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Formcoke From Thailand Lignite

Nara Pitakarnnop

FORMCOKE FROM THAILAND LIGNITE

by
Nara Pitakarnnop

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This thesis submitted by Nara Pitakarnnop in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

Donald E Severson
(Chairman)

Wayne R Kube

Edwin C. Noble

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ABSTRACT

Formcoke was made in the laboratory from Thailand and North Dakota lignites with the objective of producing briquets of adequate compressive strength for commercial blast furnace use. Optimum conditions for laboratory scale manufacture were determined.

Two lignite samples from the Li Mine, Lamphun Province, Thailand, and one from the North American Coal Company, Zap, North Dakota, were carbonized each at two different carbonization temperatures of 600°C and 900°C. Cylindrical briquets, 1 inch diameter by 2 inches high, were made from blends of the chars and asphalt or lignite tar binder. Compressive strength of formcoke was determined as a function of sample variety, carbonization temperature, char grain size, binder type, briquetting pressure, coking temperature, and heating rate during coking.

Acceptable formcoke exceeding 800 psi in compressive strength was made from both Thailand and North Dakota lignite chars.

The strongest formcoke briquets were produced from -35 mesh 900°C Thailand lignite char, with 15 per cent asphalt binder, briquetting pressure of 6,000 psi and heating rate of 10°C/min to a coking temperature of 900°C. The optimum conditions were 900°C char, -35 mesh particle size, 15 per cent asphalt binder, briquetting pressure of 3,000 psi, and heating rate of 10°C/min to a coking temperature of 900°C. Adequate formcoke from North Dakota lignite was

produced under the same optimum conditions as above except that the $600^{o}C$ char was used.

CHAPTER I

INTRODUCTION

Thailand has experienced an increasing demand for industrial solid fuel, especially coke for blast furnace operation. No deposits of coking coals have been found in the country but there are reserves of good quality lignite estimated at over 200 million tons. Very little research has been done concerning the use of Thialand lignite in the metallurgical industry. In the United States, Eastern European countries, Russia, Japan, and Australia, an abundance of low rank, non-caking coals has promoted the development of methods utilizing these non-caking coals for blast furnace use.

Coke for use in the blast furnace must be an active reductant with a suitable iron ore reducing rate and have the physical strength to support limestone-ore burden and to resist abrasive and impact action (1). Coke produced from coking coal is herein referred to as conventional coke. Non-caking coal may be carbonized and briquetted with caking coal or a binder such as coal-tar pitch and then coked to produce a product known as formcoke (2).

Present-day manufacture of formcoke involves processes using 3 different types of raw materials: (1) blends of caking and non-coking coals, with or without binder, used in Japan; (2) blends of carbonized coal (char) and caking coals, with or without binder, developed some ten years ago by the Dutch State Mines and used later in Germany; (3) a single coal, which can be completely non-caking, and a binder, developed in the United States by FMC Coke Corporation (3).

It is important to know whether blending coal can be replaced by carbonized lignite (char) made from Thailand lignite. The purpose of the present research was to investigate the feasibility of converting Thailand lignite into formcoke and to test the physical and chemical properties of this coke. Two separate samples of Thailand lignite were used, and it was necessary to establish whether these could be considered as a single sample. Briquets were made in the laboratory in which the following process conditions were varied: carbonization temperature, char grain size, binder percentage, binder type, briquetting pressure, coking temperature, and heating rate during coking. Compressive strength of the formcoke briquets was determined and optimum conditions for formcoke manufacture selected on the basis of these results.

CHAPTER II

LITERATURE SURVEY

From 1939 to 1959 the developments in coal preparation and coal blending and increased knowledge of the coking behavior of coals and coal mixtures have encouraged the construction of large ovens to meet the demand for metallurgical coke (4). Conventional coke is normally made in chambers lined with refractory brick, which are heated externally. A satisfactory technical level, as exemplified in the 20 cubic meter slot oven, was reached shortly before the second World War, and this technology remained essentially unchanged until about 1960. At that time there occurred a development of which the most striking feature was the use of much larger chambers--sometimes exceeding 40 cubic meters--grouped in large batteries designed to give efficient utilization of the set of machines. These improvements in scale did not change the general method of coke manufacture (2).

Conventional industrial coking consists of heating coal in the absence of air in a closed space by external application of heat. External heating requires a flattened and narrow chamber to reduce the time of carbonization (2).

Another process for making suitable metallurgical coke has received considerable attention. The process uses technical methods different from conventional coke. First the coal is carbonized to form a char. The carbonized coal (char) is blended with a binder, or a binder and a caking coal, or with a caking coal. A briquetting or pelletizing process follows, in which the briquets are formed by heating and pressing at a high pressure. The briquets or pellets are further devolatilized by an additional carbonization, yielding a high carbon, low volatile product of suitable strength for blast furnace use, known commercially as formcoke (3).

Presently there are several processes commercially available for the production of formcoke.

The FMC process employs either coking or non-coking coals and produces a consistently uniform coke. The development of this process began in 1956. A 50,000 ton per year plant was built in 1960 at Kemmerer, Wyoming, using low cost subbituminous coal to produce a superior grade of coke. The plant has recently been expanded to 85,000 tons annual capacity (5).

After grinding the coal to the proper particle size, the coal is put through a series of controlled fluid bed vessels in which a tar and a char are generated. The tar is processed to a pitch-like binder which is then recombined with the calcinate and briquetted to the desired size and shape. The briquets are then cured and coked by reheating (5).

FMC produces pillow shape briquets with several sizes, the most common size being 1 1/4" X 1" X 3/4". FMC reported an average crushing strength of 450 pounds. Although these values are not directly comparable to measurements of conventional coke, it is claimed that these briquets exceed the strength of blast furnace coke (6).

This formcoke has been used both in experimental and in industrial blast furnaces, and may be considered commercial. Positive pollution control using conventionally proved equipment has been demonstrated, and the dusting problem has been successfully solved (6).

The BFL hot briquetting process, which was developed jointly by Bergbau-Forschung and Lurgi in Germany, features the briquetting of two components. Hot char and predried caking coal are mixed and then briquetted in a double roll press while the caking coal is in a plastic condition. Briquets between 25 and 300 gm in weight are produced and several blast furnace tests have been successfully performed (7).

A BFL hot briquetting plant with a capacity of 300 metric tons per day of briquets is under construction at Ruhrkohle A.G. in Germany for the purpose of large-scale testing. The British Steel Corporation has decided to install a BFL plant with a capacity of 650 metric tons per day (7).

In Japan, a formcoke process for blast furnace use consists of 3 parts: first non-coking coal and caking coal are preheated separately in a fluidized high-temperature preheater and a low-temperature preheater, respectively. The coals are then blended and hot briquets are formed in a double-roll press. The briquets are further heated to higher temperature and carbonized. It was found that formcoke made by this process has strength satisfactory for blast furnance use (8).

The Nord-FUVO process, was recently developed in France by the Houillères du Bassin du Nord et du Pas-de-Calais and the FUVO company. Conventional briquetting with pitch as binder is applied to a mixture of a non-caking coal having a low volatile content, with 10 to 15 per cent of a caking coal. Non-caking low-volatile coals can be replaced by caking high-volatile coals in the briquetting blend, but it is advantageous to char the latter before blending. Carbonization is carried out in a shaft oven through which hot gases are blown (2).

The Ancit process was developed by the Dutch State Mines and was used by Eschweiler Bergwerks-Verein to produce a blast furnace fuel in a demonstration plant of 10 to 12 tons per hour capacity. The process uses either high volatile coals or caking low volatile coals. The feed coals are preheated in a pneumatic transport stream reactor, then cooled. This pretreated coal is reheated to about 600^{o}C and is crushed hot, then blended with a preheated caking coal (used as a binder) to a mixture temperature between 460^{o}C to 520^{o}C. The mixture is then briquetted and the briquets charged to a well-insulated vessel where they are held in an inert atmosphere for several hours. This holding time results in substantial increase in spot crushing and abrasion strength of the briquets. All blast furnace tests made to date with the Ancit formcoke have been successful (9).

In the Auscoke (Australian Coke) process, developed by the Broken Hill Proprietary Co. Ltd., precarbonizing of coal at low or medium temperatures is the primary step. The char is crushed, and the fine particles briquetted using a coal-tar pitch binder. The briquets are indurated at temperatures sufficient to impart the strength required for metallurgical use. It was decided in 1969 to build a 100 ton per day coke plant. If this plant functions satisfactorily, a 1000 ton per day plant will be built (2).

The coal Research Laboratory, Department of Geology, University of North Dakota produced formcoke in the laboratory from a North Dakota lignite and a Wyoming subbituminous coal. The formcoke was made by blending of char or devolatilized coal with asphalt and then briquetting. The briquets were further carbonized and the compressive strength of the resulting formcoke was determined. It was reported that a North Dakota lignite could be used successfully for formcoke production (3).

Thailand has no coking coal usable for producing metallurgical slot oven coke. In this investigation, formcoke was produced from Thailand lignite by the method previously used at the University of North Dakota Coal Research Laboratory.

CHAPTER III

MATERIALS AND METHODS

This chapter describes the properties of the raw materials used, the experimental procedure for producing formcoke, and the test procedures used for formcoke evaluation.

Formcoke was produced from Thailand lignite and North Dakota lignite.

Materials

Two Thailand lignite samples of approximately 60 and 90 pounds were collected from the Li Mine, Lamphun Province, Thailand, by the Applied Scientific Research Corporation of Thailand. The first was stored for 2 to 3 months, while the second sample was used shortly after it was received. About 80 pounds of North Dakota lignite from the North American Coal Company, Zap, North Dakota, was supplied by the U.S. Bureau of Mines, Grand Forks, North Dakota. The proximate analyses of Thailand lignite(A), lignite(B) and North Dakota lignite(C) are given in Table 1.

Asphalt, lignite tar and solvent refined lignite were used as binders. Roofing asphalt was purchased from B & C Heating & Roofing Company, Grand Forks, North Dakota. Lignite tar was the total tar collected during carbonization of Dickinson, North Dakota, lignite, obtained from the Husky Briquetting Company plant at Dickinson, North

TABLE 1

PROXIMATE ANALYSES OF LIGNITES USED

	Lignite(A) (Thailand)	Lignite(B) (Thailand)	Lignite(C) (North Dakota)
Moisture --- % as received	23.0[a]	14.8[a]	22.2[a]
Ash --- % as received	5.7	7.6	7.7
Volatile Matter --- % m.a.f.[b]	49.5	50.5	46.9
Fixed Carbon --- % m.a.f.[b]	50.5	49.5	53.1
Heating Value --- Btu/lb. m.a.f.[b]	12,168	12,145	11,900

[a]Samples had lost some moisture in storage
[b]Moisture and ash free basis

Dakota. The solvent refined lignite was produced from lignite by the Pittsburg and Midway Coal Mining Company, Kansas City, by solvent hydrogenation.

Laboratory Methods

The formcoke was produced in five steps: (1) coal preparation, (2) coal carbonization or charring, (3) blending of char and binder, (4) briquetting using hydraulic press, and (5) coking briquets at high temperature to increase the fixed carbon content. Figure 1 is a block diagram of the process used.

Coal Preparation

The lignite was crushed to approximately 90 per cent passing 1/8 inch screen with about 95 per cent being retained on a No. 325 mesh screen (U.S. Standard Sieve). The crushed material was sampled for analysis and the remainder air dried overnight. The air dried lignite was subdivided using a sample splitter, placed in stainless retorts 8 inches inside diameter and 38 inches long (10), and placed into the preheated experimental coke oven at the Bureau of Mines laboratory for carbonization.

Lignite Carbonization

Carbonization increased fixed carbon content of the char by removal of volatile matter.

The experimental slot oven was preheated to 600°C, and four retorts containing lignite were inserted into the preheated oven. The oven door was closed and automatic controls were adjusted to maintain the desired temperature of 600°C. After 16 hours (overnight), two

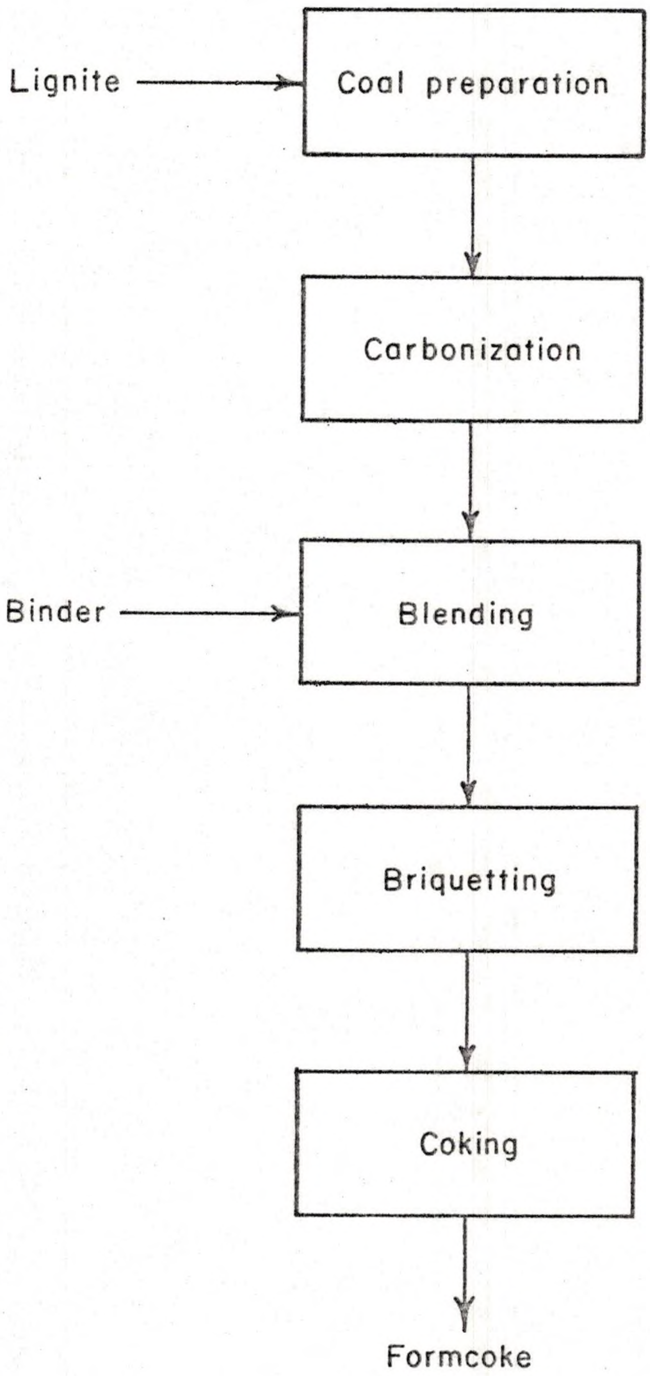

Fig. 1. - Process for producing formcoke.

retorts were removed from the oven and cooled. Oven temperature was then increased to 900°C for at least 4 hours. Carbonization times were sufficient to complete devolatilization on the basis of experience on previous work by the Bureau of Mines staff.

After cooling, the chars were split into 3 subsamples. Each subsample was crushed and sieved to separate into size functions. One fraction was crushed to pass an 18 mesh (1,000 microns), one a 35 mesh (500 microns) and the third a 60 mesh (250 microns) screen. Cumulative sieve analysis of char grain size are shown in Figures 8-9 (Appendix III).

Blending of Char and Binder

Asphalt, lignite tar and solvent refined lignite were used as binders. Compositions of 10, 15 and 20 per cent by weight of binder were used in different test series.

The char and binder were weighed out according to ratio desired and placed into a container. The mixture was heated in an oven at temperature between 120°C and 160°C, and then mixed with a spatula until uniform blending was achieved.

Briquetting

The cylindrical molds of 1 inch diameter by 3 inches high were preheated to the temperature used for blending. The blended mixture of char and binder was then transferred to the preheated molds so as to maintain the binder in the fluid condition.

The briquets were pressed in a hydraulic press for 1 minute at a selected pressure from 2,000 psi to 6,000 psi depending on test.

conditions. Four briquets were made from each blend at each test condition. The briquets were removed from the molds after they had cooled to room temperature overnight. The formed briquets were approximately 1 inch in diameter by 2 inches long.

Coking

The cooled briquets were placed in a loosely-covered steel box which restricted air circulation but allowed evolving gas to escape during heating. The briquets were coked in the box in a standard muffle furnace at heating rates of 5°C/min and of 10°C/min up to a maximum of 600°C or 900°C depending on test conditions. The temperature was maintained at the maximum for 10 to 15 minutes. The coked briquets were taken from the furnace and cooled in the box to room temperature overnight before compressive strength was measured.

Compressive Strength Testing

The compressive strength of formcoke briquets was determined by using a Soiltest AP-170 Stability Compression Machine located in the Civil Engineering Laboratory, University of North Dakota. A sample calculation is shown in Appendix II.

Analytical Procedures

These procedures were conducted in accordance with ASTM Standard Part 19 (11), using the facilities and equipment at the U.S. Bureau of Mines.

Proximate analyses of chars and selected formcoke samples are shown in Table 2 and Table 3, respectively.

TABLE 2

PROXIMATE ANALYSES OF CHARS

	Lignite(A)		Lignite(B)		Lignite(C)	
	600°C Char	900°C Char	600°C Char	900°C Char	600°C Char	900°C Char
Moisture --- %	2.0[a]	1.4[a]	1.3[a]	0.7[a]	1.6[a]	0.8[a]
Ash --- % as received	11.4	12.9	13.5	15.5	12.5	13.8
Volatile Matter --- % m.a.f.[b]	10.1	2.7	13.1	2.2	12.6	4.6
Fixed Carbon --- % m.a.f.[b]	89.9	97.3	86.9	97.8	87.4	95.4

[a]Moisture absorbed from the air
[b]Moisture and ash free basis

TABLE 3

PROXIMATE ANALYSES OF SELECTED FORMCOKE

	Formcoke made from					
	Lignite(A)		Lignite(B)		Lignite(C)	
	600°C Char	900°C Char	600°C Char	900°C Char	600°C Char	900°C Char
Moisture --- %	3.1[a]	3.0[a]	1.2[a]	1.2[a]	1.2[a]	1.2[a]
Ash --- % as received	11.8	11.4	12.2	12.0	13.8	14.5
Volatile Matter --- % m.a.f.[b]	2.6	2.6	2.5	2.3	3.5	3.4
Fixed Carbon --- % m.a.f.[b]	97.4	97.4	97.5	97.7	96.5	96.6

[a]Moisture absorbed from the air
[b]Moisture and ash free basis

CHAPTER IV

RESULTS AND DISCUSSION

About 120 tests were carried out to determine the optimum conditions for the production of formcoke from lignite. Basis for evaluation was compressive strength of briquets produced. Four briquets were made in each test. Variables studied were lignite variety, initial carbonization temperature, char grain size, binder percentage, binder type, briquetting pressure, coking temperature and heating rate to coking temperature. These effects are interrelated, but an attempt was made to establish best conditions for a few variables at a time.

Lignite(A) and Lignite(B)

The average compressive strength of formcoke briquets made from lignite(A) and lignite(B) at carbonization temperature of 600°C and 900°C are listed in Table 4.

The compressive strengths of formcoke produced from lignite(A) and lignite(B) responded similarly to variables but lignite(B) produced slightly less compressive strength than lignite(A). The 900°C lignite(A) char produced the strongest briquets with a compressive strength of 1054 psi, while the 900°C lignite(B) char produced a briquet with compressive strength of 988 psi.

TABLE 4

AVERAGE COMPRESSIVE STRENGTH OF FORMCOKE PRODUCED FROM THAILAND LIGNITE(A) AND LIGNITE(B)[a]

Carbonization Temperature (°C)	Char Grain Size (mesh)	Average Compressive Strength (psi)	
		Lignite(A)	Lignite(B)
600	18	779	685
	35	620	514
	60	490	467
900	18	807	613
	35	1,054	988
	60	617	596

[a]Briquetting Conditions:
- binder used: asphalt
- binder content: 15 per cent by weight
- briquetting pressure: 3000 psi
- heating rate during coking: 10°C/min.
- final coking temperature: 900°C

Formcoke produced from blends of 900°C lignite(A) char, regardless of grain size, was higher in compressive strength (1054 psi compared to 779 psi), than formcoke produced from blends of 600°C char of the same lignite. Again the formcoke strength made from lignite(B) decreased from 988 psi to 685 psi when the carbonization temperature was reduced from 900°C to 600°C.

Table 11 (Appendix IV) gives a statistical comparison of lignite(A) with lignite(B). Using the F-test for significance, the calculated F equalled 38.5. The 0.05 significance level value for F with 1 and 28 degrees of freedom from the F-Table (12) was equal to 2.56. Thus, a significant difference exists between lignite(A) and lignite(B).

Lignite(A) and lignite(B) from Thiland were, therefore, not considered as a single sample. Lignite(A) was used for investigating the effect of coking temperature, heating rate and carbonization temperature, while lignite(B) was used for the remaining variables. Since these two samples were obtained from the same mine and differed only slightly in heating value and proximate analysis, it appears that the handling and storage of the coal before processing to briquets may have a significant effect on formcoke properties.

Effect of Heating Rate and Coking Temperature

The highest average compressive strength obtained (1,054) psi was with briquets made from 900°C Thailand lignite(A) char and 15 per cent asphalt binder using a heating rate of 10°C/min to a coking temperature of 900°C (Figure 2). This compressive strength is almost twice that of similar briquets made at a heating rate of 5°C/min. The

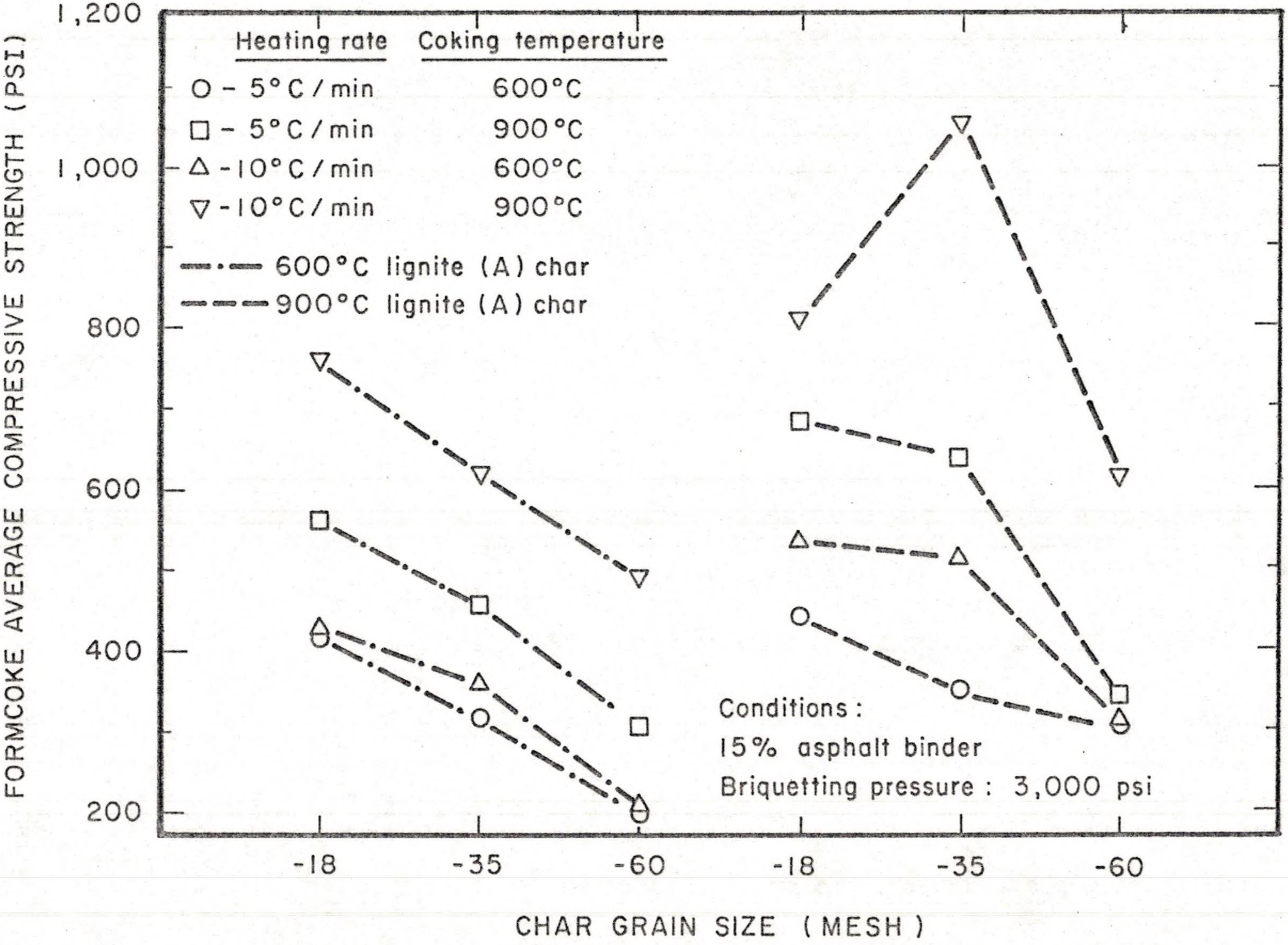

Fig. 2 - Effect of heating rate and coking temperature.

formcoke average compressive strength decreased to 537 psi when the coking temperature was reduced to 600°C at the 10°C/min rate. Briquets produced at a heating rate of 5°C/min to a coking temperature of 600°C and otherwise identical conditions gave a compressive strength of 350 psi.

Formcoke produced from 600°C Thailand lignite(A) char had its highest compressive strength (779 psi) at a heating rate of 10°C/min to a coking temperature of 900°C but the strength decreased to 425 psi when the coking temperature was reduced to 600°C. Again the formcoke strength dropped when the heating rate was reduced to 5°C/min for coking temperatures of 600°C and 900°C.

The detailed results of these tests are presented in Table 5 (Appendix I).

Because the heating rate of 10°C/min and coking temperature of 900°C produced the strongest briquets, these conditions were used in all subsequent tests.

Effect of Binder Percentage

Having established a suitable heating rate and coking temperature, these conditions were used to determine a suitable percentage of asphalt binder.

At the heating rate of 10°C/min and coking temperature of 900°C, briquets were made containing 10, 15 and 20 per cent asphalt binder and formed at briquetting pressures of 2,000 psi to 6,000 psi with 900°C Thailand lignite(B) char.

Formcoke produced using 15 per cent binder showed higher compressive strengths than formcoke made with 10 per cent binder at all briquetting pressures and with 20 per cent binder at higher briquetting pressures as shown in Figure 3.

Formcoke made with 10 per cent asphalt binder had average compressive strengths from 92 psi to 275 psi; with 15 per cent binder, 510 psi to 773 psi; and with 20 per cent binder, 575 psi to 610 psi. The test data are summaried in Table 6 (Appendix I).

The briquets made with 15 per cent binder showed increasing compressive strength with increasing briquetting pressure, and gave the highest strengths obtained. Because of this, 15 per cent binder was selected for subsequent experiments.

Effect of Char Grain Size

The average compressive strength of formcoke produced from -18, -35 and -60 mesh samples of 600°C and 900°C lignite(B) chars with 15 per cent asphalt binder at briquetting pressures from 2,000 psi to 6,000 psi, are shown in Figure 4.

The -35 mesh fraction of 900°C char gave the strongest briquets having compressive strengths from 720 psi to 1,290 psi; the -18 mesh char resulted in briquets with compressive strengths from 510 psi to 773 psi; and the -60 mesh material gave strengths from 490 psi to 588 psi.

In contrast, formcoke from 600°C char of lignite(B) exhibited a uniform decrease in compressive strength with a decrease in grain size of char. Formcoke made from -18 mesh 600°C char exhibited 500 psi to 965 psi compressive strengths, while that from -35 mesh was 405 psi to 586 psi, and that from -60 mesh, 394 psi to 588 psi.

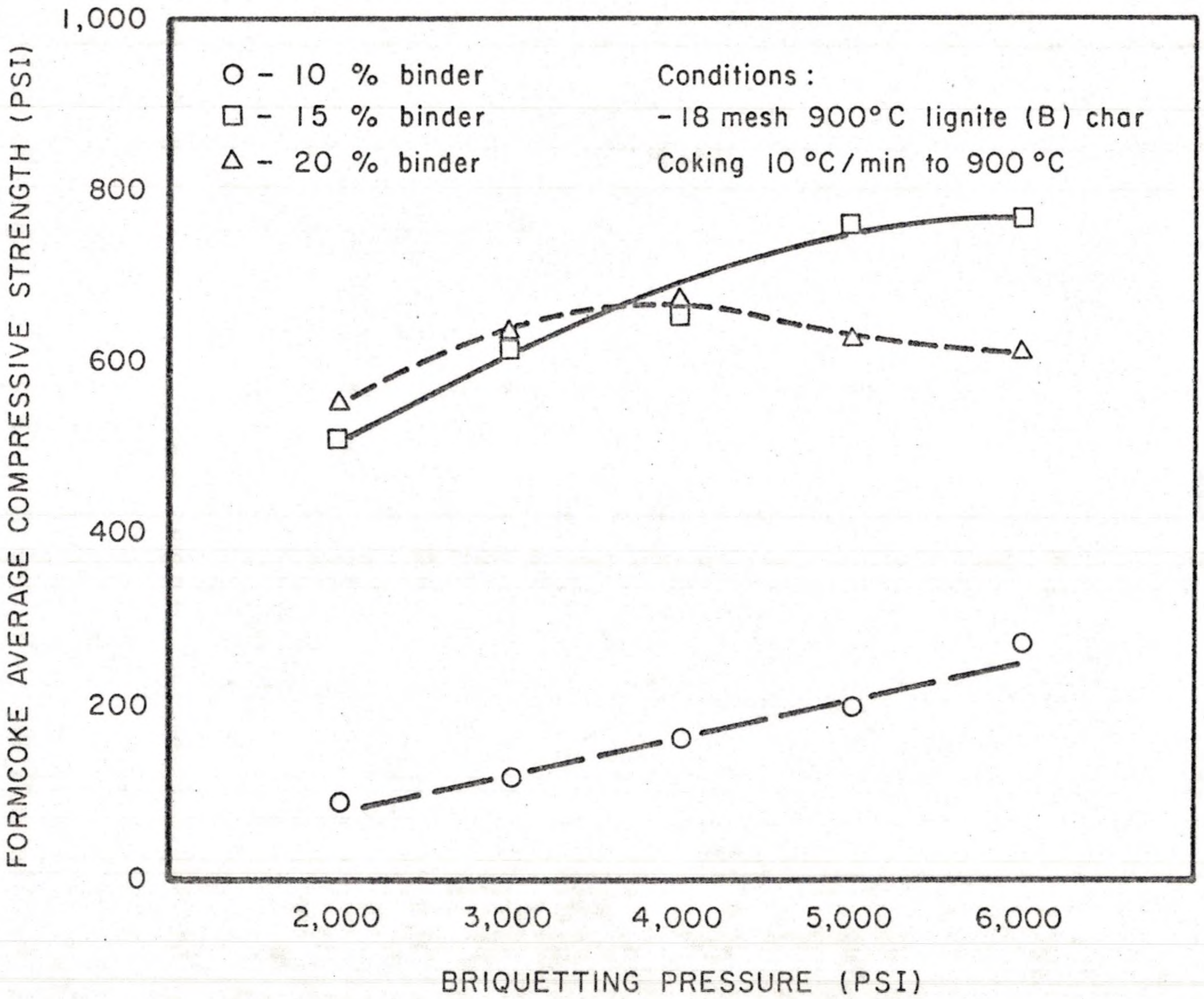

Fig. 3 - Effect of binder percentage.

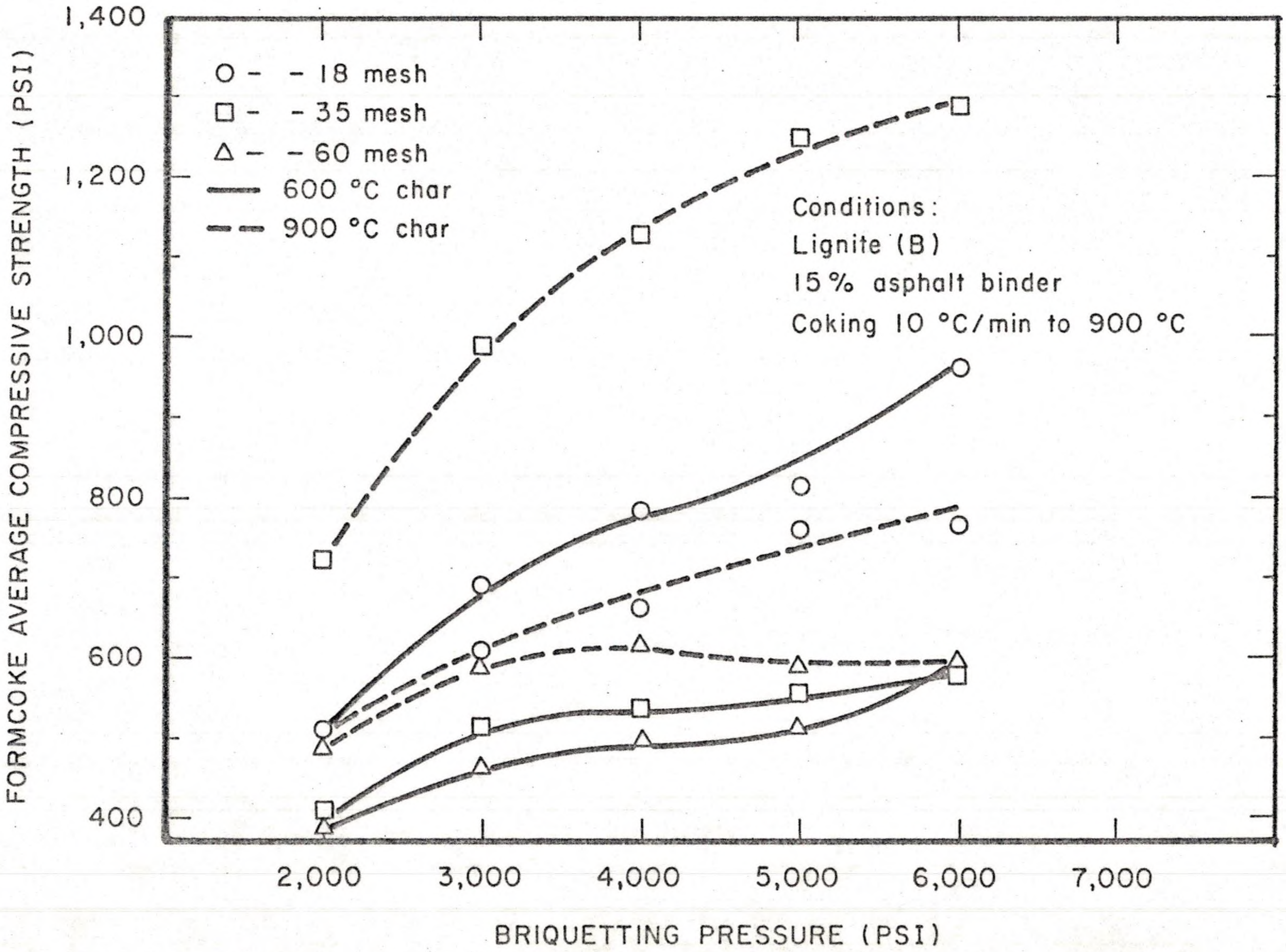

Fig. 4 - Effect of char grain size.

The response to variables of compressive strength for lignite(A) was similar to that for lignite(B) (see Table 4), although the actual values were higher for lignite(A) under the same conditions.

The char size of -35 mesh for 900°C char was thus considered best for producing formcoke under the conditions employed.

Effect of Carbonization Temperature

Formcoke produced from 900°C lignite(B) char, regardless of grain size, gave highest average compressive strengths ranging from 720 psi to 1,290 psi. Formcoke from 600°C lignite(B) char had average compressive strengths ranging from 500 psi to 965 psi, as shown in Figure 4. Table 4 shows that briquets made from lignite(A) gave better results with 900°C char than with 600°C. Thus, for both lignites, the strengths of briquets made from 900°C char were higher than the ones made from 600°C char.

Effect of Briquetting Pressure

The compressive strengths of formcoke made from lignite(B) usually increased with increasing briquetting pressure as shown in Figure 4. An exception was for mixtures containing 20 per cent asphalt binder in which the average compressive strength decreased from 674 psi to 610 psi when the briquetting pressure was raised from 4,000 psi to 6,000 psi (Figure 3). The strongest briquets having a compressive strength of 1,290 psi were obtained using a 6,000 psi briquetting pressure. In production a minimal briquetting pressure is advantageous when consistent with adequate compressive strength.

Since 1 1/4" X 1" X 3/4" briquets having a crushing strength of 450 pounds were found adequate for blast furnace use by other researchers (6), it was considered that formcoke briquets having 800 psi crushing strength as produced in this study exceed this value sufficiently to be adequate for commercial production.

The briquetting pressure as determined for cylindrical briquets is not directly comparable to briquetting pressure obtained in a roll press, but in the present work, a 3,000 psi briquetting pressure was considered sufficiently high for producing satisfactory formcoke in bench scale tests as the briquets had crushing strengths of over 800 psi.

Effect of Binder Type

Asphalt, lignite tar and solvent refined lignite were tested for effectiveness as binders. Figure 5 shows the average compressive strength of formcoke produced from blends asphalt and from blends of lignite tar using Thailand lignite(B) chars.

Formcoke produced from char blends with asphalt resulted in higher compressive strengths, 1,254 psi compared to 924 psi, than did formcoke from blends of char and lignite tar at all test conditions.

The mixture of 900°C lignite(B) char and 15 per cent asphalt produced formcoke exhibiting greater compressive strength (1,254 psi compared to 551 psi), than that from 600°C lignite(B) char.

Similarly formcoke made from lignite tar and 900°C lignite(B) char had a higher compressive strength (924 psi), than obtained with 600°C char and lignite tar.

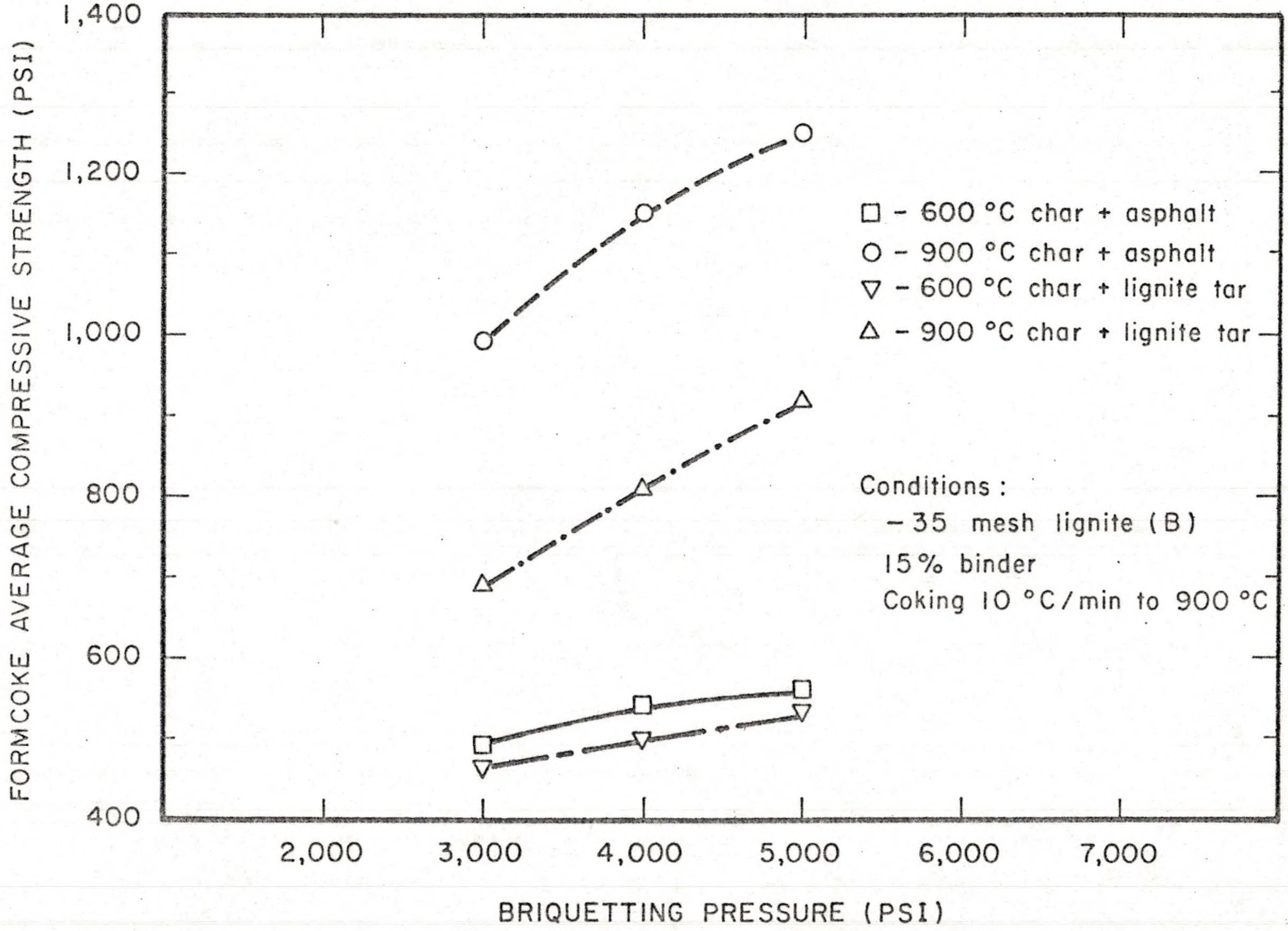

Fig. 5 - Effect of binder type.

Solvent refined lignite binder did not produce an acceptable briquet at concentration to 20 per cent when blended at 160°C. This was anticipated since this temperature is less than the softening point of the solvent refined lignite.

Asphalt was the best binder for production of bench scale formcoke. Because of this, asphalt was used as a binder for subsequent test work.

North Dakota Lignite(C)

Formcoke was made from a North Dakota lignite(C) in a limited test series to indicate suitability to the process, and for comparison with the Thailand lignite.

Figure 6 shows the effect of heating rate on the compressive strength of formcoke from lignite(C). A heating rate of 10°C/min to a coking temperature of 900°C and a carbonization temperature of 600°C produced the strongest briquets, 831 psi. Using a 5°C/min heating rate under similar conditions, produced briquets of lower strength, regardless of char size.

Similarly, the strength of briquets produced from 900°C char decreased (from 491 psi to 442 psi) when the heating rate was reduced from 10°C/min to 5°C/min at the same coking temperature.

It was previously shown (page 20) that the strongest formcoke produced from lignite(A) was also at a 10°C/min heating rate to 900°C.

Average compressive strength of formcoke from lignite(C) as a function of carbonization temperature and briquetting pressure varied widely, as shown in Figure 7. The strongest briquets having compressive strengths from 831 psi to 1,255 psi were formed at

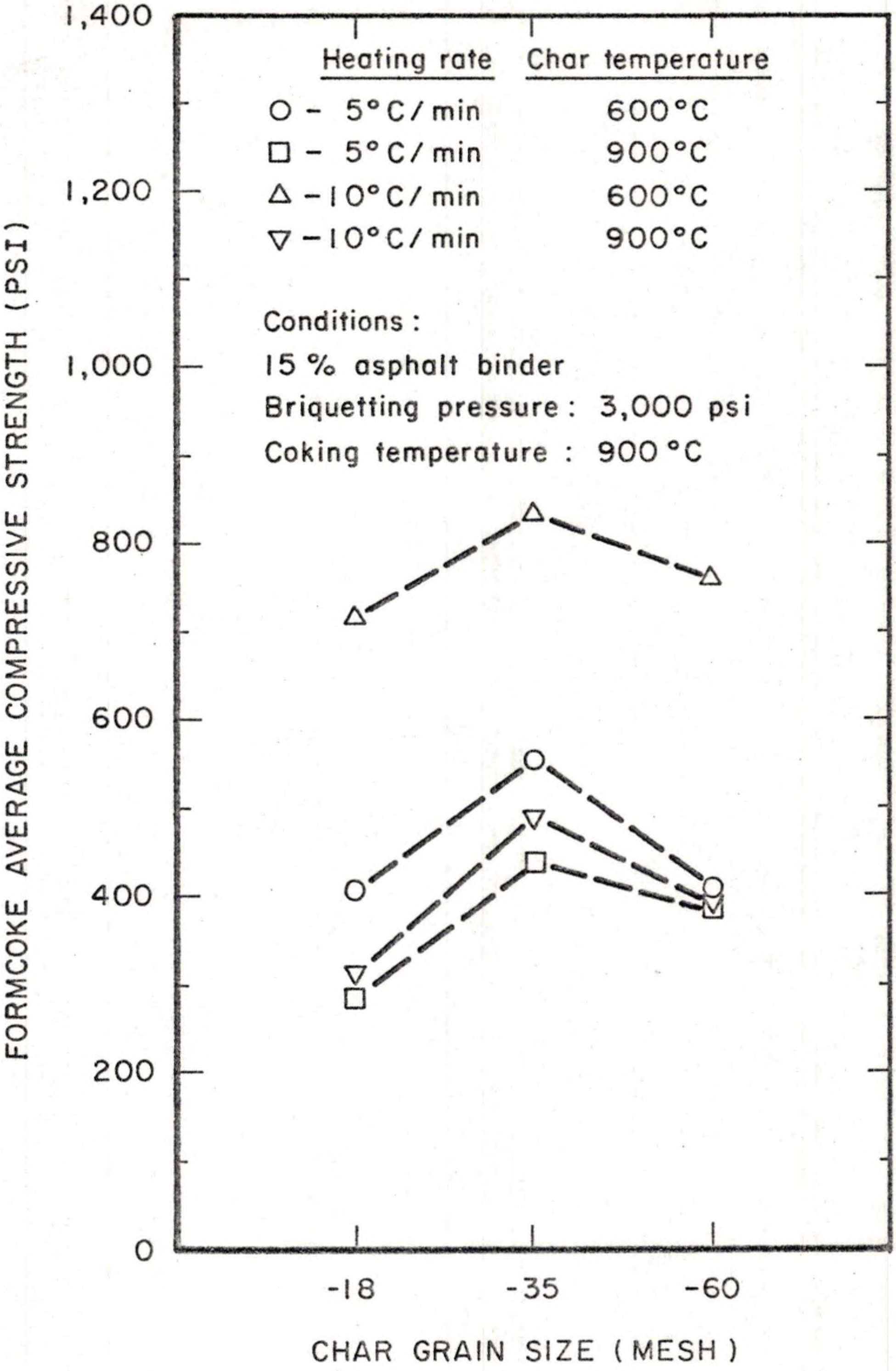

Fig. 6 - Effect of heating rate on formcoke made from lignite (C)

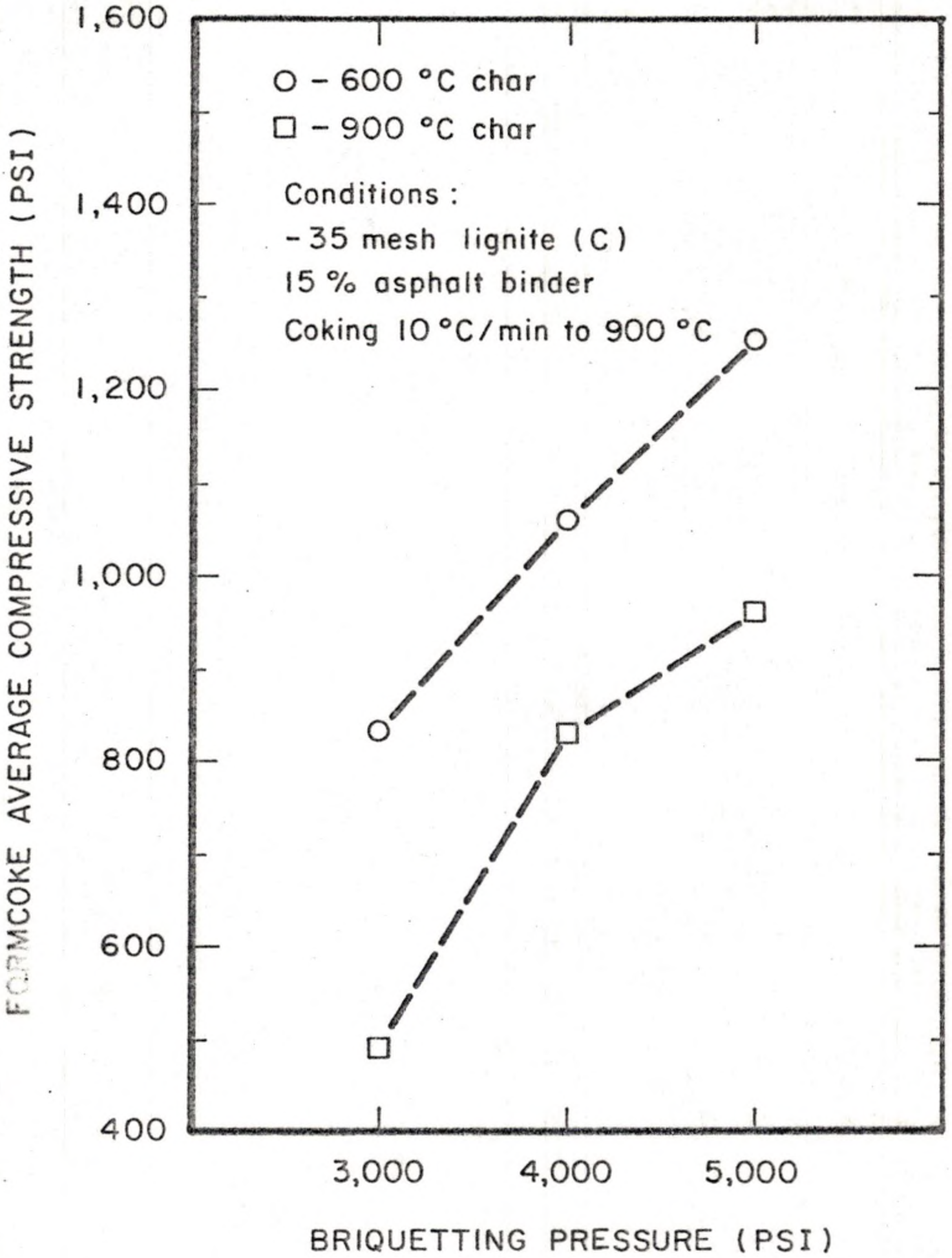

Fig. 7 - Effect of carbonization temperature and briquetting pressure.

briquetting pressure of 3,000 psi to 5,000 psi using 600°C char from lignite(C). With 900°C char, briquets have compressive strengths 491 psi to 962 psi using the same range of briquetting pressure.

Formcoke produced from 600°C lignite(C) char using 15 per cent asphalt binder, 3,000 psi briquetting pressure, heating rate of coking temperature 10°C/min to 900°C was considered as an acceptable briquets for metallurgical use. This differs from the results with lignite(A) and lignite(B) in which the 900°C char gave superior crushing strengths.

CHAPTER V

CONCLUSIONS

The following conclusions were drawn from the results of this study:

1. Formcoke of strength adequate for blast furnace use can be made from Thailand lignite and from North Dakota lignite.
2. The optimum conditions for production of formcoke from Thailand lignite were 900°C carbonization temperature, particle size -35 mesh, binder 15 per cent asphalt, briquetting pressure 3,000 psi, and heating rate 10°C/min to a coking temperature of 900°C.
3. Optimum conditions for formcoke from North Dakota lignite were the same as in conclusion (2) except that a 600°C carbonization temperature was better.
4. The highest compressive strength of formcoke briquets was obtained using 900°C Thailand lignite char, -35 mesh particle size, 15 per cent asphalt binder, a briquetting pressure of 6,000 psi and a heating rate of 10°C/min to a coking temperature of 900°C.
5. Acceptable briquets were made from 600°C Thailand lignite char under similar conditions but a minimum briquetting pressure of 5,000 psi was required.
6. Acceptable formcoke briquets were made from 900°C Thailand lignite char blended with 15 per cent lignite tar, at -35 mesh particle

size, briquetting pressure of 4,000 psi and heating rate of $10^{o}C/min$ to a coking temperature of $900^{o}C$.

APPENDIX I

COMPRESSIVE STRENGTH OF FORMCOKE

TABLE 5

EFFECT OF HEATING RATE AND COKING TEMPERATURE[a]

Carbonization Temperature (°C)	Heating Rate (°C/min)	Coking Temperature (°C)	Char Grain Size (mesh)	Compressive Strength (psi)				Average Compressive Strength (psi)
600	5	600	18	427	427	420	408	421
			35	318	344	293	318	318
			60	191	223	166	217	199
		900	18	592	535	631	586	586
				541	554	561	535	541
			35	446	465	478	428	454
				522	427	446	510	472
			60	287	306	299	299	298
				344	274	318	287	306
	10	600	18	398	433	465	408	425
			35	369	331	377	363	360
			60	191	204	217	210	205
		900	18	777	815	777	815	796
				752	764	764	764	761
			35	650	605	611	643	627
				592	605	637	618	613
			60	516	490	401	471	470
				510	510	504	516	510
900	5	600	18	433	433	471	446	446
			35	299	369	363	369	350
			60	331	306	299	280	304

TABLE 5--Continued

Carbonization Temperature (°C)	Heating Rate (°C/min)	Coking Temperature (°C)	Char Grain Size (mesh)	Compressive Strength (psi)				Average Compressive Strength (psi)
900	5	900	18	701	643	662	701	677
				675	713	675	713	695
			35	713	647	662	662	671
				643	611	599	624	619
			60	375	306	363	376	351
				350	331	350	338	342
	10	600	18	554	548	459	586	537
			35	484	503	561	522	518
			60	310	336	268	342	314
		900	18	834	764	758	847	801
				854	790	854	752	813
			35	1,011	1,026	1,051	1,064	1,038
				1,045	1,057	1,083	1,096	1,070
			60	592	650	641	628	628
				624	612	586	599	605

[a]Briquetting Conditions:
- lignite used: lignite(A)
- binder used: asphalt
- binder content: 15 per cent by weight
- briquetting pressure: 3,000 psi

TABLE 6

EFFECT OF BINDER PERCENTAGE[a]

Binder Percentage	Briquetting Pressure (psi)	Compressive Strength (psi)				Average Compressive Strength (psi)
10	2,000	89	89	102	89	92
	3,000	115	127	127	127	124
		127	115	122	134	125
	4,000	172	166	178	166	171
	5,000	204	204	210	195	203
	6,000	268	280	275	275	275
15	2,000	510	510	510	510	510
	3,000	650	611	592	624	619
		599	624	618	586	607
		612	586	630	619	612
		624	599	612	612	612
	4,000	702	662	637	650	663
	5,000	752	777	752	764	761
	6,000	773	782	773	764	773
20	2,000	573	586	580	561	575
	3,000	631	624	612	643	627
	4,000	713	662	657	662	674
	5,000	594	643	650	624	628
	6,000	599	612	612	617	610

[a]Briquetting Conditions:
- lignite used: lignite(B)
- carbonization temperature: 900°C
- char grain size: -35 mesh
- binder used: asphalt
- heating rate during cooking: 10°C/min
- coking temperature: 900°C

TABLE 7

EFFECT OF CARBONIZATION TEMPERATURE, CHAR GRAIN SIZE AND BRIQUETTING PRESSURE[a]

Carbonization Temperature (^{o}C)	Char Grain Size (mesh)	Briquetting Pressure (psi)	Compressive Strength (psi)				Average Compressive Strength (psi)
600	18	2,000	510	497	491	502	500
		3,000	701	688	675	694	690
			689	634	713	681	679
		4,000	803	777	764	764	777
		5,000	835	790	803	835	816
		6,000	955	975	968	962	965
	35	2,000	408	408	414	395	405
		3,000	497	484	497	487	491
			561	586	536	561	561
			510	459	491	497	489
		4,000	535	548	561	522	541
		5,000	554	548	561	541	551
		6,000	592	580	586	586	586
	60	2,000	376	408	382	395	394
		3,000	484	472	472	472	475
			459	459	459	459	459
		4,000	510	484	497	510	500
		5,000	522	510	510	517	515
		6,000	599	580	586	586	588

TABLE 7--Continued

Carbonization Temperature (°C)	Char Grain Size (mesh)	Briquetting Pressure (psi)	Compressive Strength (psi)				Average Compressive Strength (psi)
900	35	2,000	713	726	739	701	720
		3,000	987	981	1,006	1,016	997
			955	994	1,006	1,000	989
			866	1,096	1,083	854	975
			981	943	1,026	981	982
			1,016	994	981	994	996
		4,000	1,153	1,108	1,096	1,143	1,125
		5,000	1,274	1,256	1,248	1,236	1,254
			1,248	1,299	1,217	1,253	1,254
		6,000	1,299	1,312	1,274	1,274	1,290
	60	2,000	497	471	484	510	491
		3,000	631	569	599	599	600
			599	580	580	593	588
			612	586	605	605	602
		4,000	618	612	624	606	615
		5,000	586	599	593	586	591
		6,000	593	586	586	586	588

[a]Briquetting Conditions:
lignite used: lignite(B)
binder used: asphalt
binder content: 15 per cent by weight
heating rate during coking: 10°C/min
coking temperature: 900°C

TABLE 8

COMPRESSIVE STRENGTH OF FORMCOKE PRODUCED FROM BLENDS OF LIGNITE TAR AND LIGNITE(B) CHAR[a]

Carbonization Temperature (°C)	Briquetting Pressure (psi)	Compressive Strength (psi)			Average Compressive Strength (psi)
600	3,000	471	497	446	471
	4,000	510	484	510	501
	5,000	535	548	522	535
900	3,000	624	701	746	690
	4,000	815	803	796	804
	5,000	930	917	924	924

[a]Briquetting Conditions:
char grain size: -35 mesh
binder content: 15 per cent by weight
heating rate during coking: 10°C/min
coking temperature: 900°C

TABLE 9

COMPRESSIVE STRENGTH OF FORMCOKE PRODUCED FROM LIGNITE(C)[a]

Carbonization Temperature (°C)	Heating Rate (°C.min)	Briquetting Pressure (psi)	Char Grain Size (mesh)	Compressive Strength (psi)			Average Compressive Strength(psi)
600	5	3,000	18	433	382	395	403
			35	548	555	561	555
			60	420	408	382	403
	10		18	713	701	739	719
			35	815	873	803	831
			60	739	764	777	760
900	5		18	293	280	268	280
			35	433	484	408	442
			60	382	408	369	386
	10		18	319	293	319	310
			35	471	491	510	491
			60	408	389	401	399
600		4,000	35	1,057	1,064	1,064	1,062
		5,000		1,313	1,217	1,236	1,255
900		4,000		803	854	838	828
		5,000		1,006	930	950	962

[a]Briquetting Conditions:
binder used: asphalt
binder content: 15 per cent by weight
coking temperature: 900°C

APPENDIX II

SAMPLE CALCULATION

SAMPLE CALCULATION

The compressive strength test was used. Dial readings were converted to actual load in pounds using the tabulated calibration data shown below:

Stability Compressive Machine: Soiltest Model AP-170

Dial Readings 10^{-4}	Actual Load lbs.
20	202
50	508
100	1,030
150	1,521
200	2,031
250	2,541
300	3,070
350	3,581
400	4,090
450	4,584
500	5,097

Example

Dial reading X 10^{-4} = 100

Actual load = 1,030 lbs.

$$\text{Compressive strength} = \frac{1{,}030}{\pi r^2}$$

$$= \frac{1{,}030}{3.14 \times (0.5)^2}$$

$$= \underline{\underline{1{,}312.2}} \text{ psi}$$

APPENDIX III

CUMULATIVE SIEVE ANALYSIS OF CHAR

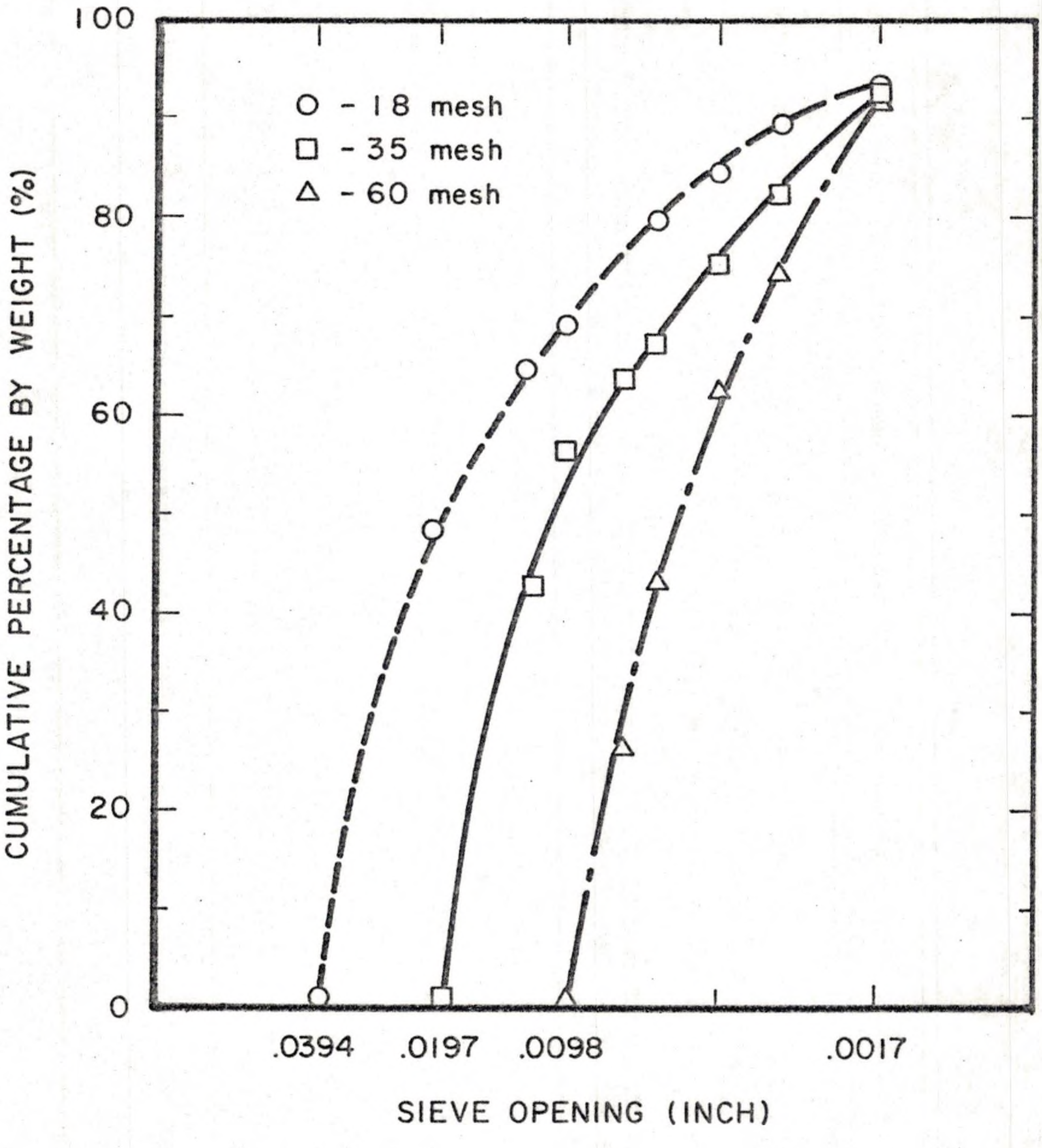

Fig. 8 - Cumulative logarithmic of sieve analysis (600 °C char).

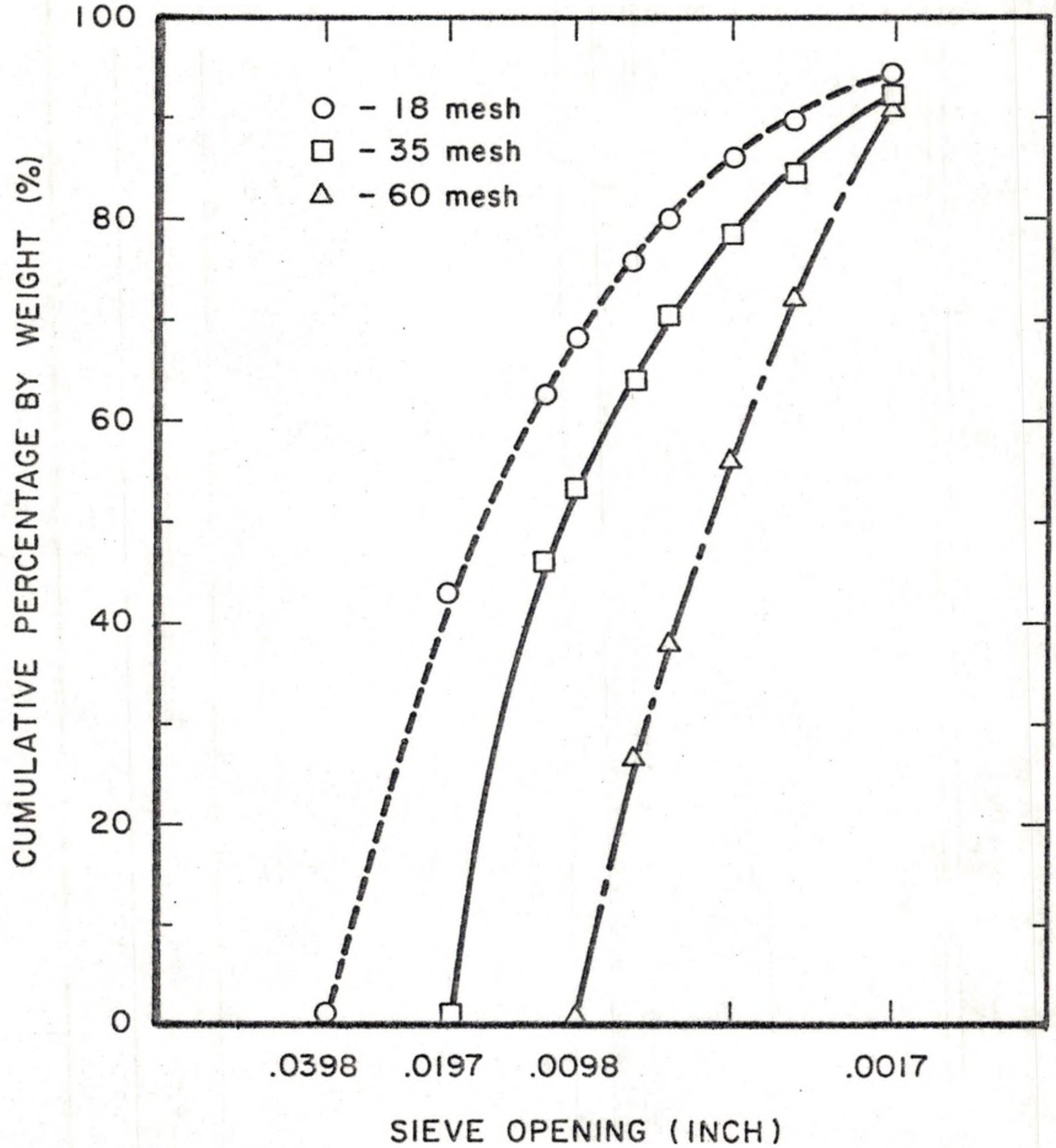

Fig. 9 - Cumulative logarithmic of sieve analysis (900 °C char).

APPENDIX IV

STATISTICAL INTERPRETATION OF RESULTS

STATISTICAL INTERPRETATION OF RESULTS

Two to 5 determination of average compressive strength were determined for 21 replicated conditions. Differences in average compressive strength within replicated tests is caused by random variation of test conditions. Using the random (error) variation, a test for significant for differences between average of result from two lignites can be obtained by the "F" test (12).

Table 10 shows the calculation of the error sum of squares for compressive strength, where

x_i = average compressive strength of formcoke for individual test

$\overline{x}$ = mean of average compressive strength of replicated runs

s_x^2 = variance or the arithmetic mean of the deviations squared for replicated tests or $\Sigma \frac{(x_i-\overline{x})^2}{(n-1)}$

n = number of value used to calculate error

SS_x = $(n-1)s_x^2$

s_p^2 = pooled sample variance of average compressive strength (error variance)

$$= \frac{SS_{x1} + \text{-----------------} + SS_{xk}}{(n_1-1) + \text{----------------} + (n_k-1)}$$

The pooled error variance is calculated from the total sum of squares and degrees of freedom as:

$$s_p^2 = \frac{9,210.7}{(49-21)} = \underline{\underline{329}}$$

TABLE 10

CALCULATION OF THE ERROR SUM OF SQUARES FOR
AVERAGE COMPRESSIVE STRENGTH

No.	x_i	$\bar{x}$	$(x_1-\bar{x})^2$	$(x_2-\bar{x})^2$	$(x_3-\bar{x})^2$	$(x_4-\bar{x})^2$	$(x_5-\bar{x})^2$	s_x^2	SS_x
1	586, 541	563.5	506.2	506.3				1,012.5	1,012.5
2	796, 761	778.5	306.3	306.3				612.5	612.5
3	677, 695	686.0	81.0	81.0				162.5	162.5
4	801, 803	807.0	36.0	36.0				72.0	72.0
5	454, 472	463.0	81.0	81.0				162.0	162.0
6	627, 613	620.0	49.0	49.0				98.0	98.0
7	671, 619	645.0	676.0	676.0				1,352.0	1,352.0
8	1,038, 1,070	1,054.0	256.0	256.0				512.0	512.0
9	298, 306	302.0	16.0	16.0				32.0	32.0
10	470, 510	490.0	400.0	400.0				800.0	800.0
11	351, 342	346.5	20.3	20.3				40.5	40.5
12	628, 605	616.5	132.3	132.3				264.5	264.5
13	124, 125	124.5	0.3	0.3				0.5	0.5
14	619, 607, 612, 612	612.5	42.3	30.3	0.3	0.3		24.3	73.0
15	997, 989, 975, 982, 996	687.8	84.7	1.4	163.8	33.6	67.3	87.7	350.8
16	1,254, 1,254	1,254.0	0.0	0.0				0.0	0.0
17	600, 588, 602	596.7	11.1	75.2	28.4			57.3	114.7
18	627, 626	626.5	0.3	0.3				0.5	0.0
19	690, 679	684.5	30.3	30.3				60.5	60.5
20	491, 561, 489	513.7	513.9	2,240.2	608.6			1,681.3	3,362.7
21	475, 459	467.0	64.0	64.0				128.0	128.0
									9,210.7

Calculation of sum of squares for between variations for lignite(A) and lignite(B) is shown in Table 11, where $\overline{x}_A$, $\overline{x}_B$ are the mean compressive strengths of formcoke made from lignite(A) and lignite(B), respectively, under replicated conditions.

The sum of square for this case is:

$$\Sigma(\overline{x}_A - \overline{x}_B) = 63{,}298.1$$

and the variance is: $S^2_{AB} = \dfrac{\Sigma(\overline{x}_A - \overline{x}_B)}{(n-1)}$

$$= \frac{63{,}298.1}{6-1}$$

$$= 12{,}659.6$$

the calculated F value is: $F_c = \dfrac{S^2_{AB}}{S^2_p}$

$$= \frac{12{,}659.6}{329}$$

$$= \underline{\underline{38.5}}$$

At 5 per cent significance level ($\alpha = 0.05$), the critical F value with 5 and 28 degrees of freedom is: $F_{.05}(5,28) = \underline{\underline{2.56}}$.

Since the calculated F value of 38.5 exceed the critical value of F, there is a significant difference between the observed value for lignite(A) and lignite(B) for the experimental conditions employed.

TABLE 11

CALCULATION OF SUM OF SQUARES FOR BETWEEN VARIATIONS FOR LIGNITE(A) AND LIGNITE(B)

$\bar{x}_A$	$\bar{x}_B$	$(\bar{x}_A - \bar{x}_B)$	$(\bar{x}_A - \bar{x}_B)^2$
778.5	684.5	94.0	8,836.0
620.0	513.7	106.3	11,306.1
490.0	467.0	23.0	529.0
807.0	612.5	194.5	37,830.3
1,054.0	987.8	66.2	4,382.4
617.0	596.7	20.3	414.3
			63,298.1

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