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STATISTICAL CORRELATION OF ASTM AND JIS COKE TUMBLER TEST RESULTS

W.R. Leeder and K.A. Jonasson

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STATISTICAL CORRELATION OF ASTM AND JIS COKE TUMBLER TEST RESULTS

by

W.R. Leeder* and K.A. Jonasson**

ABSTRACT

The Coal Resource and Processing Laboratory (CRPL) has accumulated an extensive file of ASTM and JIS coke tumbler test results using coke obtained from single technical-scale coke oven tests. The parallel ASTM stability and CRPL modified JIS DI_{15}^{30} or DI_{15}^{150} coke quality indices are compared graphically and correlated using regression analysis. Before 1972, CRPL used plus 3-in. coke in the JIS test and it was found that the CRPL DI_{15}^{30} index could be related to the stability factor using a quartic equation. After 1972, CRPL used 2-in. by 3-in. coke in the JIS test and the current CRPL DI_{15}^{30} and DI_{15}^{150} indices are found to correlate with the ASTM stability factor using quartic and linear equations respectively.

Correlation between the stability factor and the CRPL DI_{15}^{30} results are better for high quality coke than for poorer quality coke with a stability factor <45. The current CRPL JIS practice gives DI_{15}^{30} index values estimated to be 0.65 units higher than the values before 1972, and about 1 unit higher than if the test were conducted exactly to JIS specification using plus 2-in. coke. The results also indicate the JIS DI_{15}^{30} index is poorer for differentiating high quality coke strength than the DI_{15}^{150} index or ASTM stability factor. It is concluded, in agreement with other authors, that the JIS drum test at 30 revolutions is inadequate and that the test procedure should be carried out for a longer period such as by the JIS method at 150 revolutions.

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CORRELATION STATISTIQUE DES RESULTATS D'ESSAIS AU CULBUTEUR ASTM ET JIS

par

W.R. Leeder* et K.A. Jonasson**

RESUME

Le Laboratoire du traitement et des ressources en charbon (CRPL) a accumulé un dossier important de résultats d'essais au culbuteur ASTM et JIS du coke provenant d'essais effectués avec un four à coke à l'échelle technique. La stabilité parallèle obtenue au ASTM et les indices de la qualité du coke JIS DI_{15}^{30} ou DI_{15}^{150} modifiés du CRPL sont comparés sur un graphique et mis en rapport par l'analyse de la régression. Avant 1972, le CRPL employait du coke de plus de 3 pouces pour les essais JIS et a découvert que l'indice CRPL DI_{15}^{30} pouvait dépendre du facteur de stabilité si l'équation quartique était employée. Après 1972, le CRPL utilisait le coke de 2 pouces par 3 pouces pour effectuer les essais JIS. On a démontré que les indices CRPL DI_{15}^{30} et DI_{15}^{150} correspondent avec le facteur de stabilité ASTM lorsque les équations quartiques et linéaires sont employées respectivement.

La corrélation entre le facteur de stabilité et les résultats des essais CRPL DI_{15}^{30} est meilleure pour le coke de haute qualité que pour le coke de pauvre qualité ayant un facteur de stabilité de <45. Avec la pratique du CRPL JIS actuelle on estime que les valeurs de l'indice DI_{15}^{30} sont de 0.65 unités de plus que les valeurs mesurées avant 1972 et environ une unité de plus que si les essais étaient effectués selon les specification JIS avec du coke de plus de 2 pouces. Les résultats ont aussi démontré que l'indice JIS DI_{15}^{30} est inférieur à l'indice DI_{15}^{150} ou au facteur de stabilité ASTM pour la différentiation de la résistance du coke de haute qualité. En conclusion, l'essai tambour JIS effectué à 30 révolutions est inadéquat et les essais devraient se poursuivre plus longtemps tel que par la methode JIS à 150 révolutions. D'autres auteurs ont appuyé cette recommandation.

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CONTENTS

FIGURES

TABLES

APPENDICES

INTRODUCTION

The objective of this report is to provide a means of relating results of the principal North American and Japanese standard tests of blast furnace coke quality, i.e., coke tumbler test factors or indices. Such relationships are needed to better understand the many advances being made by the Japanese as a world leader in cokemaking research. For example, recent Japanese publications of importance to North American cokemakers, coal producers and researchers have related coal petrographic reflectance and thermal rheological properties to Japanese, but not to North American coke quality parameters (1). The relationship between the coke tumbler test indices is necessary to interpret the quality of Canadian coking coal resources as seen from either the North American or Japanese points of view, and as such is important to the CANMET program for Canadian self-sufficiency for coking coals.

The most important metallurgical coke quality parameter that can be related to blast furnace behaviour is a strength index calculated from the mechanical breakdown of coke in a tumble drum (2,3). Although several standard forms of such tests are used in different parts of the world, all follow essentially the same procedure. Each tumbles a given weight of sized coke in a cylindrical drum at a specified speed of rotation for a given number of revolutions. A strength index is then calculated using some measure of coke size reduction such as the cumulative weight of a tumbled sample remaining above a minimum size (4,5,6,7). Two mechanisms of mechanical degradation, respectively attributed to impact and abrasion forces, are considered to act on the coke lumps in the drum (5,7,8). Although a simple mathematical model based on ball mill theory has been proposed to estimate these two forces (8), no comprehensive theory exists to calculate or relate coke degradation observed with different tumbler tests. Consequently, relationships between such test methods cannot be predicted and must be derived empirically.

For some years the CRPL has been using several tumbler tests to assess the quality of coke produced from in-house slot-type technical-scale coke ovens (9). The two most important coke tumbler tests in Canada are the ASTM, American Society for Testing and Materials, and the JIS, Japanese Industrial Standard, methods (10,11). Both are carried out routinely at

CRPL on coke produced from single oven tests. The key coke strength indices calculated from the coke strength tests are the ASTM stability factor (10) and the JIS DI_{15}^{30} and DI_{15}^{150} indices (11). CRPL has accumulated an extensive file of such parallel results from work done over the last 15 years. The object of this report is to compare them graphically and statistically, thus making it possible to relate the coke quality indices from the two methods. As well, it was also hoped that the CRPL-derived coke tumbler strength relationships would clarify differences between the coke degradation mechanisms of the ASTM and JIS methods (5).

EXPERIMENTAL

This section contains details of ASTM and JIS coke tumbler test methods used at CRPL, and explains statistical methods to compare the results.

CRPL Coke Tumbler Test Methods

Each technical-scale coke oven test done at CRPL normally provides sufficient coke to carry out both the ASTM and JIS coke tumbler tests. The coke is handled in the following manner before testing. After the hot coke is pushed from an oven it is immediately cooled with water in a "quench" box, dropped 10 feet to a concrete floor to simulate coke handling in a commercial plant, dried, and finally screened for testing. Before the tumbler tests are conducted, the coke is hand picked to remove the weaker coke from the door ends. This end coke represents a far larger fraction of the coke produced from a technical-scale oven than from a commercial oven. Since the object is to produce a commercial quality coke in the technical-scale oven, such end coke is discarded to prevent bias in the results. If sufficient coke of the size to be tested is not available, more coke of the correct size is produced by cracking the larger pieces along existing fissures using the tip of a screwdriver.

The standard methods used to carry out the coke tumbler tests are summarized in Appendix A.

CRPL carries out the ASTM test exactly to specification. However, some of the stability data used in this study was corrected to account for wear of the ASTM drum lifters that resulted in an average coke stability

increase of 1.4 stability units after about 1500 tumbler tests had been carried out. The correction assumed the lifter wear resulted in a linear increase in stability with the number of tests performed.

CRPL uses a modified JIS coke tumbler test method. The Japanese standard specifies that plus 2-in. coke be used. However, CRPL has used two different size consists during the last 15 years. From the JIS introduction at CRPL in 1961 until 1972, the test was performed with plus 3-in. coke. In 1972, coke size was changed after discussions with the Japanese and the test is now being run with 2-in. by 3-in. coke. If this size is used then the same results could be expected from both the 12- and 18-in. ovens operated at CRPL. If this modification had not been made, then the plus 2-in. coke from the 12-in. oven would tend to give higher JIS DI_{15}^{30} indices than plus 2-in. coke from the 18-in. oven, because the 18-in. oven tends to produce more coke in the plus 3-in. and plus 4-in. sizes (Leeder, W.R. and Price, J.T.; Unpublished results; 1977). The different size consists of coke used by CRPL in the JIS tumbler test are summarized in Table 1.

Statistical Analysis

Since the ASTM and JIS results were obtained from single random oven tests, it is assumed that the observations represent samples from a population that has an independent normal distribution. The test results that appear in Appendix B were compared with the aid of a Hewlett-Packard 9810A programmable calculator fitted with a 9862A plotter. The data were plotted and regressed using the following regression models: linear ($Y = A+BX$), parabolic ($Y = A + BX + CX^2$), quartic ($Y = A + BX + CX^2 + DX^3 + EX^4$), semi-log ($Y = A + B \ln X$), exponential ($Y = Ae^{BX}$) and power ($\ln Y = A + B \ln X$) (12,13,14). Because least-squares regression models assume that all the error is inherent in either X or Y, and because it seems reasonable to assume that errors of roughly equivalent magnitude occur in both indices, a modified linear least-squares regression method that takes the error into account was used to correlate the stability and JIS DI_{15}^{150} indices (12). It was not used where a non-linear model was considered.

RESULTS AND DISCUSSION

The data to derive the correlations appear in Fig. 1, 2 and 3. The stability versus DI_{15}^{150} data in Fig. 3, and the stability versus the pre- and post-1972 CRPL JIS DI_{15}^{30} data in Fig. 1 and 2, visually appear to be well scattered. The data in Fig. 1, 2 and 3 were treated statistically using least-squares regression models, the details of which appear in appendices C, D and E. The regression models, chosen to relate the stability to the CRPL JIS DI_{15}^{30} or DI_{15}^{150} indices, appear in Table 2 and are plotted in the figures.

For the data in Fig. 1 and 2, comparing stability and CRPL JIS DI_{15}^{30} indices, it was shown that linear, parabolic, quartic, exponential, power and semi-log models could all be used in regressing the data in the 30-55 stability range (Appendices C and D). The quartic and parabolic models were found better for estimating functions for stability factors of 55-60 which is the range of most interest to steel makers. Since there is no proven method to relate the different tumbler test results, the quartic model was chosen since it includes more variables than other models and allows data trends to be followed more closely. The coefficients of this model are given in Table 2; the limits of prediction lie in the 30-60 stability range.

The comparison between the stability and CRPL JIS DI_{15}^{150} indices given in Fig. 3 was found to be adequately described by a modified linear regression model using the Visman and Picard method (12), the details of which appear in Appendix E. Since the modified regression slope lay closer to the slope of the regression model that assumed all of the error was inherent in the stability factor results (X on Y), it can be concluded that the ASTM stability factor is a more sensitive indicator of differences in coke quality than the JIS DI_{15}^{150} index (12). This is in agreement with previous work where ASTM test results have been shown to be more reproducible between different laboratories and are superior to JIS indices because of their ability to distinguish between coke tumbler strength (4,15).

Figures 1 and 2 also include plots of ASTM/JIS relationships derived or taken from previous Japanese work (16,17). It can be seen that the Japanese ASTM/JIS relationships are displaced from the CRPL equation, although they are also of a non-linear form. This displacement could result from the Japanese relationships being derived using a narrower range of coke quality typical of that produced in a commercial coke plant and may be biased by the coke sampling point in the Japanese steel-plant. For example, the tumbler quality of coke taken at the coke-oven (wharf) is significantly lower than the tumbler quality of the same coke at the blast furnace, owing to the mechanical conditioning of the coke in the intervening handling.

Figures 1 and 2 and the regression expressions in Table 2 were used to determine the influence of the size of coke being tested on the resulting DI_{15}^{30} index. It has been shown that the size of coke used in a coke tumbler test can change the resulting coke quality parameters (18,19,20). Two studies indicated that the JIS DI_{15}^{30} index was greater for 2-in. by 3-in. than for plus 3-in. coke, which is in agreement with findings in this report. A t-test indicated that the mean difference of 0.49 (s = standard deviation ≃ 0.35) between the pre- and post-1972 CRPL JIS DI_{15}^{30} indices (calculated by integrating the difference between the regression expressions in Table 2) is statistically equivalent to a mean difference of 0.87 (s = 0.25) determined from similar experimental data in Reference 21. Consequently all data were used to calculate a mean difference of 0.65 (s ≃ 0.3) to represent the increase in the DI_{15}^{30} index that would be expected in the current as compared with the pre-1972 CRPL results for blast-furnace quality coke.

The data in Reference 21 were used to estimate the differences that exist in the JIS DI_{15}^{30} index values obtained at CRPL compared with those obtained with the standard method. Statistical analysis of the data determined for blast-furnace quality coke suggests that the pre-1972 CRPL procedure using plus 3-in. coke gives results that are more similar to the standard results than the current CRPL procedure using 2-in. by 3-in. coke. The 2-in. by 3-in. coke is estimated to give JIS DI_{15}^{30} values for blast-furnace quality coke that are about 1 unit higher (s = 0.5) than by the standard test. This difference can be important since changes of less than

1 DI_{15}^{30} unit are considered significant in Japan, especially for coke of DI_{15}^{30} values above 91.5.

It can be seen that the spread in the data is greater in Fig. 1 than in Fig. 2, particularly for the weaker coke with a stability factor of <45. This is probably due to the use of less consistently sized material to generate the data in Fig. 1. This observation is similar to that observed in Reference 21 and agrees with Russian work that suggests one method of getting blast-furnace coke of higher, more consistent quality is to do mechanical work on it to generate a narrower size range before using it in the blast furnace (21).

The JIS DI_{15}^{30} test results do not seem able to differentiate between the strengths of high quality coke and those of the ASTM stability test, although the results in Fig. 3 suggest the JIS DI_{15}^{150} test is closer to the ASTM test and should be preferred to the DI_{15}^{30} method. This observation agrees with other authors (4,5,15,16). Russian work has shown that the rates of abrasion and shattering reach their maxima at about 20-30 drum revolutions and tend to even out after about 100-150 revolutions (22). Their results indicate that the JIS DI_{15}^{30} test was run for too few drum revolutions, leading to more variable and insensitive results than from the ASTM method, in agreement with observations of the present authors.

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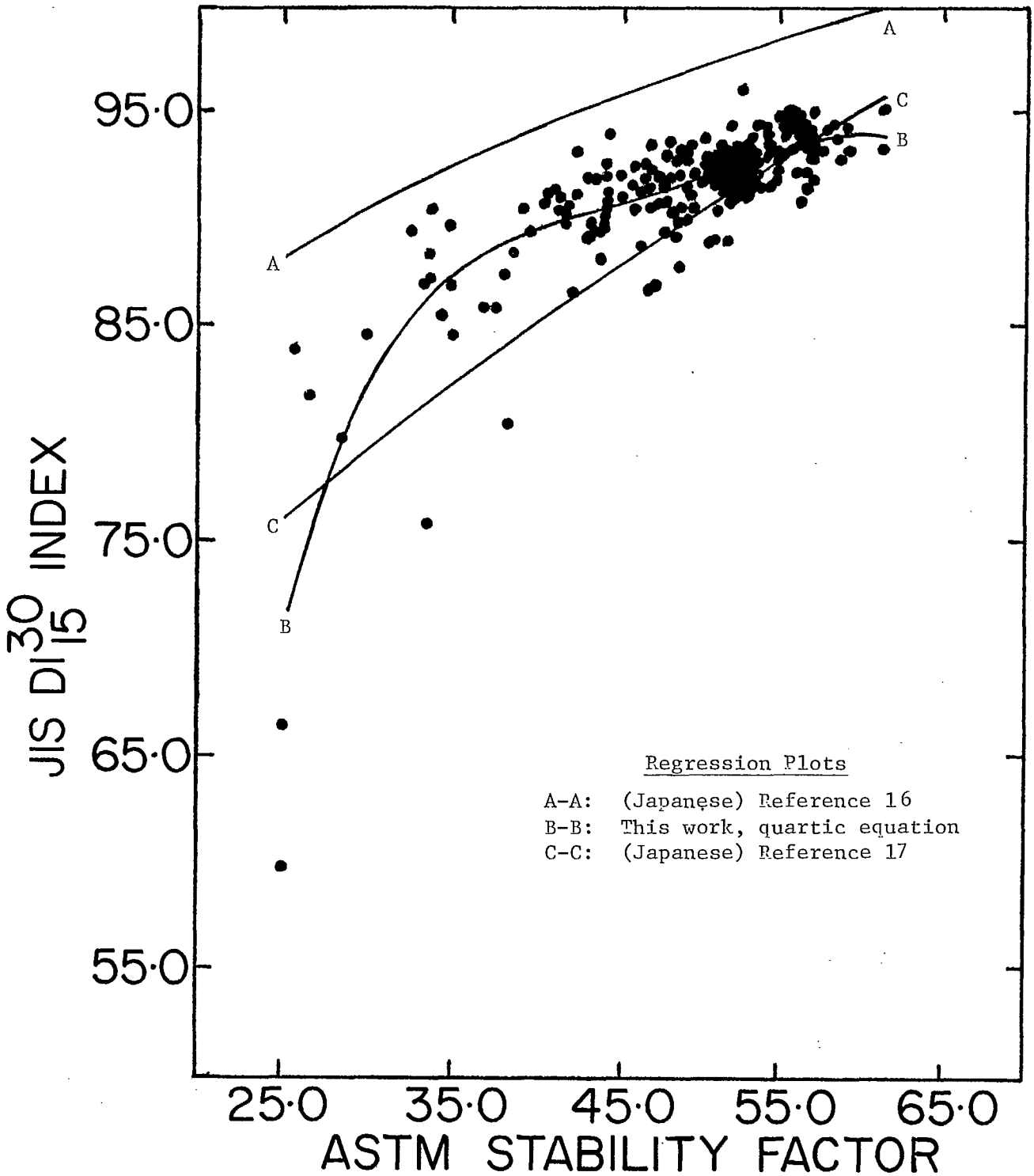

FIGURE 1: Correlation between the pre-1972 CRPL JIS DI_{15}^{30} Index determined with plus 3-in. coke and the ASTM Stability factor

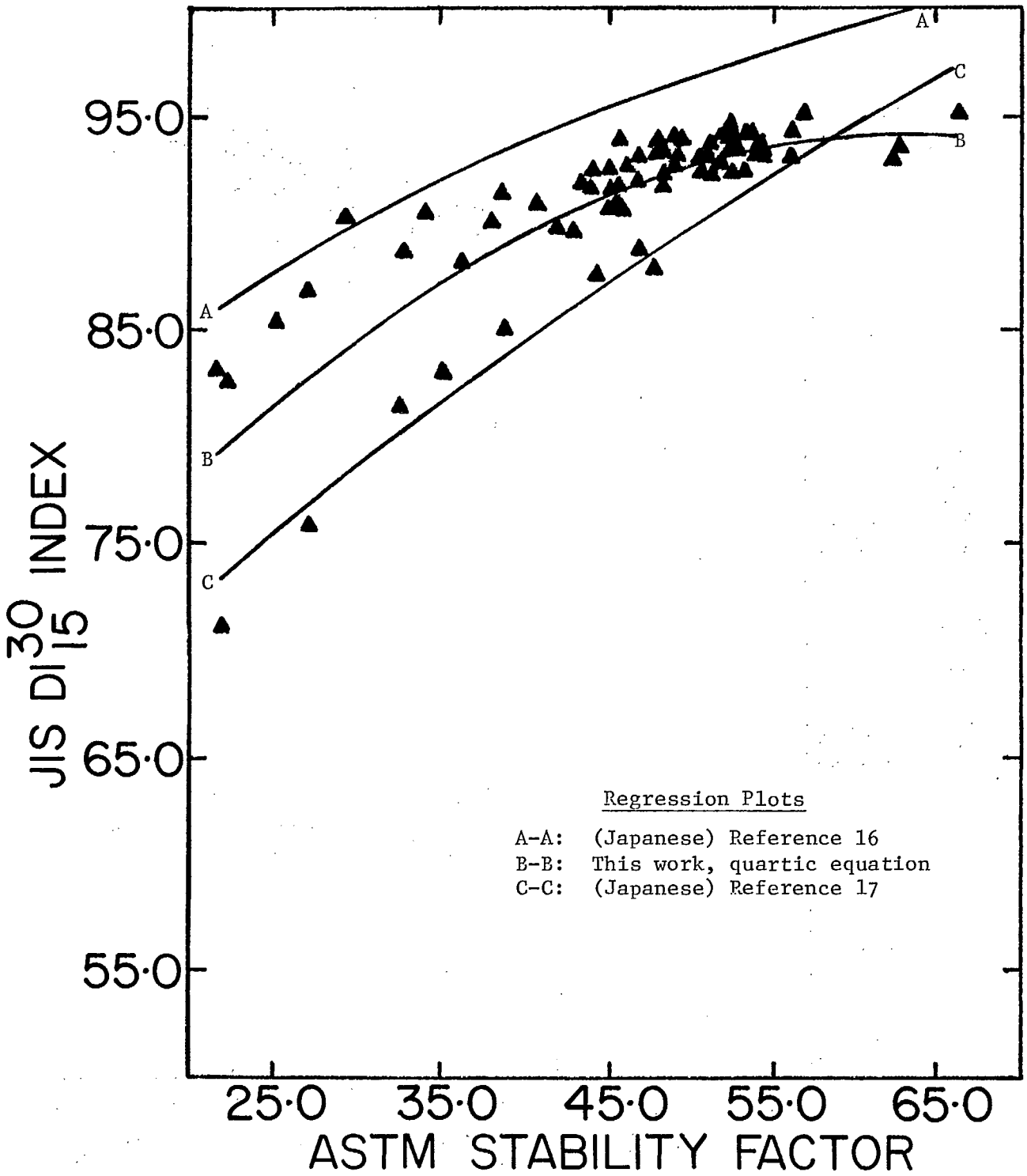

FIGURE 2: Correlation between the post-1972 CRPL JIS DI_{15}^{30} Index determined with 2-in. by 3-in. coke and the ASTM Stability factor

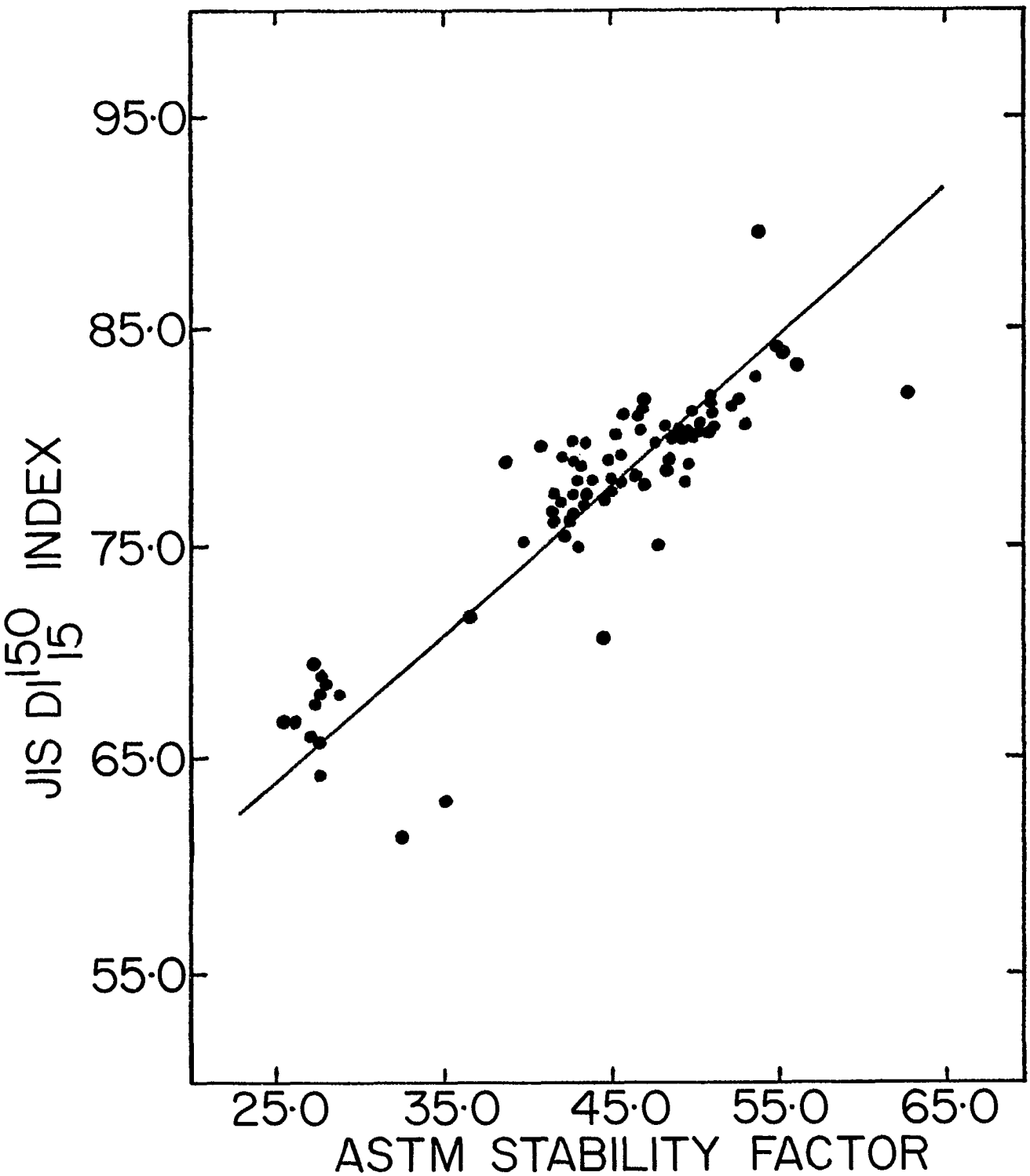

FIGURE 3: Correlation between the CPRL JIS DI_{15}^{150} Index determined with 2-in. by 3-in. coke and the ASTM Stability factor

TABLE 1

Size Consist of Coke Used in JIS
Coke Tumbler Test Methods

Test Method	Size Consist of Coke Tested (in.)
Standard JIS coke tumbler test (11)	+2
1961 to 1972 - CRPL JIS method	+3
1972 to present - CRPL JIS method	-3 x +2

TABLE 2

Regression Models for the ASTM Stability Versus CRPL JIS DI_{15}^{30} or DI_{15}^{150} Relationships*

Figure No	Comparison X	Comparison Y	Regression Model	Range of X For Which Model Is Valid
1.	Stability	DI_{15}^{30} (using plus 3-in. coke)	$Y = -247.649 + 27.9042\ X - 0.871400\ X^2 + 1.21249 \times 10^{-2}\ X^3 - 6.28613 \times 10^{-5}\ X^4$	35 to 60
2.	Stability	DI_{15}^{30} (using 2-in. by 3-in. coke)	$Y = 60.4582 + 1.09900X - 1.19356 \times 10^{-2}\ X^2 + 9.37569 \times 10^{-5}\ X^3 - 7.40236 \times 10^{-7}\ X^4$	25 to 65
3.	Stability	DI_{15}^{150} (using 2-in. by 3-in. coke)	$Y = 46.4 + 0.696\ X$	25 to 60

* Details in Appendices C, D and E

APPENDIX A

A SUMMARY OF THE ASTM AND JIS COKE TUMBLER TESTS

The ASTM tumbler test for coke is carried out at CPRL according to the ASTM Standard (a). In this test, 22 lb of 2-in. by 3-in. coke is tumbled for 1400 revolutions at 24 ± 1 rpm in a 3-ft diam by 1.5-ft long cylindrical drum equipped with two equispaced 2-in. lifters set at 90 degrees to the drum wall. All the tumbled coke is screened over two square mesh sieves having hole diameters of 1 and 0.25 in. respectively, and the percentages remaining on these screens are called the stability and hardness factors respectively.

The Japanese coke tumble standards specify that 10 kg of plus 2-in. coke be tumbled for 30 and 150 revolutions at 15 ± 5 rpm in a 1.5-m diameter by 1.5-m long cylindrical drum equipped with six equispaced 0.25-m wide lifters set 90 degrees to the drum wall (b). The coke is tumbled for 2 min or 30 revolutions and is screened over square mesh sieves having hole diameters of 50, 25 and 15 mm. The cumulative percentage remaining on the 15-mm sieve after 30 revolutions is known as the JIS DI_{15}^{30} index. In a recent test modification, the coke sample is reconstituted and tumbled for an additional 8 min for a total of 150 revolutions, after which it is screened again. The cumulative percentage retained on the 15-mm screen after 150 revolutions is known as the JIS DI_{15}^{150} index.

(a) "Tumble test for coke, ASTM standard method for test, designation: D 294-64 (reapproved 1972)"; Annual Book of Standards, Part 26 - Gaseous Fuels, Coal and Coke, Atmospheric Analysis; American Society for Testing and Materials, Philadelphia; 1974.

(b) "Japanese testing method for coke strength"; Japanese Industrial Standard JIS K 2151-1972, Translation by Y. Okuyama, Nippon Kokan KK, Technical Research Centre, Kawasaki, Japan.

APPENDIX B

DATA USED TO CORRELATE THE ASTM AND JIS COKE TUMBLER TEST RESULTS

The data used to correlate the ASTM and JIS coke tumbler test strengths appear in tabular form in this appendix. Cokes prepared in several ovens were used in obtaining the data. The ovens are identified by name, or by their coking chamber width and year of construction. For example 12"-61 was a 12-in. wide coking chamber oven built in 1961. The oven test or J number refers to a particular test in the oven indicated.

ASTM stabilities determined in Ottawa were corrected to reflect wear in the Ottawa ASTM drum, whereas no adjustments were made to results from the Koppers oven that used the new ASTM Edmonton drum, or to any of the JIS results as no significant JIS drum wear was detected.

TABLE B-1: Comparative Data

No.	Sample Identification		Tumbler Test Results			
	Oven	Test or J No.	DI^{30}_{15}	DI^{150}_{15}	ASTM Stability	Corrected ASTM Stab.
1	12"-61	139	81.8		27	26.8
2	"	150	93.4		52.8	52.6
3	"	152	91.2		46.7	46.5
4	"	160	91.8		52.8	52.6
5	"	159	85.9		37.9	37.7
6	"	191	92.0		50.9	50.7
7	"	192	91.2		48.3	48.1
8	"	208	93.0		57.9	57.7
9	"	201	91.4		47.9	47.7
10	"	202	91.3		45.6	45.4
11	"	200	93.5		53.6	53.4
12	"	204	90.6		42.4	42.2
13	"	203	92.0		43.7	43.5
14	"	239	84.5		30.5	39.15
15	"	240	86.9		34.0	33.65
16	"	238	87.1		34.2	33.85
17	"	241	90.7		41.2	40.85
18	"	261	94.0		58.5	58.15
19	"	262	93.1		55.0	54.65
20	"	263	94.0		55.8	54.45
21	"	264	93.2		53.5	53.15
22	"	299	91.9		44.2	43.85
23	"	303	93.5		48.7	47.35
24	"	317	90.9		53.5	53.15
25	"	304	89.5		36.7	36.35
26	"	305	94.3		53.0	52.65
27	"	306	90.9		45.8	45.45
28	"	308	93.6		48.7	48.35
29	"	310	92.8		49.6	49.25
30	"	311	91.4		41.6	41.25
31	"	312	90.2		42.4	42.05
32	"	364	93.5		55.1	54.6
33	"	366	92.6		49.9	49.4
34	"	368	93.0		53.9	53.4
35	"	369	91.8		52.9	52.4
36	"	402	92.7		54.9	54.4
37	"	414	91.0		42.3	41.8
38	"	429	93.2		43.5	43.0
39	"	439	92.0		45.5	45.0
40	"	437	88.4		34.5	34.0
41	"	447	91.4		47.5	47.0
42	"	445	91.3		51.9	51.4
43	"	527	93.2		57.6	57.1
44	"	518	89.8		42.7	42.2
45	"	488	94.5		57.2	56.7
46	"	484	93.1		54.3	53.8
47	"	494	94.1		56.8	56.3
48	"	499	92.3		53.1	52.6
49	"	496	94.8		56.2	55.7
50	"	497	93.2		56.1	55.6
51	"	498	92.8		52.8	52.3
52	"	501	92.1		52.6	51.1

TABLE B-1 Cont'd

No.	Sample Identification		Tumbler Test Results			
	Oven	Test or J No.	DI^{30}_{15}	DI^{150}_{15}	ASTM Stability	Corrected ASTM Stab.
53	12"-61	502	92.0		55.7	55.2
54	"	500	92.7		52.2	51.7
55	"	580	92.8		50.2	49.55
56	"	574	91.8		49.2	48.55
57	"	576	91.7		48.4	47.75
58	"	619	91.3		41.6	40.95
59	"	573	86.7		36.1	35.45
60	"	601	91.9		45.3	44.65
61	"	602	83.7		26.4	25.75
62	"	586	85.9		38.0	37.35
63	"	590	91.4		43.7	43.05
64	"	637	86.8		48.4	47.75
65	"	636	91.4		57.6	56.95
66	"	638	92.4		53.2	52.55
67	"	633	92.0		52.4	52.75
68	"	634	93.7		58.2	57.55
69	"	593	66.3		26.1	25.45
70	"	577	92.1		52.5	51.85
71	"	594	75.8		34.4	33.75
72	"	578	90.5		50.6	49.95
73	"	595	92.1		48.2	47.55
74	"	597	89.7		44.5	43.85
75	"	596	91.6		48.5	47.85
76	"	635	93.3		62.2	61.55
77	"	598	93.3		56.7	56.05
78	"	631	93.6		54.4	53.75
79	"	632	96.0		53.7	53.05
80	"	660	94.0		45.5	44.85
81	"	661	89.0		51.8	51.15
82	"	662	88.3		39.6	38.95
83	"	663	93.0		49.0	48.35
84	"	664	90.5		48.2	47.65
85	"	688	92.5		45.4	44.6
86	"	694	89.5		45.1	44.3
87	"	712	92.3		52.1	51.3
88	"	705	91.7		51.6	50.8
89	"	709	90.4		45.6	44.8
90	"	716	90.1		50.7	49.9
91	"	708	92.3		53.0	52.2
92	"	715	91.8		52.5	51.7
93	"	706	92.8		50.3	49.5
94	"	713	90.4		52.4	51.6
95	"	707	92.0		53.8	53.0
96	"	714	91.9		54.8	54.0
97	"	710	92.0		52.1	51.3
98	"	717	92.3		52.7	51.9
99	"	711	90.6		53.1	52.3
100	"	704	92.1		57.8	57.0
101	"	726	92.4		56.0	55.2
102	"	727	92.6		52.9	52.1
103	"	729	89.0		44.4	43.6
104	"	728	84.6		36.2	35.4
105	"	725	89.4		44.7	43.9

TABLE B-1 Cont'd

No.	Sample Identification		Tumbler Test Results			
	Oven	Test or J No.	DI^{30}_{15}	DI^{150}_{15}	ASTM Stability	Corrected ASTM Stab.
106	12"-61	739A	91.2		50.5	49.7
107	"	738	91.6		49.4	48.6
108	"	737	89.9		45.3	44.5
109	"	773	92.5		52.2	51.4
110	"	774	91.6		52.0	51.2
111	"	769	92.7		55.3	54.5
112	"	775	91.6		54.2	53.4
113	"	770	91.4		53.2	52.4
114	"	777	92.0		50.6	49.65
115	"	776	79.8		29.6	28.65
116	"	724	88.8		47.9	46.85
117	"	780	90.9		52.6	51.65
118	"	788	92.7		58.3	57.35
119	"	783	91.4		54.8	53.85
120	"	784	92.6		54.7	53.75
121	"	772	91.7		51.5	50.55
122	"	771	89.4		40.9	39.95
123	"	787	85.3		35.9	34.95
124	"	789	92.1		56.2	55.25
125	"	790	90.7		45.6	44.65
126	"	791	92.9		56.2	55.25
127	"	792	92.2		51.7	50.75
128	"	799	91.6		49.7	48.75
129	"	797	93.4		60.5	59.55
130	"	798	91.5		50.6	49.65
131	"	800	90.6		56.5	55.55
132	"	830	90.8		43.5	42.55
133	"	834	91.1		52.4	51.45
134	"	826	90.3		47.2	46.25
135	"	832	80.4		39.8	38.85
136	"	835	92.9		51.7	50.75
137	"	836	91.1		45.7	44.75
138	"	838	93.6		57.8	56.85
139	"	840	92.7		60.1	59.15
140	"	842	91.6		49.4	48.45
141	12"-71	25	89.1		49.6	48.65
142	"	24	90.3		40.5	39.55
143	12"-61	880	93.6		54.8	53.7
144	"	872	93.0		53.5	52.4
145	"	873	93.4		51.0	49.9
146	"	877	92.9		54.0	52.9
147	"	874	93.6		58.7	57.6
148	"	876	93.4		54.9	53.8
149	"	875	92.5		52.1	51.0
150	"	878	92.1		54.3	53.2
151	"	881	92.5		53.4	52.3
152	"	883	92.5		51.7	50.6
153	"	882	92.5		52.7	51.6
154	12"-71	48	93.1		55.7	54.6
155	"	51	94.2		59.6	58.5
156	"	52	91.3		50.5	49.4
157	12"-61	888	90.4		49.5	48.4

TABLE B-1 Cont'd

No.	Sample Identification		Tumbler Test Results			
	Oven	Test or J No.	DI^{30}_{15}	DI^{150}_{15}	ASTM Stability	Corrected ASTM Stab.
158	12"-61	892	90.9		53.5	52.4
159	"	893	88.9		53.1	52.0
160	12"-71	54	95.0		63.0	61.9
161	"	53	91.9		52.2	51.1
162	"	67	92.6		48.4	47.3
163	"	70	91.3		47.4	46.3
164	12"-61	897	89.6		50.1	49.0
165	"	896	94.3		55.3	54.2
166	"	895	92.3		47.2	46.1
167	12"-71	71	93.4		50.3	49.2
168	"	68	92.0		50.4	49.3
169	"	82	86.5		43.8	42.7
170	"	83	93.6		57.2	56.1
171	"	94	94.1		56.4	55.3
172	"	106	92.7		50.0	48.9
173	"	100	93.6		56.6	55.5
174	"	97	94.1		57.0	55.9
175	"	101	94.0		55.0	53.9
176	"	107	91.7		49.8	48.7
177	"	110	89.3		34.3	33.2
178	"	103	94.8		57.4	56.3
179	"	105	94.2		57.8	56.7
180	"	120	92.8		50.7	49.6
181	"	109	90.3		35.3	34.2
182	"	60	93.7		60.0	58.9
183	"	62	92.2		50.6	49.5
184	12"-61	446	92.9		52.6	52.1
185	"	583	92.4		50.7	49.95
186	"	603	93.3		51.9	50.25
187	"	604	93.0		51.7	50.85
188	"	894	86.5		48.3	47.2
189	"	905	92.1		52.3	51.2
190	"	575	90.8		46.3	45.45
191	"	730	87.2		39.6	38.6
192	"	731	91.6		53.7	54.9
193	"	788	92.7		58.3	57.35
194	"	814	88.1		45.5	44.55
195	"	831	89.2		49.1	48.15
196	"	788	92.7		58.3	57.35
197	"	814	88.1		45.5	44.55
198	"	831	89.2		49.1	48.15
199	"	503	94.7		55.8	55.15
200	"	497	93.9		57.5	56.85
201	"	504	92.5		54.7	53.05
202	"	498	89.2		45.2	44.55
203	"	494	95.0		57.9	57.25
204	"	488	94.3		57.2	56.55
205	"	500	91.9		52.1	51.45
206	"	505	93.5		52.2	51.55
207	"	501	92.2		51.4	50.75
208	"	506	92.0		53.8	53.15
209	"	502	91.8		54.6	53.95

TABLE B-1 Cont'd

No.	Sample Identification		Tumbler Test Results			
	Oven	Test or J No.	DI^{30}_{15}	DI^{150}_{15}	ASTM Stability	Corrected ASTM Stab.
210	12"-61	507	92.1		56.8	56.15
211	"	499	93.3		53.3	52.65
212	"	508	91.3		52.9	52.25
213	"	793	60.0		26.1	25.05
214	"	801	87.6		50.2	49.15
215	"	802	93.2		55.8	54.75
216	"	808	93.6		57.5	56.45
217	"	809	90.1		50.3	49.25
218	"	879	92.7		50.0	48.9
219	"	783	91.5		55.4	54.45
220	"	784	92.8		54.4	53.45
221	"	785	91.2		54.1	53.15
222	"	786	92.4		54.9	53.95
223	"	882	92.5		52.7	51.6
224	12"-71	63	92.2		50.6	49.5
225	"	52	93.8	81.1	51.0	49.9
226	"	56	92.8	80.3	50.4	49.3
227	"	51	91.8	77.0	44.7	43.6
228	"	57	91.5	78.0	45.1	44.0
229	"	32	92.0		52.3	51.2
230	"	33	91.9		50.9	49.8
231	"	30	92.6		50.5	49.4
232	"	31	92.8		50	49.1
233	"	26	92.0		49.1	48.9
234	"	27	90.6		52.9	48.0
235	"	28	92.6		23.9	51.8
236	"	55	94.6		58.5	57.4
237	"	59	94.6		58.7	57.6
238	"	60	94.1		57.1	56.0
239	"	56	94.4		58.2	57.1
240	"	58	94.5		56.4	55.3
241	"	53	94.4		59.0	57.9
242	"	57	93.8		58.1	57.0
243	"	54	94.2		60.5	59.4
244	"	112	93.3		55.8	54.55
245	"	120	92.5		50.7	49.45
246	"	90	93.8		54.8	53.7
DATA RELATED TO 2" x 3" JIS COKE SIZE						
247	12"-71	141	91.8		47.7	46.45
248	"	147	90.9		42.4	41.15
249	"	148	90.6		46.8	45.55
250	"	153	88.6		48.2	46.95
251	"	158	93.0		52.8	51.55
252	"	154	92.6	81.4	53.6	52.35
253	"	155	92.4	82.0	53.3	52.05
254	"	157	92.8	81.0	52.2	50.95
255	"	166	81.5	61.4	33.8	32.55
256	"	183	94.1	82.7	54.9	53.65
257	"	161	92.0	78.5	49.8	48.55
258	"	173	91.2	78.9	40.0	38.75
259	"	180	83.1	63.1	36.4	35.15

TABLE B-1 Cont'd

No.	Sample Identification		Tumbler Test Results			
	Oven	Test or J No.	DI^{30}_{15}	DI^{150}_{15}	ASTM Stability	Corrected ASTM Stab.
260	12"-71	179	87.8	75.0	49.3	48.05
261	"	181	91.5		46.8	45.55
262	"	156	90.5	77.5	47.5	45.25
263	"	189	92.9		51.7	50.45
264	"	190	95.1		58.8	57.35
265	"	200	93.4		54.4	53.15
266	"	199	92.2		52.5	51.25
267	"	202	93.0		63.8	62.55
268	"	201	95.0		67.9	66.65
269	"	222	71.3		23.7	22.45
270	"	223	76.0		28.4	27.15
271	"	232	88.0	71.6	37.8	36.55
272	"	233	85.5	66.8	26.8	25.55
273	"	230	86.9	69.4	28.7	27.45
274	"	239	89.4		44.4	43.0
275	"	J-4417		89.5	55.5	54.10
276	"	252	87.4	70.6	46.1	44.70
277	"	256	94.5	81.8	54.2	52.80
278	"	264	93.7	82.0	64.4	63.0
279	"	267	93.0	83.3	57.8	56.4
280	"	270	92.0	78.7	51.1	49.7
281	"	276	92.5	77.8	48.6	47.2
282	"	277	93.9	81.0	47.4	46.0
283	"	282	93.0	81.3	48.5	47.1
284	"	281	94.0	80.6	54.7	53.3
285	"	280	89.8		43.5	42.1
286	"	288	90.0	75.5	43.7	42.3
287	"	253	88.6		34.2	32.8
288	"	257	89.9		39.6	38.2
289	"	254	92.0		47.7	46.3
290	"	255	92.5		46.8	45.4
291	"	258	93.3		49.7	48.3
292	"	259	93.8		49.5	48.1
293	"	367	93.9		51.9	51.4
294	"	368	92.6		51.9	51.4
295	"	369	92.4		44.3	43.8
296	"	370	91.9		47.0	46.5
297	"	372	91.5		44.2	43.7
298	"	373	91.5		46.1	45.6
299	"	375	94.0		49.2	48.7
300	"	376	93.3		48.7	48.2
301	"	386	92.6		49.1	48.6
302	"	325	92.3		53.9	53.4
303	"	384	85.2		39.4	38.9
304	"	144	82.7		23.9	22.35
305	"	145	83.2		23.2	21.65
306	"	154	90.2		31.3	29.75
307	"	315	93.1		55.9	54.5
308	"	317	92.2		54.0	52.6
309	"	318	94.2		56.3	54.9
310	"	322	94.0		57.7	56.3

TABLE B-1 Cont'd

No.	Sample Identification		Tumbler Test Results			
	Oven	Test or J No.	DI^{30}_{15}	DI^{150}_{15}	ASTM Stability	Corrected ASTM Stab.
311	12"-71	241	93.6		54.9	53.5
312	"	242	93.4		54.1	52.7
313	"	189	92.7	80.7	51.7	50.45
314	"	182	93.1		51.0	49.75
315	"	200	93.4		54.4	53.15
316	"	202	93.0		63.8	62.55
317	"	155	92.4	82.0	53.3	51.05
318	"	183	94.1	82.7	54.9	53.65
319	"	147	90.9		42.4	41.15
320	"	148	90.6		46.8	45.55
321	"	210	92.5		51.0	49.6
322	"	216	92.8		51.1	49.7
323	"	211	93.1		56.5	55.1
324	"	217	93.7		55.7	54.3
325	"	214	93.4		53.9	52.5
326	"	226	93.5		52.7	51.3
327	"	227	92.2		52.2	50.8
328	"	231	93.9		53.9	52.5
329	"	212	93.9		53.4	52.0
330	"	218	93.9		53.8	52.4
331	"	213	92.5		52.6	51.2
332	"	220	93.4		55.5	54.1
333	Koppers	Fr-2		77.4	43.7	
334	"	Fr-3		81.5	51.1	
335	"	Fr-4		80.2	51.1	
336	"	Lv-1		84.0	55.5	
337	"	Lv-4		84.2	55.1	
338	"	Lv-2		76.2	42.6	
339	"	Lv-3		74.8	43.0	
340	"	45		80.4	51.2	
341	"	43		76.4	41.6	
342	"	44		76.2	41.6	
343	"	42		78.0	49.7	
344	"	C-1		80.1	49.3	
345	"	C-2		80.3	49.8	
346	"	C-6		78.7	43.2	
347	"	C-7		68.5	28.1	
348	"	C-8		66.1	27.3	
349	"	C-10		67.9	27.7	
350	"	C-11		64.3	27.7	
351	"	C-12		67.4	27.4	
352	"	C-13		65.9	27.6	
353	"	C-5		79.8	42.9	
354	"	C-14		81.7	47.2	
355	"	C-15		80.9	46.9	
356	"	C-21		77.4	41.6	
357	"	C-22		79.0	42.2	
358	"	C-23		78.9	42.8	
359	"	Mc-2		81.1	51.0	
360	"	Mc-1		77.0	44.7	
361	"	Mc-3		80.3	50.4	

TABLE B-1 Cont'd

No.	Sample Identification		Tumbler Test Results			
	Oven	Test or J No.	DI^{30}_{15}	DI^{150}_{15}	ASTM Stability	Corrected ASTM Stab.
362	Koppers	Mc-4		78.0	45.1	
363	"	64		79.4	40.9	
364	"	65		80.9	50.7	
365	"	C-16		66.5	26.2	
366	"	C-17		68.8	27.9	
367	"	C-18		68.0	28.7	
368	"	C-24		80.0	45.5	
369	"	C-25		79.1	45.8	
370	"	Fr-1		76.4	42.9	
371	"	C-26		78.0	45.8	
372	"	C-16		79.6	43.6	
373	"	C-27		78.9	45.0	
374	"	C-28		77.9	43.1	
375	"	C-29		76.9	42.1	
376	"	C-31		79.9	49.3	
377	"	C-32		79.9	48.9	
378	"	C-33		75.1	39.8	
379	"	C-35		77.3	42.8	
380	"	C-37		78.6	43.3	
381	"	C-36		78.1	46.4	
382	"	C-3		79.8	47.8	
383	"	C-4		80.5	48.5	
384	"	C-9		80.4	47.1	

APPENDIX C

ASTM STABILITY VERSUS PRE-1972 CRPL MODIFIED JIS DI_{15}^{30} REGRESSION ANALYSES

Table C-1 contains details of the regression analyses carried out to relate the ASTM stability factor to the pre-1972 CRPL JIS DI_{15}^{30} index determined using plus 3-in. coke. The resulting regression equations are plotted in Figure C-1.

The definitions of the symbols used in the tables of Appendices C, D and E are:

$\bar{X}$	:	mean of X
s_X	:	standard deviation of X
$\bar{Y}$	:	mean of Y
s_Y	:	standard deviation of Y
REG. SS	:	regression sum of squares of deviation
RES. SS	:	residual sum of squares is the sum of squares of deviations
Tot. SS	:	total sum of squares
REG. MS	:	regression mean sum of squares
RES. MS	:	residual mean sum of squares
R	:	correlation coefficient

The constants associated with the regression models are defined in the appendices tables, for the particular form of the equation analyzed.

TABLE C-1

Summary of Least-squares Regression Analyses to Compare:
ASTM Stability Factor and the CRPL pre-1972 JIS DI_{15}^{30} Results Determined with plus 3-in. Coke

Regression Details	Regression Model					
1. Coefficients:	$Y=A+BX+CX^2+DX^3+EX^4$	$Y=A+BX+CX^2$	$Y=A+BX$	$Y=Ae^{BX}$	$Y=AX^B$	$Y=A+B \ln X$
A	- 247.649	36.5	71.3	72.0	38.7	19.4
B	27.9042	2.00	0.405	0.0048	0.22	18.5
C	- 0.871400	- 0.018	-	-	-	-
D	0.0121249	-	-	-	-	-
E	- 6.28613×10^{-5}	-	-	-	-	-
2. Analysis of Variance:						
$\bar{X}$	49.5	49.5	49.5	49.5	49.5	49.5
s_X	45.4	45.4	45.4	45.4	45.4	45.4
$\bar{Y}$	91.4	91.4	91.4	91.4	91.4	91.4
s_Y	13.3	13.3	13.3	13.3	13.3	13.3
Reg. SS	2339.6	2168.7	1810.0	-	-	2006.3
Res. SS	890.7	1061.6	1420.3	-	-	1224.0
Tot. SS	3230.3	3230.3	3230.3	-	-	3230.3
Reg. MS	584.9	1084.3	1810.0	-	-	2006.3
Res. MS	3.727	4.40	5.87	-	-	5.06
Degrees of freedom	243	243	243	243	243	243
Correlation coefficient (R)	0.85	0.82	0.75	0.72	0.76	0.79
F-ratio	157	246	308	262	340	397.7
F-table value	5.66	3.07	3.92	3.92	3.92	3.92
Standard error	-	-	2.42	-	-	2.25

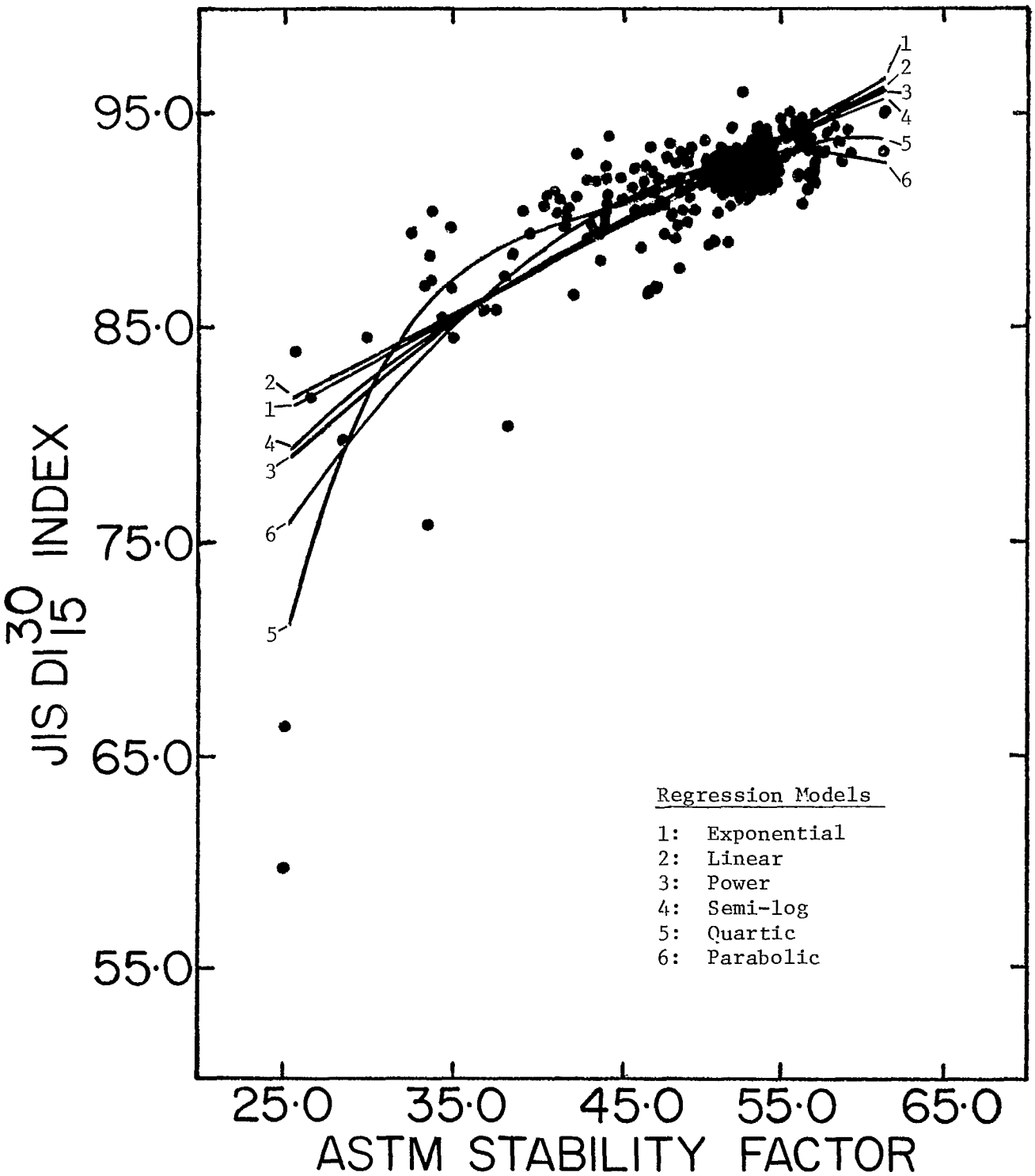

FIGURE C-1: Least Squares Regression Model Plots Relating the ASTM Stability factor and the pre-1972 CRPL JIS DI^{30}_{15} Index determined using plus 3-in. coke

APPENDIX D

ASTM STABILITY VERSUS POST-1972 CRPL MODIFIED JIS DI_{15}^{30} REGRESSION ANALYSES

Table D-1 contains details of the regression analyses carried out to relate the ASTM stability factor to the post-1972 CRPL JIS DI_{15}^{30} index determined using 2-in. by 3-in. coke. Definitions of the nomenclature appear in the introduction to Appendix C. The regression equations from this appendix are plotted in Figure D-1.

TABLE D-1

Summary of Least-squares Regression Analyses to Compare:
ASTM Stability Factor and the CRPL post-1972 JIS DI_{15}^{30} Results Determined with 2-in. by 3-in Coke

Regression Details	Regression Model					
1. Coefficients:	$Y=A+BX+CX^2+DX^3+EX^4$	$Y=A+BX+CX^2$	$Y=A+BX$	$Y=Ae^{BX}$	$Y=AX^B$	$Y=A+B \ln X$
A	60.4582	60.0	74.5	75.2	47.7	35.3
B	1.09900	1.08	0.35	4.1×10^{-3}	0.17	14.6
C	-1.19356×10^{-2}	0.0085	-	-	-	-
D	9.37569×10^{-5}	-	-	-	-	-
E	-7.40236×10^{-7}	-	-	-	-	-
2. Analysis of variance:						
$\bar{X}$	47.1	47.1	47.1	47.1	47.1	47.1
s_X	82.0	82.0	82.0	82.0	82.0	82.0
$\bar{Y}$	91.2	91.2	91.2	91.2	91.2	91.2
s_Y	15.6	15.6	15.6	15.6	15.6	15.6
Reg. SS	959.8	959.5	874.2	-	-	936.7
Res. SS	361.8	362.1	447. 4	-	-	384.9
Tot. SS	1321.6	1321.6	1321.6	-	-	1321.6
Reg. MS	239.9	479.8	874.2	-	-	936.7
Res. MS	4.47	4.36	5.33	-	-	4.58
Degrees of freedom	85	85	85	85	85	85
Correlation coefficient (R)	0.85	0.85	0.81	0.80	0.83	0.84
F-ratio	54	110	164	150	188	205
F-table value	2.45	3.07	3.92	3.92	3.92	3.92
Standard error	-	-	-	-	0.026	2.14

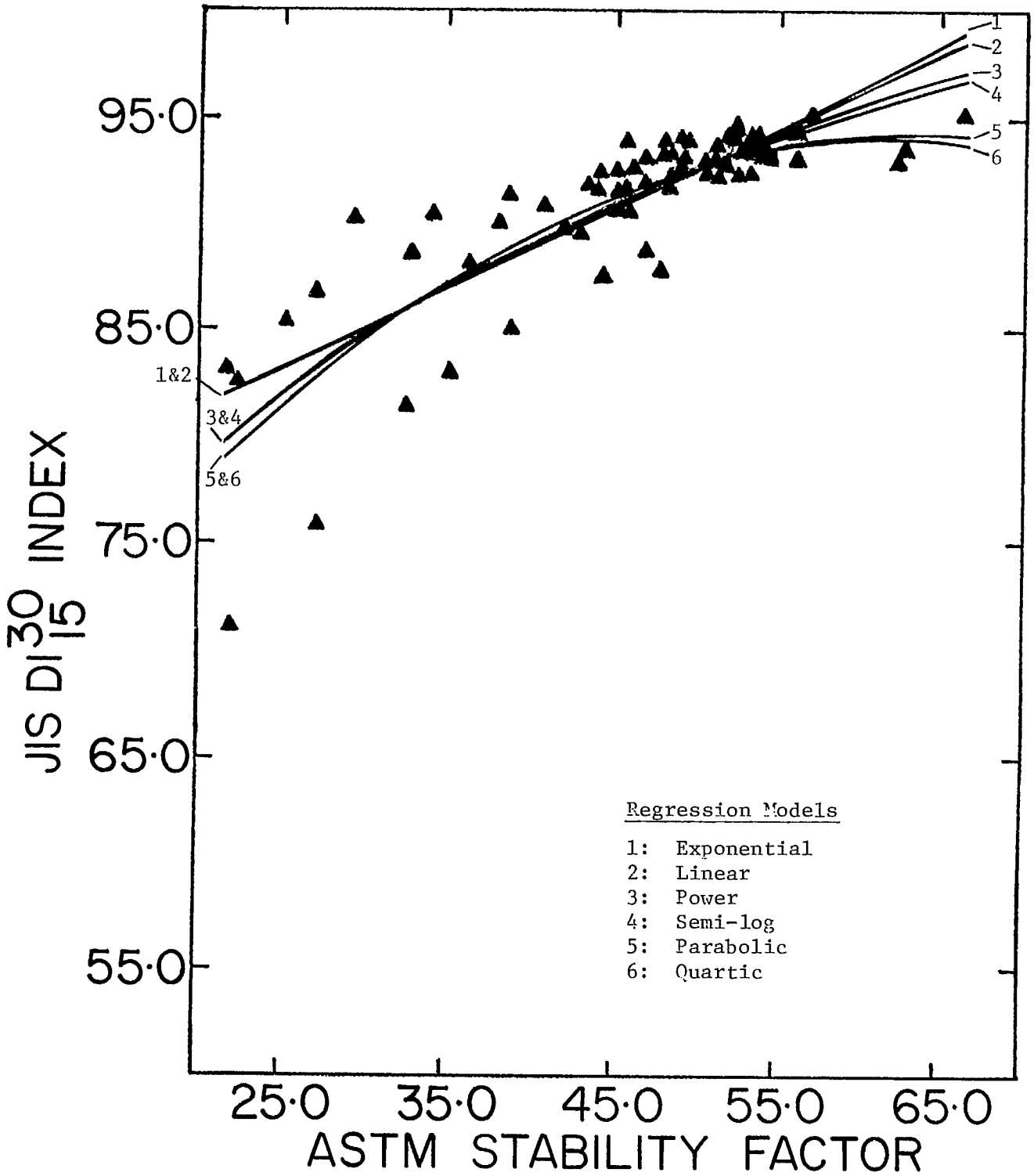

FIGURE D-1: Least Squares Regression Model Plots Relating the post-1972 CRPL JIS DI^{30}_{15} Index determined with 2-in. by 3-in. coke and the ASTM Stability factor

APPENDIX E

ASTM STABILITY VERSUS CRPL MODIFIED JIS DI_{15}^{150} REGRESSION ANALYSES

Table E-1 contains details of the regression analyses carried out to relate the ASTM stability factor to the CRPL JIS DI_{15}^{150} index determined using 2-in. by 3-in. coke. Definitions of the nomenclature appear in the introduction to Appendix C. The regression equations from this appendix are plotted in Figure E-1.

TABLE E-1

Summary of Least-squares Regression Analyses to Compare: ASTM Stability Factor (X) and the CRPL Modified JIS DI_{15}^{150} Index (Y) Determined with 2-in. by 3-in. Coke

Regression Details	Regression Model: Y=A+BX		
1. Coefficients:			
	Error in Y only	Error in X only	Error in both X & Y
A	51.0	44.6	46.4
B	0.59	0.74	0.70
2. Analysis of variance:			
$\bar{X}$	44.3		
s_X	8.22		
$\bar{Y}$	77.3		
s_Y	5.44		
Reg. SS	1949.2		
Res. SS	479.3		
Tot. SS	2428.5		
Reg. MS	1949.2		
Res. MS	5.92		
Degree of freedom	83		
Correlation coefficient (R)	0.90		
F-ratio	329.4		
F-table value (upper 5 percentage points)	4.00		
Standard error	2.43		

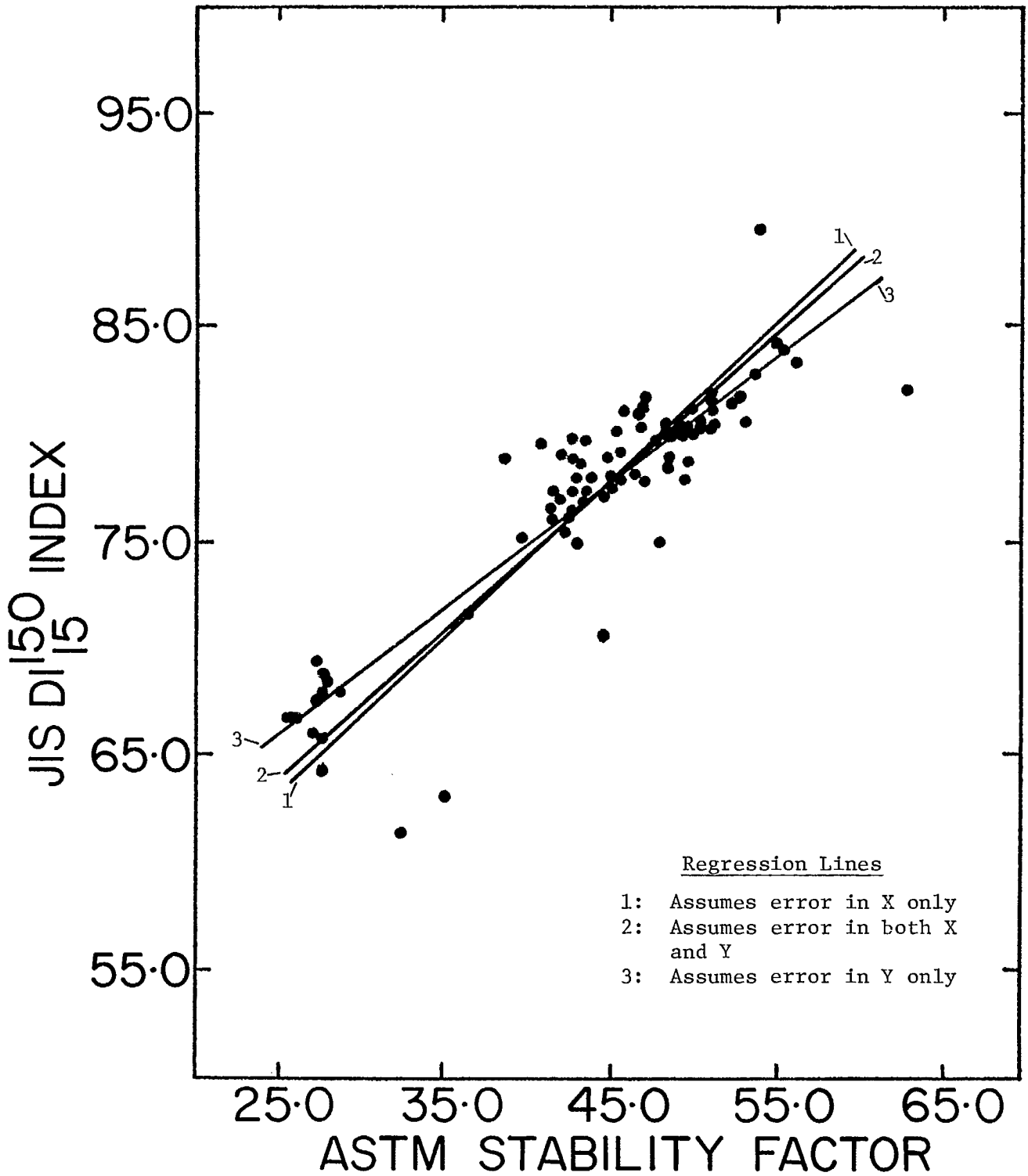

FIGURE E-1: Least Squares Linear Regression Plots Relating the CRPL JIS DI^{150}_{15} Index determined with 2-in. by 3-in. coke with the ASTM Stability factor

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