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MORPHOLOGICAL FORMS OF CHARS IN SLAG AND FLY ASH FROM THE BĘDZIN POWER STATION, UPPER SILESIA, POLAND

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A b s t r a c t . Combustion of coal is still one of the main sources of energy and electricity in Poland. For cost reasons, and because of the need to protect the environment, it is important to use coal as efficiently as possible. One of the indicators of coal combustion efficiency is the amount of unburned organic matter in slag and fly ash. This organic matter occurs in different morphological forms. This paper provides an overview of the char morphological forms found in slag and fly ash from selected boilers installed in Będzin Power Station (Poland). The relative quantities of particular morphological forms are compared with the maceral composition of the feed coal. The aim is the better understanding of the influence that maceral composition has on combustion performance.

K e y w o r d s : coal, pulverised fuel combustion, fly ash, slag, chars.

INTRODUCTION

International investigations on the morphological forms of unburned organic matter have tended, in the past, to concentrate on fly ash with attention focussed on the morphology of these forms, their classification and their origin. Relatively little attention has been given to these forms in slag.

Coal combustion involves several stages: heating, softening, devolatilisation and swelling, ignition and soot formation, char burnout and fragmentation. Initially, the coal particle reaching the combustion chamber is heated. The moisture is removed and devolatilisation starts. In the temperature range 350–600^{o}C, further devolatilisation takes place and the coal softens and become plastic (Solomon *et al.*, 1993). Devolatilisation causes the coal grains to rotate. According to Saito and his co-workers (1991) the rotation rate is 3000–5000 cycles s^{-1}. These various processes take up about 10% of the duration of combustion. The products of these processes are chars containing unburned organic matter and transformed inorganic matter (Kordylewski, 1993). Combustion of released volatile matter in the close vicinity results in an increase in char temperature. Char ignition and combustion occurs at a temperature of about 1800^{o}C (Solomon *et al*., 1993). Char combustion occupies 90% of the time of coal grain burnout (Kordylewski, 1993). Coal combustion finishes with char fragmentation which, in turn, depends on the size and rank of the burnt-out coal (Baxter, 1992).

Several methods of coal combustion are used in large power stations and local thermal power stations operating in Poland. These are: combustion in stoker boilers, pulverised fuel combustion and fluidised combustion (van Krevelen, 1993). In Będzin Power Station, pulverised fuel boilers are installed (Materials, 1995). This type of combustion is characterised by the shortest residence times, the highest combustion rates and temperatures and the use of the smallest coal particles (van Krevelen, 1993).

Many factors connected with coal properties and combustion conditions influence combustion processes and the quantity of unburned organic matter in slag and fly ash. Influencing factors related to coal properties are maceral composition, coal rank, volatile matter content, heat value, mineral matter content and composition. Factors related to combustion are temperature, rate of combustion, residence time and the oxygen content in the combustion chamber (expressed as an excess air coefficient). Coal particle size also influences these processes.

Different macerals behave in different ways during combustion.

Reactive macerals are a group of macerals characterised by the highest volatile matter content and the lowest carbon content. Their reflectivity is the lowest of all macerals. Volatiles released from these macerals during combustion increase coal particle temperatures and cause ignition under suitable

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conditions. These macerals are usually not recognisable after combustion. Vitrinite and liptinite macerals belong to this group (Falcon, Snyman, 1986) as do the reactive parts of inertinite macerals, for example, reactive semifusinite, low reflective funginite, secretinite, micrinite, macrinite and inertodetrinite (Kruszewska, 1990).

Inert macerals belong to a group of macerals characterised by the highest carbon contents and by the lowest contents of volatiles. Their reflectivity is the highest of all macerals. They do not undergo softening and devolatilisation (Falcon, Snyman, 1986). They undergo little or no change during the combustion process (Kruszewska, 1990); in solid wastes they look much the same as in the feed coal. Fusinite (pyrofusinite) and semifusinite (pyrosemifusinite) belong to this group.

Semiinert macerals exhibit, as their name suggests, properties that are intermediate between those of reactive and inert macerals. Their carbon and volatile-matter contents are intermediate between those of reactive and inert macerals as is their reflectivity. Depending on the intensity of the combustion processes, they may behave as reactive, inert or semiinert macerals.

Będzin Power Station is sited in Będzin city in the south of Poland. Five pulverised fuel boilers are installed there. Samples were collected from two of these boilers (K-6 and K-7). These OP-140 type boilers are the main operating boilers in the station. They are steam boilers with a maximum continuous capacity of 96.7 MW and a thermal efficiency of 90%. Exhaust gases pass through electrofilters with particulate collection efficiencies of 99.7% for the K-6 boiler and 99.5% for the K-7 boiler (Materials, 1995).

The coal burned in the Będzin Power Station comes from three collieries in the Upper Silesian Coal Basin: Staszic, Kazimierz Juliusz and Niwka Modrzejów. Their annual output is 279.1 thousands tonnes of coal.

SAMPLE COLLECTION AND PREPARATION

Coal, slag and fly ash samples were collected once a week during the period 6.11.1996 – 26.06.1997. Coal samples were collected from a belt delivering coal to the coal mills. Fly ash samples were collected at the bottom of the electrofilters. Slag samples were collected from the wet slag trap. In total, 27 coal, slag and fly ash samples were collected from the K-6 boiler and 26 from K-7.

The coal samples were crushed to less than 1 mm, mixed with epoxy resin, and polished blocks were prepared. Fly ash was mixed with the same epoxy resin, and polished sections were made. Wet slag samples were dried at a temperature of 105^{o}C, mixed with epoxy resin, and briquettes were prepared.

For all coal samples, the contents of moisture, ash, volatile matter and sulphur, and the heating value were determined. The contents of vitrinite, liptinite and inertinite were determined. As it is the most inert of all macerals, fusinite was distinguished from the inertinite group and determined separately. The vitrinite reflectivity was also determined. For every sample, the analyses of reflectance and maceral content were carried out at 500 points.

For the slag and fly ash samples, the content of unburned organic matter and the quantities of the different char morphological forms present were determined. For each sample, the morphological forms were identified and counted to 500 points.

RESULTS

Coal characterisation

The coals combusted in both steam boilers are, as expected, very similar with regard to their chemical and petrographic parameters. They contain up to 20% ash and 0.8% sulphur. The heating value is 21.2 MJ/kg.

The dominant maceral in the coal is vitrinite (47.6–47.8%). Liptinite (6.0%) and inertinite (28.2–28.9%) are also important. The average content of fusinite is 1.6–1.7%. The average vitrinite reflectance is 0.73%.

Slag and fly ash characterisation

The quantity of unburned organic matter is always higher in slag than in fly ash samples collected on the same day from the same boiler (Figs. 1, 2).

The morphological forms of unburned organic matter may be classified into several types on the basis of porosity, wall thickness, and the presence/absence of anisotropy.

Crassispheres — large round or oval pores, or clusters of 2–3 pores, surrounded by walls of unburned organic matter thicker than 3 μm (Plate I, Figs. 1, 2). Many small, round pores that typically occur within the cenosphere walls indicate pyrolysis after swelling (Rosenberg *et al.*, 1996).

Tenuisphere — round or oval pores, or clusters of 2–3 pores, surrounded by walls of unburned organic matter thinner than 3 μm. Only rarely do small round pores occur within these walls (Plate I, Figs. 3, 4).

Isotropic networks — several round or oval pores surrounded by isotropic walls of unburned organic matter. Many small, round pores and/or fragments of inertinite typically occur within the walls (Plate I, Figs. 5, 6).

Anisotropic networks — several round or oval pores surrounded by anisotropic walls of unburned organic matter. Many small round pores and/or fragments of inertinite occur within the walls (Plate II, Figs. 1, 2).

Tenuinetworks — clusters of several round or oval pores usually surrounded by isotropic walls of unburned organic matter that are thinner than 1 μm and which usually do not contain small round pores (Plate II, Fig. 3).

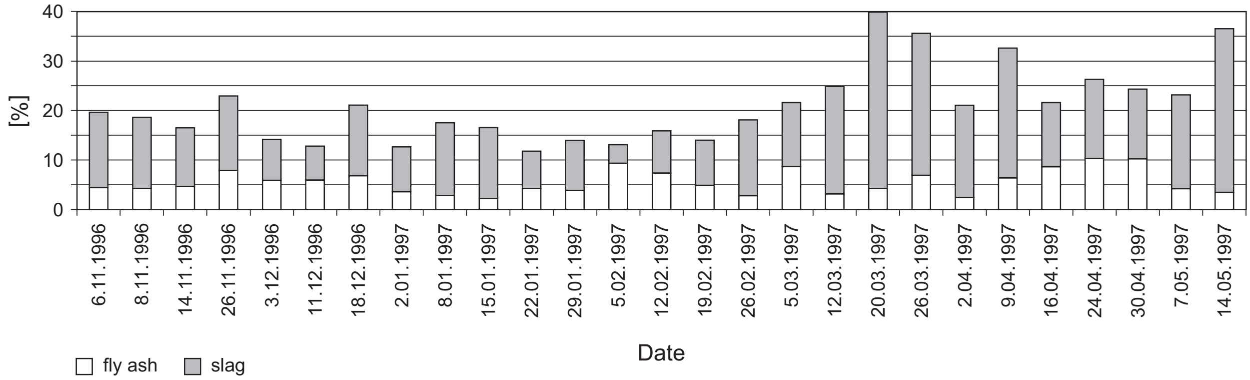

Fig. 1. Unburned organic matter content in slag and fly ash from K-6 boiler

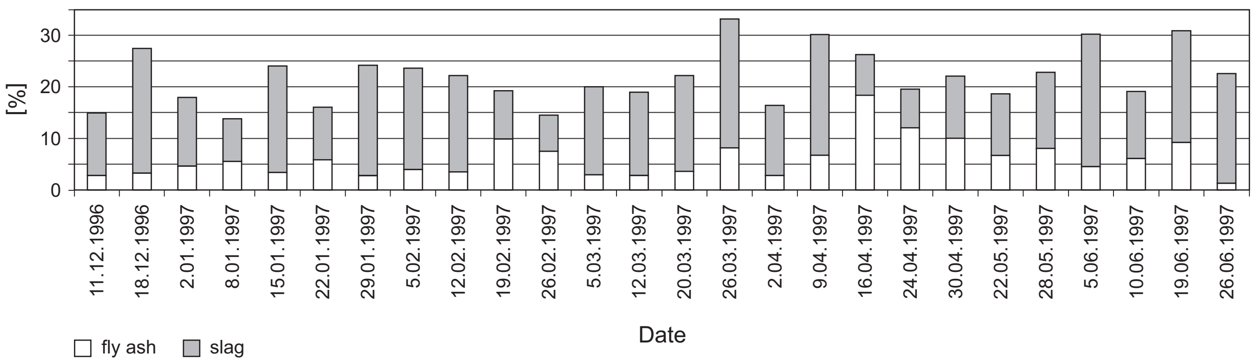

Fig. 2. Unburned organic matter content in slag and fly ash from K-7 boiler

Honeycomb — narrow, elongate, parallel oval pores separated by isotropic walls of unburned organic matter (Plate II, Figs. 4, 5).

Inertinite — unchanged or slightly changed particles of inertinite. Slightly changed particles contain only a few small round pores or/and a few small fractures, and show rounded edges (Plate III, Figs. 1–3).

Detritus — small particles of unburned organic matter which are formed during the final stages of combustion (fragmentation). They range in size from 1 to 10 µm. They may be isotropic or anisotropic (Plate III, Fig. 3).

Some isotropic networks and some honeycombs exhibit concentric pore patterns. These may reflect the release of volatiles during the rotation of plasticised coal particles. Resolidification trapped these patterns.

Particles of unburned organic matter may contain more than one morphological form. These probably result from the combustion of coal particles containing macerals differing in reactivity. Very commonly networks and inertinite exist in the same particle, e.g. inertinite and crassispheres. Individual particles may comprise forms differing in porosity, e.g., networks and honeycombs in some cases, crassispheres and honeycombs in others.

The classification used here is a modified classification which draws on a number of existing classification systems previously established by Lightmann, Street (1968), Jones *et al.* (1985), Tsai, Scaroni (1987), Oka *et al.* (1987), Bailey *et al.* (1990), Bend *et al.* (1992), Rosenberg *et al.* (1996), and by the ICCP (2001). The distinguishing of the detritus forms is an addition to the latest classification system (ICCP, 2001). This morphological group is potentially an indicator of combustion conditions. As shown below, detritus and the amount of unburned organic matter are linked.

The proportions of the individual char morphologies differ between slag and fly ash. Detritus is always dominant in fly ash. Isotropic networks and crassispheres dominate in slag samples. Tenuinetworks, tenuispheres and anisotropic networks are always in a minority in both slag and fly ash. Except for detritus, the amount of all the other morphological forms is usually higher in slag than in fly ash samples.

ORIGIN AND DISTRIBUTION OF DIFFERENT MORPHOLOGICAL FORMS

Crassispheres most probably originate from vitrinite. They are typically present in greater amounts in slag when compared to their occurrence in fly ash samples collected on the same day. The differences are usually less than 10%. In samples from the K-6 boiler, the determined difference is about 3%. In those from the K-7 boiler, the difference is only 0.5% (Table 1).

Tenuispheres probably formed from the combustion of clarite. It is possible that, during their formation, the combusting coal particles became relatively plastic due to the release of volatiles resulting, in turn, in thinner sphere walls. The quantity of tenuispheres, which never exceeds 6.2%, is always considerably smaller than that of crassispheres. As with the crassispheres, tenuispheres are usually more abundant in slag when compared to fly ash. Average contents in slag from the K-6 boiler is 2.3% and in fly ash from the same boiler is 1.6%. In samples from the K-7 boiler, the corresponding values are 1.5% and 1.6% (Table 1).

Isotropic networks are of common occurrence in both slag and fly ash. The origin of these forms is probably connected with the combustion of vitrinertite and clarodurite. They could possibly also arise as a result of vitrinite burnout on the periphery of the combustion chamber where the temperature would be lower. Lower temperatures and the slower release of volatiles will result in lower coal grain plasticities, and porosities lower than those of crassispheres and tenuispheres. Isotropic networks are always more abundant in slag when compared to fly ash: on average by a factor of two (Table 1). In slag, the isotropic network content may reach 56%. In fly ash, it never exceeds 38%.

The formation of anisotropic networks is probably due to the combustion of vitrinertite and trimacerite. Their porosity is similar to that of isotropic networks. The content of anisotropic networks is invariably much lower than that of isotropic networks in same-day samples. The quantities of anisotropic networks in slag ranges up to 18.2%. In fly ash, it never exceeds 6.0%. Average contents of these forms in slag exceed those in fly ash by a factor of four (see Table 1).

The rarest morphological forms in the solid wastes remaining after coal combustion are tenuinetworks. This form probably results from the combustion of clarite in which the liptinite content far exceeds the vitrinite content. As these forms are easily fragmented due to their low wall thickness and their high porosity, they preferentially disintegrate and form detritus during combustion. Their maximum content in slag is up to 4.0% and in fly ash up to 1.2%. Their average content in slag is 1.2% and, in fly ash, 0.1% (Table 1).

The morphological form that originates from semiinert inertinite is honeycomb. Honeycomb porosity is lower than that of both networks and crassispheres. In slag, the content of honeycomb forms ranges up to 23.2%. In fly ash, it never exceeds 5.0%. The average content in slag is four times higher than in fly ash (Table 1).

Inertinite shows the least morphological change when compared to its precursor in the feed coal. It is possible to draw a distinction between unaltered inertinite and slightly altered inertinite. It is likely that the unaltered inertinite formed from inertinite of the highest reflectivity and the highest carbon content (mainly pyrofusinite). It looks exactly as it does in the feed coal. The unaltered inertinite content in slag ranges up to 7.2% and, in fly ash, up to 8.6%. The slightly altered inertinite contrasts in showing a few small round pores, some irregular cracks and somewhat rounded outlines. The cellular structure was only slightly changed during combustion. This slightly altered inertinite has a reflectance and a carbon content only slightly lower than that of unaltered inertinite. The content of slightly altered inertinite in slag ranges up to 15.1% and, in fly ash, up to 6.2%. The average content of this form in fly ash is about four times lower than that in slag (Table 2). The unaltered inertinite content in fly ash is higher than that of slightly altered inertinite content. In slag, it is the reverse.

The total inertinite content is typically higher in slag than in fly ash (Tables 1, 2). Interestingly, in fly ash, the unaltered inertinite content increases with increasing total inertinite content. The correlation coefficients for this relationship are 0.95 for boiler K-6 and 0.85 for K-7 boiler.

The morphological form showing the greatest differentiation between slag and fly ash is detritus (Table 1). It was probably formed by the fragmentation of the other morphological forms. High contents of this form likely reflect higher temperatures and shorter combustion times. Under such conditions, combusting coal particles would have been plastic for a short

Table 1

Average contents [in %] of various morphological forms of chars in slag and fly ash from boilers K-6 and K-7

Morphological form of chars	K-6		K-7	
	Slag	Fly ash	Slag	Fly ash
Crassispheres	23.2	20.5	20.0	19.5
Tenuispheres	2.3	1.6	1.5	1.6
Isotropic networks	43.1	20.2	43.1	17.8
Anisotropic networks	5.3	1.6	7.3	1.7
Tenuinetworks	1.2	0.1	1.2	0.0
Honeycombs	6.9	1.7	8.2	1.8
Inertinite	8.4	5.8	10.7	4.7
Detritus	9.6	48.6	7.8	52.8

Table 2

The average contents [in %] of inertinite in slag and fly ash from boilers K-6 and K-7

Inertinite		K-6	K-7
Slag	Total	8.4	10.7
	Unaltered	3.3	4.7
	Slightly altered	5.1	6.0
Fly ash	Total	5.8	4.7
	Unaltered	4.2	3.3
	Slightly altered	1.5	1.4

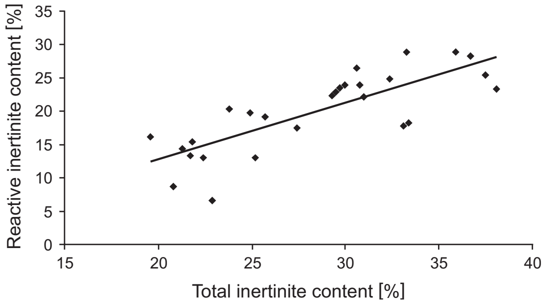

Fig. 3. Relation between total inertinite and reactive inertinite contents in feed coals from K-6 boiler. Correlation coefficient is 0.79

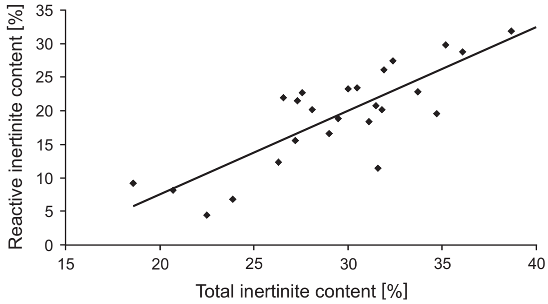

Fig. 4. Relation between total inertinite and reactive inertinite contents in feed coals from K-7 boiler. Correlation coefficient is 0.84

period of time, would have had little time for coagulation and would have been prone to fragment. The porosity of detritus mirrors that of the fragmented forms, e.g., porous detritus would have resulted from the fragmentation of spheres and networks and detritus of limited porosity from that of inertinite and honeycomb. In addition, the presence/absence of anisotropy is related to the anisotropy of the fragmented forms. The high detritus content (82.6%) in fly ash can be simply ascribed to its low specific gravity and the ease with which it can be, as a result, convected from the combustion chamber to the electrofilters.

The characteristic features of the different morphological forms depend on the burnout. The greater the conversion, the smaller the sizes of the various forms, the thinner their walls, and the higher the detritus content. On the other hand, however, fly ash with high contents of unburned organic matter may occasionally show forms with sizes and wall thicknesses similar to those of forms seen in slag. Also sometimes slag samples with relatively low unburned organic matter content may contain smaller forms with thinner walls.

Comparison of maceral composition and the contents of particular char forms allows some conclusions to be drawn. Calculations based on sample masses allow the conclusion that that crassisphere and tenuisphere contents is lower than what might be expected from determined feed-coal vitrinite contents (Misz, 1999). Clearly, a part of the precursor vitrinite was completely burned out or, perhaps, was altered to spheres and networks. It is also possible to determine the inert, semiinert and reactive inertinite contents of the feed coal. Inert and semiinert inertinite contents are typically lower than the content of reactive inertinite in the feed coal. The reactive inertinite content increases with total inertinite content in the feed coal (Figs. 3, 4).

Feed coal fusinite contents are always lower than the unaltered-inertinite contents in both slag and fly ash. Combustion conditions in which inertinite of lower reflectivity than that of pyrofusinite has been burned seem to be suggested.

DISCUSSION

The physico–chemical and petrographical properties of the feed coal used in each of the two pulverised fuel boilers at Będzin Power Station examined during this study were very similar. Combustion conditions (temperature, quantity of air, quality of the feed coal, boiler load demand) are the key factors influencing the char content in both slag and ash. The unburned organic-matter content is greater in slag than in fly ash collected on the same day. The dominant morphological form in fly ash is detritus: the smallest and most easily convected of all the morphological forms. Slags are characterised by the greatest contents of isotropic networks and crassispheres. Anisotropic networks, tenuinetworks and tenuispheres occur as minority forms in both slag and fly ash.

This distribution pattern is probably a function of the specific gravities of the different forms; each considered as an entity comprising both pores (voids) and solid material. For any given form, the greater the size of the partical, the more likely it is to be trapped in slag.

The char particle size and wall thickness also depend on the extent of burnout. The higher the conversion, the smaller the forms, the thinner the walls and the higher the detritus content. Thus fly ash, which on any given day and/or from any given boiler always contains less organic matter than does slag, is characterised by greater amounts of detritus and smaller forms.

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PLATE I

Figure 1. Double crassisphere. Slag. Magnification 100x

Figure 2. Crassisphere. Fly ash. Magnification 200x

Figure 3. Tenuisphere. Slag. Magnification 100x

Figure 4. Tenuisphere. Fly ash. Magnification 200x

Figure 5. Isotropic network. Slag. Magnification 100x

Figure 6. Isotropic network. Fly ash. Magnification 200x

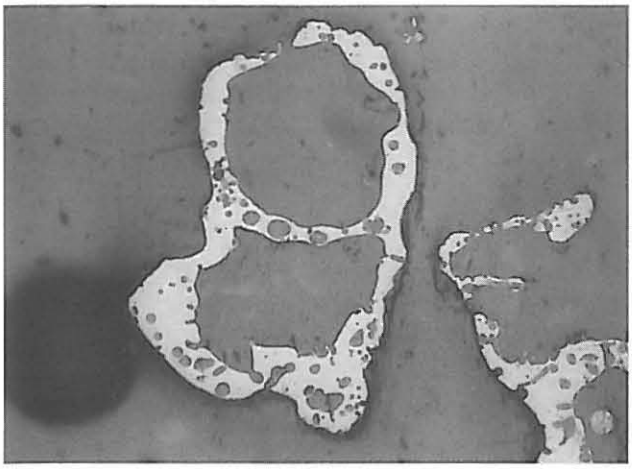
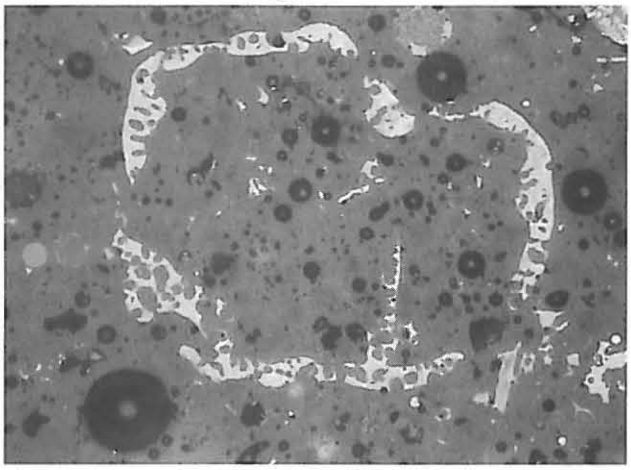


Figure 1



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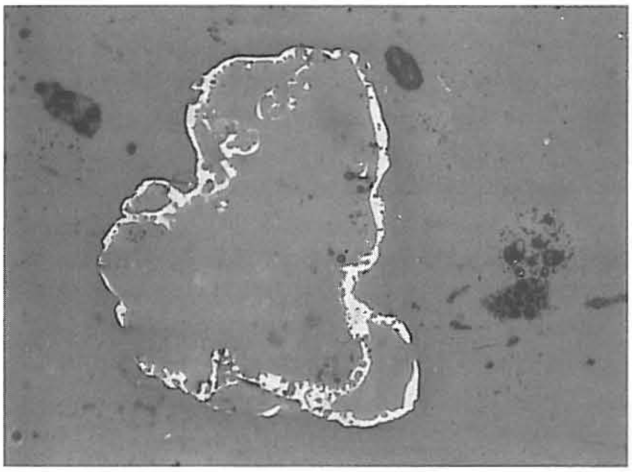

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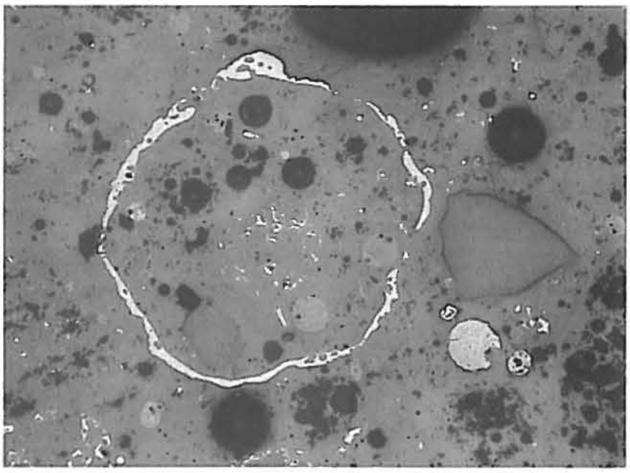

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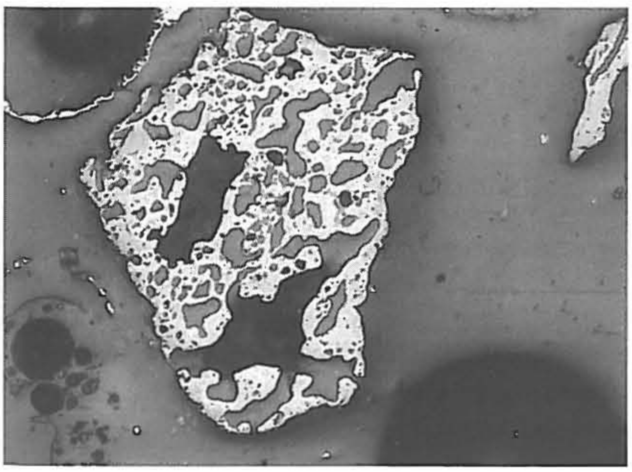
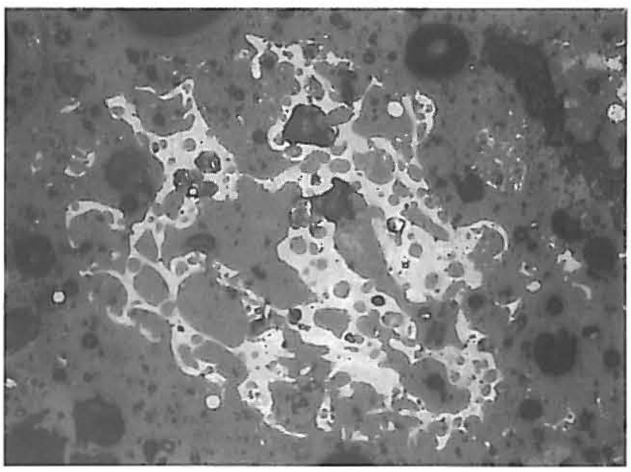


Figure 5



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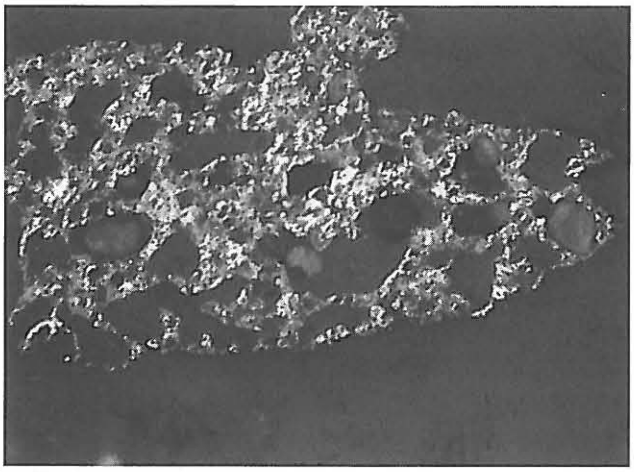

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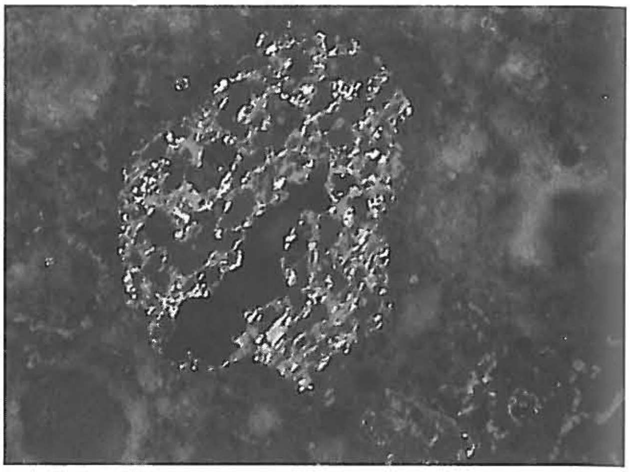

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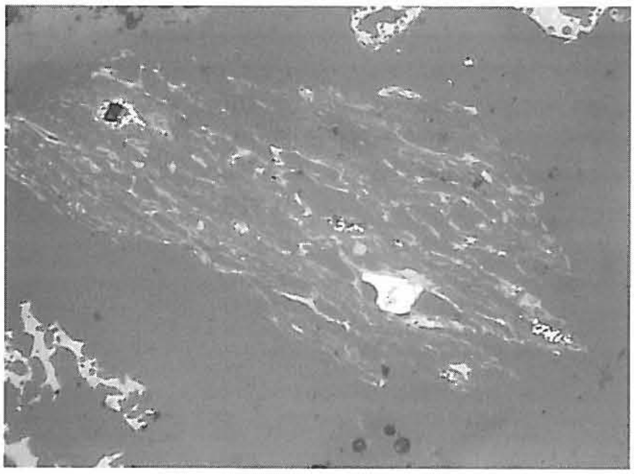

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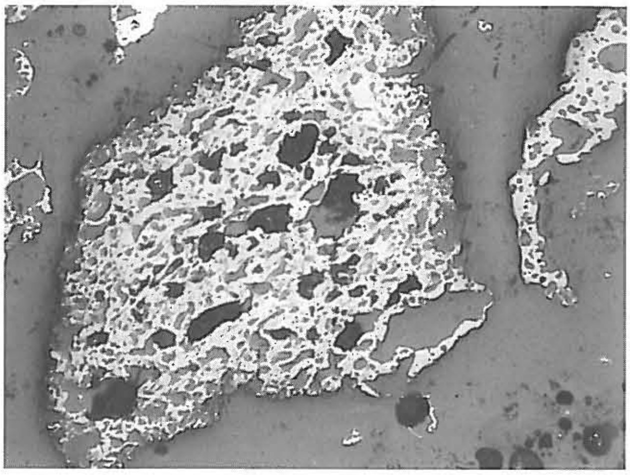

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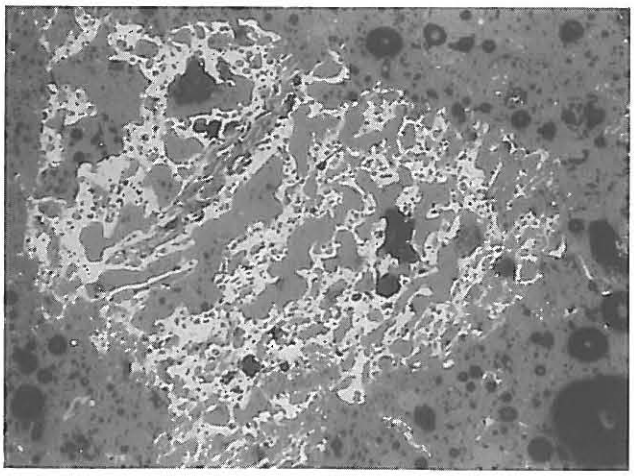


Figure 5

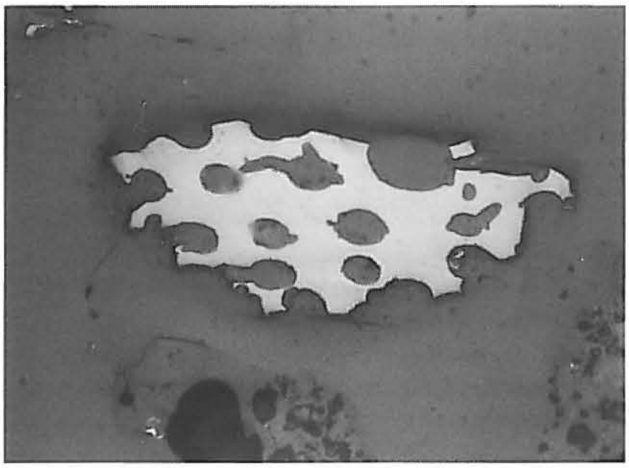
Figure 1. Anisotropic network. Slag.
Magnification 100x

Figure 2. Anisotropic network. Fly ash.
Magnification 200x

Figure 3. Tenuinetwork. Slag.
Magnification 100x

Figure 4. Honeycomb. Slag.
Magnification 100x

Figure 5. Honeycomb. Fly ash.
Magnification 200x



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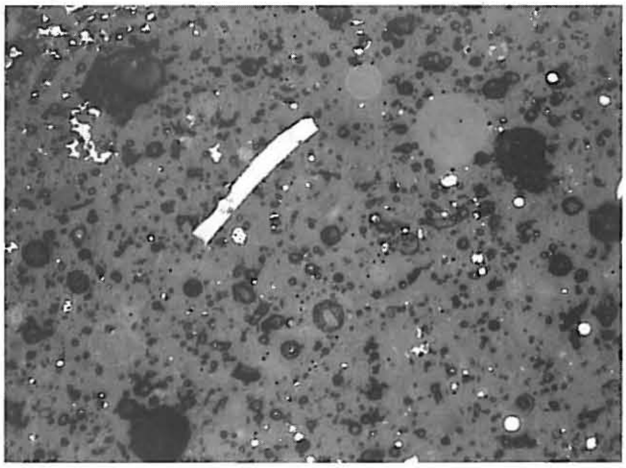

Figure 2

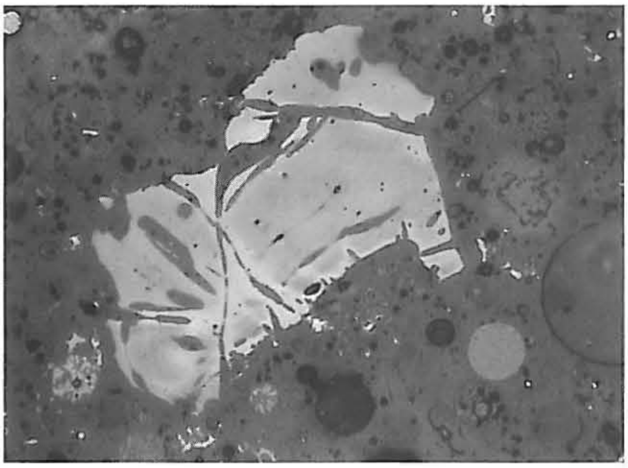

Figure 3

Figure 1. Inertinite. Slag. Magnifcation 100x
Figure 2. Inertinite. Fly ash. Magnification 200x
Figure 3. Inertinite. Fly ash. Magnification 200x