between Mo and sulphur content in Turkish coals.

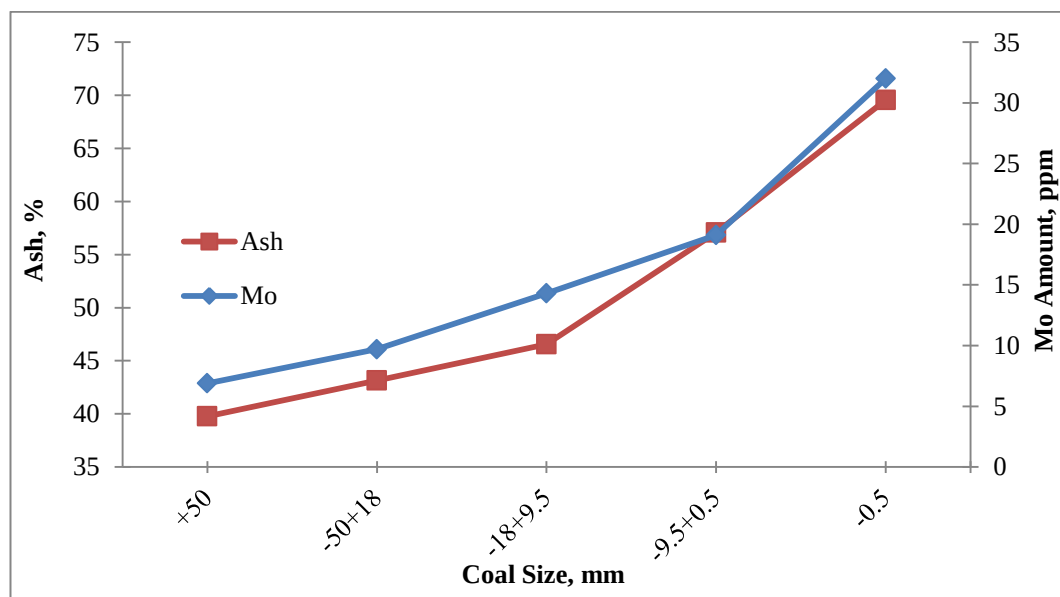


Fig. 5.7. Molybdenum content vs. size fractions of Salihpaşa ROM Coal

Table 5.4. Distributions of Mo, Mn, Ni with respect to size fractions of Salihpaşa ROM Coal

Size (mm)	Weight (g)	Weight (%)	Ash (%)	Molybdenum, Mo		Manganese, Mn		Nickel, Ni	
				Assay (ppm)	Dist. (%)	Assay (ppm)	Dist. (%)	Assay (ppm)	Dist. (%)
+50	31323.15	19.49	39.78	6.9	9.89	56.1	8.81	32.3	19.07
-50+18	51888.05	32.28	43.15	9.7	23.03	92.2	23.98	33	32.28
-18+9.5	23074.49	14.36	46.55	14.3	15.09	108.2	12.52	32.9	14.31
-9.5+0.5	46969.94	29.22	57.08	19.1	41.04	196.5	46.27	32.2	28.51
-0.5	7475.37	4.65	69.56	32.0	10.94	224.8	8.42	40	5.64
Total	160731	100		13.60	99.99	124.11	100.0	32.94	99.82

Manganese (Mn) content of -0.5 mm size fraction is four times higher than the coarsest fraction (+50 mm) (Table 5.4, Fig. 5.8.). Mn content was inversely related with coal particle size. Increase in Mn content with increase in ash revealed strong association with inorganic constituents. According to the Swaine (1990) modes of occurrence for Mn were encountered as associations both with carbonate minerals and in clays. Similarly, Finkelman (1994) reported that Mn content might occur in bituminous coal as a solid solution within the carbonate minerals, siderite and

ankerite. Therefore, the findings for Mn in Salihpaşa coal in this study are in agreement with previous notable observations in literature.

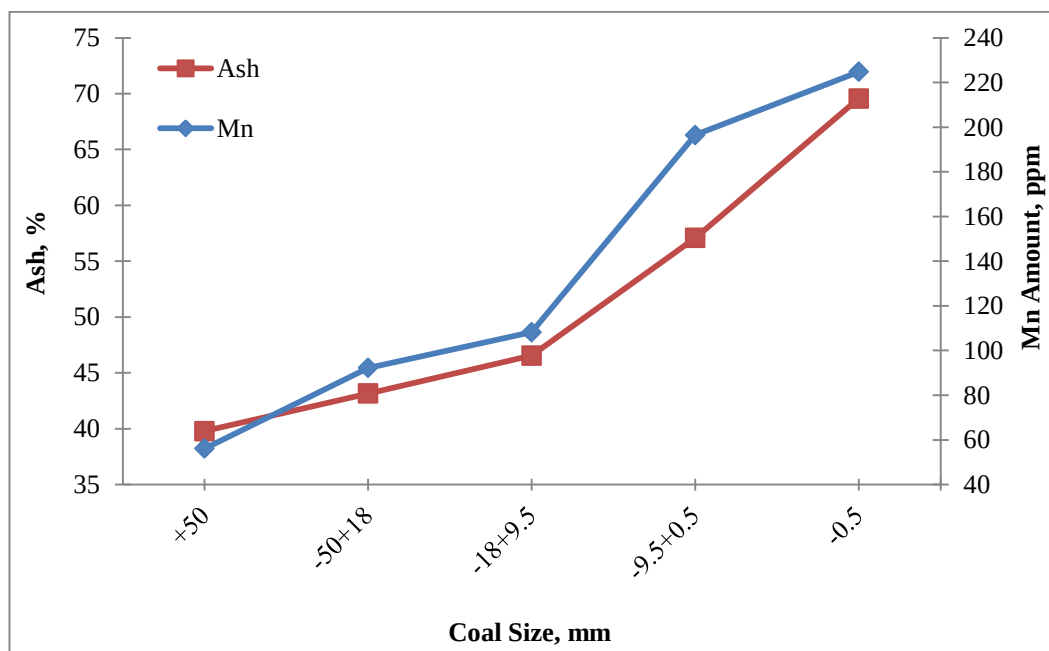


Fig. 5.8. Manganese content vs. size fractions of Salihpaşa ROM Coal

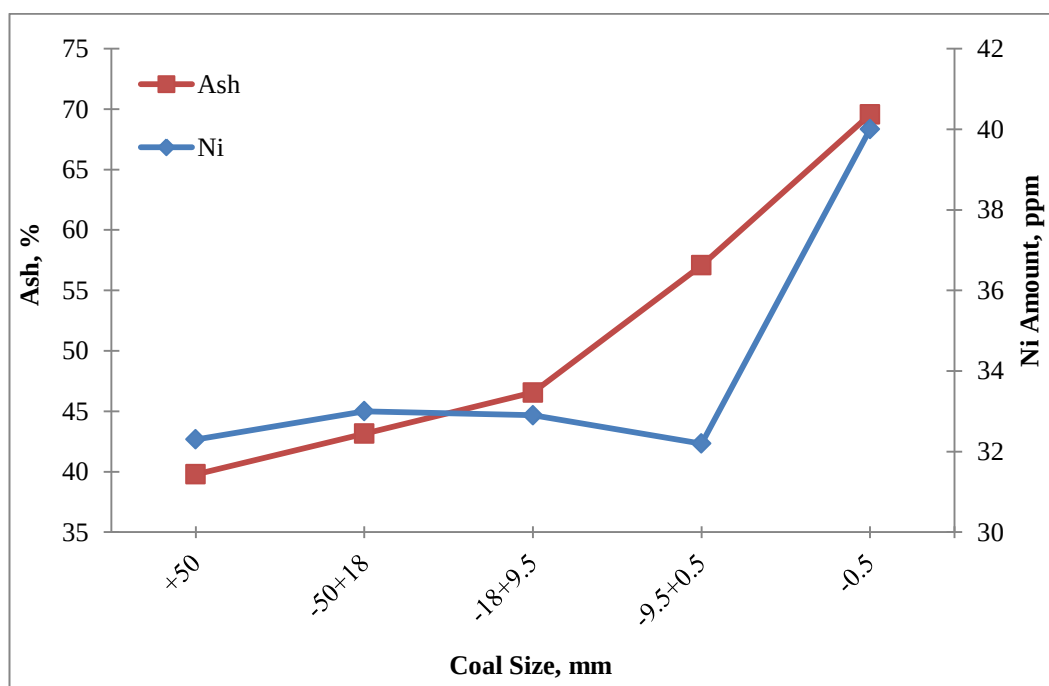


Fig. 5.9. Nickel content vs. size fractions of Salihpaşa ROM Coal

Nickel (Ni) content remained stable for coal sizes except the apparent increase at -0.5 mm. This could be attribute to obtaining the maximum liberation at the finest fraction of -0.5 mm. This could be attributed to higher degree of liberation at -0.5 mm (Table 5.4, Fig. 5.9.). This behaviour showed that Ni was associated both with organic and inorganic constituents in Salihpaşa coal. Previous work have shown that Ni may be either organically bound or found as associated with sulphides. Mukherjee et al. (1988) reported Ni was partially associated as organic chelates, while, Swaine (1990) suggested that Ni may be inorganically linked with sulfide minerals. Similarly, Gürdal (2011) reported that Ni showed positive correlation with inorganic minerals in Çan (Turkey) coal.

A slight increase in lead (Pb) content with decreasing coal particle size was observed (Table 5.5, Fig. 5.10.). Maximum Pb content was obtained at -0.5 mm and it was approximately 50% less than the lead content at the coarsest fraction of +50 mm. Proportional increase with ash showed that Pb was associated with inorganic minerals in Salihpaşa coal and Galena is the identified as the most common form of lead found in coal. Finkelman (1994) reported that Pb was observed mainly as a metallic sulfide (Galena, PbS) or as associated with other sulfide minerals. Gürdal's (2011) findings for Çan coal also showed that Pb was associated mainly with the inorganic constituents.

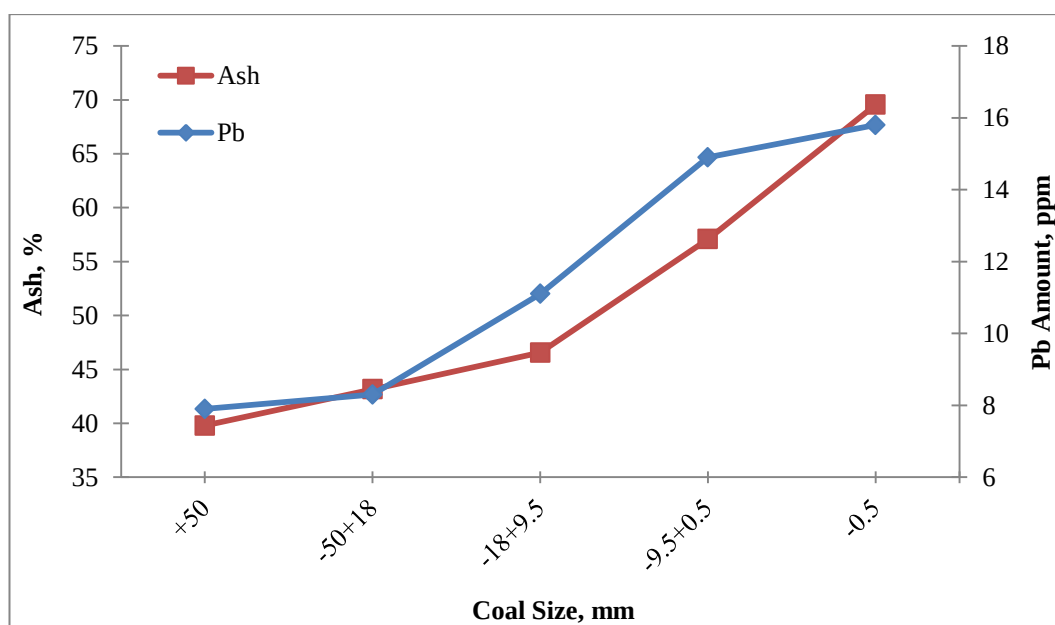


Fig. 5.10. Lead content vs. size fractions of Salihpaşa ROM Coal

Table 5.5. Distributions of Pb, Se with respect to size fractions of Salihpaşa ROM Coal

Size (mm)	Weight (g)	Weight (%)	Ash (%)	Lead, Pb		Selenium, Se	
				Assay (ppm)	Dist. (%)	Assay (ppm)	Dist. (%)
+50	31323.15	19.49	39.78	7.9	14.12	2.77	22.49
-50+18	51888.05	32.28	43.15	8.3	24.58	2.53	34.03
-18+9.5	23074.49	14.36	46.55	11.1	14.62	2.42	14.48
-9.5+0.5	46969.94	29.22	57.08	14.9	39.95	2.02	24.6
-0.5	7475.37	4.65	69.56	15.8	6.74	1.67	3.24
Total	160731	100.00		10.90	100.01	2.37	98.83

After nickel maximum decrease ratio between the trace mineral extents in the coarsest and finest fractions was determined for Selenium (Se). Se content was inversely proportional with ash and directly proportional with fineness (Table 5.5, Fig. 5.11.). Reverse relation with ash showed that Se was mostly associated with the organic part in coal. There are several modes of occurrence reported for Se in coal (Swaine, 1990). Se was found organically associated (Finkelman, 1994), while Some Se content was also found linked with the inorganic part, particularly with sulfide minerals in coal, mainly with pyrite (Swaine, 1990). Gürdal (2011) reported that coal from Çan/Turkey basin had Se-S association and pyrite was possibly the host mineral for Se.

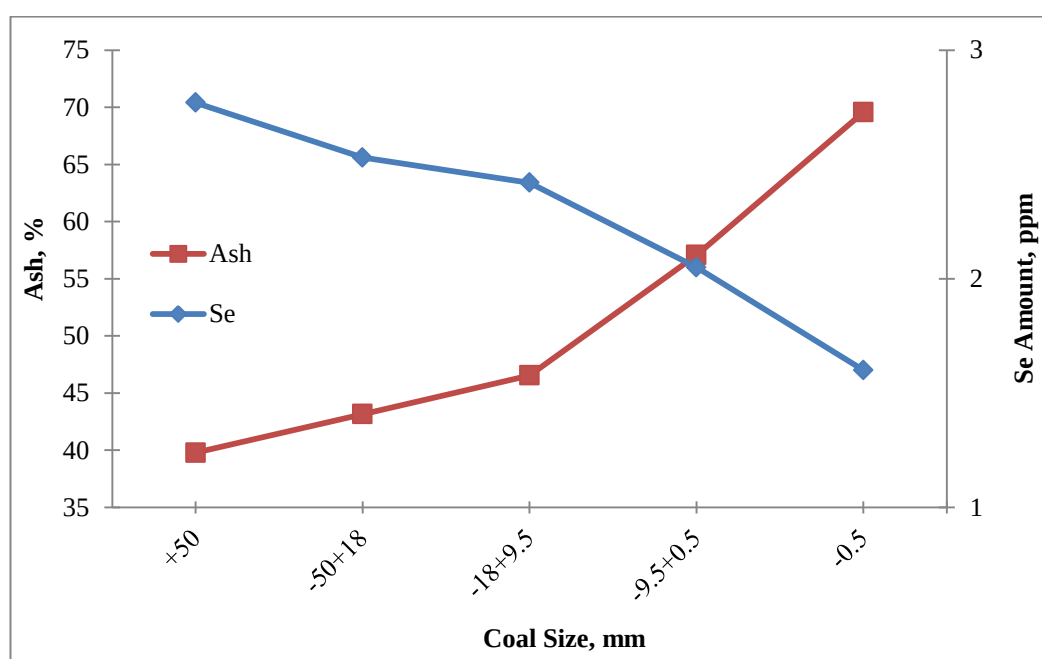


Fig. 5.11. Selenium content vs. size fractions of Salihpaşa ROM Coal

The trend of Antimony (Sb) content was opposite of ash content with respect to particle size (Table 5.6, Fig. 5.12.). Amount of Sb decreased with decreasing particle size. This implies organic affinity of Sb in Salihpasa coal. Findings reported by Gluskoter et al. (1977) and Swaine (1990) comply with the observations related to antimony content of Salihpasa coal: Gluskoter et al. (1977) indicated that Sb in coal was organically associated. In agreement with these findings, Swaine (1990) also showed that presence of Sb in coal was hosted mainly by the organic matter.

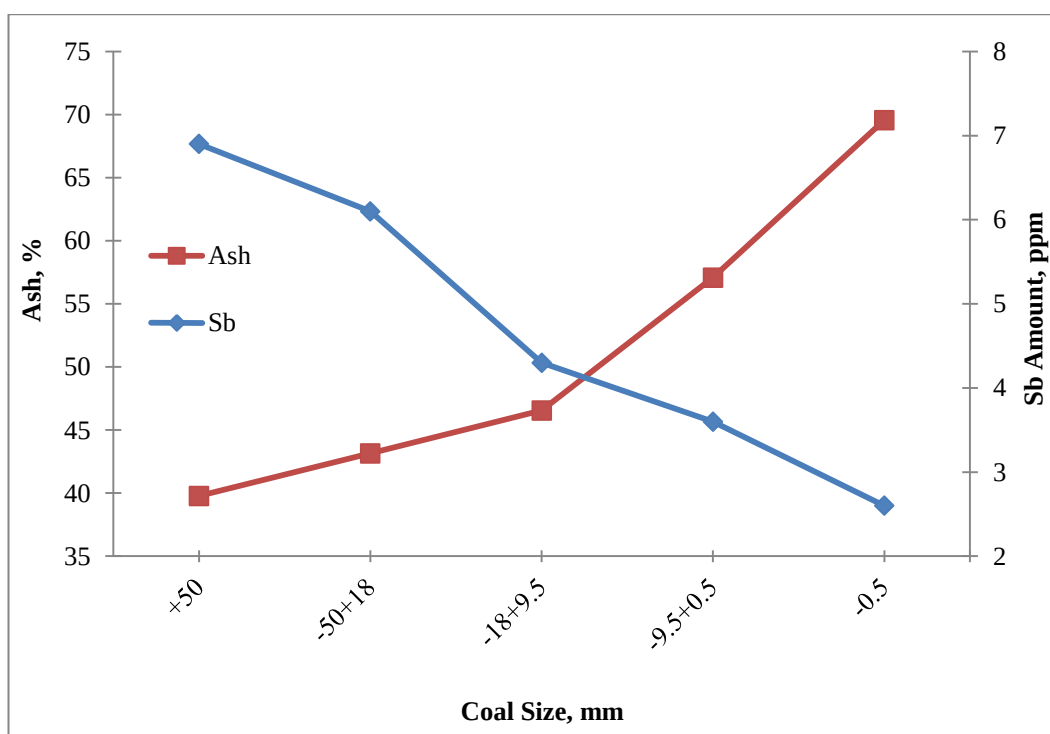


Fig. 5.12. Antimony content vs. size fractions of Salihpasa ROM Coal

Table 5.6. Distributions of Sb and U with respect to size fractions of Salihpasa ROM Coal

Size (mm)	Weight (g)	Weight (%)	Ash (%)	Antimony, Sb		Uranium, U	
				Assay (ppm)	Dist. (%)	Assay (ppm)	Dist. (%)
+50	31323.15	19.49	39.78	6.9	26.37	23.4	25.33
-50+18	51888.05	32.28	43.15	6.1	38.61	21.4	38.38
-18+9.5	23074.49	14.36	46.55	4.3	12.1	17.4	13.88
-9.5+0.5	46969.94	29.22	57.08	3.6	20.63	12.5	20.29
-0.5	7475.37	4.65	69.56	2.6	2.37	8.0	2.07
Total	160731	100.00		5.1	100.08	17.99	99.95

An apparent decrease in Uranium (U) content was determined from the coarsest to the finest fraction in Salihpaşa coal. The extent of U in the +50 mm fraction was approximately three times higher than the extent of U in the -0.5 mm fraction (Table 5.6, Fig. 5.13.). U content decreased with the fineness of coal particles and it was also inversely proportional with the amount of ash as the coal particle size became finer. These findings point to uranium-organic matter association in Salihpaşa coal. These observations comply with those reported by Finkelman (1995) regarding the organic-association of uranium in coal.

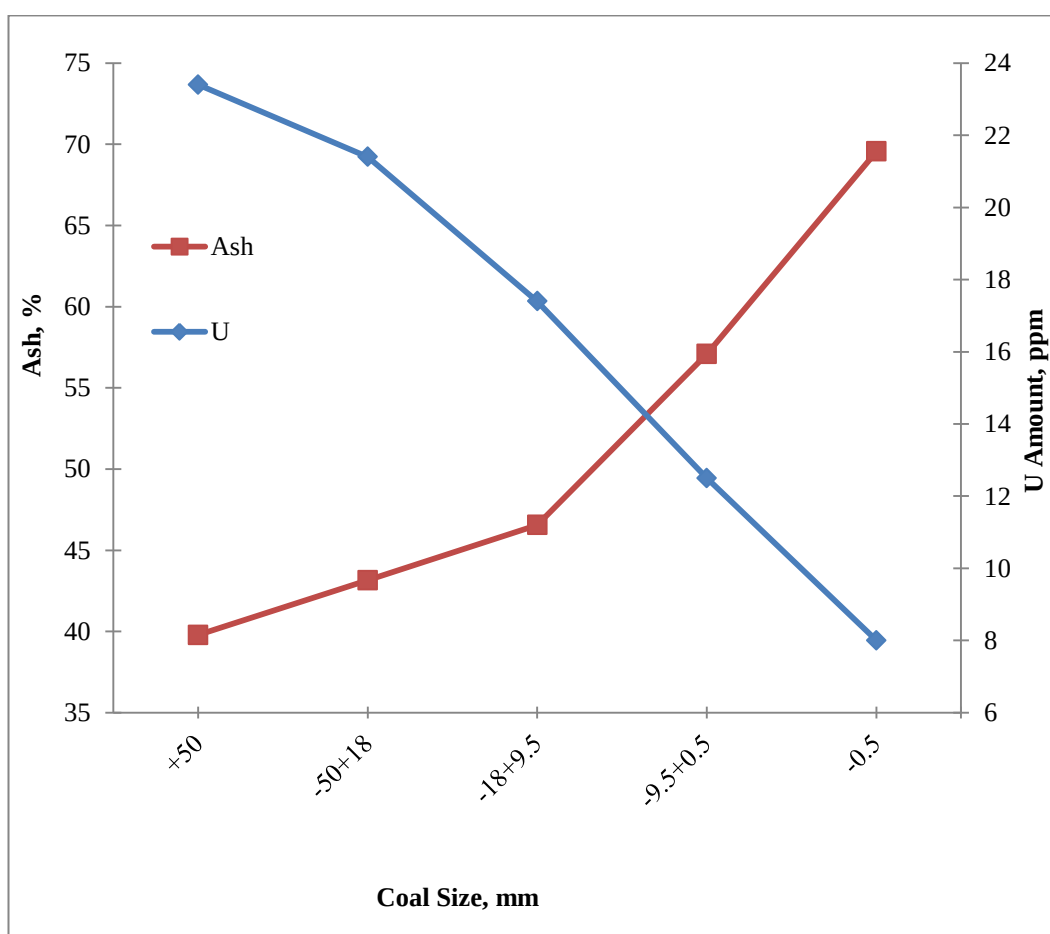


Fig. 5.13. Uranium content vs. size fractions of Salihpaşa ROM Coal

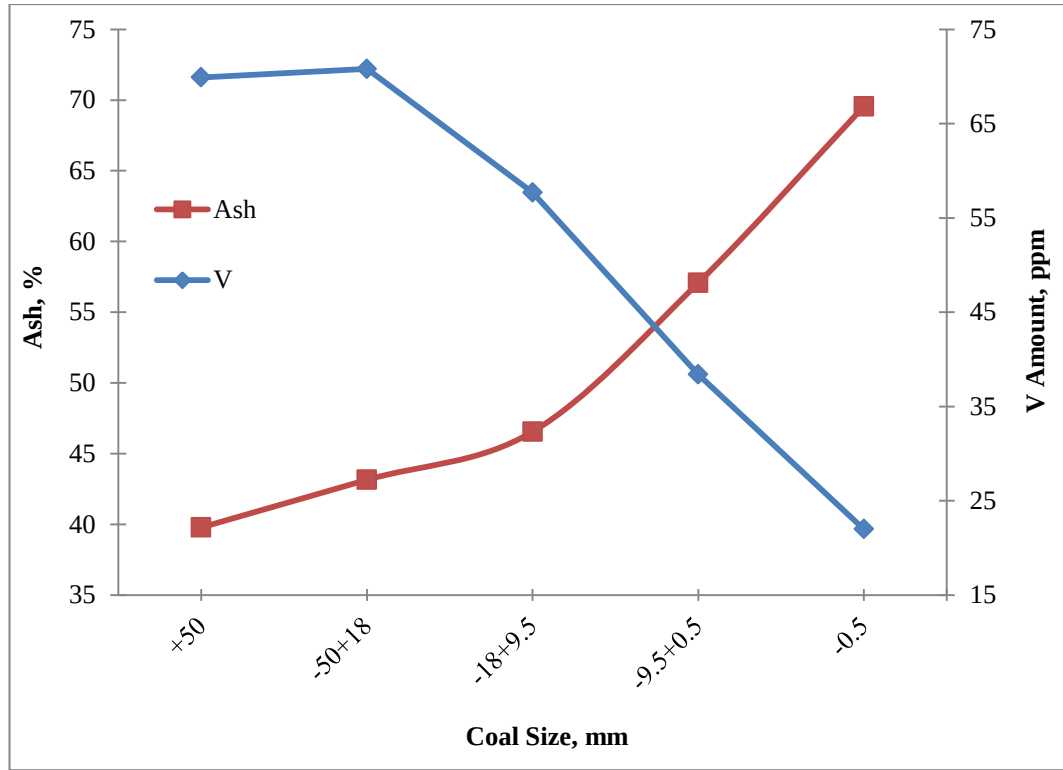


Fig. 5.14. Vanadium content vs. size fractions of Salihpaşa ROM Coal

Table 5.7. Distributions of V and Zn with respect to size fractions of Salihpaşa ROM Coal

Size (mm)	Weight (g)	Weight (%)	Ash (%)	Vanadium, V		Zinc, Zn	
				Assay (ppm)	Dist. (%)	Assay (ppm)	Dist. (%)
+50	31323.15	19.49	39.78	69.9	23.9	38.7	15.71
-50+18	51888.05	32.28	43.15	70.8	40.1	38.8	26.1
-18+9.5	23074.49	14.36	46.55	57.7	14.53	50.6	15.13
-9.5+0.5	46969.94	29.22	57.08	38.4	19.69	59.8	36.41
-0.5	7475.37	4.65	69.56	22.0	1.8	69.0	6.69
Total	160731	100.00		57.01	100.01	48.02	100.3

Having no direct correlation with increasing ash, Vanadium (V) revealed association with organic matter in Salihpaşa coal (Table 5.7, Fig. 5.14.). Vanadium content tended to decrease with decreasing coal size. In contrast with Salihpaşa coal, Gürdal (2011) for Çan/Turkey and Querol et al. (1996) for Mequinenza/Spain coals reported that vanadium was mainly concentrated in the inorganic part of the coal. However, it was also reported that vanadium might be linked to both inorganic and organic parts in coal (Finkelman, 1995).

Zinc (Zn) content increased with decreasing particle size and was directly proportional with ash (Table 5.7, Fig. 5.15.). The change in the extent of zinc from the coarsest fraction (+50 mm, 38.7 ppm) to the finest fraction (-0.5 mm, 69 ppm) was quite remarkable. The extent of zinc also follows the increase in ash content towards finer fractions. These observations imply strong association of zinc with the inorganic constituents in Salihpaşa coal as well as its tendency to disintegrate and become more abundant with increasing fineness. These findings for Salihpaşa coal were supported by Goodarzi (2002), who showed zinc association with the inorganic matter in coal, especially with sulphides. Similarly, Gürdal (2011) reported that Zn was most likely to be associated with the inorganic mineral content of coal, particularly with sulphide

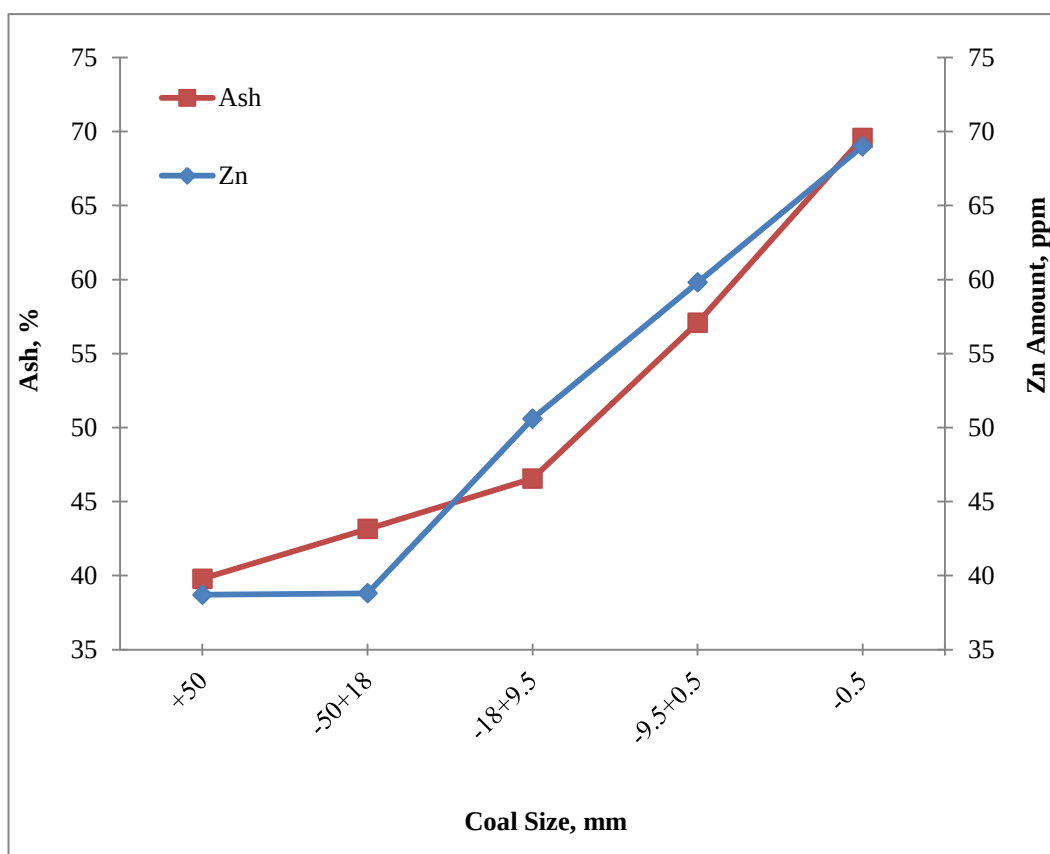


Fig. 5.15. Zinc content vs. size fractions of Salihpaşa ROM Coal

Overall evaluation on the relation of various trace elements with particle size of Salihpaşa coal and the association of these elements with the ash making constituents and/or organic matter can be summarized as:

All evaluated trace elements showed some change in their extents with respect to size fractions. Maximum and minimum changes in the extent of trace elements between the coarsest (+50 mm) and finest (-0.5 mm) fractions were observed with molybdenum (4.64 times) and zinc (1.78 times) respectively, for inorganic associated trace elements. At this point it should be noted that nickel was distinguished as an exception, as nickel showed no meaningful trend with respect to changes in particle size, and therefore to variations in ash content. For organic associated trace elements, maximum and minimum changes in the trace element content between the coarsest (+50 mm) and finest (-0.5 mm) fractions were observed with vanadium (3.18 times) and cadmium (1.17 times) respectively. The amounts of arsenic, barium, copper, mercury, manganese, molybdenum, lead and zinc were directly related with increasing fineness. Cadmium, chromium, antimony, selenium, uranium and vanadium, on the other hand were inversely proportional with decreasing particle size. The elements which were positively correlated with the ash were arsenic, barium, copper, mercury, manganese, molybdenum, lead and zinc. These elements showed inorganic affinity which means possible association with ash making constituents in Salihpaşa coal. In contrast, cadmium, chromium, antimony, selenium, uranium and vanadium revealed organic affinity implying linkage with organic matter in Salihpaşa coal. The unstable changes in nickel content with respect to particle size could be attributed to uneven association of this element with both organic matter and inorganic constituents in Salihpaşa coal. Trace elements which were strongly or weakly bound with ash making minerals in coal present an opportunity for their significant or partial removal through heavy media separation.

5.2. Removal of Trace Elements by Heavy Media Separation

Rejection possibilities of trace elements in Salihpaşa coal were assessed through laboratory sink and float tests. Representative coal samples were subjected to cleaning, using a series of densities from 1.3 to 1.9 g/cm³. The details of the procedure given in the Materials and Methods section. As mentioned previously, the tests were applied on distinct size fractions of +50 mm, -50+18 mm, -18+9.5 mm and -9.5+0.5 mm. The -0.5 mm was separated from the Salihpaşa run-of-mine coal prior to the tests.

Table 5.8. Pearson correlation coefficients between trace element and ash contents with respect to coal size fractions

TEs	r_{ash}				
	ROM coal	+50 mm	-50+18 mm	-18+9.5 mm	-9.5+0.5 mm
As	0.97	0.93	0.89	0.95	0.98
Ba	0.94	0.94	0.98	0.96	0.97
Cd	-0.5	-0.9	-0.57	-0.36	No Data
Cr	-0.99	-0.96	-0.92	-0.87	-0.95
Cu	0.97	0.94	0.96	0.96	0.47
Hg	0.99	0.51	0.88	0.86	0.95
Mn	0.97	0.92	0.95	0.97	0.99
Mo	0.99	0.91	0.99	0.96	0.9
Ni	0.82	-0.61	-0.71	-0.85	-0.21
Pb	0.95	0.94	0.95	0.94	0.9
Sb	-0.92	-0.97	-0.98	-0.92	-0.97
Se	-0.99	-0.95	-0.95	-0.96	-0.99
U	-0.98	-0.93	-0.99	-0.97	-0.96
V	-0.99	-0.98	-0.95	-0.94	-0.93
Zn	0.97	0.94	0.9	0.96	0.97

Ash content of the products (%) on dry basis was used for evaluating the effectiveness of sink and float procedure and therefore a possible heavy media separation (HMS) application on each size fraction. Rejection of trace elements was also assessed with respect to separation specific gravity and correlated with the changes in ash percentages. Pearson correlation coefficients were also calculated between ash and trace element contents to evaluate association of trace elements. These correlations are presented in Table 5.8.

Table 5.9. Arsenic content of sink and float products at different coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.1	16	0.28	15.11
	+1.30-1.40	4.91	20.42	1.6	16.23
	+1.40-1.50	1.69	20.22	0.55	29.92
	+1.50-1.60	0.82	22.74	0.3	41.57
	+1.60-1.70	1.4	37.86	0.85	51.32
	+1.70-1.80	1.24	36.48	0.72	56.33
	+1.80-1.90	6.33	49.86	5.04	62.74
	+1.90	2	60.48	1.93	72.15
-50+18	-1.30	0.81	18.5	0.24	16.95
	+1.30-1.40	14.27	22.68	5.17	27.98
	+1.40-1.50	2.93	28.89	1.35	40.34
	+1.50-1.60	1.2	30.62	0.59	52.46
	+1.60-1.70	2	52.98	1.69	64.3
	+1.70-1.80	2.32	56.18	2.08	67.62
	+1.80-1.90	5.71	86.12	7.86	74.36
	+1.90	3.06	94.22	4.6	75.32
-18+9.5	-1.30	0.05	16.42	0.01	19.93
	+1.30-1.40	7.42	38.97	4.62	38.16
	+1.40-1.50	1.9	49.86	1.51	46.26
	+1.50-1.60	0.6	60.99	0.59	57.3
	+1.60-1.70	0.35	68.98	0.39	66.61
	+1.70-1.80	0.77	84.96	1.05	70.19
	+1.80-1.90	1.58	102.92	2.6	76.88
	+1.90	1.68	122.94	3.3	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	50.22	2.27	43.85
	+1.40-1.50	5.73	64.46	5.91	48.81
	+1.50-1.60	5.38	76.12	6.55	58.91
	+1.60-1.70	2.34	88.69	3.31	69.31
	+1.70-1.80	1.57	99.59	2.5	70.3
	+1.80-1.90	1.68	120.46	3.23	77.32
	+1.90	9.7	125.7	19.5	80.87

Relationship between arsenic content and ash in ROM coal was explained in the previous section. It was seen that arsenic was associated with ash making constituents. Similar tendency (Table 5.9, Fig. 5.16.) was obtained for +50 mm fraction with increasing separation specific gravity. As seen in the Table 5.8, As content was 16 ppm at the -1.3 product whereas it raised up to 60.48 ppm in the densest product (+1.9). This corresponds to an almost four times higher concentration in the densest product, showing that the heavier part of coal, i.e. the inorganic dominant portion, became enriched in terms of As content. For size fractions of -50+18 mm, -18+9.5 mm, As contents determined at the lightest media (-1.3) were 18.50 ppm and 16.42 ppm, respectively. As content reached its maximum

at +1.9 products and were 94.22 ppm, 122.94 ppm and 125.70 ppm for -50+18 mm, -18+9.5 mm and -9.5+0.5 mm, respectively. Also, positive correlations between As content and ash at all size fractions were revealed by the Pearson correlation coefficients as seen in Table 5.8. The findings indicated that As content and ash making minerals in Salihpaşa coal were strongly associated. Similar findings were reported for Antaibao coals from China and higher extent of As rejection was achieved by conventional heavy media separation (Wenfeng et al., 2009). Luttrell et al. (1999) studied the coals from USA and reported that rejection of As via pyritic sulfur was achieved by conventional cleaning methods. In some other previous studies reduction of As by flotation was not found effective since the host mineral, pyrite, had similar surface properties with coal (Akers and Raleigh, 1998; Bergh et al., 2010).

Barium (Ba) content was seen to be directly related with the extent of ash (Table 5.10, Fig. 5.17.). Maximum Ba content was obtained at +1.9 product (108 ppm) for +50 mm fraction and minimum Ba content was almost constant at -1.3, +1.3-1.4 and +1.4-1.5 products (~39 ppm). Similar findings were observed for -50+18 mm, -18+9.5 mm and -9.5+0.5 mm coal sizes where Ba was also positive correlated (Table 5.8) with ash and heavier products. According to the results, the highest increase ratio was calculated for -18+9.5 mm fraction. There is an apparent tendency between Ba content and the ash extent in all fractions with respect to separation specific gravities. This illustrates that a significant association between Ba and inorganic constituents exists. It can be concluded that rejection of Ba by HMS from Salihpaşa coal via relatively heavier, inorganic-rich sink products is possible. Similarly, Wenfeng et al. (2009) reported that Ba was mostly associated with the ash making constituents in Antaibao coals (China) and so higher extent of Ba rejection was achieved by HMS. However, in another study again by Wenfeng et al. (2004) on different Chinese coals from the Northern Ordos basin and Shanxi Province, it was found that Ba was strongly associated with the organic matter in coal, which means that removal of Ba content by HMS/conventional methods was not viable.

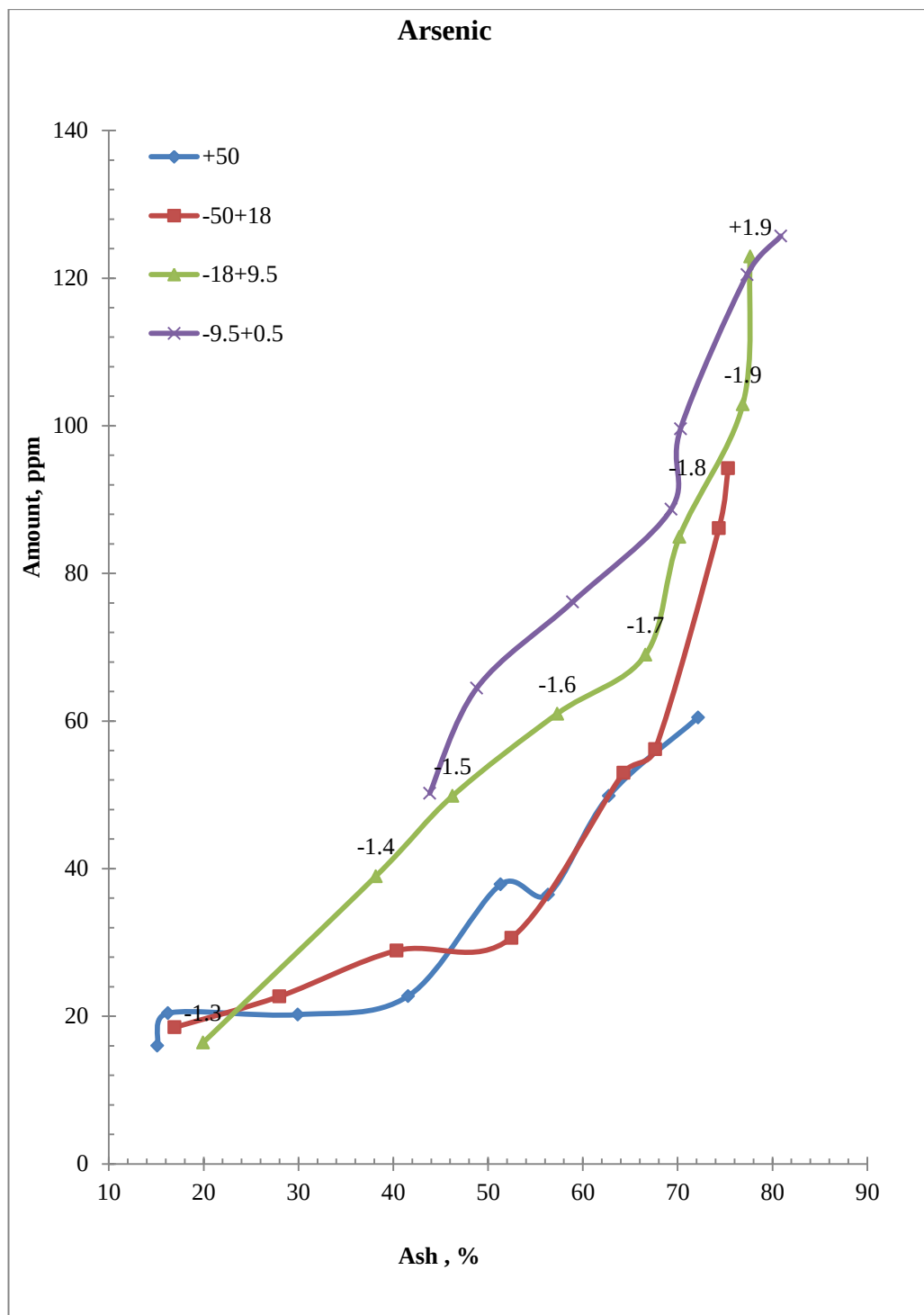


Fig. 5.16. Arsenic content vs. ash % of sink and float products at different coal size fractions

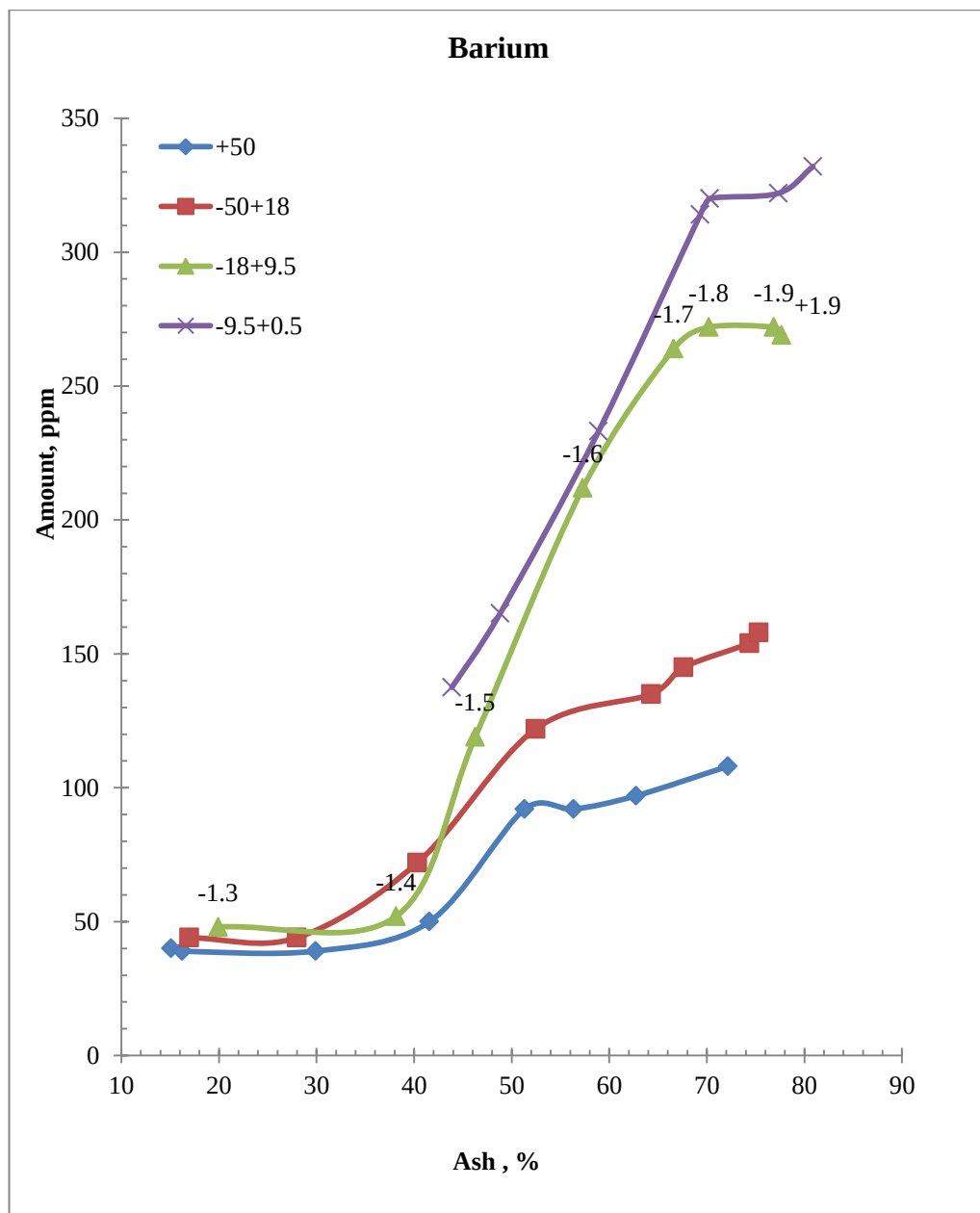


Fig. 5.17. Barium content vs. ash % of sink and float products at different coal size fractions

As seen in Table 5.11. and Fig. 5.18, the amount of Cadmium (Cd) was not stable with respect to size fractions. Therefore, a reasonable relation between Cd content, ash, size fractions and separation densities could not be determined. Non-stable behavior was statistically calculated and negative correlations was observed except for the finest coal size (Table 5.8). For +50 mm fraction, cadmium content decreased from 1.7 ppm (-1.3) to 1.10 ppm (+1.9), showing possible organic association. For -50+18 mm fraction, unsteady changes were observed between Cd content and the ash.

Table 5.10. Barium content of sink and float products at different coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	40.00	0.29	15.11
	+1.30-1.40	4.91	39.00	1.25	16.23
	+1.40-1.50	1.69	39.00	0.43	29.92
	+1.50-1.60	0.82	50.00	0.27	41.57
	+1.60-1.70	1.40	92.00	0.85	51.32
	+1.70-1.80	1.24	92.00	0.75	56.33
	+1.80-1.90	6.33	97.00	4.03	62.74
	+1.90	2.00	108.00	1.42	72.15
-50+18	-1.30	0.81	44.00	0.23	16.95
	+1.30-1.40	14.27	44.00	4.12	27.98
	+1.40-1.50	2.93	72.00	1.38	40.34
	+1.50-1.60	1.20	122.00	0.96	52.46
	+1.60-1.70	2.00	135.00	1.77	64.30
	+1.70-1.80	2.32	145.00	2.20	67.62
	+1.80-1.90	5.71	154.00	5.76	74.36
	+1.90	3.06	158.00	3.17	75.32
-18+9.5	-1.30	0.05	48.00	0.02	19.93
	+1.30-1.40	7.42	52.00	2.53	38.16
	+1.40-1.50	1.90	119.00	1.48	46.26
	+1.50-1.60	0.60	212.00	0.84	57.30
	+1.60-1.70	0.35	264.00	0.61	66.61
	+1.70-1.80	0.77	272.00	1.37	70.19
	+1.80-1.90	1.58	272.00	2.82	76.88
	+1.90	1.68	269.00	2.96	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	137.50	2.56	43.85
	+1.40-1.50	5.73	165.10	6.24	48.81
	+1.50-1.60	5.38	233.20	8.26	58.91
	+1.60-1.70	2.34	314.00	4.83	69.31
	+1.70-1.80	1.57	320.00	3.31	70.30
	+1.80-1.90	1.68	322.00	3.55	77.32
	+1.90	9.70	332.00	21.22	80.87

The non-stable variations in cadmium assay were also seen in the -18+9.5 mm fraction, corresponding to association of Cd with both organic and inorganic constituents. For -18+9.5 mm fraction Cd content remained almost unchanged. For -9.5+0.5 mm fraction, similar behavior to -18+9.5 mm fraction was observed, where no significant changes in Cd content were detected. Overall, it could be suggested that Cd in Salihpasa coal occurred associated to both organic and inorganic constituents and did not reveal a certain affinity, but was rather, randomly distributed petrographically. Ozbayoglu (2013) reported that cadmium was strongly bound with the inorganic constituents in Soma coal, which could be easily rejected with these ash making constituents using heavy medium separation. Bergh et al. (2010) reported that Cd removal was possible to some extent by the rejection of pyritic sulfur by

gravity-based separation methods, on the other hand, advance methods such as flotation was found to be ineffective on removal of Cd due to similar surface behavior of coal and the pyrite. Similar to the Salihpasa coal, Cd was found partly associated both in the organic and inorganic portions of Chinese coals (Wenfeng et al., 2004).

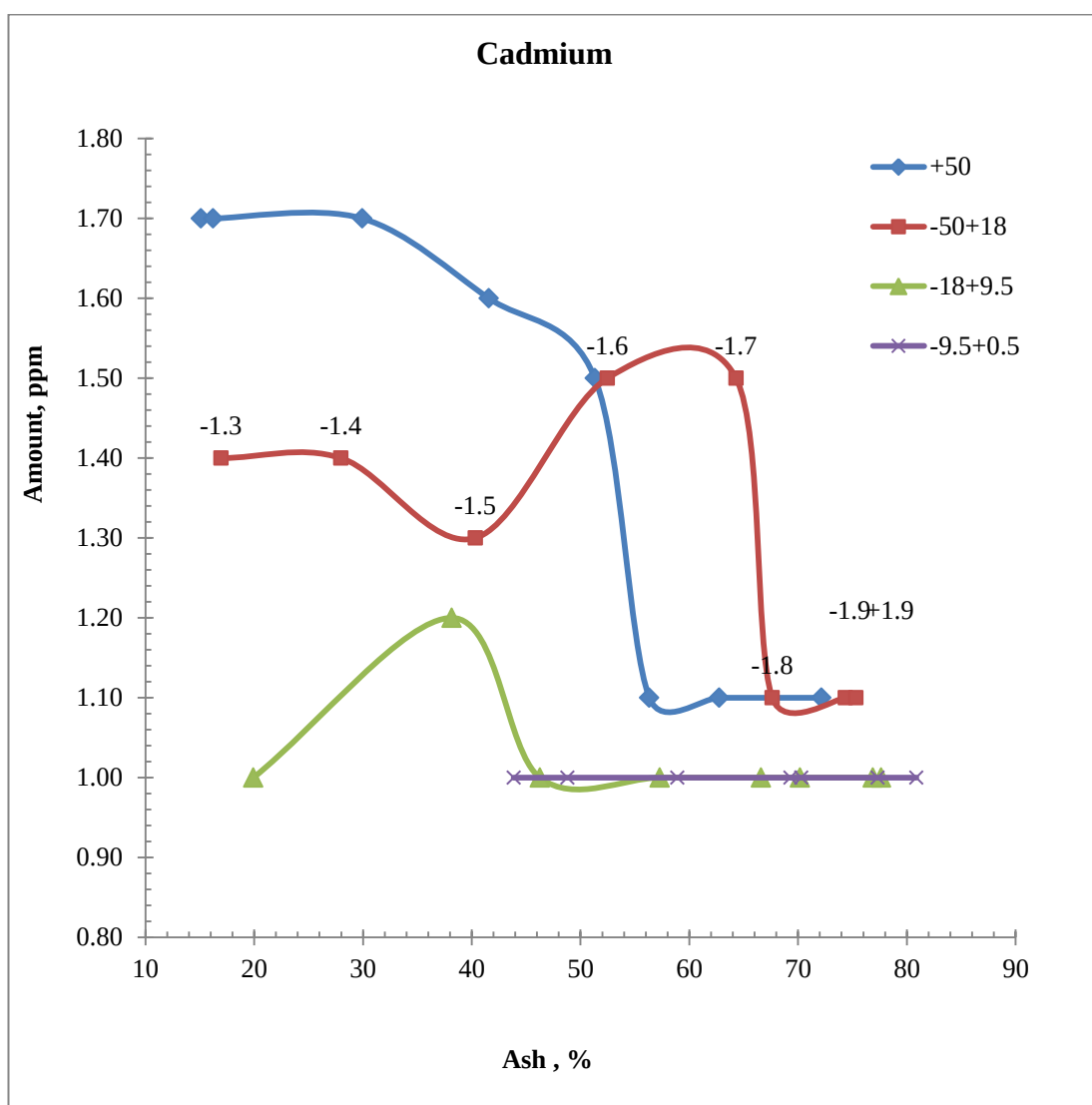


Fig. 5.18. Cadmium content vs. ash % of sink and float products at different coal size fractions

Table 5.11. Cadmium content of sink and float products at different coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	1.70	1.56	15.11
	+1.30-1.40	4.91	1.70	6.95	16.23
	+1.40-1.50	1.69	1.70	2.39	29.92
	+1.50-1.60	0.82	1.60	1.09	41.57
	+1.60-1.70	1.40	1.50	1.76	51.32
	+1.70-1.80	1.24	1.10	1.14	56.33
	+1.80-1.90	6.33	1.10	5.80	62.74
-50+18	+1.90	2.00	1.10	1.83	72.15
	-1.30	0.81	1.40	0.94	16.95
	+1.30-1.40	14.27	1.40	16.65	27.98
	+1.40-1.50	2.93	1.30	3.17	40.34
	+1.50-1.60	1.20	1.50	1.50	52.46
	+1.60-1.70	2.00	1.50	2.50	64.30
	+1.70-1.80	2.32	1.10	2.13	67.62
-18+9.5	+1.80-1.90	5.71	1.10	5.23	74.36
	+1.90	3.06	1.10	2.80	75.32
	-1.30	0.05	1.00	0.04	19.93
	+1.30-1.40	7.42	1.20	7.42	38.16
	+1.40-1.50	1.90	1.00	1.58	46.26
	+1.50-1.60	0.60	1.00	0.50	57.30
	+1.60-1.70	0.35	1.00	0.30	66.61
-9.5+0.5	+1.70-1.80	0.77	1.00	0.64	70.19
	+1.80-1.90	1.58	1.00	1.32	76.88
	+1.90	1.68	1.00	1.40	77.65
	-1.30	-	-	-	-
	+1.30-1.40	2.82	1.00	2.35	43.85
	+1.40-1.50	5.73	1.00	4.78	48.81
	+1.50-1.60	5.38	1.00	4.48	58.91
	+1.60-1.70	2.34	1.00	1.95	69.31
	+1.70-1.80	1.57	1.00	1.31	70.30
	+1.80-1.90	1.68	1.00	1.40	77.32
	+1.90	9.70	1.00	8.09	80.87

Chromium (Cr) content tended to decrease from 81.90 ppm to 59 ppm by increasing separation specific gravity at +50 mm fraction. Cr extent was reversely proportional with ash (Table 5.12, Fig. 5.19.). This points to possible organic association of Cr in Salihaşa coal. Negative Pearson correlation coefficients for all coal sizes also proved that Cr was mostly associated with the organic constituents (Table 5.8.). In previous studies, Cr was found linked to both organic and inorganic constituents. Chromium was found as associated with the organic part in USA Illinois coals (Demir, 1998). In partial agreement, Mohanty et al. (1997) found that chromium was moderately associated with ash making minerals in Illinois coal (Mohanty et al., 1997). On the contrary, in some other work, inorganic association of Cr was reported for various coals from Soma (Turkey), Eastern Kentucky and Virginia (USA), Antaibao (China) and for Northern Appalachian coals (Hower et al., 1998; Akers and

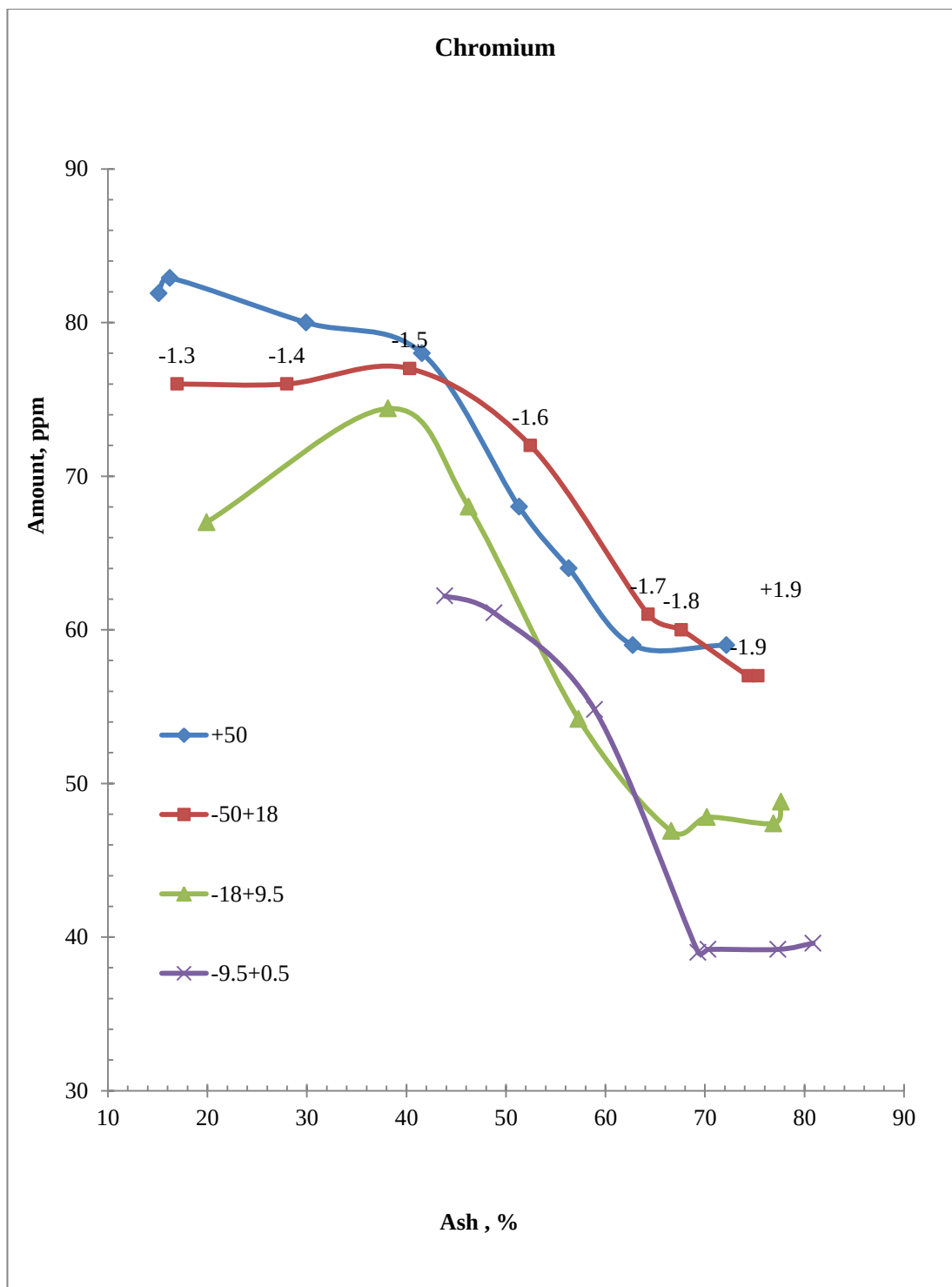


Fig. 5.19. Chromium content vs. ash % of sink and float products at different coal size fractions

Raleigh, 1998; Wenfeng et al., 2009; Ozbayoglu, 2013). For all finer fractions, the trend was almost similar with an exception at -18+9.5 mm fraction. -18+9.5 mm fraction revealed a non-stable characteristic with respect to Cr content. The amount of chromium tended to vary irregularly with the separation specific gravity (Table 5.12). In view of these observations, association with organic matter is likely for

chromium in Salihpaşa coal. However, the non-correlated Cr content with ash at -18+9.5 mm fraction also points to a possible link of chromium to inorganic constituents at least to some extent. Therefore, gravity-based separation, such as HMS does not seem to be a viable option for effective rejection of chromium from Salihpaşa coal.

Table 5.12. Chromium content of sink and float products at different coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	81.90	1.48	15.11
	+1.30-1.40	4.91	82.90	6.67	16.23
	+1.40-1.50	1.69	80.00	2.22	29.92
	+1.50-1.60	0.82	78.00	1.05	41.57
	+1.60-1.70	1.40	68.00	1.57	51.32
	+1.70-1.80	1.24	64.00	1.30	56.33
	+1.80-1.90	6.33	59.00	6.12	62.74
	+1.90	2.00	59.00	1.93	72.15
-50+18	-1.30	0.81	76.00	1.00	16.95
	+1.30-1.40	14.27	76.00	17.78	27.98
	+1.40-1.50	2.93	77.00	3.70	40.34
	+1.50-1.60	1.20	72.00	1.41	52.46
	+1.60-1.70	2.00	61.00	2.00	64.30
	+1.70-1.80	2.32	60.00	2.28	67.62
	+1.80-1.90	5.71	57.00	5.33	74.36
	+1.90	3.06	57.00	2.86	75.32
-18+9.5	-1.30	0.05	67.00	0.05	19.93
	+1.30-1.40	7.42	74.40	9.06	38.16
	+1.40-1.50	1.90	68.00	2.11	46.26
	+1.50-1.60	0.60	54.20	0.53	57.30
	+1.60-1.70	0.35	46.90	0.27	66.61
	+1.70-1.80	0.77	47.80	0.60	70.19
	+1.80-1.90	1.58	47.40	1.23	76.88
	+1.90	1.68	48.80	1.34	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	62.20	2.88	43.85
	+1.40-1.50	5.73	61.10	5.74	48.81
	+1.50-1.60	5.38	54.80	4.83	58.91
	+1.60-1.70	2.34	39.00	1.49	69.31
	+1.70-1.80	1.57	39.20	1.01	70.30
	+1.80-1.90	1.68	39.20	1.08	77.32
	+1.90	9.70	39.60	6.30	80.87

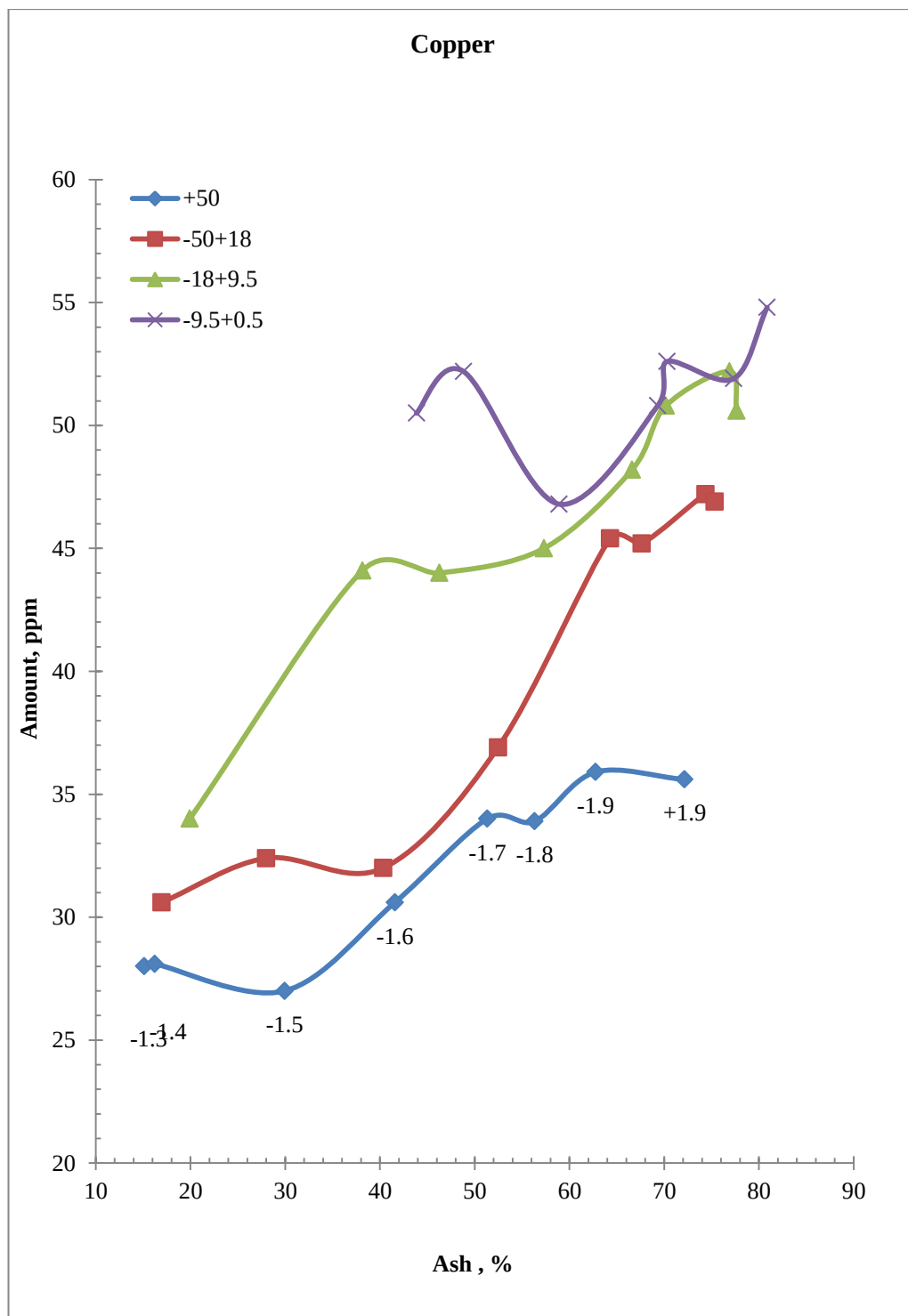


Fig. 5.20. Copper content vs. ash % of sink and float products at different coal size fractions

Copper (Cu) content was observed to be enriched in heavier fractions as compared to the lighter specific gravity products (Table 5.13, Fig. 5.20.). This was also supported by positive Pearson correlations coefficients for ash contents and coal size fractions (Table 5.8.). Copper assay followed the increase in ash; it became higher with increasing fineness and increasing separation specific gravity. For instance at +50

mm fraction, maximum Cu was 35.60-35.90 ppm (at +1.80-1.90 and -1.90) while it reduced to 27-28 ppm at lighter specific gravity products (Table 5.13.). This showed that copper occurrence was approximately 1.3 times higher in the relatively heavier specific gravity products. These tendencies illustrated strong association between copper and inorganic constituents in all size fractions of Salihpaşa coal. This is in agreement with findings of Firth and Dale (1998) who deduced that copper is found inorganically associated in coals and hence, its rejection with the ash making constituents through gravity-based separation methods is strongly possible. Also, inorganic association of copper in Çan coal was reported by Gürdal (2011). On the other hand, Wefeng et al. (2009) showed that organic association of copper would also be possible, as observed in Antaibao coals (China).

Table 5.13. Copper content of sink and float products at different coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	28.00	0.71	15.11
	+1.30-1.40	4.91	28.10	3.18	16.23
	+1.40-1.50	1.69	27.00	1.05	29.92
	+1.50-1.60	0.82	30.60	0.58	41.57
	+1.60-1.70	1.40	34.00	1.10	51.32
	+1.70-1.80	1.24	33.90	0.97	56.33
	+1.80-1.90	6.33	35.90	5.25	62.74
	+1.90	2.00	35.60	1.64	72.15
-50+18	-1.30	0.81	30.60	0.57	16.95
	+1.30-1.40	14.27	32.40	10.68	27.98
	+1.40-1.50	2.93	32.00	2.17	40.34
	+1.50-1.60	1.20	36.90	1.02	52.46
	+1.60-1.70	2.00	45.40	2.10	64.30
	+1.70-1.80	2.32	45.20	2.42	67.62
	+1.80-1.90	5.71	47.20	6.22	74.36
	+1.90	3.06	46.90	3.31	75.32
-18+9.5	-1.30	0.05	34.00	0.04	19.93
	+1.30-1.40	7.42	44.10	7.56	38.16
	+1.40-1.50	1.90	44.00	1.93	46.26
	+1.50-1.60	0.60	45.00	0.63	57.30
	+1.60-1.70	0.35	48.20	0.39	66.61
	+1.70-1.80	0.77	50.80	0.90	70.19
	+1.80-1.90	1.58	52.20	1.91	76.88
	+1.90	1.68	50.60	1.96	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	50.50	3.30	43.85
	+1.40-1.50	5.73	52.20	6.92	48.81
	+1.50-1.60	5.38	46.80	5.82	58.91
	+1.60-1.70	2.34	50.80	2.75	69.31
	+1.70-1.80	1.57	52.60	1.91	70.30
	+1.80-1.90	1.68	51.90	2.01	77.32
	+1.90	9.70	54.80	12.30	80.87

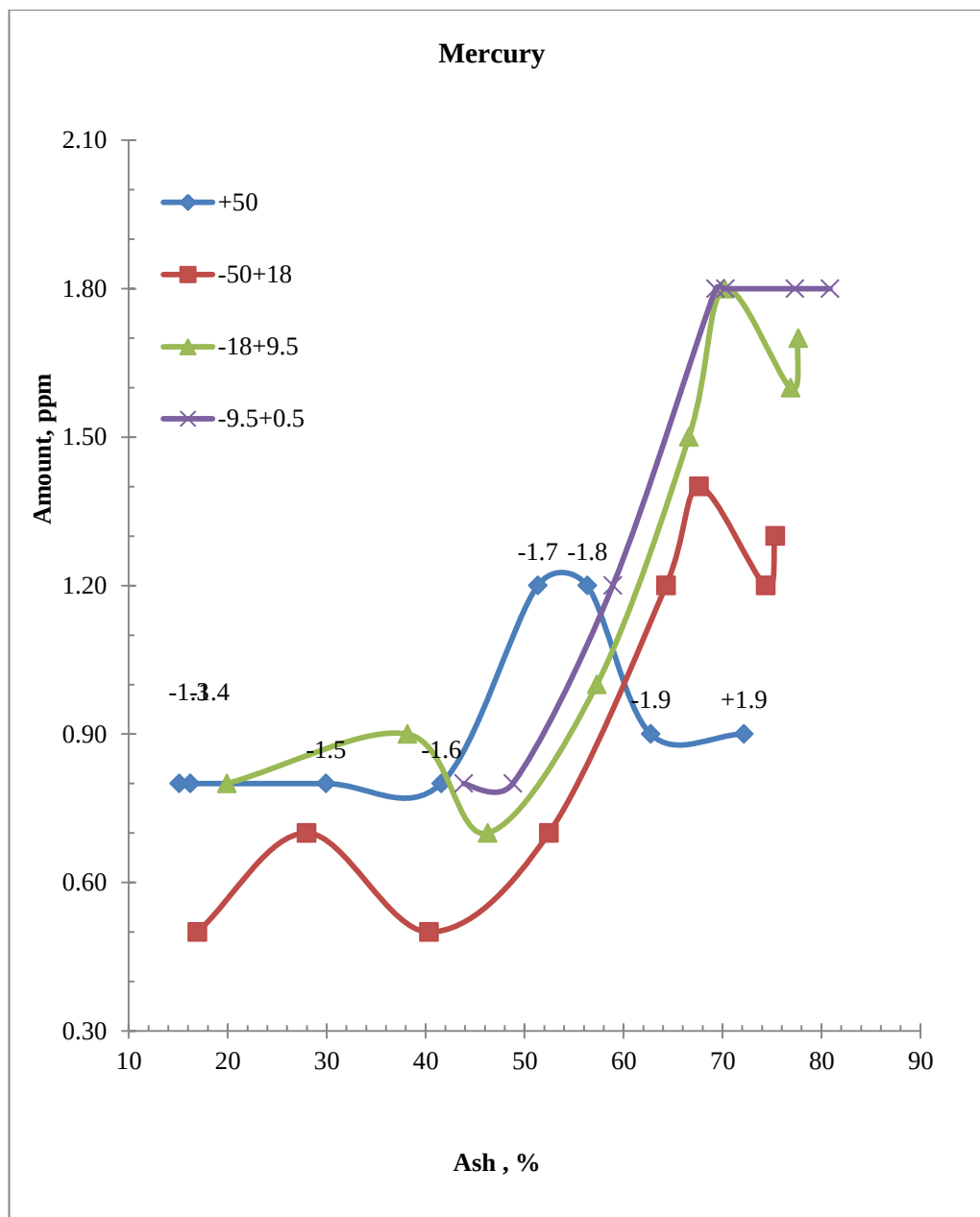


Fig. 5.21. Mercury content vs. ash % of sink and float products at different coal size fractions

When the results regarding the content of Mercury (Hg) with respect to size fractions and separation specific gravities were evaluated, it was seen that amount of Hg varied between 0.5 to 1.80 ppm (Table 5.14, Fig. 5.21.). It should be noted that the finest two fractions, namely -18+9.5 mm and -9.5+0.5 mm were particularly enriched in terms of Hg, and the highest Hg assay of 1.8 ppm were recorded for separations within these fractions. Thus, it could be deduced that Hg tended to concentrate with increasing fineness and positive correlations with the ash content were obtained (Table 5.8.). However, the fluctuations of Hg content with respect to different separation specific gravities within the coarse size fractions (for instance -

50+18 mm), were higher as compared to the previously assessed trace elements. This could either be attributed to the uneven distribution of mercury in Salihpaşa coal and/or association of mercury both with organic and inorganic constituents (although association to inorganic constituents was more likely) or due to the difficulty in mercury analysis and detection. Observing the lowest Hg extent at the -1.3 product for all size fractions supported the inorganic dominated association of Hg in Salihpaşa coal. Similar to the findings in this study, Hg was found mostly associated with ash making constituents in Turkish coals (Soma, Çan), Pittsburgh, Illinois and Northern Appalachian coals from USA, as well as Antaibao coals from China, (Mohanty et al., 1997; Akers and Raleigh, 1998; Luttrell et al., 1999; Wenfeng et al., 2009; Gürdal, 2011; Ozbayoglu, 2013).

Table 5.14. Mercury content of sink and float products at different coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	0.80	0.79	15.11
	+1.30-1.40	4.91	0.80	3.54	16.23
	+1.40-1.50	1.69	0.80	1.22	29.92
	+1.50-1.60	0.82	0.80	0.59	41.57
	+1.60-1.70	1.40	1.20	1.52	51.32
	+1.70-1.80	1.24	1.20	1.34	56.33
	+1.80-1.90	6.33	0.90	5.13	62.74
	+1.90	2.00	0.90	1.62	72.15
-50+18	-1.30	0.81	0.50	0.36	16.95
	+1.30-1.40	14.27	0.70	9.00	27.98
	+1.40-1.50	2.93	0.50	1.32	40.34
	+1.50-1.60	1.20	0.70	0.76	52.46
	+1.60-1.70	2.00	1.20	2.16	64.30
	+1.70-1.80	2.32	1.40	2.92	67.62
	+1.80-1.90	5.71	1.20	6.17	74.36
	+1.90	3.06	1.30	3.58	75.32
-18+9.5	-1.30	0.05	0.80	0.04	19.93
	+1.30-1.40	7.42	0.90	6.02	38.16
	+1.40-1.50	1.90	0.70	1.20	46.26
	+1.50-1.60	0.60	1.00	0.54	57.30
	+1.60-1.70	0.35	1.50	0.48	66.61
	+1.70-1.80	0.77	1.80	1.25	70.19
	+1.80-1.90	1.58	1.60	2.28	76.88
	+1.90	1.68	1.70	2.57	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	0.80	2.05	43.85
	+1.40-1.50	5.73	0.80	4.17	48.81
	+1.50-1.60	5.38	1.20	5.87	58.91
	+1.60-1.70	2.34	1.80	3.82	69.31
	+1.70-1.80	1.57	1.80	2.57	70.30
	+1.80-1.90	1.68	1.80	2.74	77.32
	+1.90	9.70	1.80	15.88	80.87

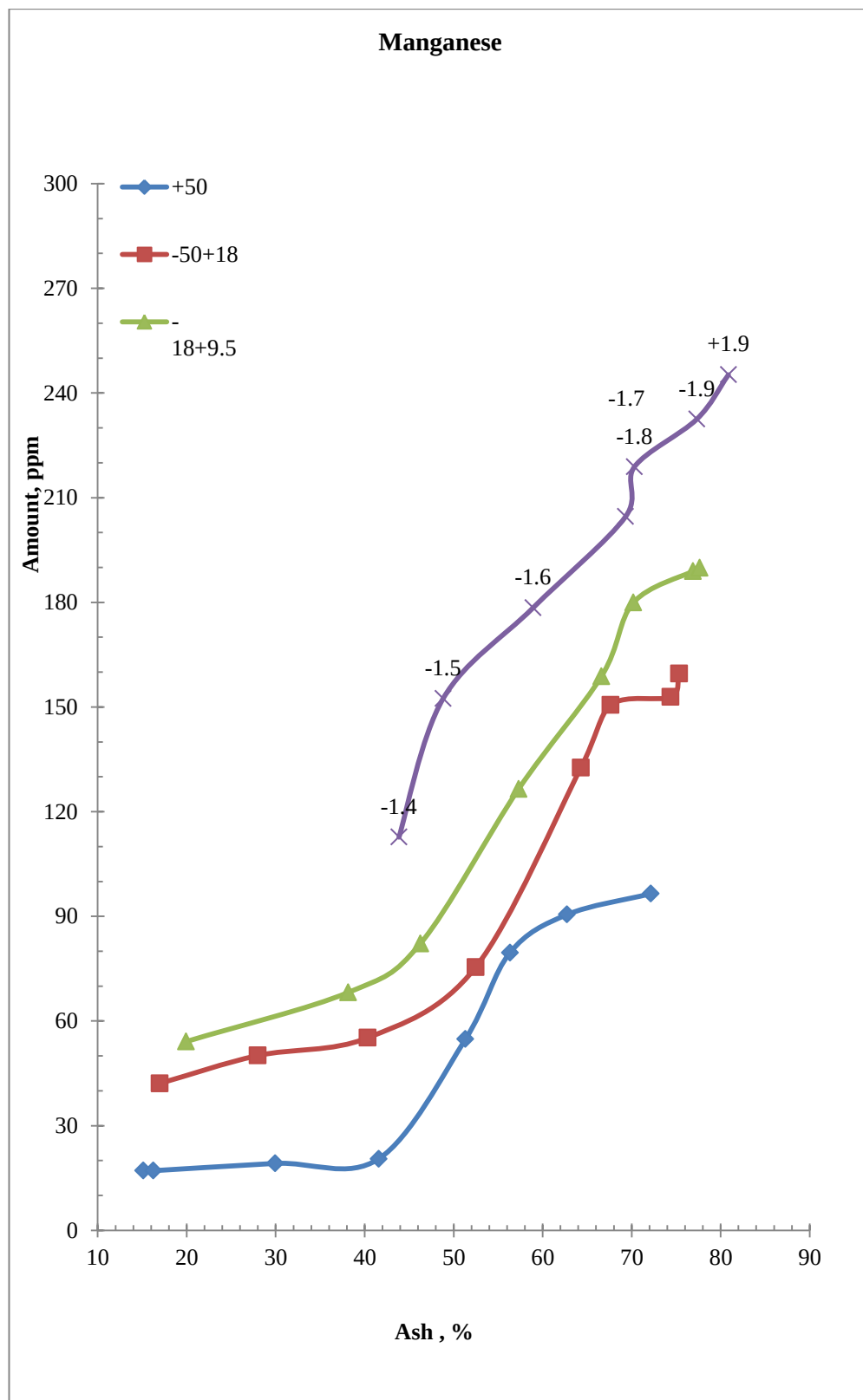


Fig. 5.22. Manganese content vs. ash % of sink and float products at different coal size fractions

For Manganese (Mn), an obvious correlation (from Table 5.8.) with ash was identified with respect to all size fractions and separation densities (Table 5.15, Fig. 5.22.). For all size fractions minimum manganese content was found for the -1.3 product and maximum extent of manganese occurred within the +1.8 and +1.9 products. Also, amount of Mn remarkably increased towards finer coal fractions. These observations clearly showed that Mn could be rejected by HMS along with the ash making constituents. Possibilities of manganese rejection was also claimed due to its inorganic association for some Turkish and USA coals (Demir, 1998; Hower et al., 1998; Ozbayoglu., 2013). However, investigations on coal samples from washeries in Australia revealed that removal of manganese remained limited due to its partly organic association in some Australian coals (Firth and Dale, 1998).

Table 5.15. Manganese content of sink and float products at different coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	17.10	0.15	15.11
	+1.30-1.40	4.91	17.10	0.68	16.23
	+1.40-1.50	1.69	19.20	0.26	29.92
	+1.50-1.60	0.82	20.50	0.14	41.57
	+1.60-1.70	1.40	54.80	0.62	51.32
	+1.70-1.80	1.24	79.60	0.80	56.33
	+1.80-1.90	6.33	90.50	4.62	62.74
-50+18	+1.90	2.00	96.50	1.55	72.15
	-1.30	0.81	42.10	0.27	16.95
	+1.30-1.40	14.27	50.10	5.76	27.98
	+1.40-1.50	2.93	55.20	1.30	40.34
	+1.50-1.60	1.20	75.40	0.73	52.46
	+1.60-1.70	2.00	132.60	2.14	64.30
	+1.70-1.80	2.32	150.56	2.81	67.62
-18+9.5	+1.80-1.90	5.71	152.90	7.03	74.36
	+1.90	3.06	159.60	3.93	75.32
	-1.30	0.05	54.10	0.02	19.93
	+1.30-1.40	7.42	68.20	4.08	38.16
	+1.40-1.50	1.90	82.20	1.26	46.26
	+1.50-1.60	0.60	126.50	0.61	57.30
	+1.60-1.70	0.35	158.80	0.45	66.61
-9.5+0.5	+1.70-1.80	0.77	179.90	1.12	70.19
	+1.80-1.90	1.58	188.90	2.41	76.88
	+1.90	1.68	189.90	2.57	77.65
	-1.30	-	-	-	-
	+1.30-1.40	2.82	112.70	2.56	43.85
	+1.40-1.50	5.73	152.40	7.04	48.81
	+1.50-1.60	5.38	178.40	7.73	58.91
	+1.60-1.70	2.34	204.56	3.85	69.31
	+1.70-1.80	1.57	218.80	2.77	70.30
	+1.80-1.90	1.68	232.50	3.14	77.32
	+1.90	9.70	245.20	19.17	80.87

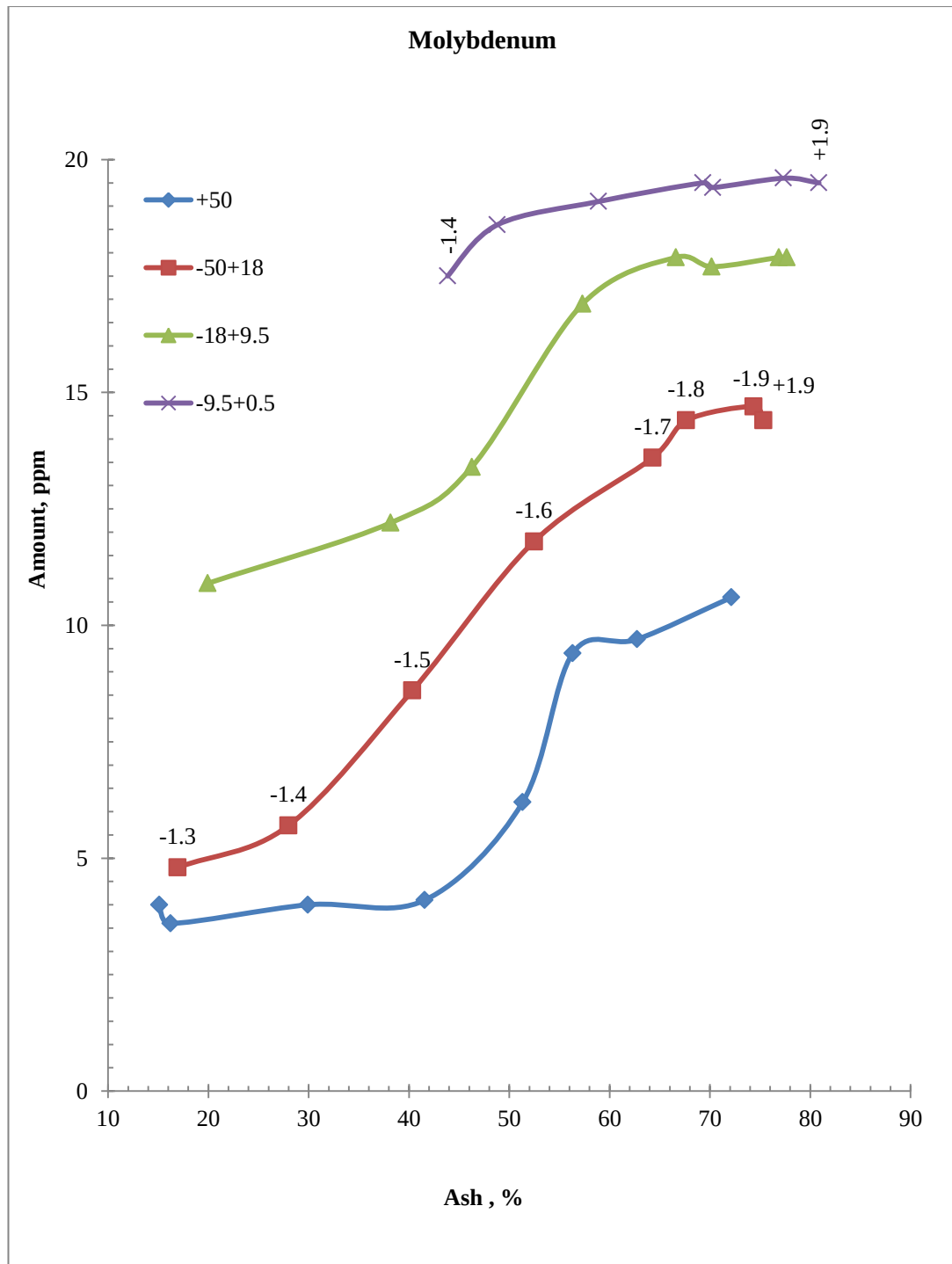


Fig. 5.23. Molybdenum content vs. ash % of sink and float products at coal size fractions

Molybdenum (Mo) revealed almost similar behavior with manganese in Salihpaşa coal. Content of Mo increased with increasing separation specific gravity and decreasing particle size (Table. 5.16, Fig. 5.23.). This means that Mo was directly correlated with increasing ash content, as supported by the positive Pearson

correlation coefficient values (Table 5.8.). The lowest Mo assay was identified at the organically enriched -1.3 products for all size fractions (except for the -9.5+0.5 mm fractions, due to absence of -1.3 product at this size range). The amount of Mo increased with increasing separation specific gravity with slight exceptions. Therefore, with the application of HMS, Mo content could be significantly reduced with the rejection of ash making inorganic constituents in Salihpaşa coal. Similar observations were achieved for molybdenum in Çan coal by Gürdal (2011). On the other hand opposing these findings for Salihpaşa and Çan coals from Turkey, occurrence of molybdenum in organic matter of coal was reported (Goodarzi, 2002), implying that a generalization regarding the association of molybdenum in coals is not possible as presence of molybdenum in coals is highly variable and should be assessed carefully for different coal types.

Table 5.16. Molybdenum content of sink and float products at different coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	4.00	0.32	15.11
	+1.30-1.40	4.91	3.60	1.30	16.23
	+1.40-1.50	1.69	4.00	0.50	29.92
	+1.50-1.60	0.82	4.10	0.25	41.57
	+1.60-1.70	1.40	6.20	0.64	51.32
	+1.70-1.80	1.24	9.40	0.86	56.33
	+1.80-1.90	6.33	9.70	4.51	62.74
-50+18	+1.90	2.00	10.60	1.56	72.15
	-1.30	0.81	4.80	0.28	16.95
	+1.30-1.40	14.27	5.70	5.98	27.98
	+1.40-1.50	2.93	8.60	1.85	40.34
	+1.50-1.60	1.20	11.80	1.04	52.46
	+1.60-1.70	2.00	13.60	2.00	64.30
	+1.70-1.80	2.32	14.40	2.45	67.62
-18+9.5	+1.80-1.90	5.71	14.70	6.17	74.36
	+1.90	3.06	14.40	3.24	75.32
	-1.30	0.05	10.90	0.04	19.93
	+1.30-1.40	7.42	12.20	6.66	38.16
	+1.40-1.50	1.90	13.40	1.87	46.26
	+1.50-1.60	0.60	16.90	0.75	57.30
	+1.60-1.70	0.35	17.90	0.47	66.61
-9.5+0.5	+1.70-1.80	0.77	17.70	1.00	70.19
	+1.80-1.90	1.58	17.90	2.08	76.88
	+1.90	1.68	17.90	2.21	77.65
	-1.30	-	-	-	-
	+1.30-1.40	2.82	17.50	3.63	43.85
	+1.40-1.50	5.73	18.60	7.84	48.81
	+1.50-1.60	5.38	19.10	7.56	58.91
	+1.60-1.70	2.34	19.50	3.35	69.31
	+1.70-1.80	1.57	19.40	2.24	70.30
	+1.80-1.90	1.68	19.60	2.42	77.32
	+1.90	9.70	19.50	13.91	80.87

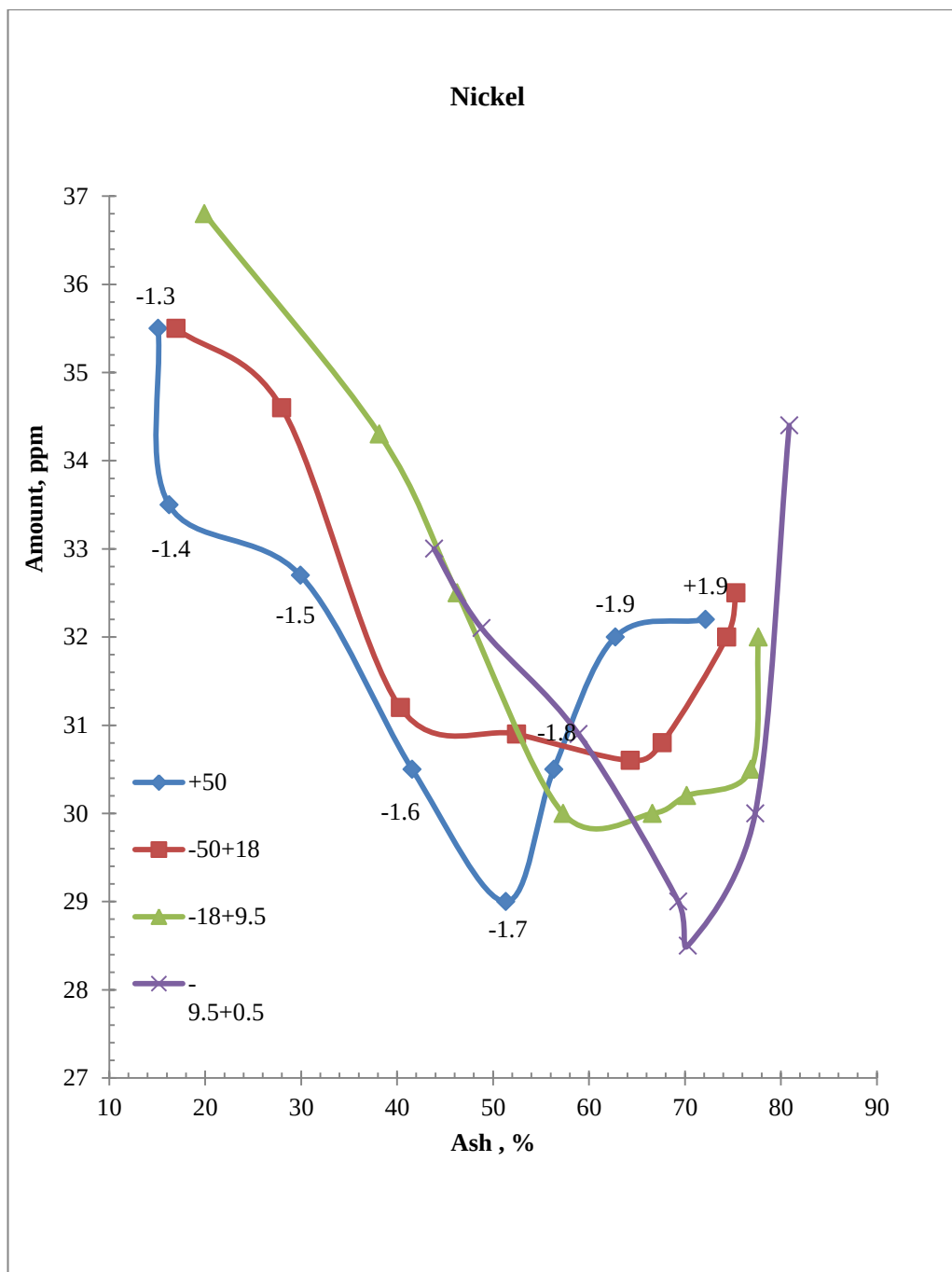


Fig. 5.24. Nickel content vs. ash % of sink and float products at coal size fractions

For Nickel (Ni), no meaningful and stable trend could be achieved with size fractionation and sink and float application. Rather, Ni was unevenly distributed and varied irregularly in a range of 28.5-36.80 ppm. (Table 5.17, Fig. 5.24.). This unstable distribution of nickel was confirmed by the fluctuation of Pearson correlation coefficients (Table 5.8.). Having observed no significant correlation with ash even at the inorganic-rich finer size fractions (i.e. -18+9.5 mm and -9.5+0.5 mm) it could be suggested that nickel did not show a liability towards organic portions

and/or inorganic matter in Salihpaşa coal. These results, therefore, imply the uneffective nature of cleaning by HMS with respect to nickel rejection from Salihpaşa coal. According to Demir (1998), Ni might occur as finely disseminated grains in macerals or organic bonding was also possible for Illinois coals from USA. Similarly, weak association in Soma coal resulted in relatively less rejection of this trace element by HMS (Ozbayoglu, 2013). On the other hand, Gürdal, (2011) reported that Ni association on mineral bearing constituents was possible for Çan coal from Turkey.

Table 5.17. Nickel content of sink and float products at coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	35.50	1.19	15.11
	+1.30-1.40	4.91	33.50	4.98	16.23
	+1.40-1.50	1.69	32.70	1.67	29.92
	+1.50-1.60	0.82	30.50	0.76	41.57
	+1.60-1.70	1.40	29.00	1.23	51.32
	+1.70-1.80	1.24	30.50	1.15	56.33
	+1.80-1.90	6.33	32.00	6.14	62.74
	+1.90	2.00	32.20	1.95	72.15
-50+18	-1.30	0.81	35.50	0.87	16.95
	+1.30-1.40	14.27	34.60	14.96	27.98
	+1.40-1.50	2.93	31.20	2.77	40.34
	+1.50-1.60	1.20	30.90	1.12	52.46
	+1.60-1.70	2.00	30.60	1.85	64.30
	+1.70-1.80	2.32	30.80	2.16	67.62
	+1.80-1.90	5.71	32.00	5.53	74.36
	+1.90	3.06	32.50	3.01	75.32
-18+9.5	-1.30	0.05	36.80	0.05	19.93
	+1.30-1.40	7.42	34.30	7.72	38.16
	+1.40-1.50	1.90	32.50	1.87	46.26
	+1.50-1.60	0.60	30.00	0.55	57.30
	+1.60-1.70	0.35	30.00	0.32	66.61
	+1.70-1.80	0.77	30.20	0.70	70.19
	+1.80-1.90	1.58	30.50	1.46	76.88
	+1.90	1.68	32.00	1.63	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	33.00	2.82	43.85
	+1.40-1.50	5.73	32.10	5.58	48.81
	+1.50-1.60	5.38	30.90	5.04	58.91
	+1.60-1.70	2.34	29.00	2.05	69.31
	+1.70-1.80	1.57	28.50	1.36	70.30
	+1.80-1.90	1.68	30.00	1.52	77.32
	+1.90	9.70	34.40	10.11	80.87

For Lead (Pb), linkage between Pb and ash making minerals were seen at heavier specific gravity products as compared to lighter separation densities (Table 5.18, Fig. 5.25.). For the coarsest coal size of Salihpaşa coal (+50 mm), maximum content Pb

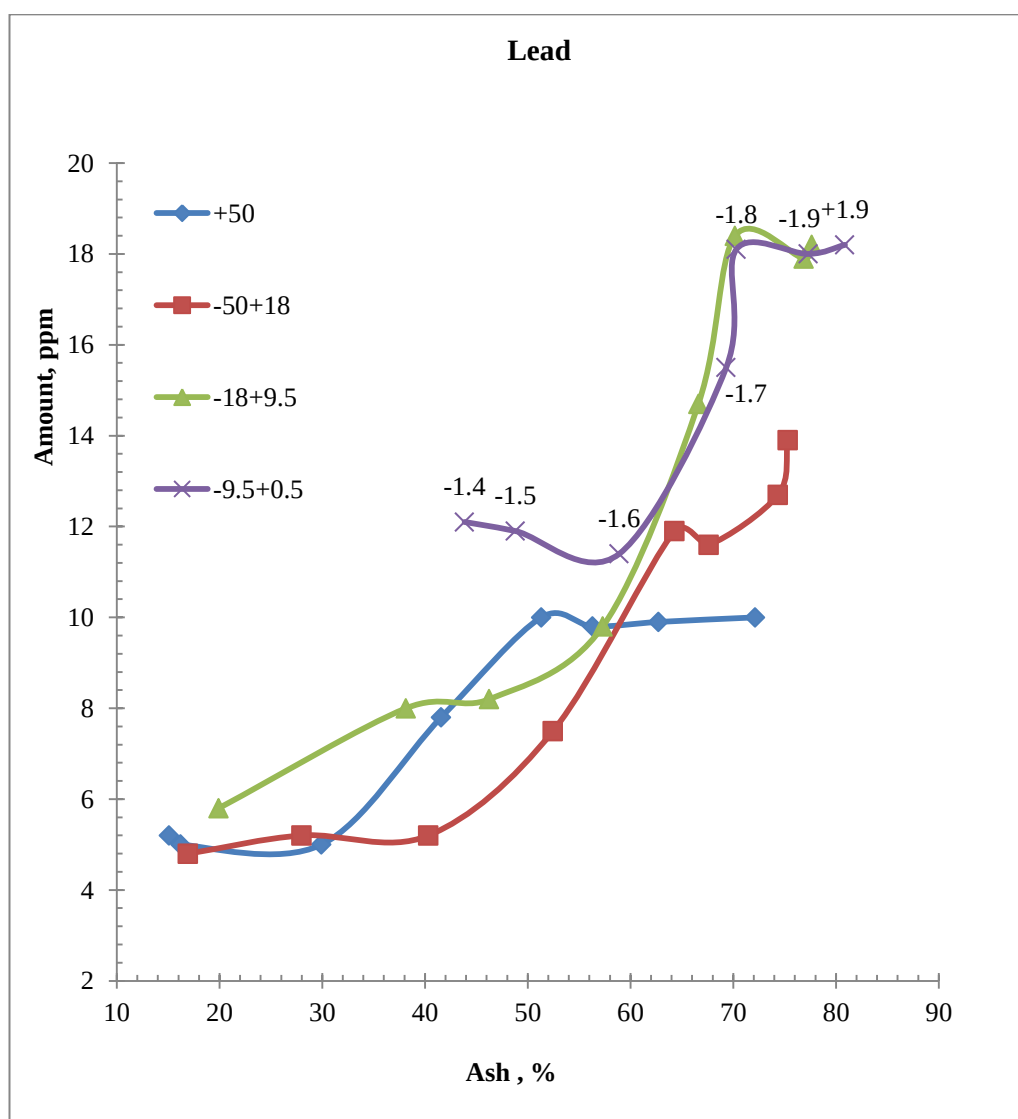


Fig. 5.25. Lead content vs. ash % of sink and float products at coal size fractions

assay was observed at +1.9 product (10 ppm) while the -1.3, -1.4 and -1.5 products yielded minimum lead (5-5.2 ppm). For -50+18 mm coal size, maximum content was determined at the densest product (+1.9) and minimum lead occurred in the -1.3 product, which also had the lowest ash in this size fraction (Table 5.18.). The increase in Pb was dramatic at this size fraction where the extent of Pb in the +1.9 product was almost three times higher as compared to that of -1.3 product. In the -

18+9.5 mm fraction, Pb content was 5.8 ppm for the -1.3 product. The highest extent of lead was recorded in the +1.7-1.8 product, corresponding to almost 3.2 times enrichment with the increase in ash (Table 5.18.). Highest and the lowest contents of lead in the -9.5+0.5 mm fraction were 18.20 ppm and 11.40 ppm for +1.90 and +1.50-1.60 products, respectively. It was obvious that lead tended to concentrate at relatively heavier products. This could be attributed to the association of Pb with inorganic constituents in Salihpaşa coal. Ozbayoglu reported that lead rejection as high as 60 % could be achieved by HMS at a separation specific gravity of 1.80 for Soma coal (Özbayoğlu, 2010; Ozbayoglu, 2013). Similarly, inorganic bonding was also reported by Gürdal (2011) for Çan coal and by Wenfeng et al., (2009) for Antaibao coals from China.

Table 5.18. Lead content of sink and float products at coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	5.20	0.53	15.11
	+1.30-1.40	4.91	5.00	2.25	16.23
	+1.40-1.50	1.69	5.00	0.77	29.92
	+1.50-1.60	0.82	7.80	0.58	41.57
	+1.60-1.70	1.40	10.00	1.29	51.32
	+1.70-1.80	1.24	9.80	1.12	56.33
	+1.80-1.90	6.33	9.90	5.75	62.74
	+1.90	2.00	10.00	1.83	72.15
-50+18	-1.30	0.81	4.80	0.35	16.95
	+1.30-1.40	14.27	5.20	6.81	27.98
	+1.40-1.50	2.93	5.20	1.40	40.34
	+1.50-1.60	1.20	7.50	0.82	52.46
	+1.60-1.70	2.00	11.90	2.18	64.30
	+1.70-1.80	2.32	11.60	2.47	67.62
	+1.80-1.90	5.71	12.70	6.65	74.36
	+1.90	3.06	13.90	3.90	75.32
-18+9.5	-1.30	0.05	5.80	0.03	19.93
	+1.30-1.40	7.42	8.00	5.45	38.16
	+1.40-1.50	1.90	8.20	1.43	46.26
	+1.50-1.60	0.60	9.80	0.54	57.30
	+1.60-1.70	0.35	14.70	0.48	66.61
	+1.70-1.80	0.77	18.40	1.30	70.19
	+1.80-1.90	1.58	17.90	2.60	76.88
	+1.90	1.68	18.20	2.80	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	12.10	3.13	43.85
	+1.40-1.50	5.73	11.90	6.26	48.81
	+1.50-1.60	5.38	11.40	5.63	58.91
	+1.60-1.70	2.34	15.50	3.32	69.31
	+1.70-1.80	1.57	18.10	2.61	70.30
	+1.80-1.90	1.68	18.00	2.77	77.32
	+1.90	9.70	18.20	16.20	80.87

Antimony (Sb) content was generally enriched with the relatively organic-rich products at all size fractions (Table 5.19, Fig. 5.26.). Negative correlation with ash content was also identified, confirming the association of Sb with the organic portions in Salihpaşa coal. In accordance with this finding the highest Sb extent was identified at the lightest two products, i.e. -1.3 and +1.3-1.4 for all size fractions

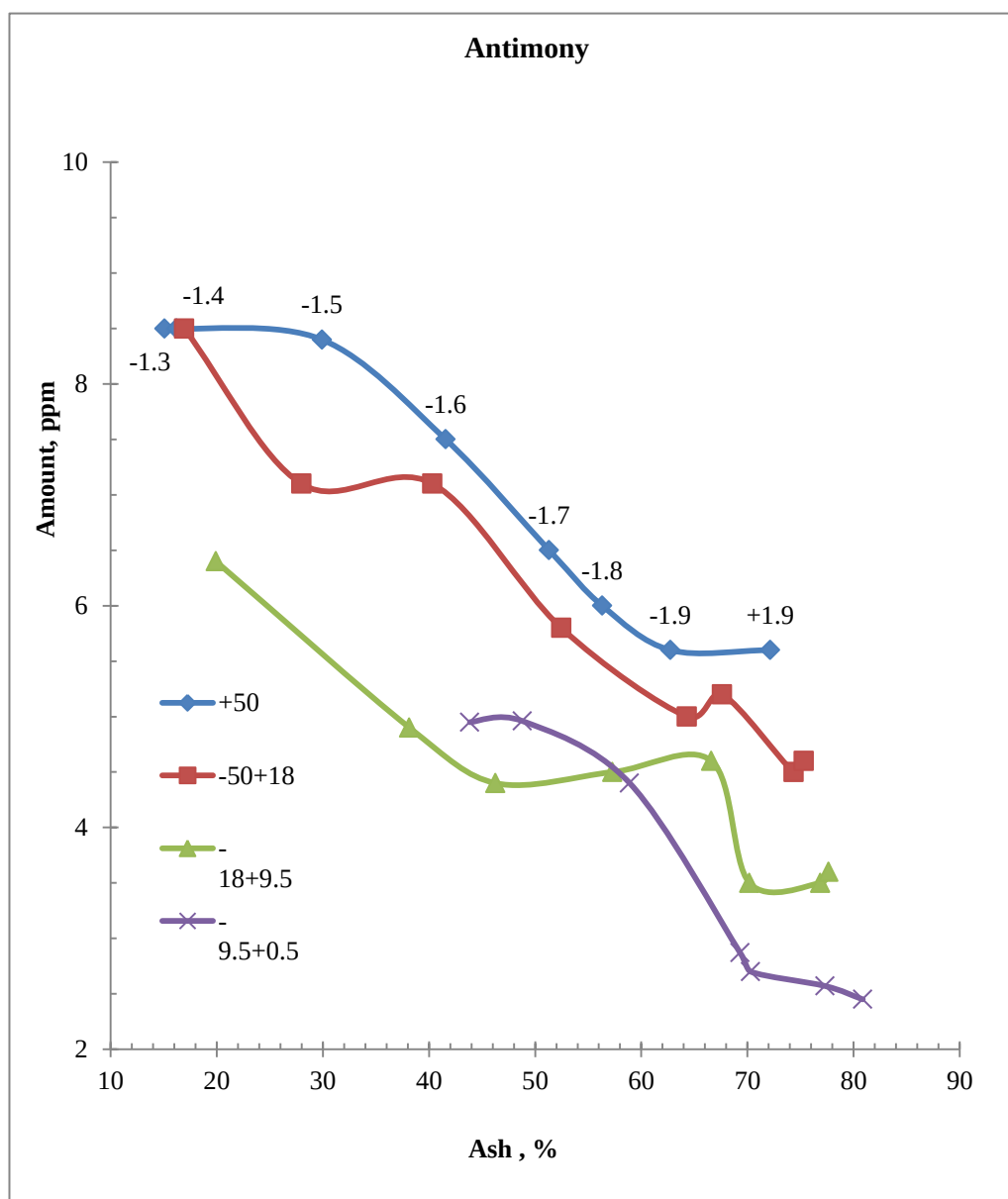


Fig. 5.26. Antimony content vs. ash % of sink and float products at coal size fractions

(Table 5.19, Fig. 5.26.). Evident to its organic association, the highest Sb assay of 8.5 ppm was determined at the -1.3 product of +50 mm fraction. It should be noted that the highest extent of ash rejection by sink and float application on Salihpaşa coal was achieved for the -1.3 product of +50 mm fraction and the ash could be decreased

down to 15.11% at this product (Table 5.19). Despite the lesser extent of antimony in the -9.5+0.5 mm fraction, a clear tendency of increasing Sb with decreasing ash was still observed. Similar findings confirming the strong organic association of antimony in coal were obtained for several other coals (Gluskoter et al., 1977; Swaine, 1990). Also, the rejection of antimony by HMS remained remarkably limited in Soma coal due to the cocentration of Sb with the organic-enriched, i.e. cleaned part of the coal (Ozbayoglu, 2011).

Table 5.19. Antimony content of sink and float products at coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	8.50	1.84	15.11
	+1.30-1.40	4.91	8.50	8.18	16.23
	+1.40-1.50	1.69	8.40	2.78	29.92
	+1.50-1.60	0.82	7.50	1.20	41.57
	+1.60-1.70	1.40	6.50	1.79	51.32
	+1.70-1.80	1.24	6.00	1.46	56.33
	+1.80-1.90	6.33	5.60	6.95	62.74
	+1.90	2.00	5.60	2.19	72.15
-50+18	-1.30	0.81	8.50	1.34	16.95
	+1.30-1.40	14.27	7.10	19.86	27.98
	+1.40-1.50	2.93	7.10	4.08	40.34
	+1.50-1.60	1.20	5.80	1.36	52.46
	+1.60-1.70	2.00	5.00	1.96	64.30
	+1.70-1.80	2.32	5.20	2.36	67.62
	+1.80-1.90	5.71	4.50	5.04	74.36
	+1.90	3.06	4.60	2.76	75.32
-18+9.5	-1.30	0.05	6.40	0.06	19.93
	+1.30-1.40	7.42	4.90	7.13	38.16
	+1.40-1.50	1.90	4.40	1.64	46.26
	+1.50-1.60	0.60	4.50	0.53	57.30
	+1.60-1.70	0.35	4.60	0.32	66.61
	+1.70-1.80	0.77	3.50	0.53	70.19
	+1.80-1.90	1.58	3.50	1.08	76.88
	+1.90	1.68	3.60	1.18	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	4.95	2.74	43.85
	+1.40-1.50	5.73	4.96	5.58	48.81
	+1.50-1.60	5.38	4.40	4.64	58.91
	+1.60-1.70	2.34	2.87	1.32	69.31
	+1.70-1.80	1.57	2.70	0.83	70.30
	+1.80-1.90	1.68	2.57	0.84	77.32
	+1.90	9.70	2.45	4.66	80.87

Despite some exceptions, Selenium (Se) content generally decreased with increasing specific gravities of separation, implying possible organic association of this trace element in Salihpaşa coal (Table 5.20, Fig. 5.27.). The organic association of selenium was also confirmed by the negative Pearson correlation coefficients of Se

with regard to ash content (Table 5.8.). In the coarsest fraction of +50 mm, Se decreased from 3.42 ppm (assay at -1.3 and +1.3-1.4 products) to 1.82 ppm at +1.9 product. For -50+18 mm fraction the tendency of selenium extents was similar: The highest Se assay of 3.18 ppm at the -1.3 product reduced down to 1.78 ppm at the +1.9

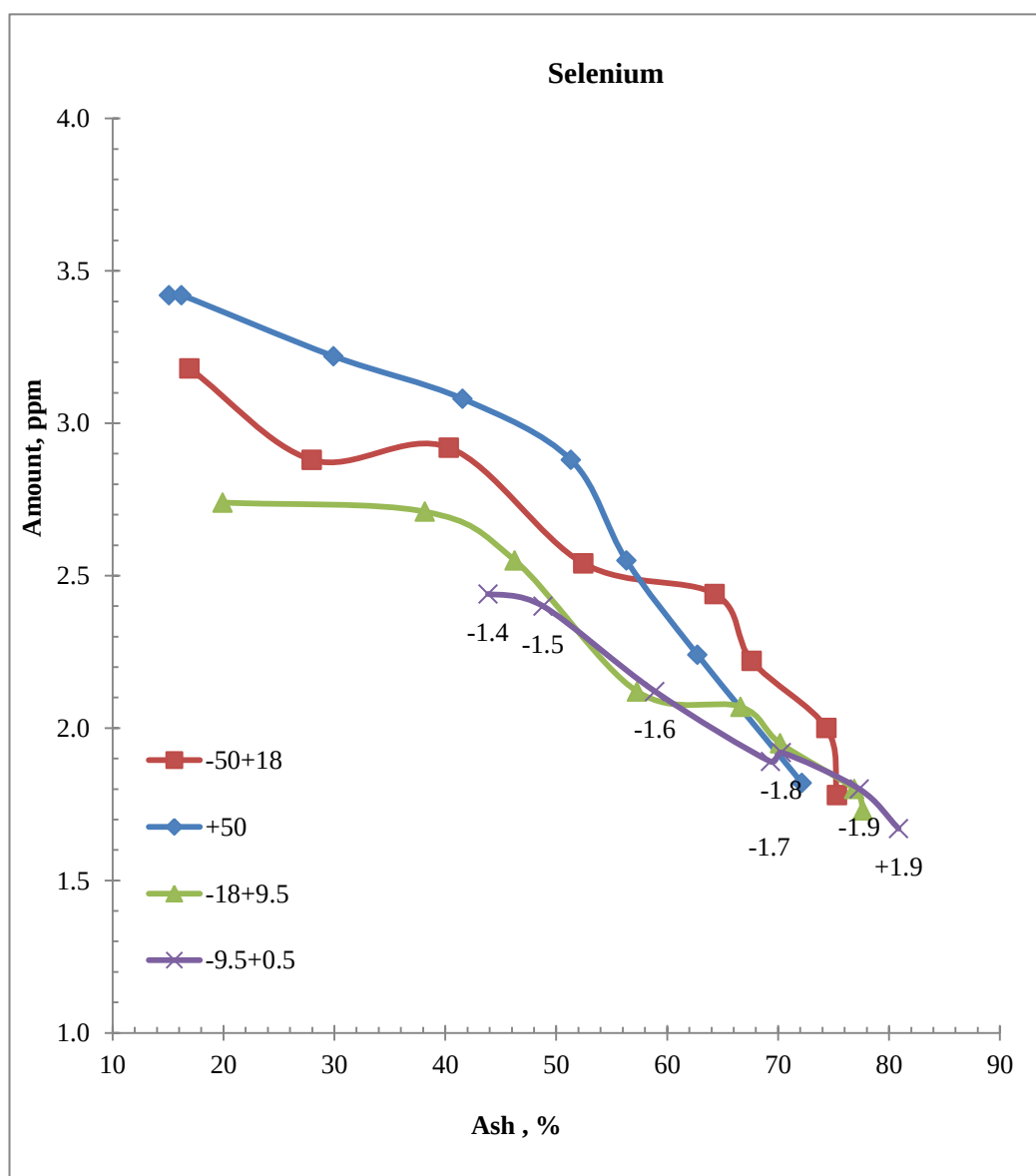


Fig. 5.27. Selenium content vs. ash % of sink and float products at coal size fractions

product. For the -18+9.5 mm fraction, again the highest and the lowest selenium assays were detected for the lightest and heaviest specific gravity products, respectively, i.e. Se and separation specific gravity were conversely related (Table 5.20.). It should also be noted that selenium and ash % also revealed an opposite correlation: First of all, selenium content became higher with increasing ash

rejection; and secondly, with increasing fineness in size fractions, which corresponded to a regularly increasing extent of ash, selenium content gradually increased. On the basis of the obvious inverse relation of selenium with ash, organic association of this trace element in Salihpasa coal could be deduced. The findings in literature show both organic and inorganic association of selenium, presenting selenium presence a feature specific to coal type. Wenfeng et al. (2009) showed that Se was organically bonded for Antaibao coals, but, Ozbayoglu (2011) found that in Soma coal Se was inorganically linked. Also, it was seen that selenium tends to become enriched in the relatively heavier fractions of Çan coal (Gürdal, 2011).

Table 5.20. Selenium content of sink and float products at coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	3.42	1.58	15.11
	+1.30-1.40	4.91	3.42	7.05	16.23
	+1.40-1.50	1.69	3.22	2.29	29.92
	+1.50-1.60	0.82	3.08	1.06	41.57
	+1.60-1.70	1.40	2.88	1.70	51.32
	+1.70-1.80	1.24	2.55	1.33	56.33
	+1.80-1.90	6.33	2.24	5.96	62.74
	+1.90	2.00	1.82	1.53	72.15
-50+18	-1.30	0.81	3.18	1.07	16.95
	+1.30-1.40	14.27	2.88	17.12	27.98
	+1.40-1.50	2.93	2.92	3.56	40.34
	+1.50-1.60	1.20	2.54	1.27	52.46
	+1.60-1.70	2.00	2.44	2.03	64.30
	+1.70-1.80	2.32	2.22	2.14	67.62
	+1.80-1.90	5.71	2.00	4.76	74.36
	+1.90	3.06	1.78	2.27	75.32
-18+9.5	-1.30	0.05	2.74	0.06	19.93
	+1.30-1.40	7.42	2.71	8.38	38.16
	+1.40-1.50	1.90	2.55	2.02	46.26
	+1.50-1.60	0.60	2.12	0.53	57.30
	+1.60-1.70	0.35	2.07	0.31	66.61
	+1.70-1.80	0.77	1.95	0.63	70.19
	+1.80-1.90	1.58	1.80	1.19	76.88
	+1.90	1.68	1.73	1.21	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	2.44	2.87	43.85
	+1.40-1.50	5.73	2.40	5.73	48.81
	+1.50-1.60	5.38	2.12	4.75	58.91
	+1.60-1.70	2.34	1.89	1.84	69.31
	+1.70-1.80	1.57	1.92	1.26	70.30
	+1.80-1.90	1.68	1.80	1.26	77.32
	+1.90	9.70	1.67	6.75	80.87

Presence of Uranium (U) in Salihpaşa coal is also one of the critical aspects and negative features that would adversely influence utilisation of a particular type of coal. The change of U amount with respect to size fractions and separation densities is presented in Table 5.21. and Fig. 5.28. The organic rich -1.3 and -1.4 products were distinguished with their relatively higher U content as compared to denser products.

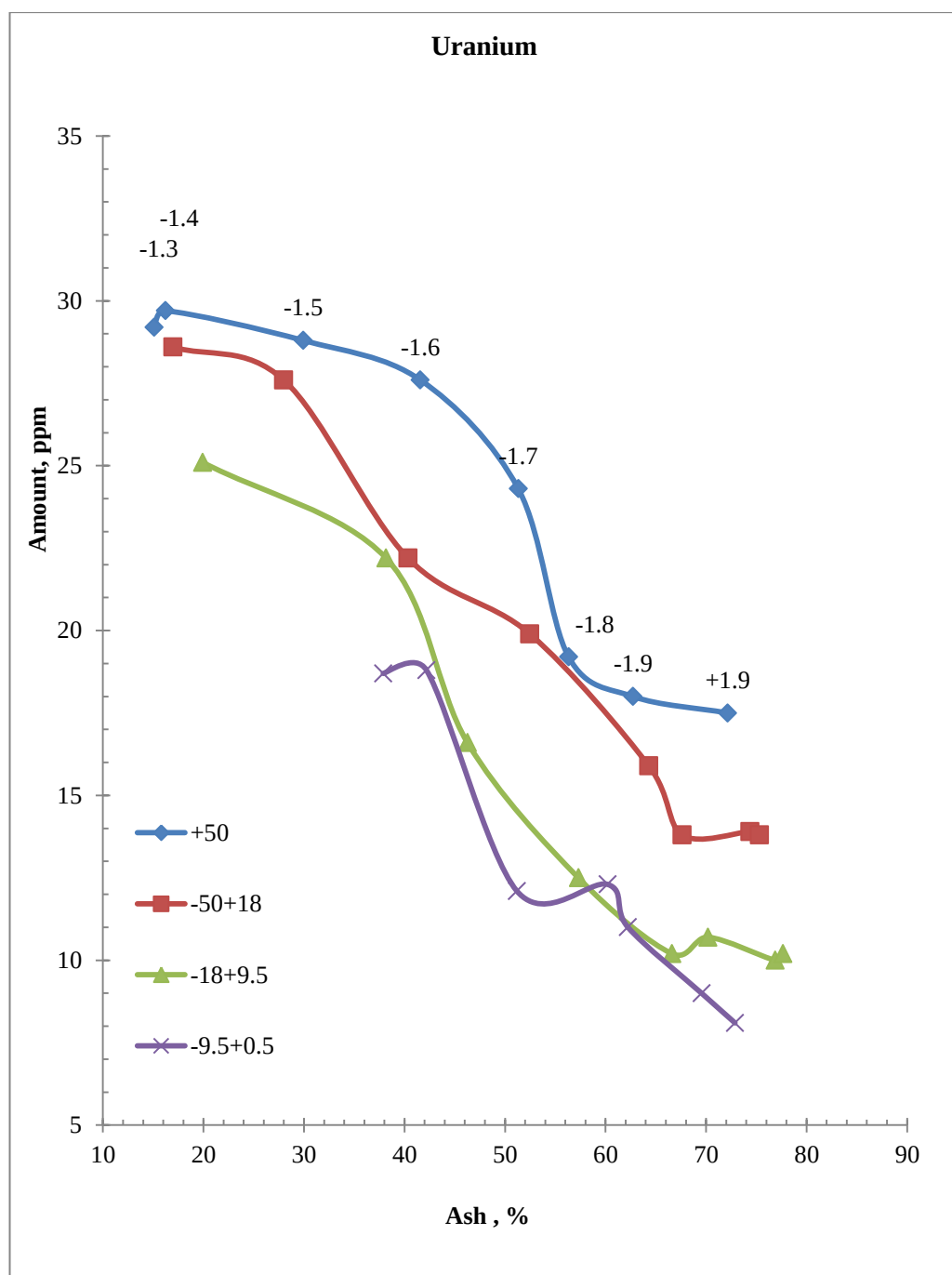


Fig. 5.28. Uranium content vs. ash % of sink and float products at coal size fractions

Also, the decrease of U with increase in ash should be noted. This inverse correlation (Table 5.21.) was observed with increasing fineness in coal as well as with an increasing extent in cleaning. The organic rich products tended to include increasing extents of uranium. Uranium assay was as high as ~30 ppm in the lightest products of +50 mm fraction. These findings were attributed to the strong association of U with the organic content of Salihpaşa coal, i.e. sink and float application resulted in cleaned, but uranium enriched products. Association of uranium with the organic constituents in coal is well established. Previous findings, similar to the presence and association of uranium in Salihpaşa coal were reported stating the strong link amongst uranium and organic matter in coal (Demir, 1998; Wenfeng et al., 2009; Ozbayoğlu, 2010; Gürdal, 2011; Ozbayoglu, 2013).

Table 5.21. Uranium content of sink and float products at coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	29.20	1.79	15.11
	+1.30-1.40	4.91	29.70	8.09	16.23
	+1.40-1.50	1.69	28.80	2.70	29.92
	+1.50-1.60	0.82	27.60	1.25	41.57
	+1.60-1.70	1.40	24.30	1.90	51.32
	+1.70-1.80	1.24	19.20	1.32	56.33
	+1.80-1.90	6.33	18.00	6.33	62.74
	+1.90	2.00	17.50	1.94	72.15
-50+18	-1.30	0.81	28.60	1.28	16.95
	+1.30-1.40	14.27	27.60	21.88	27.98
	+1.40-1.50	2.93	22.20	3.61	40.34
	+1.50-1.60	1.20	19.90	1.32	52.46
	+1.60-1.70	2.00	15.90	1.77	64.30
	+1.70-1.80	2.32	13.80	1.78	67.62
	+1.80-1.90	5.71	13.90	4.41	74.36
	+1.90	3.06	13.80	2.34	75.32
-18+9.5	-1.30	0.05	25.10	0.07	19.93
	+1.30-1.40	7.42	22.20	9.16	38.16
	+1.40-1.50	1.90	16.60	1.75	46.26
	+1.50-1.60	0.60	12.50	0.42	57.30
	+1.60-1.70	0.35	10.20	0.20	66.61
	+1.70-1.80	0.77	10.70	0.46	70.19
	+1.80-1.90	1.58	10.00	0.88	76.88
	+1.90	1.68	10.20	0.95	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	18.70	2.93	43.85
	+1.40-1.50	5.73	18.80	5.99	48.81
	+1.50-1.60	5.38	12.10	3.62	58.91
	+1.60-1.70	2.34	12.30	1.60	69.31
	+1.70-1.80	1.57	11.00	0.96	70.30
	+1.80-1.90	1.68	9.00	0.84	77.32
	+1.90	9.70	8.10	4.37	80.87

Similar to Uranium, the findings showed that Vanadium (V) in Salihpaşa coal was also distinguished with its organic association (Table 5.22, Fig. 5.29.). Presence of negative Pearson correlation coefficients also support this finding (Table 5.8.). First of all, vanadium content was apparently higher in the highest, organically enriched float products (i.e. -1.3, -1.4 and -1.5) for all size fractions. Also, the increase in fineness,

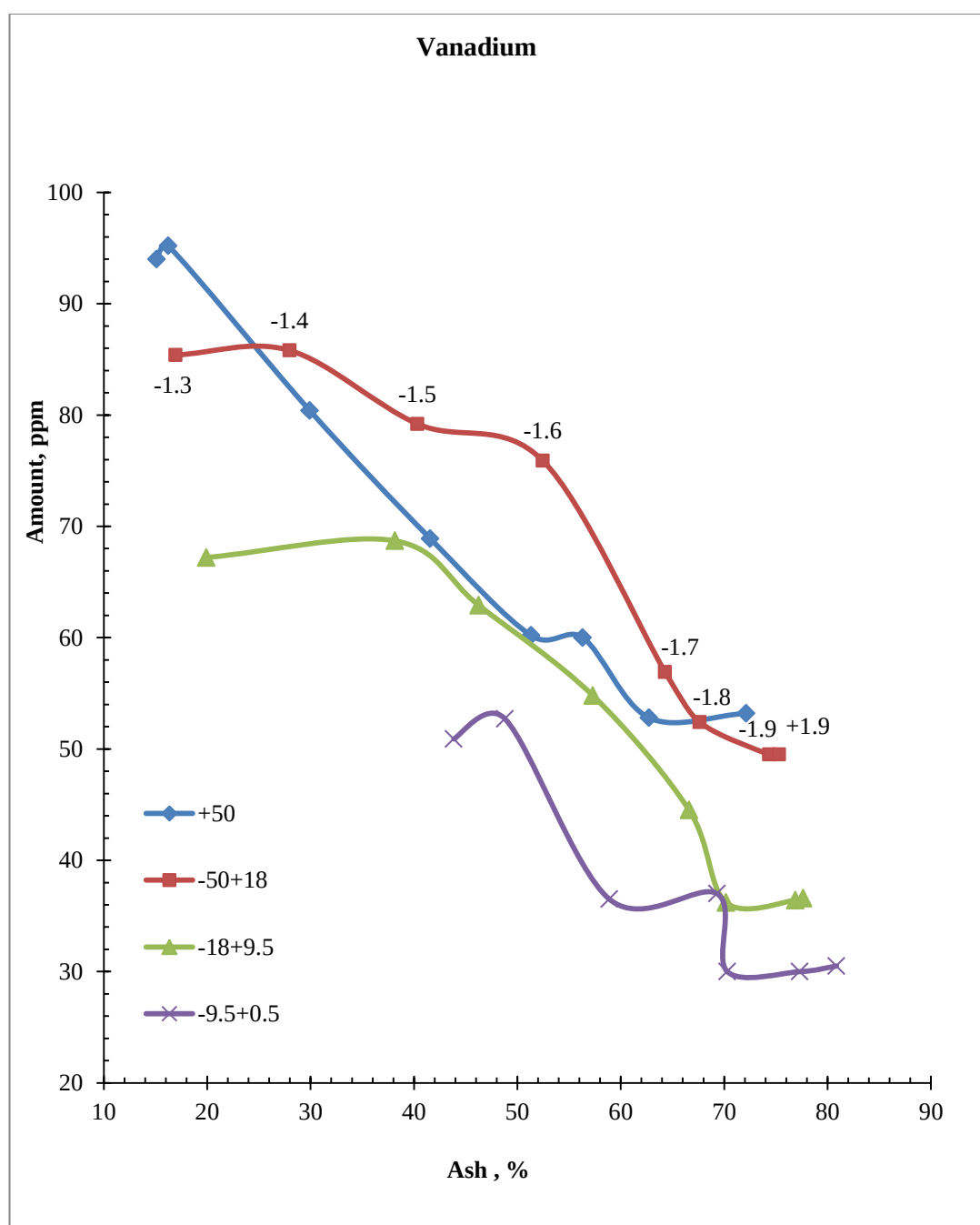


Fig. 5.29. Vanadium content vs. ash % of sink and float products at coal size fractions

which was very much characterized with an increasing ash content, resulted in a clear reduction in the extent of vanadium. Thus, the same conclusion for V could also be deduced and possible cleaning of Salihpaşa coal by HMS would concentrate vanadium in the low-ash, products. Demir (1998) reported that vanadium was associated with the organic matter in coal or might be finely disseminated in macerals for Illinois coals from USA.

Table 5.22 Vanadium content of sink and float products at coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	94.00	1.82	15.11
	+1.30-1.40	4.91	95.20	8.19	16.23
	+1.40-1.50	1.69	80.40	2.38	29.92
	+1.50-1.60	0.82	68.90	0.99	41.57
	+1.60-1.70	1.40	60.20	1.48	51.32
	+1.70-1.80	1.24	60.00	1.31	56.33
	+1.80-1.90	6.33	52.80	5.86	62.74
	+1.90	2.00	53.20	1.87	72.15
-50+18	-1.30	0.81	85.40	1.21	16.95
	+1.30-1.40	14.27	85.80	21.48	27.98
	+1.40-1.50	2.93	79.20	4.07	40.34
	+1.50-1.60	1.20	75.90	1.59	52.46
	+1.60-1.70	2.00	56.90	2.00	64.30
	+1.70-1.80	2.32	52.40	2.13	67.62
	+1.80-1.90	5.71	49.50	4.96	74.36
	+1.90	3.06	49.50	2.66	75.32
-18+9.5	-1.30	0.05	67.20	0.06	19.93
	+1.30-1.40	7.42	68.70	8.95	38.16
	+1.40-1.50	1.90	62.90	2.09	46.26
	+1.50-1.60	0.60	54.80	0.58	57.30
	+1.60-1.70	0.35	44.50	0.28	66.61
	+1.70-1.80	0.77	36.20	0.49	70.19
	+1.80-1.90	1.58	36.40	1.01	76.88
	+1.90	1.68	36.60	1.08	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	50.90	2.52	43.85
	+1.40-1.50	5.73	52.70	5.30	48.81
	+1.50-1.60	5.38	36.50	3.45	58.91
	+1.60-1.70	2.34	37.00	1.52	69.31
	+1.70-1.80	1.57	30.00	0.83	70.30
	+1.80-1.90	1.68	30.00	0.88	77.32
	+1.90	9.70	30.50	5.19	80.87

Based on the content of Zinc (Zn) with respect to size fractions and separation specific gravities, zinc could be suggested to be associated with the ash making inorganic minerals in Salihpaşa coal (Table 5.23). Positive Pearson correlation coefficients were also determined for the zinc-ash relation, implying association of

zinc with the inorganic constituents (Table 5.8.). The lowest extent of zinc was obtained in the -1.3 products for all size fractions (Table 5.23, Fig. 5.30.). This demonstrates that with increasing effectiveness of cleaning and ash removal, rejection of zinc also advanced. With respect to size fractions, reduction in size

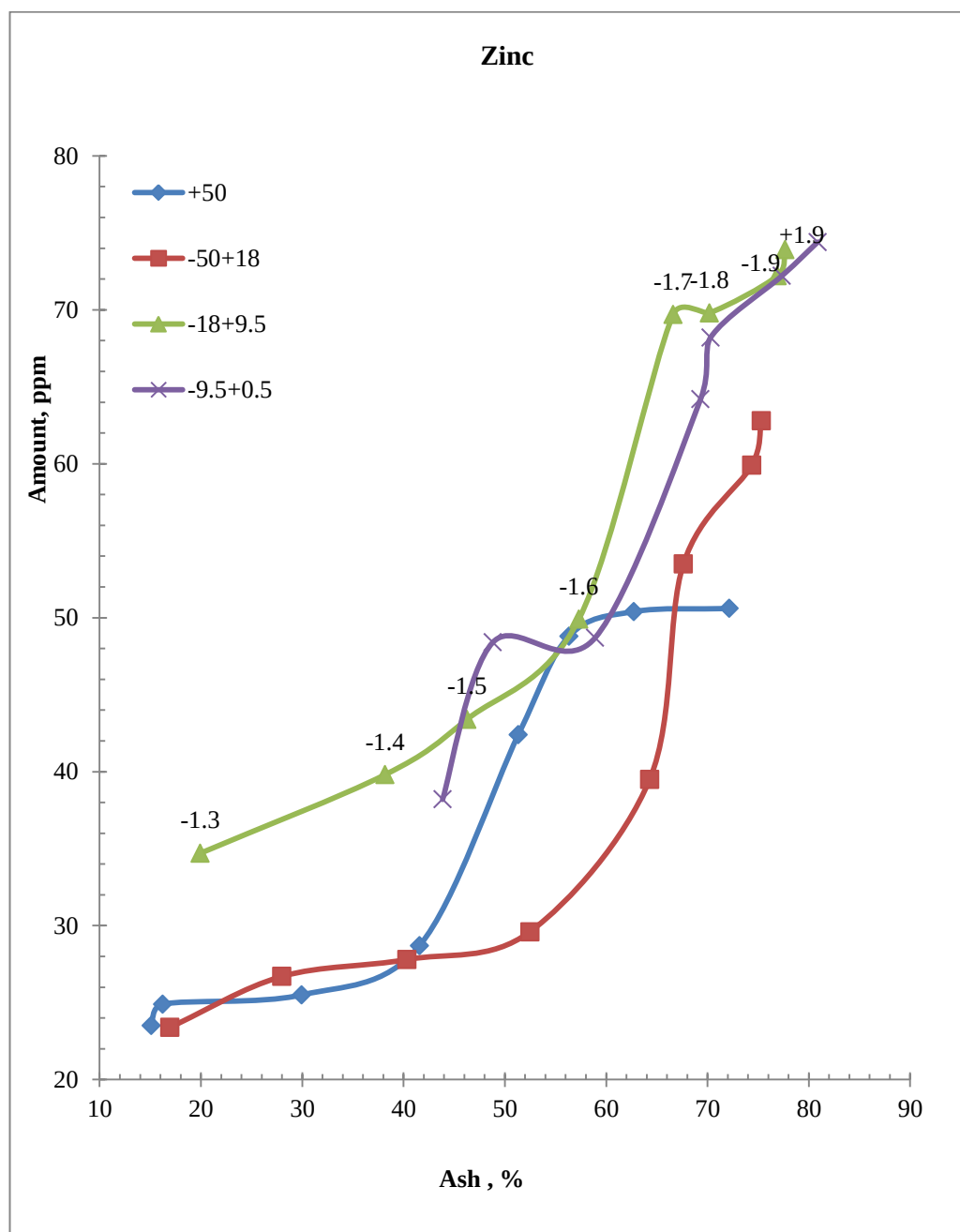


Fig. 5.30. Zinc content vs. ash % of sink and float products at coal size fractions

caused an enrichment in zinc content, following the increase in ash. Compared to 23.50 ppm Zn in the -1.3 product of +50 mm fraction, the Zn content of the +1.9 product of -9.5+0.5 mm fraction was more than three times higher (74.40 ppm, Table

5.23). It is likely that zinc in Salihpaşa coal was linked with metallic sulfides. Previous findings for different coals also support this suggestion where sphalerite (ZnS) was reported to be the major zinc source (Finkelman, 1995; Goodarzi, 2002). These observations implied that possible HMS application on Salihpaşa coal would provide favorable results in terms of zinc rejection along with the inorganic matter and, i.e. reduction of ash.

Table 5.23. Zinc content of sink and float products at coal size fractions

Size (mm)	Sink and Float Product	Weight (%)	Assay (ppm)	Distribution (%)	Ash (%)
+50	-1.30	1.10	23.50	0.54	15.11
	+1.30-1.40	4.91	24.90	2.54	16.23
	+1.40-1.50	1.69	25.50	0.90	29.92
	+1.50-1.60	0.82	28.70	0.49	41.57
	+1.60-1.70	1.40	42.40	1.24	51.32
	+1.70-1.80	1.24	48.80	1.26	56.33
	+1.80-1.90	6.33	50.40	6.64	62.74
	+1.90	2.00	50.60	2.11	72.15
-50+18	-1.30	0.81	23.40	0.39	16.95
	+1.30-1.40	14.27	26.70	7.94	27.98
	+1.40-1.50	2.93	27.80	1.70	40.34
	+1.50-1.60	1.20	29.60	0.74	52.46
	+1.60-1.70	2.00	39.50	1.65	64.30
	+1.70-1.80	2.32	53.50	2.58	67.62
	+1.80-1.90	5.71	59.90	7.12	74.36
	+1.90	3.06	62.80	4.00	75.32
-18+9.5	-1.30	0.05	34.70	0.04	19.93
	+1.30-1.40	7.42	39.80	6.16	38.16
	+1.40-1.50	1.90	43.40	1.72	46.26
	+1.50-1.60	0.60	49.90	0.63	57.30
	+1.60-1.70	0.35	69.70	0.52	66.61
	+1.70-1.80	0.77	69.80	1.12	70.19
	+1.80-1.90	1.58	72.20	2.38	76.88
	+1.90	1.68	73.90	2.58	77.65
-9.5+0.5	-1.30	-	-	-	-
	+1.30-1.40	2.82	38.20	2.25	43.85
	+1.40-1.50	5.73	48.40	5.78	48.81
	+1.50-1.60	5.38	48.70	5.46	58.91
	+1.60-1.70	2.34	64.20	3.13	69.31
	+1.70-1.80	1.57	68.20	2.23	70.30
	+1.80-1.90	1.68	72.20	2.52	77.32
	+1.90	9.70	74.40	15.04	80.87

Total rejections (%) of fifteen trace elements with respect to separation specific gravities were also calculated and evaluated. In industrial scale, coal washing using HMS is generally commenced at a specific gravity range of 1.5 – 1.8 where adjusting a separation specific gravity of 1.6-1.7 is the most common practice, considering the trade-off between ash rejection and clean coal yield. Therefore, results are presented

in Table 24 for separation possibilities at 1.5-1.8, but assessments were made for possible separations at 1.6 and 1.7. The results directly show the possible extent of rejection of various trace elements at varying separation specific gravities, i.e. allows the assessment of effectiveness of a possible HMS application on Salihpaşa coal with respect to each trace element considered as well as on the basis of separation specific gravity options from 1.5 to 1.8.

It was seen that a possible HMS scenario set at 1.6 as the separation specific gravity would provide around 63.56 % ash rejection for Salihpaşa coal. The rejection of arsenic, barium, mercury, manganese, molybdenum, lead and zinc was quite effective at this separation specific gravity where more than 60% of these trace elements could be removed with ash (Table 5.24.). More than half of the copper (53.89 %) could also be rejected by a separation set at 1.6 specific gravity. Rejection of chromium, antimony, selenium, uranium and vanadium remained limited on account to the affinity of these trace elements towards organic portions (<40%). Separation of nickel and cadmium were also relatively lower (47.83 % and 44.23 %, respectively). Separation possibility at 1.7, which would obviously provide a higher clean coal yield, resulted in decreases in the rejection of ash and trace elements associated with organic constituents. However, removal of arsenic, barium, mercury, manganese, molybdenum, lead and zinc were still at quite acceptable levels where rejections of As, Ba and Mn were > 60 % and rejections of Hg, Mo, Pb and Zn were still > 50 %.

Table 5.24. Total rejection of trace elements at separation specific gravities of 1.5-1.8

	Separation Sp. Gr.			
	1.5	1.6	1.7	1.8
Ash	71.66	63.56	56.57	49.49
As	76.48	68.46	62.21	55.86
Ba	79.21	68.88	60.82	53.18
Cd	51.8	44.23	37.73	32.52
Cr	47.29	39.46	34.13	28.93
Cu	61.94	53.89	47.55	41.35
Hg	70.92	63.16	55.18	47.09
Mn	76.61	67.4	60.34	52.84
Mo	69.64	60.05	53.59	47.04
Ni	55.29	47.83	42.37	37
Pb	71.58	64	56.73	49.24
Sb	45.39	37.65	32.27	27.08
Se	46.88	39.27	33.39	28.04
U	40.72	34.1	28.64	24.12
V	41.93	35.32	30.05	25.29
Zn	70.12	62.8	56.28	49.08

In view of these findings it could be stated that possible cleaning of Salihpaşa coal by HMS would not only provide a cleaner fossil fuel with reduced ash and improved fuel characteristics, but also would provide in the reduction of some of the very critical and harmful trace elements such as arsenic, mercury and lead. This would also dramatically reduce the emission of these trace elements as compared to the cumulative emission of these trace elements when Salihpaşa coal is utilized in its run-of-mine form. Despite the fact that the trace elements with organic-associations, such as uranium, vanadium, antimony and selenium can not be rejected as effectively, the HMS based cleaning process could still provide limited rejection in these trace elements (Table 5.24.).

6. CONCLUSION

In this study rejection possibilities of As, Ba, Cd, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Se, U, V and Zn from Salihpaşa coal were evaluated by sink and float analysis in order to assess the effectiveness of possible HMS cleaning. It was seen that, more or less, the amounts of all trace elements changed due to size fractionation as well as sink and float application at size fractions of +50 mm, -50+18 mm, -18+9.5 mm and -9.5+0.5 mm.

As, Ba, Cu, Hg, Mn, Mo, Pb and Zn contents were inversely proportional with increasing fineness in coal size, while Cd, Cr, Sb, Se, U and V were directly correlated with increasing fineness. With increasing fineness in Salihpaşa coal, the ash content also increased, indicating the affinity of the above mentioned trace elements to inorganic, ash making constituents.

In contrast, Cd, Cr, Sb, Se, U and V were organically linked in Salihpaşa coal. Ni content did not provide any meaningful tendency with regard to size fractionation, most probably owing to its random association with both the organic inorganic constituents.

Trace elements that show association to the inorganic minerals in Salihpaşa coal with provide a significant opportunity for their rejection along with the ash through HMS. The degree of rejection is somewhat related to the degree of association of these trace elements with the inorganic constituents. In this respect, possible HMS scenarios set at separation specific gravities of 1.6 or 1.7 proved to yield significant rejection of arsenic, barium, mercury, manganese, molybdenum, lead and zinc.

On the other hand, possible cleaning of Salihpaşa coal would not be as effective in the removal of chromium, antimony, selenium, uranium and vanadium. This was due to the organically linked occurrence of these trace elements in Salihpaşa coal.

Overall, it would be concluded that HMS proved to be a promising option for cleaning of Salihpaşa coal. The potential opportunities related with a possible HMS cleaning include, cleaner beneficiation of this important resource, reduced ash

formation, improved fuel characteristics such as increase in calorific value and reduced trace element and SO₂ emissions.

REFERENCES

- Akers, D.J., and Raleigh, C.E. (1998) The mechanisms of Trace element removal during coal cleaning, *Coal Preparation*, 19:257-269.
- ASTM D4371, (2012), *Standard Test Method for Determining the Washability Characteristics of Coal*.
- ATSDR, (2000) Toxicological profile for arsenic. US Department of Health and Human Services, Public Health Service Agency for Toxic Substances and Disease Registry, 428.
- ATSDR, (2007) Toxicological profile for arsenic. US Department of Health and Human Services, Public Health Service Agency for Toxic Substances and Disease Registry.
- Baba, A. (2002) Geochemical Assessment of Environmental Effects of Ash from Yatagan (Mugla-Turkey) Thermal Power Plant, *Water, Air, and Soil Pollution*, 144: 3-18.
- Belkin, H.E, Zheng, B. Zhou, D and Finkelman, R.B. (2008) Chronic Arsenic Poisoning from Domestic Combustion of Coal in Rural China: A Case Study of the Relationship Between Earth Materials and Human Health, *Environmental Geochemistry*, 401-419.
- Bergh, J.P., Falcon, R.M.S. and Falcon L.M. (2010) Trace element concentration reduction by beneficiation of Witbank Coalfield no. 4 Seam, *Fuel Processing Technology*, 92: 812-816.

- Boyd, R. J. (2004) *Trace elements in coal from Collinsville, Bowen Basin, Australia: In-ground mode of occurrence and behaviour during utilisation*. PhD Thesis, Queensland: Australia, James Cook University Townsville,.
- Dai, S., Ren, D., Tang, Y., Yue, M., Hao, L.M. (2005) Concentration and distribution of elements in Late Permian coals from western Guizhou Province, China, *Int. J. Coal Geol*, 61: 119–137.
- Davidson, R. M. (1997) Coal cleaning to remove trace elements-A review, *International Journal of Coal Preparation and Utilization*, 19: 159-176.
- Demir, I. (1998) Removal of ash, Sulfur, and Trace Elements of Environmental Concern from Eight Selected Illinois Coals, *International Journal of Coal Preparation and Utilization*, 19:3-4, 271-296.
- Finkelman, R. B. (1994) Modes of Occurrence of Potentially Hazardous Elements in Coal: Levels of Confidence, *Fuel Processing Technology*, 39: 21-34.
- Finkelman, R. B. (1995) *Modes of Occurrence of Environmentally - Sensitive Trace Elements in Coal*. Chpt 3, p24-50. in Swaine, D. J. and Goodarzi, F. eds *Environmental Aspects of Trace Elements in Coal*. Kluwer Academic Publishers.
- Finkelman, R.B. (1999) Trace Elements in Coal Environmental and Health Significance, *Biological Trace Element Research*, 67(3):197-204.
- Finkelman, R.B., Orem, William, Castranova, Vincent, Tatu, C.A., Belkin, H.E., Zheng, Baoshan, Lerch, H.E., Maharaj, S.V., and Bates, A.L. (2002) Health impacts of coal and coal use-Possible solutions, *International Journal of Coal Geology*, 50: 425-443.
- Firth, B. and Dale, L. (1998) Trace elements and Coal Preparation, *International Journal of Coal Preparation and Utilization*, 19:3-4, 297-317.

Gluskoter, H. J., Ruch, R. R., Miller, W. G., Cahill, R. A., Dreher, G. B. and Kuhn J. K. (1977) *Trace Elements in Coal: Occurrence and Distribution*, Illinois State Geological Survey, Circular 499.

Goodarzi, F. (2002) Mineralogy, elemental composition and modes of occurrence of elements in Canadian feed-coals, *Fuel*, 81:1199-1213.

Gürdal, G. (2011) Abundances and modes of occurrence of trace elements in the Çan coals (Miocene), Çanakkale-Turkey, *International Journal of Coal Geology*, 87:157-173.

Hower, J.C., Blanchard, L.J. and David Robertson J.D. (1998) Magnitude of Minor Element Reduction through Beneficiation of Central Appalachian Coals, *International Journal of Coal Preparation and Utilization*, 19:213-229.

Kang, Y., Liu, G., Chou, C.L., Wong, M.H., Zheng, L. And Ding, R. (2011) Arsenic in Chinese coals: Distribution, modes of occurrence, and environmental effects, *Science of the Total Environment*, 412-413, 1-13.

Karayigit, A.I., Gayer, R.A., Querol, X. and Onacak, T. (2000) Contents of major and trace elements in feed coals from Turkish coal-fired power plants, *International Journal of Coal Geology*, 44:169-184.

LeBlanc, D.C. (2003) *Statistics: Concepts and Applications for Science*, Jones and Bartlett Publishers, Canada.

Lockwood, A.H., Welker, K., Rauch, M. and Gottlieb B. (2009) *Coal's Assault on Human Health*, Physicians for Social Responsibility Report, 44.

- Luttrell, G. H., J. N. Kohmuench, and R. H. Yoon. (1999) An evaluation of coal preparation technologies for controlling trace element emissions, *Fuel Processing Technology*, 65-66:407-422.
- Mohanty, M.K., Honaker, R.Q., Mondal, K., Paul, B.C. and Ho, K. (1997) Trace Element Reduction in Fine Coal Using Advanced Physical Cleaning, *International Journal of Coal Preparation and Utilization*, 19:3-4, 195-211.
- Mukherjee, K.N., Dutta, N.R., Chandra, D., Pandalai, H.S., and Singh, M.P. (1988) Statistical Approach to the study of the distribution of trace elements and their organic/inorganic affinity in Lower Gondawana Coals of India, *International Journal of Coal Geology*, 10:99-108.
- National Research Council, (1980) Trace element Geochemistry of Coal Resource Development Related to Environmental Quality and Health, National Academy of Science, Washington, D.C.
- Ng, J.C., Wang, J. and Shraim, A. (2003) A global health problem caused by arsenic from natural sources, *Chemosphere*, 52:1353-1359.
- Ozbayoğlu, G. (2010) Potential of Removing Trace Elements from a Turkish Lignite, *International Journal of Coal Preparation and Utilization*, 30:322-330.
- Ozbayoglu, G. (2011) Partitioning of major and trace elements of a Turkish lignite with size and density, *Physicochem. Probl. Miner. Process*, 47:51-60.
- Ozbayoglu, G. (2013) Removal of hazardous air pollutants based on commercial coal preparation plant data, *Physicochem. Probl. Miner. Process*, 49:621-629.
- Palmer, C. A., Tuncali E., Dennen, K. O., Coburn, T. C. and Finkelman R. B. (2004) Characterization of Turkish coals: a nationwide perspective, *International Journal of Coal Geology*, 60:85-115.

Pavlish, J.H., Sondreal, E.A., Mann, M.D., Olson, E.S., Galbreath, K.C.,Laudal, D.L. and Benson, S.A. (2003) Status review of mercury control options for coal-fired power plants, *Fuel Processing Technology*, 82:89-165.

Querol, X., Cabrera, L., Pickel,W., Lopez-Soler, A., Hagemann, H.W., Fernandez-Turiel, J.L. (1996) Geological controls on the coal quality of the Mequinenza subbituminous coal deposit, north-east Spain, *Int. J. Coal Geol*, 29:67-91.

Rimmer, S.A., (1991) Distributions and associations of selected trace elements in the Lower Kittanning seam, western Pennsylvania, USA, *International Journal of Coal Geology*, 17(3-4), 189-212.

Swaine, D.J. (1990) *Trace elements in coal*, Butterworth, London, 292.

Swaine, D.J. (1992) Organic association of elements in coals, *Organic Geochemistry*, 18:259-261.

Swaine, D.J. (1997) Trace elements during the mining, and beneficiation of coal, *Coal Preparation* 19(3-6): 177-193.

Swaine D.J. and Goodarzi F. (1995) *Environmental Aspects of Trace Elements in Coal*, Kluwer Academic Publishing, Netherlands.

Tewalt, S.J., Bragg, L.J., Finkelman, R.B. (2001) *U.S. Geological Survey Fact Sheet 095-01*, Mercury in U.S. Coal-Abundance, Distribution, and Modes of Occurrence.

USGS, 2006a, *Fact Sheet*, Arsenic in Coal, U.S. Geological Survey.

- Vardar, N. and Yumurtaci, Z. (2009) Emissions estimation for lignite-fired power plants in Turkey, *Energy Policy*, 38:243-252.
- Vejahati, F., Xu, Z. and Gupta, R. (2009) Trace elements in coal: Associations with coal and minerals and their behavior during coal utilization - A review, *Fuel*, 89: 904-911.
- Weinberg, S.L., Abramowitz, S.K. (2002) Data Analysis for the Behavioral Sciences Using SPSS, Cambridge University Press, United States of America.
- Wenfeng, W., Yong, Q., Bo, J., Xuehai, F. (2004) Modes of occurrence and cleaning potential of trace elements in coals from the northern Ordos Basin and Shanxi Province, China, *Acta Geologica Sinica-English edition*, 78:960-969.
- Wenfeng, W., Yong, Q., Jun-yi, W., Jian, L. (2009) Partitioning of hazardous trace elements during coal preparation, *Procedia Earth and Planetary Science*, 1: 838-844.
- Zheng, B., Ding, Z., Huang, R., Zhu, J., Yu, X., Wang, A., Zhou, D., Mao D. and Su, H. (1998) Issues of health and disease relating to coal use in southwestern China, *International Journal of Coal Geology*, 40:119-132.

APPENDIX

Appendix A. Contents and Distributions of Trace Element and Ash in Coal Sizes.

Table A1. Ash content of Salihpaşa ROM coal in coal sizes.

Coal size, mm	Specific Gravity Fraction	Weight (g)	Weight (%)	Ash (%) Air Dry	Ash (%) Dry	Ash Product
+50	-1.30	1771.59	1.1	12.98	15.11	16.65
	+1.30-1.40	7884.42	4.91	14.02	16.23	79.62
	+1.40-1.50	2715.54	1.69	25.86	29.92	50.56
	+1.50-1.60	1313.91	0.82	36.12	41.57	33.99
	+1.60-1.70	2257.87	1.4	44.59	51.32	72.1
	+1.70-1.80	1995.66	1.24	49.86	56.33	69.94
	+1.80-1.90	10171.85	6.33	56.44	62.74	397.04
	+1.90	3212.31	2	65.02	72.15	144.19
-50+18	-1.30	1293.89	0.81	14.56	16.95	13.64
	+1.30-1.40	22932.42	14.27	24.17	27.98	399.22
	+1.40-1.50	4709.29	2.93	34.86	40.34	118.19
	+1.50-1.60	1925.1	1.2	45.58	52.46	62.84
	+1.60-1.70	3214.22	2	55.86	64.3	128.58
	+1.70-1.80	3726.24	2.32	59.86	67.62	156.77
	+1.80-1.90	9172.59	5.71	66.89	74.36	424.33
	+1.90	4914.29	3.06	67.88	75.32	230.29
-18+9.5	-1.30	79.14	0.05	17.12	19.93	0.98
	+1.30-1.40	11932.94	7.42	32.96	38.16	283.28
	+1.40-1.50	3049.27	1.9	39.98	46.26	87.77
	+1.50-1.60	967.79	0.6	49.78	57.3	34.5
	+1.60-1.70	570.19	0.35	57.87	66.61	23.63
	+1.70-1.80	1237.63	0.77	62.13	70.19	54.04
	+1.80-1.90	2541.05	1.58	69.16	76.88	121.54
	+1.90	2696.47	1.68	69.98	77.65	130.27
-9.5+0.5	-1.30	-	-	-	-	-
	+1.30-1.40	4536.71	2.82	37.88	43.85	123.78
	+1.40-1.50	9215.49	5.73	42.18	48.81	279.84
	+1.50-1.60	8648.17	5.38	51.18	58.91	316.96
	+1.60-1.70	3756.76	2.34	60.22	69.31	162.01
	+1.70-1.80	2523.89	1.57	62.23	70.3	110.39
	+1.80-1.90	2693.61	1.68	69.56	77.32	129.58
	+1.90	15595.31	9.7	72.88	80.87	784.66
-0.5	-	4.65	4.65	69.56		

Table A2. As, Ba and Cd contents and distributions of Salihpaşa ROM coal in coal sizes.

Coal size, mm	Sp. Gr. Fraction	Weight (g)	Weight (%)	As			Ba			Cd		
				Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)
+50	-1.30	1771.59	1.1	16	17.64	0.28	40	44.09	0.29	1.7	1.87	1.56
	+1.30-1.40	7884.42	4.91	20.42	100.17	1.6	39	191.31	1.25	1.7	8.34	6.95
	+1.40-1.50	2715.54	1.69	20.22	34.16	0.55	39	65.89	0.43	1.7	2.87	2.39
	+1.50-1.60	1313.91	0.82	22.74	18.59	0.3	50	40.87	0.27	1.6	1.31	1.09
	+1.60-1.70	2257.87	1.4	37.86	53.18	0.85	92	129.24	0.85	1.5	2.11	1.76
	+1.70-1.80	1995.66	1.24	36.48	45.29	0.72	92	114.23	0.75	1.1	1.37	1.14
	+1.80-1.90	10171.85	6.33	49.86	315.54	5.04	97	613.86	4.03	1.1	6.96	5.8
	+1.90	3212.31	2	60.48	120.87	1.93	108	215.84	1.42	1.1	2.2	1.83
-50+18	-1.30	1293.89	0.81	18.5	14.89	0.24	44	35.42	0.23	1.4	1.13	0.94
	+1.30-1.40	22932.42	14.27	22.68	323.59	5.17	44	627.77	4.12	1.4	19.97	16.65
	+1.40-1.50	4709.29	2.93	28.89	84.65	1.35	72	210.95	1.38	1.3	3.81	3.17
	+1.50-1.60	1925.1	1.2	30.62	36.67	0.59	122	146.12	0.96	1.5	1.8	1.5
	+1.60-1.70	3214.22	2	52.98	105.95	1.69	135	269.97	1.77	1.5	3	2.5
	+1.70-1.80	3726.24	2.32	56.18	130.24	2.08	145	336.16	2.2	1.1	2.55	2.13
	+1.80-1.90	9172.59	5.71	86.12	491.47	7.86	154	878.85	5.76	1.1	6.28	5.23
	+1.90	4914.29	3.06	94.22	288.07	4.6	158	483.08	3.17	1.1	3.36	2.8
-18+9.5	-1.30	79.14	0.05	16.42	0.81	0.01	48	2.36	0.02	1	0.05	0.04
	+1.30-1.40	11932.94	7.42	38.97	289.32	4.62	52	386.06	2.53	1.2	8.91	7.42
	+1.40-1.50	3049.27	1.9	49.86	94.59	1.51	119	225.76	1.48	1	1.9	1.58
	+1.50-1.60	967.79	0.6	60.99	36.72	0.59	212	127.65	0.84	1	0.6	0.5
	+1.60-1.70	570.19	0.35	68.98	24.47	0.39	264	93.65	0.61	1	0.35	0.3
	+1.70-1.80	1237.63	0.77	84.96	65.42	1.05	272	209.44	1.37	1	0.77	0.64
	+1.80-1.90	2541.05	1.58	102.92	162.71	2.6	272	430.01	2.82	1	1.58	1.32
	+1.90	2696.47	1.68	122.94	206.25	3.3	269	451.28	2.96	1	1.68	1.4
-9.5+0.5	-1.30	-	-	-	-	-	-	-	-	-	-	-
	+1.30-1.40	4536.71	2.82	50.22	141.75	2.27	137.5	388.1	2.56	1	2.82	2.35
	+1.40-1.50	9215.49	5.73	64.46	369.58	5.91	165.1	946.6	6.24	1	5.73	4.78
	+1.50-1.60	8648.17	5.38	76.12	409.57	6.55	233.2	1254.74	8.26	1	5.38	4.48
	+1.60-1.70	3756.76	2.34	88.69	207.29	3.31	314	733.91	4.83	1	2.34	1.95
	+1.70-1.80	2523.89	1.57	99.59	156.38	2.5	320	502.48	3.31	1	1.57	1.31
	+1.80-1.90	2693.61	1.68	120.46	201.87	3.23	322	539.62	3.55	1	1.68	1.4
	+1.90	15595.31	9.7	125.7	1219.63	19.5	332	3221.31	21.22	1	9.7	8.09

Table A3. Cr, Cu and Hg contents and distributions of Salihpaşa ROM coal in coal sizes.

Coal size, mm	Sp. Gr. Fraction	Weight (g)	Weight (%)	Cr			Cu			Hg		
				Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)
+50	-1.30	1771.59	1.1	81.9	90.27	1.48	28	30.86	0.71	0.8	0.88	0.79
	+1.30-1.40	7884.42	4.91	82.9	406.65	6.67	28.1	137.84	3.18	0.8	3.92	3.54
	+1.40-1.50	2715.54	1.69	80	135.16	2.22	27	45.62	1.05	0.8	1.35	1.22
	+1.50-1.60	1313.91	0.82	78	63.76	1.05	30.6	25.01	0.58	0.8	0.65	0.59
	+1.60-1.70	2257.87	1.4	68	95.52	1.57	34	47.76	1.1	1.2	1.69	1.52
	+1.70-1.80	1995.66	1.24	64	79.46	1.3	33.9	42.09	0.97	1.2	1.49	1.34
	+1.80-1.90	10171.85	6.33	59	373.38	6.12	35.9	227.19	5.25	0.9	5.7	5.13
	+1.90	3212.31	2	59	117.92	1.93	35.6	71.15	1.64	0.9	1.8	1.62
-50+18	-1.30	1293.89	0.81	76	61.18	1	30.6	24.63	0.57	0.5	0.4	0.36
	+1.30-1.40	22932.42	14.27	76	1084.34	17.78	32.4	462.27	10.68	0.7	9.99	9
	+1.40-1.50	4709.29	2.93	77	225.6	3.7	32	93.76	2.17	0.5	1.46	1.32
	+1.50-1.60	1925.1	1.2	72	86.24	1.41	36.9	44.2	1.02	0.7	0.84	0.76
	+1.60-1.70	3214.22	2	61	121.98	2	45.4	90.79	2.1	1.2	2.4	2.16
	+1.70-1.80	3726.24	2.32	60	139.1	2.28	45.2	104.79	2.42	1.4	3.25	2.92
	+1.80-1.90	9172.59	5.71	57	325.29	5.33	47.2	269.36	6.22	1.2	6.85	6.17
	+1.90	4914.29	3.06	57	174.28	2.86	46.9	143.4	3.31	1.3	3.97	3.58
-18+9.5	-1.30	79.14	0.05	67	3.3	0.05	34	1.67	0.04	0.8	0.04	0.04
	+1.30-1.40	11932.94	7.42	74.4	552.36	9.06	44.1	327.41	7.56	0.9	6.68	6.02
	+1.40-1.50	3049.27	1.9	68	129	2.11	44	83.47	1.93	0.7	1.33	1.2
	+1.50-1.60	967.79	0.6	54.2	32.63	0.53	45	27.1	0.63	1	0.6	0.54
	+1.60-1.70	570.19	0.35	46.9	16.64	0.27	48.2	17.1	0.39	1.5	0.53	0.48
	+1.70-1.80	1237.63	0.77	47.8	36.81	0.6	50.8	39.12	0.9	1.8	1.39	1.25
	+1.80-1.90	2541.05	1.58	47.4	74.94	1.23	52.2	82.52	1.91	1.6	2.53	2.28
	+1.90	2696.47	1.68	48.8	81.87	1.34	50.6	84.89	1.96	1.7	2.85	2.57
-9.5+0.5	-1.30	-	-	-	-	-	-	-	-	-	-	-
	+1.30-1.40	4536.71	2.82	62.2	175.56	2.88	50.5	142.54	3.3	0.8	2.26	2.05
	+1.40-1.50	9215.49	5.73	61.1	350.32	5.74	52.2	299.29	6.92	0.8	4.59	4.17
	+1.50-1.60	8648.17	5.38	54.8	294.85	4.83	46.8	251.81	5.82	1.2	6.46	5.87
	+1.60-1.70	3756.76	2.34	39	91.15	1.49	50.8	118.73	2.75	1.8	4.21	3.82
	+1.70-1.80	2523.89	1.57	39.2	61.55	1.01	52.6	82.6	1.91	1.8	2.83	2.57
	+1.80-1.90	2693.61	1.68	39.2	65.69	1.08	51.9	86.98	2.01	1.8	3.02	2.74
	+1.90	15595.31	9.7	39.6	384.23	6.3	54.8	531.71	12.3	1.8	17.46	15.88

Table A4. Mn, Mo and Ni contents and distributions of Salihpaşa ROM coal in coal sizes.

Coal size, mm	Sp. Gr. Fraction	Weight (g)	Weight (%)	Mn			Mo			Ni		
				Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)
+50	-1.30	1771.59	1.1	17.1	18.85	0.15	4	4.41	0.32	35.5	39.13	1.19
	+1.30-1.40	7884.42	4.91	17.1	83.88	0.68	3.6	17.66	1.3	33.5	164.33	4.98
	+1.40-1.50	2715.54	1.69	19.2	32.44	0.26	4	6.76	0.5	32.7	55.25	1.67
	+1.50-1.60	1313.91	0.82	20.5	16.76	0.14	4.1	3.35	0.25	30.5	24.93	0.76
	+1.60-1.70	2257.87	1.4	54.8	76.98	0.62	6.2	8.71	0.64	29	40.74	1.23
	+1.70-1.80	1995.66	1.24	79.6	98.83	0.8	9.4	11.67	0.86	30.5	37.87	1.15
	+1.80-1.90	10171.85	6.33	90.5	572.73	4.62	9.7	61.39	4.51	32	202.51	6.14
	+1.90	3212.31	2	96.5	192.86	1.55	10.6	21.18	1.56	32.2	64.35	1.95
-50+18	-1.30	1293.89	0.81	42.1	33.89	0.27	4.8	3.86	0.28	35.5	28.58	0.87
	+1.30-1.40	22932.42	14.27	50.1	714.81	5.76	5.7	81.33	5.98	34.6	493.66	14.96
	+1.40-1.50	4709.29	2.93	55.2	161.73	1.3	8.6	25.2	1.85	31.2	91.41	2.77
	+1.50-1.60	1925.1	1.2	75.4	90.31	0.73	11.8	14.13	1.04	30.9	37.01	1.12
	+1.60-1.70	3214.22	2	132.6	265.17	2.14	13.6	27.2	2	30.6	61.19	1.85
	+1.70-1.80	3726.24	2.32	150.56	349.04	2.81	14.4	33.38	2.45	30.8	71.4	2.16
	+1.80-1.90	9172.59	5.71	152.9	872.57	7.03	14.7	83.89	6.17	32	182.62	5.53
	+1.90	4914.29	3.06	159.6	487.97	3.93	14.4	44.03	3.24	32.5	99.37	3.01
-18+9.5	-1.30	79.14	0.05	54.1	2.66	0.02	10.9	0.54	0.04	36.8	1.81	0.05
	+1.30-1.40	11932.94	7.42	68.2	506.33	4.08	12.2	90.57	6.66	34.3	254.65	7.72
	+1.40-1.50	3049.27	1.9	82.2	155.94	1.26	13.4	25.42	1.87	32.5	61.66	1.87
	+1.50-1.60	967.79	0.6	126.5	76.17	0.61	16.9	10.18	0.75	30	18.06	0.55
	+1.60-1.70	570.19	0.35	158.8	56.33	0.45	17.9	6.35	0.47	30	10.64	0.32
	+1.70-1.80	1237.63	0.77	179.9	138.52	1.12	17.7	13.63	1	30.2	23.25	0.7
	+1.80-1.90	2541.05	1.58	188.9	298.64	2.41	17.9	28.3	2.08	30.5	48.22	1.46
	+1.90	2696.47	1.68	189.9	318.58	2.57	17.9	30.03	2.21	32	53.68	1.63
-9.5+0.5	-1.30	-	-	-	-	-	-	-	-	-	-	-
	+1.30-1.40	4536.71	2.82	112.7	318.1	2.56	17.5	49.39	3.63	33	93.14	2.82
	+1.40-1.50	9215.49	5.73	152.4	873.78	7.04	18.6	106.64	7.84	32.1	184.05	5.58
	+1.50-1.60	8648.17	5.38	178.4	959.89	7.73	19.1	102.77	7.56	30.9	166.26	5.04
	+1.60-1.70	3756.76	2.34	204.56	478.12	3.85	19.5	45.58	3.35	29	67.78	2.05
	+1.70-1.80	2523.89	1.57	218.8	343.57	2.77	19.4	30.46	2.24	28.5	44.75	1.36
	+1.80-1.90	2693.61	1.68	232.5	389.64	3.14	19.6	32.85	2.42	30	50.28	1.52
	+1.90	15595.31	9.7	245.2	2379.11	19.17	19.5	189.2	13.91	34.4	333.77	10.11

Table A5. Pb, Sb and Se contents and distributions of Salihpaşa ROM coal in coal sizes.

Coal size, mm	Sp. Gr. Fraction	Weight (g)	Weight (%)	Pb			Sb			Se		
				Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)
+50	-1.30	1771.59	1.1	5.2	5.73	0.53	8.5	9.37	1.84	3.42	3.77	1.58
	+1.30-1.40	7884.42	4.91	5	24.53	2.25	8.5	41.7	8.18	3.42	16.78	7.05
	+1.40-1.50	2715.54	1.69	5	8.45	0.77	8.4	14.19	2.78	3.22	5.44	2.29
	+1.50-1.60	1313.91	0.82	7.8	6.38	0.58	7.5	6.13	1.2	3.08	2.52	1.06
	+1.60-1.70	2257.87	1.4	10	14.05	1.29	6.5	9.13	1.79	2.88	4.05	1.7
	+1.70-1.80	1995.66	1.24	9.8	12.17	1.12	6	7.45	1.46	2.55	3.17	1.33
	+1.80-1.90	10171.85	6.33	9.9	62.65	5.75	5.6	35.44	6.95	2.24	14.18	5.96
	+1.90	3212.31	2	10	19.99	1.83	5.6	11.19	2.19	1.82	3.64	1.53
-50+18	-1.30	1293.89	0.81	4.8	3.86	0.35	8.5	6.84	1.34	3.18	2.56	1.07
	+1.30-1.40	22932.42	14.27	5.2	74.19	6.81	7.1	101.3	19.86	2.88	41.09	17.12
	+1.40-1.50	4709.29	2.93	5.2	15.24	1.4	7.1	20.8	4.08	2.92	8.56	3.56
	+1.50-1.60	1925.1	1.2	7.5	8.98	0.82	5.8	6.95	1.36	2.54	3.04	1.27
	+1.60-1.70	3214.22	2	11.9	23.8	2.18	5	10	1.96	2.44	4.88	2.03
	+1.70-1.80	3726.24	2.32	11.6	26.89	2.47	5.2	12.06	2.36	2.22	5.15	2.14
	+1.80-1.90	9172.59	5.71	12.7	72.48	6.65	4.5	25.68	5.04	2	11.41	4.76
	+1.90	4914.29	3.06	13.9	42.5	3.9	4.6	14.06	2.76	1.78	5.44	2.27
-18+9.5	-1.30	79.14	0.05	5.8	0.29	0.03	6.4	0.32	0.06	2.74	0.13	0.06
	+1.30-1.40	11932.94	7.42	8	59.39	5.45	4.9	36.38	7.13	2.71	20.12	8.38
	+1.40-1.50	3049.27	1.9	8.2	15.56	1.43	4.4	8.35	1.64	2.55	4.84	2.02
	+1.50-1.60	967.79	0.6	9.8	5.9	0.54	4.5	2.71	0.53	2.12	1.28	0.53
	+1.60-1.70	570.19	0.35	14.7	5.21	0.48	4.6	1.63	0.32	2.07	0.73	0.31
	+1.70-1.80	1237.63	0.77	18.4	14.17	1.3	3.5	2.7	0.53	1.95	1.5	0.63
	+1.80-1.90	2541.05	1.58	17.9	28.3	2.6	3.5	5.53	1.08	1.8	2.85	1.19
	+1.90	2696.47	1.68	18.2	30.53	2.8	3.6	6.04	1.18	1.73	2.9	1.21
-9.5+0.5	-1.30	-	-	-	-	-	-	-	-	-	-	-
	+1.30-1.40	4536.71	2.82	12.1	34.15	3.13	4.95	13.97	2.74	2.44	6.89	2.87
	+1.40-1.50	9215.49	5.73	11.9	68.23	6.26	4.96	28.44	5.58	2.4	13.76	5.73
	+1.50-1.60	8648.17	5.38	11.4	61.34	5.63	4.4	23.67	4.64	2.12	11.41	4.75
	+1.60-1.70	3756.76	2.34	15.5	36.23	3.32	2.87	6.71	1.32	1.89	4.42	1.84
	+1.70-1.80	2523.89	1.57	18.1	28.42	2.61	2.7	4.24	0.83	1.92	3.01	1.26
	+1.80-1.90	2693.61	1.68	18	30.17	2.77	2.57	4.31	0.84	1.8	3.02	1.26
	+1.90	15595.31	9.7	18.2	176.59	16.2	2.45	23.77	4.66	1.67	16.2	6.75

Table A6. U, V and Zn contents and distributions of Salihpaşa ROM coal in coal sizes.

Coal size, mm	Sp. Gr. Fraction	Weight (g)	Weight (%)	U			V			Zn		
				Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)	Assay (ppm)	Element Product	Distribution (%)
+50	-1.30	1771.59	1.1	29.2	32.18	1.79	94	103.61	1.82	23.5	25.9	0.54
	+1.30-1.40	7884.42	4.91	29.7	145.69	8.09	95.2	466.99	8.19	24.9	122.14	2.54
	+1.40-1.50	2715.54	1.69	28.8	48.66	2.7	80.4	135.84	2.38	25.5	43.08	0.9
	+1.50-1.60	1313.91	0.82	27.6	22.56	1.25	68.9	56.32	0.99	28.7	23.46	0.49
	+1.60-1.70	2257.87	1.4	24.3	34.14	1.9	60.2	84.57	1.48	42.4	59.56	1.24
	+1.70-1.80	1995.66	1.24	19.2	23.84	1.32	60	74.5	1.31	48.8	60.59	1.26
	+1.80-1.90	10171.85	6.33	18	113.91	6.33	52.8	334.14	5.86	50.4	318.96	6.64
	+1.90	3212.31	2	17.5	34.97	1.94	53.2	106.32	1.87	50.6	101.13	2.11
-50+18	-1.30	1293.89	0.81	28.6	23.02	1.28	85.4	68.75	1.21	23.4	18.84	0.39
	+1.30-1.40	22932.42	14.27	27.6	393.79	21.88	85.8	1224.16	21.48	26.7	380.94	7.94
	+1.40-1.50	4709.29	2.93	22.2	65.04	3.61	79.2	232.05	4.07	27.8	81.45	1.7
	+1.50-1.60	1925.1	1.2	19.9	23.83	1.32	75.9	90.91	1.59	29.6	35.45	0.74
	+1.60-1.70	3214.22	2	15.9	31.8	1.77	56.9	113.79	2	39.5	78.99	1.65
	+1.70-1.80	3726.24	2.32	13.8	31.99	1.78	52.4	121.48	2.13	53.5	124.03	2.58
	+1.80-1.90	9172.59	5.71	13.9	79.32	4.41	49.5	282.49	4.96	59.9	341.84	7.12
	+1.90	4914.29	3.06	13.8	42.19	2.34	49.5	151.34	2.66	62.8	192.01	4
-18+9.5	-1.30	79.14	0.05	25.1	1.24	0.07	67.2	3.31	0.06	34.7	1.71	0.04
	+1.30-1.40	11932.94	7.42	22.2	164.82	9.16	68.7	510.04	8.95	39.8	295.48	6.16
	+1.40-1.50	3049.27	1.9	16.6	31.49	1.75	62.9	119.33	2.09	43.4	82.34	1.72
	+1.50-1.60	967.79	0.6	12.5	7.53	0.42	54.8	33	0.58	49.9	30.05	0.63
	+1.60-1.70	570.19	0.35	10.2	3.62	0.2	44.5	15.79	0.28	69.7	24.73	0.52
	+1.70-1.80	1237.63	0.77	10.7	8.24	0.46	36.2	27.87	0.49	69.8	53.75	1.12
	+1.80-1.90	2541.05	1.58	10	15.81	0.88	36.4	57.55	1.01	72.2	114.14	2.38
	+1.90	2696.47	1.68	10.2	17.11	0.95	36.6	61.4	1.08	73.9	123.98	2.58
-9.5+0.5	-1.30	-	-	-	-	-	-	-	-	-	-	-
	+1.30-1.40	4536.71	2.82	18.7	52.78	2.93	50.9	143.67	2.52	38.2	107.82	2.25
	+1.40-1.50	9215.49	5.73	18.8	107.79	5.99	52.7	302.15	5.3	48.4	277.5	5.78
	+1.50-1.60	8648.17	5.38	12.1	65.1	3.62	36.5	196.39	3.45	48.7	262.03	5.46
	+1.60-1.70	3756.76	2.34	12.3	28.75	1.6	37	86.48	1.52	64.2	150.05	3.13
	+1.70-1.80	2523.89	1.57	11	17.27	0.96	30	47.11	0.83	68.2	107.09	2.23
	+1.80-1.90	2693.61	1.68	9	15.08	0.84	30	50.28	0.88	72.2	121	2.52
	+1.90	15595.31	9.7	8.1	78.59	4.37	30.5	295.93	5.19	74.4	721.88	15.04

CURRICULUM VITAE

Ercan POLAT was born in Erzincan. He had his high school education in Alanya High School and then he attended to mining Engineering Department in Dokuz Eylül University. He graduated his master education at Muğla Sıtkı Koçman University, Mining Engineering Department in 2014.