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Canada Centre for Mineral and Energy Technology
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PITCH AND PETROLEUM COKE ADDITIONS TO COKE OVEN CHARGES

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by

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ABSTRACT

Asphalt, pitches, solvent refined coal (SRC) and petroleum coke were added to coke oven charges in an attempt to make good metallurgical coke from Canadian coal of poor coking quality. Asphalt, pitches and SRC were added to a low fluid western Canadian coal of medium volatile butiminous rank, and the blends coked in a technical-scale moveable wall test oven having a 230-kg charge capacity. Pitches improved coke tumble test indices, the principal coke quality parameter related to blast furnace performance. Varying levels of petroleum coke wereadded to an eastern Canadian coal of high volatile bituminous rank, and the blends, some partially briquetted, were carbonized in a test oven. Tumble indices of coke from the partially briquetted charges approached an acceptable level. These investigations confirm that petroleum products as well as coal derivative can play a useful part in the production of a metallurgical strength coke from poor or non-coking coals.

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INTRODUCTION

The Canada Centre for Mineral and Energy Technology (CANMET) has two pilot-scale coke ovens to advance carbonization research in conjunction with the Canadian coal and steel industries and to evaluate the quality of Canada's coal resources. This paper describes a pilot plant investigation into the addition of pitch and petroleum coke to Canadian coking coal charges in an attempt to improve the quality of the resulting coke.

Metallurgical coke is a strong, porous, carbonaceous material which is conventionally produced from the destructive distillation of crushed coking coals in heated refractory chambers called coke ovens. Ninety per cent of the world's coke production is consumed during the manufacturing of primary iron by the blast furnace process. Coke is the main source of heat and the reductant in the blast furnace. It must have sufficient strength to support the iron oxide burden and a size range that allows adequate flow of gases and molten iron and slag. Coke strength has become particularly important with the advent of very large blast furnaces as they require a more consistent and higher strength coke than the older, smaller blast furnaces. A strength index for iron blast furnace coke is calculated from the mechanical breakdown of coke at ambient temperatures in a tumble drum (1,2). The tumbler test most extensively used on coke from CANMET's technical scale ovens is the American Society for Testing and Materials (ASTM) tumbler test (1) - the coke strength index being the ASTM stability factor. High temperature (3) and After Reaction Strength (ARS) tests (4) which simulate the chemical and thermal conditions in blast furnaces are gaining acceptance by some steelmakers.

Metallurgical coke-making has evolved from simple beginnings to its present position as a highly technical, though empirical, operation involving the blending and charging of coals into slot-type by-product coke ovens. Bituminous coals are used because they become plastic (melt) in the temperature range 300-500°C. The properties of coking coals that influence coke strength are their caking capacities, often measured by a Gieseler plastometer (5) or Ruhr dilatometer (6), and their rank, which is assessed by the coal volatile matter content or by the coals' aromaticity as indicated by the reflectivity of the vitrinite macerals to visible light.

Coke strength has been predicted and several methods of blending coals have been formulated from rank and caking properties (7,8,9,10). For example, the shaded areas of Fig. 1 represent the caking properties (Gieseler fluidity and Ruhr dilatation) and rank of blends that have been found empirically to produce good metallurgical cole (11). A blend should have a Gieseler fluidity of 200-1000 dial divisions per minute (ddpm) or a total dilatation (contraction plus dilatation) of 50-150% according to European and Japanese investigators (7,9). The rank of the blend should be adjusted so that the mean maximum reflectance (R_o) of visible light from the microscopic vitrinite particles is 1.15-1.25%, corresponding to coal volatile matter content (VM) of 28-32%.

Figure 1 includes iso-stability lines that were derived from petrographic data (11). Each coal rank has an optimum caking level which maximizes coke stability. Coals with larger than optimum caking properties are rich in reactive (melting) macerals, where as coals with poor caking properties are rich in inert (non-melting) macerals. Blending of high, medium and low volatile coals is often required to optimize caking and rank properties and to maximize coke strength. Other blending considerations include avoiding excessive amounts of coals that expand during coking as they could dammage coke oven walls, and minimizing sulfur and ash contents.

An alternative (or additional) method of coal blending is to optimize the caking property of a coal or blend by adding carbonaceous materials other than coal. Binder-like materials such as oils, tars, or pitches could be added to inert-rich coals while coke fines, char, or petroleum coke could be added to highly fluid coals to improve coke strength (12,13,14).

The role played by the binder during carbonization is to behave like the reactive macerals and to provide inert-rich coals with fluidity and a source of molecular structure needed for development and growth of the anisotropic mesophase. The mesophase, a liquid crystal-like intermediate, ultimately fuses; it then bonds with or entraps inert macerals during its solidification to produce a strong coke structure. The size and amount of inert macerals in conjunction with coal rank are thought to control the size and growth rate of mesophase and hence affect coke strength (15). Presently, Sumikin Coke Co. uses up to 20% non-coking coal in their coke blends by also adding a petroleum-derived aromatic pitch material, Eureka pitch (16). Mitsubishi Heavy Industries Ltd., in its"Chery Process", has also made a binder for coke-making by converting a mixture of asphalt and powdered coal to liquid, binder, and solid products (17).

Although many western Canadian coals make excellent coke, pitch additions to some of these coals would probably improve coke strength because these coals generally have high ash and inert maceral contents. Some are partially oxidized, which effectively further increases the coals' inert content and decreases the caking properties. In the present work several experimental and industrial pitch materials were added to an oxidized medium-volatile (mv) western Canadian coal and the test blends carbonized in a 250-kg capacity oven to determine the effect of different pitches on coke strength.

Coking coal from eastern Canada has excessive caking properties and must be blended with high-inert coals having higher rank to make good metallurgical coke. Therefore petroleum coke was added to eastern Canadian coal and carbonized in CANMET's 325-kg capacity oven in an effort to increase coke strength.

COAL PROPERTIES

Table 1 lists the properties of the medium and high volatile (hv) coals used in this investigation. Three lots (L_1, L_2, L_3) of the medium volatile coal were used to complete the study. Proximate and ultimate analyses of the three lots were similar. The R_o of this coal is 1.1% and could fall within the blending area suggested by the National Coal Board (NCB, Fig. 1), provided the coal had sufficient caking properties. The poorer rheological parameters for L_1 and L_3 than for L_2 were probably caused by oxidation (Table 1). These differences in rheological properties and the tendency of this coal to oxidize during the test period presented some difficulties in comparing the carbonization results from tests with different pitch additions.

The properties of the hv coal from eastern Canada are included in Table 1. The total dilatation and Gieseler fluidity values of this coal indicate this reactive-rich coal requires an inert additive such as petroleum coke to maximize coke strength. Figure 1 would suggest that this coal, with an R_o of 0.99%, could not have the desired blending properties even at optimum inert levels. However, maximizing coke strength through inert additions may be economic in eastern Canada if the coke is used in small blast furnaces.

PROPERTIES OF PITCHES AND PETROLEUM COKE

Six commercial and experimental pitches, A through F in Table2, were used as additives to the western Canadian coal. Pitches marked D_1, D_2, and D_3, for example, represent different samples but are similar material derived from the same process. Samples A through D are petroleum products while E and F are coal derivatives. The latter pitches have smaller H/C ratios indicative of the greater aromaticity of these pitches. A good variety of pitches were examined as seen from the large range of values for the Conradson carbon, VM, ash, sulfur, and asphaltenes. The specific gravities (SG) of the coal-derived pitches are greater than petroleum pitches. Proximate and ultimate analyses of the petroleum coke are also included in Table 2.

Figure 2 compares the rate of thermal cracking of pitches, hv coal, and petroleum coke. Pitches D and F appear to devolatilize most similarly to the highly fluid hv coal.

TESTING PROCEDURES

The carbonization tests were made in two CANMET coke ovens which are operated under different conditions.

The electrically-heated, moveable-wall test oven having a width of 310 mm was used for the tests in which pitches were blended with western Canadian coal. The target bulk density of coal in the oven is 815 kg/m^3 and the coking time 9.7 h. Pitches A, B, C, and E, having low softening points, were melted then mixed with the coal of size 80% minus 3 mm; pitches D and F, with high softening points, were crushed to 0.8 mm prior to blending with the coal.

The 460-mm wide oven at CANMET was used for the carbonization tests in which petroleum coke was added to hv eastern Canadian coal. The coal was crushed to 80% minus 3 mm and blended with minus 0.8 mm petroleum coke prior to being dropped into the oven. This oven is also electrically heated with a moveable wall but has silica brick refractories, can hold 325 kg of dry coal and has a target bulk density of 745 kg/m^3. Coking time in the oven is 18 h to reach a centre temperature of 1000°C.

After carbonization, coke from both ovens is treated similarly. It is quenched with water, dropped from a height of 3 m to simulate industrial handling, dried, screened; the 50 x 75 mm coke is then tumbled according to the ASTM standard (1). Cokes made from the same coal in both test ovens have similar stabilities but other properties vary (18). Carbonization results from this investigation are included in Tables 3, 4, 5, and 6.

After Reaction Strength (ARS) tests were made on selected cokes from both the pitch and petroleum coke addition studies. The ARS test was done according to the Nippon Steel Corporation (NSC) proposal (4) in which 200 g of

20 mm coke is reacted with 5 L/min of CO_2 for 2 h at 1100°C. The weight per cent of coke that survives the reaction is the reaction percentage; the ARS is the weight per cent of reaction product greater than 10 mm after tumbling in the NSC tumbler for 600 revolutions. Results are included in Tables 5 and 6.

PITCH ADDITIONS TO POOR COKING WESTERN CANADIAN COAL

Rheology of Western Canadian Coal Blends Containing Pitch Materials

According to Japanese and NCB blending methods (7,9), coking coal blends should have total dilatations between 50 and 150% or Gieseler fluidities between 200 and 1000 ddpm to make good metallurgical coke (Fig. 1). To approximate the amount of binder required, Ruhr dilatation measurements were made on blends with pitchesD, E, and F added at 5, 10, 20, and 30% levels to coal L_2. Figure 3 indicated 5 to 12% pitch must be added to L_2 to have a dilatation of 50%.

The actual amount of pitch added to the coals charged to the oven ranged from 5 to 15%. Figure 4 shows the Gieseler fluidity of the actual coke oven charges L_3 as a function of the type and amount of pitch added. A minimum of 8% pitch is necessary to meet the minimum fluidity line suggested by Japanese researchers (9), and pitches C, D_3, and F enhance caking properties the most.

Carbonization Results

The ASTM stability factor is the prime strength index used in North America to evaluate metallurgical coke. Stability factors greater than 52-55% are indicative of the quality of coke currently used in Canadian blast furnaces. One Canadian company has found that a 1% increase in coke stability factor decreases the fuel rate by 8 kg per tonne of iron product, indicating the importance of coke strength to the industry (19). The ASTM hardness factor, a measure of cokes' resistance to abrasion, is considered of secondary importance.

Preliminary carbonization tests with the first lot of coal L_1 indicated that adding 11% pitch D improved coke stability and hardness factors from 36.7% and 56.8% respectively for the coal carbonized alone to 42.1% and 69.4% for the coal-pitch blend. These improvements were encouraging and a thorough investigation was carried out on two additional lots (L_2 and L_3) of the same coal.

Two practical problems arose during this investigation. The first was achieving the same bulk density in the oven of the coal-pitch blends for each oven test. Normally, bulk density can be closely controlled by adjusting the coal moisture and drop height into the oven. Changes in coal bulk density affect the coke stability factor, hardness factor, coking pressure, and apparent specific gravity, and the amount of coke breeze (-13 mm material) as shown in Fig. 5 for L_1, L_2, and L_3 coal. With pitch additions it was impossible to obtain the same coal-pitch bulk density for different oven tests because all test blends tended to hold up in the charging hopper and flowed into the oven at different rates, perhaps depending on the softening of the pitch. However, the empirical relationships between measured bulk density and carbonization results (Fig. 5) did not apply to blends with pitch additives. Correlations between stability factors or hardness factors and coal bulk densities might not have been expected because of the different caking properties of each pitch-blend but a relationship between apparent specific gravity and coal bulk density was expected. This was not found when apparent specific gravity was regressed against bulk density and VM of the charge, the two parameters upon which apparent specific gravity is normally dependent (correlation coefficient of 0.17). This result was interpreted to mean that the blends containing pitch materials soften and slump during heat-up in the coke oven so that actual coal bulk density in the oven is larger than initially measured. It was assumed throughout the analyses of these results that all blends reached similar bulk densities after slumping in the oven and that no corrections for bulk density were needed. This assumption may not be valid for a few of the coal-pitch blends which had unusually large measured bulk densities (generally the higher melting pitch-coal blends).

The second problem encountered during addition of pitch to coal L_2 was that oxidation of the coal during storage decreased coke stability for coal coked alone from the time of the first oven test. Figure 6 illustrates the effect of time and bulk density on the stability factor for L_3 coal as derived from regression analysis of data from Table 3. Changes in the stability factor indicated the influence of oxidation on this coal was important for about 15 weeks from the first oven test. The hardness factor also changed with time but most differences could be attributed primarily to bulk density. The improvements in coke quality through pitch additions have therefore been calculated from the expected ASTM tumbler factors if the coal alone had been carbonized at the same time as the coal-pitch blend at the standard bulk density of 815 kg/m^3.

Table 4 and Fig. 7 show the improvement of coke stability factors by adding different amounts of pitches to coals L_2 and L_3. All additions improved coke stability factors but improvements to L_3, the more oxidized coal, were larger than for L_2. However, improvements to L_3 may not be as significant as the smaller improvements to L_2 because the final stability factors for the latter coal-pitch blends were larger. The maximum stability factor after pitch addition was 50.3%, possibly strong enough for use in a small blast furnace. For coal L_2, the petroleum-based pitches A and D were more effective in improving coke stability than the coal-derived pitches E and F. However, this coal oxidized during the test period and the corrected stability factors for coke from the coal alone showed considerable variation. The effectiveness of the pitch additives is probably more reliable if based on the stability improvements made to L_3 because, during the test period, this coal oxidized more slowly than L_2. At the 5% level of pitch addition the low-softening, petroleum-derived pitch C gave the largest improvement to coke stability but improvements with this pitch decreased at higher levels of addition. All pitches gave similar improvements to the coke stability factors of L_3 at the 8% pitch level, but the coal-based pitch F showed the biggest improvement at an 11% addition level.

The caking properties of the 11%F_2-L_3 coal blend had a total dilatation of 35%, a value lower than the optimum range suggested by the NCB (7), but a Gieseler fluidity of 760 ddpm, within the optimum fluidity range suggested by Japanese workers (9). The actual stability factor for this blend was 47.5%, a value closer to that predicted by dilatation than plasticity (Fig. 1). Increasing total dilatation to 47% by using a 15%F_2-L_3 blend unexpectedly made coke stabilities poorer. Similar inconsistencies between rheology and carbonization results were found for blends containing other pitches. Optimum coke strength for the C-L_3 coal blends was at the 5% level of pitch addition - a blend which had both dilatation and fluidity properties further from the predicted optimum than the 8 and 11% blends. Apparently, existing theories for blending and the prediction of coke strength from rheological properties do not apply well to blends containing pitch materials.

Improvements to coke hardness factors from pitch additions to coals L_2 and L_3 are shown in Fig. 8 and Table 4. All pitches improved hardness factors from about 57% to 65-70%, comparable to the values found for some of the best metallurgical cokes. Better improvements were found for the more oxidized coal

L_3 than for L_2 blends. The effectiveness of the petroleum derived pitches increased with decreased softening temperatures and the largest improvements were found for pitch C. Hardness factors generally improved with increased pitch contents in the blends.

Many investigators suggest the "After Reaction Strength" and/or "Hot Tumbler Strength" tests of coke are more meaningful than cold tumbler tests because the former tests simulate reaction and degradation conditions in the blast furnace. ARS results from tests on selected cokes made from charges with pitch additions are included in Table 5. The reaction per cent (RP) and the ARS of cokes from blends of coal-derived pitch E were much superior to the cokes from blends containing petroleum pitches. However, with one exception, the ARS and RP of all cokes tested from pitch additions were better than for a carefully sampled coke from one Canadian steel maker.

PETROLEUM COKE ADDITONS TO HIGH VOLATILE EASTERN CANADIAN COAL

Addition of inert materials to eastern Canadian coking coal should decrease the excessive caking properties of this coal, and enhance coke quality parameters. Figure 9 shows that 10-25% petroleum coke additions would give blends with total dilatations consistent with the optimum blending criteria suggested by the NCB (7). Addition of 20% petroleum coke to the eastern Canadian coal coked in the 325 kg oven improved coke stability to 46.0% compared with 38.0% for the coal alone (Table 6). The coke hardness factor decreased to 52.1% from 55.6% for the coke from coal alone. Increasing the bulk density of the charge by partially briquetting the 20% petroleum coke/coal blend, a technology extensively used in the Japanese coke industry (20,21,22), improved both hardness and stability factors to 56.2 and 48.5% respectively. This technology enabled even larger amounts of petroleum coke to be added to the briquetted portion of the charge. The best ASTM tumbler results occurred for a 50% partially briquetted charge in which the briquets contained 59% coal, 35% petroleum coke, and 6% pitch A; the matrix blend contained 20% petroleum coke. The stability and hardness factors of 51.2 and 60.0% respectively would probably meet the requirements for small blast furnaces. Table 6 shows ARS and RP of coke from eastern Canadian coal improved by adding 20% petroleum coke but further improvements were not found for blends containing more petroleum coke.

This investigation has revealed that inert materials can be added to eastern Canadian hv coal and improve coke quality. Large additions may be of academic interest to many cokemakers, in view of the large sulfur content of the petroleum coke. Other benefits from petroleum coke addition are the improvements in coke yield, because of the low VM content of petroleum coke, and in coke oven productivity (shorter coking times) presumably caused by the better thermal conductivity of the petroleum coke.

CONCLUSIONS

Pitch and petroleum coke additives to coke oven charges improved coke quality when added to coals with suitable rheological properties.

ASTM coke tumbler factors were improved more by adding pitches to the more oxidized lots of the western Canadian coal, L_1 and L_3, than for L_2 although the best coke stability factor achieved during testing, 50.3%, resulted from a blend using L_2 coal. Coke of this stability may be adequate for use in smaller blast furnaces under agreeable economic circumstances. At low concentrations, petroleum pitches improved stability factors more than coal pitches but at higher levels of addition the coal pitches may be more effective. Hardness factors improved most for blends with pitch C, the petroleum derivative with lowest softening temperature. All cokes from pitch addition tests had greatly enhanced ARS properties but best results were from blends containing coal pitches.

Although current theories for blending coals and predicting coke quality from rank and rheological properties did not apply well to the coal-pitch blends, they appeared to be consistent for cokes made from additions of petroleum coke to highly fluid hv coal. Stability, hardness, and ARS parameters of cokes from charges with petroleum coke additives improved relative to those obtained from the coal alone. A maximum coke stability of 51.3% was achieved in a 50% partially briquetted blend containing an overall petroleum coke content of 27.5%. Improved coke yields and better oven productivity were other benefits achieved by adding petroleum coke to the hv eastern Canadian coal.

Although these studies were limited in scope with one petroleum coke added to a highly fluid coal and six pitches added to one low fluid coal, results have been sufficiently encouraging to warrant further investigation with other additives and ranks of coal.

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TABLE 1 Summary of Coal Properties

Properties	Western Canadian MV Coal Lot 1	Western Canadian MV Coal Lot 2	Western Canadian MV Coal Lot 3	Eastern Canadian HV Coal
Proximate Analysis (%)				
VM (db)	24.8	23.8	24.4	35.4
Ash	10.8	10.3	10.9	4.1
Fixed carbon	64.4	65.9	64.7	62.0
Ultimate Analyses (%)				
C	77.7	79.7	78.6	82.3
H	4.4	4.5	4.7	5.4
S	0.35	0.36	0.40	1.25
N	1.2	1.2	1.2	1.7
Rheology and Petrography				
FSI	4	5	4	8.5
Maximum fluidity (ddpm)	6.0	8.1	2.0	27,800.
Total dilatation (%)	0	23.	0	226.
Mean max. reflectance (%)	1.10	1.11	1.10	0.99
Sieve Analyses (coal charged)				
+ 6.35 mm	0.7	0.3	0.4	0.9
+ 3.2 mm	12.5	9.5	11.0	20.9
+ 1.6 mm	33.5	28.7	28.7	44.4
+ 0.8 mm	54.0	50.9	47.9	64.2

TABLE 2. Summary of Pitch Properties

Properties	Pitch Materials									
	A	B	C	D_1	D_2	D_3	E	F_1	F_2	Petroleum Coke
Conradson Carbon (%)	21.0	22.1	22.9	65.1	50.7	62.6	63.1	49.0	-	
Ash (%)	0.04	0.04	0.03	5.7	3.2	5.3	0.28	0.35	0.16	3.9
VM (%)										12.8
Ultimate Analyses (%)										
C	85.1	85.5	87.3	-	81.2	80.4	80.8	85.8	86.3	83.3
H	10.2	10.0	10.2		7.4	6.5	4.1	5.8	5.7	3.8
S	3.8	3.9	0.96	4.8	6.3	5.7	0.5	0.6	-	5.83
N	0.41	0.40	0.68	1.77	1.36	1.6	0.74	2.1	2.4	1.51
Benzene Insolubles	0.18	0.15	0.08	20.6	11.7	18.1	51.3	52.7	53.4	-
Pentane (heptane) Insol.	34.4	35.6	8.2	(75.8)	59.7	(72.9)	94.4	(99.0)	97.9	
Asphaltene content	34.2	35.4	8.1	55.2	48.0	54.8	43.1	46.3	44.5	
Softening point °C	77	93	58	-	-	-	106	170	-	-
Specific Gravity	1.01	1.01	1.01	1.25	1.17	1.21	1.35	1.23	1.28	

TABLE 3. Carbonization Test Results for Western Canadian Coal Coked Alone

	Type of Coal										
Rheology	L_1	L_1	L_2	L_2	L_3	L_3	L_3	L_3	L_3	L_3	L_3
Max fluidity		6.	8.1	8.1	2.						
T. Dilatation		0	22.	22.	0						
Test Conditions											
Time of test (wks)	-	-	-	-	0	1	12	15	36	38	39
Oven bulk density (kg/m^3)	810	816	848	818	832	834	848	846	819	757	891
Max. oven pressure (kPa)	1.6	1.6	4.1	2.8	-	2.5	3.9	4.3	4.1	1.4	7.6
Coking time (h:min)	9:45	9:45	9:40	9:45	9:45	9:30	9:30	8:25	9:20	9:35	9:35
Coke Parameters											
Coke yield (%)	75.2	74.8	76.9	75.7	72.3	74.7	76.4	74.6	76.0	72.3	74.9
Mean coke size (mm)	52.6	52.3	48.8	49.5	49.8	50.0	48.8	50.8	48.0	48.8	48.3
% breeze (% -13 mm coke)	7.2	7.6	4.1	5.3	8.8	8.5	10.2	9.9	13.6	15.5	7.5
ASG	0.988	.989	.999	-	.991	.986	.994	.984	1.00	.930	1.04
Stability factor (%)	36.6	36.8	46.8	46.3	39.8	39.0	35.5	34.7	32.4	30.5	39.5
Hardness factor (%)	57.7	55.9	68.4	63.3	57.5	60.8	57.8	57	53.8	46.4	61.3

TABLE 4. Carbonization test Results for Western Canadian Coal with Pitch Additions.

	Type of Coal-Pitch Blend											
	Blends from petroleum pitches					Blends from coal pitches						
Blend Properties	11%-D_1-L_1	11%-D_2-L_2	11%-A-L_2	2%-D_2-L_2	2%-A-L_2	11%-E-L_2	11%-F-L_2	8%-E-L_3	5%-E-L_3	15%-F_2-L_3	11%-F_2-L_3	8%-F_2-L_3
%VM (daf)	25.9	27.5	30.7	25.3	25.8	26.1	27.7	25.7	25.4	28.8	27.7	26.5
Max. fluidity (ddpm)		625	208	-	-	70	48	10.8	43.5	3018	760.	73
T. dilatation (%)		24	11			3950	1015	3.	4.	47	34	18
Test Conditions												
Time of test (wks)	-	0.8	2	3	3	0	0	2.7	2	44	39	44
Oven bulk density (kg/m^3)	818	824	738	858	848	819	811	904	846	830	816	832
Max. oven pressure (kPa)	3.0	6.4	2.27	2.0	2.7	1.7	1.2	3.4	2.6	5.5	3.4	6.2
Coking time (h:min)	10:40	9:40	8:30	9:45	9:40	9:40	9:45	9:46	-	8:55	8:40	8:45
Coke Parameters												
Coke yield (%)	74.7	75.8	71.5	74.1	77.6	76.2	75.3	77.0	-	72.6	75.6	76.1
Mean coke size (mm)	-	47.8	45.8	44.4	47.5	48.5	51.6	48.5	48.3	49.0	46.2	49.3
% breeze (% -13 mm)	3.1	3.2	5.9	6.6	6.2	3.3	3.3	4.3	4.6	3.1	3.6	3.3
ASG	1.00	0.980	.941	.979	.987	-	0.970	-	1.00	1.00	0.980	0.980
Stability factor	42.1	50.3	50.2	43.7	47.6	48.3	48.2	46.6	42.9	43.9	47.4	41.1
Hardness factor	69.4	69.1	72.2	64.6	66.1	70.4	69.0	71.7	69.2	67.1	68.3	67.8
Corrected stability for coal alone	37.2	43.2	40.9	39.0	39.0	45.3	45.3	36.4	36.3	32.1	32.1	32.1
Corrected hardness for coal alone	55.9	61.6	60.0	58.6	58.6	63.3	63.3	55.7	56.0	53.9	53.9	53.9
Improvements by Pitch												
Stability factor	4.9	7.1	9.3	4.7	8.6	3.0	2.9	10.2	6.6	11.8	15.3	9.0
Hardness factor	13.5	7.5	12.2	6.0	7.5	7.1	5.7	16.0	13.2	13.2	14.4	13.9

TABLE 4. Carbonization test Results for Western Canadian Coal with Pitch Additions (cont.)

Type of Coal-Pitch Blend

Petroleum pitches with L_3 coal

Blend Properties	11%A-L_3	8%A-L_3	5%A-L_3	8%B-L_3	5%B-L_3	11%C-L_3	8%C-L_3@	5%C-L_3@	11%D_3-L_3@
%VM (daf)	30.7	29.1	27.5	29.0	27.5	30.6	28.9	27.4	26.2
Max. fluidity (ddpm)	16.3	9.8	4.4	19.5	6.3	726	313	46.2	1793.
T. dilatation (%)	11.	7.	4.	16.	0.	12.	13.	10.	32.
Test Conditions									
Time of test (wks)	15.	13.5	11	9	8	42	41	41	39
Oven bulk density (kg/m^3)	741.	738.	816.	768.	838	826	883	840	-
Max. oven pressure (kPa)	2.1	2.3	2.3	2.1	3.3	4.1	-	-	-
Coking time (h:min)	9:15	9:00	9:00	9:30	9:30	8:55	8:55	8:35	9:00
Coke Parameters									
Coke yield (%)	70.6	73.0	72.8	72.2	73.3	76.0	74.4	74.9	74.0
Mean coke size (mm)	46.7	46.0	53.1	47.2	49.8	57.4	47.2	47.5	47.5
% breeze (% -13mm)	6.1	7.1	7.4	6.6	7.7	4.2	4.7	4.7	4.0
ASG	0.991	0.958	0.951	0.990	1.00	1.00	1.00	0.960	1.00
Stability factor	44.2	43.5	42.6	43	36.4	42.6	43.6	44.9	43.7
Hardness factor	70.8	67.3	63.4	67.3	62.4	72.3	70.4	70.8	68.6
Corrected stability for coal alone	32.3	32.4	32.6	32.9	33.2	32.1	32.1	32.1	32.1
Corrected hardness for coal alone	54.0	54.0	54.1	54.3	54.4	53.9	53.9	53.9	53.9
Improvements by Pitch									
Stability factor	11.9	11.1	10.0	10.1	3.2	10.5	11.5	12.8	11.6
Hardness factor	16.8	13.3	9.3	13.0	8.0	18.4	16.5	16.9	14.7

@ tests carried out in side charge box

TABLE 5. Results from ARS Testing of Coke from Coal-Pitch Blends

Source of Coke	Reaction %	ARS	Stability	Hardness
Commercial coke	34.9	50.9	55.6	66.8
100 % L_2	33.5	44.9		
11%A - L_2	27.6	60.7		
11%D - L_2	21.9	70.7		
100% L_3	34.5	37.3		
11% A - L_3	26.5	58.6		
5%A - L_3	31.1	43.7		
5%E - L_3	24.8	62.2		

TABLE 6. Carbonization Test Results of hv Eastern Canadian Coal Containing Petroleum Coke Additives

	Type of Blends				
	non-briquetted		Partially briquetted charges		
Test Conditions	EC	80%EC-20%PC	m(80%EC-20%PC) B(80%EC-20%PC)	m(80%EC-20%PC) B(47%EC-47%PC-6%BR)	m(80%EC-20%PC) B(35%PC-59%EC-6%BR)
Oven bulk density (kg/m^3)	738	723	782	792	798
Max. oven pressure (kPa)	2.06	2.1	2.5	2.1	2.5
Coking time (h:min)	18:00	15:45	17:00	15:40	17:30
Coke Parameters					
Coke yield (%)	64.5	71.5	71.0	75.6	69.7
Mean coke size (mm)	57.9	58.9	54.4	53.6	54.1
% breeze (% -13 mm coke)	3.6	4.3	3.5	3.9	3.3
ASG	0.760	0.826	-	-	0.875
Stability factor (%)	38.0	46.0	48.5	49.6	51.2
Hardness factor (%)	55.1	52.1	56.2	59.7	60.0
ARS	27.6	-	39.0	37.4	34.7
Reaction percent	50.0	-	33.5	44.8	43.1

* EC represents eastern Canadian coal
PC represents petroleum coke
m represents matrix coal content
B represents briquet content
ASG represents apparent specific gravity
ARS represents after reaction strength
BR represents binder

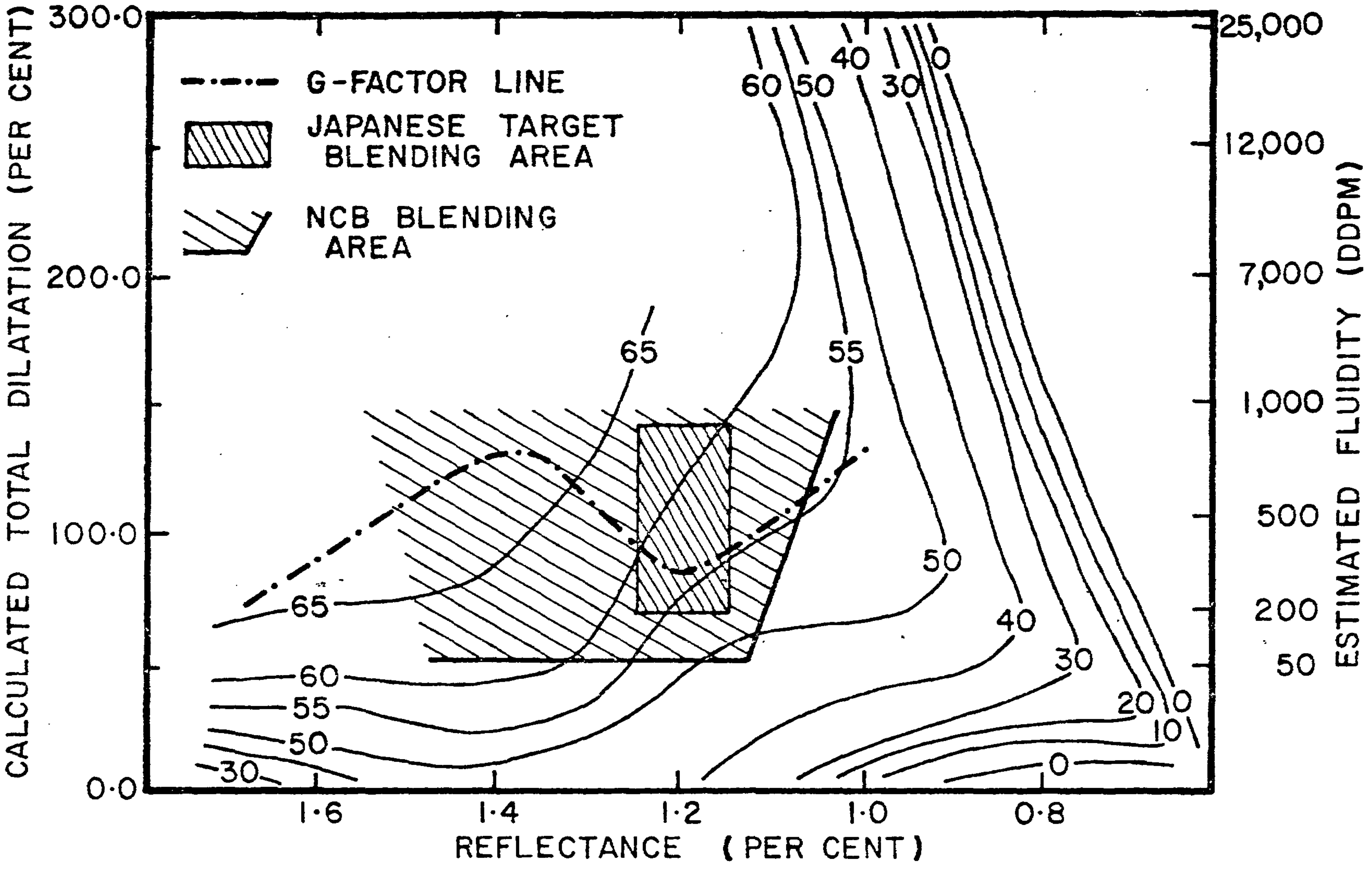

Fig. 1 Comparison of different blending methods showing estimated coke stability factors as a function of coal rank and caking properties.

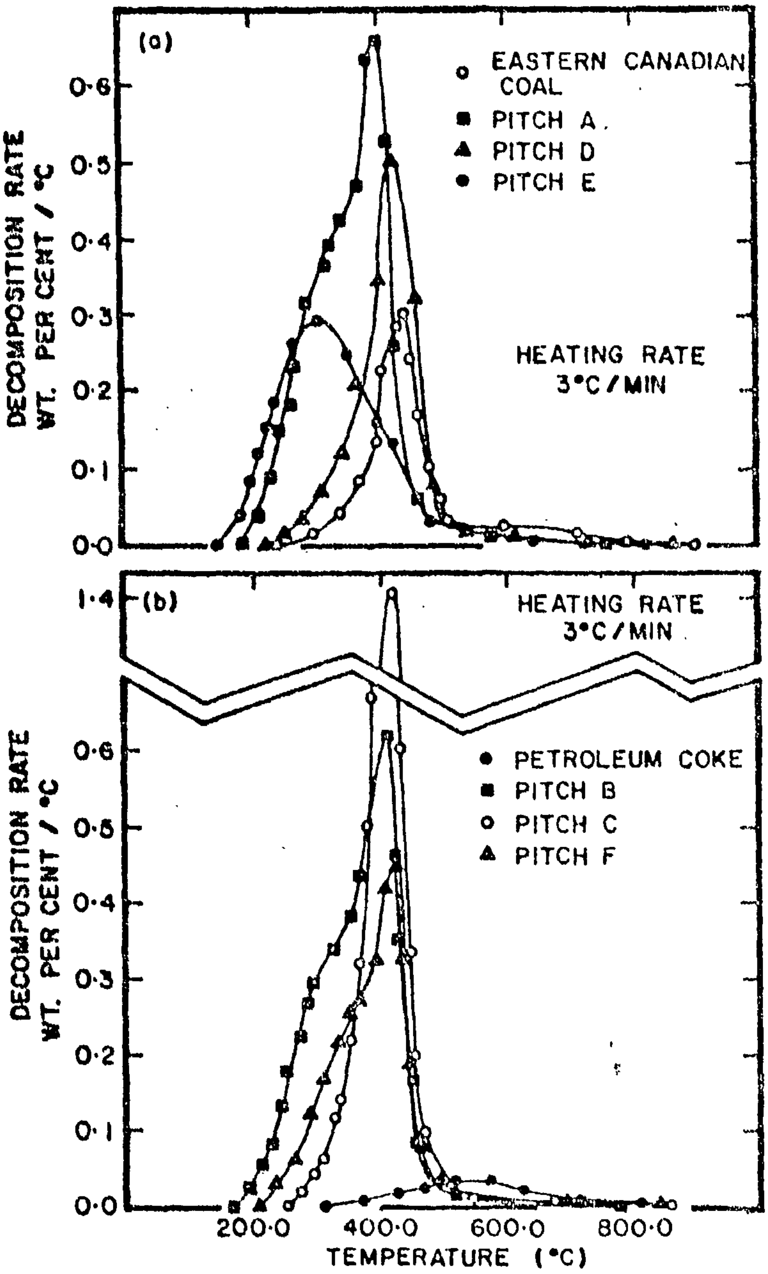

Fig. 2 Rates of decomposition of hv coal, petroleum coke and six pitches.

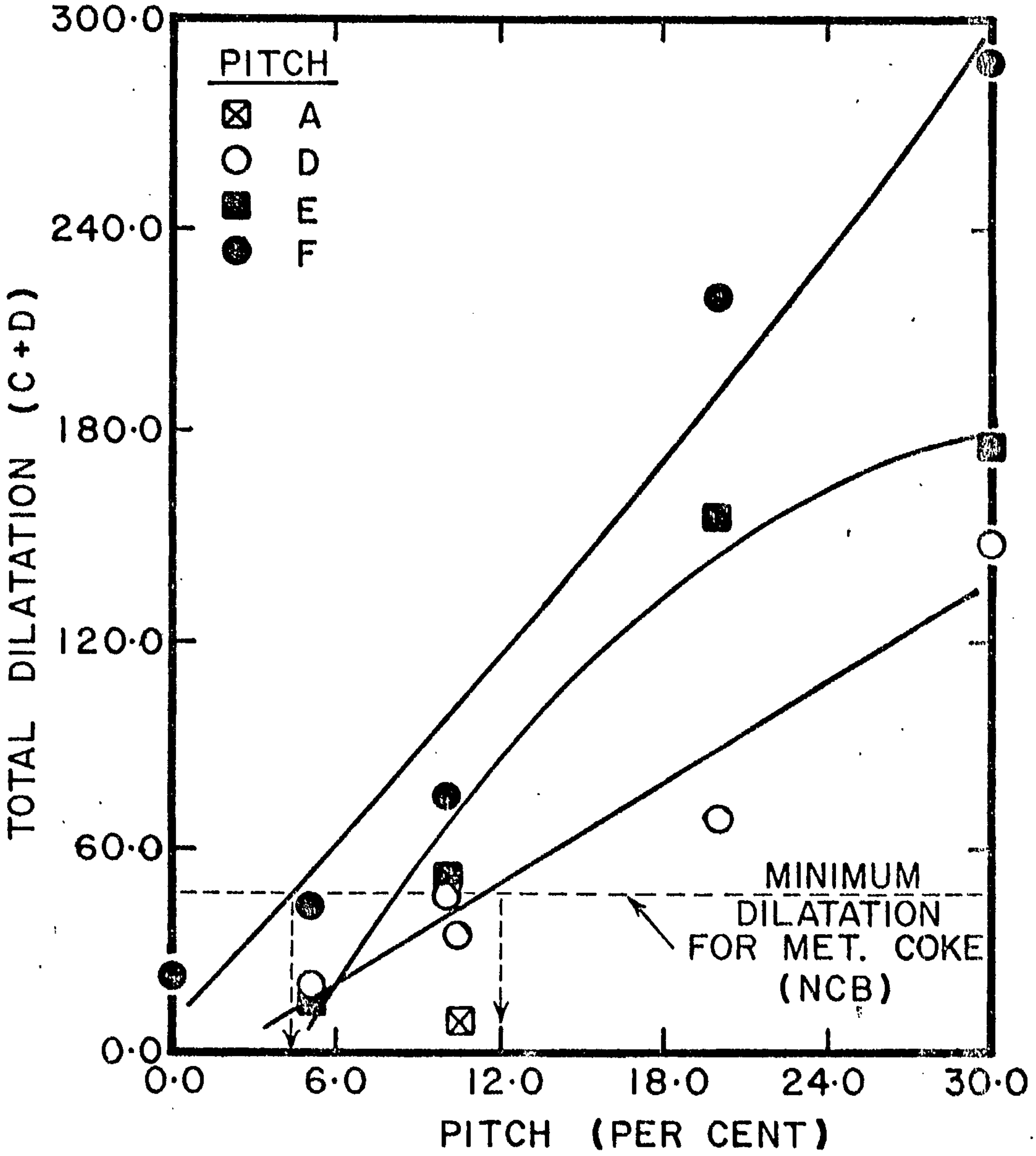

Fig. 3 Effect of type and amount of pitch on total dilatation of western Canadian coal.

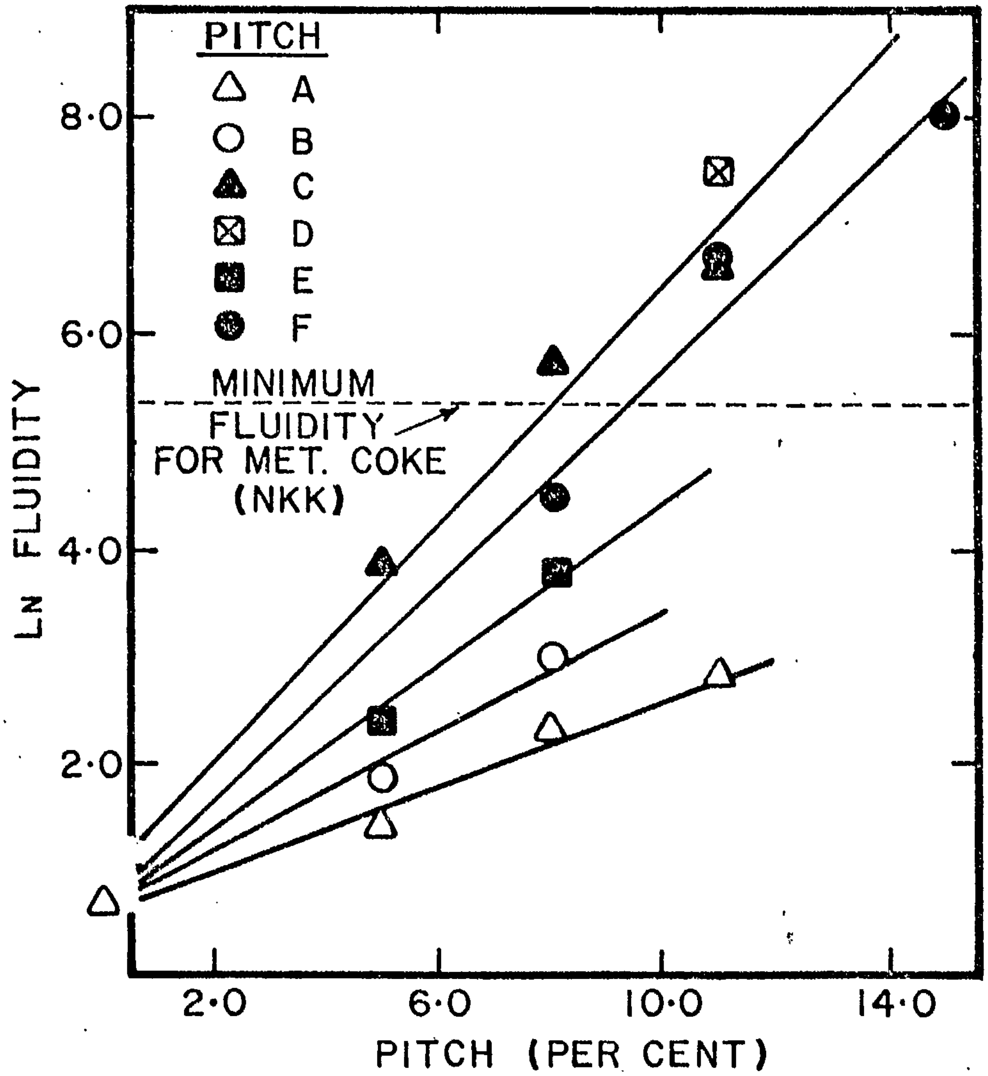

Fig. 4 Effect of type and amount of pitch in coke oven charges on Gieseler fluidity properties of western Canadian coal.

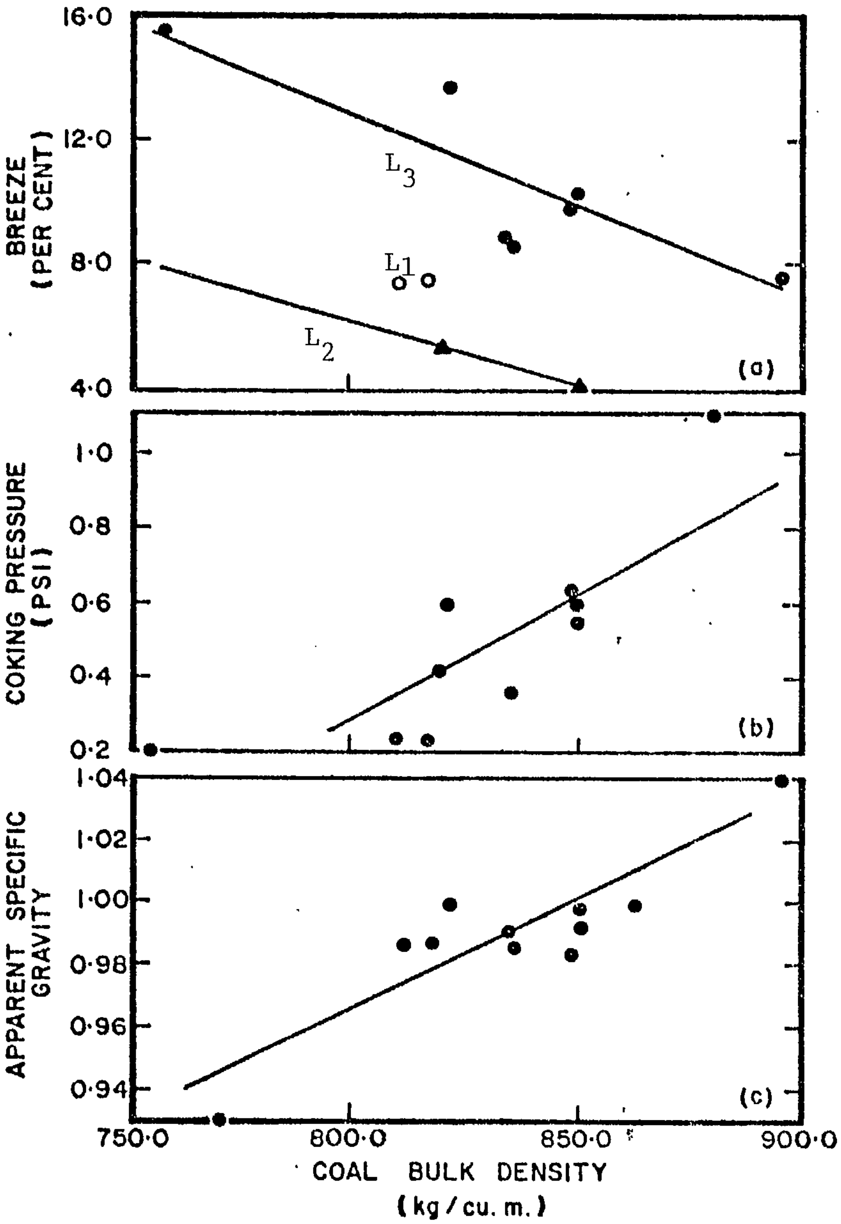

Fig. 5 Linear relationships between coke properties and bulk density for the western Canadian coal.

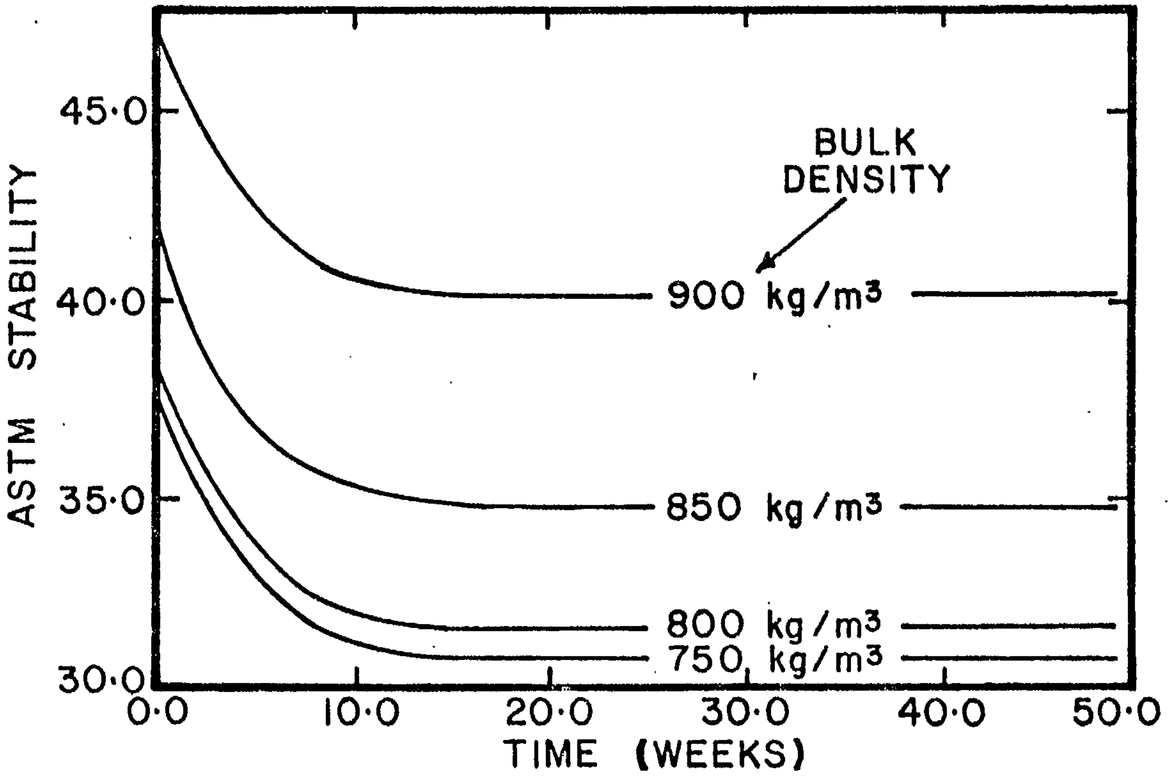

Fig. 6 Effects of time and bulk density on the coke stability factor.

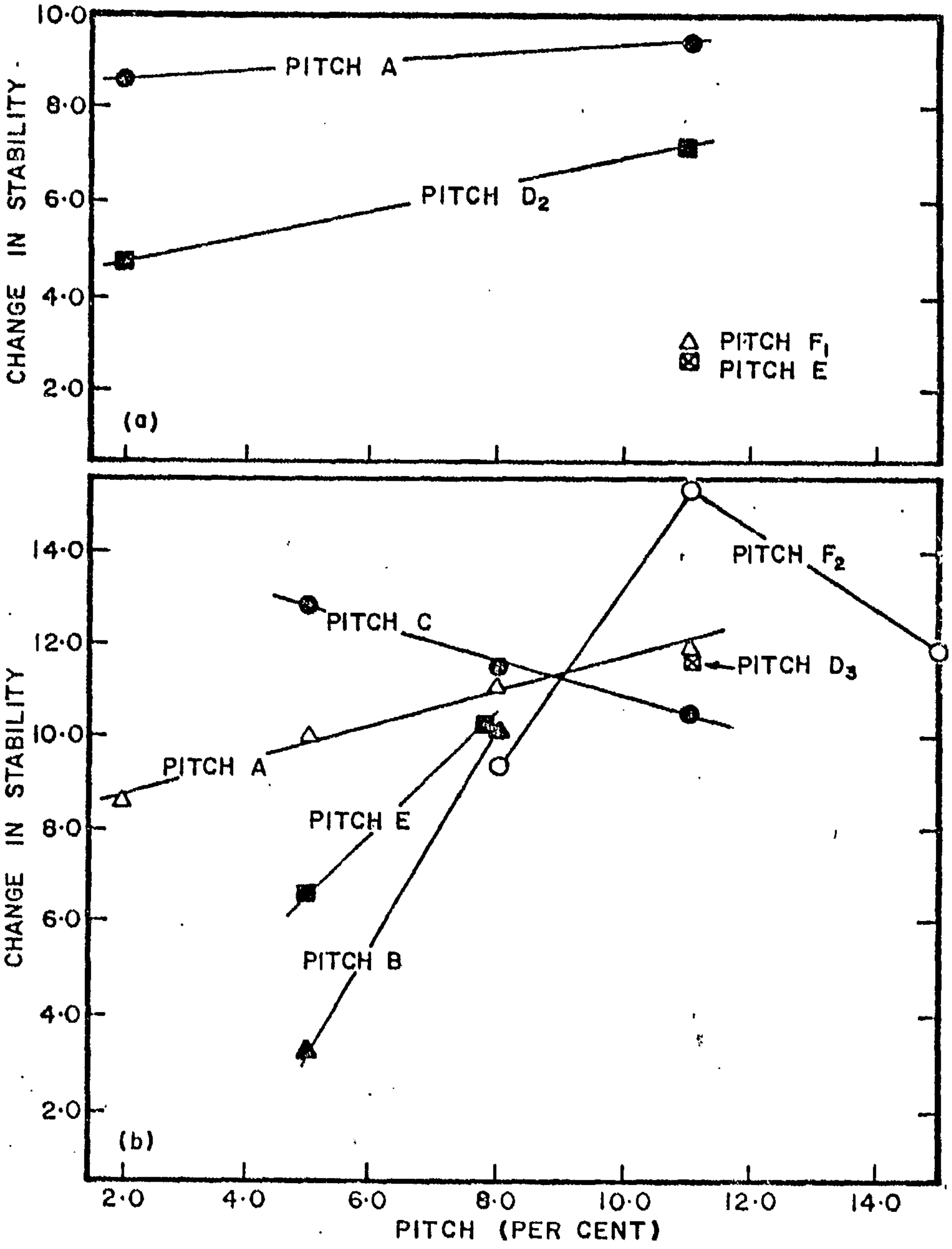

Fig. 7 Improvements in coke stability factors for (a) L_2 and L_3 coal using different types and amounts of pitch.

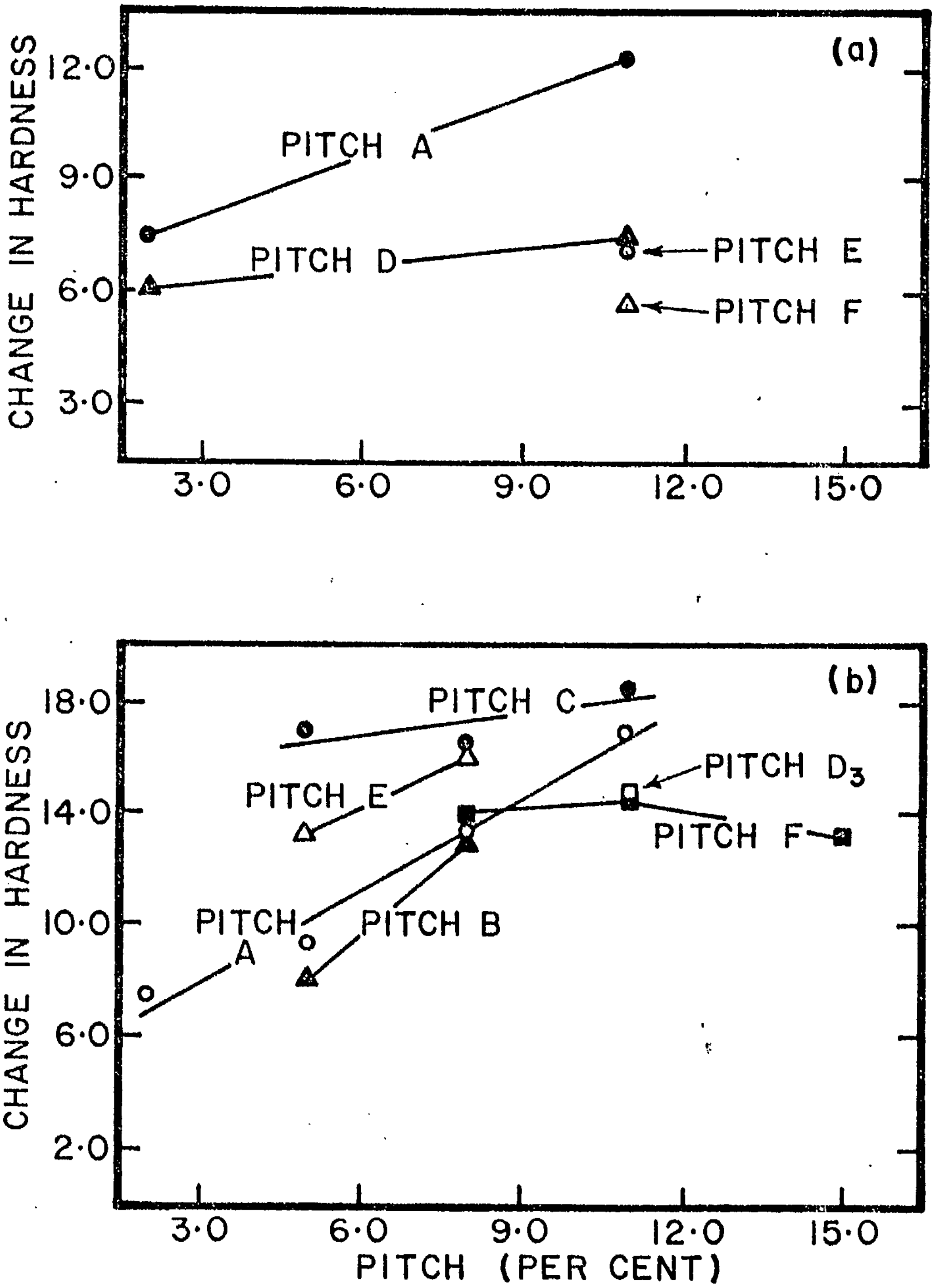

Fig. 8 Improvements in coke hardness factors for (a) L_2 and (b) L_3 coal using different types and amounts of pitch.

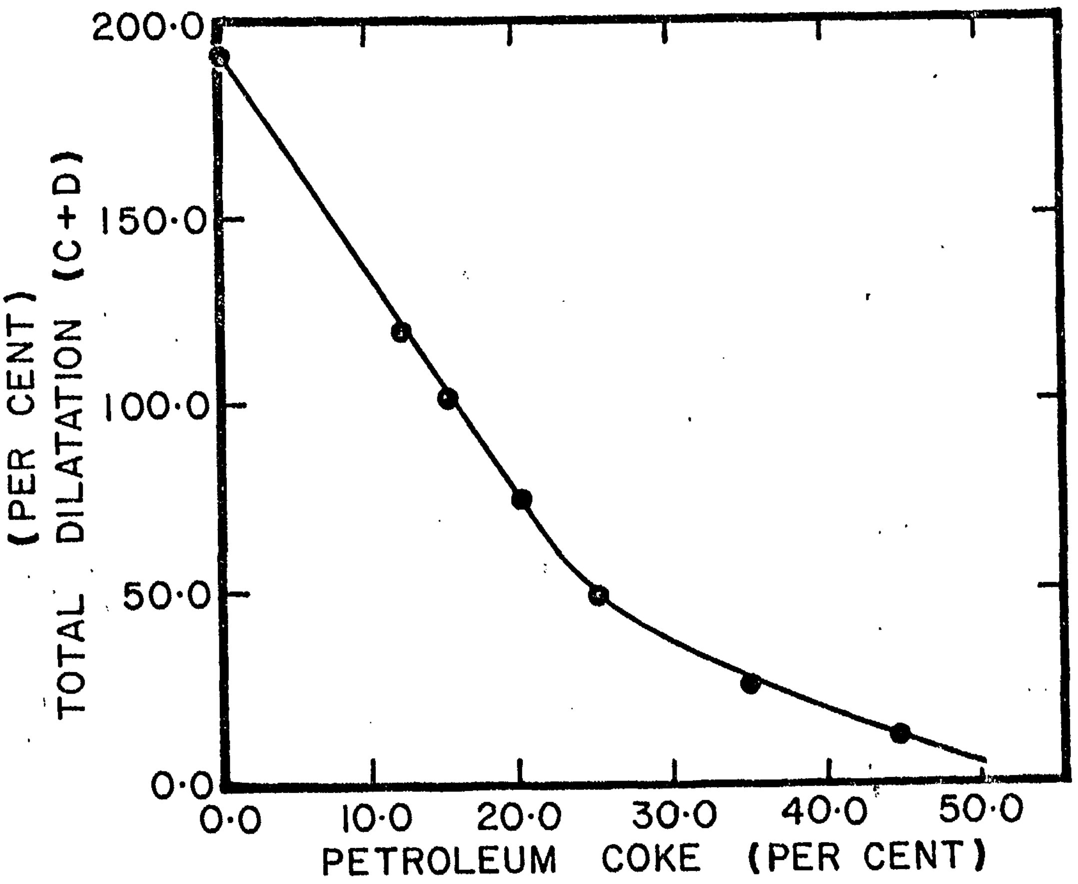

Fig. 9 Effect of the amount of petroleum coke upon the total dilatation properties of hv eastern Canadian coal.