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The petrographic composition of Southern African coals in relation to friability, hardness, and abrasive indices*

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SYNOPSIS

The prediction of the mechanical behaviour of South African coal on the basis of current proximate and other chemical parameters gives rise to problems, and the use of ultimate analyses and inferred maceral and rank analyses, although it has improved the situation to some extent, is still not satisfactory.

In an attempt to reach a new level of understanding, this paper gives an in-depth review of the fundamental petrographic characteristics of coal and compares these parameters with the main types of mechanical performance. A two-tiered system of primary and secondary parameters is proposed for the prediction of coal behaviour. The primary or inherent parameters include rank and organic composition. The secondary or extraneous factors include such parameters as mineral matter, cracks or cleats, degree of oxidation, and size. In addition, an explanation is offered of several anomalous behavioural conditions in some South African coals.

SAMEVATTING

Die voorspelling van die meganiese gedrag van Suid-Afrikaanse steenkool aan die hand van huidige benaderde en ander chemiese parameters, skep probleme, en hoewel die gebruik van elementontledings en afgeleide maseraal- en rangontledings die toedrag van sake in 'n mate verbeter het, is dit nog nie bevredigend nie.

In 'n poging om 'n nuwe vlak van begrip te bereik, gee hierdie referaat 'n indringende oorsig oor die fundamentele petrografiese eienskappe van steenkool en vergelyk hierdie parameters met die vernaamste soorte meganiese werkverrigting. Daar word 'n tweelaagstelsel van primêre en sekondêre parameters voorgestel vir die voorspelling van die gedrag van steenkool. Die primêre of inherente parameters sluit in rang en organiese samestelling. Die sekondêre of uitwendige faktore sluit parameters soos mineraalstof, krake of nate, mate van oksidasie en grootte in. Verder word daar gepoog om 'n verduideliking te gee van verskeie anomale gedragspatrone in sommige soorte Suid-Afrikaanse steenkool.

Introduction

As the domestic and export coal markets continue to expand in South Africa, the production of coal must also increase. This expansion has resulted in more rapid mechanized-mining techniques, higher capacities in crushing and washing plants, and better transport facilities. In addition, larger boilers, gasifiers, and furnaces are being installed.

During this phase of expansion, many items of equipment designed for use in European and North American coal mines have been commissioned, and problems have emerged relating to unexpected differences between some South African coals and those of the northern hemisphere in terms of mechanical cutting, breakage, crushing, and abrasion. Some coals have produced high proportions of dust, thus reducing the quantities and qualities of the sized products, and often leading to an increased liability to spontaneous combustion. Highly variable cutting and strength indices have reduced the life of some mechanized mining gear and cut down the production as a result of the replacement or non-operation of equipment. The differential crushing and breaking capacity of certain types of coal has also affected the coal quality during crushing and screening operations, and the highly variable abrasive index of many coals has led to unexpected and untoward wear and tear in transport facilities (boilers, furnaces, etc.). The reason for the differences between the coals of Southern Africa and those of other countries in the southern hemisphere and the Carboniferous coals of Europe and America are summarized elsewhere[1-3].

To date, much research into the cuttability, strength, and breakage of coal has been conducted, and is being conducted in South Africa, primarily by the Chamber of Mines Research Laboratories[4-6] and in-house by various mining houses. Also, the relationship between chemical tests, and the type, rank, and grindability of South African coals was investigated recently[7]. In all, these publications serve to review the adequacy or otherwise of the prediction and test parameters used conventionally, viz proximate analysis, Hardgrove grindability index, abrasive index, hardness, compression, and penetrometer values. In general, these parameters are unsatisfactory for the highly variable coal types of Southern Africa. More recently, MacGregor[5] attempted to introduce petrographic maceral group and geological parameters into the prediction equations with some success.

The present paper seeks to provide an extension of this

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research by reviewing further petrographic characteristics in relation to the main mechanical properties of coal. Then, it proposes a system of primary or inherent characteristics for use in the prediction of the basic or fundamental expected performance (dry, ash free). To these is added a series of secondary or external factors that also affect the mechanical properties of coal. These factors superimpose their influence upon the primary factors. These data may lead to a better understanding of several anomalies in the behaviour of coal, and it is hoped that they will be useful for the prediction of mechanical performance in new and unknown coalfields or coal seams, and for the achievement of optimum design, more suitable equipment, and greater efficiency in terms of sizing and production in all aspects of the coal industry.

Petrographic Characteristics of Coal

Composition

Coal is not a homogeneous mineral. It is composed of a number of microscopic organic constituents (*macerals*) and inorganic constituents (*minerals*), which occur together in various proportions or associations, forming microscopic bands (*microlithotypes*). A series of these bands forms the macroscopic bands known as *lithotypes*, which, as seen by the unaided eye, are the most common levels used to correlate or characterize the mechanical behaviour of coal. However, microlithotypes and the distribution, form, and nature of macerals and minerals are just as important. In addition, these microscopic parameters are also vital for the assessment of coal in its processing and utilization.

The microscopic entities in coal impart its basic properties. The organic constituents or *macerals* are divided into 3 groups: *vitrinite, exinite*, and *inertinite*. Various proportions of macerals and minerals constitute *microlithotypes*.

Minerals occur as *sedimentary rocks*, such as siltstones, shales, and sandstones, interbedded between coal bands or seams, and as mineral grains within the organic matrix of a seam. In the latter form, the most common minerals are quartz, clays, carbonates (calcite and dolomite), sulphides (pyrite), and various oxides[1,3]. Fig. 1 indicates the different levels at which coal can be investigated and the relationship between them.

Rank

Rank refers to the degree of maturity or metamorphism undergone by a coal seam, usually in response to time, temperature, or pressure. The influence of these factors on the mechanical properties of coal during its production, handling, and utilization have not yet been quantified in South Africa.

The most common parameters used to define rank in Europe and North America include volatile matter and carbon content. However, these are unsuitable for coals in the southern hemisphere, and the most reliable parameter currently used in South Africa to define rank is the reflectance of vitrinite, which is measured petrographically under oil immersion.

Lithotypes

Lithotypes are useful indicators of the original environment of coal formation, and of its approximate composition and mechanical strength[1,2,8,9]. There are basically four main types: vitrain, clarain, durain, and fusain, with intermediates.

Vitrain or 'bright' coal forms the bright, brilliantly shining, vitreous and brittle bands in bituminous coal.

Clarain, also termed 'bright-banded' intermediate coal, is bright and semi-bright coal of less brilliant lustre with poor cleat and cleavages. Clarain occurs in laminated bands, the laminations being up to 20 cm thick. It is commonly associated with vitrain.

Durain or 'dull' to 'dull-banded' coal forms bands of hard, dull, dark-grey or black, massive to granu-

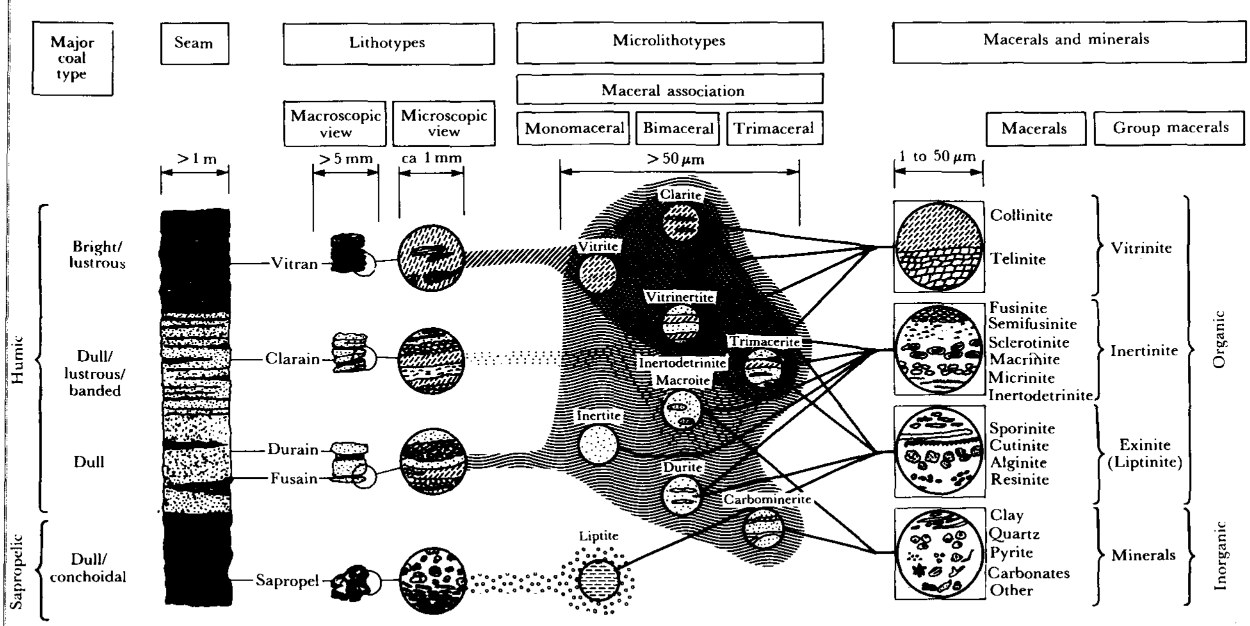


Fig. 1—The relationship between the macro- and micro-composition of coal

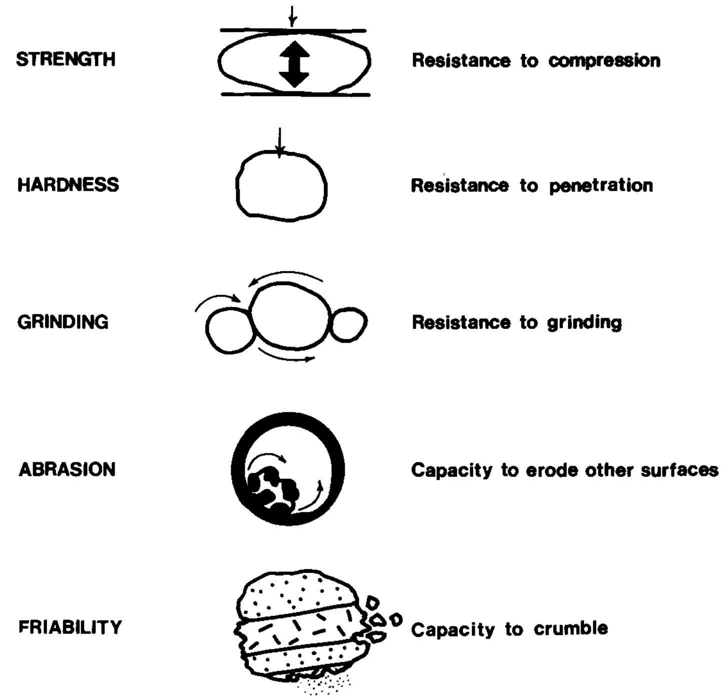


Fig. 2—The major mechanical properties of coal

lar lustreless coal, originally called hard coal in Britain[8]. It represents agglomerations of oxidized and carbonized plant remains.

Fusain is composed of narrow bands or lenses of flat, fibrous, charcoal-like rectangular patches that glisten and shine. These lenses are very soft and friable, and easily crumble to dust. On being handled, they soil the fingers. The lenses are 0,1 to 10 cm in width and appear to represent remnants of dried, oxidized wood that may have been burnt in forest fires or been subjected to lengthy, advanced processes of oxidation after death and prior to submersion in a peat swamp.

The bands listed above fall into the category of humic coals, i.e. plant tissue that accumulated *in situ* within the original peat swamp or a short distance away. Sapropelic coals, on the other hand, are bands of organic matter that accumulated in open water such as large pools, lakes, open marshes or in the distal regions of deltas[8]. Known as deep-water coals, they comprise fine wind-blown or water-born plant debris, algae, and plankton that sank to the bottom, forming layers of fine, black vegetable slime or sapropel. These bands may be associated with clays and other mineral matter (oil shales), or may be dominated by algae (boghead coals), spores (cannel coals), or fine humic matter (humo-sapropelic coals).

Mechanical Properties of Coal

The mechanical properties of coal have been reviewed extensively[1,4–6,10]. This section serves to summarize some of the major features and discusses the most important parameters influencing them (Fig. 2).

Strength

Coal strength refers to the resistance of a coal to compression, compaction, and crushing, i.e. compressive strength. The strength of coal is extremely important in mining and pulverizing, but it varies under different test conditions. For example, the strength of a coal in a seam under considerable load from overburden and lateral restraint may be quite different from that of a lump of 'free' coal in a laboratory. The results of compressive testing have direct application to the estimation of the load-bearing capacities of pillars in coal mines.

Several factors have been found to be significant.

Size. Mean compressive strength decreases with increasing size of specimen. Alternatively, the higher the heterogeneous layers in a seam, the higher the strength.

Amount and orientation of cracking. Fracture is closely dependent upon the presence of cracks; an increasing frequency of cleats results in reduced compressive strength.

Temperature. At room temperature, coal cubes fracture along planes parallel to the direction of compression. At 100°C or more, fracture occurs along planes of maximum shear stress.

Rank. A minimum compressibility is reached (in European coals) in the medium- to low-rank bituminous ranges. In South African coals, this is variable owing to the different components in the coals.

Composition. The composition of coal bands correlates directly with the strength of the coal bands[8,9]. For example, each lithotype in coal has a particular mechanical property that gives rise to differential breakage and compression characteristics in banded coal seams.

On the basis of these properties, Jeremic[9] has suggested the following classification of coal strength for Canadian coals:

Hard (durain, shaley coal, and coaly shale)

Semi-hard (clarain or combinations of clarain, durain, and vitrain)
Soft coal (vitrain)
Very soft coal (fusain).

This classification compares favourably with the crushability ratios originally presented by Plumstead[9] (Tables I and II).

However, the strength of each lithotype is determined by its constituent microlithotypes, and these in turn depend upon their maceral composition. Monomaceral or homogeneous microlithotypes are always lower in strength than bimaceral or trimaceral microlithotypes, or than those rich in minerals.

The presence of mineral matter in well-dispersed syngenetic forms distributed throughout the matrix (as opposed to secondary or epigenetic minerals filling cracks or fissures) further increases the strength of a coal. For these reasons, sapropelic coals, which are highly mixed, mineral-rich, and massive in form, possess the highest strength. Durites and durains are the next highest in strength, followed by the carbominerites or clay-rich bands[1]. The lowest strength is found in vitrinites (or layers of vitrites and vitrains) because of the highest frequency of fissures in these bands, and in fusites because of their pronounced friability[1].

Hardness

Hardness is the resistance of coal to penetration, and is most commonly determined in indentation, scratch, and impact tests[4]. Hardness varies according to the following factors

Rank. With increasing rank, the hardness of vitrinite-rich coals passes through a maximum between low-rank and medium-rank bituminous coals (70 to 80 per cent carbon), and then decreases to a minimum at the boundary between low-rank bituminous and semi-anthracite coal (90 per cent carbon on a dry, ash free (d.a.f.) basis). The hardness increases again in the anthracite levels owing to the increasing carbon content and the consequent elastic behaviour of vitrinite in these ranks. The hardness of inertinite-rich coals does not appear to be affected by rank.

Composition. The hardness of different macerals and microlithotypes is highly variable (Table III).

TABLE I
BREAKAGES AND STRENGTH CHARACTERISTICS OF LITHOTYPES

Item	Vitrain	Clarain	Durain	Fusain
Description	Bright, shining vitreous	Bright to semi-bright laminated bands	Dull, dark grey to black; massive compact to granular; lustreless structures	Flat, fibrous, bright rectangular lenses
Breakage characteristics[8,9]	Brittle, cubic blocks, angular fragments	Semi-brittle to shattering and shearing	Inelastic, dense, solid, hard, tough, resistant to breakage	Friable, soft, easily pulverized to dust
Major microlithotypes	*VITRITE* CLARITE	*CLARITE* *VITRINERTITE* *TRIMACERITE* DURITE	*DURITE* *INERTITE* SEMIFUSITE INERTODETRITE CARBONINERITE	*FUSITE* SEMIFUSITE
Major macerals	VITRINITE	MIXED	INERTINITE (Not fusinite)	INERTINITE (Only fusinite)
Crushability (de-ashed ratio)[8]	3,8	5,1	13,6	1,8
Density[8,9]	1,3 to 1,4	1,3 to 1,5	1,5 to 1,7	1,0 to 1,25
Strength categories of Jeremic[9]	*Soft* Vitrain	*Semi-hard* Clarain + composite of vitrain, clarain, and durain	*Hard* Durain shaley coal, coaly shale	*Very soft* Fusain
Cleavage[9]	Intensive regular	Irregular erratic	Traces or none, uncleated	Open fractures
Uniaxial compressive strength[9], meganeutrons/m²	1 to 7	7 to 18	20 to 40	0 to 1
Borehole-core breakage[9]	Often fragmented	Discs and half cylinders	Cylindrical core, height greater than diameter	Fines down to 320
Breakage on uniaxial compression[9]	Cracking, compaction, yielding	Elasto-plastic failure	Elasto-brittle failure	Flow deformation and pulverization
Sizing after compression[9]	Fine to nut size	Small lumps	Large lumps	Very fine sizes

TABLE II

A SUMMARY OF THE MAJOR CHARACTERISTICS OF THE THREE MACERAL GROUPS IN HARD COAL

Maceral group	Plant origin	Reflectance: Description	Reflectance: Rank	Reflectance: Reflected light, %	Chemical properties: Characteristic element	Chemical properties: Typical products on heating		Technological characteristics
VITRINITE	Woody trunks, branches, twigs, stems, stalks, bark, leaf tissue, shoots	Dark to medium grey	High vol. to medium volatile	0,5 to 1,1				• Combusts rapidly • Pyrolysis • Hydrogenation/ liquefaction
			Bituminous	1,1 to 1,6	Oxygen-rich	Light hydrocarbons	Decreasing amounts of volatiles	• Coking
		Pale grey	Low volatile Bituminous	1,6 to 2,0				Combusts with little smoke
		White	Anthracite	2,0 to 10,0				• Combusts with no smoke
EXINITE	Cuticles, spores, resin bodies, algae	Black-brown	High vol.	−0,0 to 0,5		Early methane gas		• Combusts very rapidly • Pyrolysis
		Dark grey	Bituminous	−0,5 to 1,1	Hydrogen-rich	Oil		• Hydrogenation/ liquefaction • For bitumen production
		Pale grey	Med. vol. Bituminous	−1,1 to 1,6		Condensates Wet gases (decreasing)		
		Pale grey (= vitrinite) to white shadows	Low vol. Bituminous to anthracite	−1,6 to 10,0				
INERTINITE	As for vitrinite, and oxidized detrital organic humus	Medium grey	High vol. Bituminous	0,7 to 1,6	Carbon-rich			• Combusts slowly • Maintains flame • Relatively inert in coking hydrogenation liquefaction pyrolysis
		Pale grey	All bituminous coals and anthracite					
		White		1,6 to 10,0				
		Yellow white						

Vickers micro-indentation tests indicate that, in low-rank bituminous coals (more than 30 per cent d.a.f. volatile matter in vitrite), vitrite and clarite are harder than durite. In medium-rank bituminous coals, vitrite and clarite become softer than durite, the latter remaining relatively constant. In high-rank bituminous and anthracite coal, all the microlithotypes become harder.

In terms of macerals, the inertinite group possesses the highest hardness, exinites the lowest, and vitrinite the intermediate values. Within the inertinite group, semifusinites are softest, followed by micrinite, fusinite, and sclerotinites, which are the hardest forms[11].

Grindability

Grindability refers to the resistance of a coal to grinding. The tests most commonly employed are the ball-mill test and the Hardgrove grindability test, the latter being generally preferred. The Hardgrove index (HGI) varies inversely with the grindability of a coal, i.e. a high value indicates a coal that is easily grindable, while a low value indicates a coal that is difficult to grind.

TABLE III

THE RELATIVE AND ACTUAL HARDNESS OF COMMON MACERALS AND MINERALS

Relative range of hardness values	Maceral	Mineral	Actual range of hardness values kg/mm²
Softest	Exinite Vitrinite	Shale–kaolin halide } group	<100
	Inertinite Semifusinite	Carbonate group	100 to 500
	Micrinite Fusinite	Sulphide group	1100 to 1300
	Sclerotinite	Quartz	1100 to 1500
Hardest		Topaz Corundum Tourmaline Zircon	The hardest minerals known in coal

The following factors influence grindability.

Temperature. Coal is apparently more difficult to grind with increasing temperature.

Inherent moisture content[4]. The relative humidity of the atmosphere in which the samples are air-dried appears to affect the grindability of low-rank coals, but not of higher-rank coals[12].

Rank. Grindability in the vitrinite-rich coals of Europe and America reaches a maximum in the medium- to low-rank bituminous ranges, i.e. these coals become much easier to grind. At progressively higher and lower ranks, and with increasing inertinite content, the coals become more difficult to grind[1,4].

Organic composition. Recent research has shown that grindability in terms of Hardgrove index is largely controlled by a coal's organic composition in addition to rank[1,7]. For example, within certain ranges of bituminous coal, the vitrinite (or vitrite and virtrain) is easier to grind than the inertinite (or inertite and durain) found in the same coal; at lower and higher levels of rank, the opposite occurs. Only at one level of rank (i.e. the boundary between low- and medium-bituminous coal) do microlithotype groups possess a similar grindability[7]. More specifically, vitrinite becomes very difficult to grind in low-rank bituminous coals (HGI 24), easiest to grind in mid- to high-rank bituminous coals (HGI 84), and harder again in the anthracite range. Inertinite changes slightly in bituminous coals of very low rank, and then maintains a fairly consistent grindability value (HGI 45 to 50) throughout the bituminous and semi-anthracite range and thereafter increases slightly.

No correlation could be found[12] between the ash content of South African coals and their grindability. However, the grindability of various washed fractions (sinks and floats) of a sample prepared for conventional washability tests varied significantly, in some cases reciprocally with ash. As can be noted from Table IV, which gives the grindability of low-rank bituminous coals from the Witbank Coalfield, the more difficult products to grind are the low-ash, low-density fractions. These products are typically enriched in vitrinite, vitrite, intermediate microlithotypes, and liptite. The heavy-density fractions (i.e. the sinks) have slightly higher ash contents—iron sulphides (pyrite), carbonates, and rare quartz forms—and higher inertinite macerals and microlithotypes. The latter act as the host organic matrix and are in themselves easier to grind at this level of rank.

In general, the European medium-rank, vitrinite-rich coals are much easier to grind than the generally lower-rank, and usually inertinite-rich, coal of South Africa. However, some of the lower-rank coals in the South Rand and Orange Free State Coalfields are an exception. Many of these coals are partially oxidized, friable, and as soft as those in Europe but for different reasons[7]. These observations are directly related to rank and coal type or composition, and not to mineral matter.

MacGregor[4] related grindability (HGI) to volatile matter. This relationship was indirectly applied to low-ash, vitrinite-rich coals, usually of low rank, but other situations have arisen that disagree with this correlation. Such an example is shown in Table V.

TABLE IV

GRINDABILITY RELATIVE TO PROXIMATE, ASH, AND PETROGRAPHIC ANALYSES*

Product	Sample 1 Washed	Sample 1 Average raw	Sample 2 Washed	Sample 2 Average raw	Sample 3 Washed	Sample 3 Average raw
Ash, %	11,9	14,8	11,0	17,0	11,9	17,5
Volatile matter, %	32,4	31,4	32,2	30,1	32,3	30,2
HGI	45	48	46	50	44	49
S_2O_3	46,9	40,8	50,4	45,2	49,4	51,8
Fe_2O_3	11,3	19,7	7,3	14,2	6,1	7,2
CaO	3,0	4,3	2,5	3,7	3,1	2,6
SO_3	3,6	4,3	2,5	5,0	3,7	3,0
Vitrinite	47	32	49	32	45	32
Intermediates	23,8	25	27	25	27	25
Inertites	20,3	30	17,1	30	19,3	30
Carbominerites	2,5	10	1,0	10	2,7	10
Liptites	6,4	3	5,4	3	5,7	3

*Source of data Gold Fields of South Africa Ltd

TABLE V

HGI RELATIVE TO PROXIMATE ANALYSES

Constituent	Sample 1	Sample 2
Moisture	1,1	1,8
Ash	50,0	20,2
Volatile matter	34,5	31,1
Fixed carbon	14,4	46,9
HGI	38,0	47,0

The two samples featured in Table V were taken from two bands lying one above the other within one coal seam. The ash content and the volatile matter were both high in Sample 1, which was also characterized by remarkably low grindability values, i.e. greater difficulty in grinding. Petrographic analyses indicated that this sample contained approximately 50 to 60 per cent carbonate minerals in a ground mass or matrix of a very unusual form; this material had infiltrated the botanical cavities and was intimately associated with abundant fusinite and semifusinite fragments (which were well distributed throughout the layers), rare fine-fractured vitrinite layers, and rare undisturbed intermediate microlithotypes. The carbonates would have provided significant quantities of inert carbon dioxide gas, thus contributing to the total content of volatile matter during testing. In this sample there is no correlation with vitrinite, and the low grindability is attributable mainly to the abundant and unusual forms of the carbonates.

Abrasiveness

Abrasiveness refers to the capacity of coal to wear away or erode the surfaces with which it comes into contact. The factors affecting wear rate or abrasion are not well understood. It has been suggested that a high content of mineral matter and the presence of hard minerals like quartz and pyrite contribute to the abrasive qualities of a coal[7]. Meintjies[12] suggested that there is only a general relationship between abrasion and ash content. (This is quite likely when high proportions of soft clays comprise the ash-forming minerals.) It was also suggested that the 'nature of the minerals' is the major factor governing abrasiveness[4]. No conclusions could be drawn[12] on the relationship between coal rank and abrasiveness.

Recent research conducted at the Falcon Laboratory shown in Figs. 4 and 5. the abrasion increases from 434 mg of iron per 4 kg in the finest fraction (minus 6 mm) to 1878 mg of iron per 4 kg in the coarsest fraction (plus 50 mm), although the parent raw coal, unsized, averaged 820 mg of iron per 4 kg. Histograms of selected parameters taken from each sized fraction indicate that, although the abrasion and ash values follow similar overall trends, the increasing abrasive index with increasing size is paralleled more closely by

(a) increasing carbominerite (bands of mineral-rich microlithotypes, i.e. organic matter with more than 20 per cent minerals by volume per particle of coal),
(b) increasing proportions of quartz—quartz (and clay) representing more than 50 per cent by volume per particle of coal is coded QC:1, and more than 25 per cent QC:2—and
(c) decreasing vitrite, and therefore a reciprocally increasing inertinite content.

These investigations suggest that the marked increase in quartz-rich bands, together with the intimate association of these minerals with the dense maceral inertinite plus large sizes of band, result in a combined reinforcement of strength relative to abrasive capacity. Interestingly, these coarse minerals increase particularly sharply in the size ranges larger than 32 mm (QC:1 + QC:2); in the smaller sizes, the mineral matter and ash content are same elements that cause increased abrasiveness in the larger size fractions occurs in the heavier washed fractions. Figs. 6 and 7 illustrate in more detail the distribution of selected petrographic and proximate parameters between the three float fractions of the plus 50 mm sized coal. Exactly the same distribution patterns were observed in all the remaining sized coals, although the proportions (yields) naturally varied with the composition of the original parent sized products. These results indicated that

(i) the same principles of density separation apply in all coals;
(ii) the constituents reporting to the heavier density fractions possess the highest abrasion indices;
(iii) the constituents are similar to those found in the coarse size ranges of coal and include, more specifically,
    carbominerite and inertinite
    carbominerite (Fig. 8)

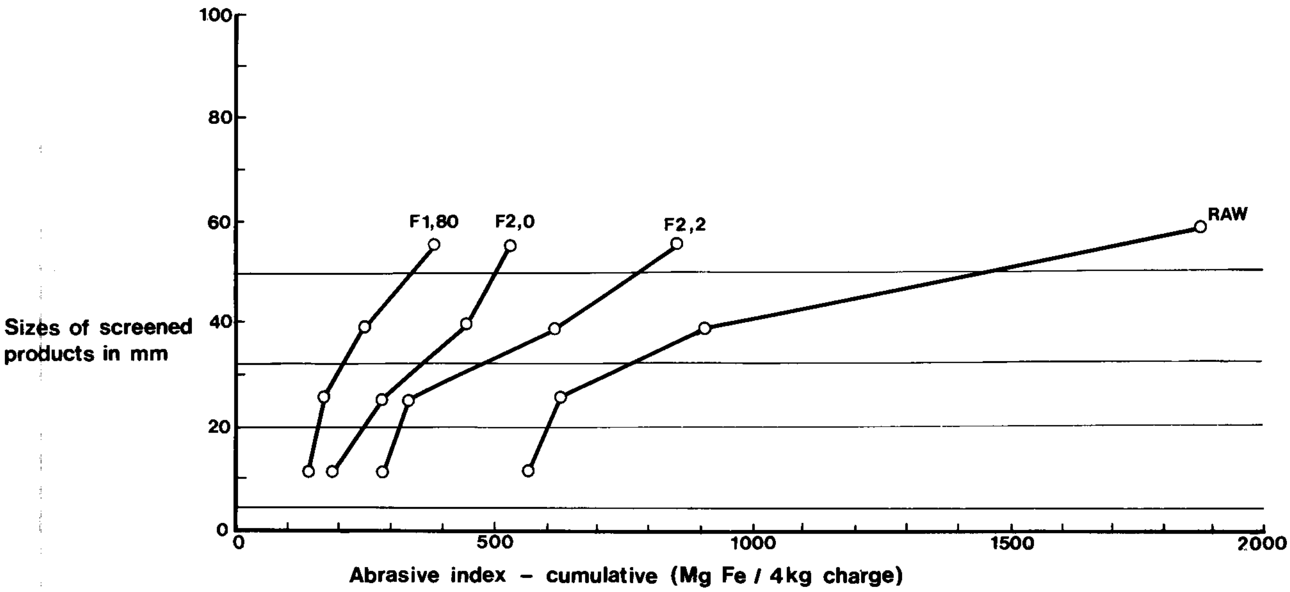


Fig. 3—Variations in abrasive index relative to different size and density fractions

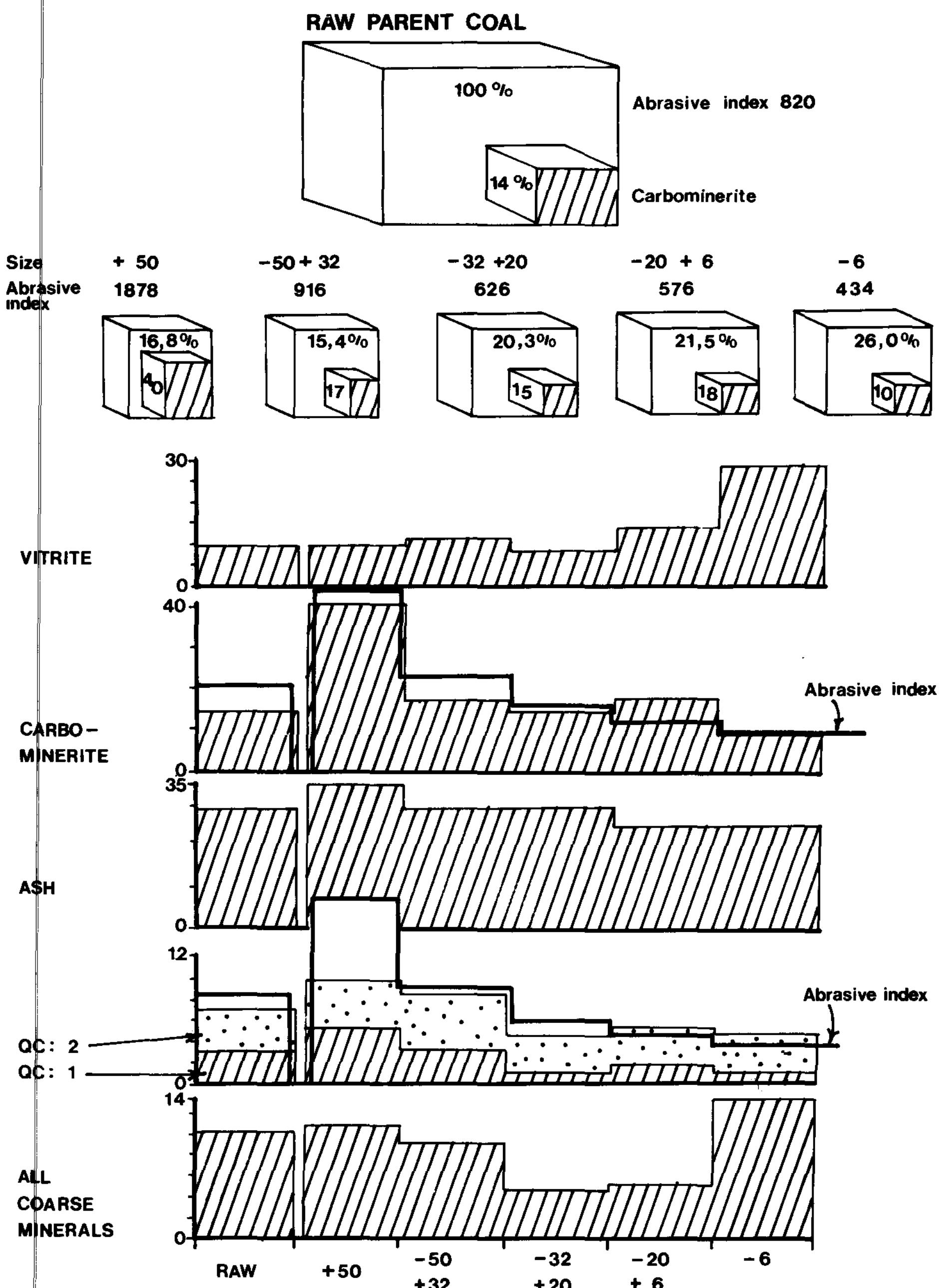


Fig. 4—The abrasive indices of parent raw coal and of sized products

inertodetrinite and macrinite (inertinite macerals)
quartz (QC:2 and QC:1), i.e. in higher proportions and invariably larger grain sizes,
coarse carbonates (more than 25 per cent), and ash;

(iv) the qualitative difference between the density fractions 2,0 and 2,2 are not significant since all organic matter floats at densities of less than 1,7 and all mineral matter at densities of over 2,0. Components with densities between these two values have varying proportions of organic matter in the mineral-rich bands.

In summary therefore, the abrasive index of these coals varies significantly with increasing size and density, both of which permit the concentration of specific constituents with high abrasive indices.

The importance of size and density is shown in Fig. 9. Here, each size fraction and each density within that size fraction are shown relative to the same indices as in Fig. 8. Each sized product appears to possess a characteristic linear angle, with the density products spread out along those lines. The resolution between the samples, relative to their size, density, abrasiveness, and carbominerite content, is resolved with surprising clarity. This becomes even clearer in Fig. 10, where QC:1, the high proportion of quartz content, is used as the abrasive constituent. The only samples not consistent with this pattern are the raw coal products. In each size fraction, these samples have very high abrasive indices and fall more in line with the characteristics of the coarser size fractions (Fig. 8).

An important fact to emerge from these findings is that the abrasive index of a low-density, coarse coal may be the same as that of a finer, high-density coal. The sig-

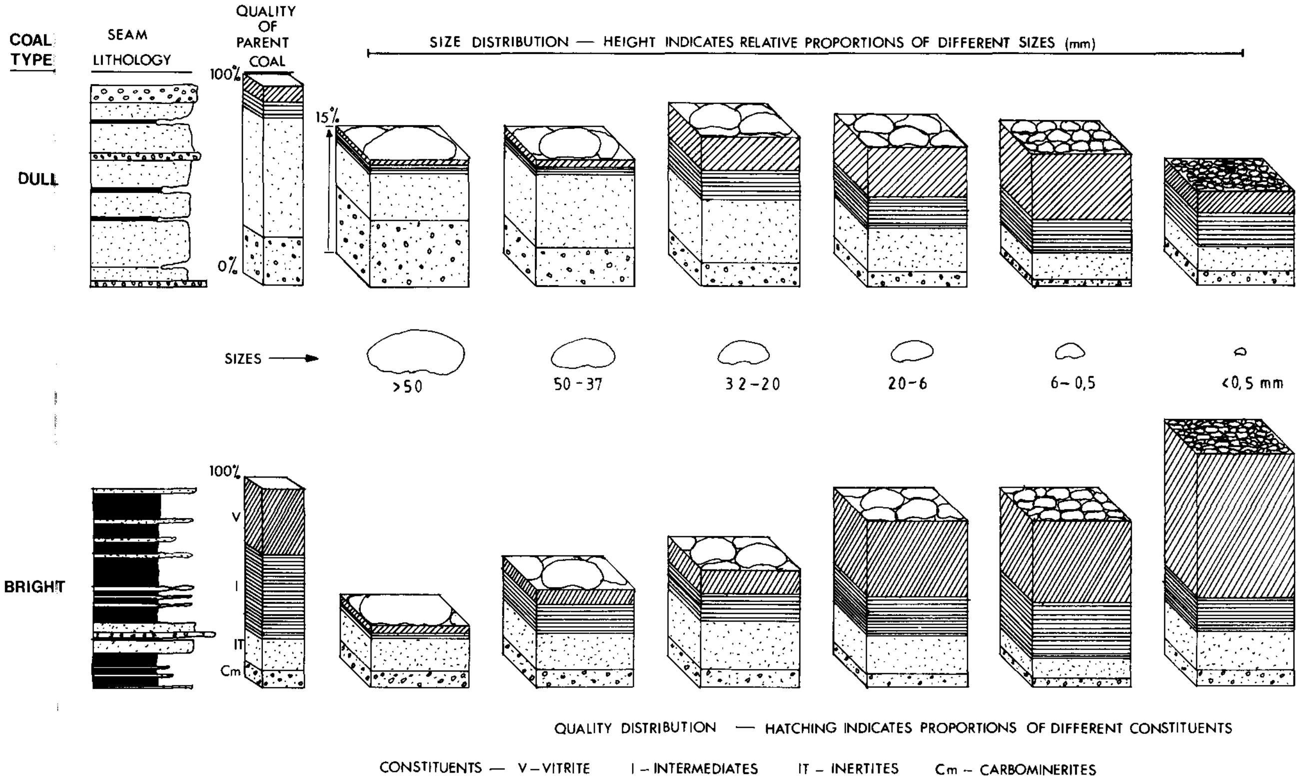


Fig. 5—Typical size gradings and quality distributions in the screened products of two major types of coal

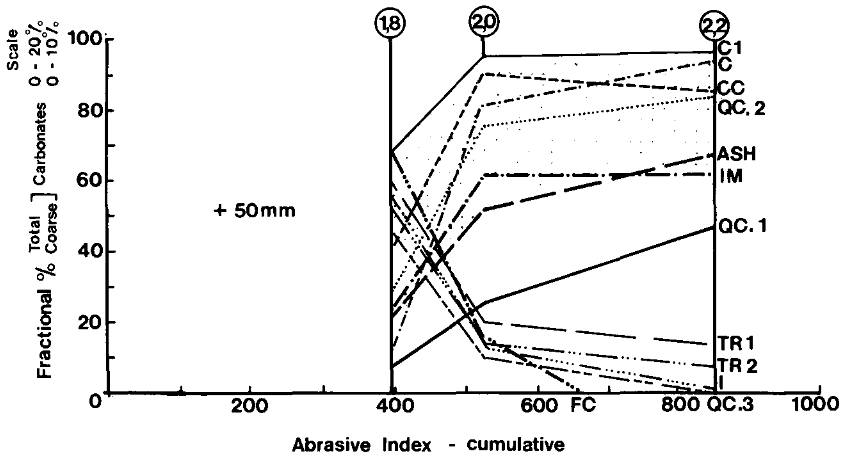


Fig. 6—The distribution of petrographic and property parameters in different flotation fractions of coarse coal (larger than 50 mm)

Key

C	Carbominerite
C + I	Carbominerite and inertite
CC	Coarse carbonates >25% per particle of coal
FC	Fine carbonates <25% per particle of coal
I	Inertite
IM	Inertodetrinite and macrinite
QC 1	>50% quartz and clay per particle of coal (M = 100%)
QC 2	>25% quartz and clay per particle of coal (M = 100%)
QC 3	<25% quartz and clay per particle of coal (M = 100%)
TC	Total carbonates (M = 100%)
TR 1	Total reactive macerals (O = 100)
TR 2	Total reactive macerals (O + M = 100)

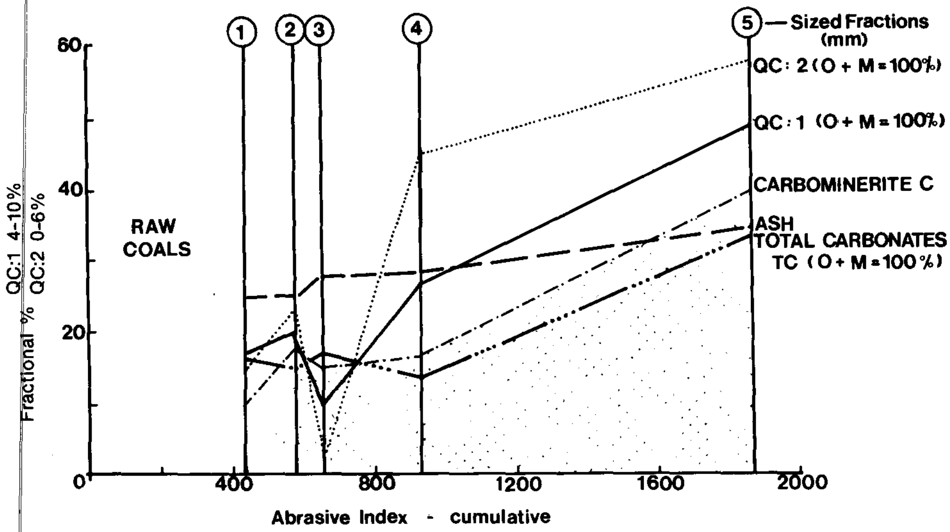


Fig. 7—Notable qualitative variations between raw coal of different sizes (See Fig. 6 for key)

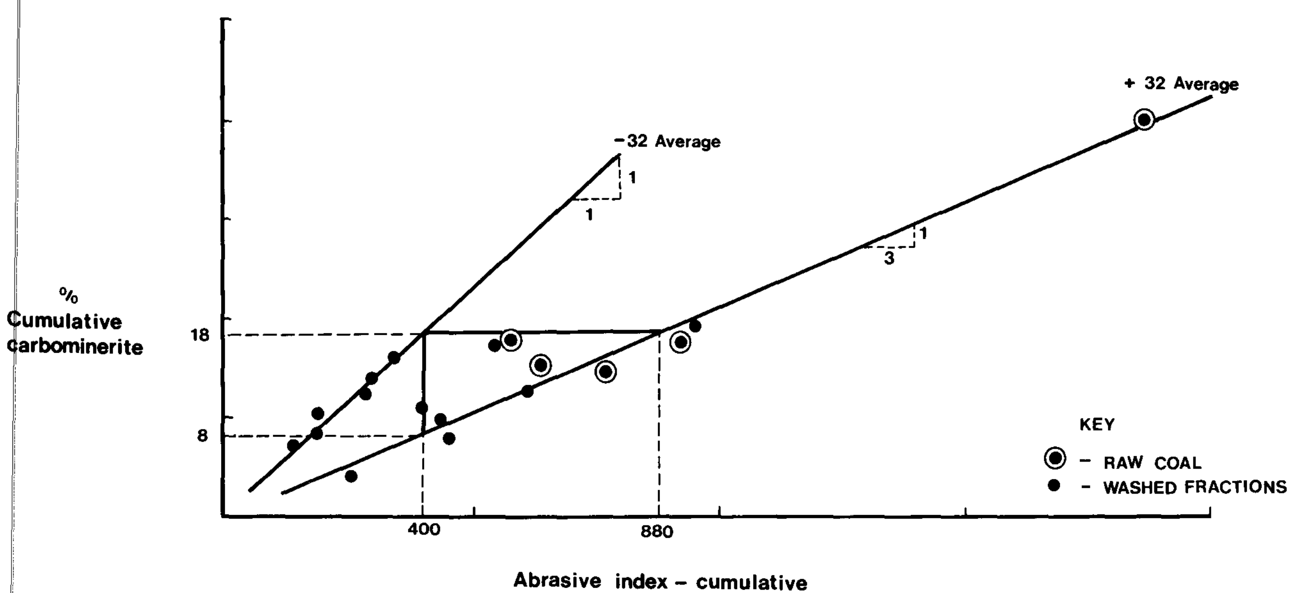


Fig. 8—The relationship between carbominerite and abrasive index

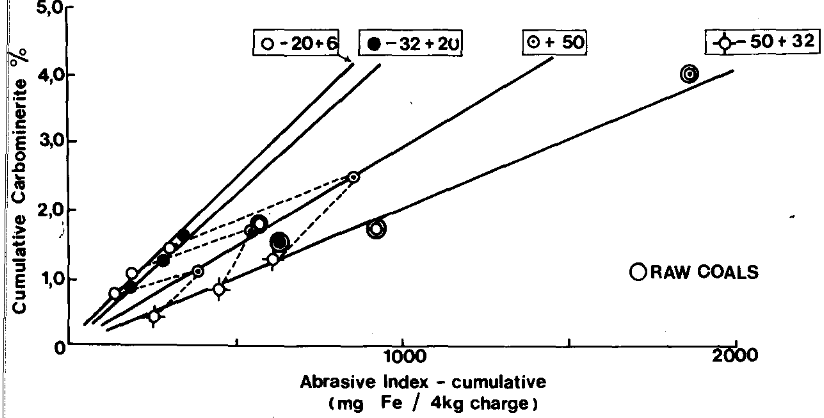
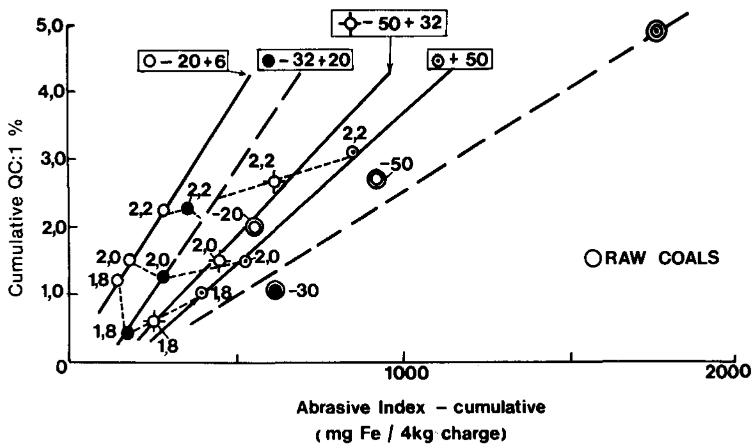


Fig. 9—The relationship between abrasive index (cumulative) and carbominerite

Fig. 10—The relationship between abrasive index (cumulative) and quartz content (QC 1 equal to or greater than 50 per cent) per particle of coal



nificance of this observation is that finer crushing of the coarser fractions is likely to reduce the abrasion index of a product (i.e. by size and mineral liberation), although a minimum will ultimately be reached that is determined by the proportion, size, nature, and distribution of the remaining quartz and carbominerite constituents.

That some coalfields and parts of some coal seams have such widely differing abrasion characteristics may be attributable to the formation of the constituents that contribute to high abrasive values in very specific coal-forming environments within the original swamp. As the environments varied considerably from area to area (in some seams more than others), it is hardly surprising that mining in different areas often yields products with highly variable abrasive characteristics.

Mining in different areas of a varied coal seam is likely to result in varying proportions of heterogeneous products with periodically variable abrasive indices. In Southern Africa, seams with these specific characteristics have been found in the lower or older coal sequences, and are usually associated with river systems and outwash deltas linked to mature glacial valleys. The presence of unique forms of carbonates and some rare pyrite lenses has also been linked to relatively higher abrasive indices than normal in some coals. Apart from these minerals, the size and form of inertinite, and the types of microlithotypes, appear to be the most important contributory factors.

Friability

Friability refers to the softness or ease of compressibility of a coal, and ultimately the amount of fines produced. In terms of mining, the friability of the coal affects the levels of dust in the air, and the elasticity, strength, or constraints of the pillars. The pillar behaviour is directly proportional to the strength of the bands within the profile of the coal seam. Different properties in each coal section along the profile lead to differential or sectional pillar behaviour, and this may lead to mine instability in a short period of time[9]. In terms of quality control and handling, friability and dust production lead to a higher liability towards spontaneous combustion, a lower quality of final sized product, and high proportions of unusable sizes.

Although friability in a coal is normally attributed to cleats, fractures, and soft bands of fusain[1,9], in Southern Africa friability often occurs in coals that do not satisfy these conditions. The significant factors are low rank (resulting in high moisture and porosity), porous inertinites, and specific forms of oxidation and weathering. In medium- and high-rank coals, which hold little moisture and possess low porosity, the loss of moisture is of no particular significance. However, low-rank coals (lignites and sub-bituminous ranges) can lose 25 to 30 per cent of their original mass during air drying[10]. Such dehydration is accompanied by extensive, partially irreversible shrinkage, and the internal stresses set up quickly cause the coal to lose its cohesion and to disintegrate into progressively smaller pieces. Commonly referred to as decrepitation or slacking, and analagous to the spalling of rocks exposed to alternate freezing and thawing, this process begins almost immediately after the coal has been mined and can be far advanced within as little as 24 to 84 hours[10].

Such decrepitation appears to be confined to coals of low rank that are highly porous and have moisture-holding capacities equal to or greater than 10 per cent. In Southern Africa, such coals include coals rich in abundant, macroporous, semi- or uncompacted semi-fusinites and fusinites (the porosity being derived from the often empty botanical cavities) and coals found at relatively shallow depths (less than 200 m and associated with porous sandstones) that have undergone oxidation and deep weathering by the passage of geothermal waters or fluctuating water tables at some stage during their development underground. In the latter case, cracking and minor fissuring, and the transport of minute detrital matter away from and into the botanical cavities and cracks, led to enhanced surface areas and/or storage capacity for gases and moisture, which are released during mining and result in a highly friable condition in the coal. These conditions cannot be identified by chemical methods alone, but they are easily observed under the microscope. The degree of moisture-holding capacity is at present the only empirical test that is able to indicate the conditions leading to decrepitation due to low rank and high moisture and porosity.

In addition, it is of interest to note that, in Southern Africa, some anomalous situations arise related to the above conditions. For example, some coals may be extremely hard (resisting breakage, cutting, and grinding during mining and initial crushing); they may also be relatively abrasive. However, within a matter of days they may decrepitate and become so friable that up to one-third of their original mass has become too fine for use, as found at the Falcon Laboratory. Such conditions are unique in coals of the southern hemisphere, and must be taken into consideration prior to extensive mining and operating procedures.

Prediction of Mechanical Strength

The apparent lack of correlation between proximate, chemical, and some physical aspects of coal found by some researchers lies in the fact that many of the prime parameters like volatile matter and ash content are insufficient to characterize the highly variable coals of the southern hemisphere. Volatile matter, for example, is influenced, not only by the proportion of volatile-rich organic constituents in a coal and its rank (degree of geological maturity), but also by the proportion of inert volatile-yielding minerals (carbonates, clays, and some sulphides) and by varying degrees of oxidation. Ash content is not suitable to characterize coal since it merely reflects the total inorganic content of a coal and not the composition, proportion, or distribution of the soft minerals (fine clays) in relation to the hard minerals (e.g. abundant quartz, pyrite). New or better parameters are therefore necessary before an adequate understanding can be obtained of the mechanical behaviour of coal and before this behaviour can be predicted.

The following three groups of parameters influence all the types of mechanical behaviour:

(a) rank (measured by vitrinite reflectance),
(b) organic composition (i.e. lithotypes, microlithotypes, and macerals), and
(c) mineral matter (mineral groups and their distribution patterns).

Apart from these, a number of external or apparently secondary features influence the mechanical behaviour of coal to varying degrees:

(d) size,
(e) presence of cleats and cracks,
(f) degree of oxidation, and
(g) temperature.

On the basis of these factors, a two-tiered system of parameters for use in the prediction of behaviour is now suggested. The *primary* or *inherent* characteristics include type (organic composition) and rank; the second tier is based upon a series of secondary or *external* factors as listed above and grade (mineral-matter composition). A diagram representing type and rank and presented in Fig. 11 forms the basis of the proposed primary classification system for the prediction of mechanical behaviour in coal. Here, the natural inherent properties of coal, i.e. the organic components calculated on the basis that they are free of mineral matter, are portrayed. Average variations in quality are shown in terms of different coalfields or basins in Southern Africa and relative to the ranges of coals in Europe. The coals of the Orange Free State and Botswana, for example, are generally more inertinite-rich and lower in rank than the typically vitrinite-rich, higher-ranking coals of Natal and Europe.

On the basis of findings recorded in the literature and testwork at the Falcon Laboratory, contours of the four main mechanical characteristics of coal were superimposed on this primary diagram and are presented in Figs 12 to 15. Abrasion was not included since mineral matter and size appear to be the most relevant prime factors. It will be noted that the variations in vitrinite-rich bands pass through maxima and minima with increasing rank, while the inertinite-rich bands change consistently and slowly with rank. To these values must now be added the influence of mineral matter and the secondary parameters of oxidation, particle or lump size, cracking/cleats, and temperature. The major advantage of this system is that almost all the physical properties of coal can be allocated to coal types and ranks within a simple common framework, and that additional factors superimposed upon these basic characteristics can be easily understood or identified. By these means, coal behaviour in new or expanding areas can be predicted with a reasonable degree of reliability.

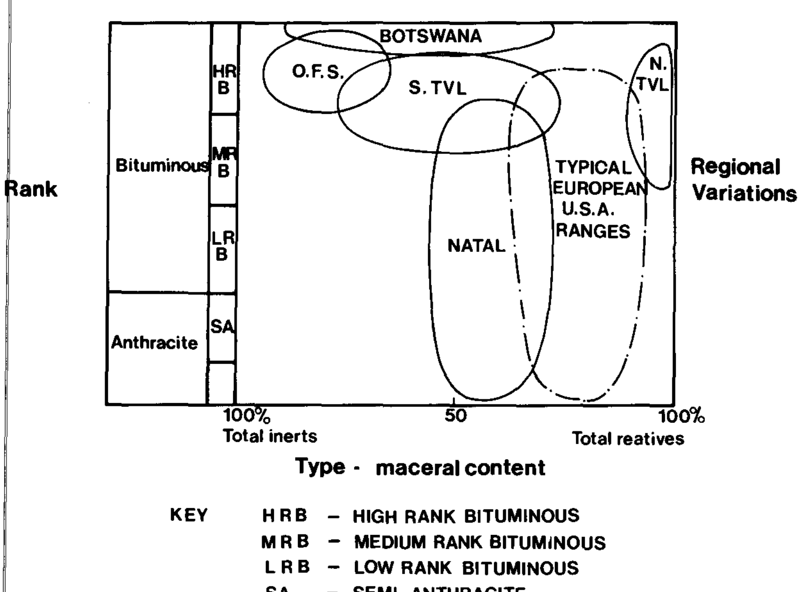


Fig. 11—Regional variations in quality based upon petrographic parameters

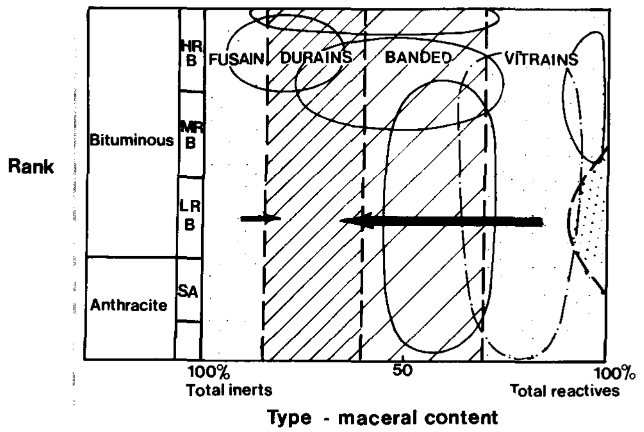


Fig. 12—The primary classification showing the trends in strength of coal relative to organic composition (type) and rank (the arrows indicate the direction of increasing strength)

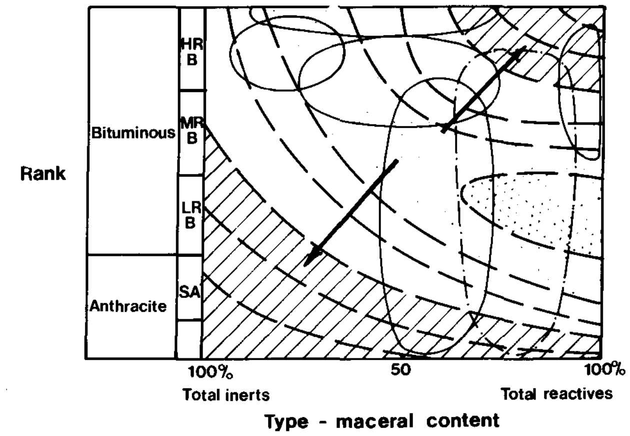


Fig. 14—The primary classification showing the trends in grindability relative to organic composition (type) and rank (the arrows indicate the direction of decreasing HGI values, i.e. increasingly more difficult grinding—reciprocal values)

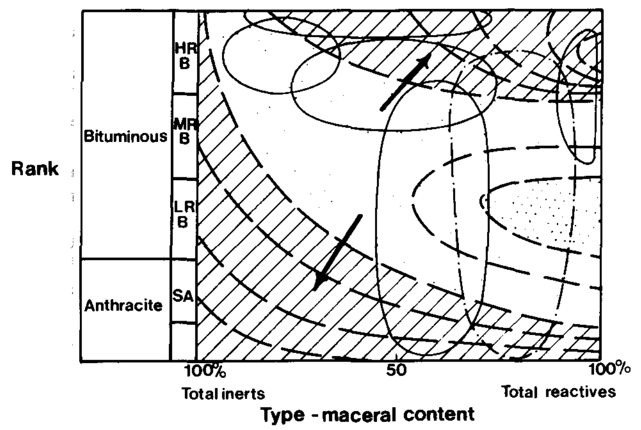


Fig. 13—The primary classification showing the trends in hardness relative to organic composition (type) and rank (the arrows indicate the direction of increasing hardness)

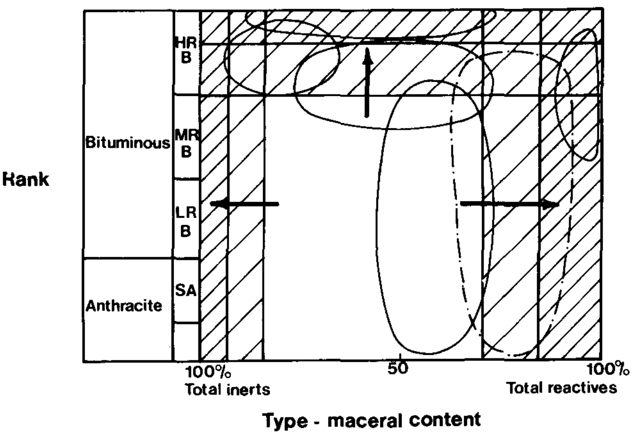


Fig. 15—The primary classification showing the trends in friability relative to organic composition (type) and rank (the arrows indicate the direction of increasing friability)

Application of Findings

These findings can be applied in industry as shown by the example of mechanized coal mining, which is affected by a combination of the following mechanical properties, the combination being termed the cuttability of the coal[4,13].

(1) hardness, which affects the penetration at the point of cutting,
(2) strength, which affects the resistance to sustained compression,
(3) friability, which affects the capacity to break up once penetrated, and
(4) abrasion, which affects the erosion and wear on the mine and transport equipment.

In the various coalfields of Southern Africa, the primary classification system can be used to indicate some of the major reasons for the characteristic mechanical behaviour of the coal. Some examples are given below.

Strength is highest in coals from the Orange Free State and southern Transvaal (apart from certain oxidized coals) because they contain bands that are rich in inertinite–durain, many with relatively high quartz contents.

Hardness is highest in the vitrinite-rich, low- to medium-rank coals of Natal, and lowest in the low-rank semifusinite–inertinite rich coals of the Orange Free State.

Grindability (Hardgrove index) is most variable in the Natal coals, ranging from 31 to 83. Transvaal coal is the least variable, ranging from 40 to 66. The coal in the Orange Free State is variable, ranging from 63 to 84. The highest values (higher than 60) or most easily grindable coals in the latter region (e.g. the South Rand) are sometimes friable because they were oxidized *in situ*, as found at the Falcon Laboratory. In contrast, the coals of Europe are generally much easier to grind than those of Southern Africa (with the exception of the unusually easy coals in the Orange Free State). This has been attributed[7] to the higher vitrinite contents and the higher ranks of the European coals, thus placing them in the least-difficult-to-grind categories (the 70 to 80 isocontours in Fig. 14).

Friability is a function of coal strength and rank. On this basis, certain seams or parts of seams in the Orange Free State, South Rand, Southern Transvaal, Botswana, and Zimbabwe are known to be 'softer' and more friable than others in the sub-continent.

Abrasive index is highest in seams or parts of seams in which thick bands rich in drift inertinite are associated with high proportions of quartz (and other hard minerals) in mineral-rich microlithotypes. Rank is not relevant. Such coals are known to occur in isolated lenses, parts of seams, or regions where consistent flooding occurred during the formation of peat. Examples are known in parts of the Witbank coalfield and the Southern Transvaal and Highveld coalfields.

Conclusion

Further research for the establishment of more precise prediction limits is necessary, but it is hoped that this approach will serve to assist in the development of better design parameters for the equipment used on Southern African coals and, ultimately, that greater efficiency will be obtained in all aspects of the mining and handling of coal.

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Mine ventilation

The Fourth International Mine Ventilation Congress, organized by The Australasian Institute of Mining and Metallurgy, will be held in Brisbane from 3rd to 6th July, 1988.

Brisbane is a sub-tropical city with a population of 1,4 million. A pleasant climate is enjoyed during July. The World Expo 88 will be held in the heart of Brisbane, April to October 1988, and Congress registrants should find time to attend while in Brisbane.

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