VAMAS

Technical Working Area 21
Mechanical Tests for Hardmetals

Bend Strength Measurements for Hardmetals International Prestandardisation Collaborative Activity

Part 2 - Analysis of Results

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September 1997
VAMAS Report No 31
ISSN 1016-2186

Versailles Project on Advanced Materials and Standards
Canada, EC, Germany, France, Italy, Japan, UK, USA

[B57:VAMBENA1-V1.8]

VAMAS

The Versailles Project on Advanced Materials and Standards (VAMAS) supports trade in high technology products through international collaborative projects aimed at providing the technical basis for drafting codes of practice and specifications for advanced materials. The scope of the collaboration embraces all agreed aspects of enabling science and technology - databases, test methods, design methods, and materials technology - which are required as a precursor to the drafting of standards for advanced materials. VAMAS activity emphasises collaboration on pre-standards measurement research, intercomparison of test results, and consolidation of existing views on priorities for standardisation action. Through this activity, VAMAS fosters the development of internationally acceptable standards for advanced materials by the various existing standards agencies.

Bend Strength Measurements for Hardmetals International Prestandardisation Collaborative Activity (VAMAS)

Part 2 - Analysis of Results

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ABSTRACT

This report analyses the results obtained in a VAMAS international collaborative activity on bend strength measurements for hardmetals. The interlaboratory tests involved fourteen laboratories, mostly industrial, in eight countries testing seven materials to eleven testpiece geometries. The main purpose of the exercise was to examine the effects on strength of testpiece geometries which are different to the rectangular bars allowed in the current ISO 5227 standard. The alternatives included round and notched testpieces in both 3 and 4 pt bend test configurations. The full set of results of the tests were reported in a previous VAMAS publication (VAMAS Technical Report No 22, June 1996). The hardmetals tested included ultrafine, fine, medium and coarse WC/Co, a medium-fine WC/Cubic Carbide/Co and a Ti(CN) based cermet.

Analysis of the results showed that although very good reproducibility was obtained between the different organisations taking part there were considerable differences in the strength values obtained from the different geometries. It was also found that annealing the as-ground testpieces reduced measurement strength values significantly. This has important consequences for standardisation of the test method.

ISSN 1016-2186

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[B57:VAMBENA1-V1.8]

CONTENTS

1 INTRODUCTION

An international interlaboratory exercise has been performed to provide additional technical data on the Transverse Rupture Test method (bend tests) for Hardmetals, ISO 3327. The exercise was planned to take account of developments in the understanding of strength measurements, the increasing desire for data more relevant to material quality and design, and to work towards a test which can give results comparable to test data obtained on competing materials, such as ceramics and cermets. A number of alternative methods of bend tests for hardmetals to that specified in ISO 3327 were examined, including geometries which can compare with standards for ceramics (3 and 4 pt), tests on small specimens, and unconventional geometries (round and notched), Fig 1. A few tests were also carried out to examine the effect of annealing as-ground surfaces. The results of the exercise have been collated in a VAMAS report [1]. VAMAS is an international organisation set up to harmonise testing practice in the materials field.

2 MATERIALS

Seven materials were provided for test by industry, Table 1; more details are given in the previous VAMAS report [1]. All rectangular testpieces were longitudinally ground to ISO 3327, 0.2 mm chamfer (45^o), out of squareness $\ngtr 2^o$, $\pm$ 0.01 mm tolerance. All the notched testpieces were annealed at 800 ^oC for 1h in a vacuum to remove residual stresses at the notch root. Some of the unnotched testpieces were also annealed before testing. These are appropriately indicated in the data tables given in the Results Set of the earlier VAMAS report [1].

A similar test procedure was used by all the participants. Cylindrical load supports and load points were used with a loading rate of $\ngtr$ 1500 N s^{-1}. Loads were measured to $\pm$ 1%.

3 TESTING AND SCHEDULE

The bend test geometries used in the testing schedules are shown in Fig 1. They included

- Current 3 pt ISO standards (R3a, R3b)
- 4 pt equivalent of ISO Type A - R3b (R4b)
- 3 and 4 pt ceramic testing equivalents (R3c and R4c)
- Notch tests on rectangular testpieces, 3 and 4 pt (RN3a, RN3b and RN4b)
- Round testpieces, 3 and 4 pt (C3 and C4)
- Notched round testpieces, 4 pt (CN4)

The testing schedules were outlined in VAMAS Report No 22.

- Standard (ISO Type B) tests were generally carried out at industry laboratories
- NPL tested all other geometries for all materials
- The testing of other geometries was spread across participating organisations.

Round testpieces were centreless ground to similar tolerances.

Table 1 - Materials
Data supplied by Manufacturers

Source	Type/binder/ grain size	Hardness	Density $Mg\ m^{-3}$	Conditions
Teledyne Advanced Materials (USA)	WC/6wt% Co Ultrafine	92.7 (HRA)	14.87	Sinter plus conventional HIP
Boart Longyear (S Africa)	WC/6wt% Co fine	1520 ± 30 (HV)	14.97	Sinter HIPped 1390 °C/45 bar argon
Sandvik Hard Materials (UK)	WC/10wt% Co fine	1600 (HV30)	14.50	As-sintered
Kennametal (USA)	WC/Cubic Carbide/Co Medium/Fine	91.2 (HRA)	12.62	As-sintered
Sandvik Coromant (Sweden)	Ti(C,N) Cermet 13.7wt% binder Co plus Ni	1660 (HV10)	6.9	As-sintered
Sandvik Coromant (Sweden)	WC/10wt% Co Medium/Coarse	1200 (HV30)	14.48	As-sintered
Boart Longyear (S Africa)	WC/9.5wt% Co Coarse	1050 (HV10) 85.8 (HRA)	14.55	Sinter HIPped 1390 °C/45 bar argon

Table 2 - Failure Stress Formulae
(Bend Tests)

Geometry	Stress, σ	Dimensions	Geometry	Stress, σ	Dimensions
R3a	$\frac{3PL}{2BW^2}$	L = 14.5 mm	C3	$\frac{8PL}{\pi D^3}$	L = 30 mm
R3b	$\frac{3PL}{2BW^2}$	L = 30 mm	C4	$\frac{16PL}{\pi D^3}$	L = 10 mm
R3c	$\frac{3PL}{2BW^2}$	L = 40 mm	RN3a	$\frac{3PL}{B(W-d)^2}$	L = 14.5 mm d = notch depth, nominally 1 mm notch radius = 0.5 mm
R4b	$\frac{3PL}{BW^2}$	L = 10 mm	RN3b	$\frac{3.26PL}{B(W-d)^2}$	L = 30 mm d = notch depth, nominally 1 mm notch radius = 0.5 mm
R4c	$\frac{3PL}{BW^2}$	L = 10 mm	RN4b	$\frac{6.31PL}{B(W-d)^2}$	L = 10 mm d = notch depth, nominally 1 mm notch radius = 0.5 mm
			CN4	$\frac{16kPL}{\pi D^3}$	L = 10 mm k = 3.55 for notch depth = 0.5 mm, notch notch radius = 0.5 mm

4 RESULTS AND DISCUSSION

The full data sets for the tests are given in the previous VAMAS report [1]. The formulae used to calculate the failure stresses are given in Table 2.

The results in the VAMAS report [1] were plotted as a set of data ranked against strength. The rank value (R) was calculated from

$$R = \frac{n_i - 0.5}{N} \tag{1}$$

where n_i is the i^{th} value of strength and N is the total number of tests.

In order to compare strength values from the different geometries and materials several methods for analysing the data were examined:

- By using Weibull analysis on all of the results in a set to investigate whether strength follows the stressed volume systematically (section 4.1 below).
- Through Weibull analysis to obtain a "characteristic strength", σ_o, value (section 4.2 below).
- By averaging the top 3-4 values in the ranked distribution (section 4.2 below).

The effects of annealing on strength values was also investigated by plotting ranked values of strength and comparing them with the results from the as-ground testpiece (section 4.3 below).

4.1 WEIBULL ANALYSIS

A Weibull rank was determined for all the materials and all the geometries. In the Weibull analysis the probability of failure is plotted against the natural logarithm of the strength, ie from:

$$P = 1\text{-}\exp\left(-(\sigma/\sigma_o)^m\right) \tag{2}$$

where $P = (n_i\text{-}0.5)/N$, σ is the bend strength and σ_o and m are constants.

Therefore, rearranging expression (2)

$$\ln(\ln(1/(1-P))) = m\ln\sigma - m\ln\sigma_o \tag{3}$$

Thus, if the full data set fits the Weibull expression then a ln ln plot of 1/(1-P) against ln σ gives a straight line of slope m, the Weibull modulus. Also, when the left hand side of expression (3) is equal to zero then

$$m\ln\sigma = m\ln\sigma_o \tag{4}$$

and σ is characterised by a representative σ_o value, the "characteristic strength" where the plot cuts the horizontal line for ln ln (1/(1-P)) equal to zero.

It is recognised that the reliability of Weibull analysis is poor on small testpiece numbers, and increasingly so for low values of Weibull modulus [2]. However, the principles of the analysis permit some correlations to be made between the different testing geometries, and thus provide a better basis for discussing the results than using arithmetic mean strengths and standard deviations.

Weibull plots for all the materials and all the geometries are given in Section 7 at the end of the report.

Because of the difficulty of analysing mathematically whether data sets belonged to mixed or single mode Weibull behaviour, best fit lines were drawn by eye through the Weibull plots in Section 7 and approximate values for the Weibull modulus were calculated from these lines. These values are given in Tables 3A-G.

It has been shown [3] that for different values of m different numbers of test specimens are required such that sufficiently accurate values of m can be estimated to allow sensible extrapolations to be made from the data. For example [3]:

m	Number of testpieces*
7	70
20	10

* to give accurate estimates for a value of 10^{-6} for the strength probability.

Summary plots of the Weibull ranked data for combined data sets for all the materials in each geometry set are shown in Figs 2a-f. A number of comments can be made about the Weibull m values calculated from the plots but it must be remembered that these are only approximate values and were not regression fitted to the data.

It was found that there were four categories of plot.

1. Those with high values of m (≥ about 20), for example for the R3b geometry Sandvik (medium/coarse) material.

2. Those with low values of m (≤ about 10), for example for most of the Ti(C,N) cermet materials.

3. Those with intermediate m values (20 > m > 10).

4. Those which have two distinct parts to the plot, eg R4c - Boart fine, R4c - Teledyne, R4b - Kennametal. This has been observed previously in tests on hardmetals [3] and was then attributed to failures from two different populations of fracture mechanisms, classed as Type A and Type B.

Type A	-	microstructure initiated
Type B	-	gross defect (pore, inclusion, large WC grain, etc)

For Category 1 plots above, it was therefore assumed that the failures were microstructure initiated, as can be seen in the notch bend testpieces, Fig 3. For Category 2 plots, failures were generally defect initiated, Fig 4. For Category 3 plots, the failure initiated sites need to be individually classified. The current project had insufficient resources to characterise all the fracture surface in all the testpieces (over 1000). However, many of the Ti(C,N) cermets were examined. These were analysed by comparing the stress at the position of the fracture site with the inverse of the square root of defect area (by fitting an ellipse to the shape of the defect), Fig 5, following a procedure discussed in previous work [4,5]. It can be seen that for large defects there is a correspondence between stress and a parameter with units of $\mu m^{-1/2}$, which is indicative of a fracture mechanics correlation; but for small defects the strength attains a limiting value [5].

Weibull analysis can be used to reference the mean strength values to a common level to see if strength follows the stressed volumes or areas in a systematic way:

$$\bar{\sigma}_{nom} = \bar{\sigma}_{ref} \left\{ \frac{V_{ref}}{V\Sigma V} \right\}^{\frac{1}{m}} \text{ or } \bar{\sigma}_{ref} \left\{ \frac{A_{ref}}{A\Sigma A} \right\}^{\frac{1}{m}} \qquad (5)$$

where $\bar{\sigma}_{nom}$ is the mean nominal strength of a test population, $\bar{\sigma}_{ref}$ is the mean strength of a reference volume or area which has been uniformly stressed; V_{ref} and A_{ref} are the relevant reference volumes or areas, V and A are the actual stressed volumes or areas and ΣV and ΣA are stress volume and stress area integrals respectively given by

$$\Sigma V = \int_V \left(\frac{\sigma(V)}{\sigma_{nom}} \right)^m \frac{dV}{V} \qquad (6)$$

$$\Sigma A = \int_A \left(\frac{\sigma(A)}{\sigma_{nom}} \right)^m \frac{dA}{A} \qquad (7)$$

ΣV and ΣA have the following values for 3pt and 4pt rectangular and round testpieces

Geometry	ΣV	ΣA
3pt Rectangular, R3b	$\frac{1}{2(m+1)^2}$	$\frac{1}{2(m+1)^2} \left\{ \frac{1+f+m}{1+f} \right\}$
4pt Rectangular, R4b	$\frac{m+2}{4(m+1)^2}$	$\frac{m+2}{4(m+1)^2} \left\{ \frac{1+f+m}{1+f} \right\}$
3pt Round, C3	$\frac{1}{\pi(m+1)}.A(m)$	$\frac{m+2}{2\pi(m+1)}.A(m)$
4pt Round, C4	$\frac{m+2}{2\pi(m+1)}.A(m)$	$\frac{(m+2)^2}{4\pi(m+1)}.A(m)$

Where f is h/b and A(m) is a function given by:

$$A(m) = \left(\Gamma\left(\frac{m+1}{2}\right)\Gamma\left(\frac{3}{2}\right)\right) / \left(\Gamma\left(\frac{m+4}{2}\right)\right) \quad (8)$$

this can be approximated by a power law

$$A(m) = 1.26(m)^{-1.3} \quad (9)$$

These integrals can then be used to examine the ratios of 3pt to 4pt strength values predicted by values of m measured from real data sets and compared with measured ratios of 3pt to 4pt strength.

For example from (5), for both rectangular (R3b and R4b) and round (C3 and C4) testpieces.

On a volume basis

$$\frac{\sigma_{3pt}}{\sigma_{4pt}} = \frac{(V_4\Sigma V_4)^{\frac{1}{m_4}}}{(V_3\Sigma V_3)^{\frac{1}{m_3}}} \quad (10)$$

On an area basis

$$\frac{\sigma_{3pt}}{\sigma_{4pt}} = \frac{(A_4\Sigma A_4)^{\frac{1}{m_4}}}{(A_3\Sigma A_3)^{\frac{1}{m_3}}} \quad (11)$$

where m_3 and m_4 are the Weibull moduli from 3 and 4 pt bend tests respectively. Weibull moduli, obtained from fits to all the data (ignoring whether data falls into 2 categories or not) are given in Table 4. Fig 6 shows a typical plot for the R3b and R4b geometries of Weibull fits to all the data. Mean values for the test data for each material type and test geometry are given in Table 5 together with values for the ratio of 3pt/4pt strength, and the predicted ratios of 3pt/4pt strength from the Weibull moduli are given in Table 6.

The results in Tables 5 and 6 indicate that:

1. It is not possible to separate predicted strength ratios assuming area or volume defect distributions. The σ_3/σ_4 ratio is the same for both defect types, for R3b/R4b and for C3/C4.

2. The predicted σ_3/σ_4 ratio for rectangular testpieces is much higher than for the σ_3/σ_4 ratio for round testpieces.

3. The R3/R4b and C3/C4 measured strength ratios are similar for the conventional hardmetals but different for the Ti(C,N) cermet.

Observations 2 and 3 indicate that the Weibull analysis is probably not appropriate for the conventional WC/Co grades since the analysis predicts different σ_3/σ_4 ratios, independent of testpiece type. However, the Ti(C,N) cermet, where it is known that many of the failures are initiated by volume-defects, the measured ratios for rectangular and round testpieces are different as predicted by the Weibull analysis. However, the values of the σ_3/σ_4 ratio predicted by the analysis for the rectangular testpieces (1.86, 1.73) are much higher than that measured (1.25).

The lack of fractographic information from samples other than the Ti(C,N) cermet clearly makes interpretation of the Weibull analysis difficult. However, insufficient resources were available to conduct the necessary SEM observations.

4.2 REPRESENTATIVE VALUES OF STRENGTH

The upper section of the Weibull ranked plot, which is clearly Type A for bimodal plots but could be Type A or Type B for single mode fractures, allows a characteristic σ_0 value to be calculated. This was chosen to be a strength parameter, characteristic of the material and geometry, by which the results from all the tests might be compared, as opposed to taking the arithmetic mean of all the tests. This value is more likely to be representative of the underlying structure. These σ_0 values are given in Table 7 and shown plotted in Fig 7 for all the geometries and materials.

An alternative method for calculating representative strength values was adopted by averaging the top 3 or 4 highest values of strength in each category. These results are given in Table 8 and also shown plotted in Fig 6. The trends between different materials and geometries were very similar whichever method of plotting was used, whether a Weibull σ_0 value or a mean strength value for the highest strength testpieces in each population.

A number of observations can therefore be made from the data shown in Fig 7.

- The materials are ranked similarly by all the unnotched geometries.
- Geometry R3a produces the highest strength values.
- The three-point bend geometries produce higher strength values than the four-point bend geometries, ie R3b > R4b, R3c > R4c, C3 > C4.
- The 5 mm x 5 mm rectangular cross-section testpieces produce higher strengths than the 4 mm x 3 mm testpieces (ie R3b and R4b > R3c and R4c respectively).
- The circular testpieces, C3 and C4, gave similar strength values to the rectangular testpieces, R3b and R4b, of similar span to depth geometries.
- For the WC hardmetals the strengths (calculated from the notch geometry) from the notched testpieces are generally lower than those from unnotched testpieces.
- For the Ti(C,N) cermet, however, the notched strengths were as high or higher than strength values obtained in unnotched tests.

There are a number of possibilities for the differences observed in Fig 7 and the following issues were examined

- Friction stresses
- Wedging stresses
- Stress volume/area effects due to different probabilities of defect-initiated fracture.

Friction Stresses

If the supporting rollers cannot easily rotate then friction stresses are set up in the outer tensile fibres of the beam which require an additional bending moment to deflect the testpiece to the curvature it would have in the absence of friction. This means that the calculated stress in the beam is higher than it really is. The correction factor, CF_f, expressed as a percentage is given by [6]:

$$CF_f\% = \{\mu/(d/h-\mu)\} \cdot 100$$

where μ is the coefficient of friction, d is one half the full span in 3 pt bend and the distance between the inner and outer rollers in 4 pt bend and h is the depth of the testpiece. A value of 0.2 was used for μ.

Wedging Stresses

Timoshenko [7] has shown that a concentrated load on a beam produces "wedging stresses" under the point load which modify the stress distribution on the tensile surface. The correction factor, CF_w, is of the same sign as the friction correction factor (ie stress is over-estimated using the nominal formula), and is given by

$$CF_w\% = \left(\frac{2h}{3\pi d}\right) \cdot 100$$

where d and h are the same as above. However, this correction only applies to the position on the tensile surface directly opposite the point load. Baratta et al [8] have shown that the correction factor differs as the point of interest moves away from the position directly beneath the load application point, and at some positions it takes on the opposite sign. Thus, it is very difficult to correct for the wedging stress in a general sense as testpieces can fail at random positions along the tensile surface. They do not always fail at the position of nominal maximum stress. However, for the purposes of correcting the nominal stress values the above formula has been used for the 3 pt tests.

A similar situation occurs in 4 pt bend and FE has been used [9] to examine the variation in stress along the testpiece for different span to depth values. For the geometries used in the current exercise, this results in quite small correction values in the 4 pt bend tests.

In summary, the following correction factors were thus used to recalculate representative strength values for all the materials and all the geometries.

Geometry	Correction Factor, % Friction CF_f	Correction Factor, % Wedging CF_w
R3a, RN3a	- 16	- 14
R3b/C3/RN3b	- 7	- 7
R3c	- 3	- 3
R4b/C4/RN4b/CN4	- 11	+ 2
R4c	- 6	0

The corrected values of the characteristic strengths are shown in Fig 8 compared with the uncorrected characteristic strength values. It can be seen that the strength values for the unnotched testpieces after correction are now very similar, indicating that in some of the geometries true stresses are some 10-30% less than those calculated using the nominal beam formula.

The strength values of the rectangular notched testpieces were not any closer brought together by the correction factors since they were quite close anyway. The values have just been reduced by a factor of about 20%. There is, however, a significant difference between the circular notched testpiece and rectangular notched testpiece results. For most of the materials the strength values from the circular notched testpieces are higher than those measured on the rectangular specimens. The reason for this is not known.

In general, the notched testpieces gave lower strength values than the unnotched testpieces and this is probably due to surface compressive residual stresses in the unnotched testpieces since the notched testpieces were annealed before testing. The difference is biggest for the harder, fine grained WC/Co hardmetals.

Thus, in summary, differences in nominal strength in the unnotched testpieces could be due to differences in friction and wedging stresses. Using nominal correction factors the strength values from the different geometries agree reasonably well. Better agreement would depend on specific FE analysis for the different testpieces and more accurate figures for the coefficient of friction. The use of strain gauged testpieces would allow some of these correction factors to be quantified more accurately.

4.3 EFFECTS OF ANNEALING

It was shown in the previous VAMAS report [1] that annealing unnotched testpieces at 800 °C for 1h in vacuum reduced the strength significantly. Further tests have been performed at NPL on a few remaining testpieces since the last report. These are summarised as follows.

Material	Geometry of Annealed Testpieces	
	Reported previously [1]	Recent tests
Teledyne (UF)	R3b, C3, C4	R3a
Boart (F)	-	-
Sandvik HM (F)	-	-
Sandvik Cermet	R3b, C3	R3a
Kennametal CC	-	-
Sandvik (M/C)	R3b, C3, C4	-
Boart (C)	R3b, R4b, C3, C4	R3a, R3c

The results of the recent tests are given in Table 9 and Table 10 summarises representative values of the annealed and unannealed strengths (taking the top 3-4 values) including a ratio of the two values. Comparative plots of the annealed and as-ground testpieces were given in the previous report [1]. Figures 9-11 show plots of the results of the tests performed since the previous report [1].

The results in Figs 9-11 and Table 10 show that annealing the as-ground testpieces reduces the strength. The amount of reduction in strength is dependent on the material type and the geometry. There are two possible reasons for the reduction:

1. The as-ground surfaces contain compressive residual stresses which are removed when the samples are annealed.

2. The as-ground surfaces contain small cracks which are held closed by the residual compressive grinding stresses. After the sample is annealed at this low temperature the cracks become stress-free and act as small defects, thus reducing strength.

Further work is needed to evaluate which of these two mechanisms (or both together) is responsible for the reduction in strength that occurs when the samples are annealed.

The reduction in strength for the Ti(C,N) cermet material was much smaller than for the other materials except for the round testpiece. This is consistent with the fact that even for the highest strength values subsurface volume distributed defects were observed.

The highest reductions in strength on annealing occurred in the Teledyne (UF) hardmetal. This could mean that the compressive residual stresses are higher in finer-grained material or that finer-grained hardmetals are more susceptible to the formation of small surface cracks.

5 CONCLUSIONS

The VAMAS report [1] of the basic data showed that there was good agreement (reproducibility) between laboratories testing a given geometry and material. However, nominal strengths were found to differ by a factor of up to two depending on the geometry of test. Analysis of representative strength values and Weibull moduli indicated that the effects of wedging stresses and friction, caused by the inability of the support rollers to rotate freely, were the most likely source of differences in strength observed between the different geometries.

Surface preparation had a very significant effect on strength. In particular, annealing reduced strength, possibly by relieving compressive residual stresses introduced during grinding. The magnitude of the strength increase introduced by surface preparation stresses is material dependent.

Further systematic work is required on the effects of surface preparation to fully elucidate the differences in strength observed for the different test geometries.

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7 ACKNOWLEDGEMENTS

Thanks are due to the many international organisations who took part in the interlaboratory exercise for their extensive contribution to the testing schedule. The NPL contribution was supported by the MTS Programme on Advanced Materials, a programme of underpinning materials measurement research financed by the EAM Directorate, UK Department of Trade and Industry. Thanks are also due to Dr R Morrell (NPL) for guidance in section 4.1 on Weibull Analysis.

Table 3A

Teledyne UFine WC/Co
Weibull Moduli - Estimated fits

Geometry	Organisation	Weibull Modulus*	
		Part A	Part B
R3a	Boart Sandvik Combined	18 18 24	- - -
R3b	NPL CERMEP Combined	26 26 21	6 - 5
R3c	NPL Kennametal Combined	6 7 8	- - 5
R4b	NPL CERMEP Combined	23 23 26	4 - 5
R4c	NPL Kennametal Combined	10 10 13	4 - 7
C3	NPL Kennametal Combined	35 35 39	- 13 10
C4	NPL CERMEP Combined	30 23 19	- 6 5
RN3a	NPL CERMEP Combined	65 40 15	10 17 -
RN3b	NPL Kennametal Combined	17 28 15	- 11 -
RN4b	NPL CERMEP Combined	52 60 15	- 11 -
CN4	NPL CERMEP Kennametal Combined	36 40 9 15	- 5 - 3

Table 3B

Boart Fine WC/Co
Weibull Moduli - Estimated fits

Geometry	Organisation	Weibull Modulus*	
		Part A	Part B
R3a	Teledyne Sandvik Combined	36 36 36	7 7 7
R3b	NPL Sandvik Combined	13 15 14	- 4 6
R3c	NPL Teledyne Combined	13 7 14	<4 <4 2
R4b	NPL Sandvik Combined	13 12 10	6 - -
R4c	NPL Teledyne Combined	18 12 10	<4 <4 <2
C3	NPL Teledyne Combined	16 16 17	- - -
C4	NPL Sandvik Combined	12 30 13	- 7 -
RN3a	NPL Sandvik Combined	16 23 18	- - -
RN3b	NPL Teledyne Combined	16 18 12	- 6 -
RN4b	NPL Sandvik Combined	14 14 15	- - -
CN4	NPL Sandvik Teledyne Combined	15 20 18 15	- - 7 -

Table 3C

Sandvik HM Fine WC/Co
Weibull Moduli - Estimated fits

Geometry	Organisation	Weibull Modulus*	
		Part A	Part B
R3a	Boart Teledyne Combined	12 13 11	9 - -
R3b	NPL Dymet Combined	10 10 9	5 - -
R3c	NPL Boart Combined	17 10 16	5 - 8
R4b	NPL Dymet Combined	9 25 13	5 5 6
R4c	NPL Boart Combined	10 12 13	- - -
C3	NPL Boart Combined	12 30 23	2 7 6
C4	NPL Dymet Combined	8 17 16	- 6 6
RN3a	NPL Dymet Combined	33 33 32	- 13 17
RN3b	NPL Boart Combined	13 21 15	- - -
RN4b	NPL Boart Combined	11 14 24	- - 10
CN4	NPL Dymet Boart Combined	53 36 64 56	- - - -

Table 3D

Kennametal Medium/Fine WC/CC/Co
Weibull Moduli - Estimated fits

Geometry	Organisation	Weibull Modulus*	
		Part A	Part B
R3a	Gen Carbide (Set 1) Gen Carbide (Set 2) CERMEP (Set 2)	18 33 17	7 - -
R3b	NPL United Combined	11 33 13	- 13 -
R3c	NPL United Combined	28 29 21	8 - -
R4b	NPL United Combined	18 17 18	6 5 4
R4c	NPL United Combined	18 18 21	- - -
C3	Not tested	-	-
C4	Not tested	-	-
RN3a	NPL United Combined	17 20 16	- - -
RN3b	NPL United Combined	43 17 49	- - 22
RN4b	NPL United Combined	17 16 17	- - -
CN4	Not tested	-	-

Table 3E

Sandvik Ti(C,N) Cermet
Weibull Moduli - Estimated fits

Geometry	Organisation	Weibull Modulus*	
		Part A	Part B
R3a	Kennametal	10	-
	CERMep	13	-
	Combined	11	8
R3b	NPL	13	6
	Sandvik	13	5
	Combined	12	6
R3c	NPL	16	3
	BAM	15	5
	Combined	14	4
R4b	NPL	10	6
	Sandvik	10	3
	Combined	11	3
R4c	NPL	-	3
	BAM	-	3
	Combined	-	3
C3	NPL	17	-
	BAM	8	3
	Combined	11	3
C4	NPL	7	-
	Sandvik	17	4
	Combined	11	6
RN3a	NPL	29	-
	Sandvik	17	-
	Combined	15	-
RN3b	NPL	23	-
	BAM	23	-
	Combined	20	-
RN4b	NPL	24	-
	Sandvik	20	-
	Combined	20	-
CN4	NPL	129	9
	BAM	24	-
	Sandvik	141	-
	Combined	62	15

Table 3F

Sandvik Med/Coarse WC/Co
Weibull Moduli - Estimated fits

Geometry	Organisation	Weibull Modulus*	
		Part A	Part B
R3a	United Gen Carbide Combined	52 22 29	35 - -
R3b	NPL EAD Combined	112 56 39	24 - -
R3c	NPL K-Hertel Combined	66 38 60	- 11 -
R4b	NPL EAD Combined	45 59 32	- 23 -
R4c	NPL K-Hertel Combined	45 28 32	10 15 18
C3	NPL K-Hertel Combined	55 62 72	- 3 5
C4	NPL EAD Combined	107 105 78	- 18 21
RN3a	NPL K-Hertel Combined	15 13 15	- - -
RN3b	NPL K-Hertel Combined	22 39 15	- - -
RN4b	NPL EAD Combined	16 49 19	- 15 -
CN4	NPL EAD K-Hertel Combined	38 38 60 41	- - - -

Table 3G

Boart Coarse WC/Co
Weibull Moduli - Estimated fits

Geometry	Organisation	Weibull Modulus*	
		Part A	Part B
R3a	NPL	36	24
R3b	NPL	23	-
R3c	NPL	23	-
R4b	NPL	27	-
R4c	NPL	27	-
C3	NPL	30	-
C4	NPL	30	-
RN3a	NPL	27	-
RN3b	NPL	27	-
RN4b	NPL	47	-
CN4	NPL	30	-

Table 4

Weibull Moduli, m
All data

Material	Geometry										
	R3a	R3b	R3c	R4b	R4c	C3	C4	CN4	RN3a	RN3b	RN4b
Teledyne (UF)	17	7	5	7	5	13	7	6	16	16	14
Boart (F)	23	7	2	10	3	18	10	13	17	8	14
Sandvik HM (F)	10	8	11	7	8	6	9	52	22	14	11
Ti(C,N) Cermet	7	6	5	3	3	5	7	23	16	24	17
Kennametal (CC)	17	13	16	6	19	-	-	-	16	19	17
Sandvik (M/C)	19	38	64	32	15	10	24	34	18	15	20
Boart (C)	17	19	21	30	24	20	16	24	25	19	24

Table 5

Mean Strength Values - All data

Material	Geometry					
	R3b	R4b	C3	C4	R3b/R4b	C3/C4
Teledyne (UF)	3400	3046	3460	3016	1.12	1.15
Boart (F)	2536	2332	2561	2380	1.09	1.08
Sandvik HM (F)	3018	2766	3610	3265	1.09	1.11
Ti(C,N) Cermet	1247	1001	1436	1351	1.25	1.06
Kennametal (CC)	2001	1794	-	-	1.11	-
Sandvik (M/C)	2723	2547	2968	2763	1.07	1.07
Boart (C)	1794	1659	2027	1859	1.08	1.09

Table 6

Predicted Strength Ratios from Weibull Analysis (assuming similar volume defect or area populations)

Material	Volume Basis		Area Basis	
	σ_3/σ_4 (Rect)	σ_3/σ_4 (Round)	σ_3/σ_4 (Rect)	σ_3/σ_4 (Round)
Teledyne (UF)	1.24	0.96	1.24	1.01
Boart (F)	1.38	0.97	1.33	1.02
Sandvik HM (F)	1.29	1.04	1.28	1.08
Ti(C,N) Cermet	1.86	1.08	1.73	1.12
Kennametal (CC)	0.93	-	1.00	-
Sandvik (M/C)	1.06	0.90	1.07	0.97
Boart (C)	1.21	1.20	1.18	1.18

Table 7

Weibull σ_0 Characteristic Strength Values

Geometry	Material						
	Teledyne Ufine	Sandvik HM fine	Boart fine	Sandvik med/coarse	Kennametal WC/CC/Co	Boart coarse	Sandvik Cermet
R3a	4188	3641	3133	3041	2670	2165	1720
R3b	3569	3229	2697	2779	2059	1845	1380
R3c	3327	3361	2616	2779	2165	1845	1525
R4b	3262	2981	2515	2540	1901	1669	1211
R4c	2922	3134	2416	2592	2059	1669	1064
C3	3569	3905	2616	3011	-	2018	1587
C4	3229	3569	2540	2836	-	1920	1480
CN4	2143	2591	2490	2779	-	2276	1919
RN3a	2670	2864	2836	2616	1998	1882	1978
RN3b	2670	2540	2540	2752	1939	1863	1603
RN4b	2618	2441	2490	2322	1737	1720	1525

Table 8

Characteristic Strength Values
Mean and Coefficient of Variation (CV) of 3 or 4 Highest Values*

Material	Test Organisation	R3a	R3b	R3c	R4b	R4c	RN3a	RN3b	RN4b	C3	C4	CN4
Teledyne σ mean N mm^{-2}	Boart	4325										
	Sandvik	4481										
	NPL	-	3651	3426	3285*	3004	2884*	2770	2621	3634	3382	2093
	CERMeP	-	3759	-	3399	-	2670	-	2669	-	3191	2238+
	Kennametal	-	-	3614	-	3195	-	2633*	-	3666	-	2049
	Combined	4403	3705	3520	3350	3100	2761	2711	2645	3650	3287	2104
Teledyne CV, %	Boart	0.7										
	Sandvik	1.5										
	NPL	-	1.5	13.3	1.7	6.0	0.8	3.3	0.8	1.8	1.9	3.5
	CERMeP	-	3.6	-	1.6	-	0.5	-	6.2	-	2.2	0.4
	Kennametal	-	-	4.9	-	4.7	-	1.6	-	1.6	-	7.4
Boart Fine σ mean N mm^{-2}	Teledyne	3212										
	Sandvik	3246										
	NPL	-	2734	2732	2553	2484	2838*	2736	2471	2738	2627	2350
	Sandvik	-	2848	-	2645	-	2925	-	2495	-	2587	2547
	Teledyne	-	-	2840	-	2621*	-	2508	-	2680	-	2538*
	Combined	3229	2791	2786	2599	2543	2888	2622	2483	2709	2607	2473
Boart Fine CV, %	Teledyne	0.1										
	Sandvik	1.0										
	NPL	-	3.3	3.0	4.6	1.7	2.2	3.8	5.8	4.3	4.0	7.4
	Sandvik	-	4.3	-	3.4	-	3.2	-	5.3	-	1.3	4.9
	Teledyne	-	-	5.9	-	4.2	-		-	3.7	-	4.6
		Teledyne data corrected by 0.96 for R3a and 0.90 for remainder - see VAMAS Report No 22.										
Sandvik HM Fine σ mean N mm^{-2}	Boart	3964										
	Teledyne	4061										
	NPL	-	3545	3493	3083	3213	2873	2562	2402	3960	3600	2505
	Dymet	-	3232	-	3139	-	-	-	2500	-	3699	2538
	Boart	-	-	3449	-	3301	2934	2627	-	3995	-	2575
	Combined	4013	3389	3471	3111	3257	2904	2595	2449	3978	3650	2540

* Highest 3 values, remainder highest four values except + which corresponds to highest 2 values.

Table 8 continued

Characteristic Strength Values
Mean and Coefficient of Variation (CV) of 3 or 4 Highest Values*

Material	Test Organisation	R3a	R3b	R3c	R4b	R4c	RN3a	RN3b	RN4b	C3	C4	CN4
CV, %	Boart	5.9										
	Teledyne	4.9										
	NPL	-	4.2	4.3	6.1	5.7	1.9	6.1	7.6	2.9	4.2	1.9
	Dymet	-	3.0	-	4.2	-	-	-	5.3	-	3.1	3.0
	Boart	-	-	5.7	-	3.8	2.0	4.8	-	1.4	-	1.6
Kennametal WC/CC/Co Med/Fine σ mean N mm^{-2}	Gen Carbide	2340										
	CERMeP	-										
	NPL	-	2282$^+$	2252	1968	2101	2069	1962	1850	-	-	-
	United	-	2117	2190	1963	2116	2112	1923	1720	-	-	-
	Combined	2340	2172	2221	1966	2109	2091	1943	1785	-	-	-
CV, %	Gen Carbide	2.0										
	CERMeP	-										
	NPL	-	0.7	2.0	4.7	2.3	4.2	0.8	5.5	-	-	-
	United	-	1.5	0.8	2.4	2.2	5.2	3.7	4.4	-	-	-
Sandvik Cermet σ mean N mm^{-2}	Kennametal	1834										
	CERMeP	1846										
	NPL	-	1454$^+$	1641	1291	1249	2013	1641	1494	1674	1313	1926*
	Sandvik	-	1433	-	1293*	-	1967	-	1594	-	1559	1947
	BAM	-	-	1556	-	1272	-	1624	-	1578	-	1864
	Combined	1840	1444	1599	1292	1261	1990	1632	1544	1626	1436	1911
CV, %	Kennametal	3.2										
	CERMeP	1.2										
	NPL	-	4.0	3.2	3.7	17.6	2.9	3.5	5.8	3.6	14.0	0.4
	Sandvik	-	3.7	-	4.9	-	7.9	-	2.7	-	5.8	0.7
	BAM	-	-	3.7	-	12.2		3.1	-	6.0	-	4.7

* Highest 3 values, remainder highest four values except $^+$ which corresponds to highest 2 values.

Table 8 continued

Characteristic Strength Values
Mean and Coefficient of Variation (CV) of 3 or 4 Highest Values*

Material	Test Organisation	R3a	R3b	R3c	R4b	R4c	RN3a	RN3b	RN4b	C3	C4	CN4
Sandvik Med/ Coarse WC/Co σ mean N mm^{-2}	Gen Carbide	3196										
	United	3135										
	NPL	-	2761	2801	2636	2626	2597	2541	2373	3023	2820	2732
	EAD	-	2776	-	2597	-	-	-	2310	-	2877	2758
	K-Hertel	-	-	2947	-	2673	2626	2898++	-	3096	-	2921
	Combined	3166	2769	2874	2620	2650	2612	2541	2342	3060	2849	2803
CV, %	Gen Carbide	1.6										
	United	0.9										
	NPL	-	4.0	1.0	2.2	1.0	4.7	3.2	4.2	1.1	1.0	2.6
	EAD	-	0.5	-	0.7	-	-	-	1.4	-	0.6	4.2
	K-Hertel	-	-	0.8	-	1.8	5.8	1.4	-	1.0	-	1.2
		++ omitted from average, apparently high.										
Boart Longyear Coarse σ mean N mm^{-2}	NPL unnotched as ground	2216	1874	1887	1702	1734	1890	1892	1760	2045++	1940	2293
CV, %	NPL	1.1	1.9	1.2	1.7	2.0	5.9	1.1	3.4	1.6	1.2	3.0
σ mean N mm^{-2}	NPL unnotched annealed	-	1695	-	1591	-	-	-	-	1779	1756	-
CV, %	NPL	-	1.9	-	1.6	-	-	-	-	3.5	1.6	-
		All notched testpieces annealed. ++ top value not selected, see plot.										
σ mean N mm^{-2}	Ratio as-ground/ annealed	-	1.11	-	1.07	-	-	-	-	1.15	1.10	-

* Highest 3 values, remainder highest four values except + which corresponds to highest 2 values.

Table 9

Teledyne UFine - NPL Bend Tests

R3a Annealed 800 °C 1h in vacuum			Span 14.3 mm	
Number	B mm	W mm	Load N	Stress N mm^{-2}
31	6.39	5.11	27530	3539
32	6.39	5.11	20570	2644
33	6.39	5.11	25740	3309
34	6.39	5.11	26600	3420
35	6.39	5.11	26470	3403
36	6.39	5.11	25870	3326
37	6.39	5.11	23190	2981
38	6.39	5.07	28270	3692
39	6.39	5.11	23140	2975
40	6.39	5.11	16910	2174
41	6.39	5.11	26140	3360

Boart Coarse - NPL Bend Tests

R3a Annealed 800 °C 1h in vacuum			Span 14.3 mm	
Number	B mm	W mm	Load N	Stress N mm^{-2}
16	6.50	5.25	16050	1922
17	6.50	5.25	15630	1871
18	6.50	5.25	15490	1855
19	6.50	5.25	15700	1880
20	6.50	5.25	16720	2002
21	6.50	5.25	16060	1923
22	6.50	5.25	15970	1912
23	6.50	5.25	15320	1834
24	6.50	5.23	16750	2021
25	6.50	5.23	15980	1928
26	6.50	5.24	15920	1913
27	6.50	5.24	16170	1943
28	6.50	5.24	15410	1852
29	6.50	5.25	15370	1840
30	6.50	5.25	16880	2021

Table 9 continued

Boart Coarse - NPL Bend Tests

R3c **Annealed 800 °C 1h in vacuum**			Span 40 mm	
Number	B mm	W mm	Load N	Stress N mm^{-2}
20	4.01	3.00	1070	1779
21	4.01	3.00	998	1659
22	4.01	3.00	1057	1757
23	4.01	3.00	1060	1762
24	4.01	3.00	999	1661
25	4.01	3.00	933	1551
26	4.01	2.96	1033	1764
27	4.01	2.96	1021	1744

Sandvik Cermet - NPL Bend Tests

R3a **Annealed 800 °C 1h in vacuum**			Span 14.3 mm	
Number	B mm	W mm	Load N	Stress N mm^{-2}
31	6.00	5.00	11740	1679
32	6.00	5.00	9609	1374
33	6.00	5.00	12510	1789
34	6.00	5.00	10930	1563
35	6.00	5.00	12940	1850
36	6.00	5.00	10780	1542

Table 10

Comparison of Annealed on As-ground Strengths

Material	Geometry	As-ground strength N mm^{-2}	Annealed strength N mm^{-2}	Ratio of As-ground/ Annealed strength
Teledyne (UF)	R3a	4403	3514	1.25
	R3b	3650	2698	1.35
	C3	3646	1967	1.85
	C4	3414	1935	1.76
Sandvik Cermet	R3a	1844	1773	1.04
	R3b	1301	1352	0.96
	C3	1674	1508	1.11
Sandvik (Med/Coarse)	R3b	2817	2599	1.08
	C3	3031	2836	1.07
	C4	2830	2605	1.09
Boart (Coarse)	R3a	2216	1997	1.11
	R3b	1874	1695	1.11
	R3c	1887	1766	1.07
	R4b	1702	1591	1.07
	C3	2099	1779	1.18
	C4	1940	1757	1.10

FIGURE CAPTIONS

Fig 1 Testpiece geometries

Fig 2a Weibull ranked plot for R3a and R3b geometries

Fig 2b Weibull ranked plot for R3c and R4b geometries

Fig 2c Weibull ranked plot for R4c and RN3a geometries

Fig 2d Weibull ranked plot for RN3b and RN4b geometries

Fig 2e Weibull ranked plot for C3 and C4 geometries

Fig 2f Weibull ranked plot for CN4 geometry

Fig 3 Microstructure initiated failures in notched testpieces of the Ti(C,N) cermet hardmetal Top - CN4 (1964 N/mm^2); Bottom - RN3b (1688 N/mm^2)

Fig 4 Defect initiated failures in Ti(C,N) cermet hardmetal Top - C3 (648 N/mm^2); Middle - R3b (1495 N/mm^2); Bottom - C4 (1504 N/mm^2)

Fig 5 Fractographic analysis of Ti(C,N) cermet testpieces (from various unnotched geometries)

Fig 6 Weibull fit to all the data for the R3b and R4b geometries.

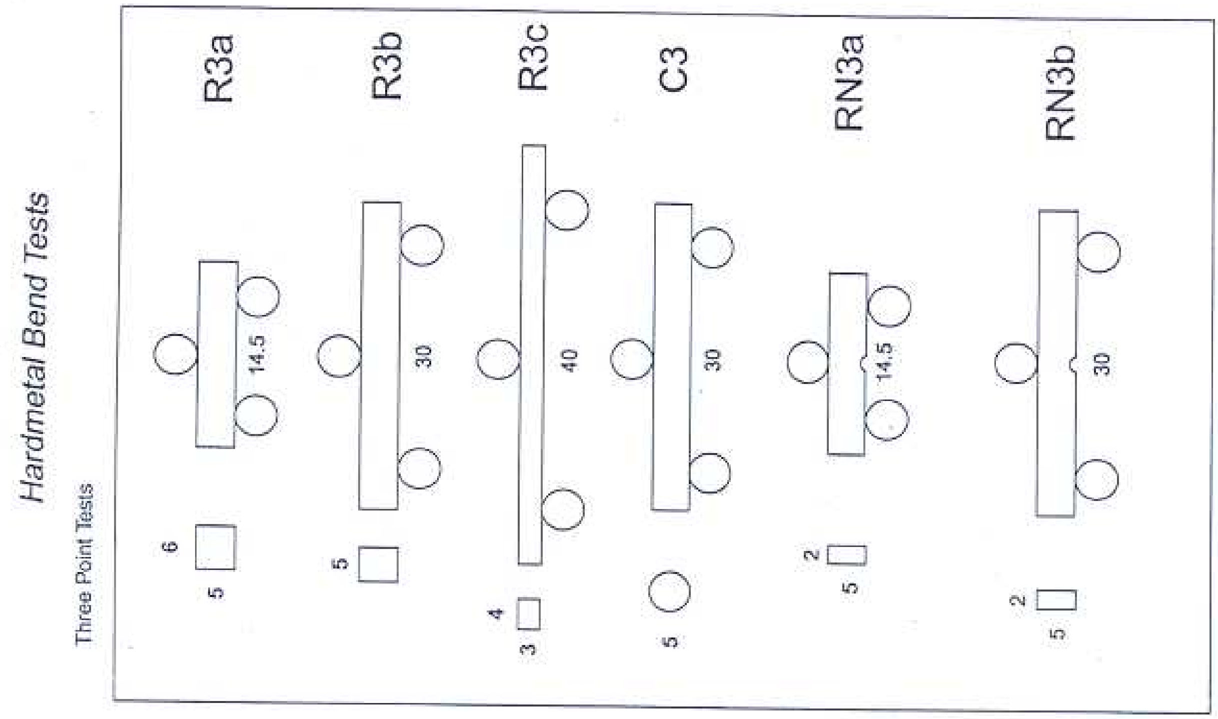
Fig 7 Representative strengths obtained from Weibull σ_0 and mean of highest 3-4 values.

Fig 8 Representative strength values corrected for friction and wedging effects compared with uncorrected results for mean of highest 3-4 values.

Fig 9 Annealed and as-ground bend test results for the R3 geometries for the Boart (C) hardmetal.

Fig 10 Annealed and as-ground bend test results for the Teledyne (UF) hardmetal.

Fig 11 Annealed and as-ground bend test results for the Sandvik Ti(C,N) Cermet hardmetal.



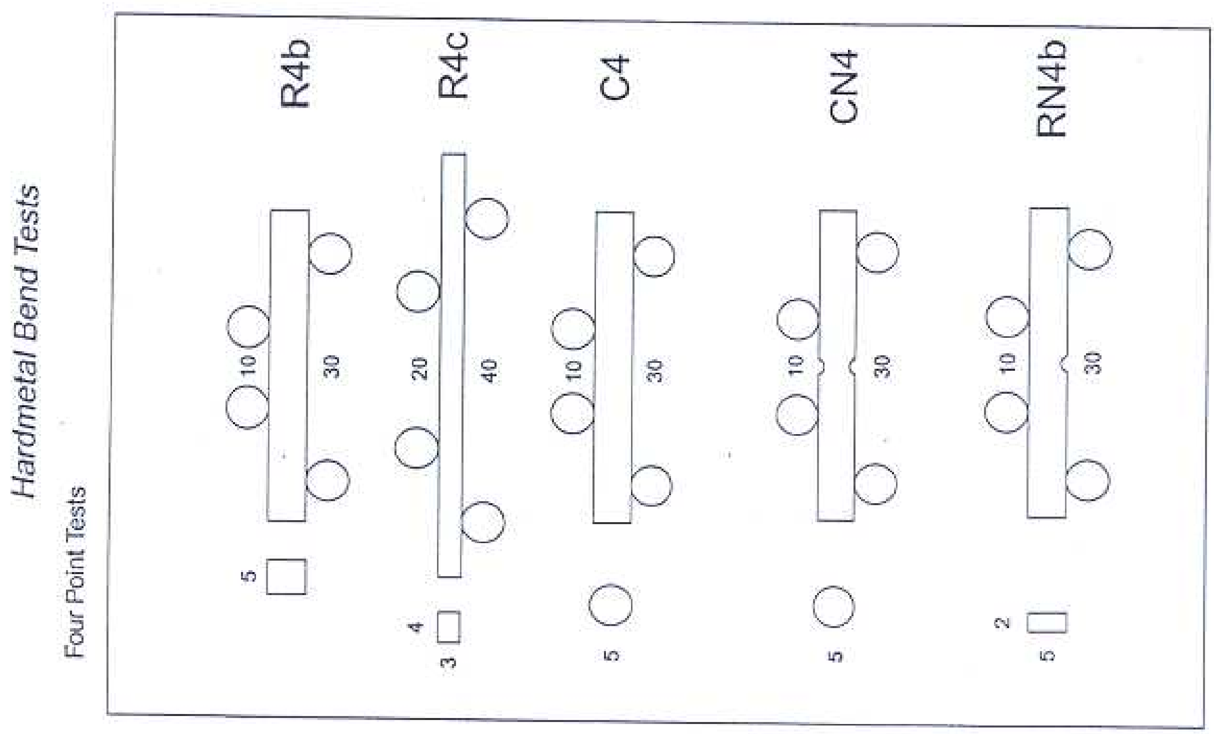
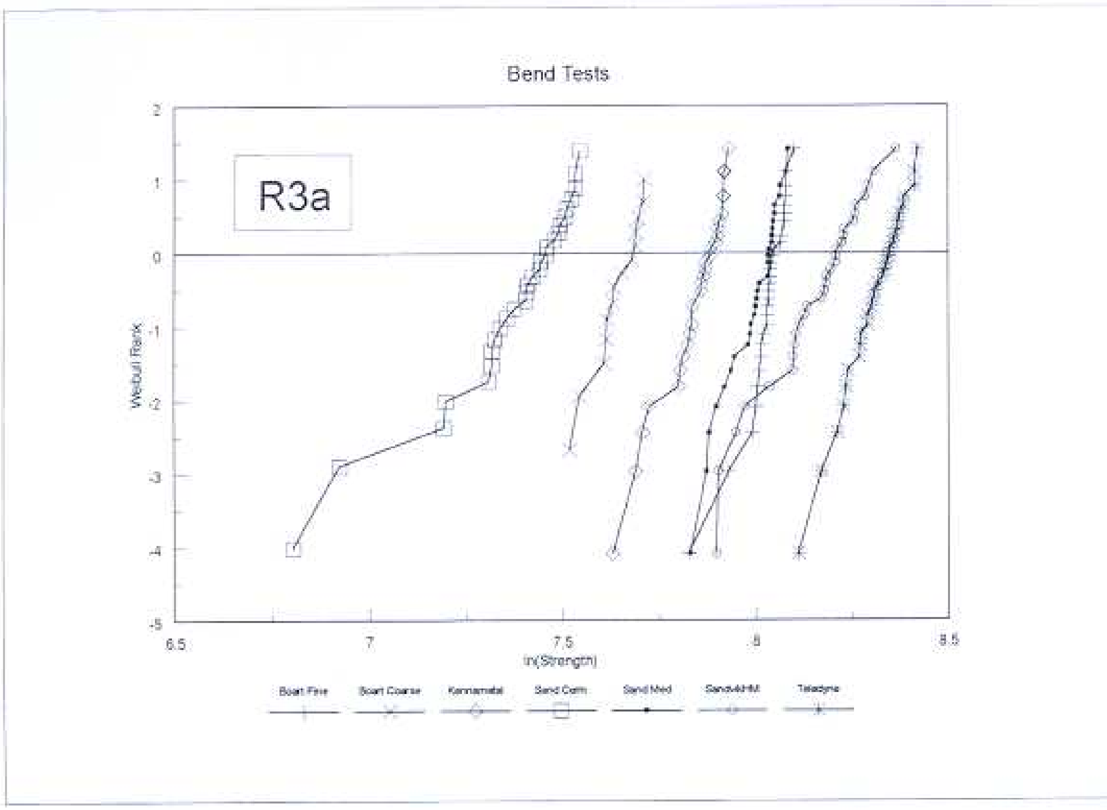


Fig 1 Testpiece geometries



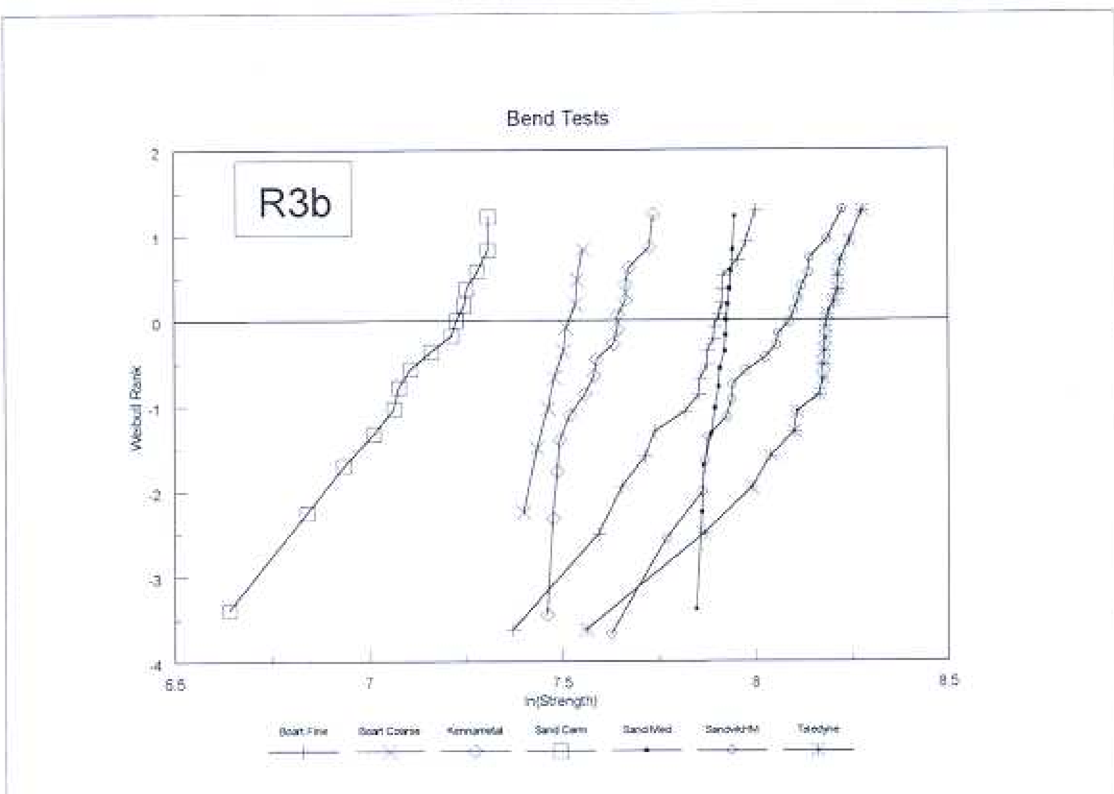
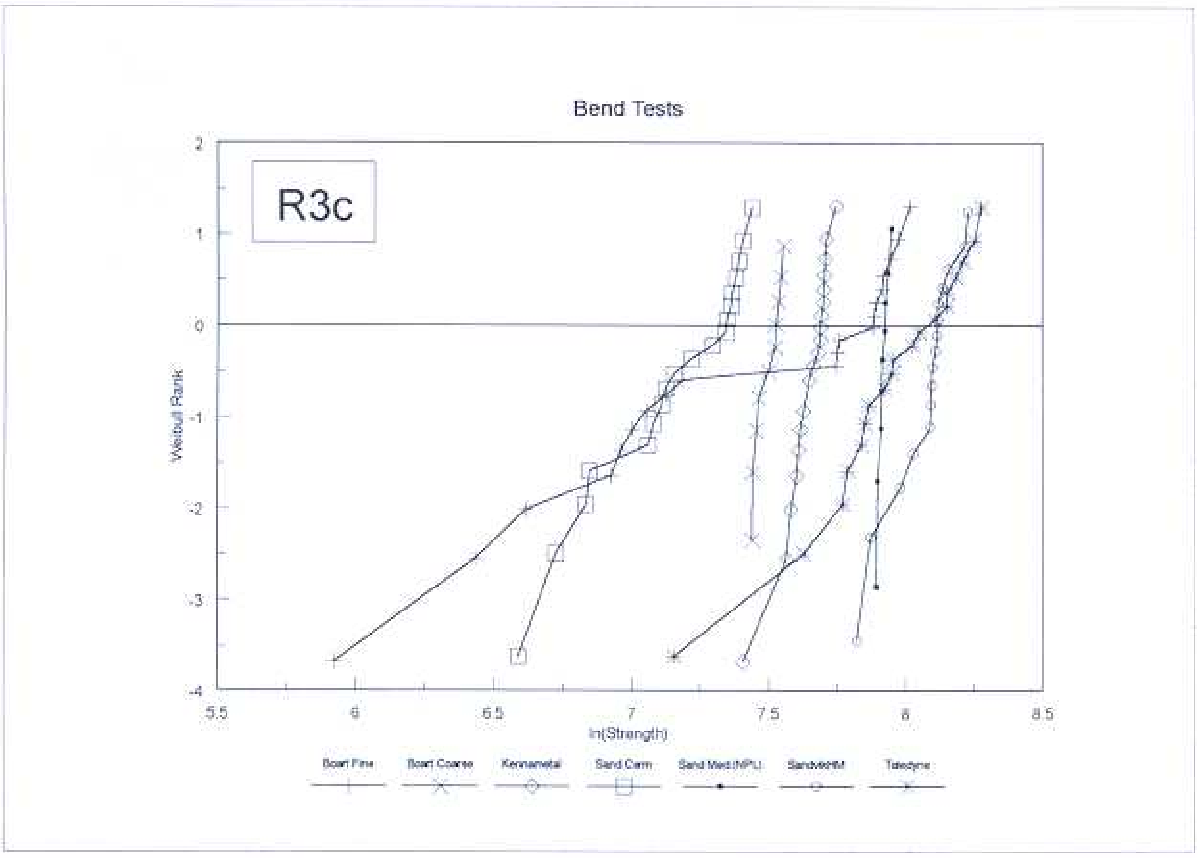


Fig 2a Weibull ranked plot for R3a and R3b geometries



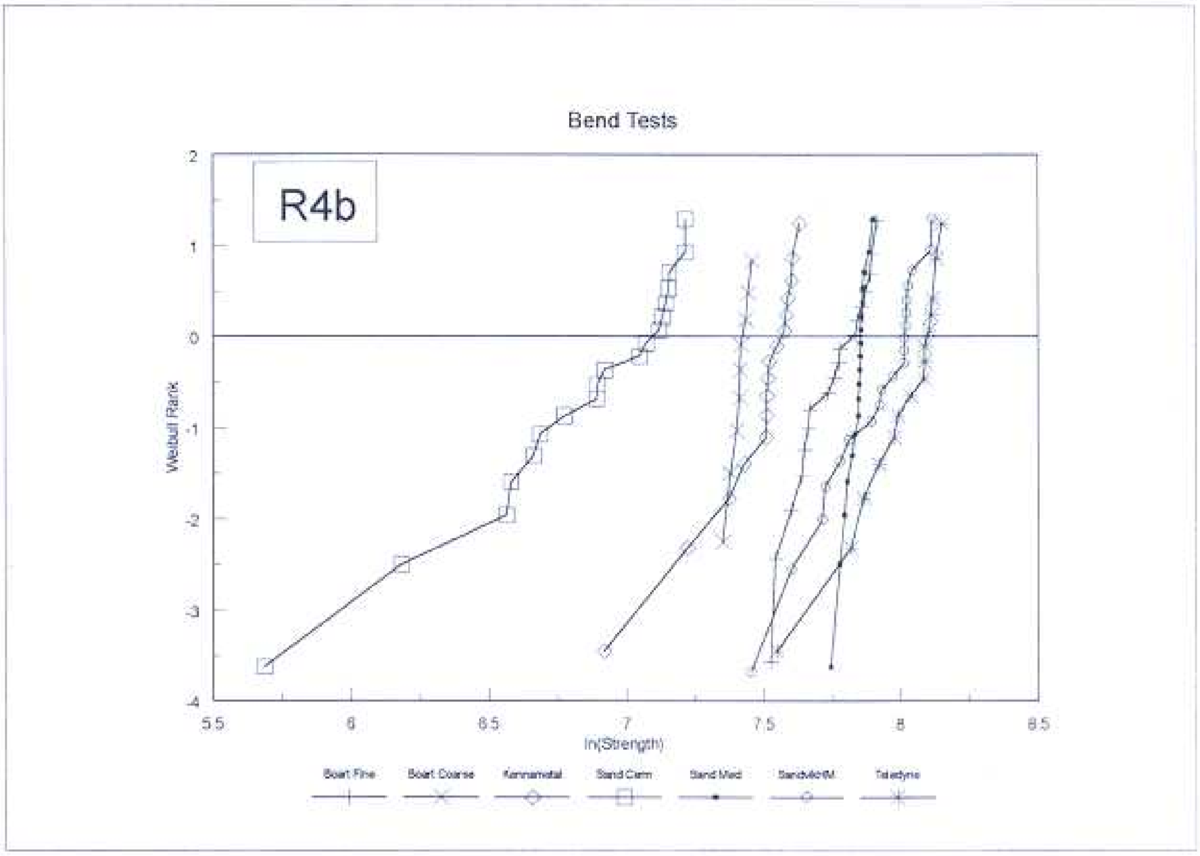
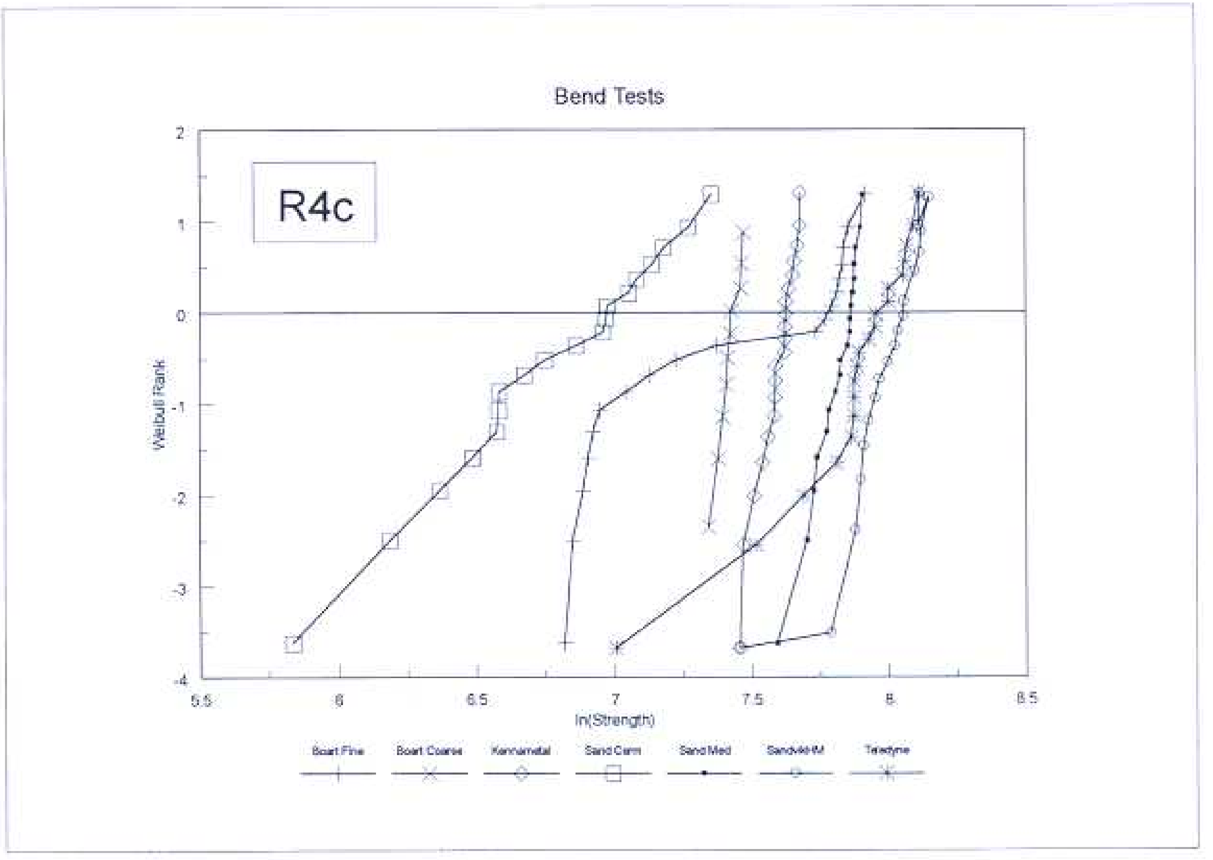


Fig 2b Weibull ranked plot for R3c and R4b geometries



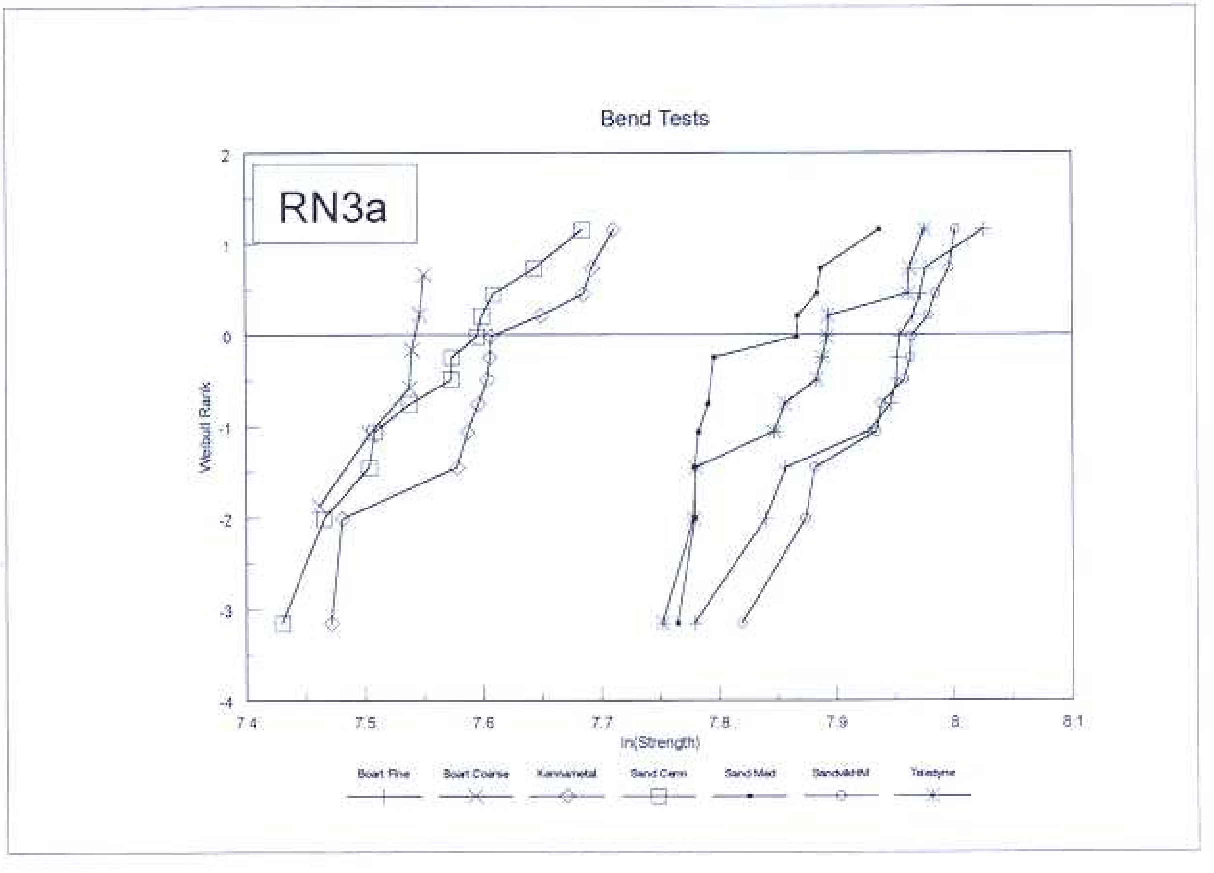
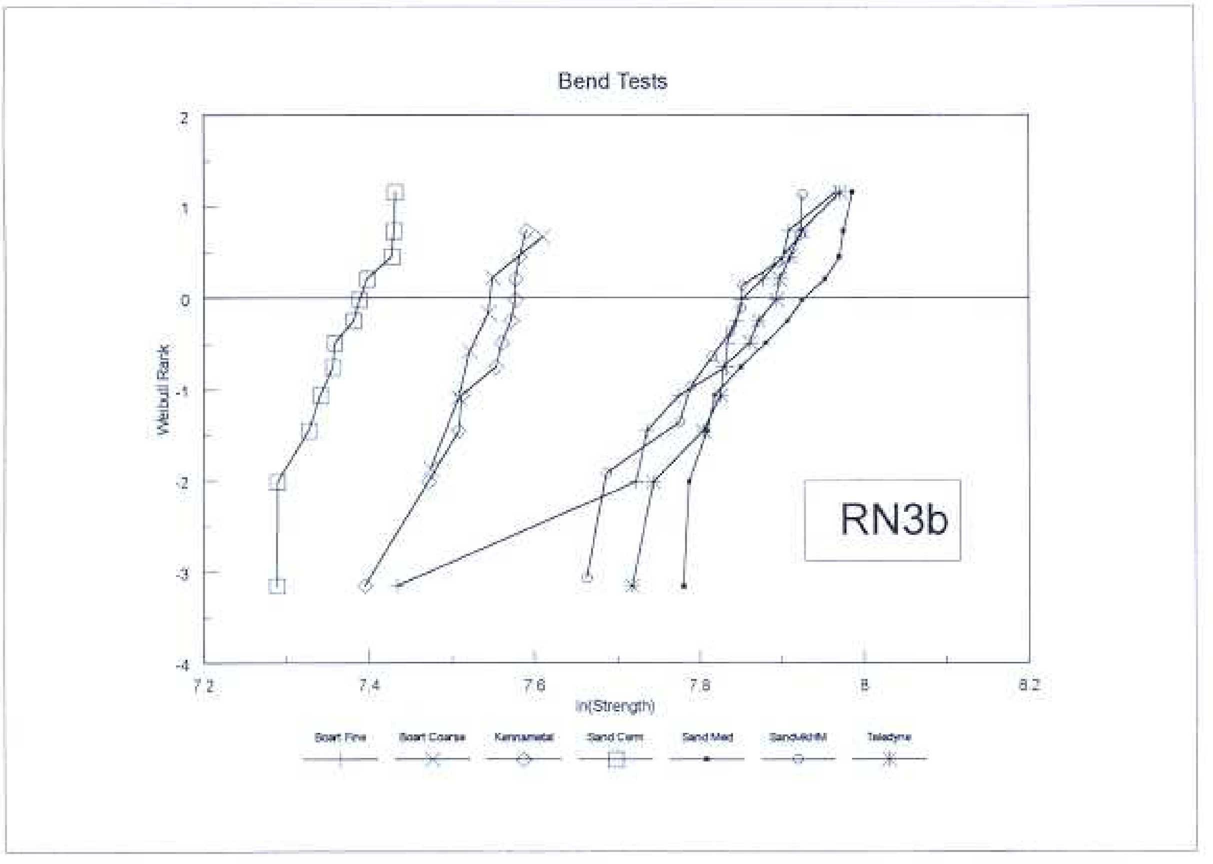


Fig 2c Weibull ranked plot for R4c and RN3a geometries



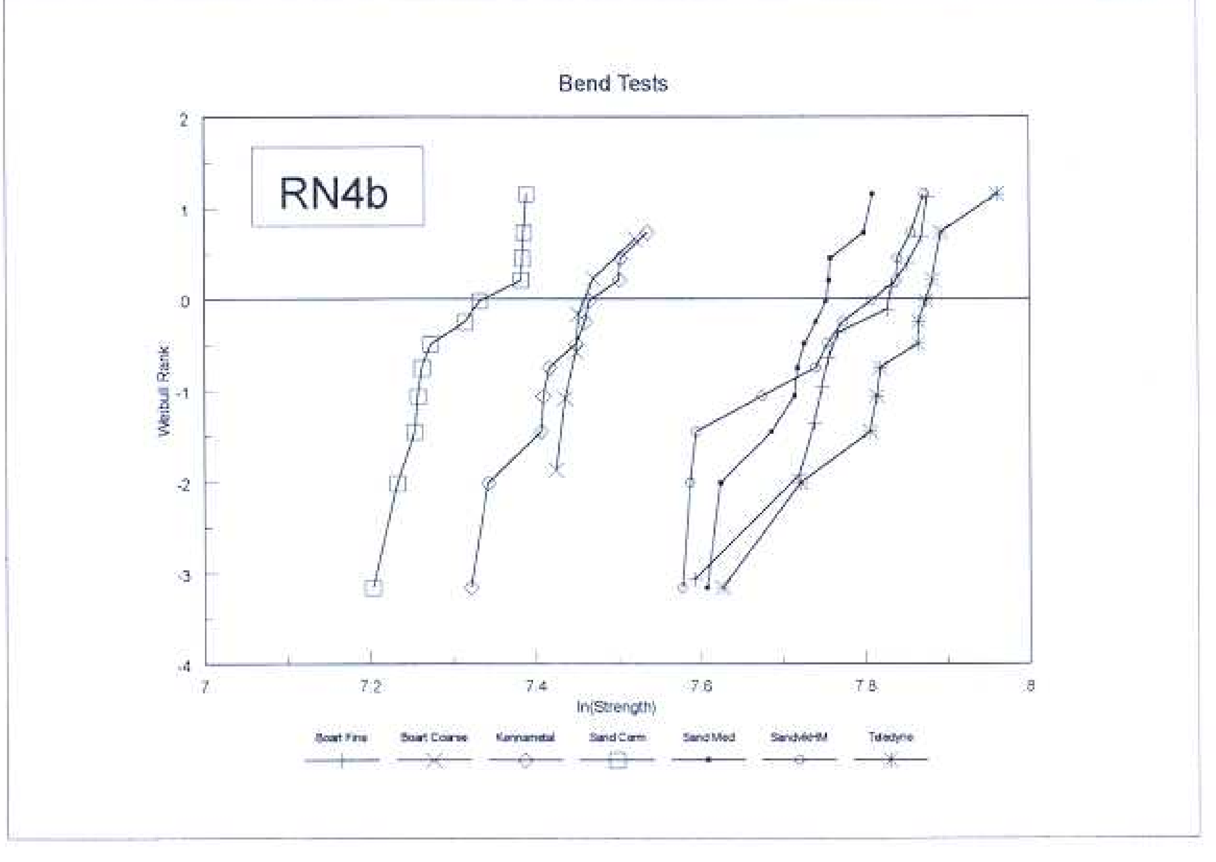
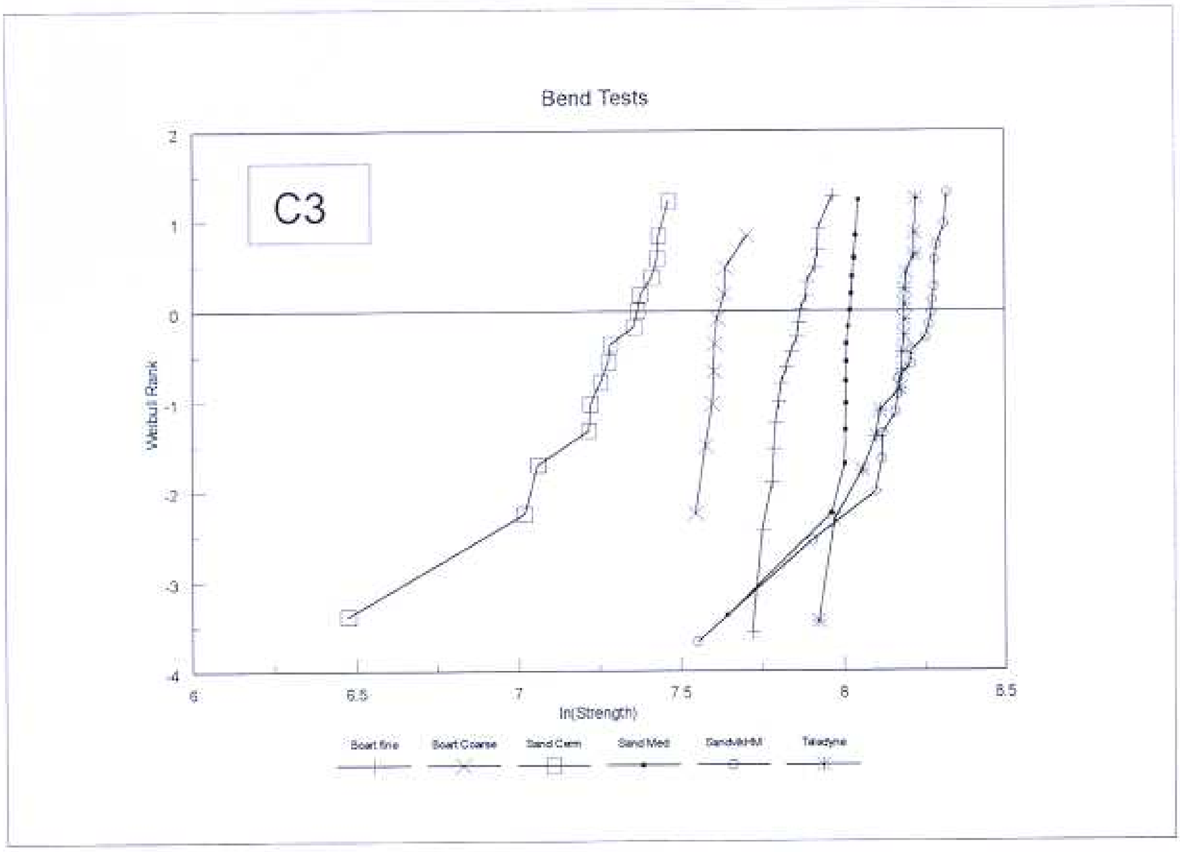


Fig 2d Weibull ranked plot for RN3b and RN4b geometries



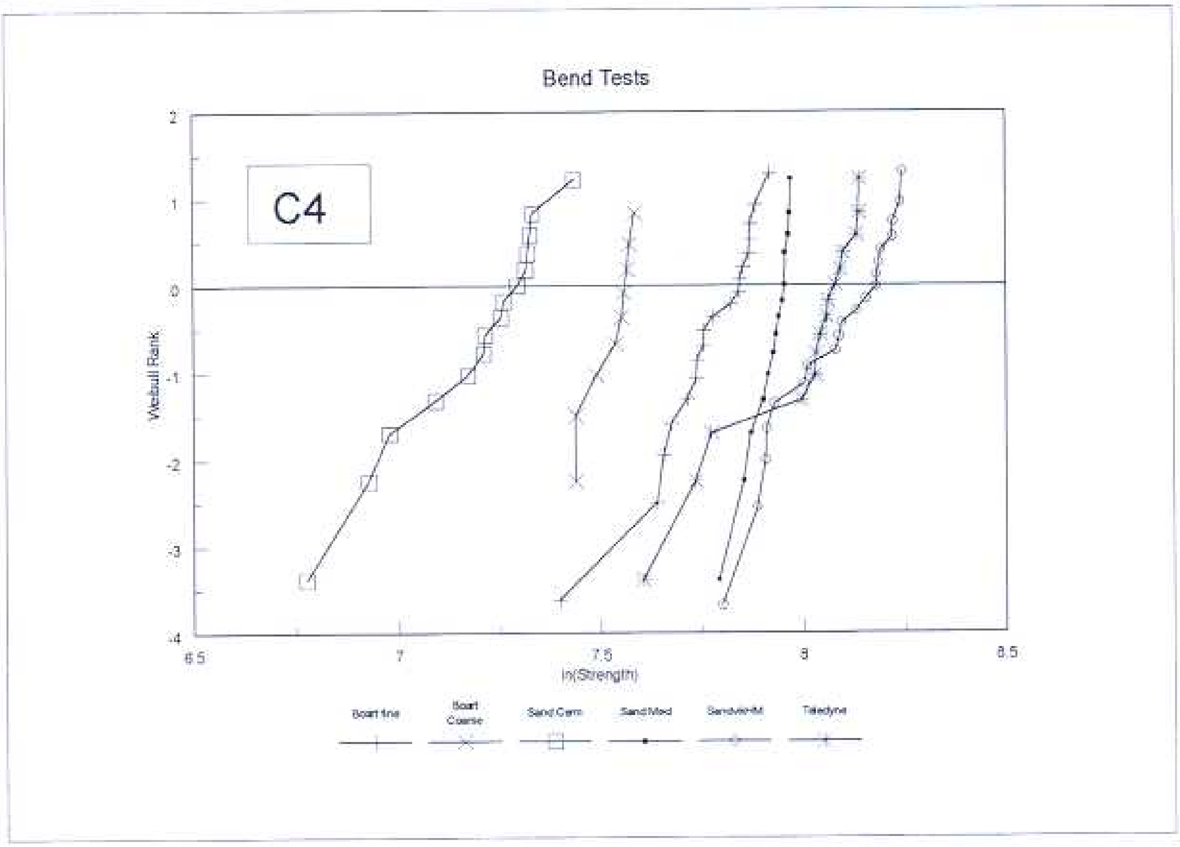


Fig 2e Weibull ranked plot for C3 and C4 geometries

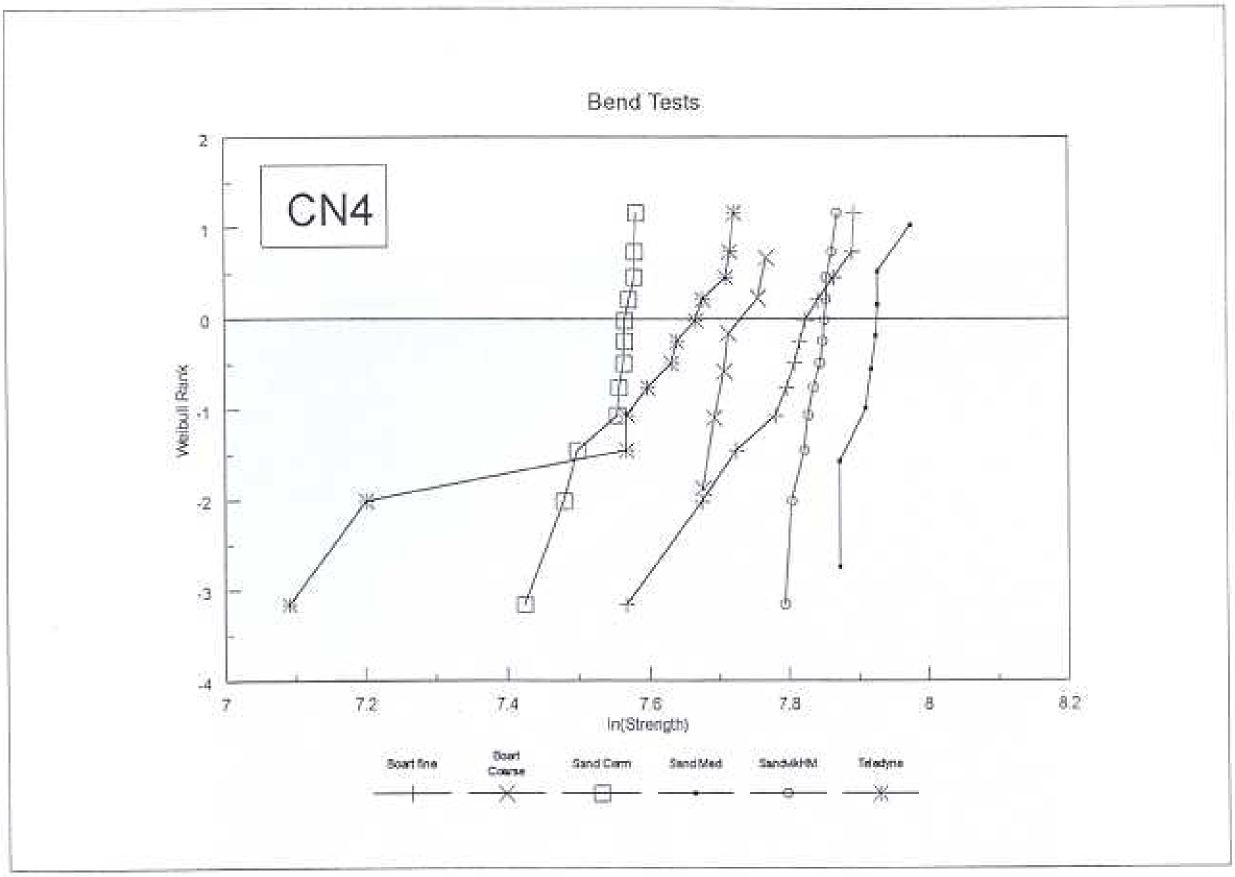


Fig 2f Weibull ranked plot for CN4 geometry

Fig 3 Microstructure initiated failures in notched testpieces of the Ti(C,N) cermet hardmetal
Top - CN4 (1964 N/mm^2); Bottom - RN3b (1688 N/mm^2)

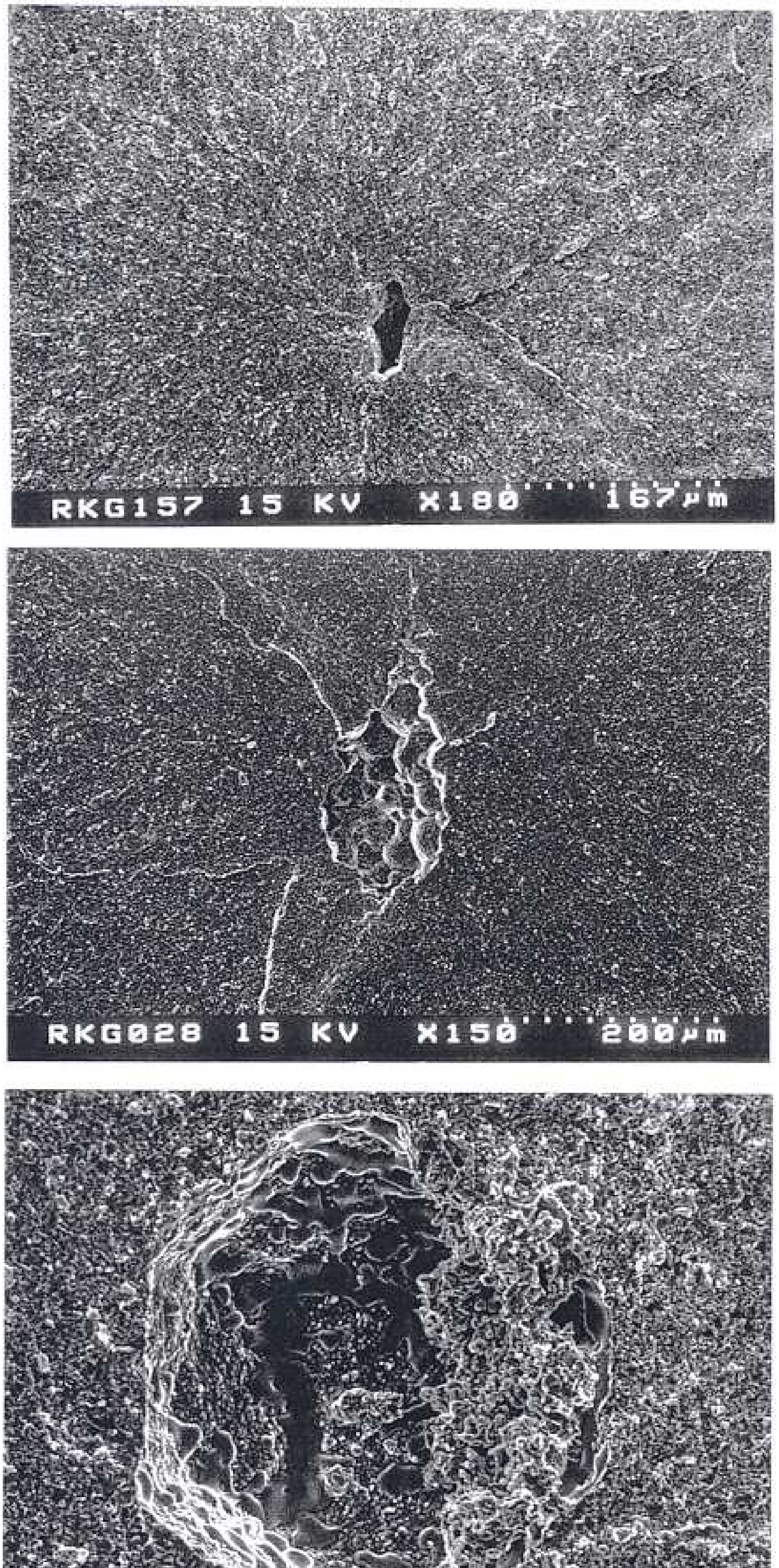


Fig 4 Defect initiated failures in Ti(C,N) cermet hardmetal
Top - C3 (648 N/mm^2); Middle - R3b (1495 N/mm^2); Bottom - C4 (1504 N/mm^2)

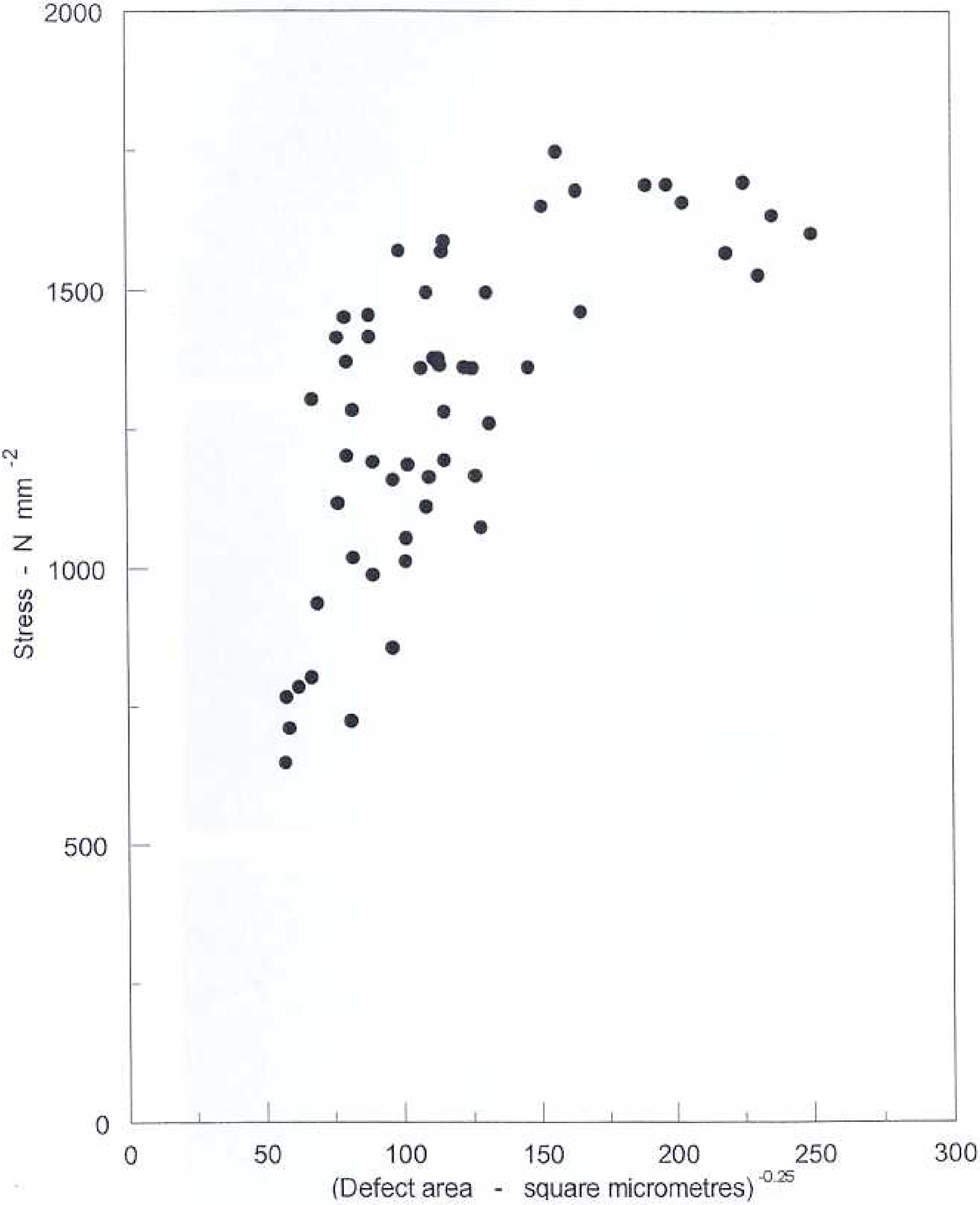
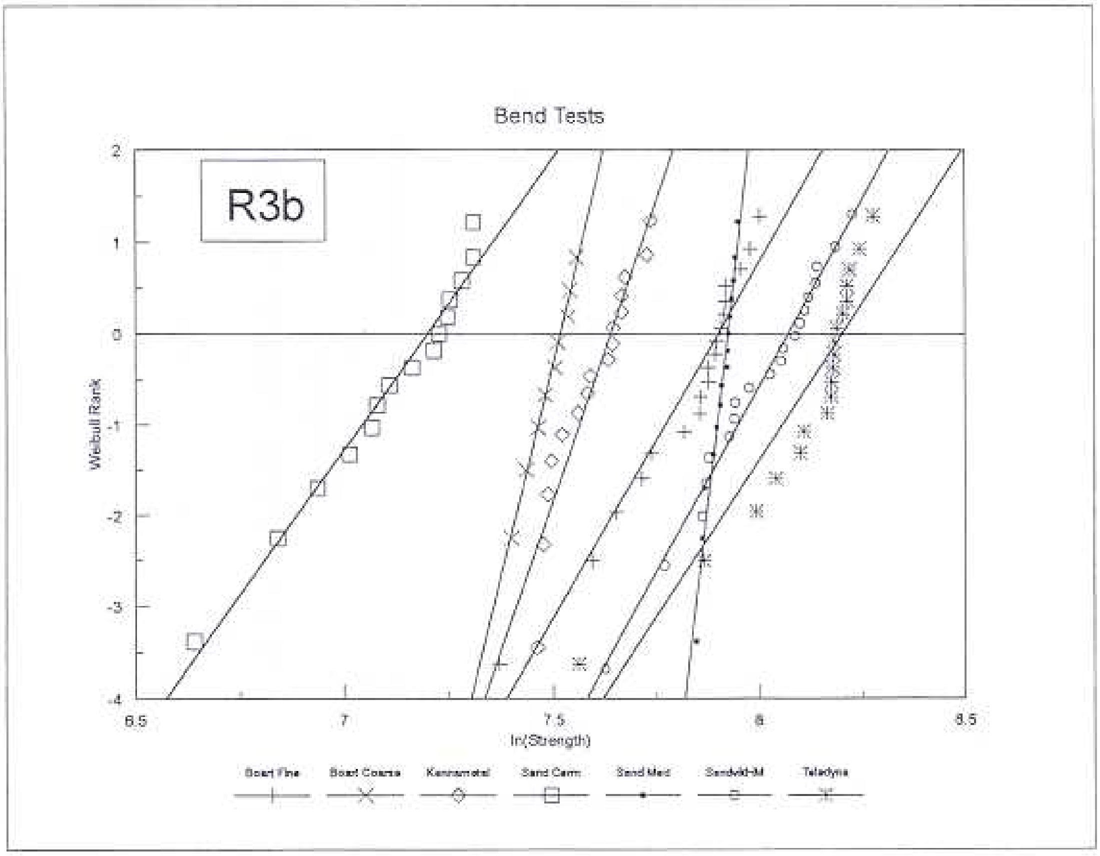


Fig 5 Fractographic analysis of Ti(C,N) cermet testpieces (from various unnotched geometries)



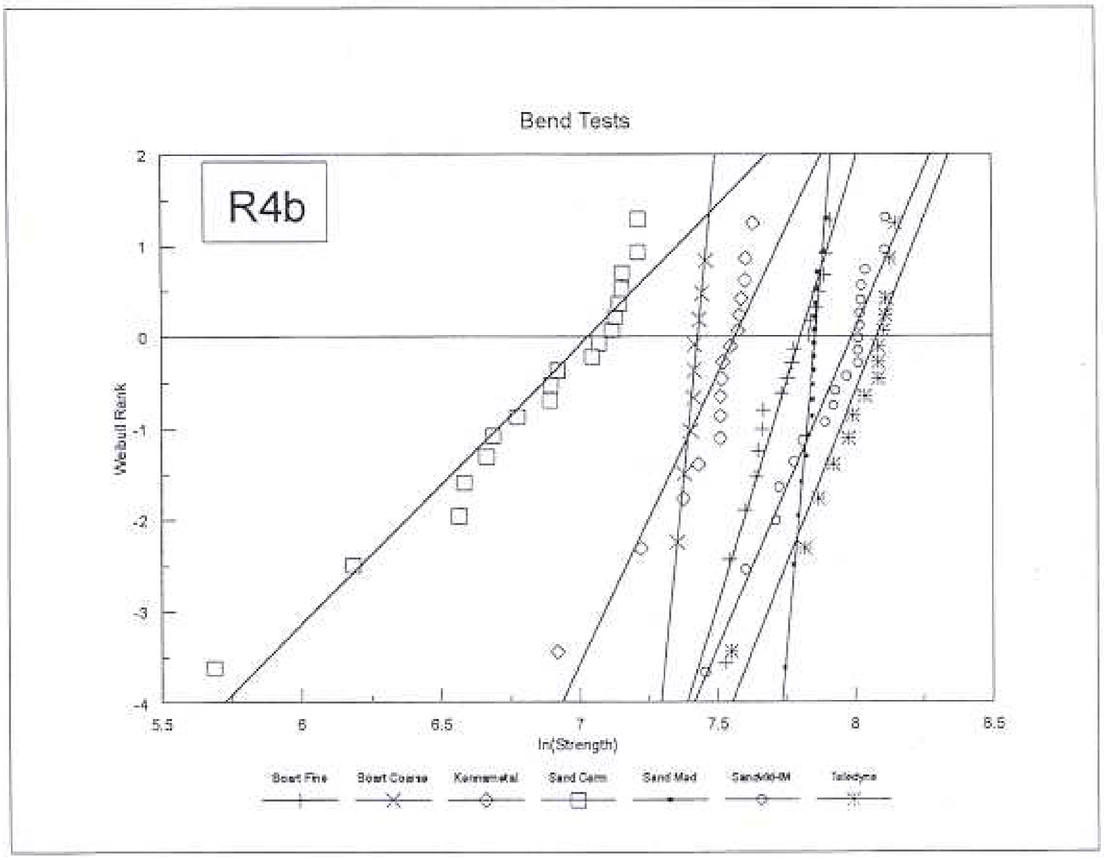


Fig 6 Weibull fit to all the data for the R3b and R4b geometries.

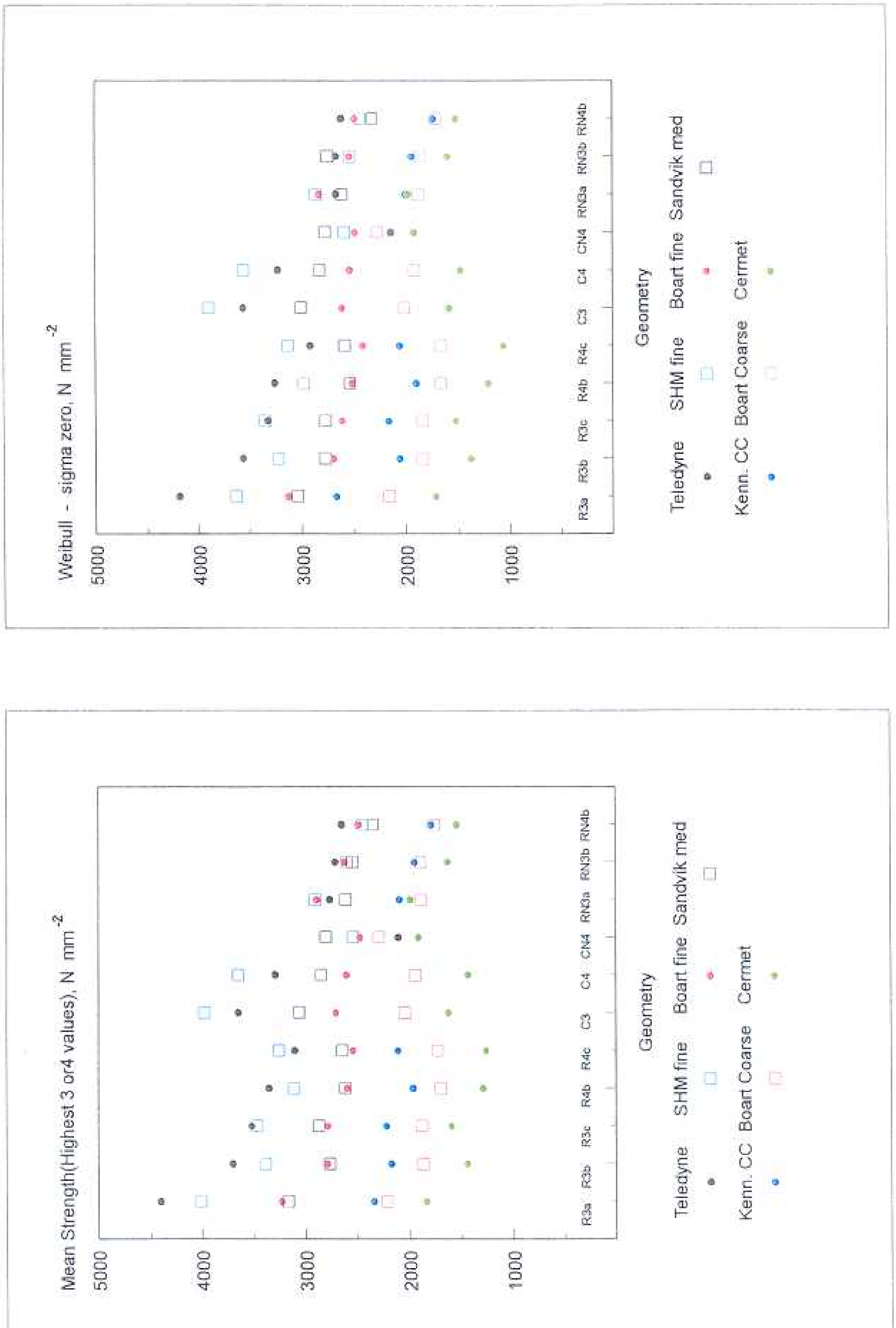
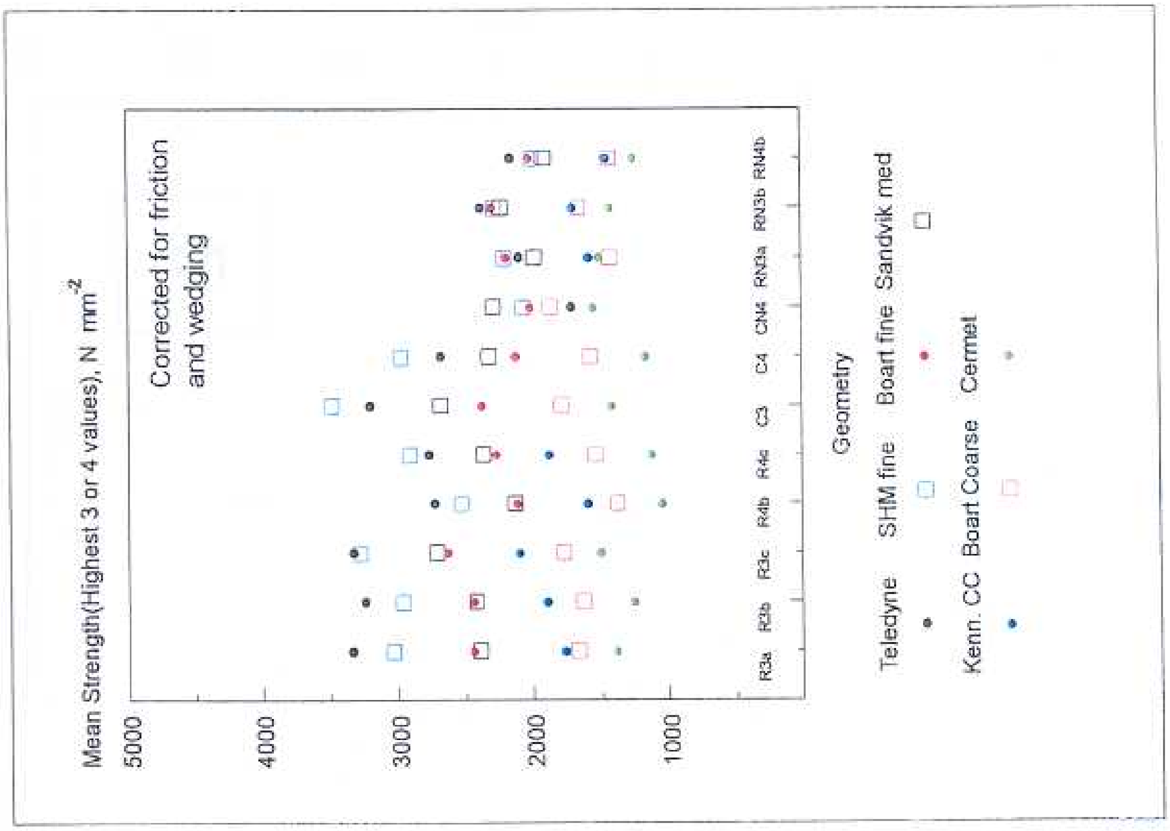


Fig 7 Representative strengths obtained from Weibull σ_0 and mean of highest 3-4 values.



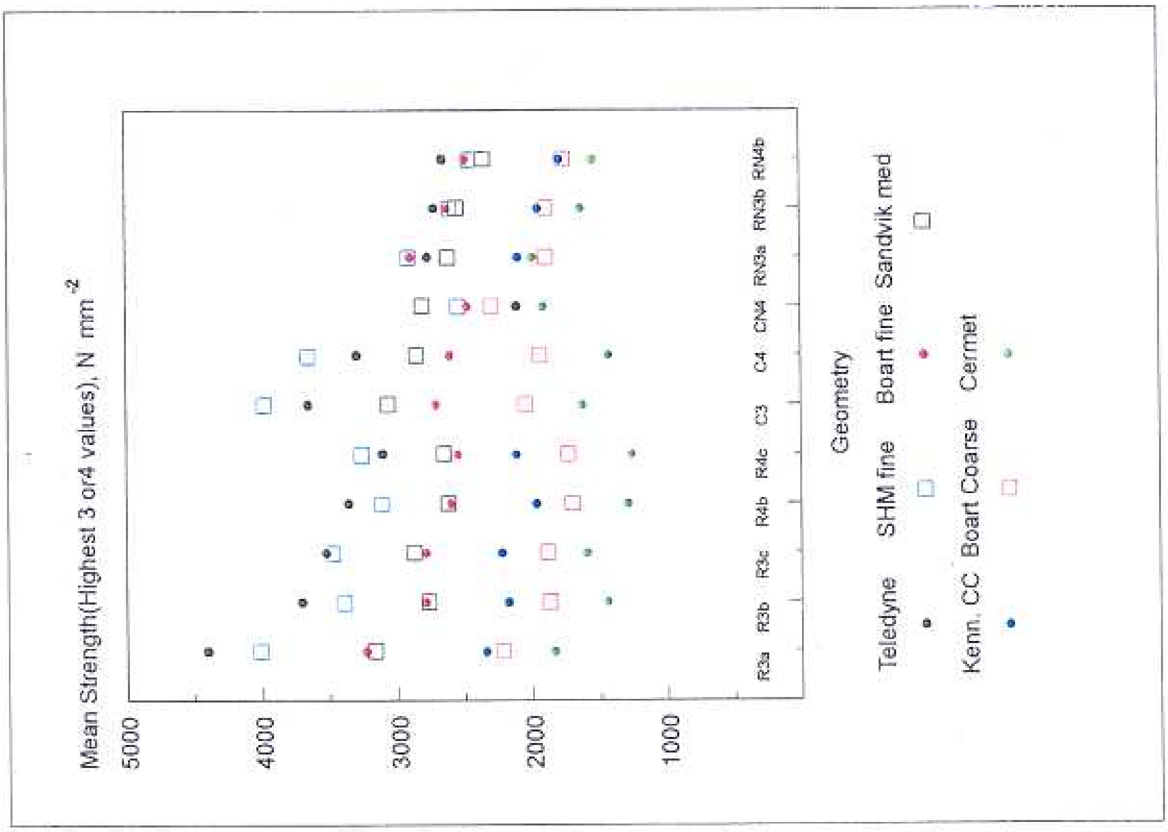


Fig 8 Representative strength values corrected for friction and wedging effects compared with uncorrected results for mean of highest 3-4 values.

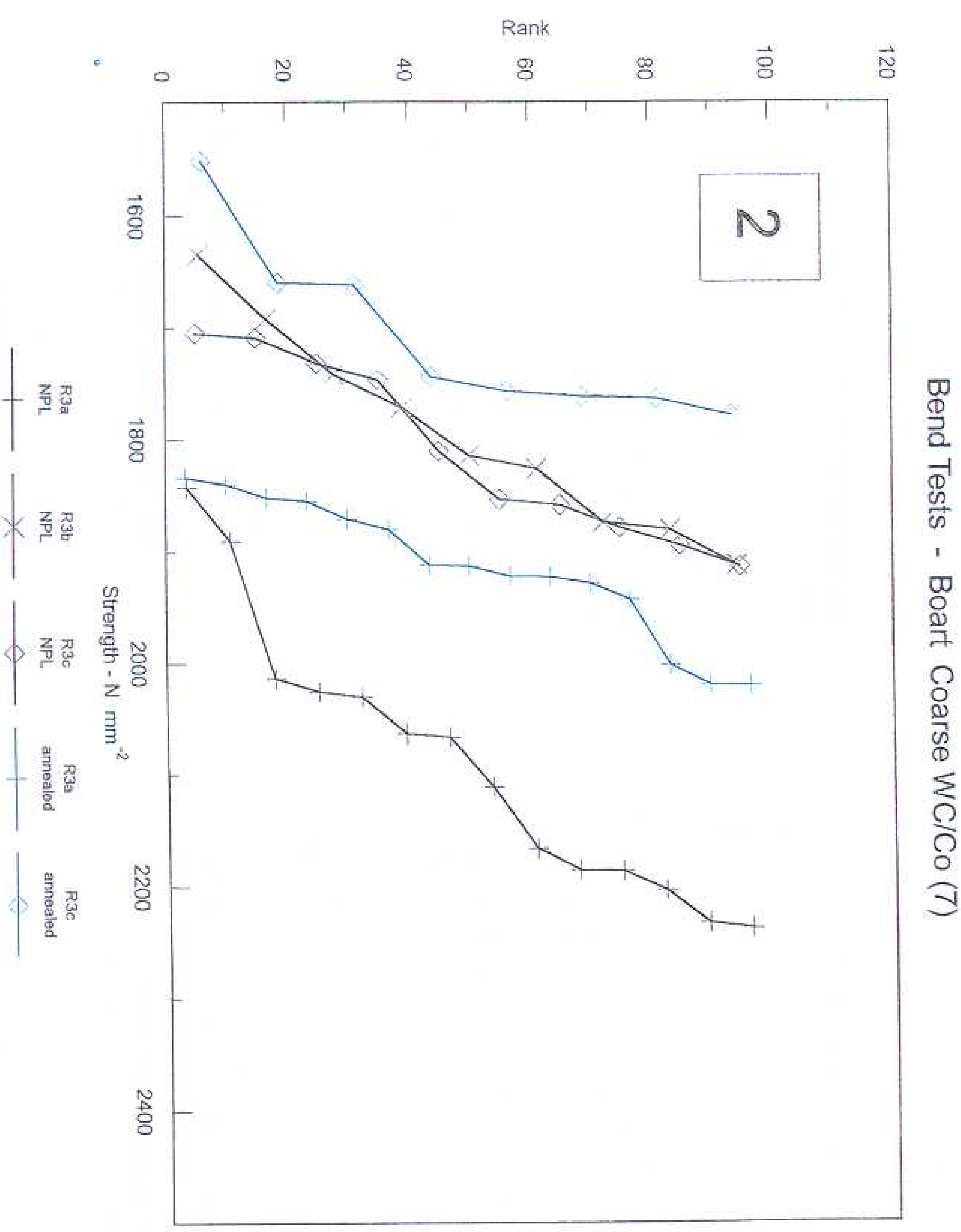


Fig 9 Annealed and as-ground bend test results for the R3 geometries for the Boart (C) hardmetal.

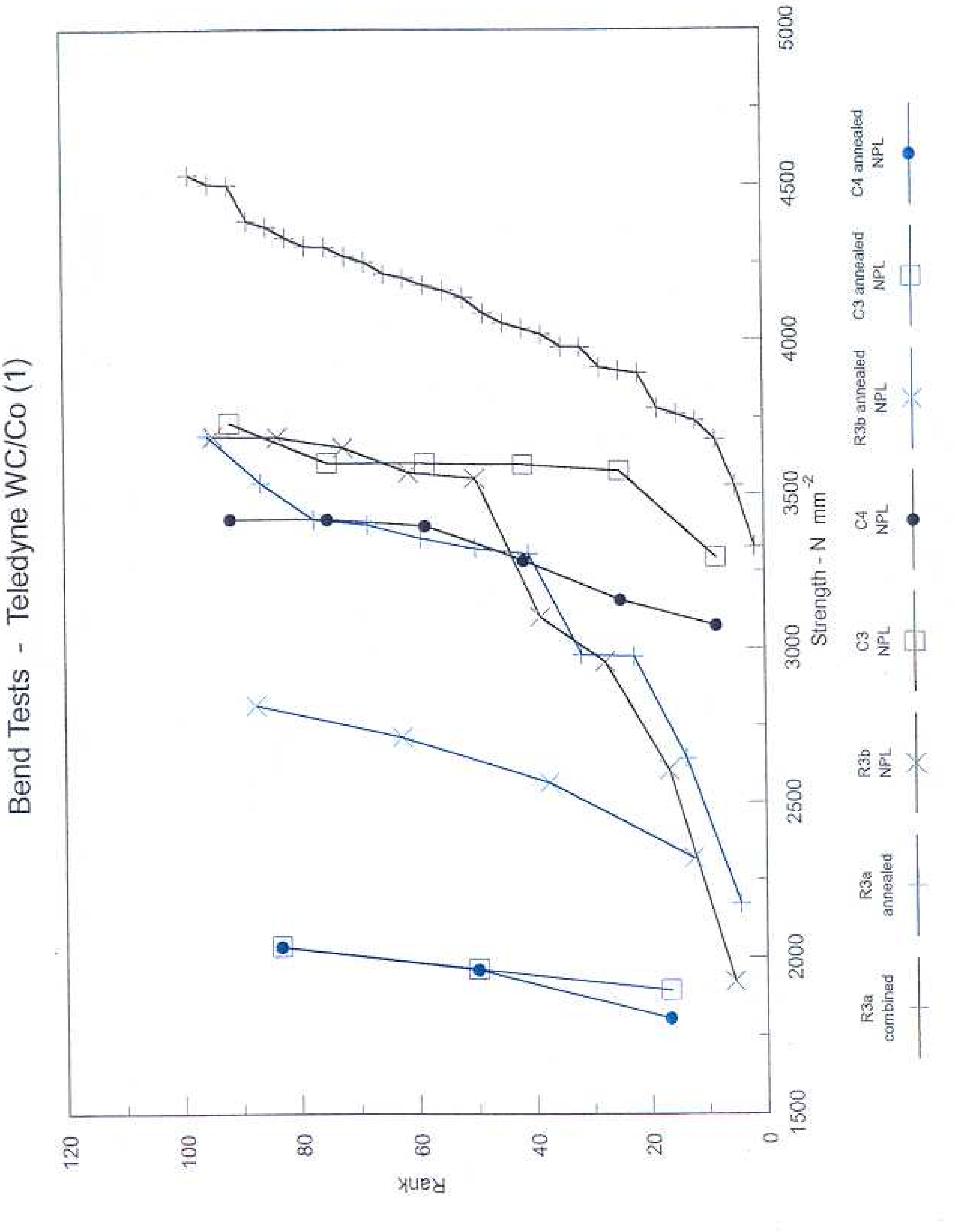


Fig 10 Annealed and as-ground bend test results for the Teledyne (UF) hardmetal.

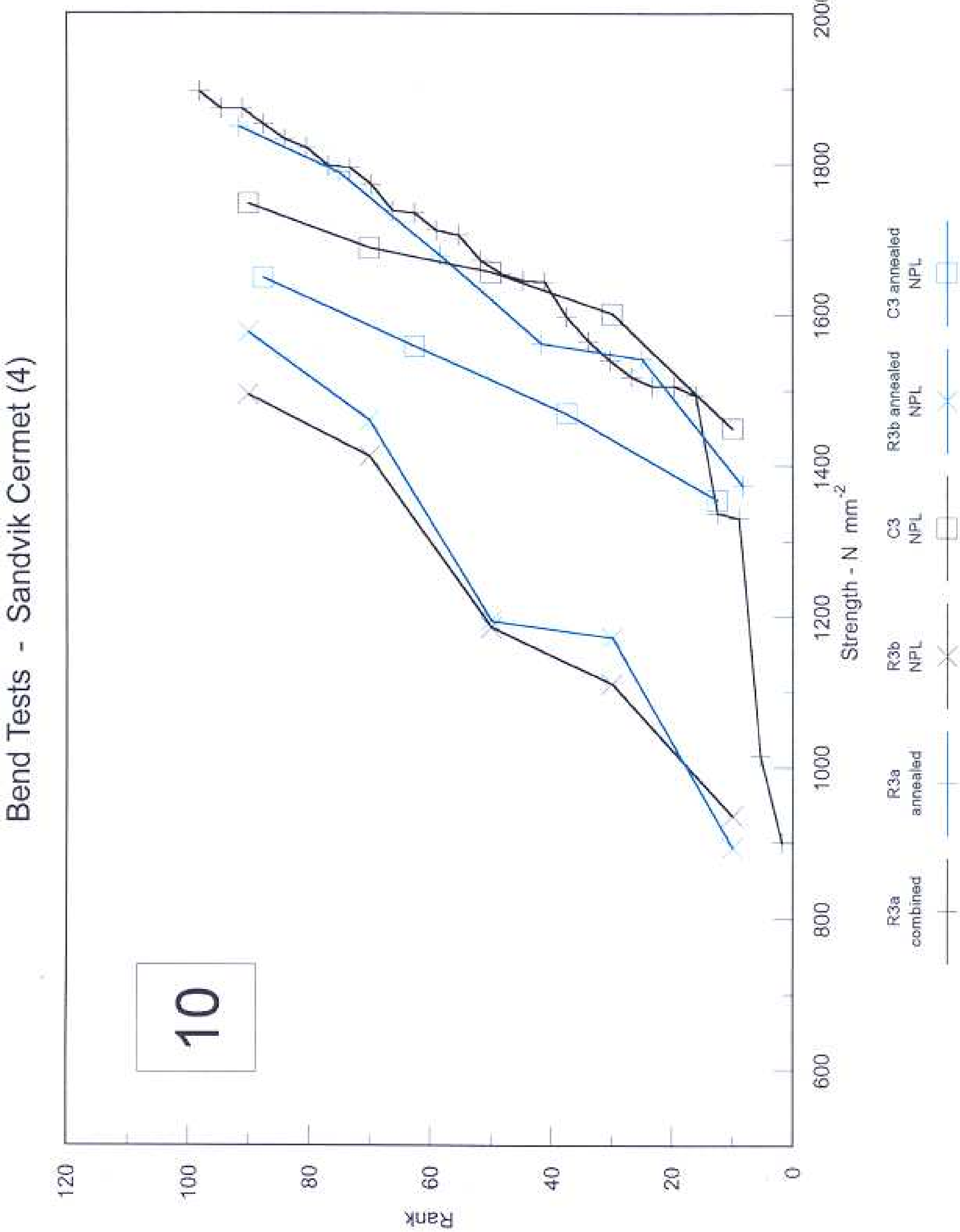


Fig 11 Annealed and as-ground bend test results for the Sandvik (Ti(C,N) Cermet hardmetal.

VAMAS Report No 31

Bend Strength Measurements for Hardmetals International Prestandardisation Collaborative Activity

Part 2 - Analysis of Results

Section 8 WEIBULL RESULTS SETS

WEIBULL RESULTS SET

(1) TELEDYNE ADVANCED MATERIAL

Ultrafine, WC/Co

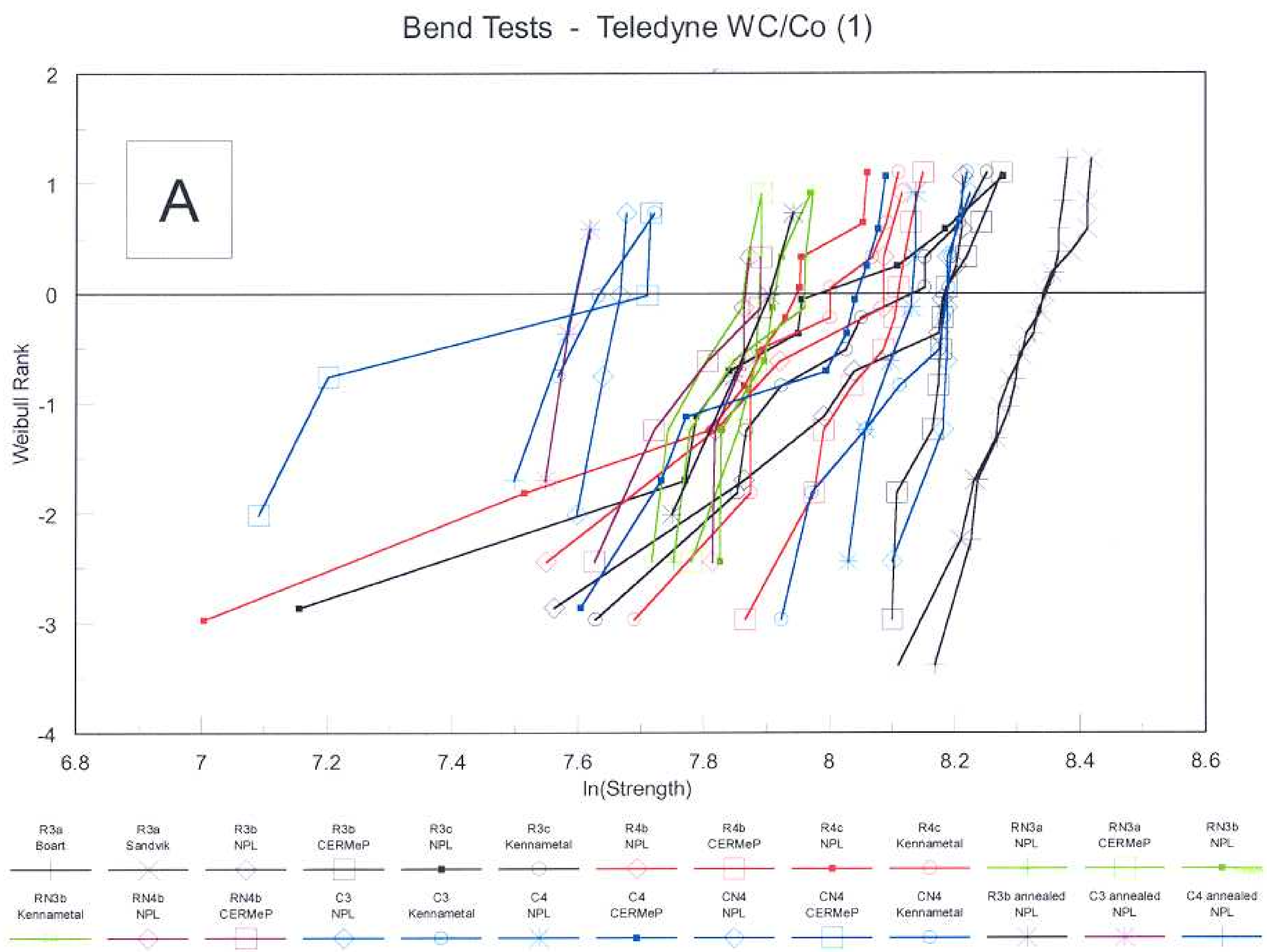
HARDMETAL BEND TESTS

Results Comment Sheet

Teledyne - Category (1) UltraFine WC/Co Hardmetal

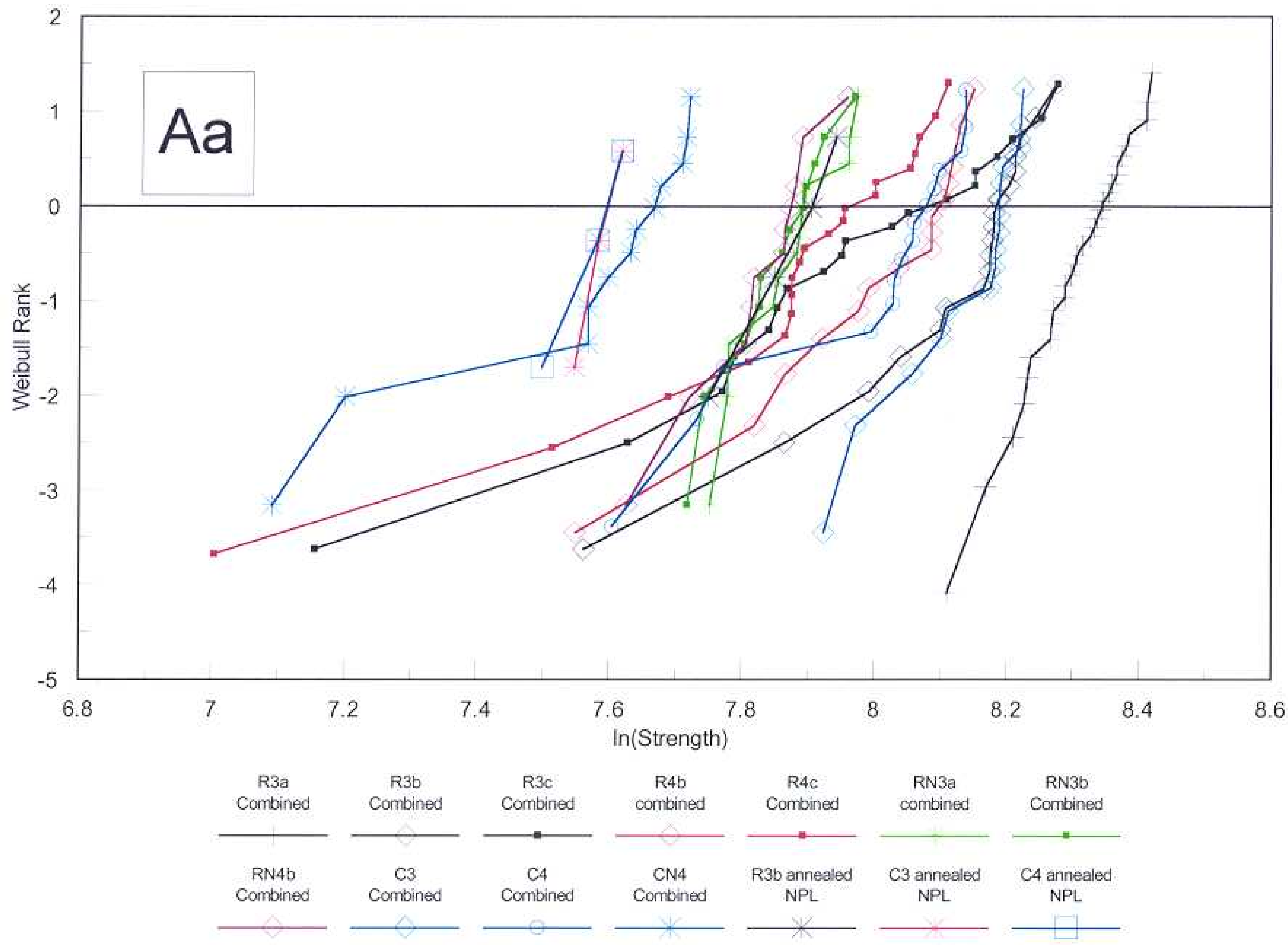
PLOT SEQUENCE

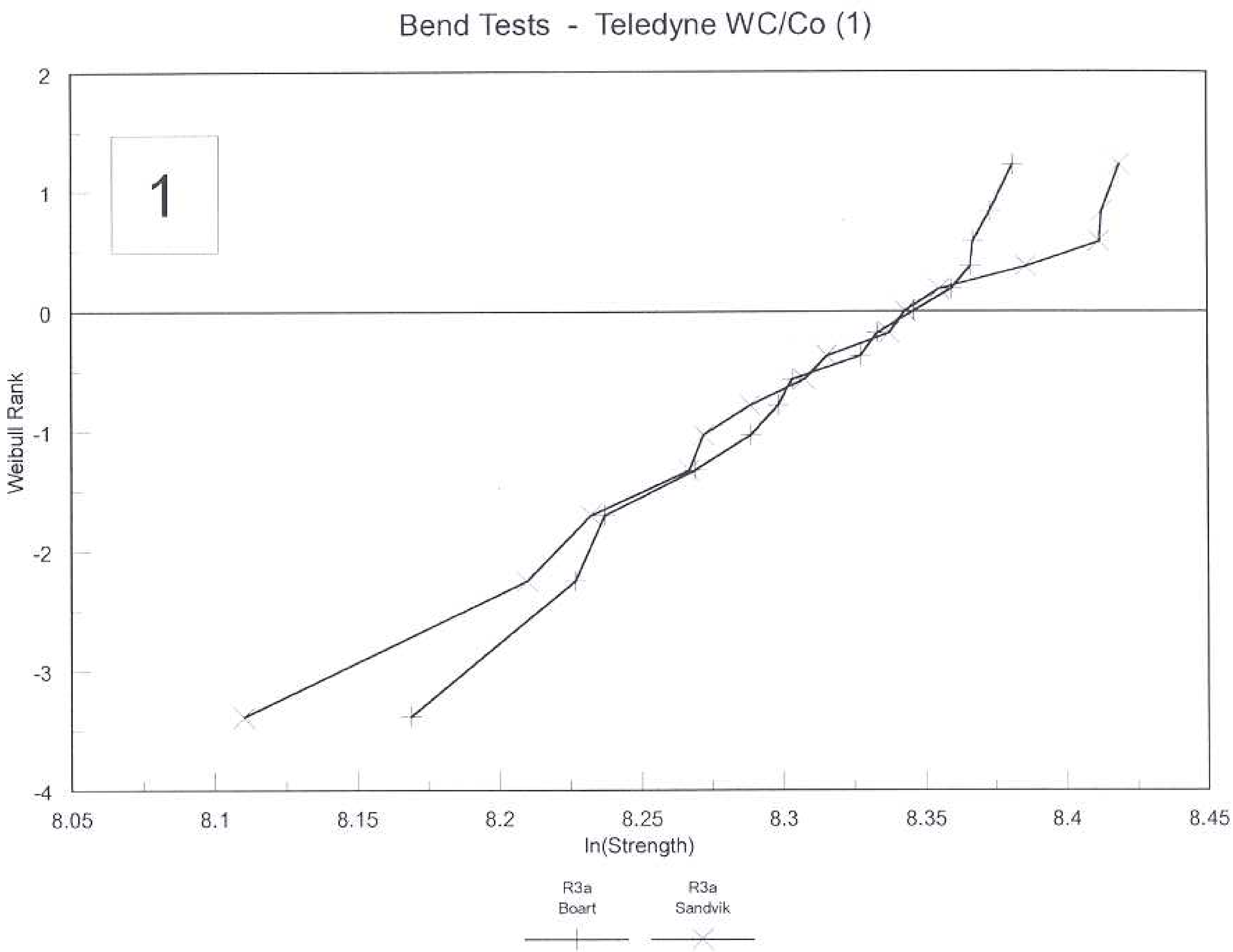
A	-	Complete set of all strength values.
Aa	-	Complete set, different laboratories combined.
1	-	Standard tests, ISO type B (R3a).
1a	-	Combined R3a.
2	-	3 pt rectangular tests; (R3a, R3b, R3c).
2a	-	Combined R3a, R3b and R3c.
3	-	4 pt rectangular tests, compared with standard ISO type B; (R3a, R4b, R4c).
3a	-	Combined R3a, R4b and R4c.
4	-	3 pt vs 4 pt tests; R3b, R3c, R4b, R4c; not including R3a.
4a	-	Combined R3b, R3c, R4b and R4c.
5	-	Round testpieces, compared with standard R3a; C3, C4 and R3a.
5a	-	Combined C3, C4 and R3a.
6	-	3 pt rectangular and round; R3b, R3c and C3; not including R3a.
6a	-	Combined C3 compared with R3b and R3c combined.
7	-	4 pt rectangular and round; R4b, R4c and C4.
7a	-	Combined C4 compared with R4b and R4c.
8	-	Notched rectangular testpieces; RN3a, RN3b and RN4b.
8a	-	Combined notched testpieces; RN3a, RN3b and RN4b.
9	-	Notched round compared with combined notched rectangular; CN4 and RN3a, RB3b and RN4b.
9a	-	Combined notched round compared with combined notched rectangular; CN4 and RN3a, RN3b and RN4b.

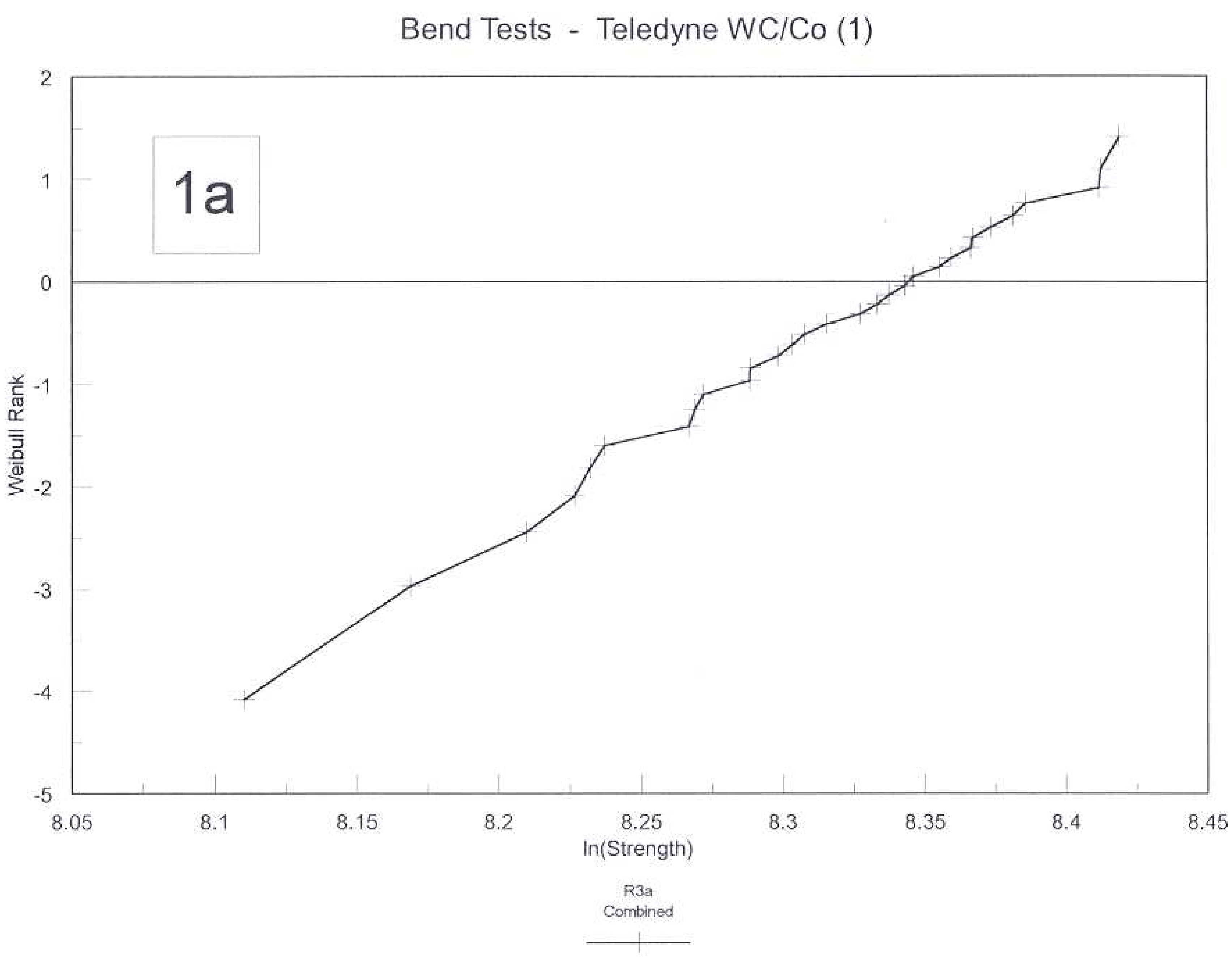


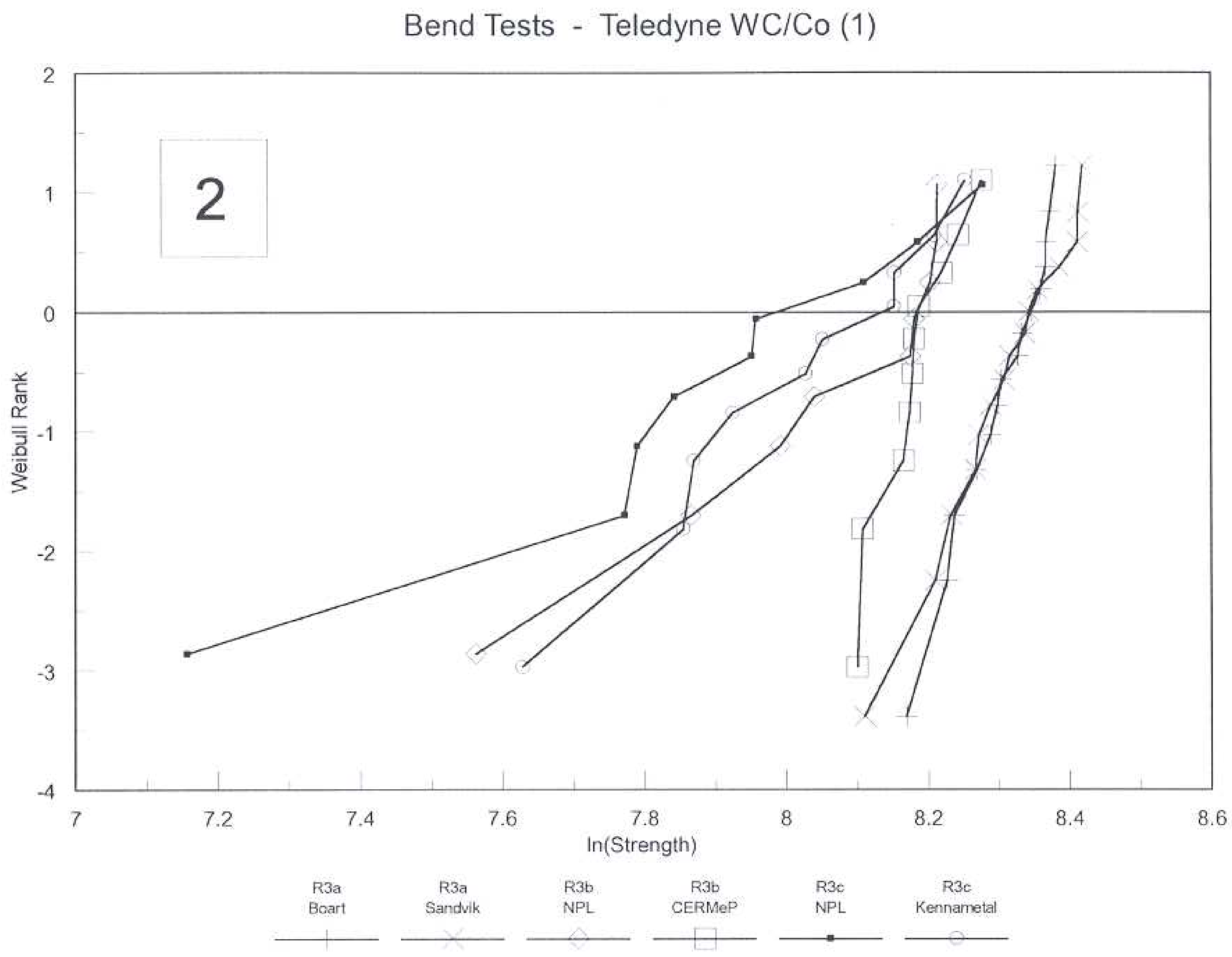
Bend Tests - Teledyne WC/Co (1)
A
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
ln(Strength)
R3a Boart
R3a Sandvik
R3b NPL
R3b CERMeP
R3c NPL
R3c Kennametal
R4b NPL
R4b CERMeP
R4c NPL
R4c Kennametal
RN3a NPL
RN3a CERMeP
RN3b NPL
RN3b Kennametal
RN4b NPL
RN4b CERMeP
C3 NPL
C3 Kennametal
C4 NPL
C4 CERMeP
CN4 NPL
CN4 CERMeP
CN4 Kennametal
R3b annealed NPL
C3 annealed NPL
C4 annealed NPL

Bend Tests - Teledyne WC/Co (1)

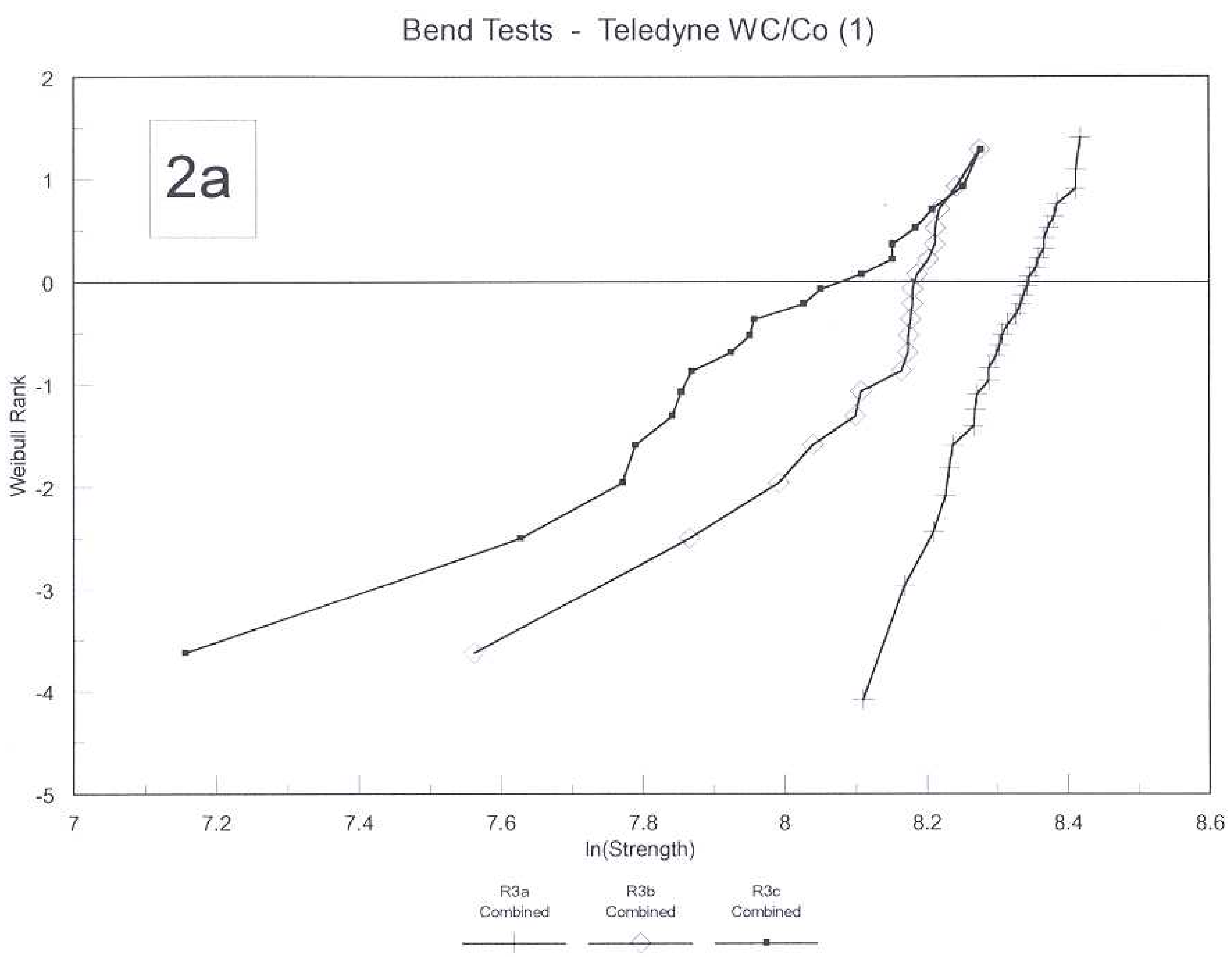


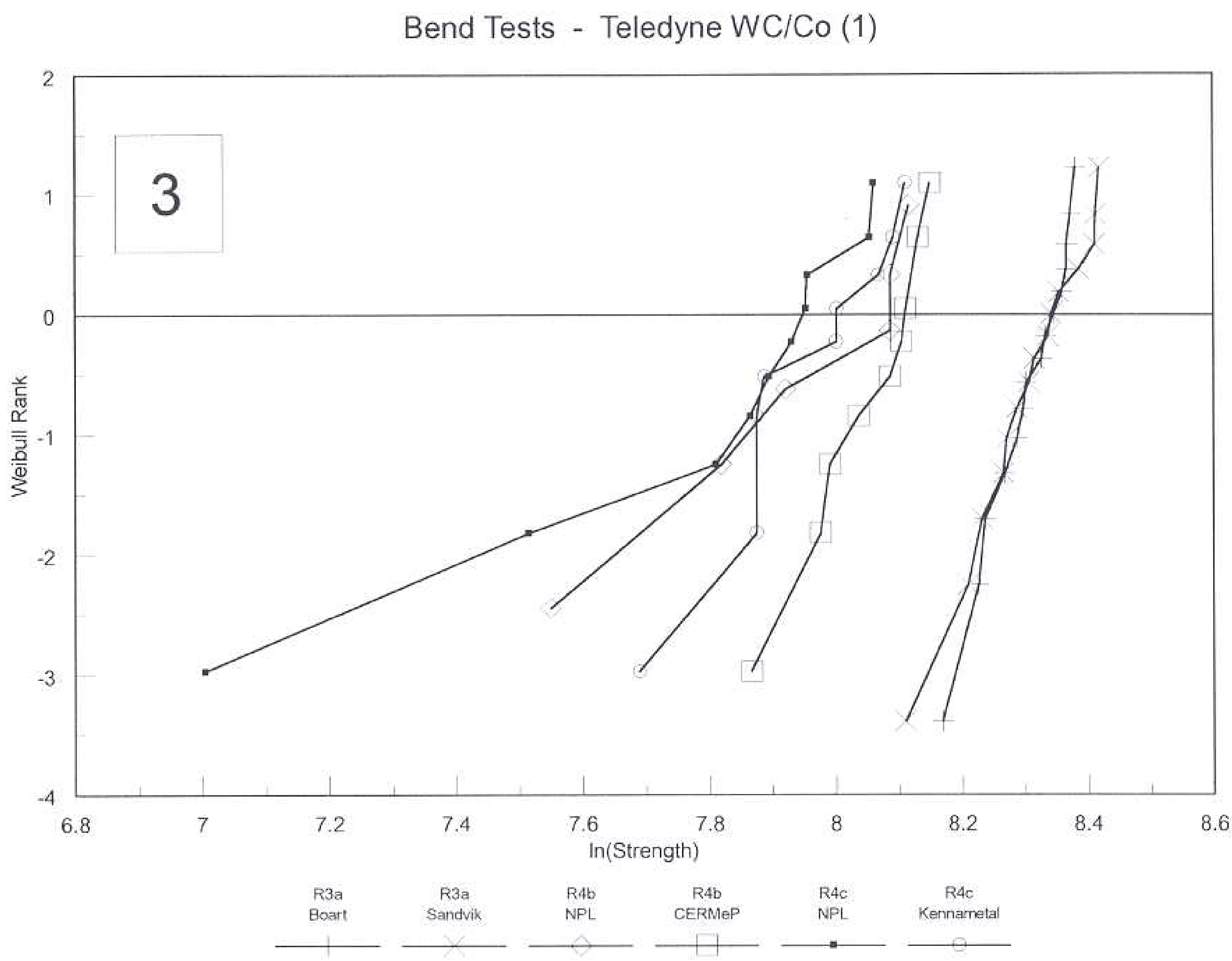

Bend Tests - Teledyne WC/Co (1)
1
Weibull Rank
2
1
0
-1
-2
-3
-4
8.05
8.1
8.15
8.2
8.25
8.3
8.35
8.4
8.45
ln(Strength)
R3a
Boart
R3a
Sandvik


Bend Tests - Teledyne WC/Co (1)
1a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
8.05
8.1
8.15
8.2
8.25
8.3
8.35
8.4
8.45
ln(Strength)
R3a
Combined



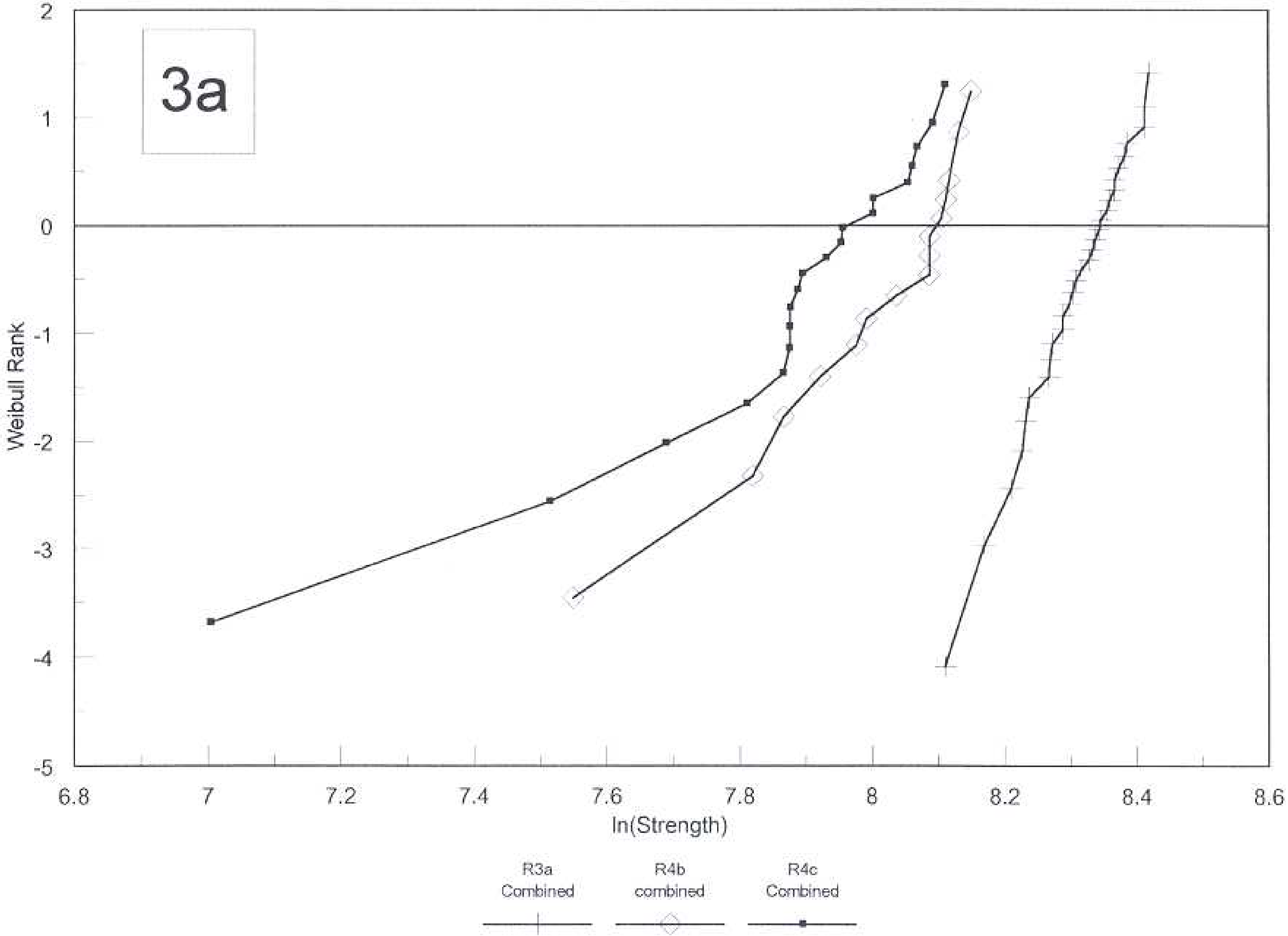
Bend Tests - Teledyne WC/Co (1)
2
Weibull Rank
2
1
0
-1
-2
-3
-4
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
ln(Strength)
R3a Boart
R3a Sandvik
R3b NPL
R3b CERMeP
R3c NPL
R3c Kennametal

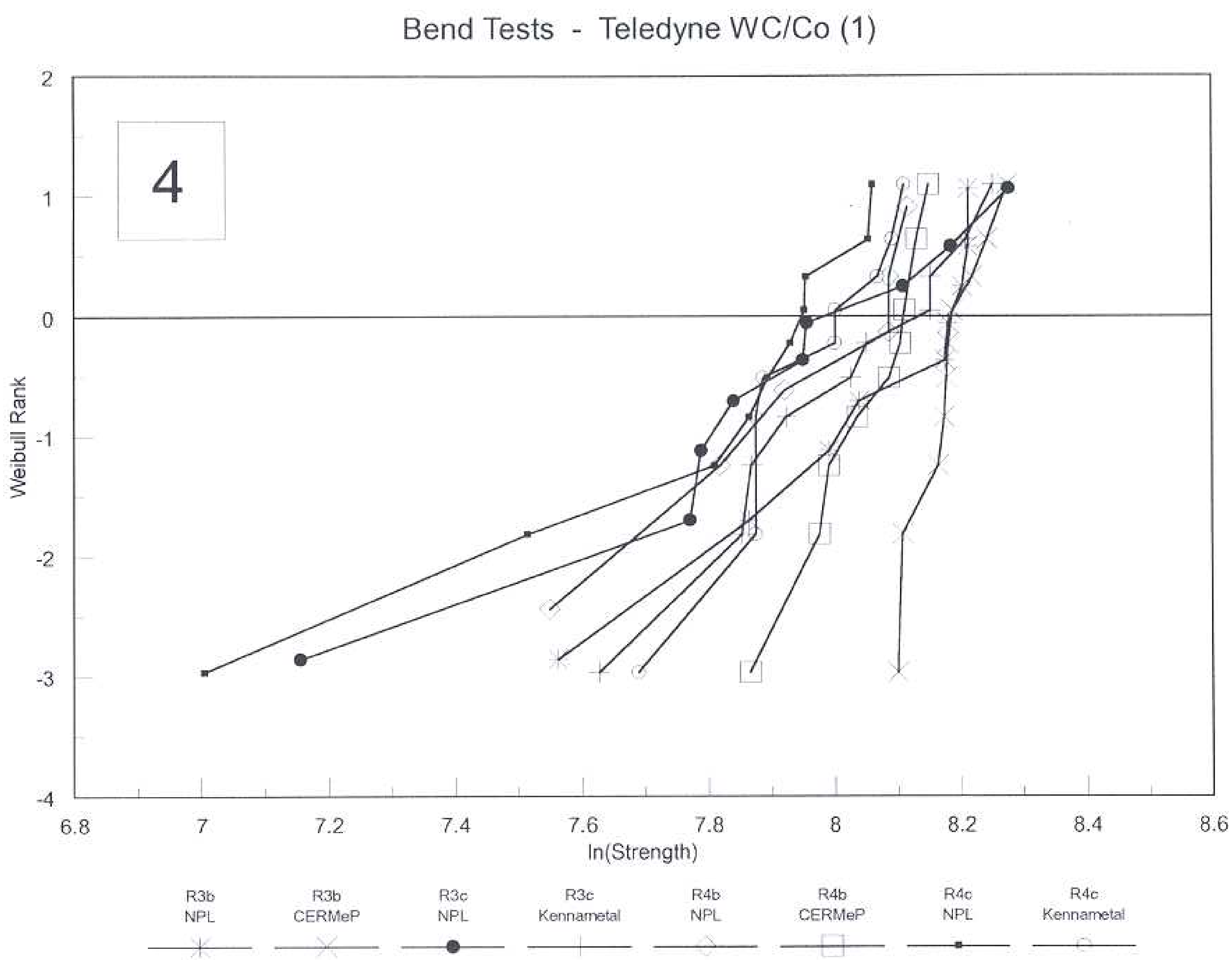

Bend Tests - Teledyne WC/Co (1)
2a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
ln(Strength)
R3a Combined
R3b Combined
R3c Combined

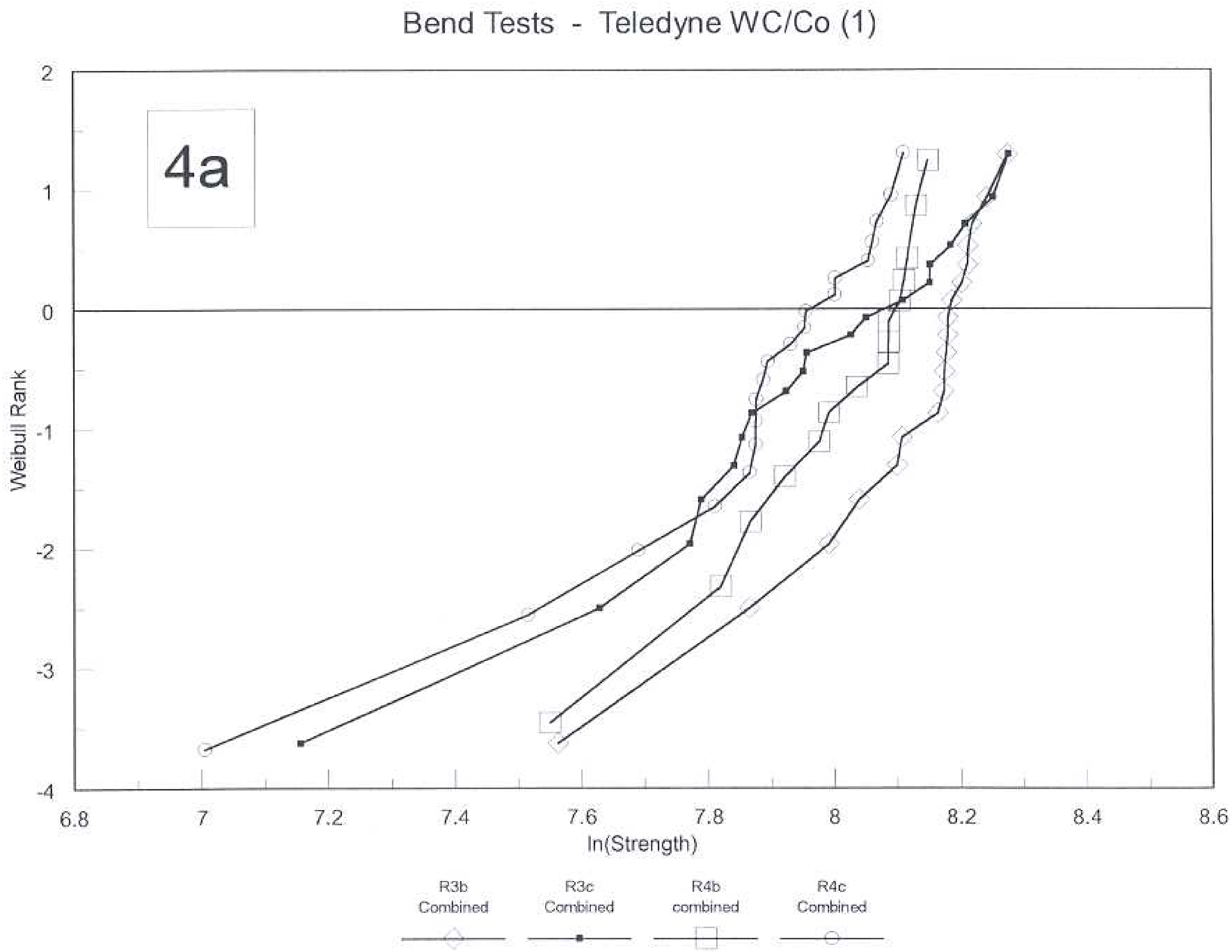


Bend Tests - Teledyne WC/Co (1)
3
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
ln(Strength)
R3a Boart
R3a Sandvik
R4b NPL
R4b CERMeP
R4c NPL
R4c Kennametal

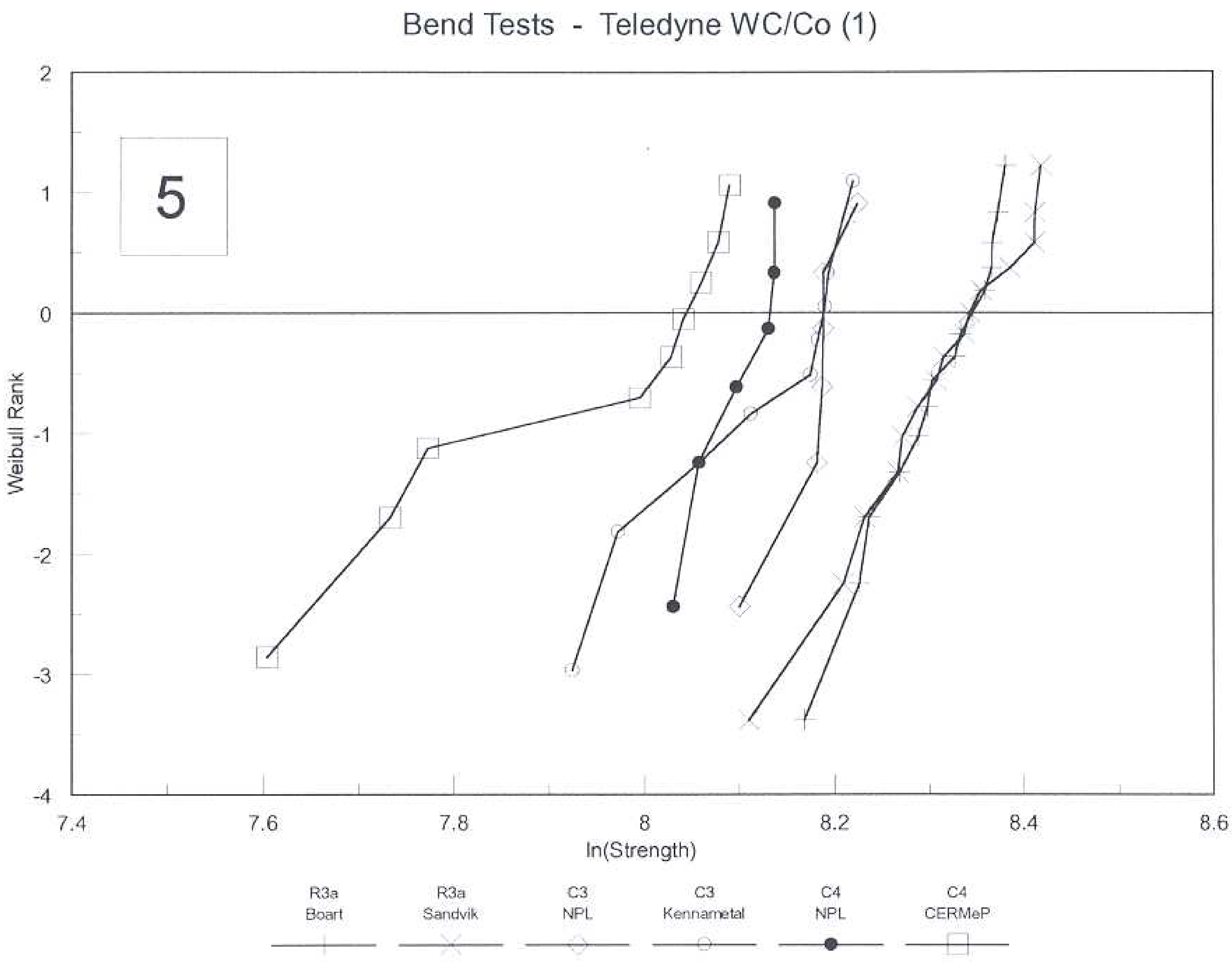
Bend Tests - Teledyne WC/Co (1)

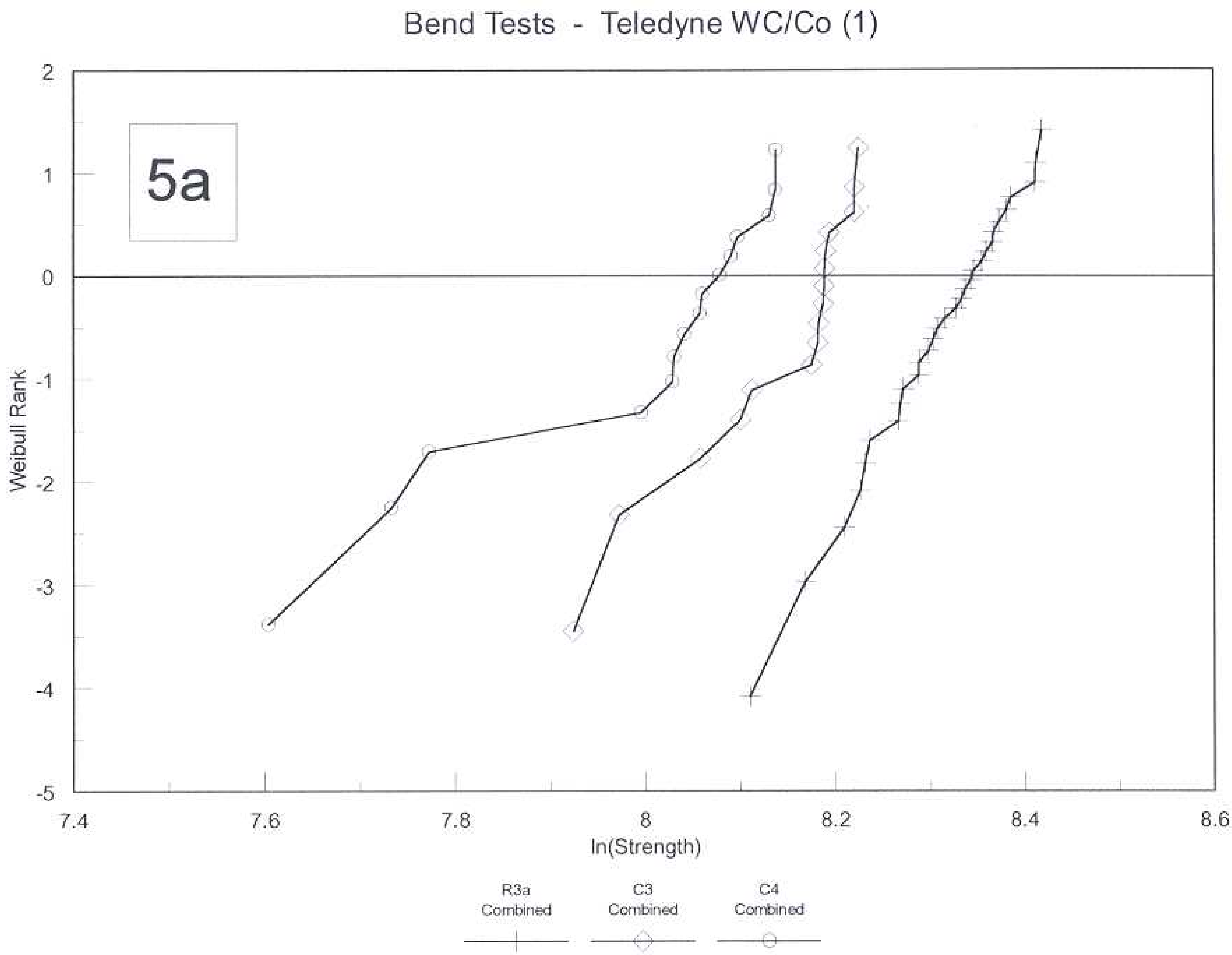


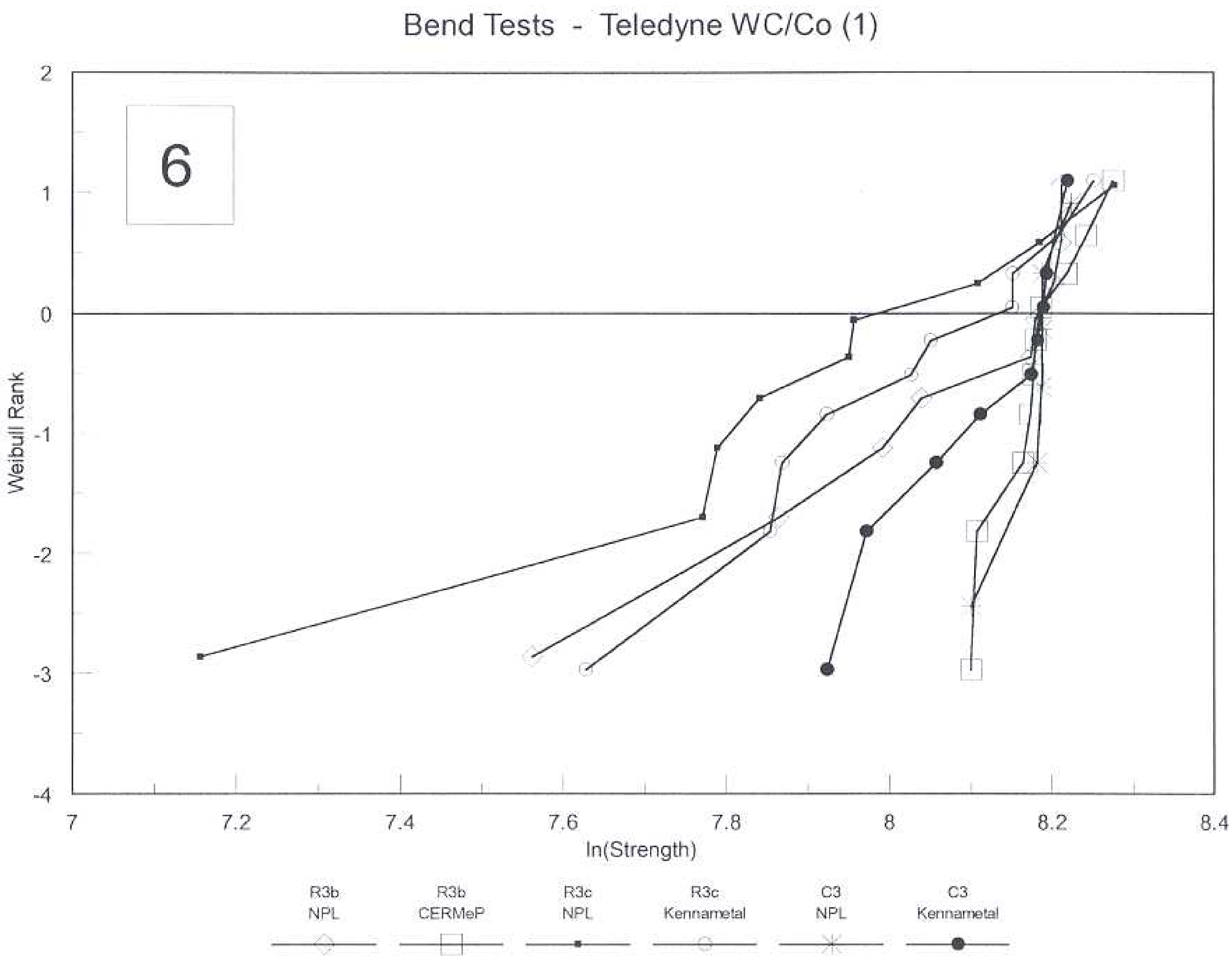

Bend Tests - Teledyne WC/Co (1)
4
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
ln(Strength)
R3b NPL
R3b CERMeP
R3c NPL
R3c Kennametal
R4b NPL
R4b CERMeP
R4c NPL
R4c Kennametal



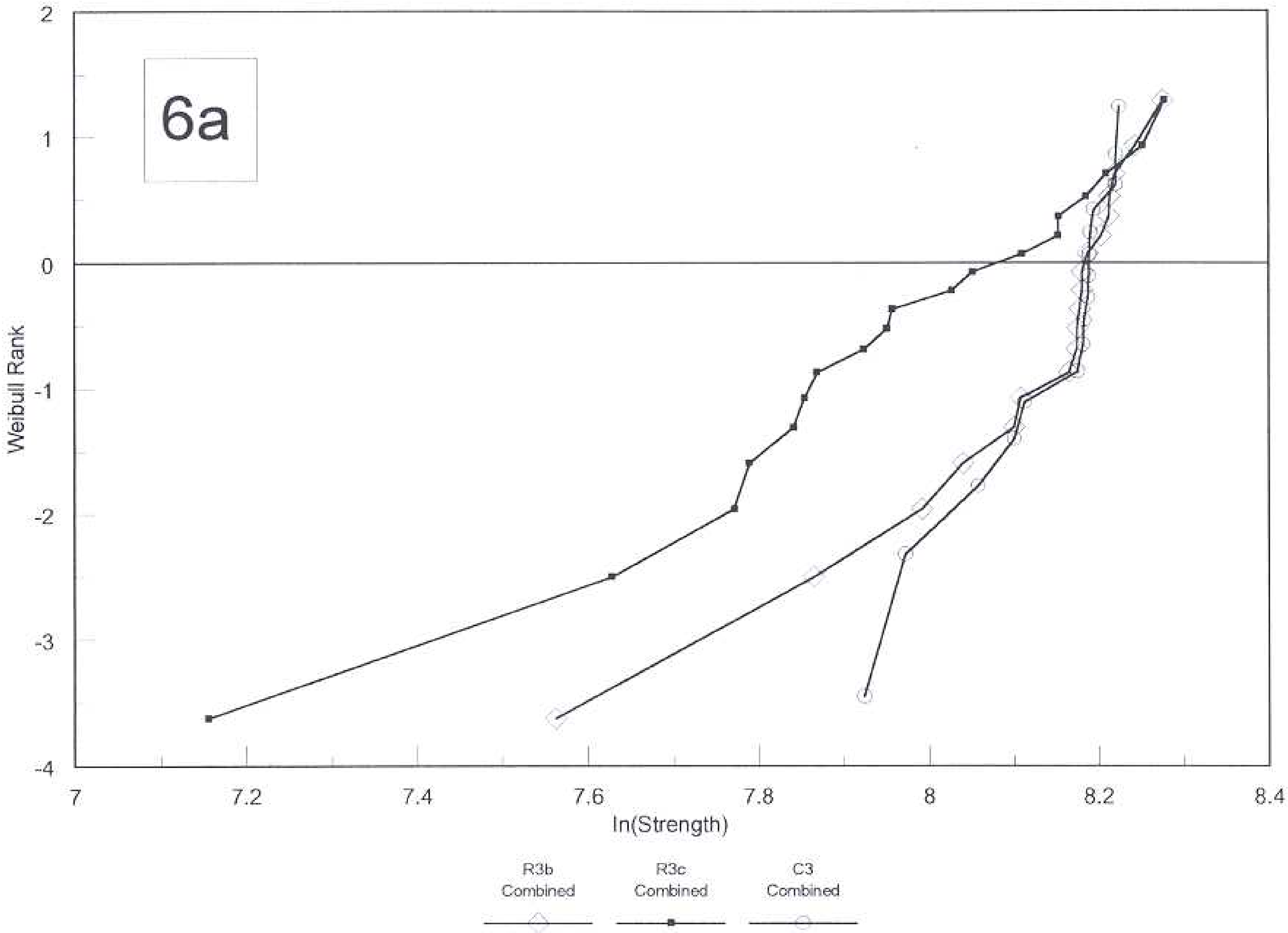
Bend Tests - Teledyne WC/Co (1)
4a
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
ln(Strength)
R3b Combined
R3c Combined
R4b combined
R4c Combined

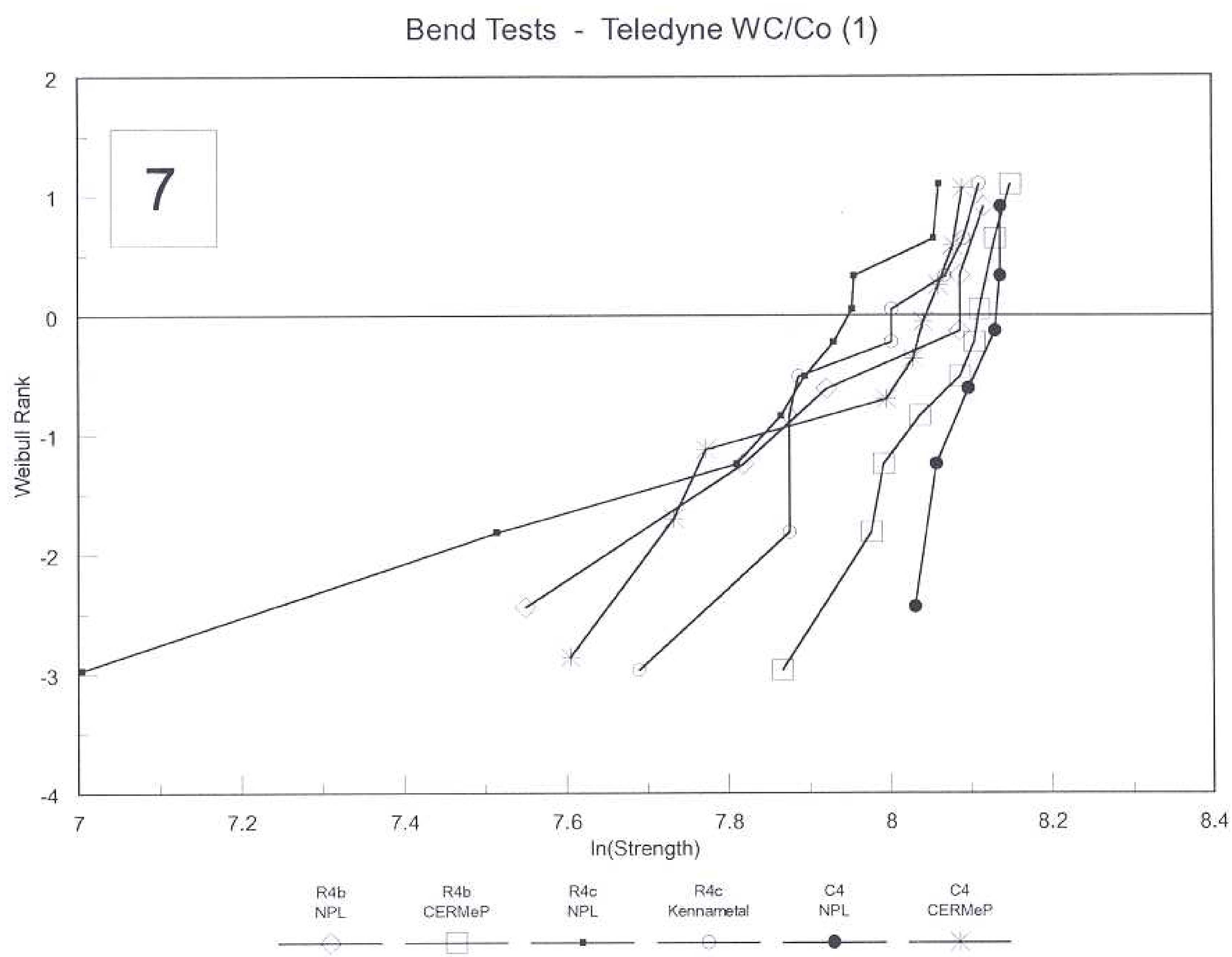

Bend Tests - Teledyne WC/Co (1)
5
Weibull Rank
2
1
0
-1
-2
-3
-4
7.4
7.6
7.8
8
8.2
8.4
8.6
ln(Strength)
R3a Boart
R3a Sandvik
C3 NPL
C3 Kennametal
C4 NPL
C4 CERMeP


Bend Tests - Teledyne WC/Co (1)
5a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
7.4
7.6
7.8
8
8.2
8.4
8.6
ln(Strength)
R3a Combined
C3 Combined
C4 Combined

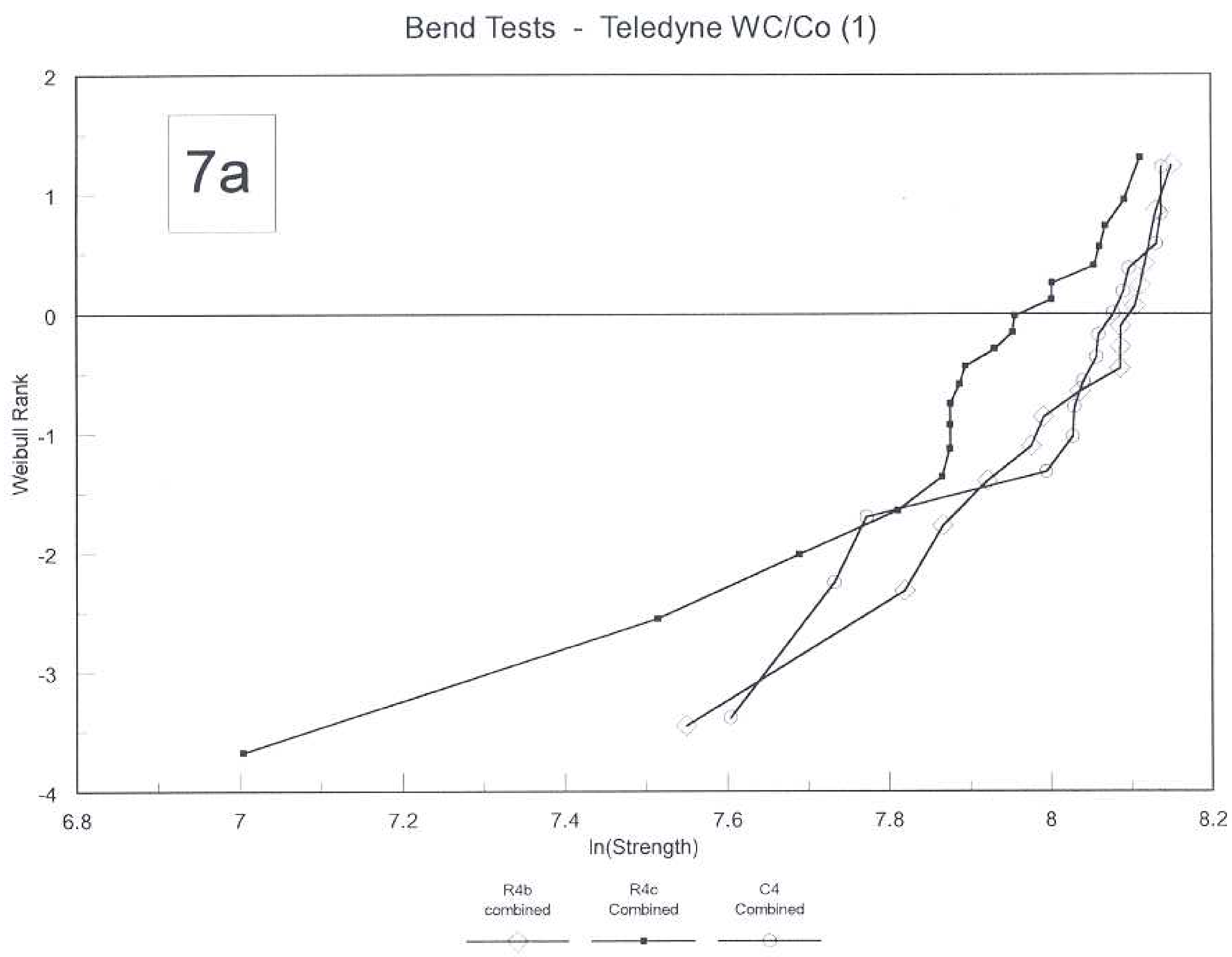

Bend Tests - Teledyne WC/Co (1)
6
Weibull Rank
2
1
0
-1
-2
-3
-4
7
7.2
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R3b NPL
R3b CERMeP
R3c NPL
R3c Kennametal
C3 NPL
C3 Kennametal

Bend Tests - Teledyne WC/Co (1)

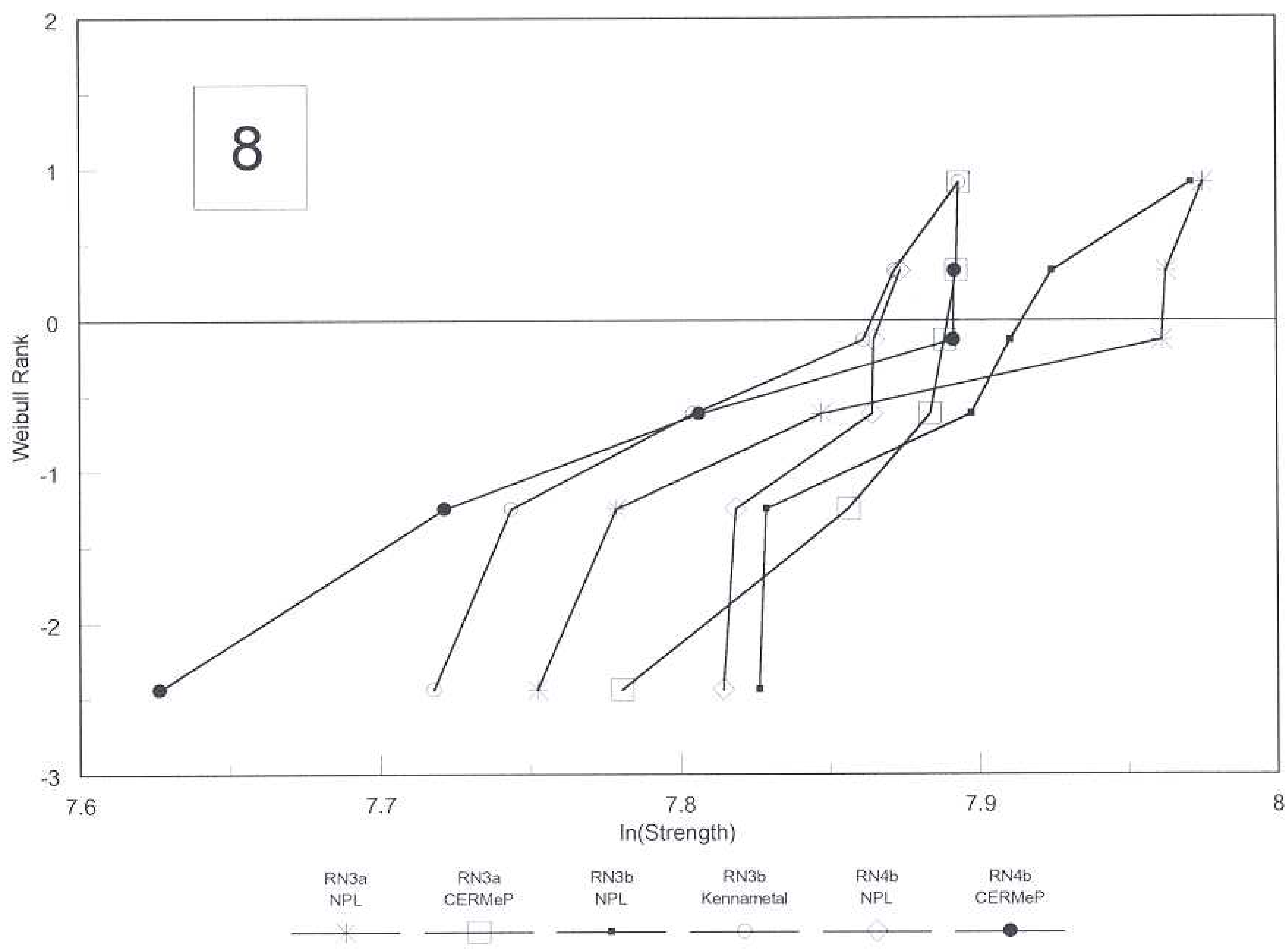


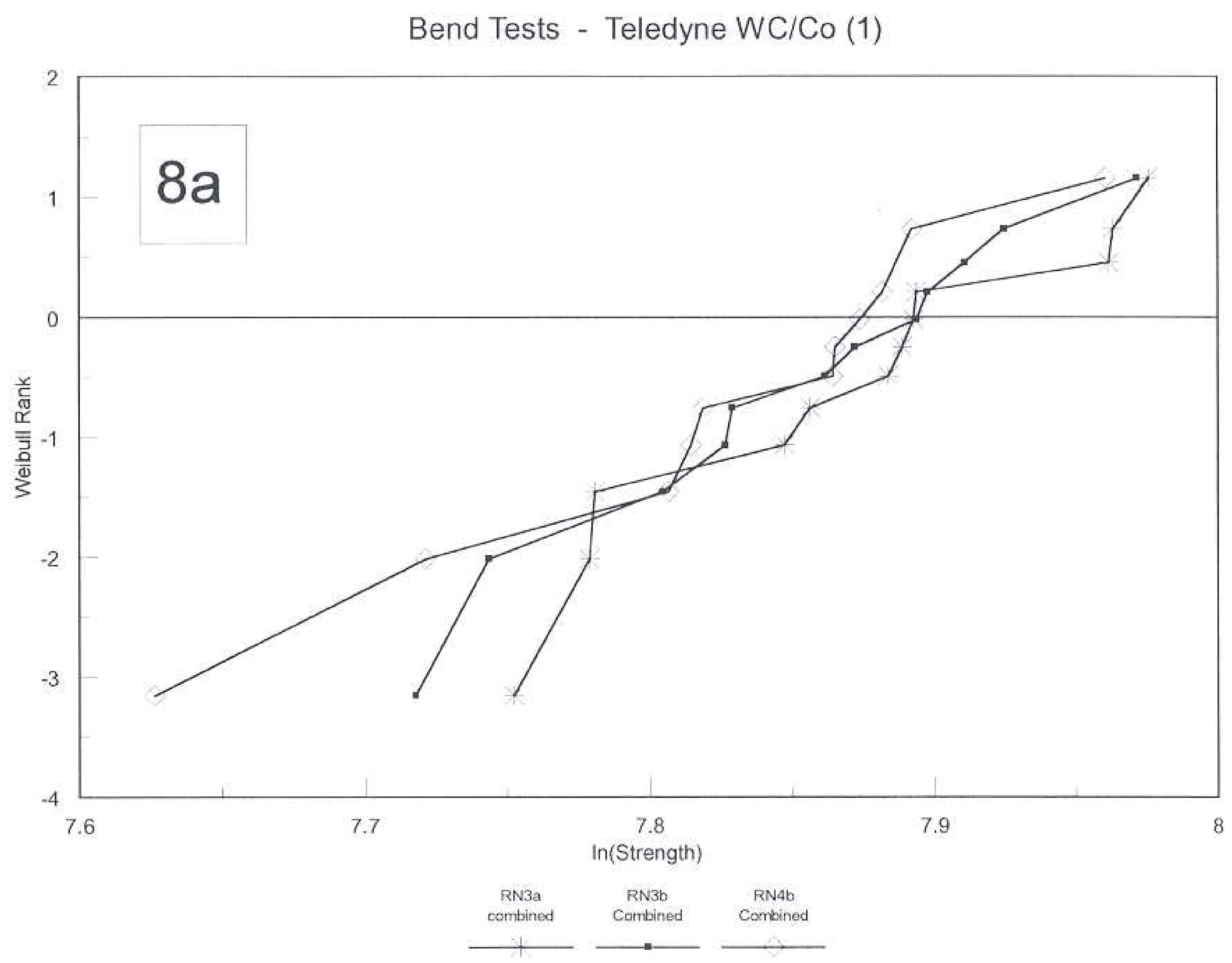


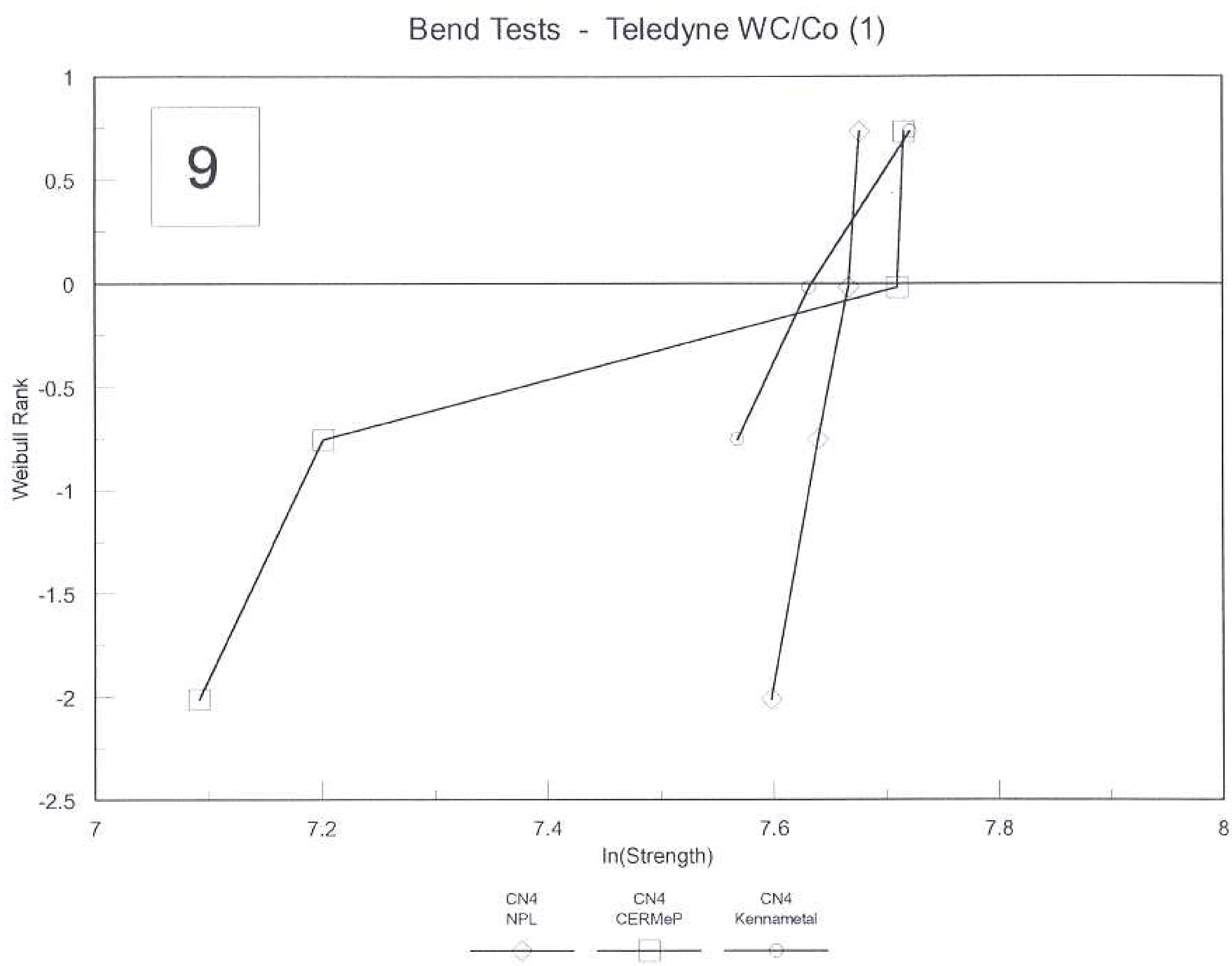
Bend Tests - Teledyne WC/Co (1)
7
Weibull Rank
2
1
0
-1
-2
-3
-4
7
7.2
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R4b NPL
R4b CERMeP
R4c NPL
R4c Kennametal
C4 NPL
C4 CERMeP

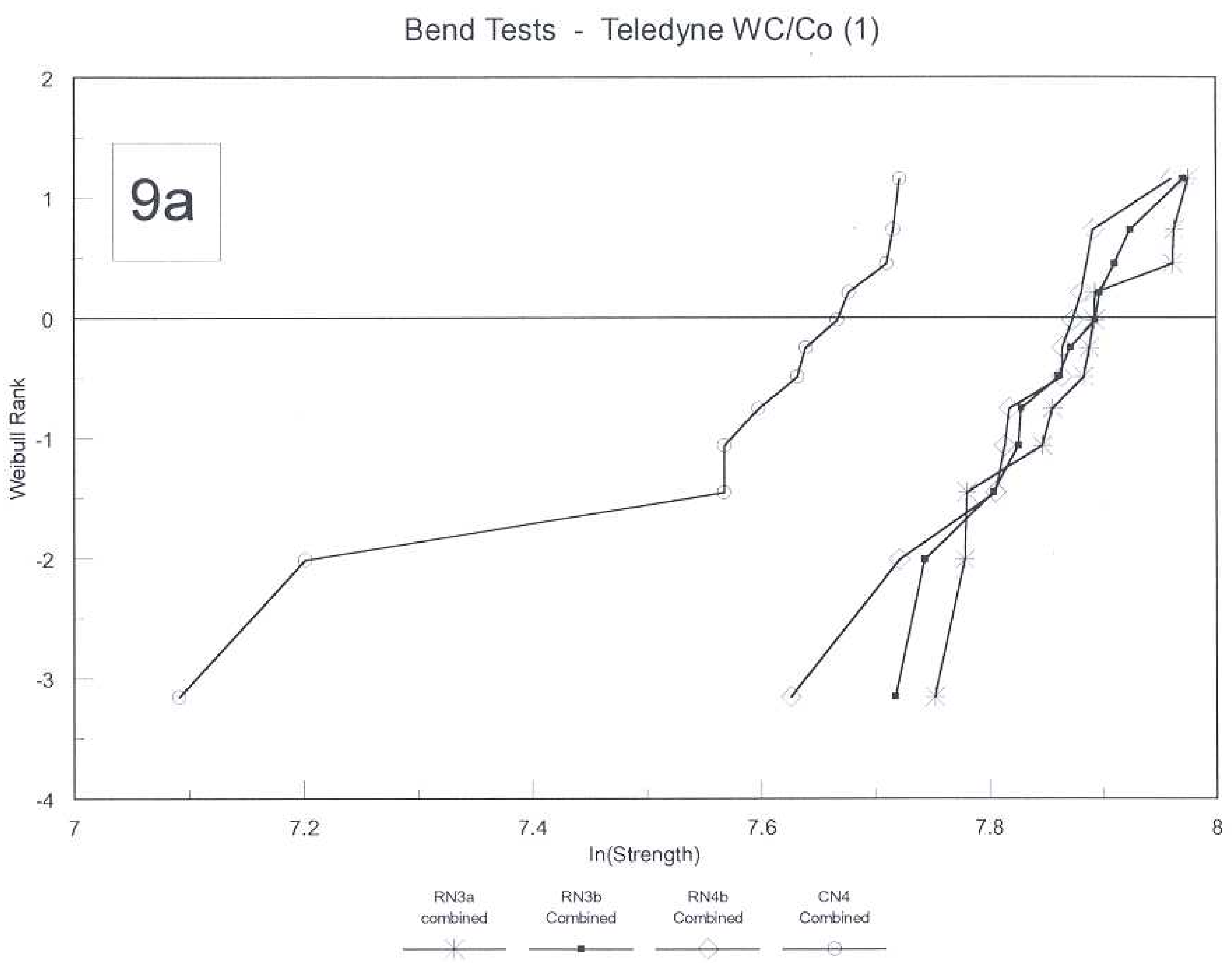

Bend Tests - Teledyne WC/Co (1)
7a
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
8
8.2
ln(Strength)
R4b combined
R4c Combined
C4 Combined

Bend Tests - Teledyne WC/Co (1)




Bend Tests - Teledyne WC/Co (1)
8a
Weibull Rank
2
1
0
-1
-2
-3
-4
7.6
7.7
7.8
7.9
8
ln(Strength)
RN3a combined
RN3b Combined
RN4b Combined


Bend Tests - Teledyne WC/Co (1)
9
Weibull Rank
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
7
7.2
7.4
7.6
7.8
8
ln(Strength)
CN4 NPL
CN4 CERMeP
CN4 Kennametal


Bend Tests - Teledyne WC/Co (1)
9a
Weibull Rank
2
1
0
-1
-2
-3
-4
7
7.2
7.4
7.6
7.8
8
ln(Strength)
RN3a combined
RN3b Combined
RN4b Combined
CN4 Combined

WEIBULL RESULTS SET

(2) BOART LONGYEAR

Fine, WC/Co

HARDMETAL BEND TESTS

Results Comment Sheet

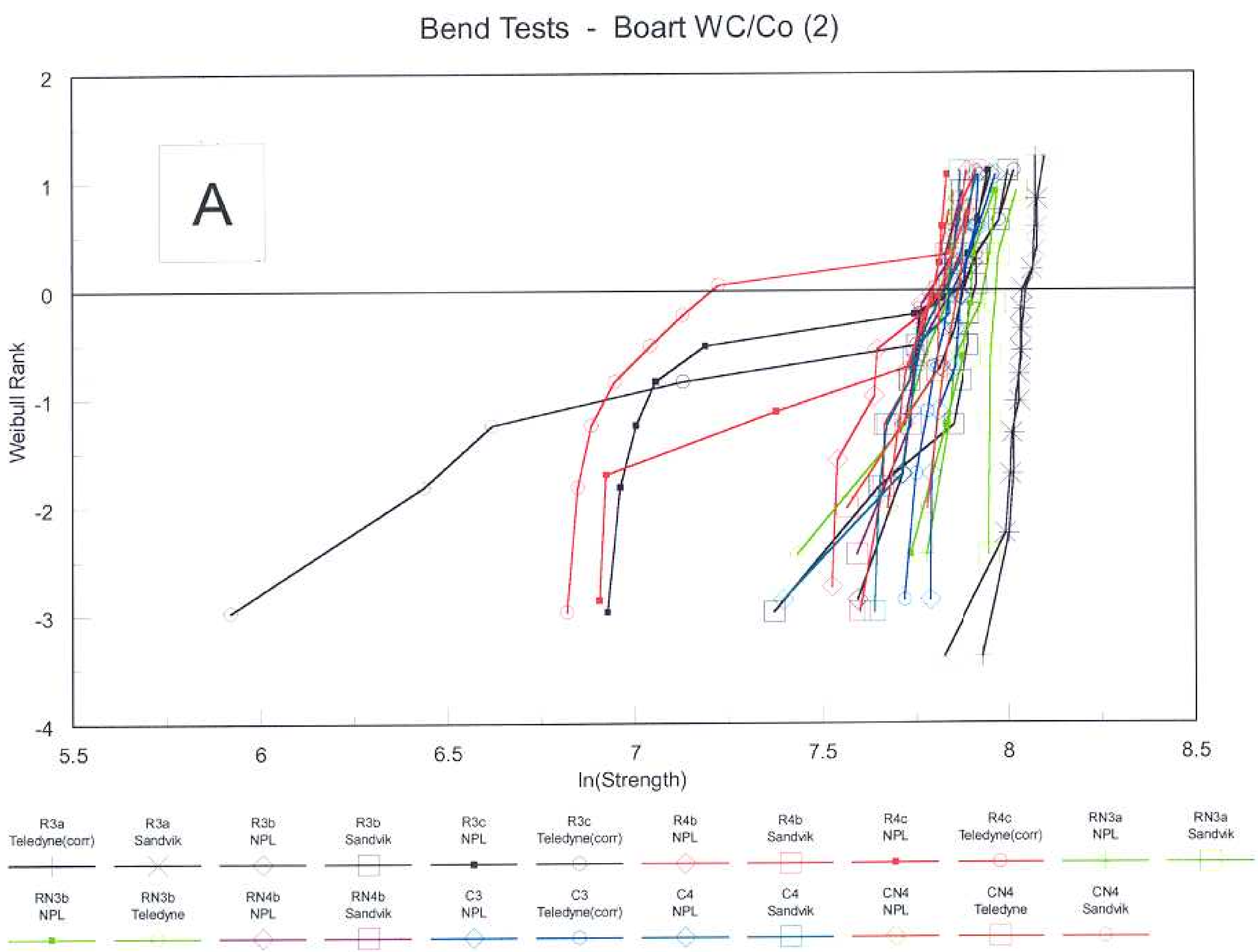
Boart Longyear Category (2) Fine WC/Co Hardmetal

PLOT SEQUENCE

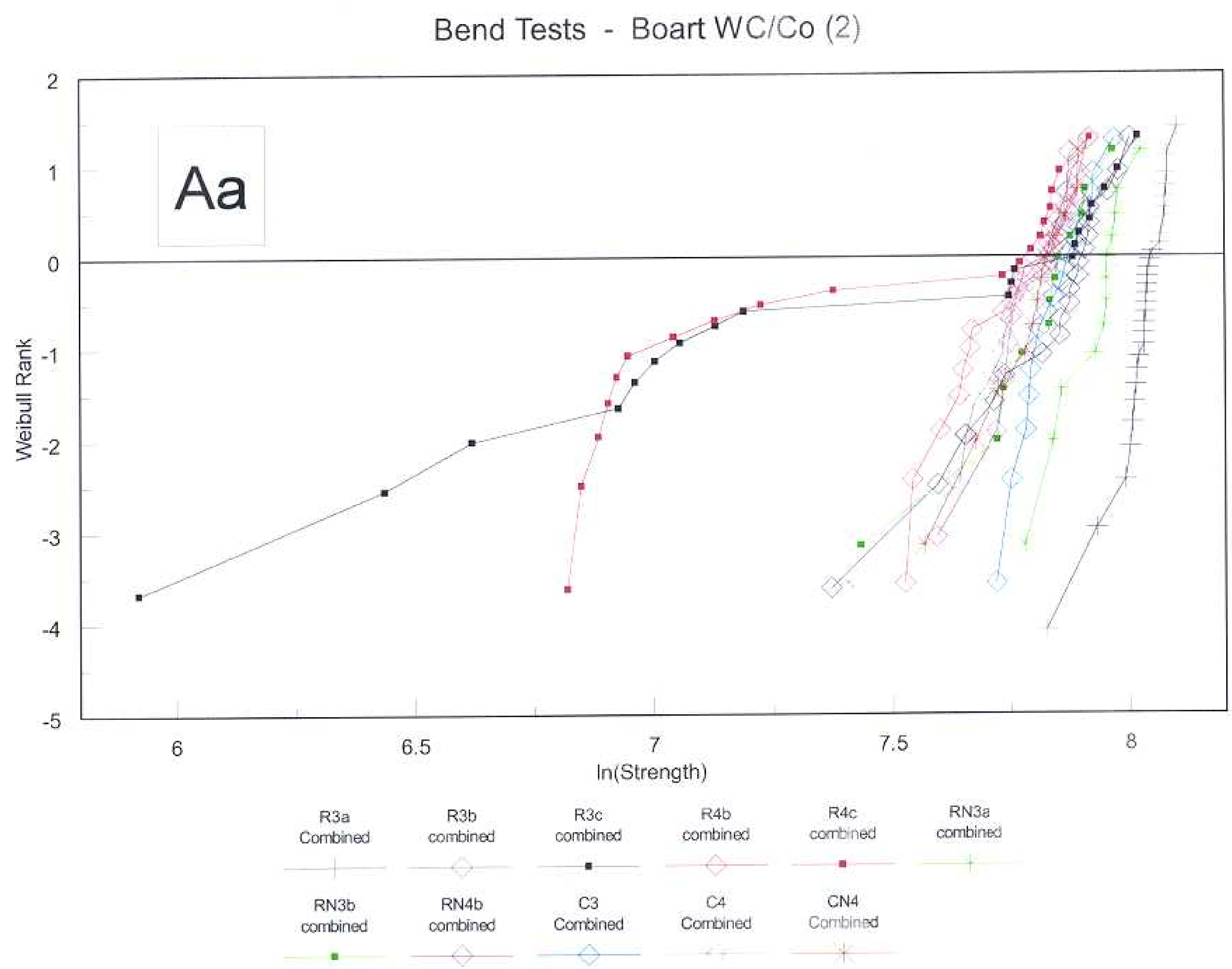
A	-	Complete set of all strength values.
Aa	-	Complete set, different laboratories combined.
Aa expanded	-	As Aa but X ordinate expanded.
1	-	Standard tests, ISO type B (R3a), including corrected Teledyne data*.
1a	-	Combined R3a.
2	-	3 pt rectangular tests; (R3a, R3b, R3c).
2a	-	Combined R3a, R3b and R3c.
3	-	4 pt rectangular tests, compared with Sandvik standard ISO type B; (R3a, R4b, R4c).
3a	-	Combined R3a, R4b and R4c.
4	-	Individual 3 pt vs 4 pt tests; not including R3a; (R3b, R3c, R4b, R4c).
4a	-	Combined 3 pt vs 4 pt tests; R3b, R3c, R4b and R4c (not including R3a).
5	-	Round testpieces, compared with standard R3a; (C3, C4 and R3a).
5a	-	Combined C3, C4 and R3a.
6	-	3 pt rectangular and round; (R3b, R3c and C3); not including R3a.
6a	-	Combined C3 compared with R3b combined and R3c combined.
7	-	4 pt rectangular and round (R4b, R4c and C4).
7a	-	Combined C4 compared with combined R4b and combined R4c.
8	-	Notched rectangular testpieces, Teledyne <u>not</u> corrected; (RN3a, RN3b and RN4b).
8a	-	Combined notched testpieces except for RN3b; (RN3a and RN4b).
9	-	Notched round compared with combined notched rectangular; (CN4, RN3a and RN4b).
9a	-	Combined notched round compared with combined notched rectangular; (CN4 and RN3a, RN3b and RN4b).

*NB *The R3a Teledyne data have been multiplied by 0.96 in the corrected data set.*

The other geometries for Teledyne data have been multiplied by 0.90 (except for the RN3b tests which have been plotted uncorrected).

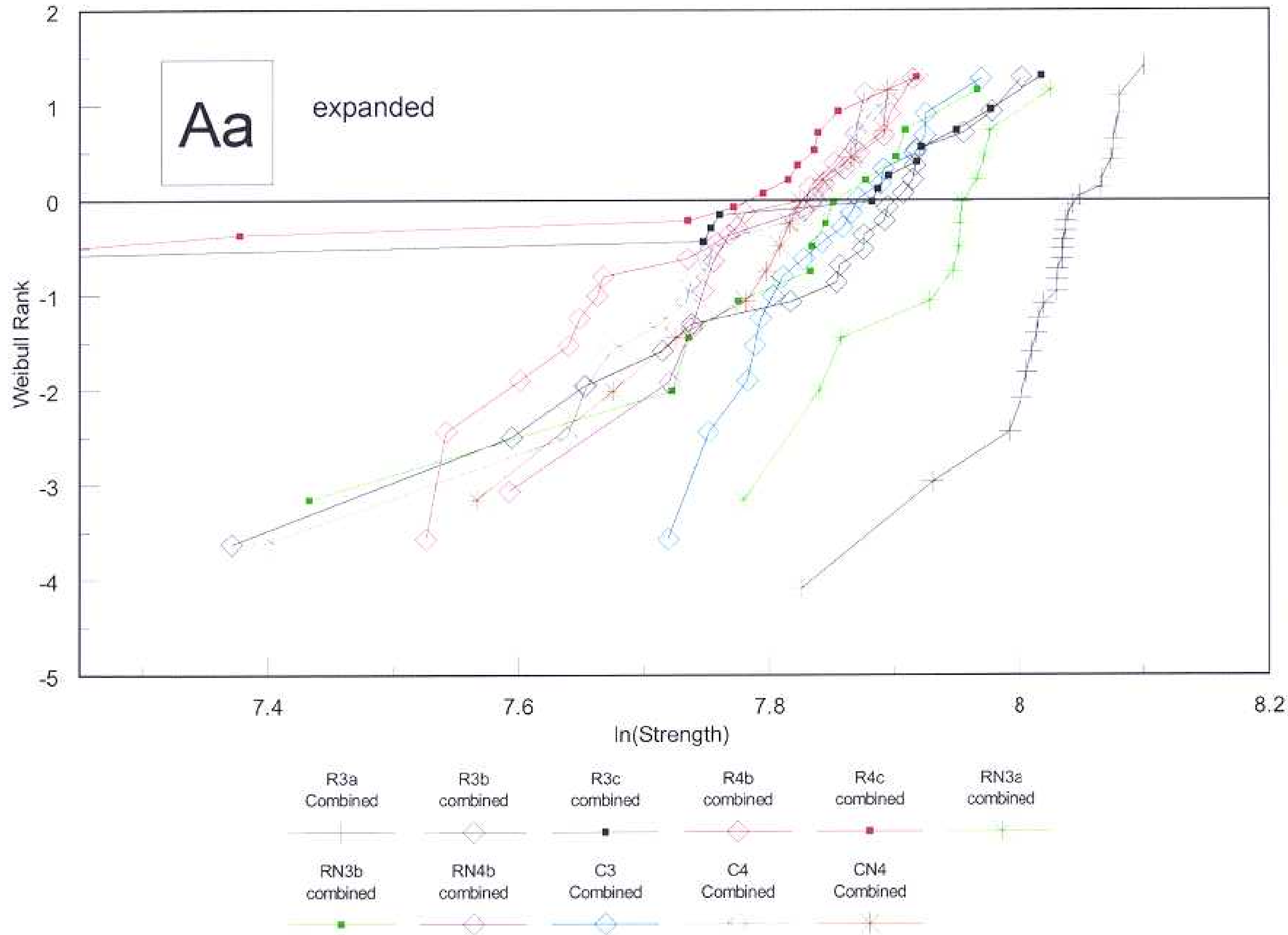


Bend Tests - Boart WC/Co (2)
A
Weibull Rank
2
1
0
-1
-2
-3
-4
5.5
6
6.5
7
7.5
8
8.5
ln(Strength)
R3a Teledyne(corr)
R3a Sandvik
R3b NPL
R3b Sandvik
R3c NPL
R3c Teledyne(corr)
R4b NPL
R4b Sandvik
R4c NPL
R4c Teledyne(corr)
RN3a NPL
RN3a Sandvik
RN3b NPL
RN3b Teledyne
RN4b NPL
RN4b Sandvik
C3 NPL
C3 Teledyne(corr)
C4 NPL
C4 Sandvik
CN4 NPL
CN4 Teledyne
CN4 Sandvik

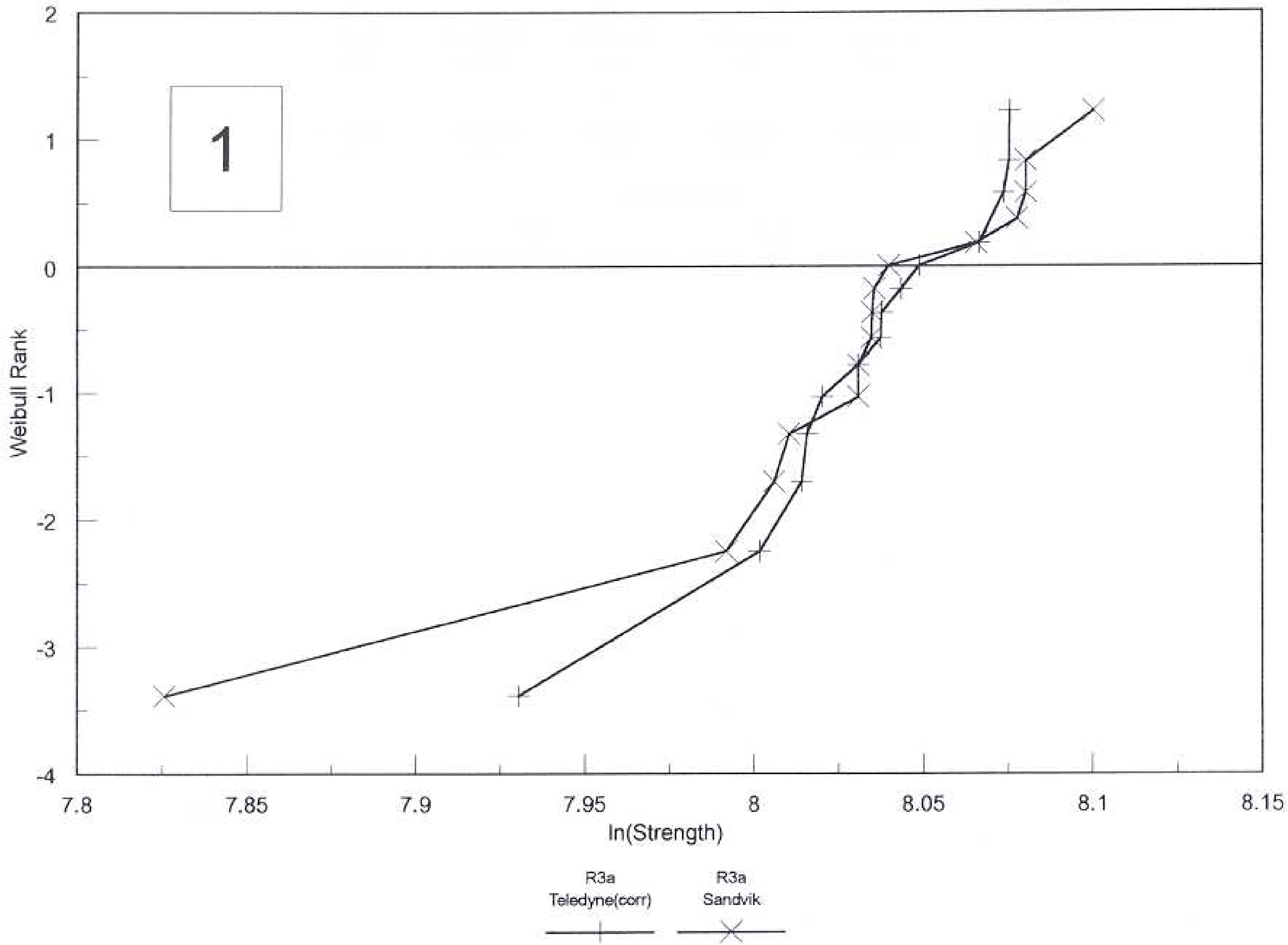


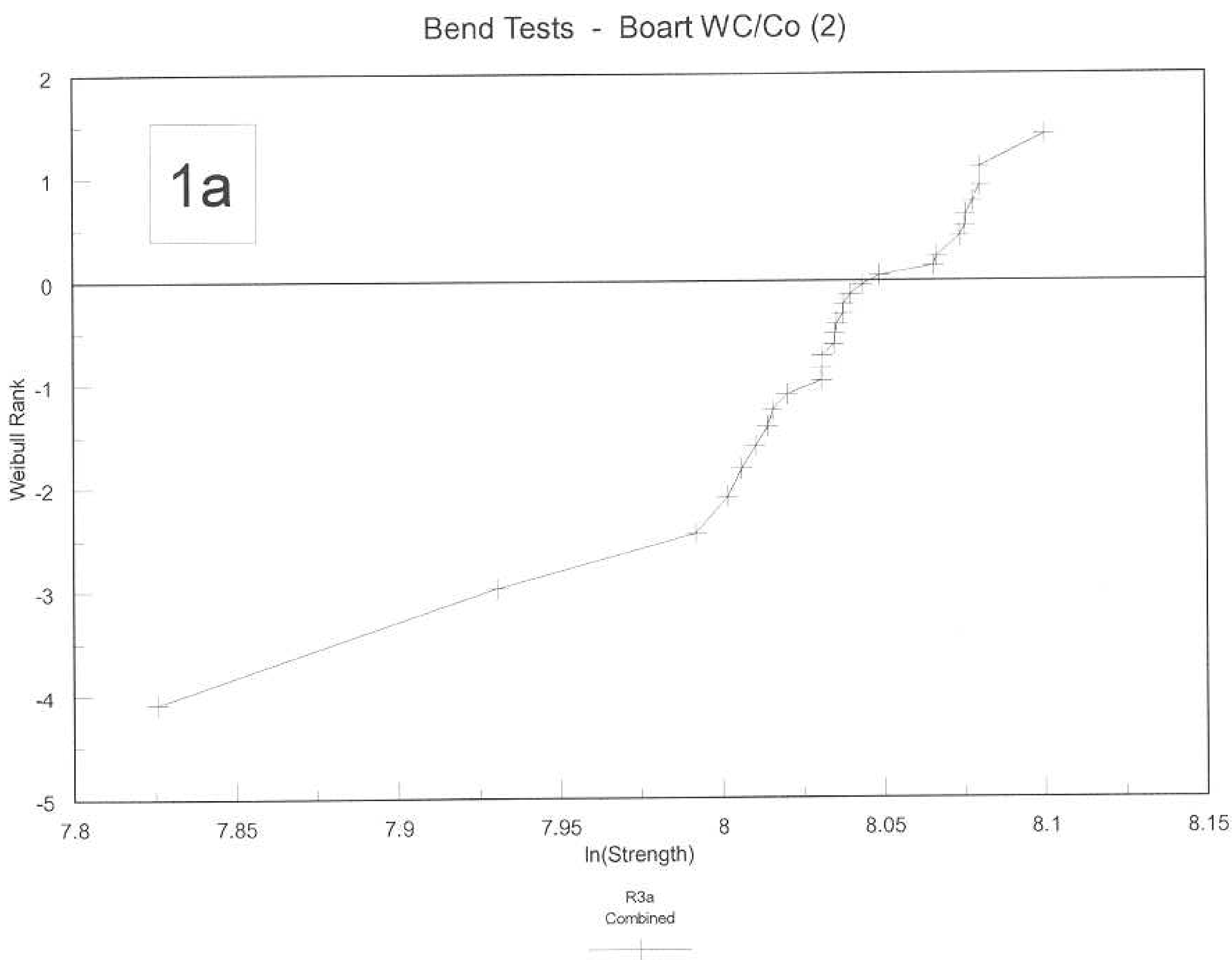
Bend Tests - Boart WC/Co (2)
Aa
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
6
6.5
7
7.5
8
ln(Strength)
R3a Combined
R3b combined
R3c combined
R4b combined
R4c combined
RN3a combined
RN3b combined
RN4b combined
C3 Combined
C4 Combined
CN4 Combined

Bend Tests - Boart WC/Co (2)

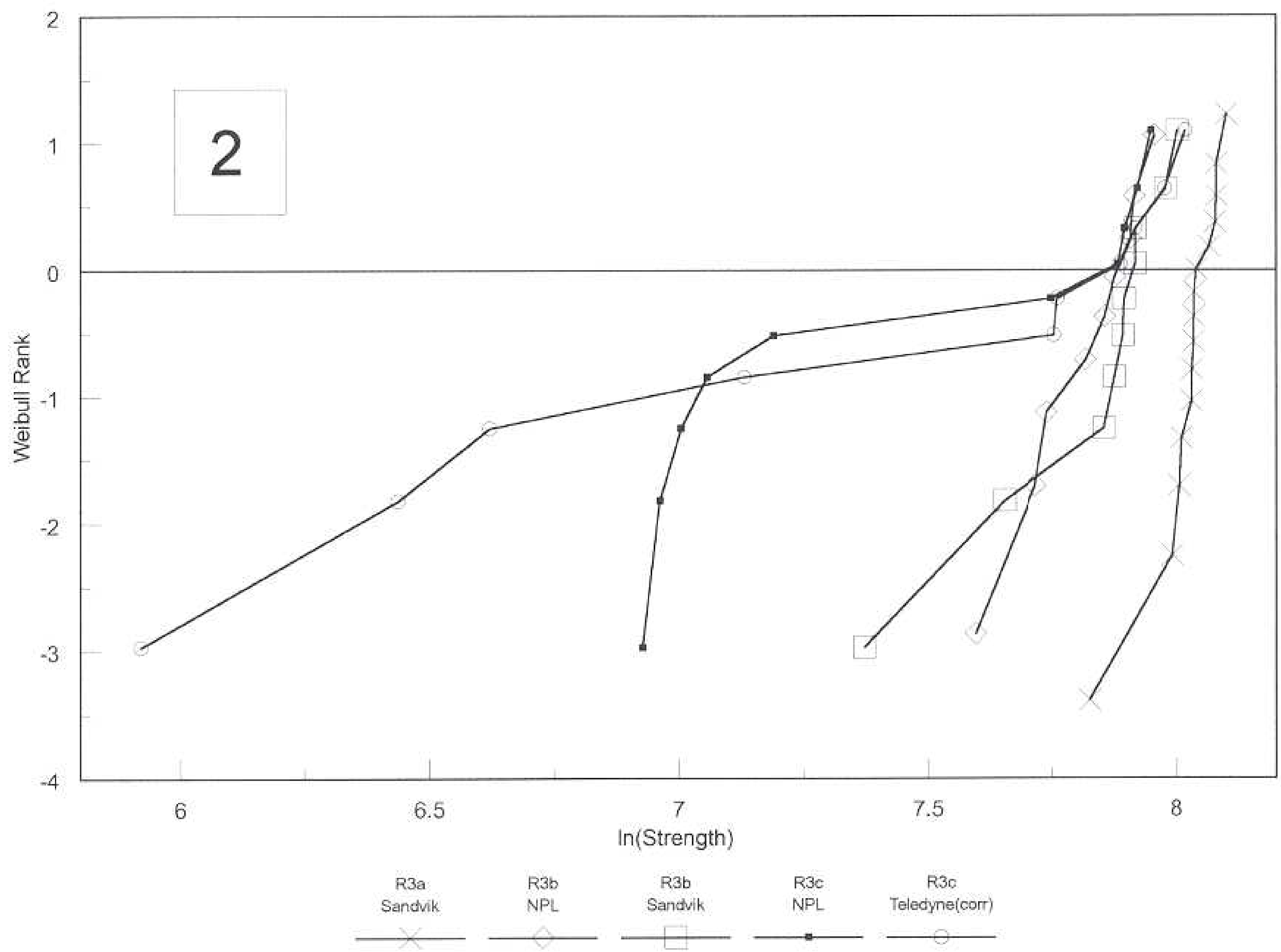


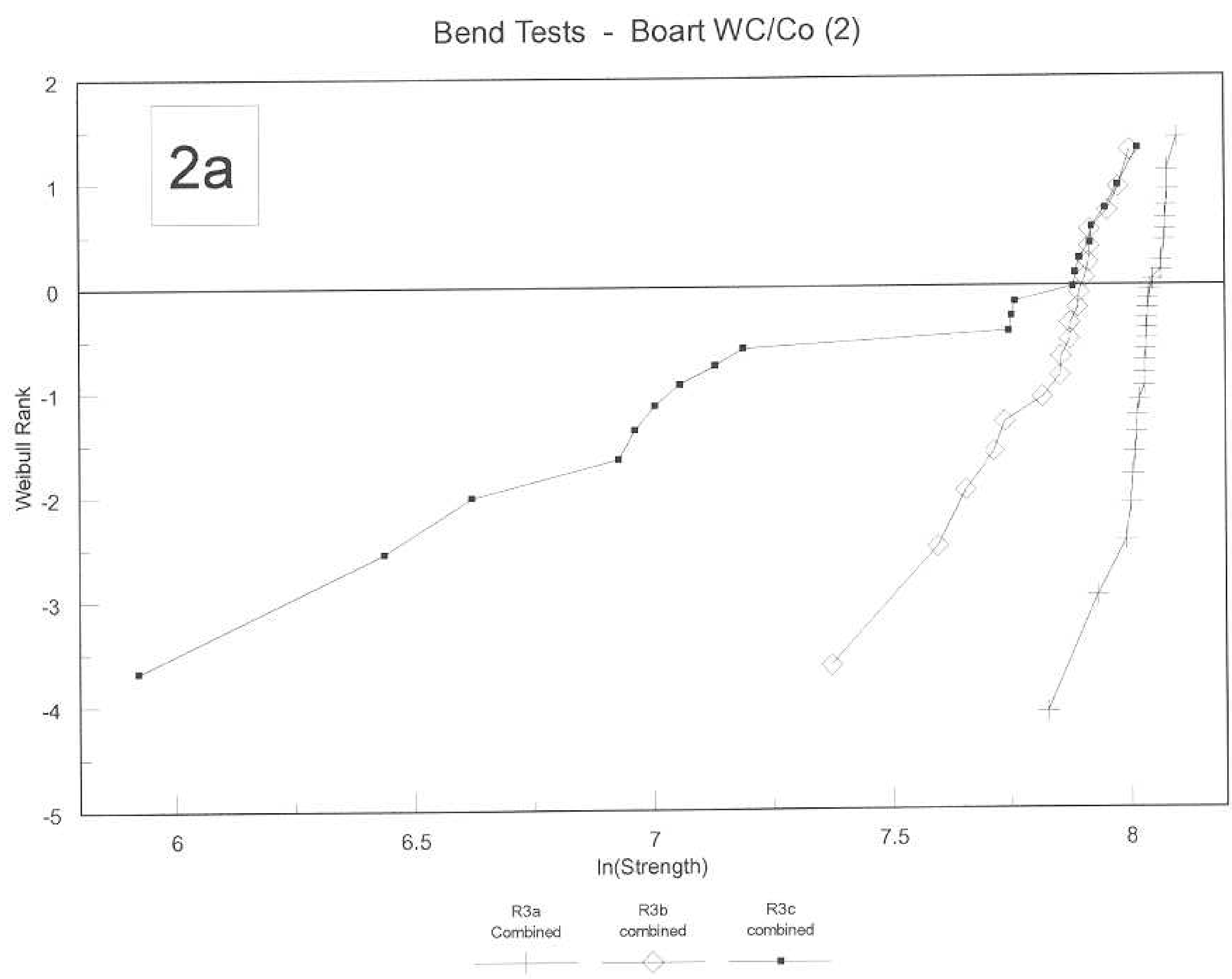
Bend Tests - Boart WC/Co (2)




Bend Tests - Boart WC/Co (2)
1a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
7.8
7.85
7.9
7.95
8
8.05
8.1
8.15
ln(Strength)
R3a
Combined

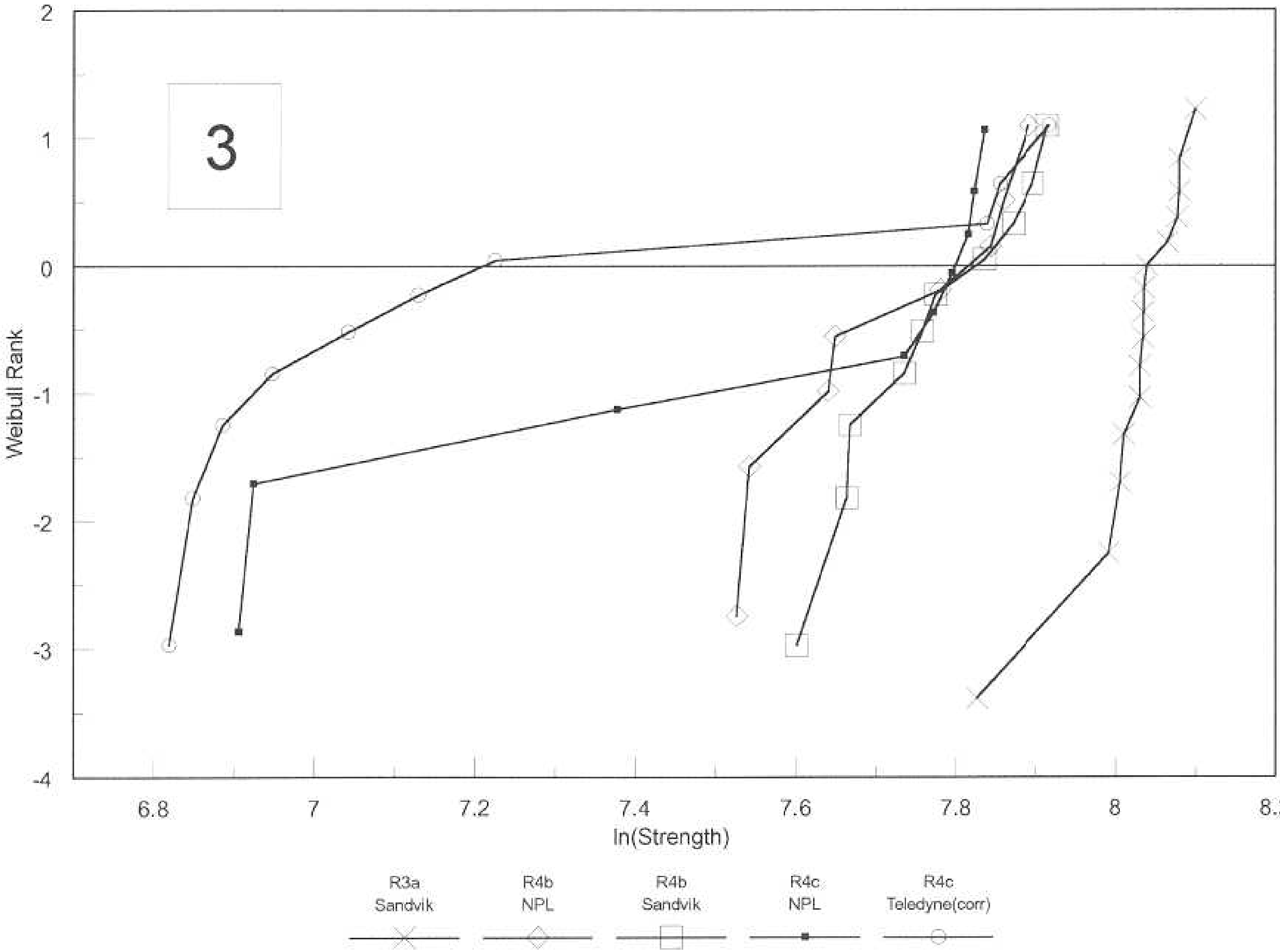
Bend Tests - Boart WC/Co (2)

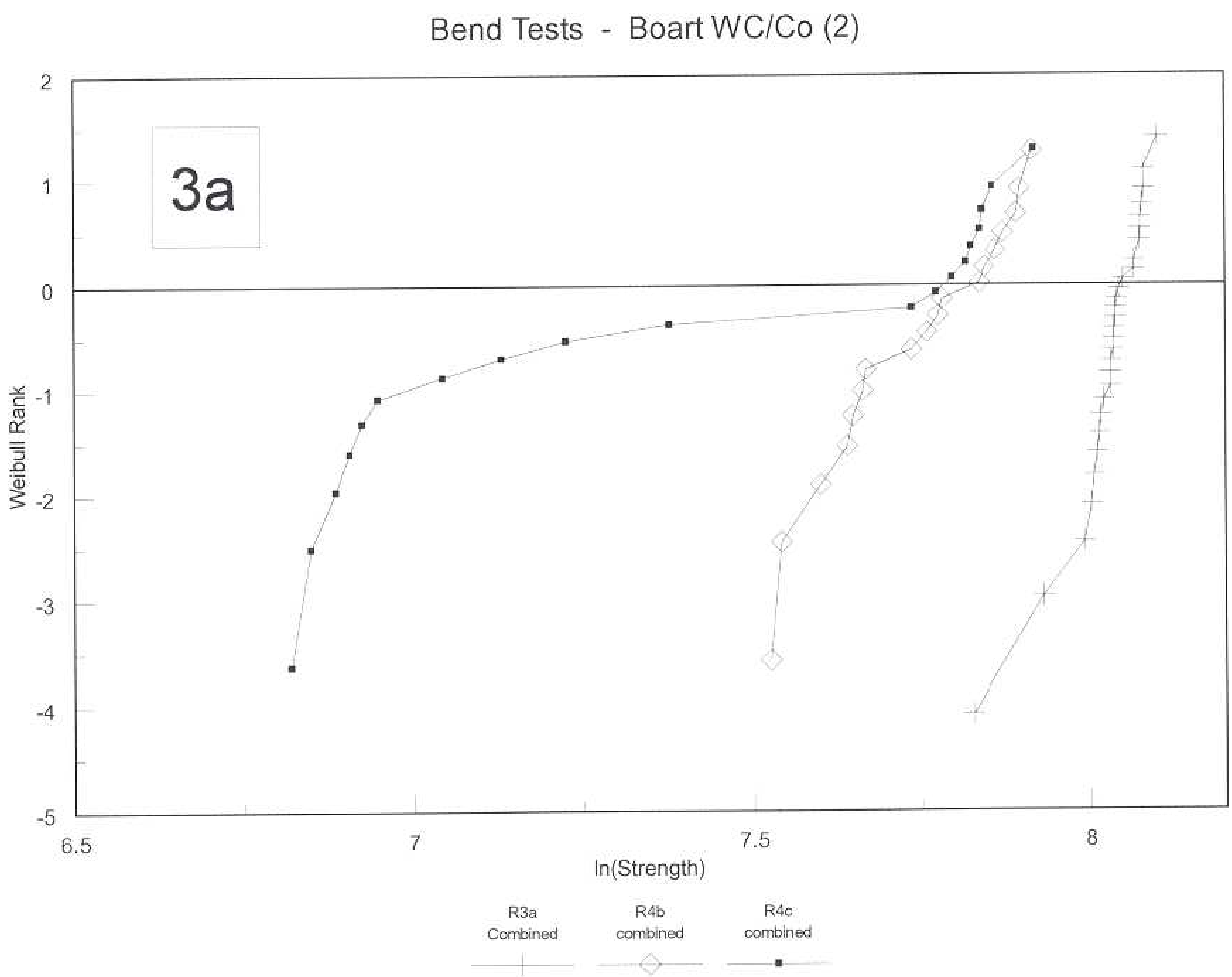




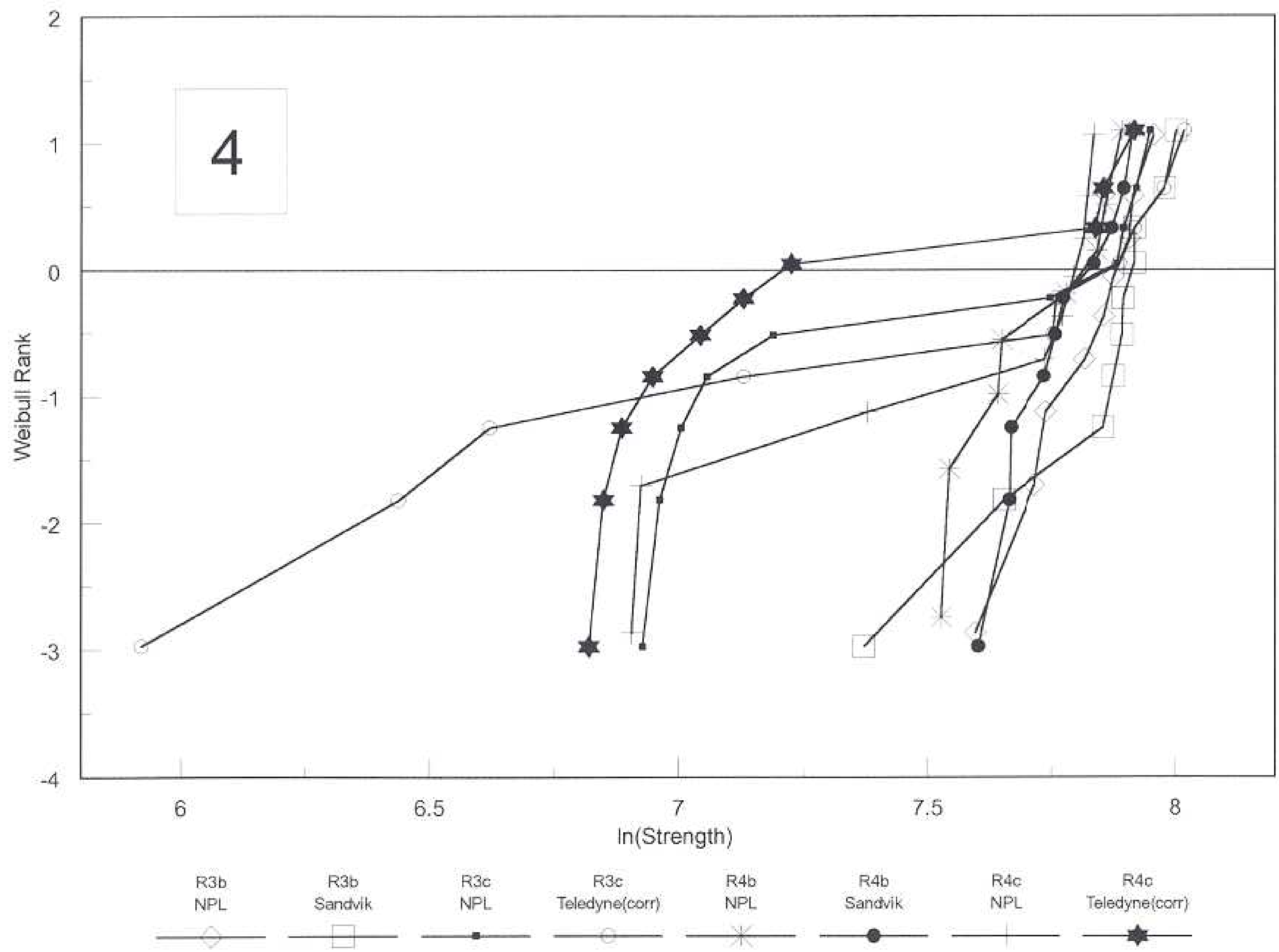
Bend Tests - Boart WC/Co (2)
2a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
6
6.5
7
7.5
8
ln(Strength)
R3a Combined
R3b combined
R3c combined

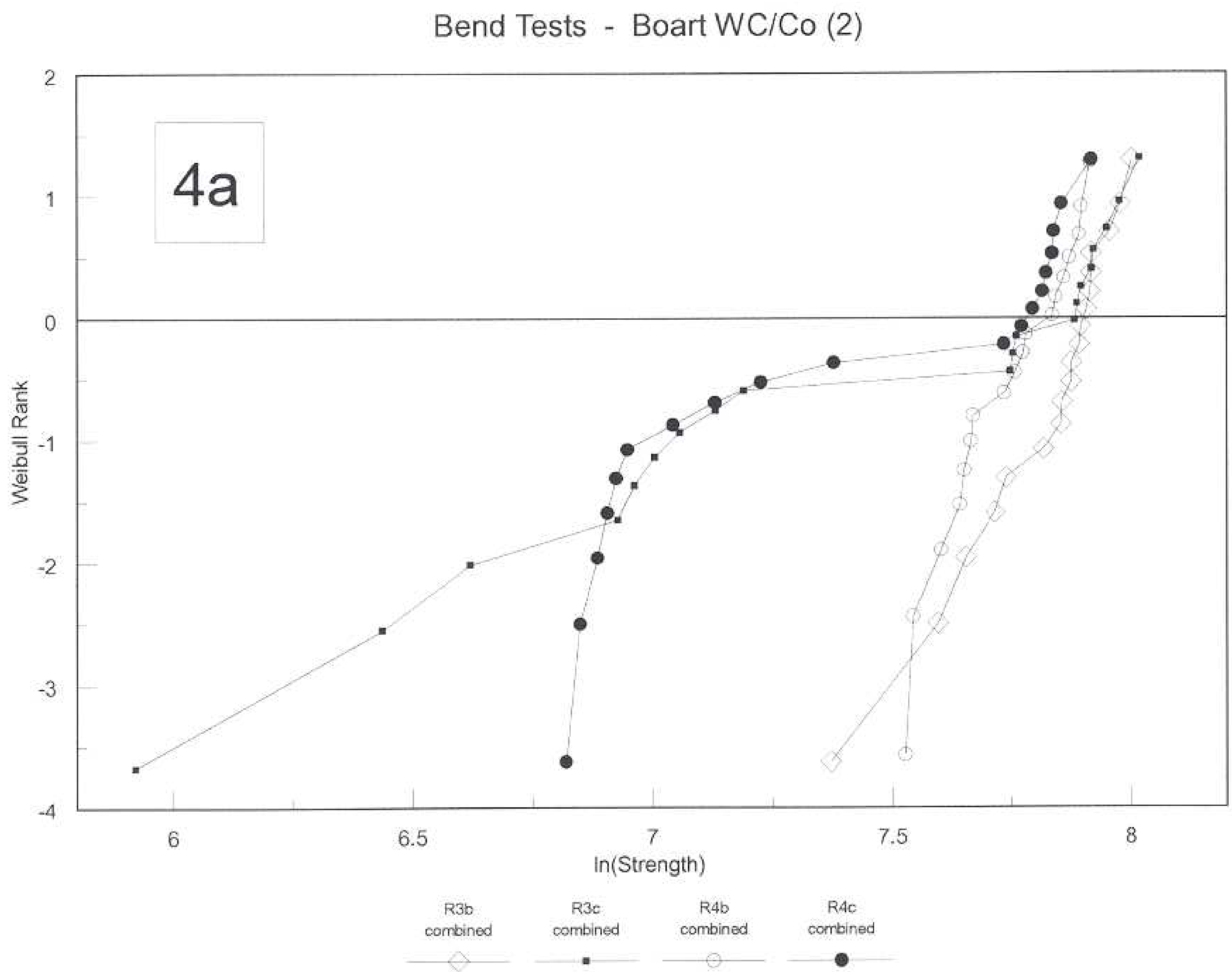
Bend Tests - Boart WC/Co (2)

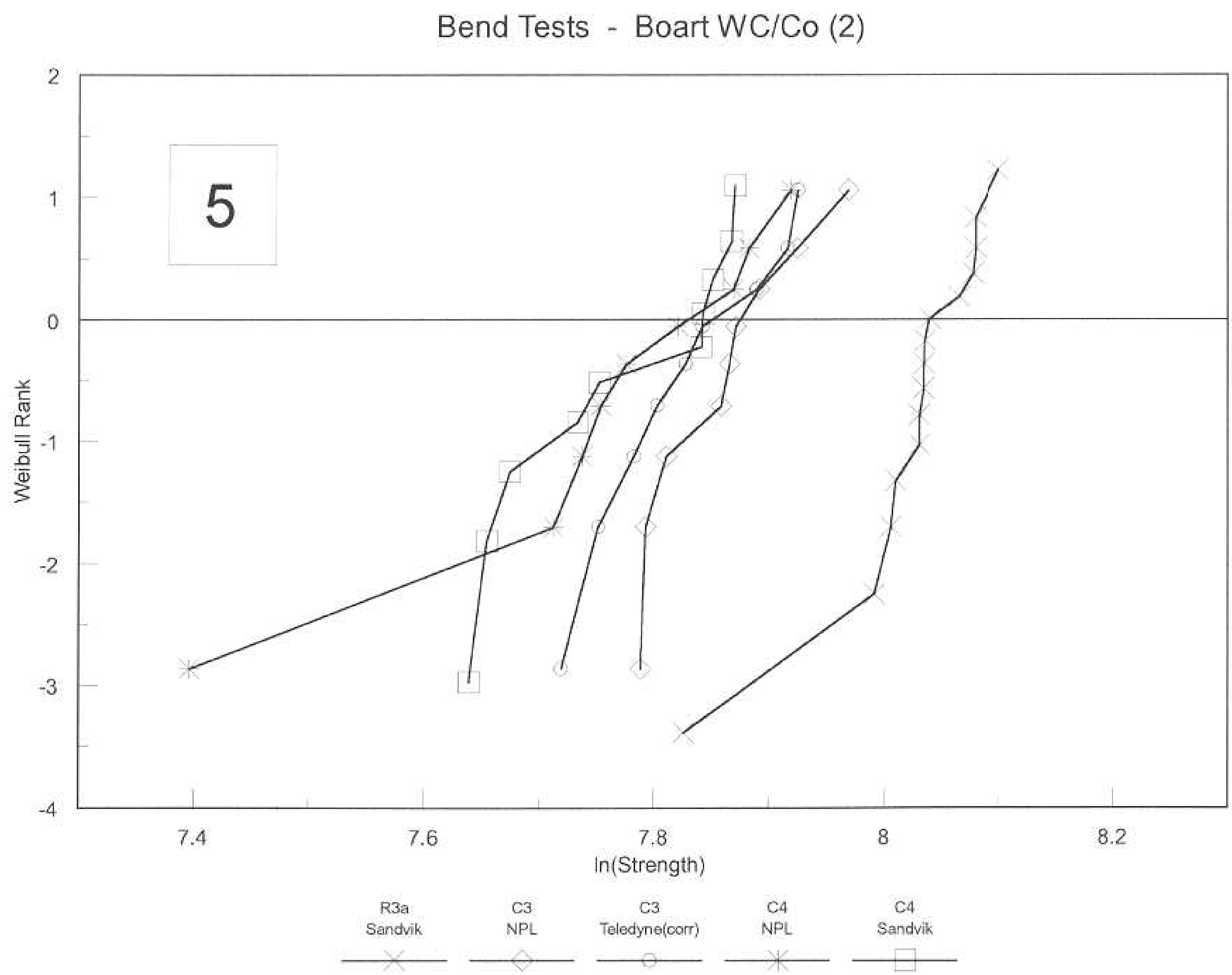



Bend Tests - Boart WC/Co (2)
3a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
6.5
7
7.5
8
ln(Strength)
R3a Combined
R4b combined
R4c combined

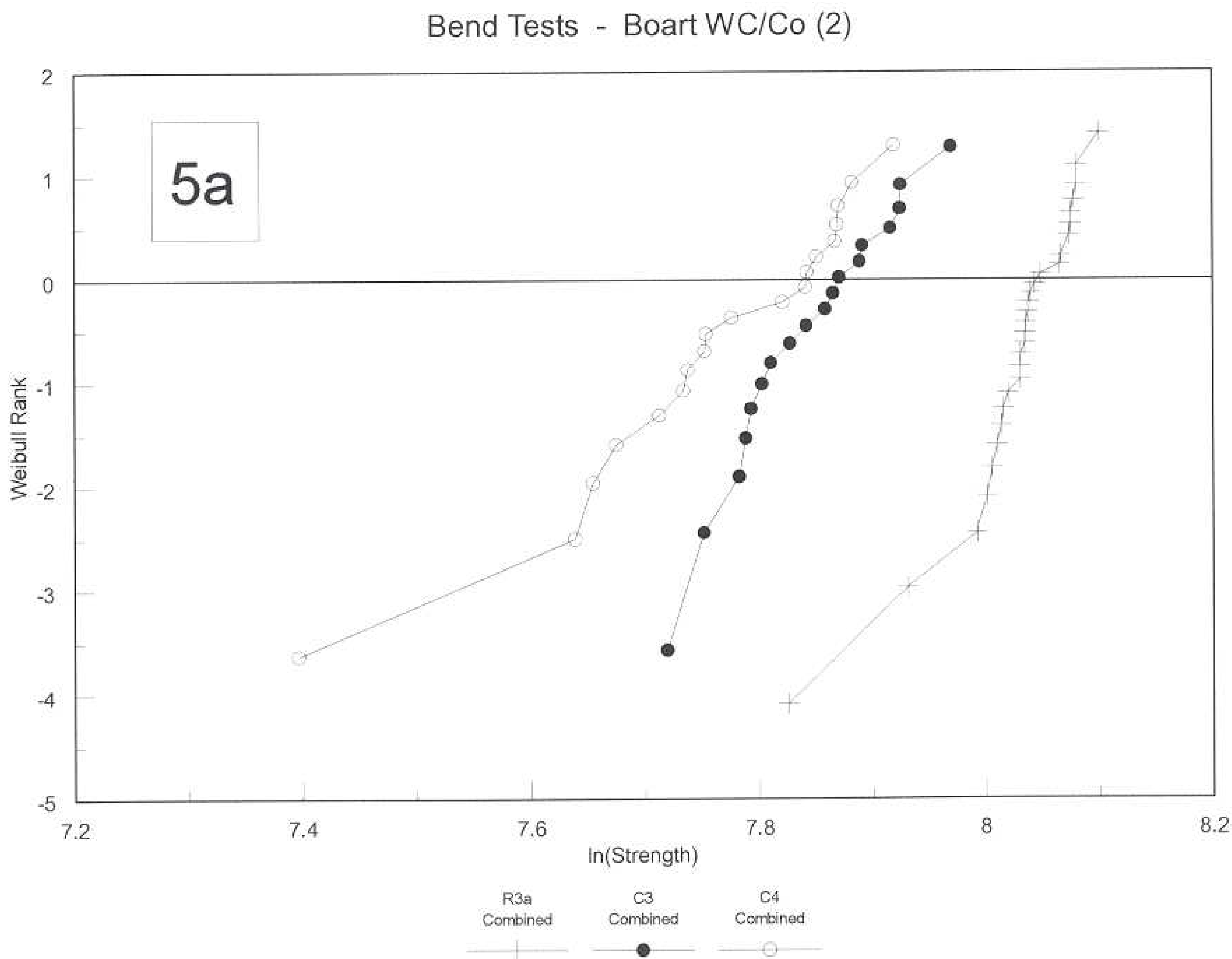
Bend Tests - Boart WC/Co (2)



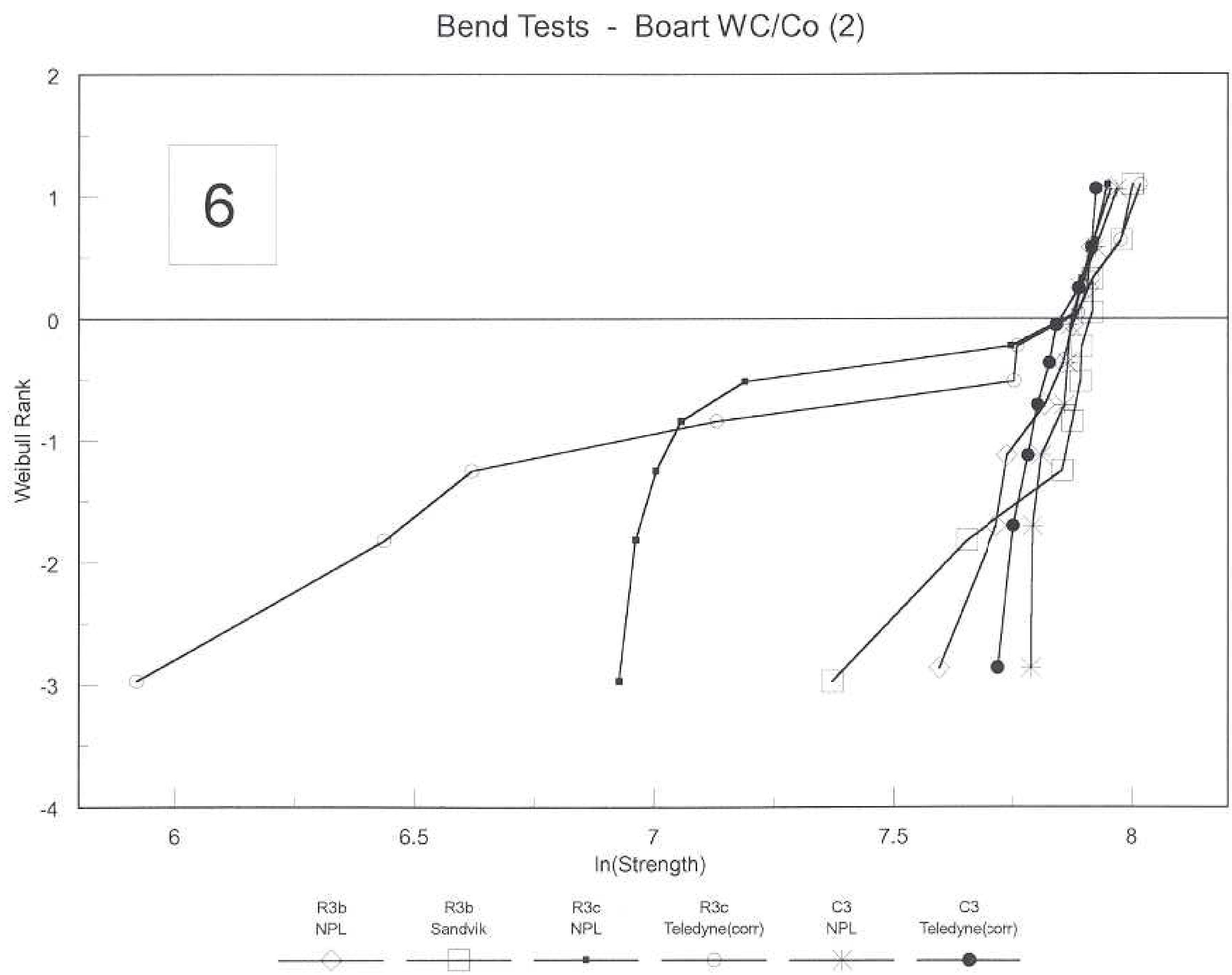

Bend Tests - Boart WC/Co (2)
4a
Weibull Rank
2
1
0
-1
-2
-3
-4
6
6.5
7
7.5
8
ln(Strength)
R3b combined
R3c combined
R4b combined
R4c combined



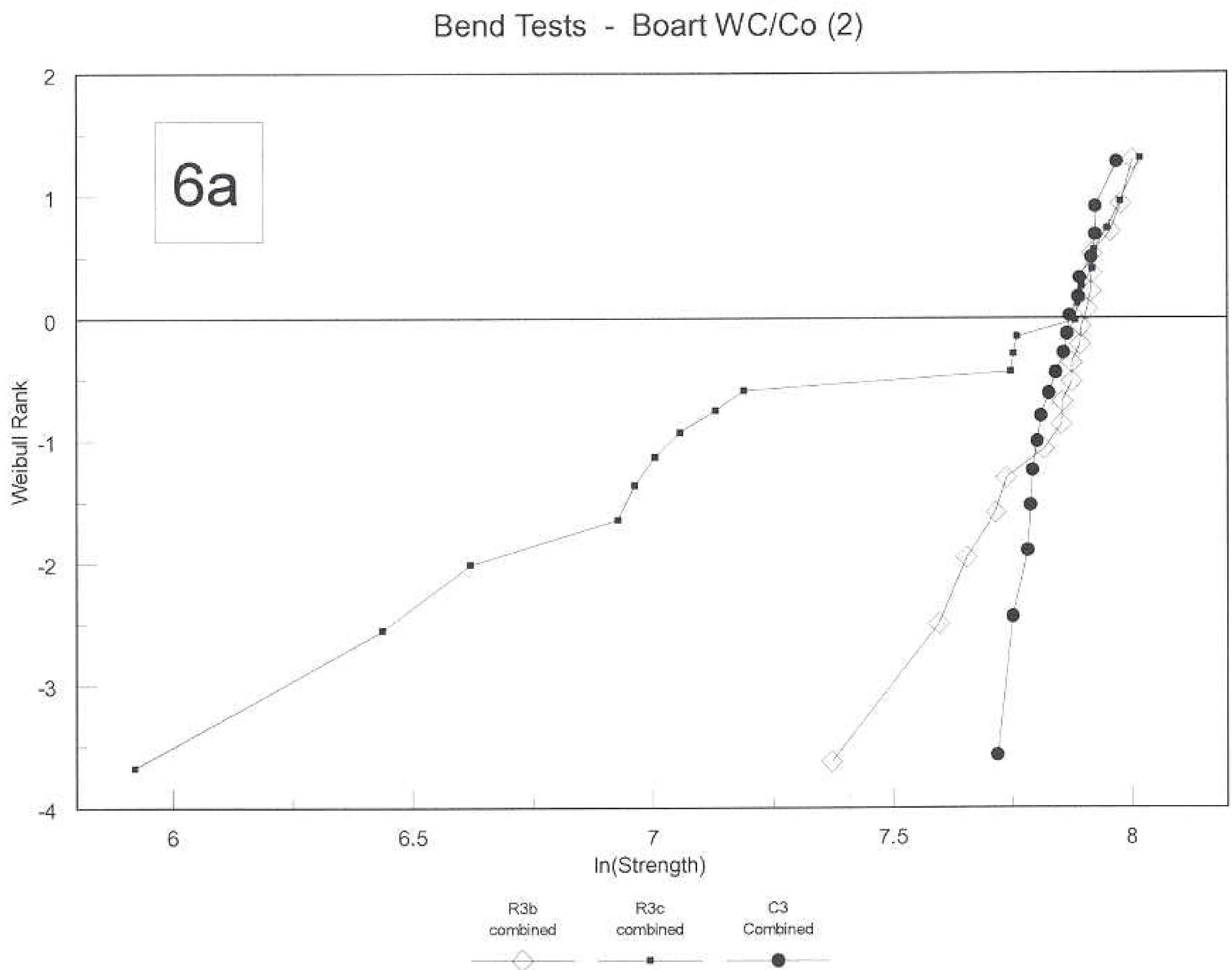
Bend Tests - Boart WC/Co (2)
5
Weibull Rank
2
1
0
-1
-2
-3
-4
7.4
7.6
7.8
8
8.2
ln(Strength)
R3a Sandvik
C3 NPL
C3 Teledyne(corr)
C4 NPL
C4 Sandvik



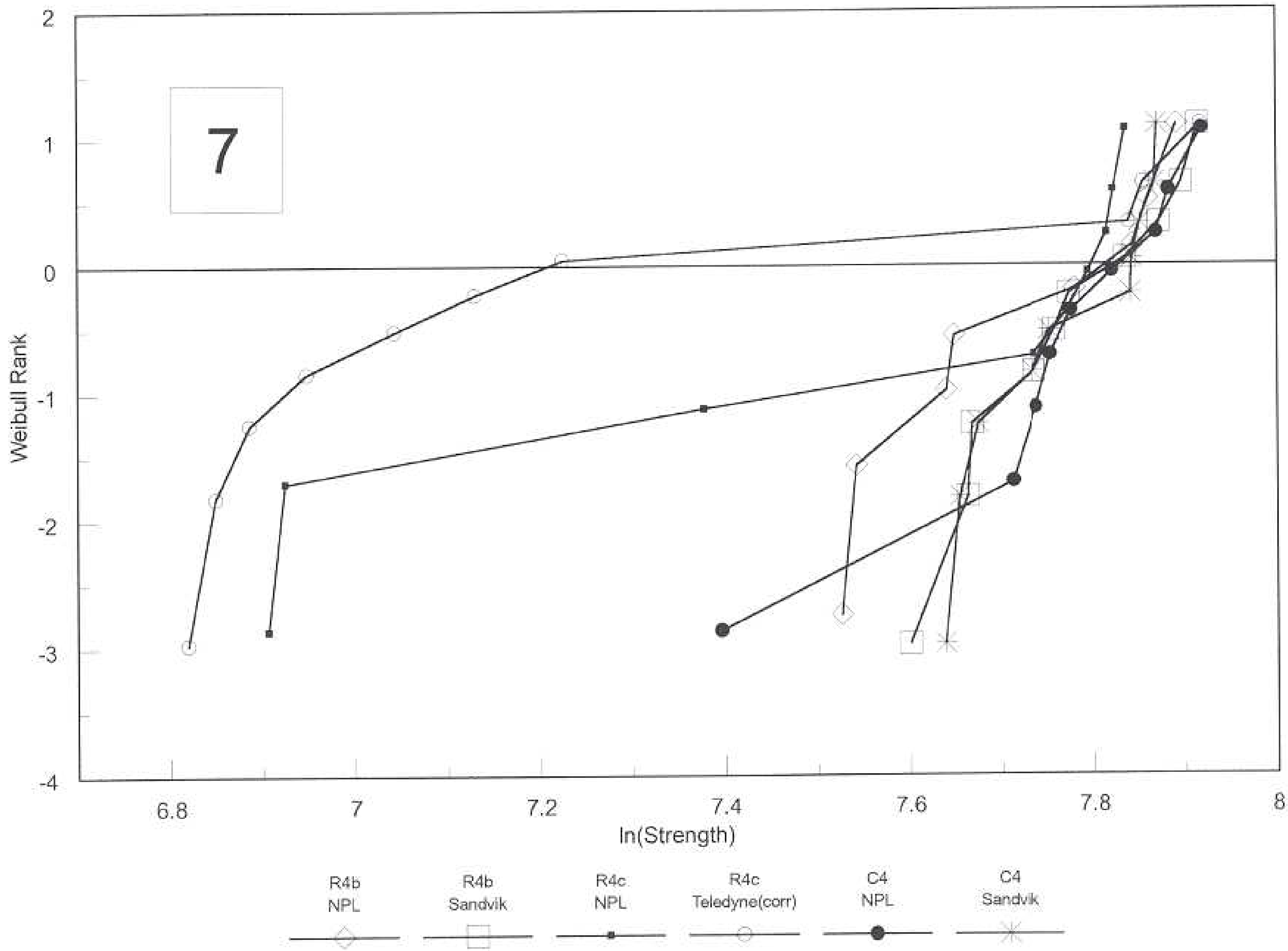
Bend Tests - Boart WC/Co (2)
5a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
7.2
7.4
7.6
7.8
8
8.2
ln(Strength)
R3a Combined
C3 Combined
C4 Combined

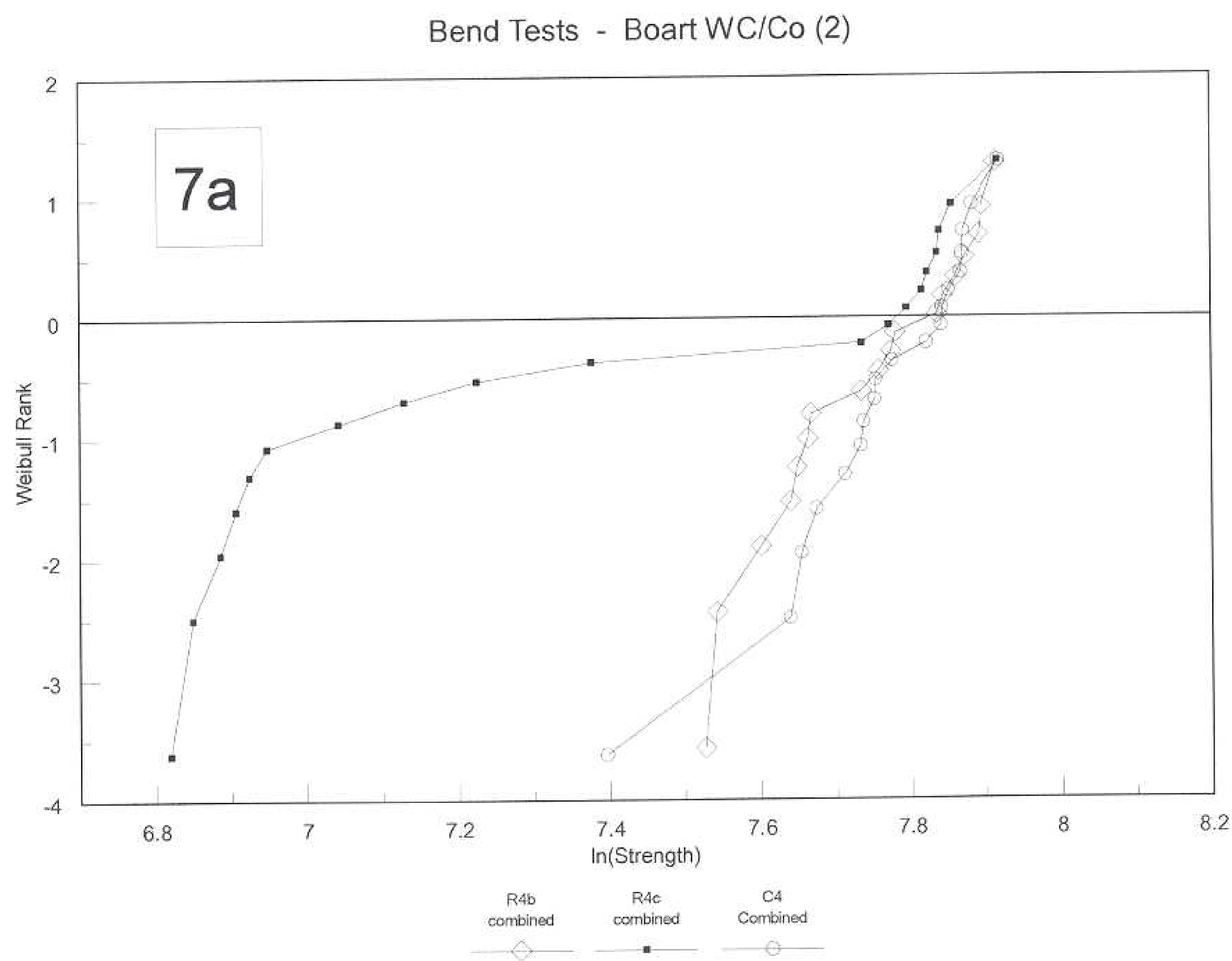


Bend Tests - Boart WC/Co (2)
6
Weibull Rank
2
1
0
-1
-2
-3
-4
6
6.5
7
7.5
8
ln(Strength)
R3b NPL
R3b Sandvik
R3c NPL
R3c Teledyne(corr)
C3 NPL
C3 Teledyne(corr)


Bend Tests - Boart WC/Co (2)
6a
Weibull Rank
2
1
0
-1
-2
-3
-4
6
6.5
7
7.5
8
ln(Strength)
R3b combined
R3c combined
C3 Combined

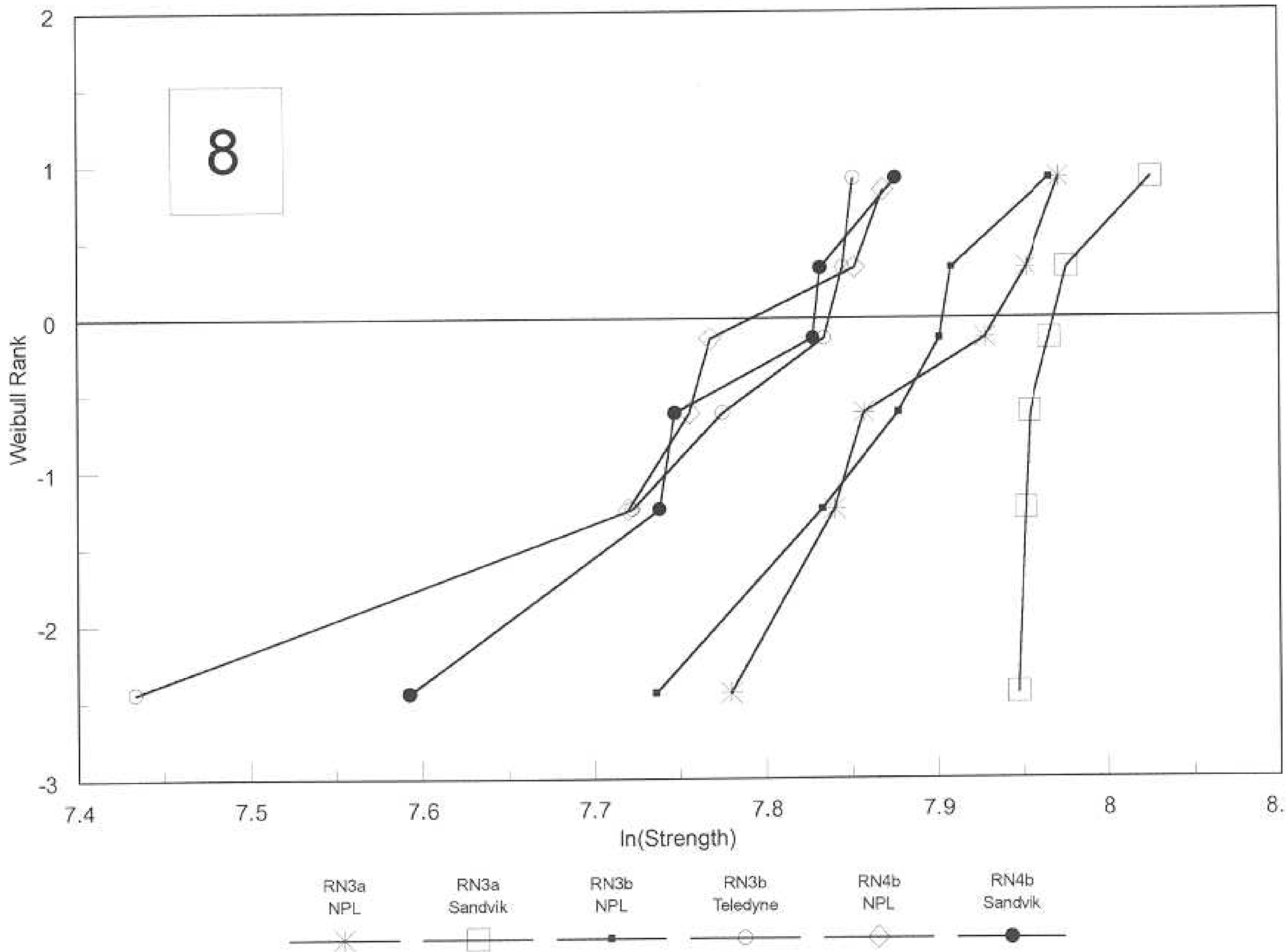
Bend Tests - Boart WC/Co (2)

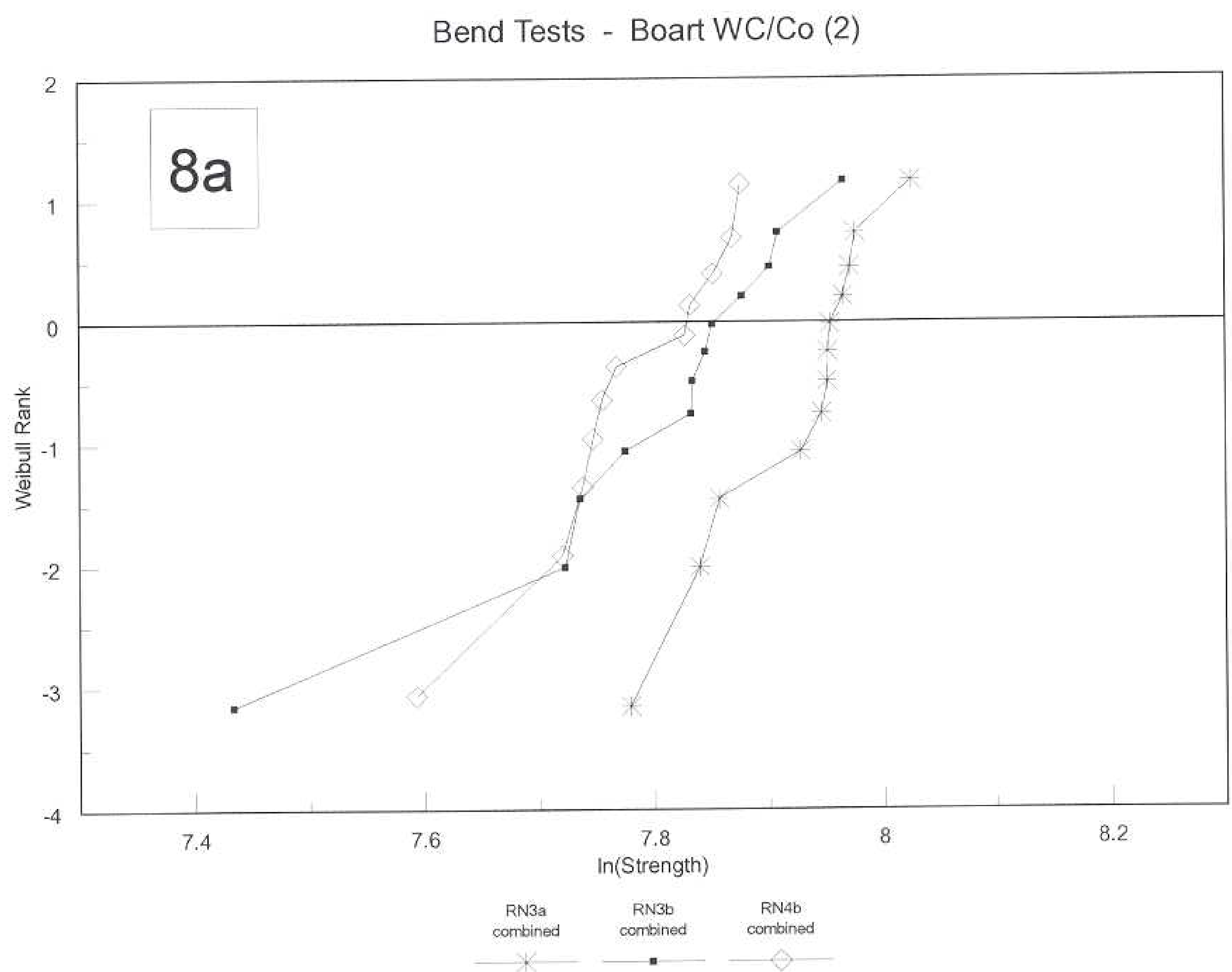




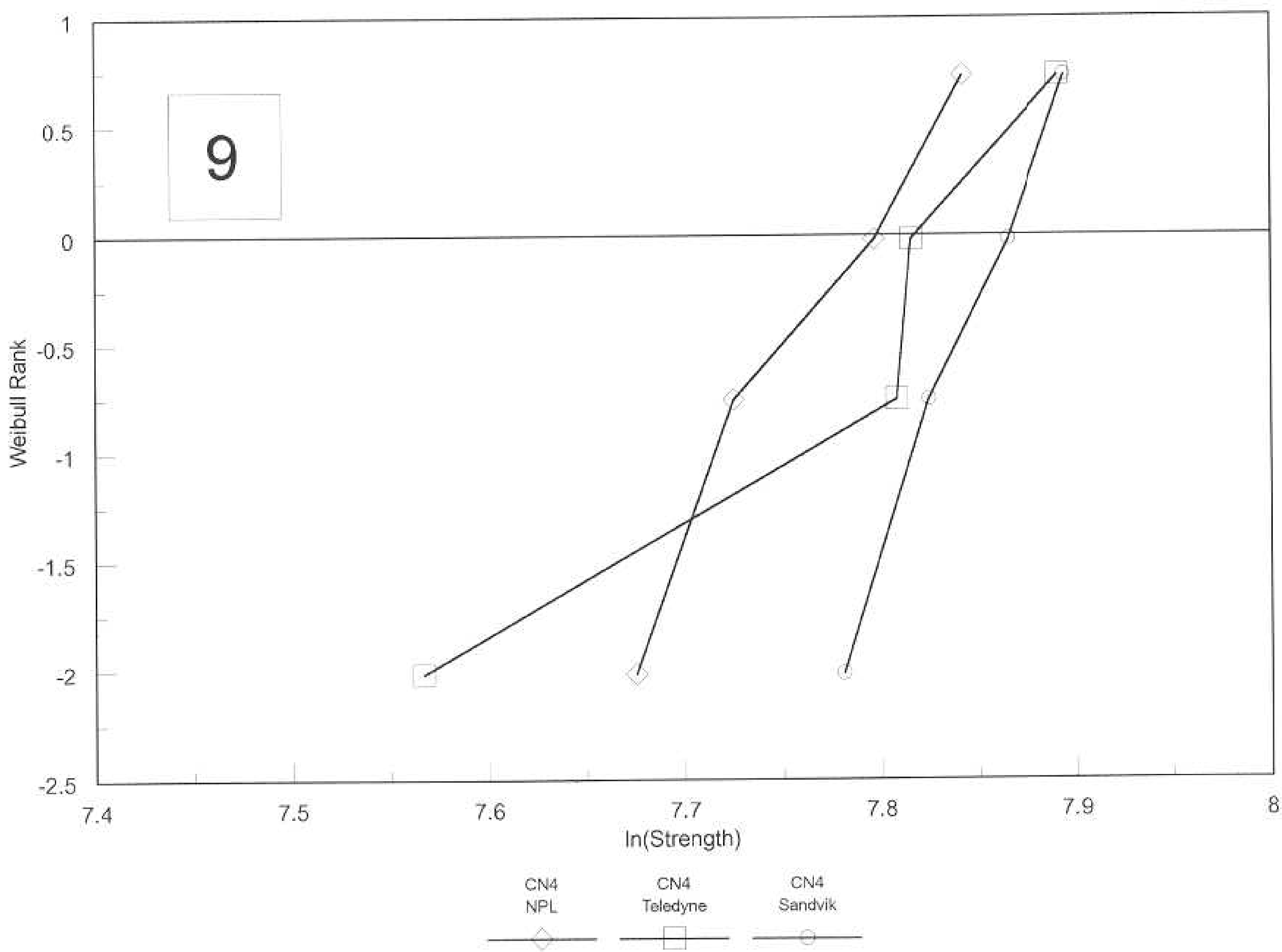
Bend Tests - Boart WC/Co (2)
7a
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
8
8.2
ln(Strength)
R4b combined
R4c combined
C4 Combined

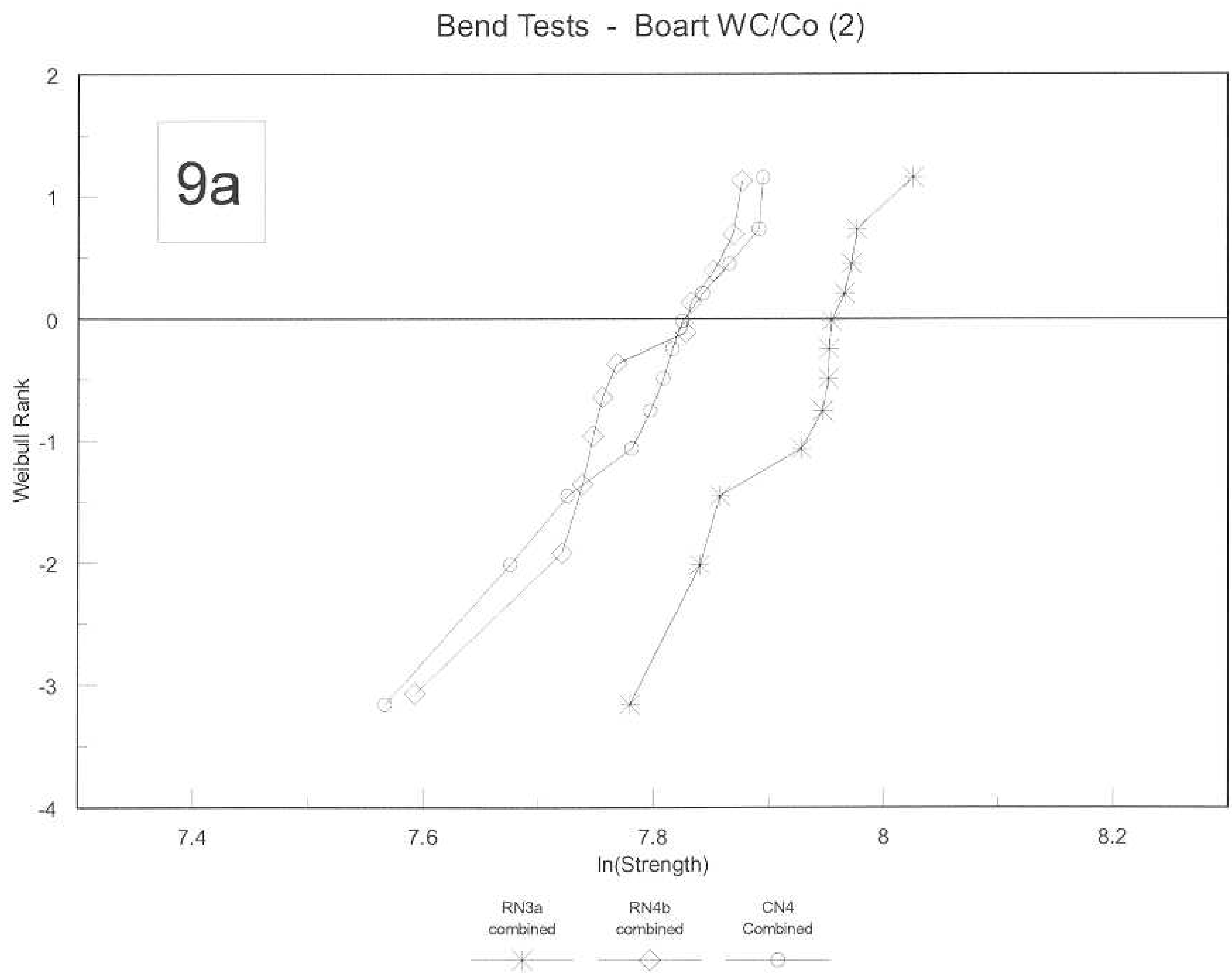
Bend Tests - Boart WC/Co (2)




Bend Tests - Boart WC/Co (2)
8a
2
1
0
-1
-2
-3
-4
Weibull Rank
7.4
7.6
7.8
8
8.2
ln(Strength)
RN3a combined
RN3b combined
RN4b combined

Bend Tests - Boart WC/Co (2)





Bend Tests - Boart WC/Co (2)
9a
Weibull Rank
2
1
0
-1
-2
-3
-4
7.4
7.6
7.8
8
8.2
ln(Strength)
RN3a combined
RN4b combined
CN4 Combined

WEIBULL RESULTS SET

(3) SANDVIK HARD MATERIALS

Fine, WC/Co

HARDMETAL BEND TESTS

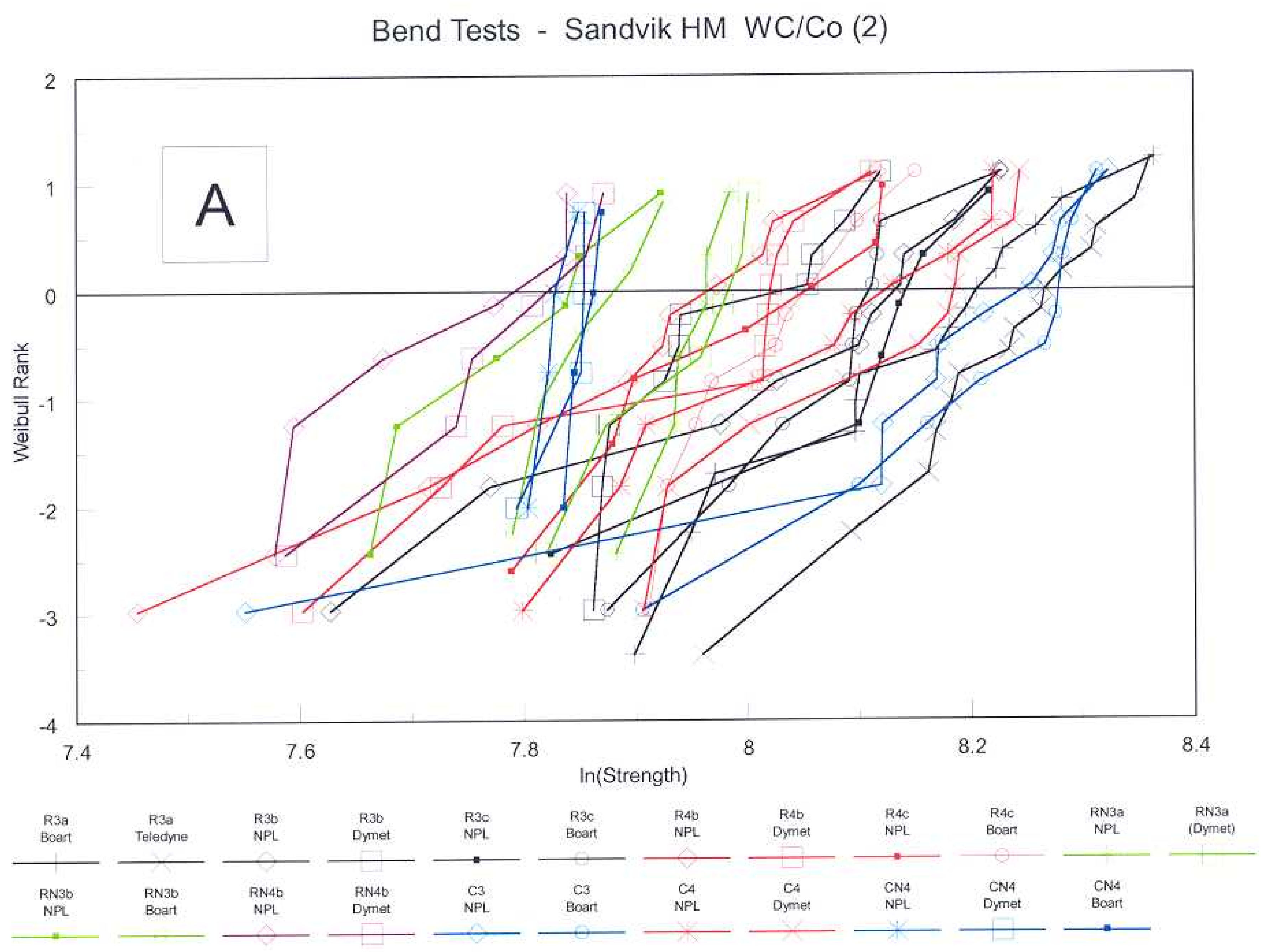
Results Comment Sheet

Sandvik Hard Materials - Category (3) Fine WC/Co Hardmetal

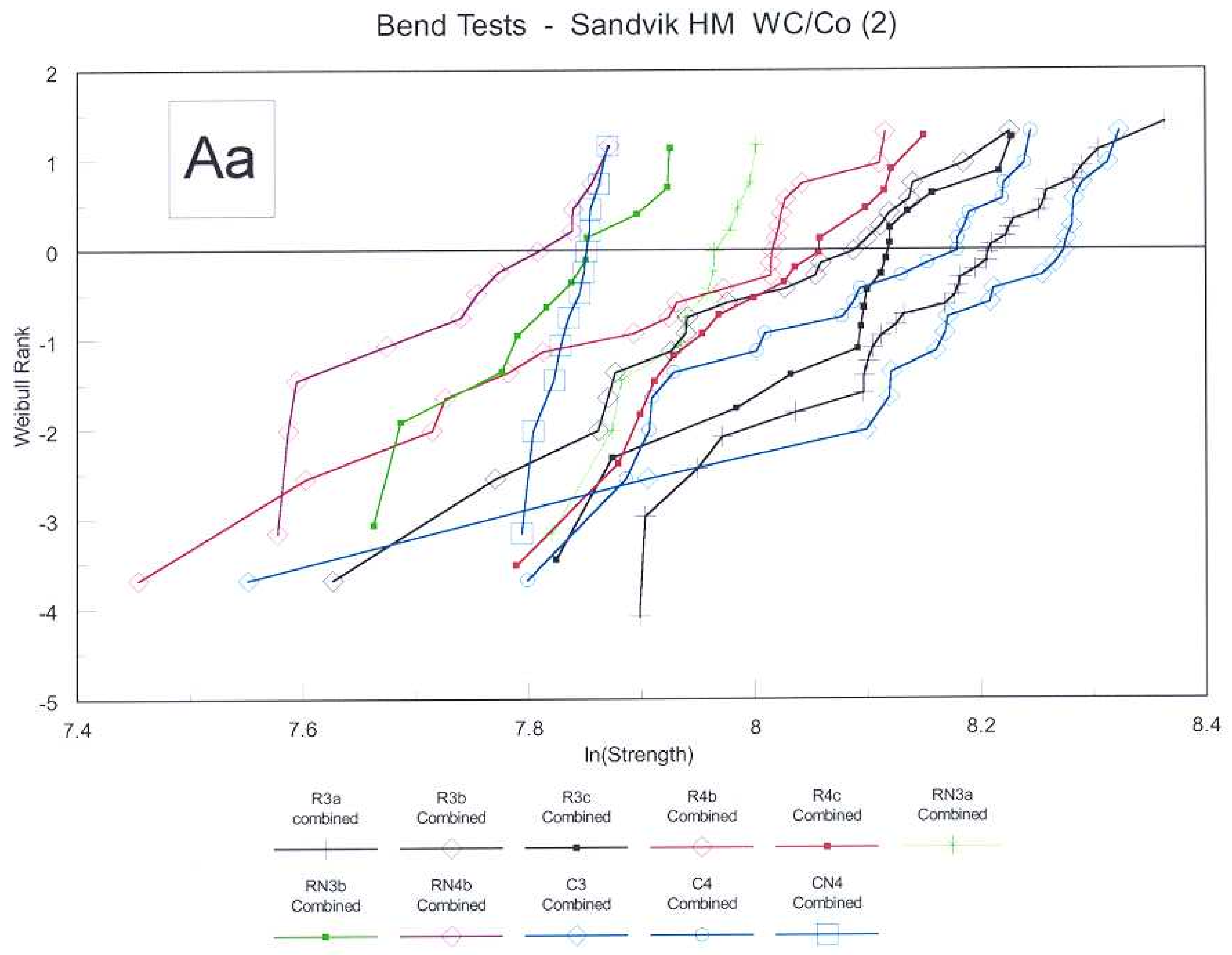
PLOT SEQUENCE

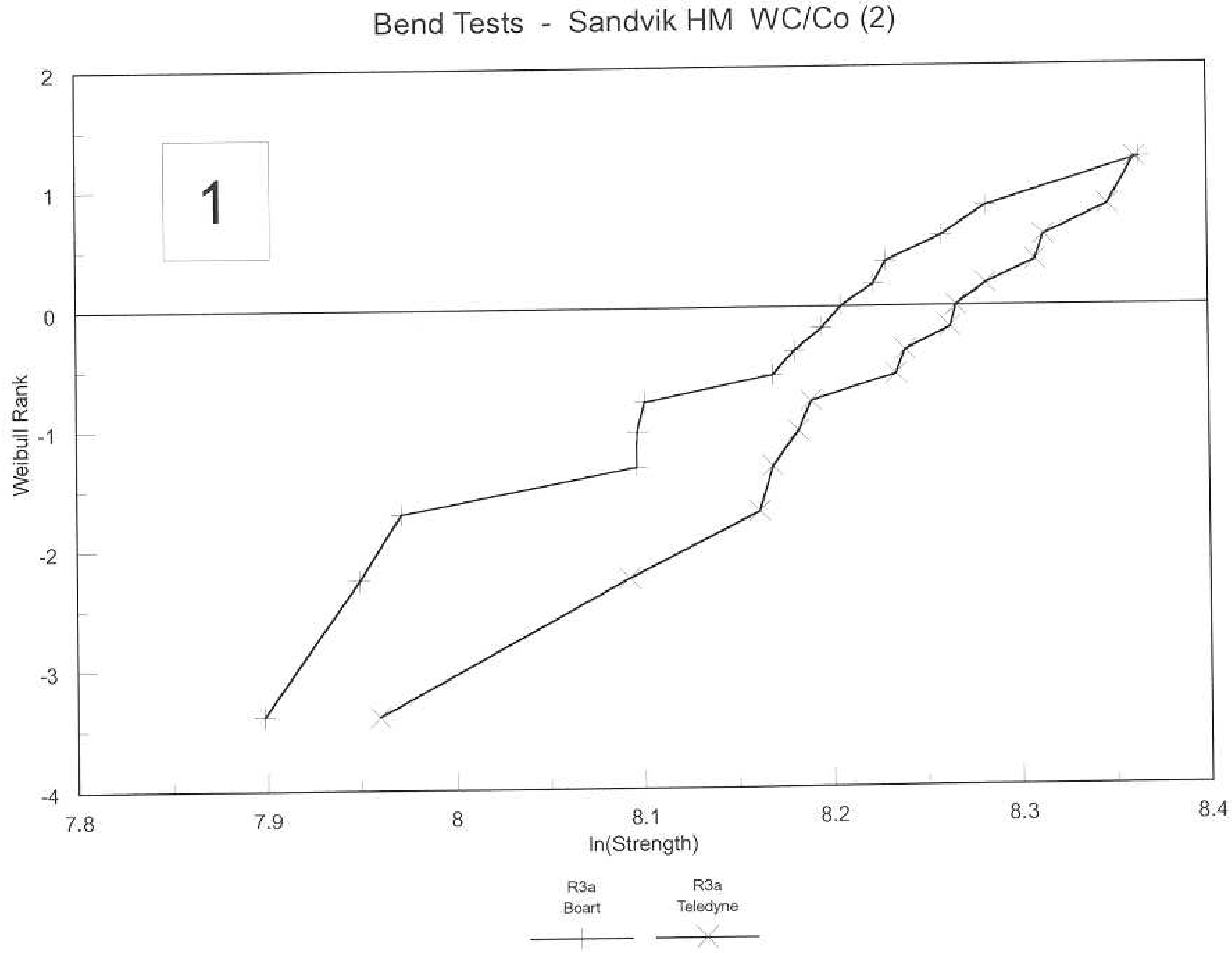
A	-	Complete set of all strength values.
Aa	-	Complete set, different laboratories combined.
1	-	Standard tests, ISO type B (R3a), including corrected Teledyne data*.
1a	-	Combined R3a.
2	-	3 pt rectangular tests; (R3a, R3b, R3c).
2a	-	Combined R3a, R3b and R3c.
3	-	4 pt rectangular tests, compared with Boart standard ISO type B; (R3a, R4b, R4c).
3a	-	Combined R3a, R4b and R4c.
4	-	Individual 3 pt vs 4 pt tests; R3b, R3c, R4b, R4c; not including R3a.
4a	-	Combined 3 pt vs 4 pt tests; R3b, R3c, R4b and R4c.
5	-	Round testpieces, compared with standard R3a; (C3, C4 and R3a).
5a	-	Combined C3, C4 and R3a.
6	-	3 pt rectangular and round; R3b, R3c and C3; not including R3a.
6a	-	Combined C3 compared with R3b combined and R3c combined.
7	-	4 pt rectangular and round (R4b, R4c and C4).
7a	-	Combined C4 compared with combined R4b and combined R4c.
8	-	Notched rectangular testpieces; (RN3a, RN3b and RN4b).
8a	-	Combined notched testpieces; (RN3a, RN3b and RN4b).
9	-	Notched round compared with combined notched rectangular; (CN4, RN3a, RB3b and RN4b).
9a	-	Combined notched round compared with combined notched rectangular; (CN4 and RN3a, RN3b and RN4b).

*NB *The R3a Teledyne data have been multiplied by 0.945 in the corrected data set.*



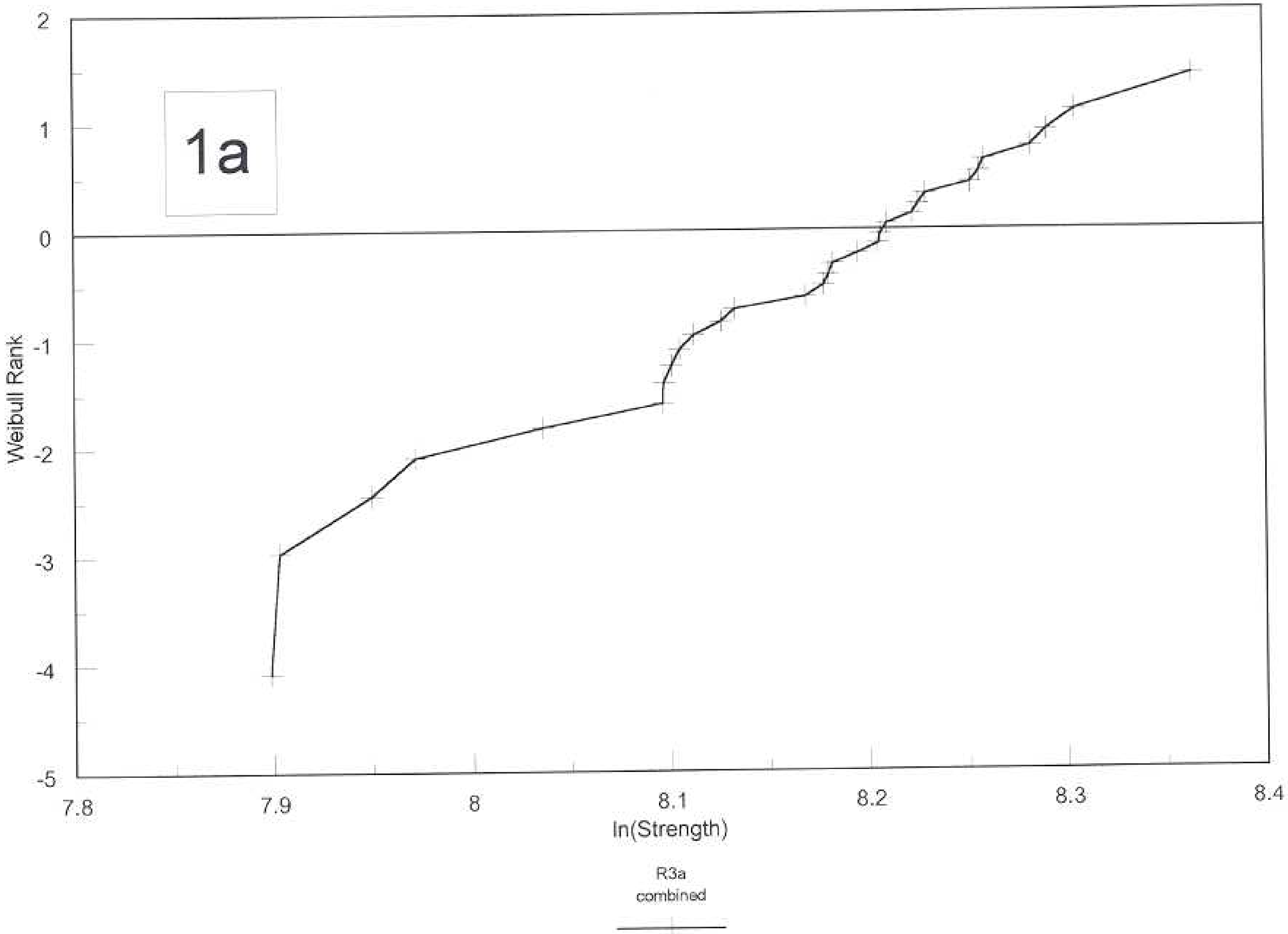
Bend Tests - Sandvik HM WC/Co (2)
A
Weibull Rank
2
1
0
-1
-2
-3
-4
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R3a Boart
R3a Teledyne
R3b NPL
R3b Dymet
R3c NPL
R3c Boart
R4b NPL
R4b Dymet
R4c NPL
R4c Boart
RN3a NPL
RN3a (Dymet)
RN3b NPL
RN3b Boart
RN4b NPL
RN4b Dymet
C3 NPL
C3 Boart
C4 NPL
C4 Dymet
CN4 NPL
CN4 Dymet
CN4 Boart


Bend Tests - Sandvik HM WC/Co (2)
Aa
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R3a combined
R3b Combined
R3c Combined
R4b Combined
R4c Combined
RN3a Combined
RN3b Combined
RN4b Combined
C3 Combined
C4 Combined
CN4 Combined

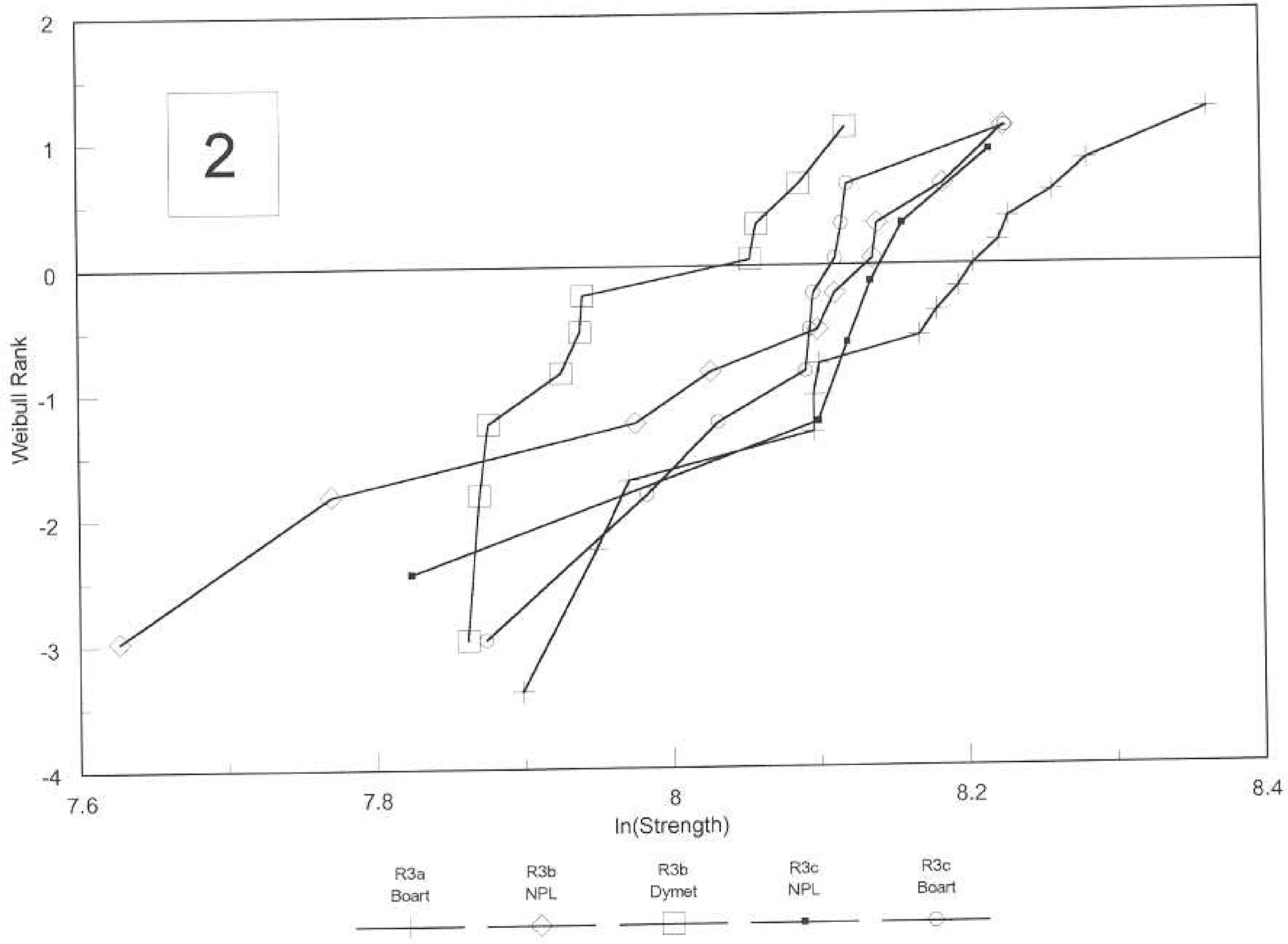


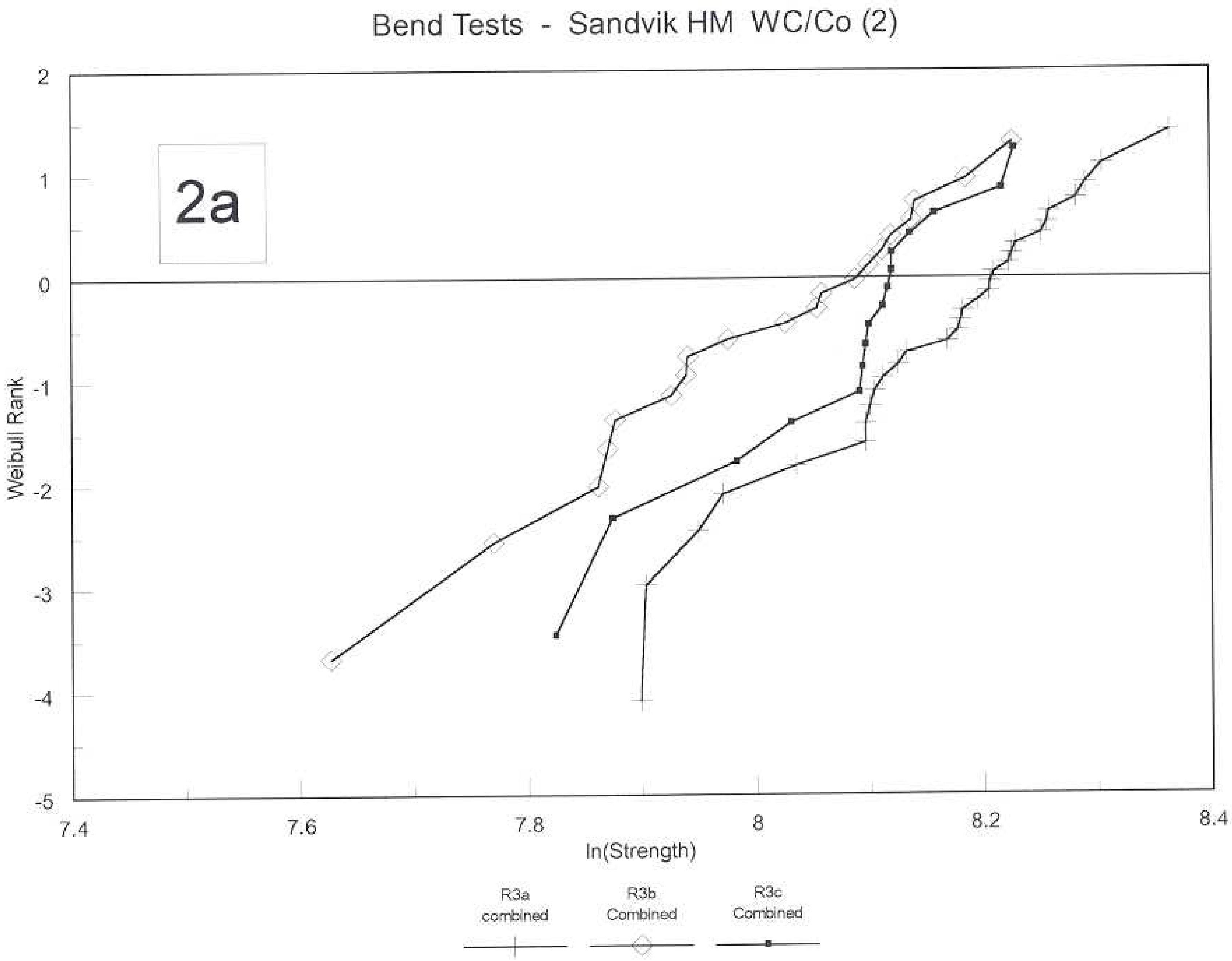
Bend Tests - Sandvik HM WC/Co (2)
1
Weibull Rank
2
1
0
-1
-2
-3
-4
7.8
7.9
8
8.1
8.2
8.3
8.4
ln(Strength)
R3a Boart
R3a Teledyne

Bend Tests - Sandvik HM WC/Co (2)

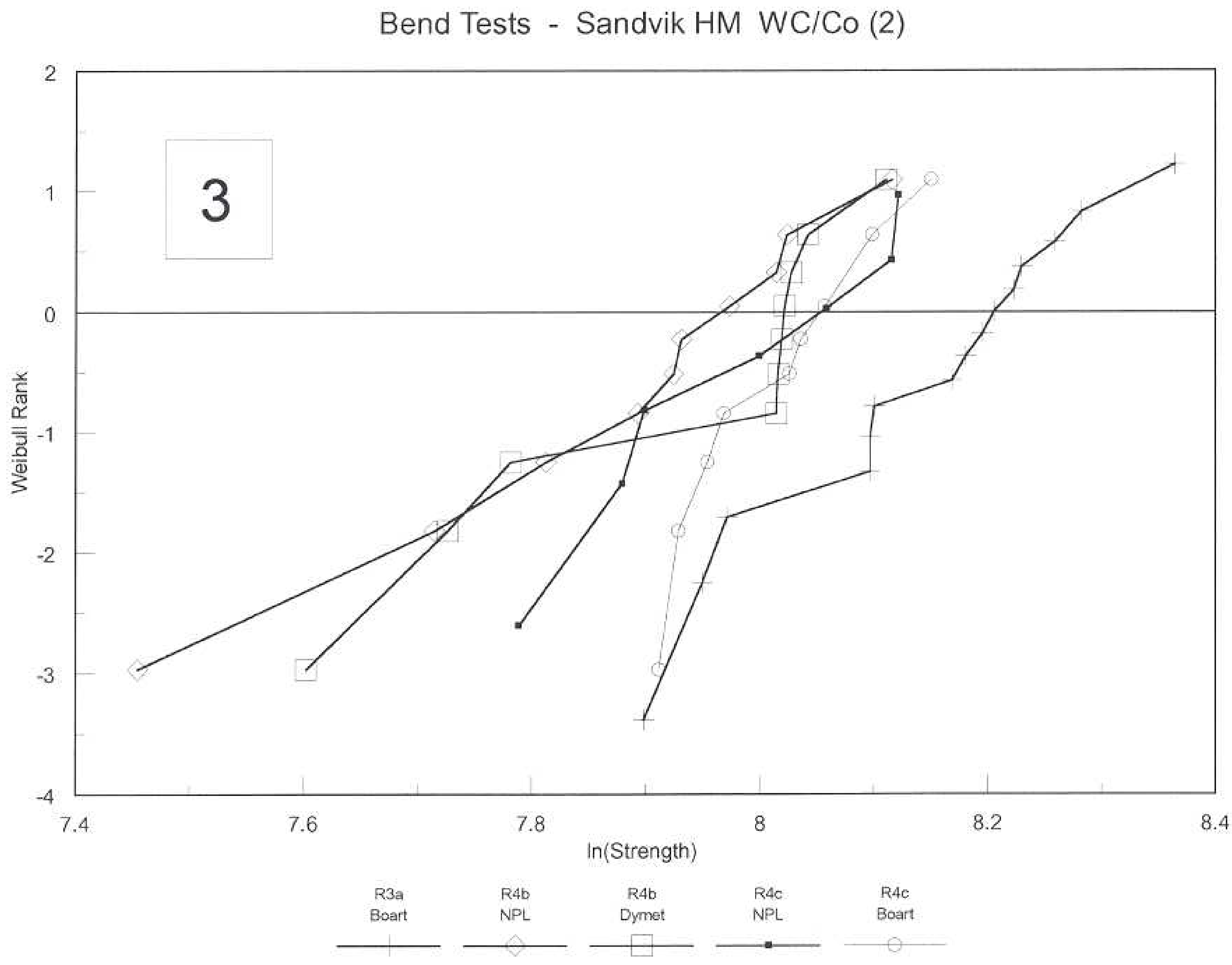


Bend Tests - Sandvik HM WC/Co (2)

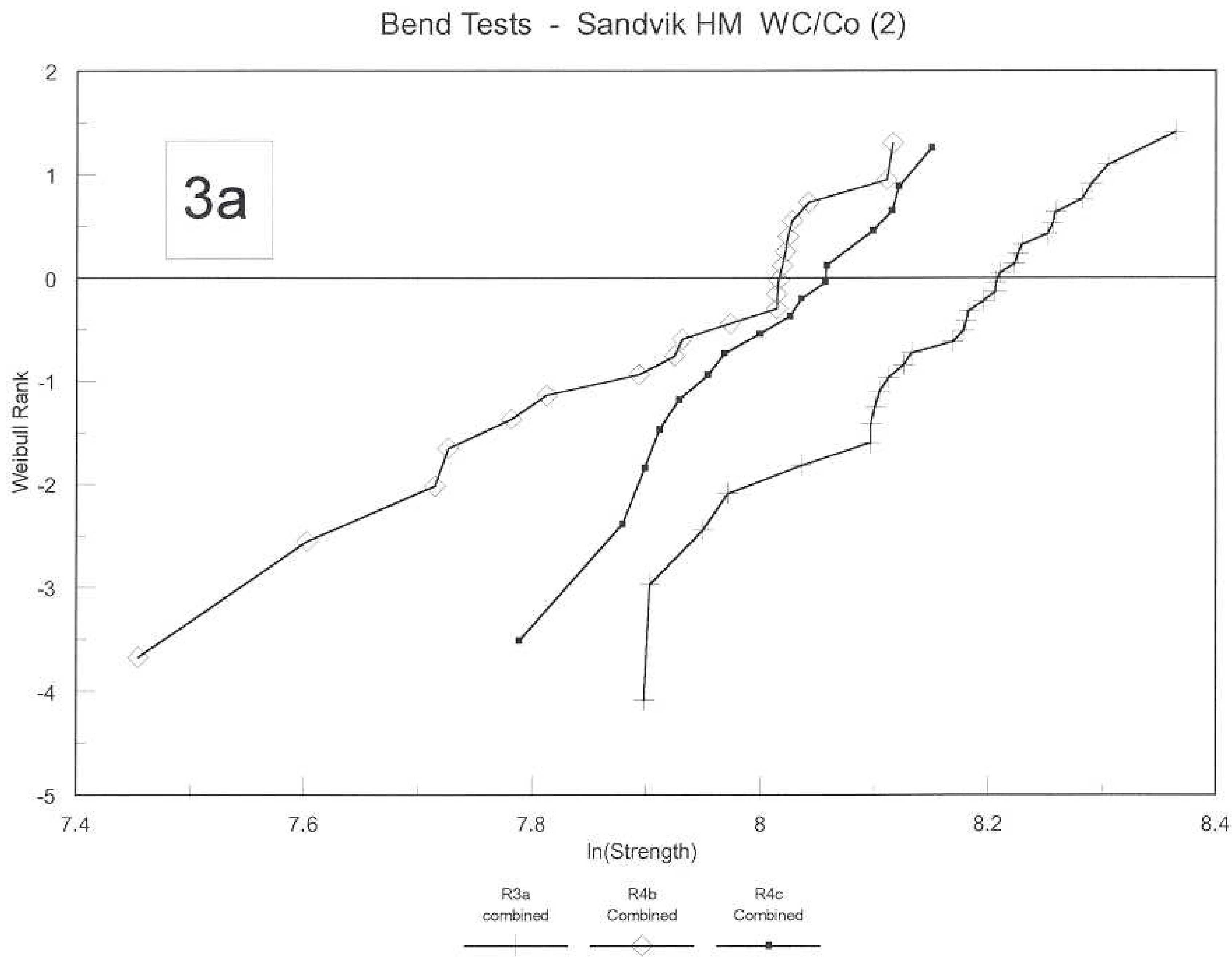




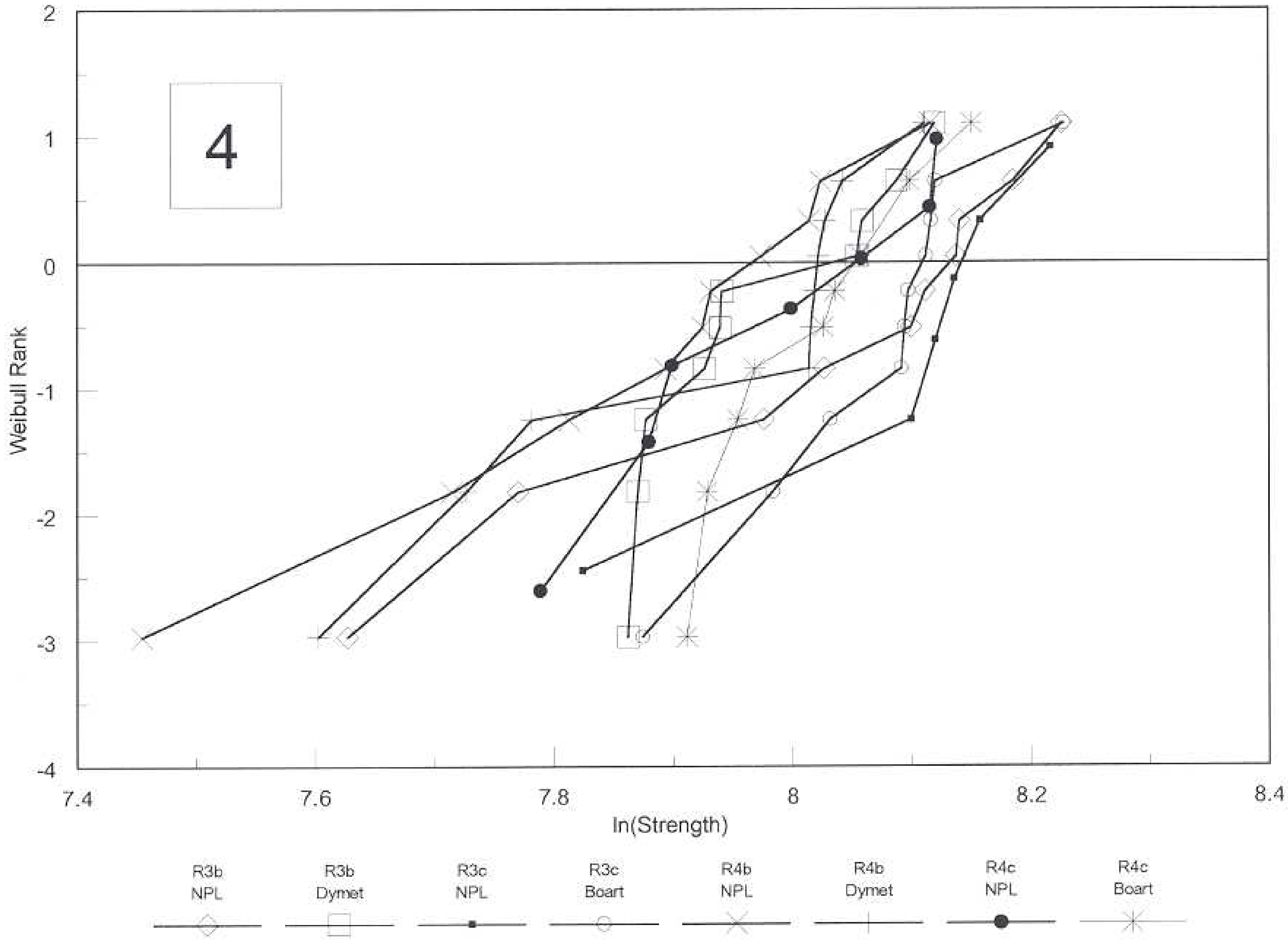
Bend Tests - Sandvik HM WC/Co (2)
2a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R3a combined
R3b Combined
R3c Combined

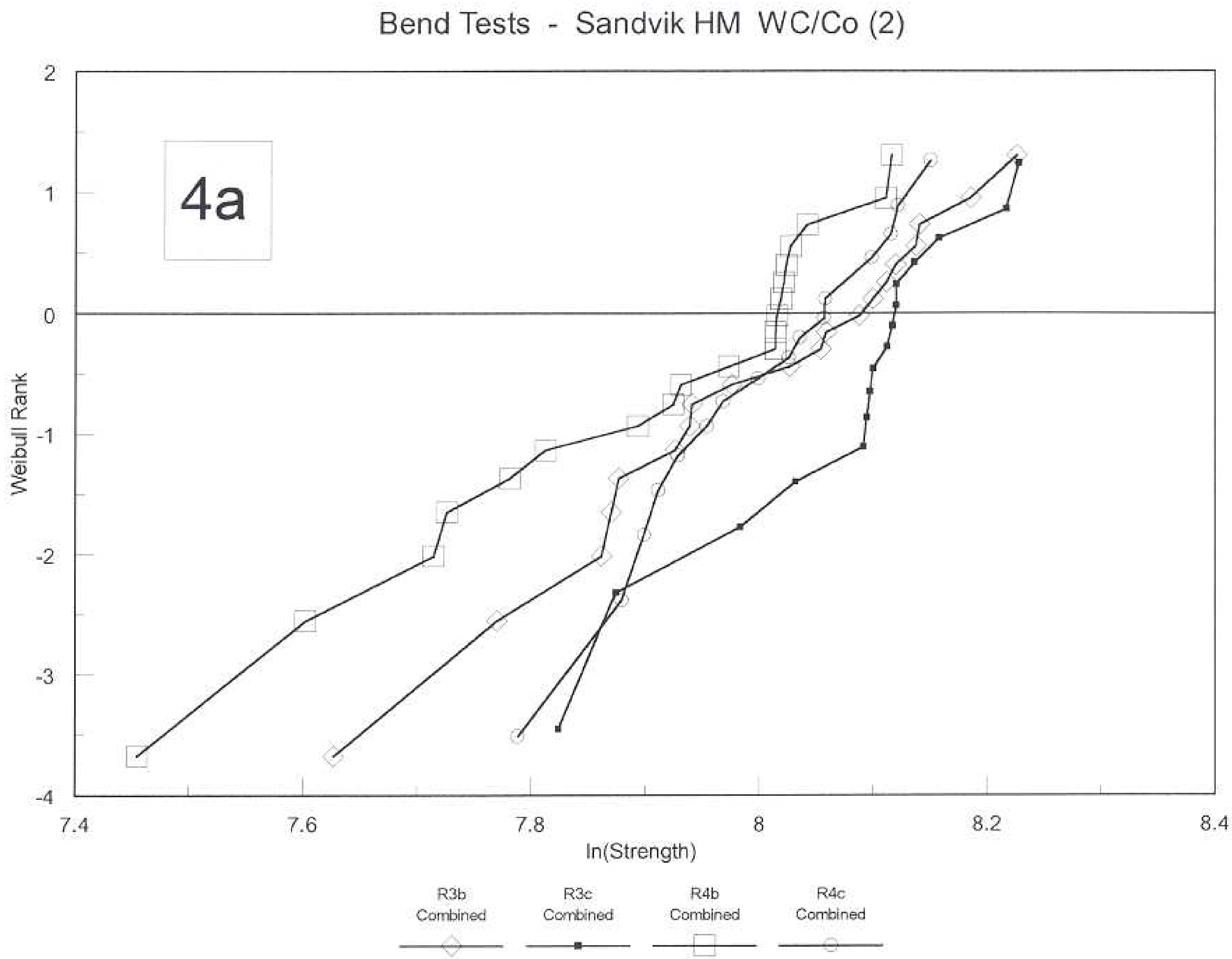


Bend Tests - Sandvik HM WC/Co (2)
3
Weibull Rank
2
1
0
-1
-2
-3
-4
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R3a Boart
R4b NPL
R4b Dymet
R4c NPL
R4c Boart

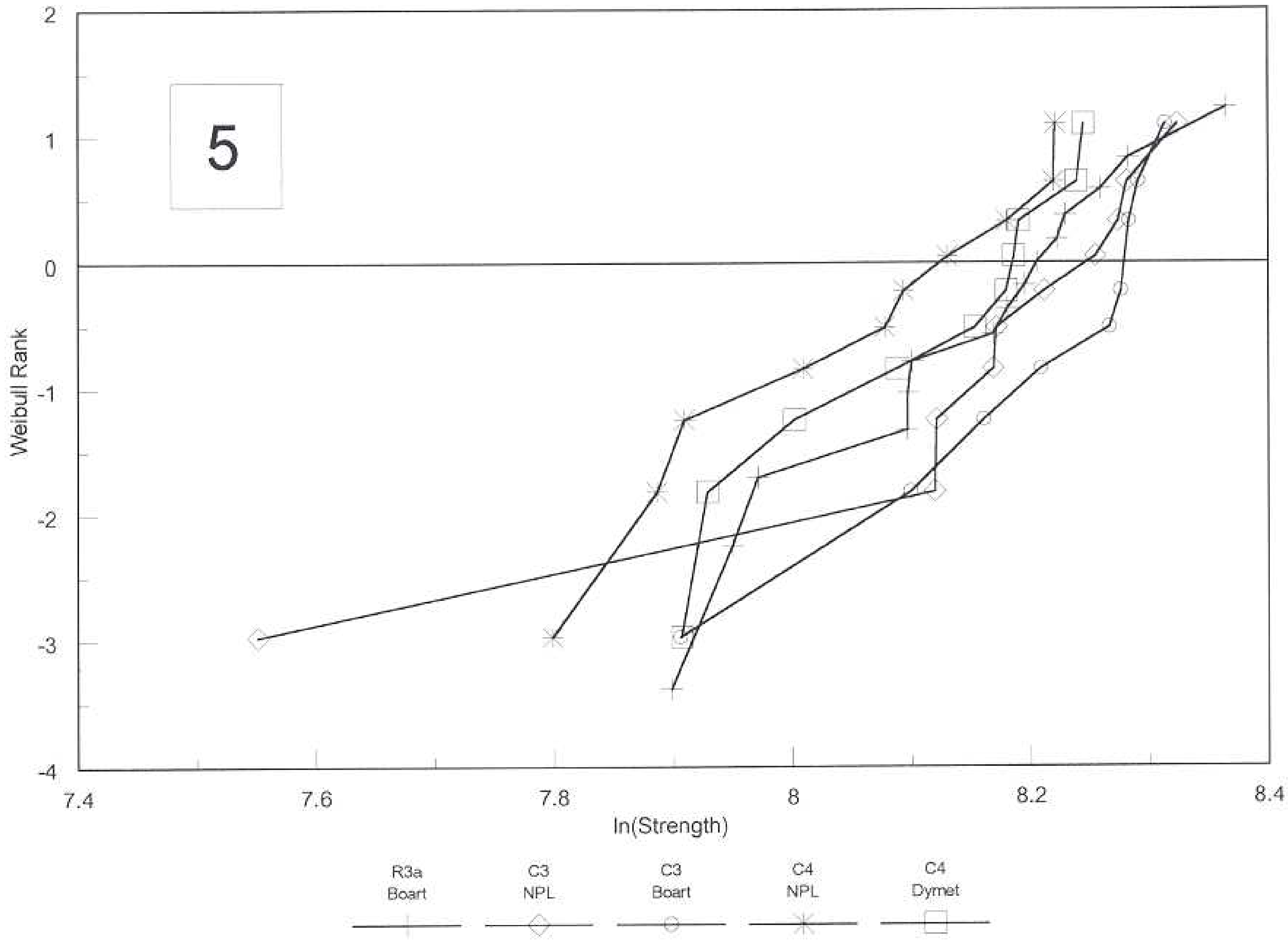

Bend Tests - Sandvik HM WC/Co (2)
3a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R3a combined
R4b Combined
R4c Combined

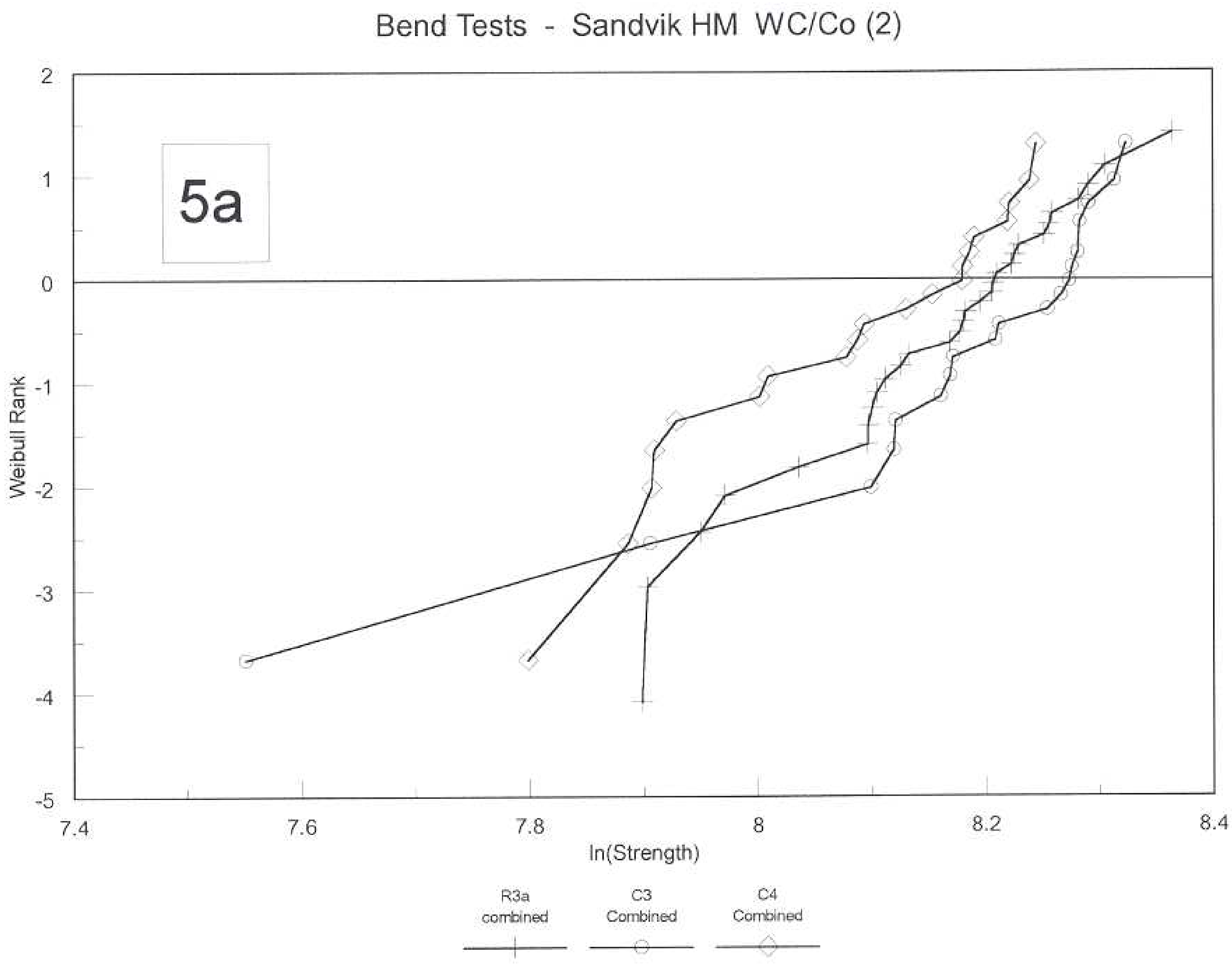
Bend Tests - Sandvik HM WC/Co (2)




Bend Tests - Sandvik HM WC/Co (2)
4a
Weibull Rank
2
1
0
-1
-2
-3
-4
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R3b Combined
R3c Combined
R4b Combined
R4c Combined

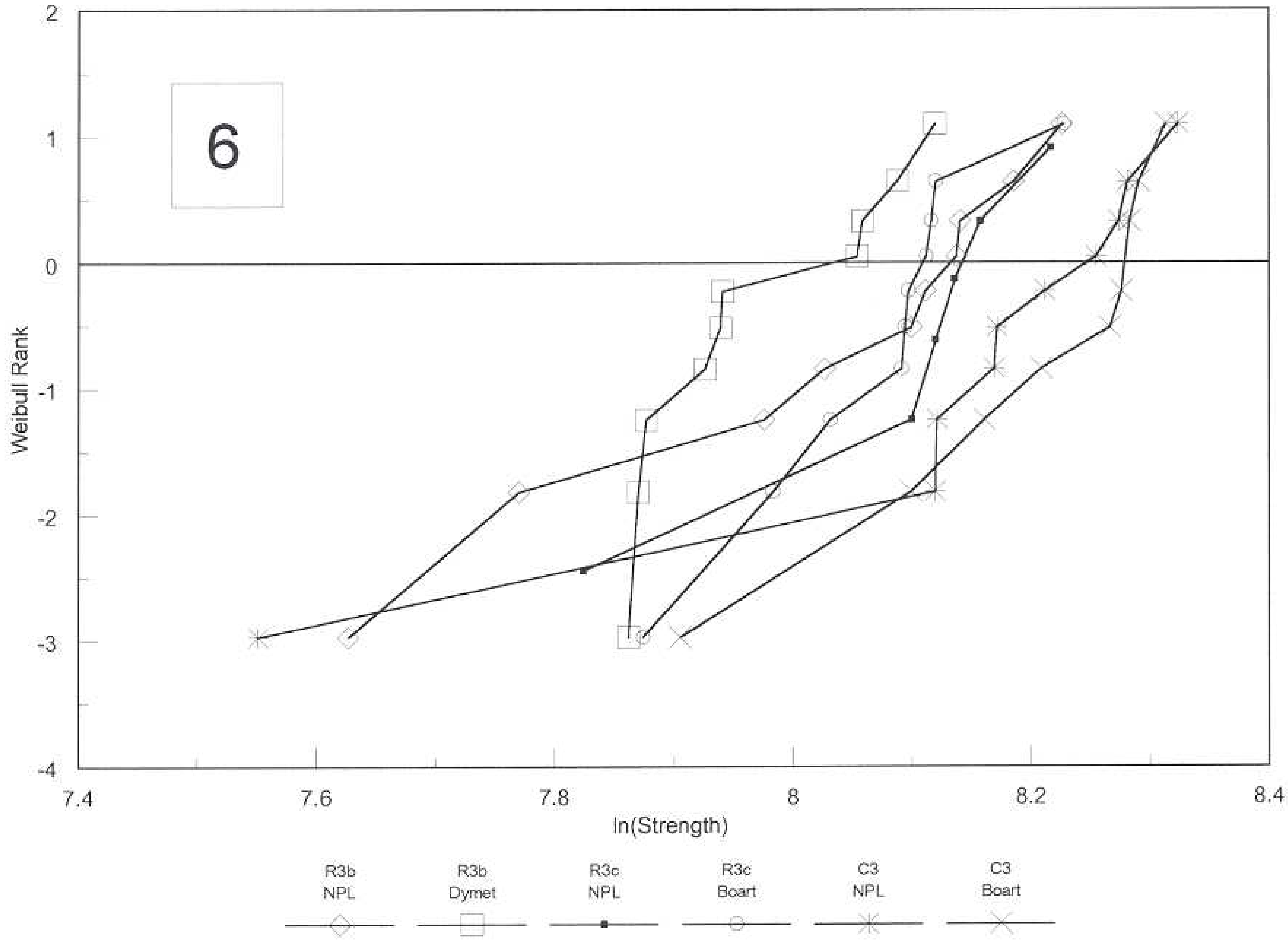
Bend Tests - Sandvik HM WC/Co (2)

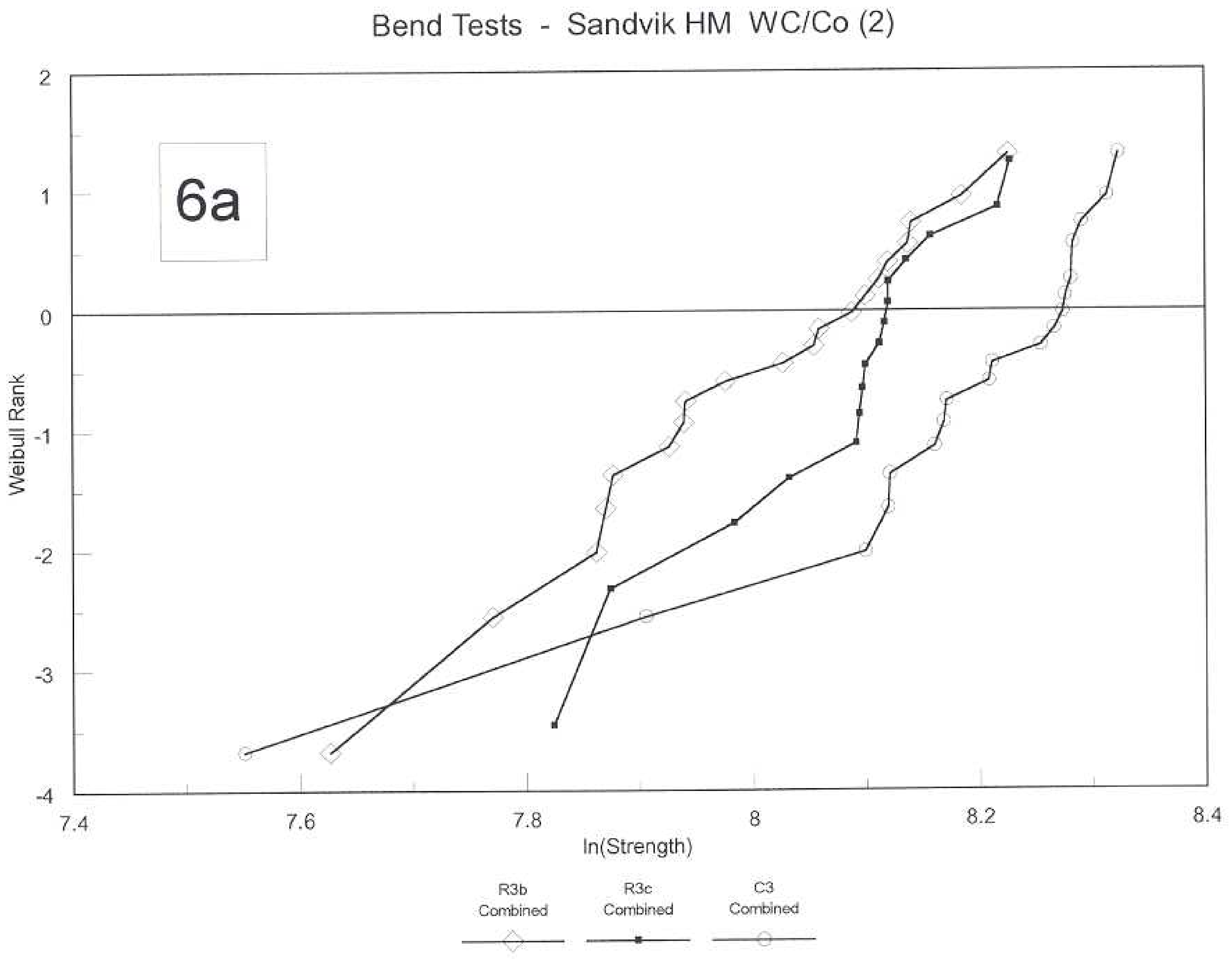




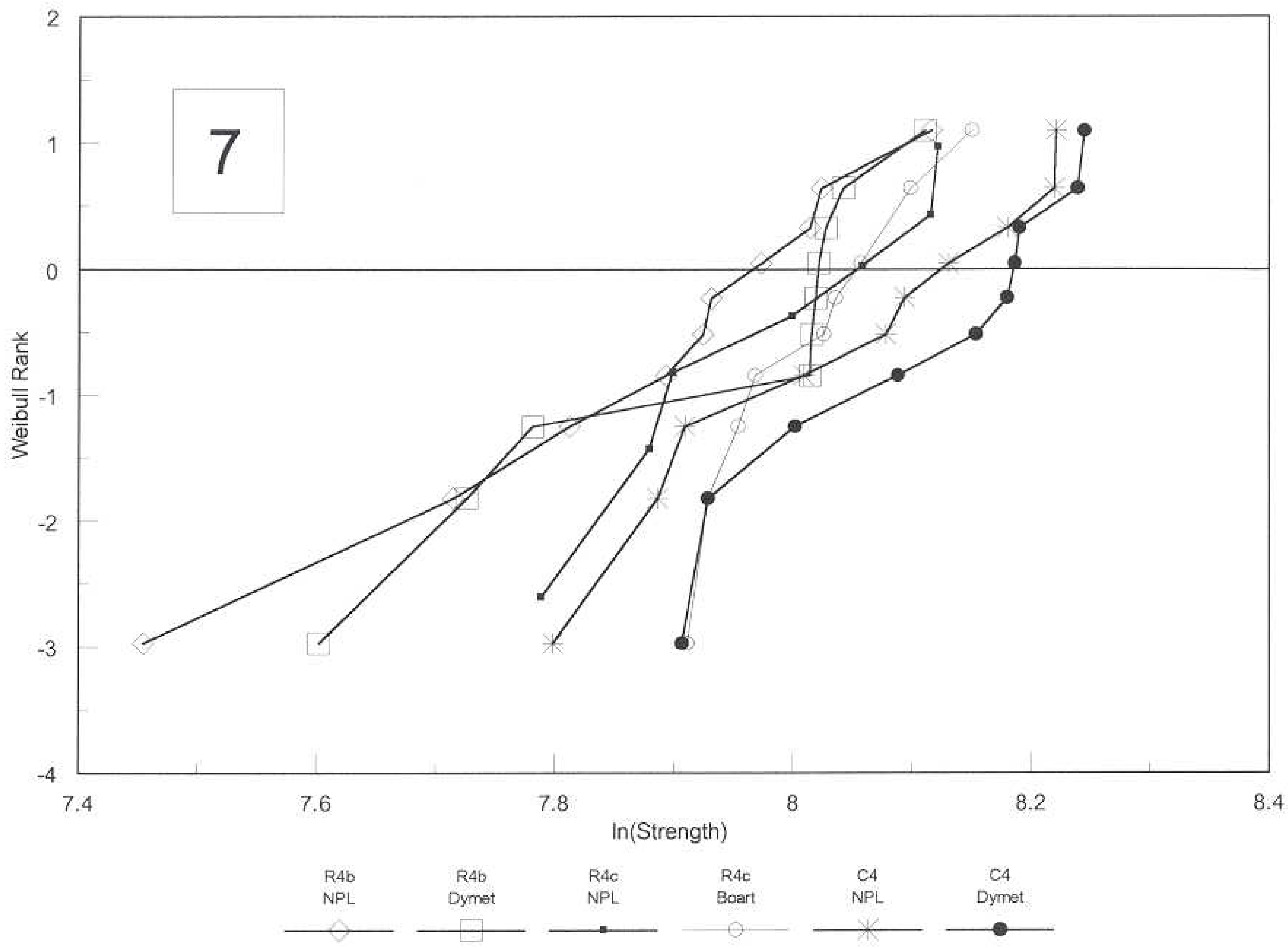
Bend Tests - Sandvik HM WC/Co (2)
5a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R3a combined
C3 Combined
C4 Combined

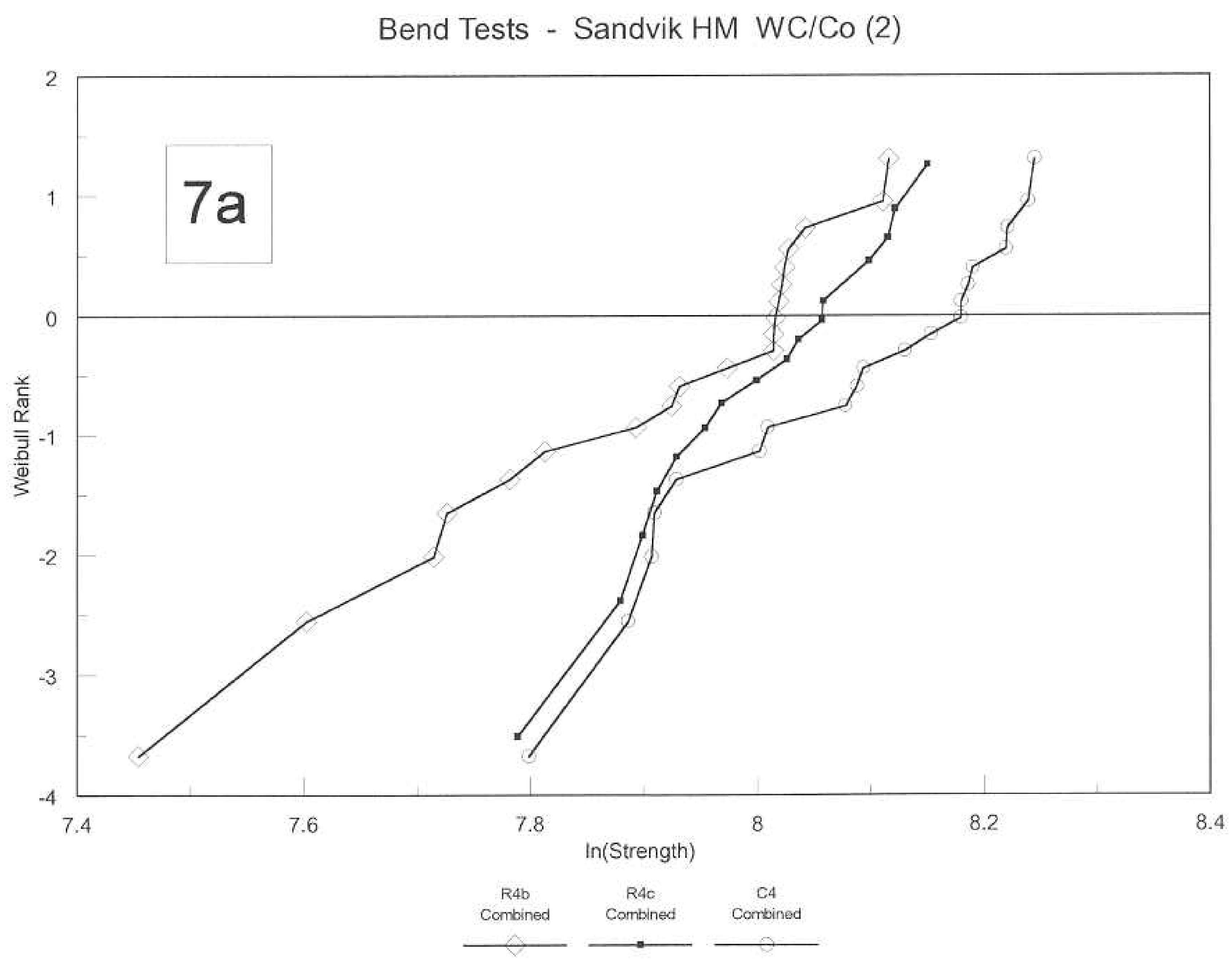
Bend Tests - Sandvik HM WC/Co (2)

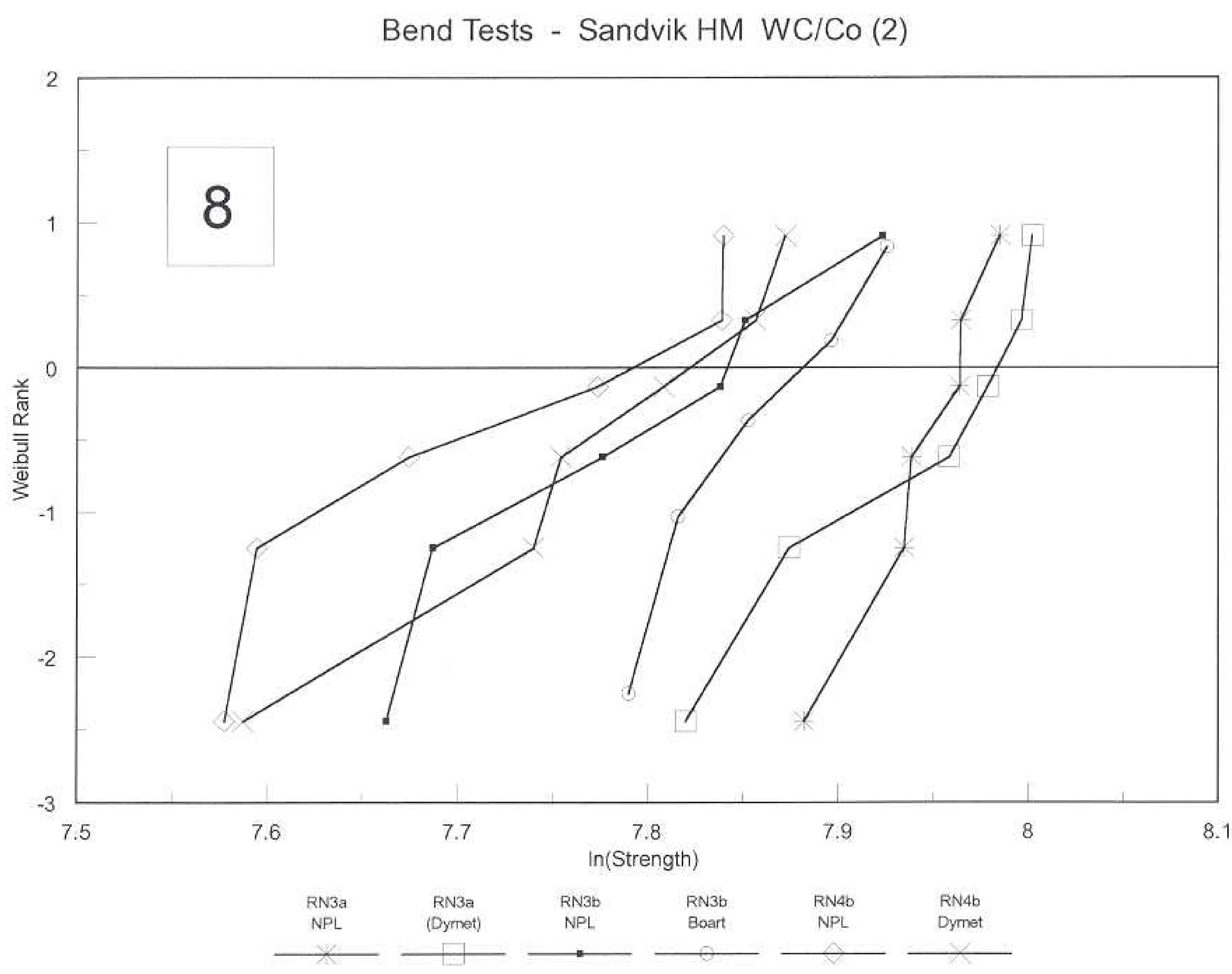


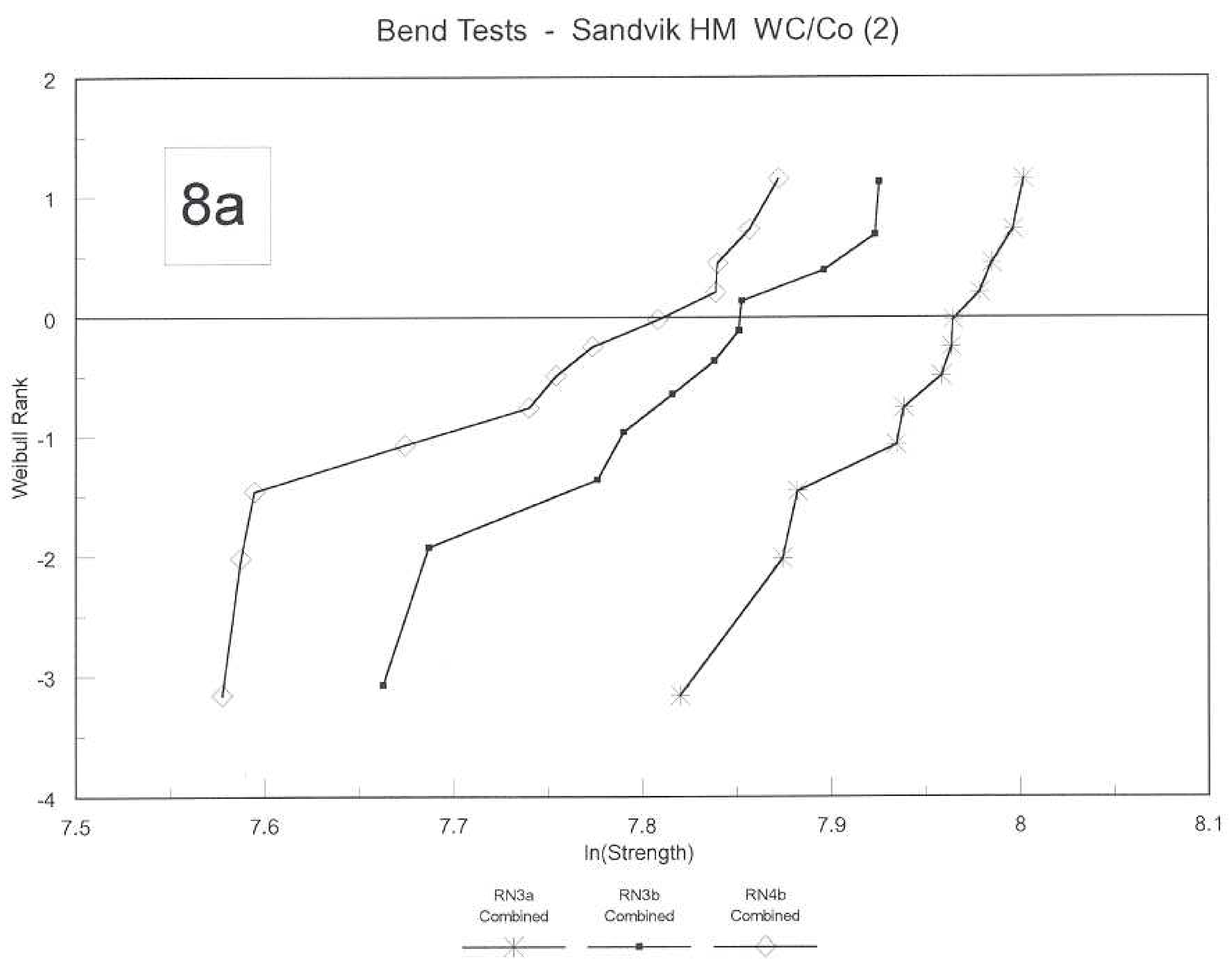

Bend Tests - Sandvik HM WC/Co (2)
6a
Weibull Rank
2
1
0
-1
-2
-3
-4
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R3b Combined
R3c Combined
C3 Combined

Bend Tests - Sandvik HM WC/Co (2)

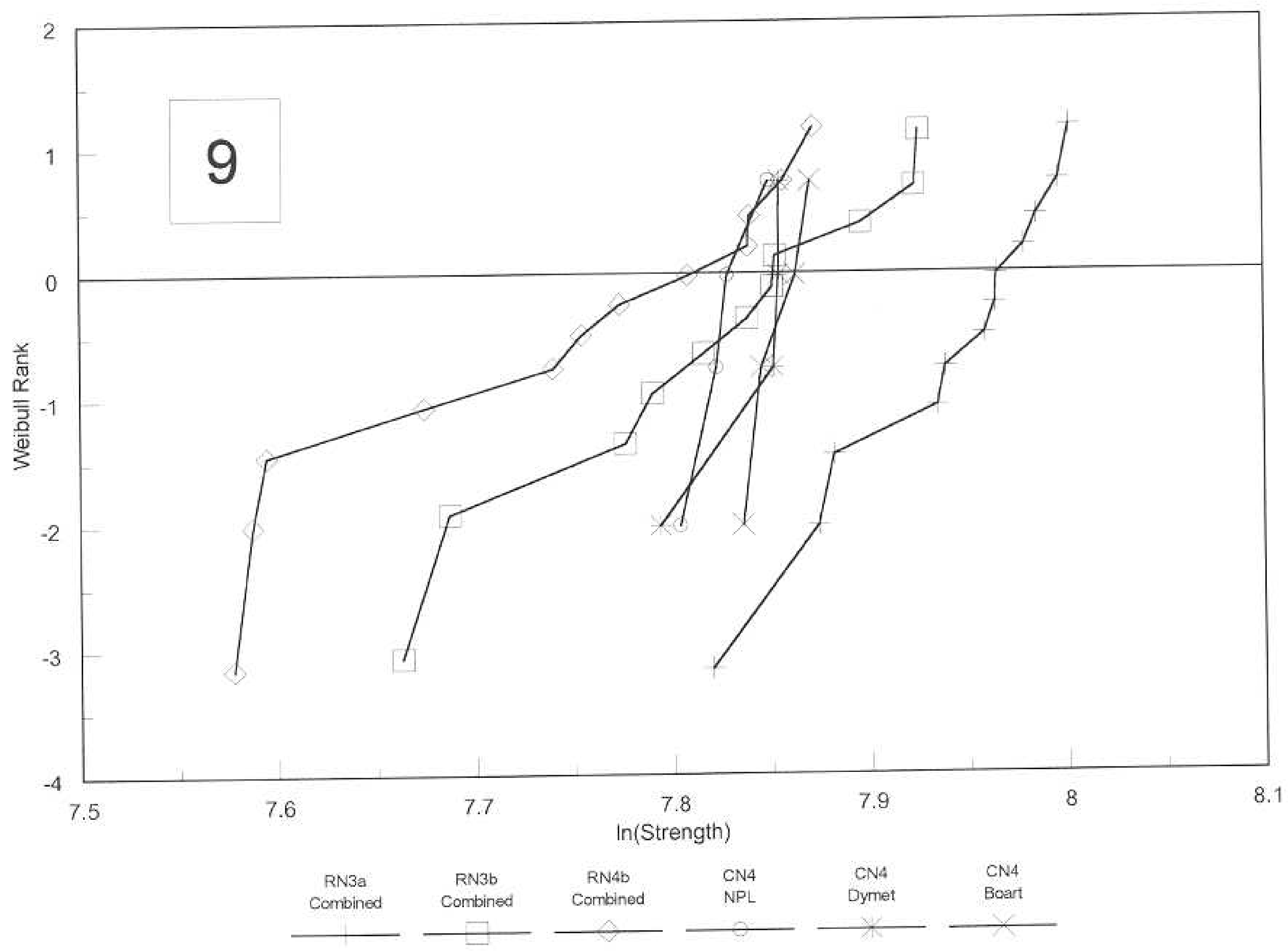



Bend Tests - Sandvik HM WC/Co (2)
7a
Weibull Rank
2
1
0
-1
-2
-3
-4
7.4
7.6
7.8
8
8.2
8.4
ln(Strength)
R4b Combined
R4c Combined
C4 Combined

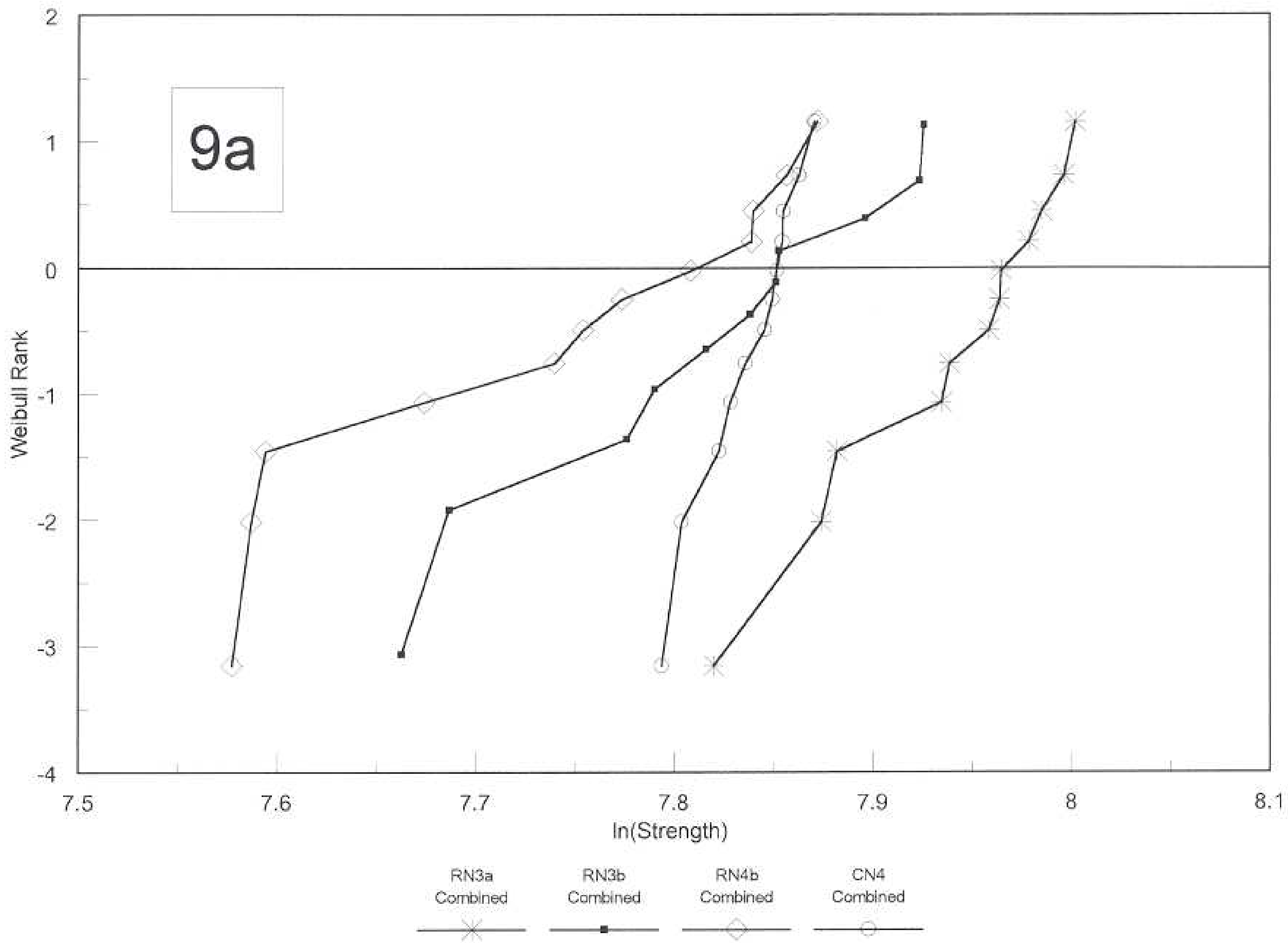

Bend Tests - Sandvik HM WC/Co (2)
8
Weibull Rank
2
1
0
-1
-2
-3
7.5
7.6
7.7
7.8
7.9
8
8.1
ln(Strength)
RN3a NPL
RN3a (Dymet)
RN3b NPL
RN3b Boart
RN4b NPL
RN4b Dymet


Bend Tests - Sandvik HM WC/Co (2)
8a
Weibull Rank
2
1
0
-1
-2
-3
-4
7.5
7.6
7.7
7.8
7.9
8
8.1
ln(Strength)
RN3a Combined
RN3b Combined
RN4b Combined

Bend Tests - Sandvik HM WC/Co (2)



Bend Tests - Sandvik HM WC/Co (2)



WEIBULL RESULTS SET

(4) KENNAMETAL

Medium/Fine, WC/CC/Co

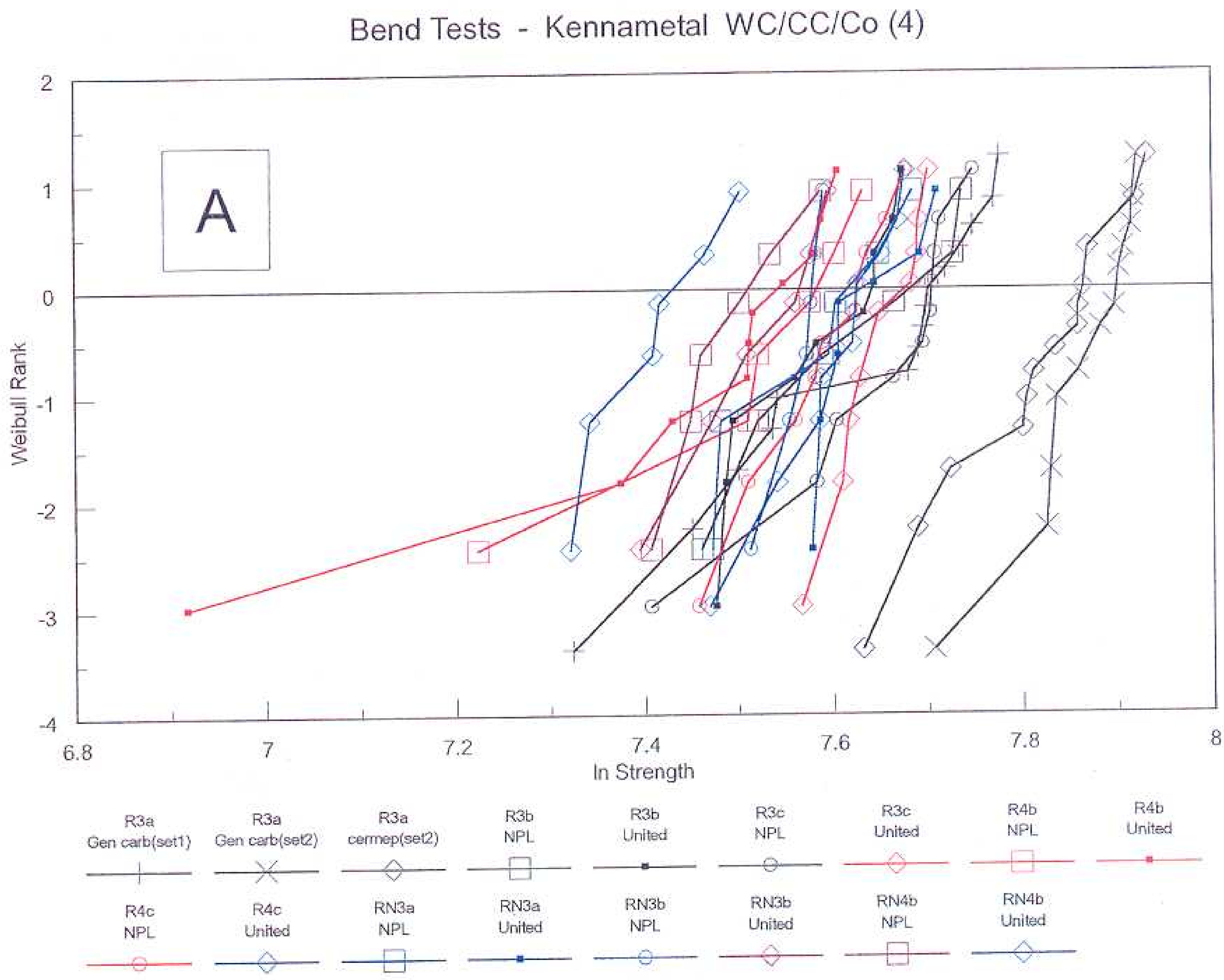
HARDMETAL BEND TESTS

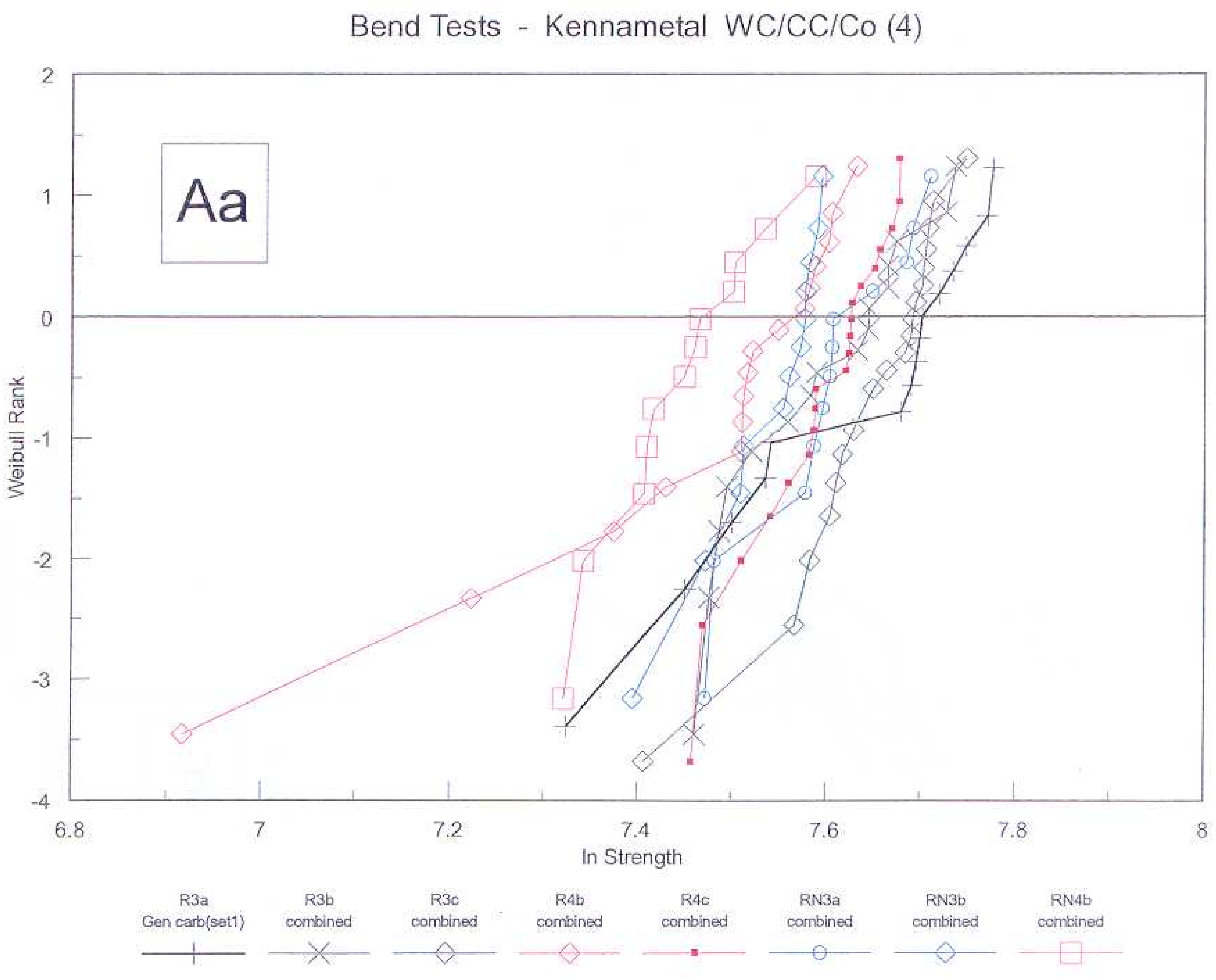
Results Comment Sheet

Kennametal - Category (4) WC/CC/Co Hardmetal

PLOT SEQUENCE

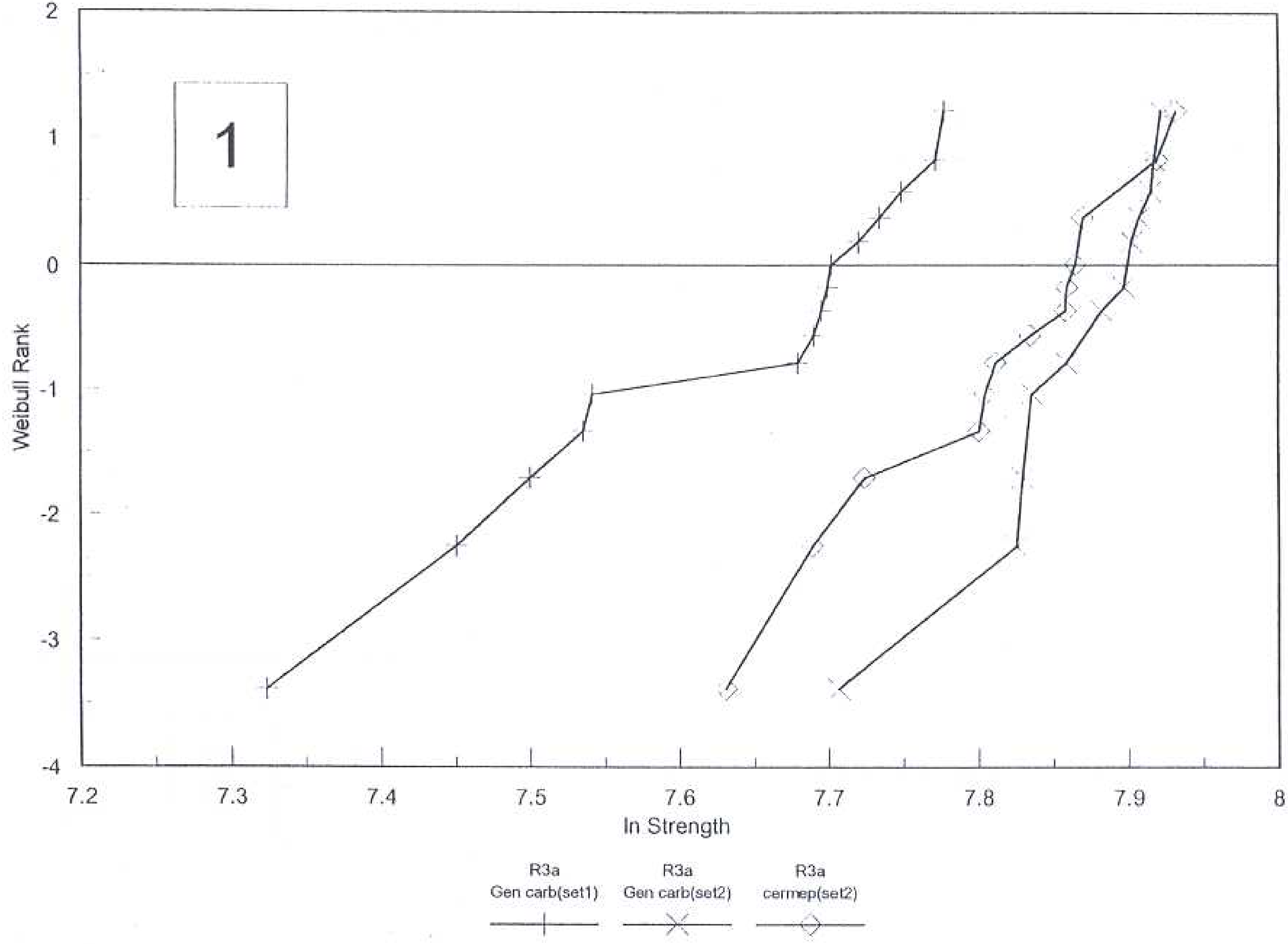
A	-	Complete set of all strength values.
Aa	-	Complete set, different laboratories combined.
1	-	Standard tests, ISO type B (R3a).
2	-	3 pt rectangular tests; R3a, R3b, R3c.
2a	-	Combined R3a, R3b and R3c.
3	-	4 pt rectangular tests, compared with standard ISO type B; R3a, R4b, R4c.
3a	-	Combined R3a, R4b and R4c.
4	-	Individual 3 pt vs 4 pt tests; R3b, R3c, R4b, R4c; not including R3a.
4a	-	Combined R3b, R3c, R4b and R4c.
8	-	Notched rectangular testpieces, RN3a, RN3b and RN4b.
8a	-	Combined notched testpieces; RN3a, RN3b and RN4b.

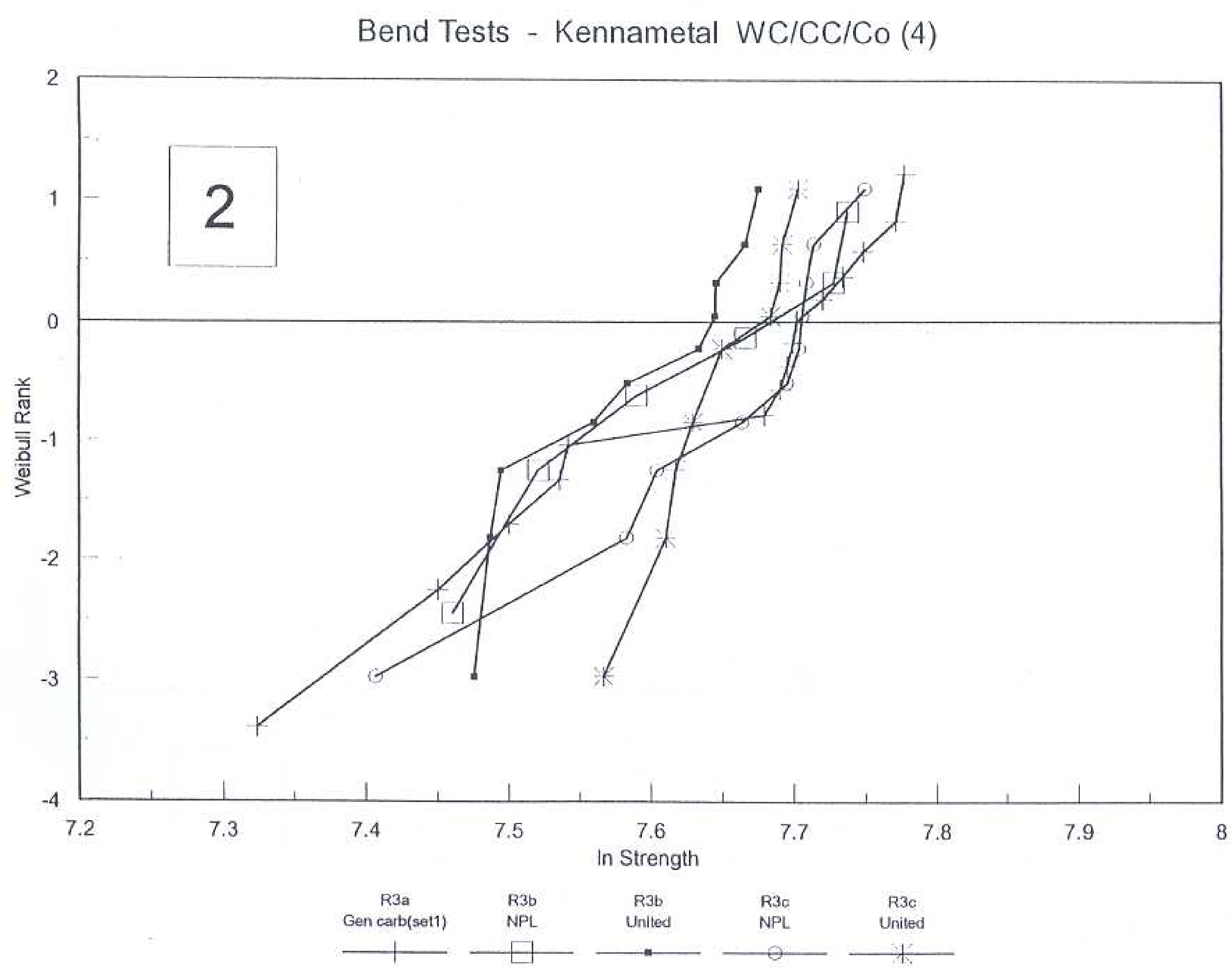

Bend Tests - Kennametal WC/CC/Co (4)
A
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
8
ln Strength
R3a Gen carb(set1)
R3a Gen carb(set2)
R3a cermep(set2)
R3b NPL
R3b United
R3c NPL
R3c United
R4b NPL
R4b United
R4c NPL
R4c United
RN3a NPL
RN3a United
RN3b NPL
RN3b United
RN4b NPL
RN4b United



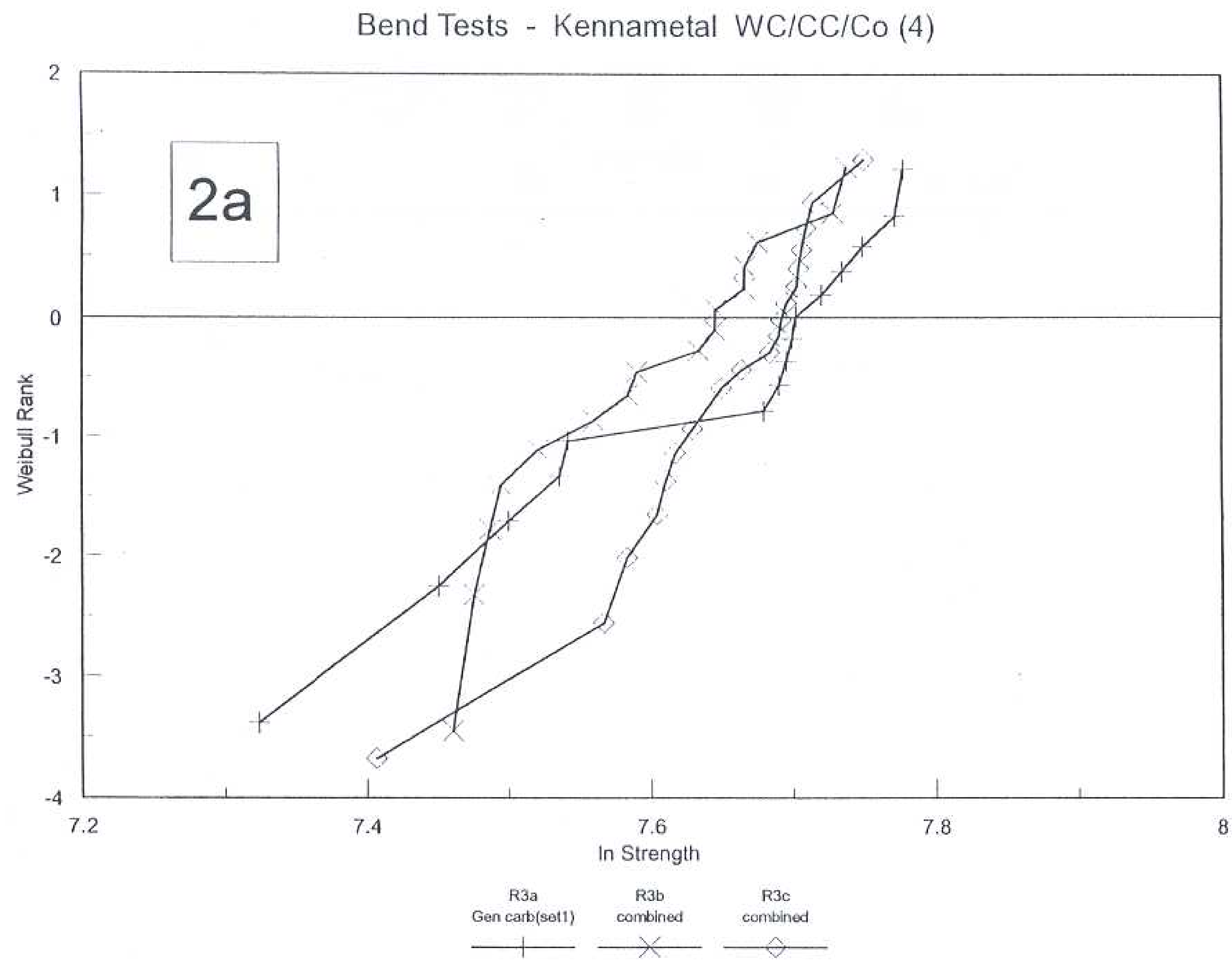
Bend Tests - Kennametal WC/CC/Co (4)
Aa
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
8
ln Strength
R3a Gen carb(set1)
R3b combined
R3c combined
R4b combined
R4c combined
RN3a combined
RN3b combined
RN4b combined

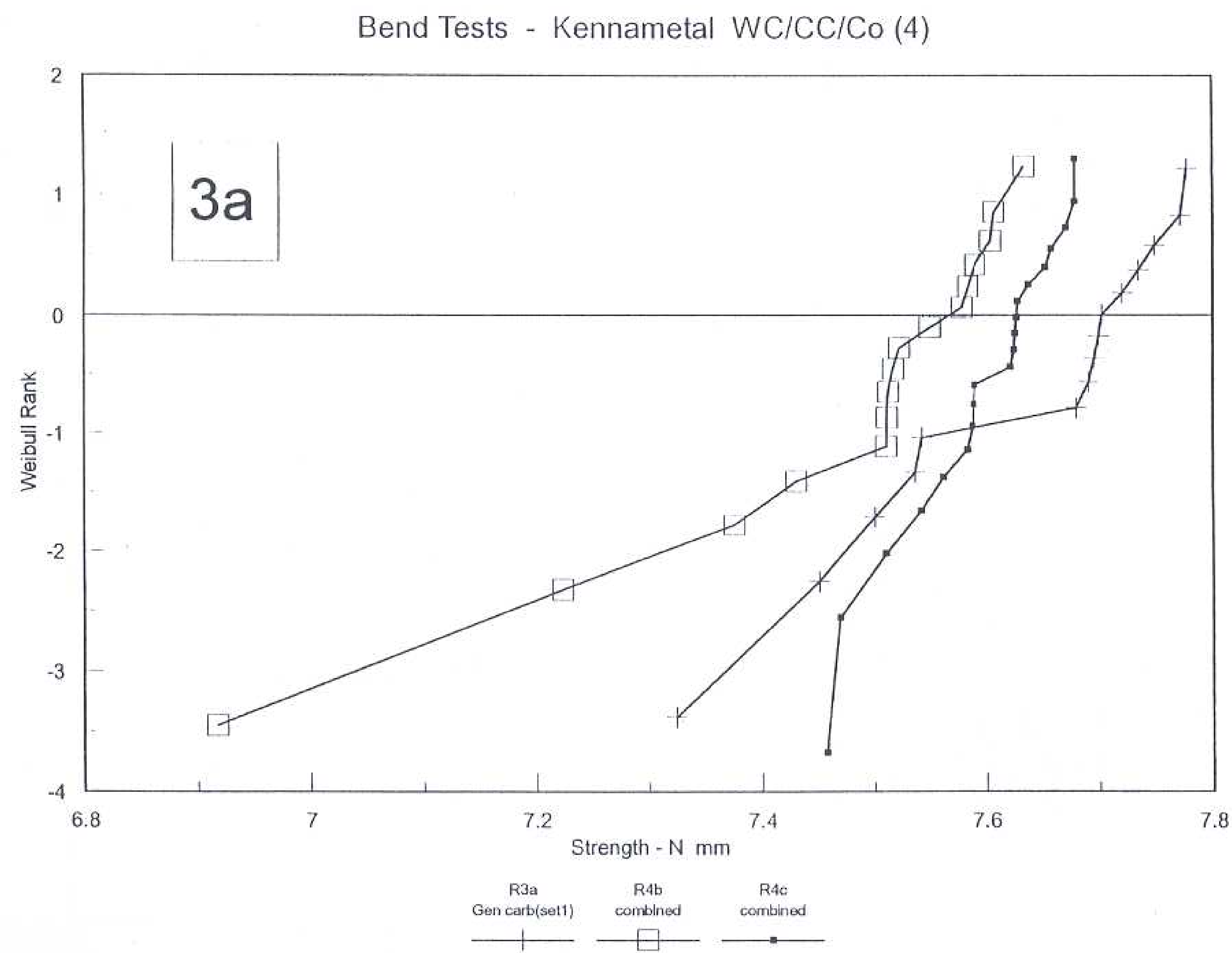
Bend Tests - Kennametal WC/CC/Co (4)

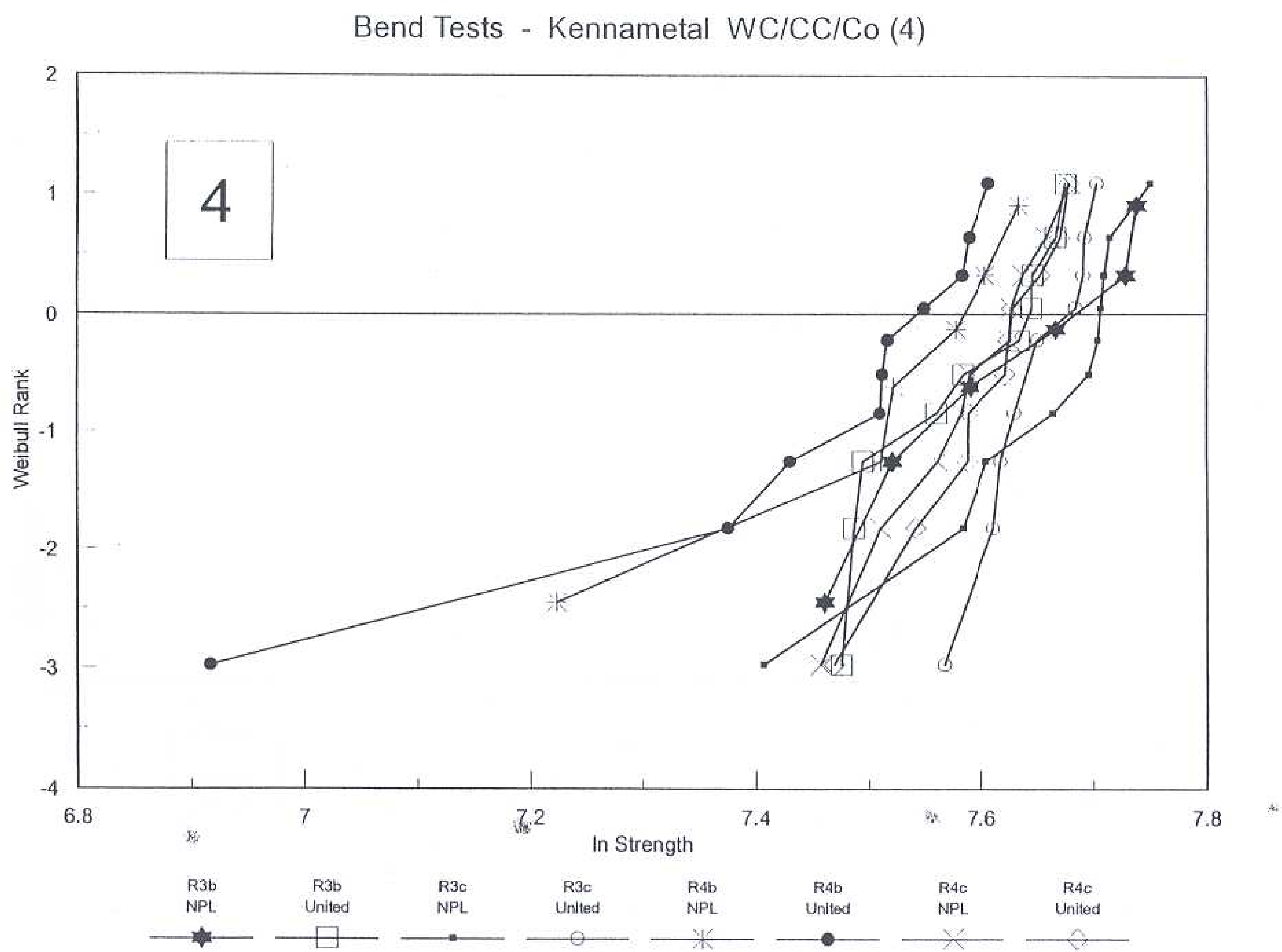




Bend Tests - Kennametal WC/CC/Co (4)
2
Weibull Rank
2
1
0
-1
-2
-3
-4
7.2
7.3
7.4
7.5
7.6
7.7
7.8
7.9
8
ln Strength
R3a Gen carb(set1)
R3b NPL
R3b United
R3c NPL
R3c United

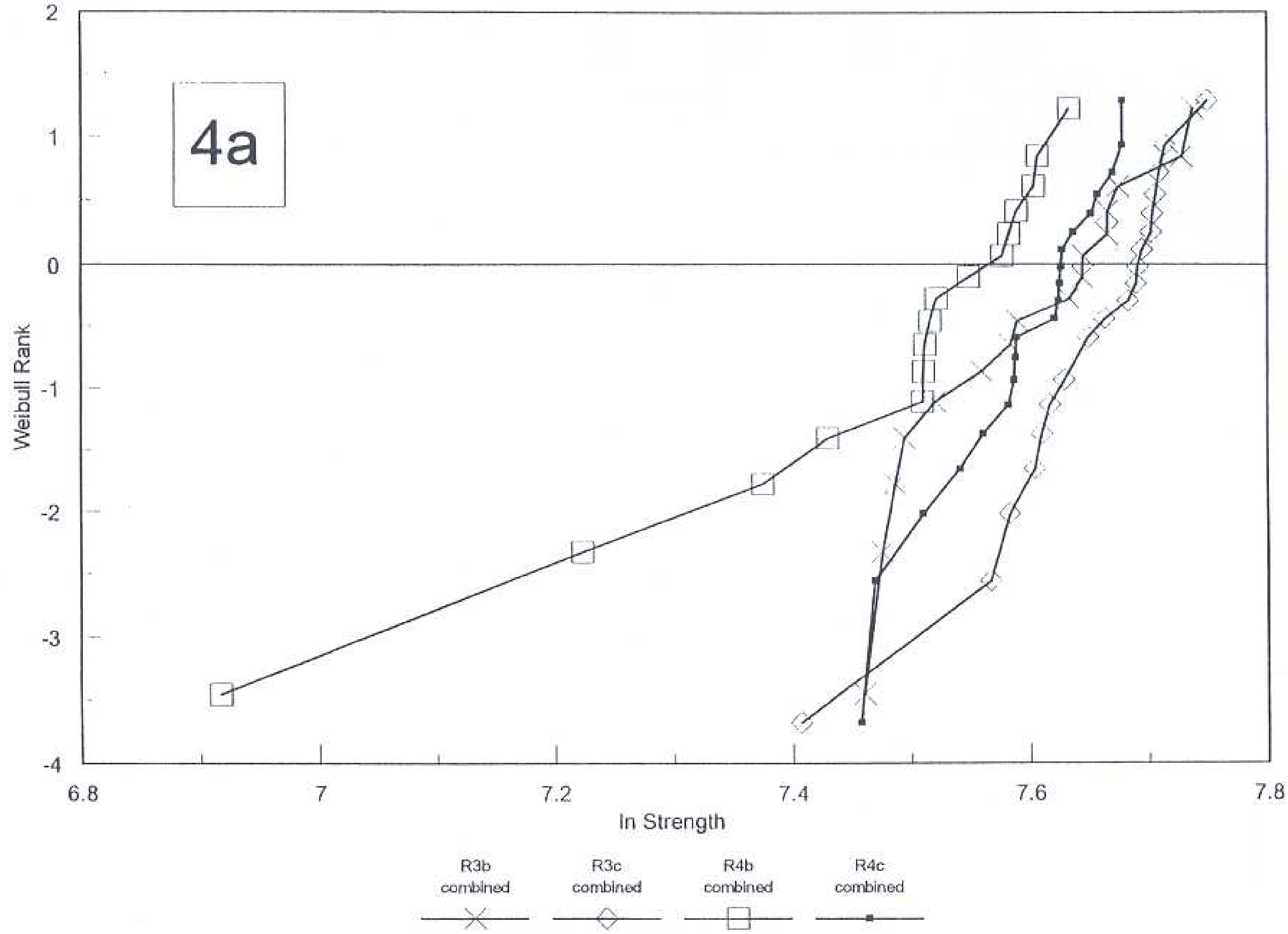

Bend Tests - Kennametal WC/CC/Co (4)
2a
Weibull Rank
2
1
0
-1
-2
-3
-4
7.2
7.4
7.6
7.8
8
ln Strength
R3a
Gen carb(set1)
R3b
combined
R3c
combined


Bend Tests - Kennametal WC/CC/Co (4)
3a
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
Strength - N mm
R3a
Gen carb(set1)
R4b
combined
R4c
combined

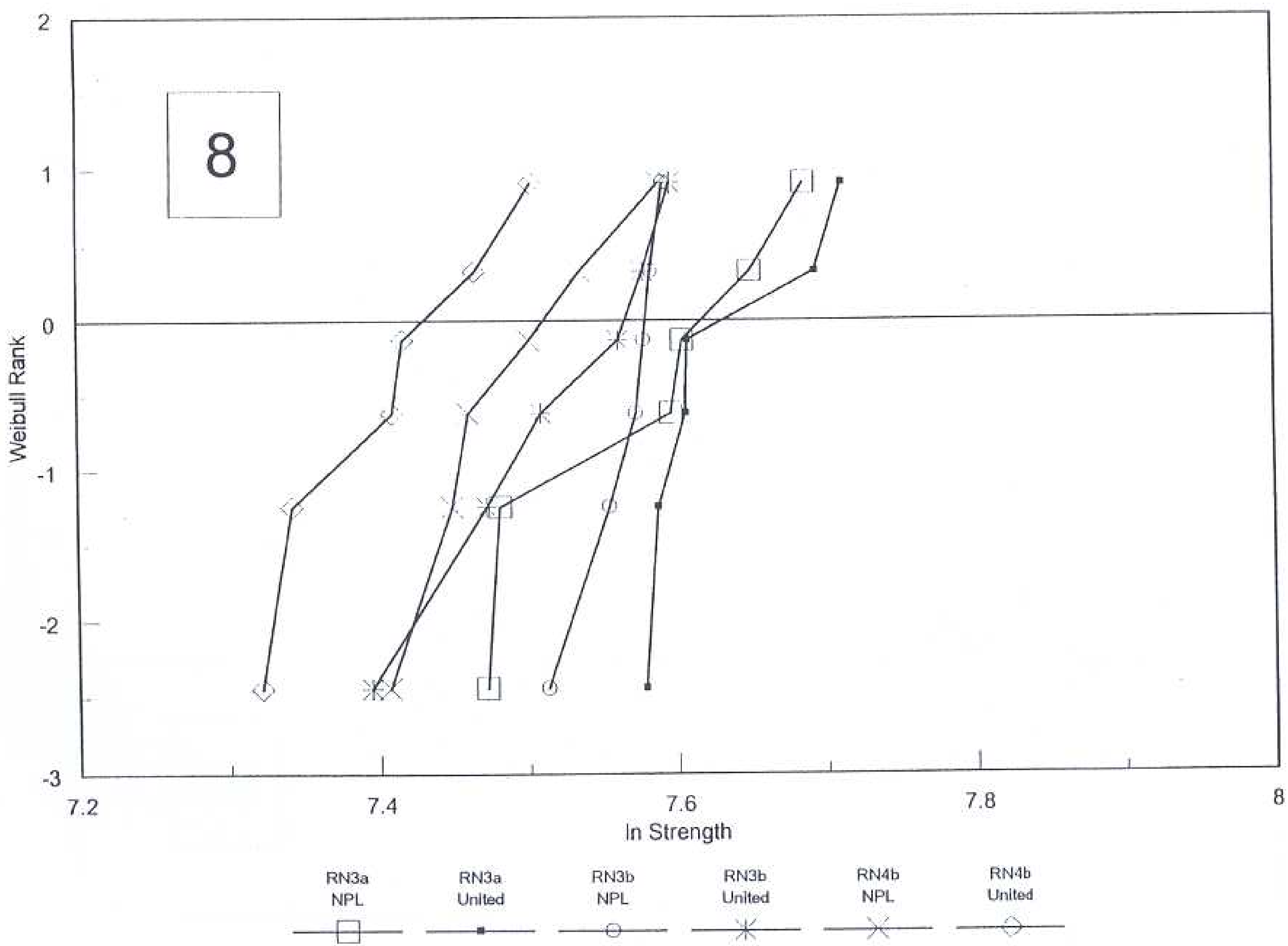


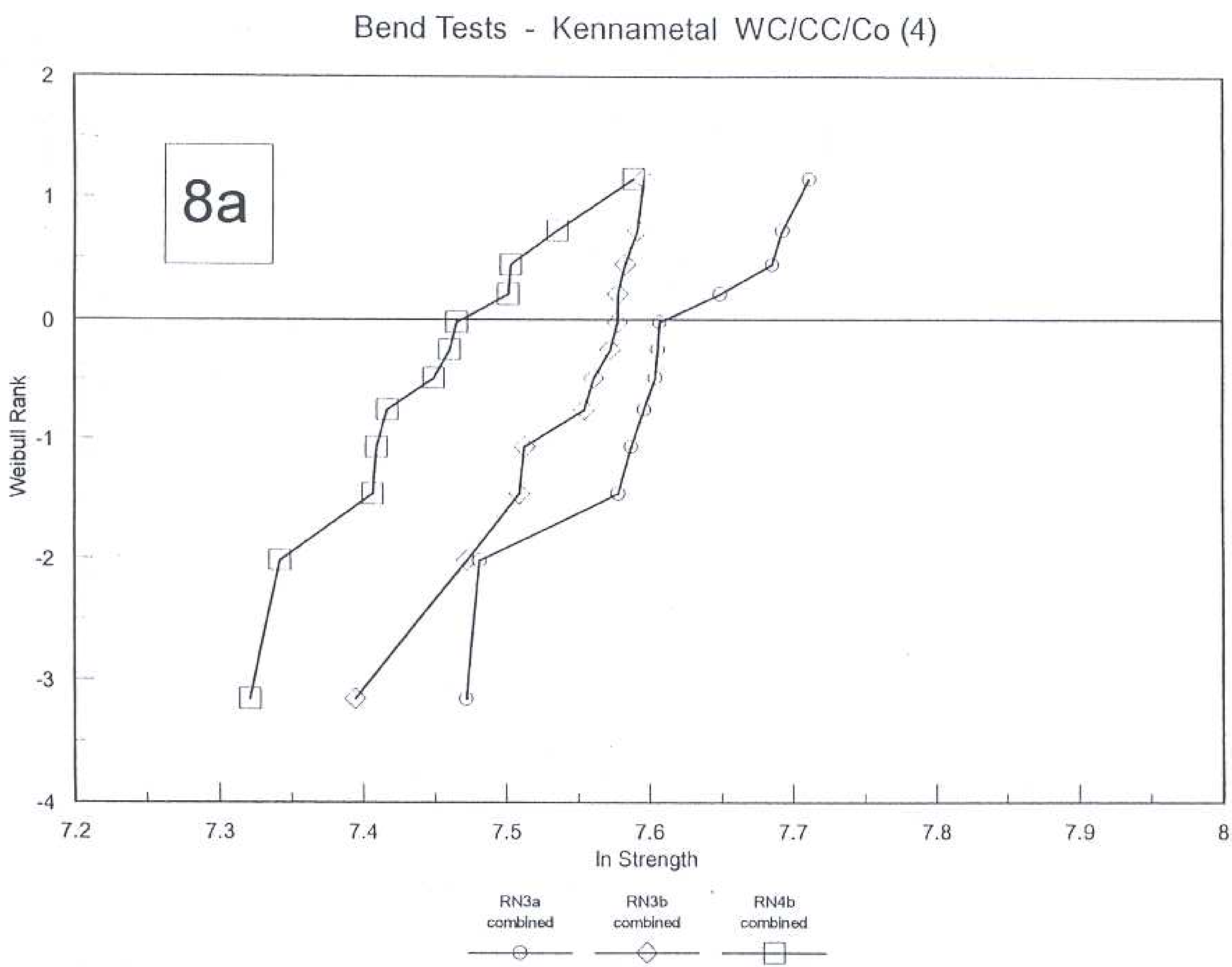
Bend Tests - Kennametal WC/CC/Co (4)
4
Weibull Rank
2
1
0
-1
-2
-3
-4
6.8
7
7.2
7.4
7.6
7.8
ln Strength
R3b NPL
R3b United
R3c NPL
R3c United
R4b NPL
R4b United
R4c NPL
R4c United

Bend Tests - Kennametal WC/CC/Co (4)



Bend Tests - Kennametal WC/CC/Co (4)





Bend Tests - Kennametal WC/CC/Co (4)
8a
Weibull Rank
2
1
0
-1
-2
-3
-4
7.2
7.3
7.4
7.5
7.6
7.7
7.8
7.9
8
ln Strength
RN3a combined
RN3b combined
RN4b combined

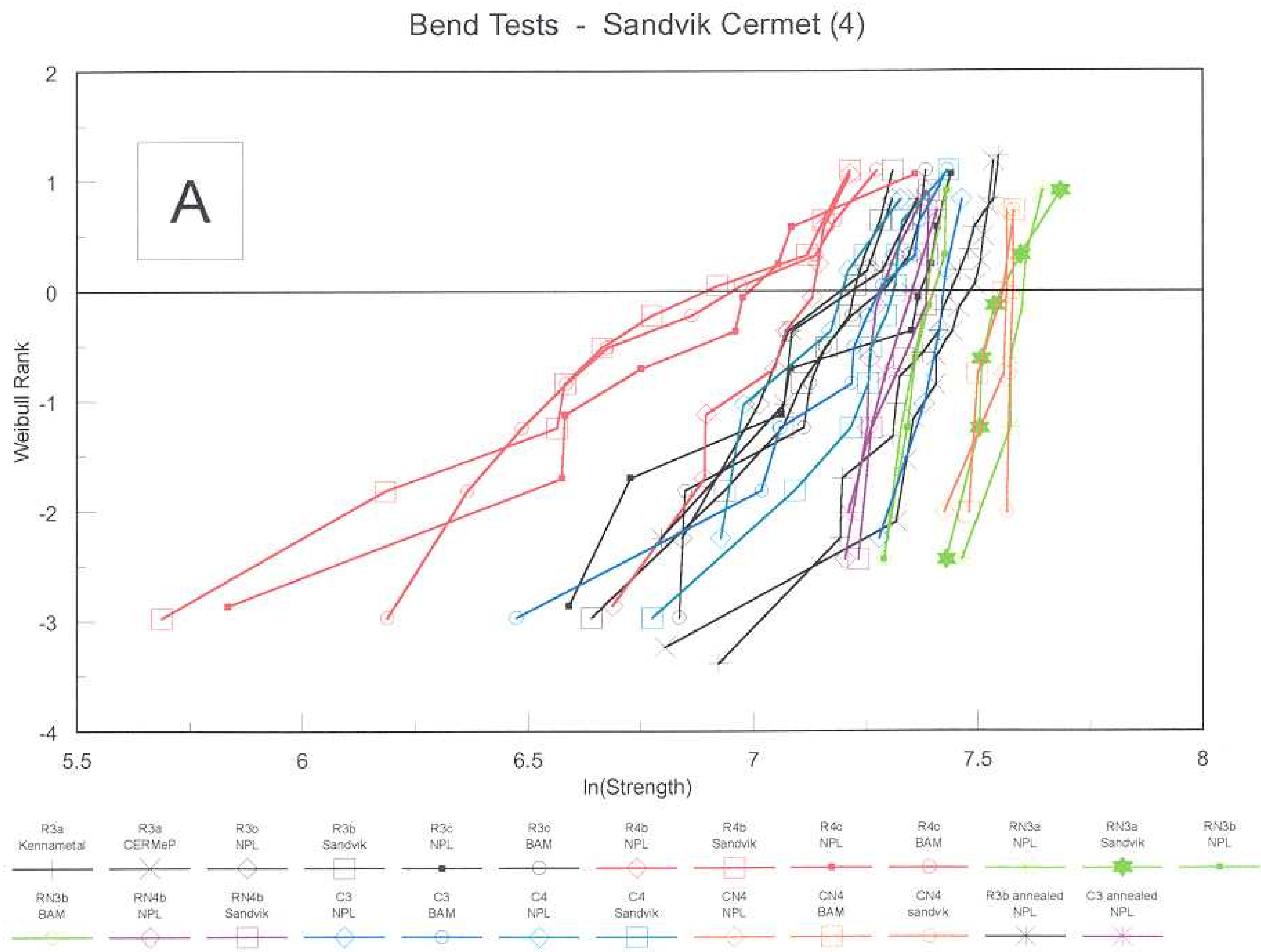
HARDMETAL BEND TESTS

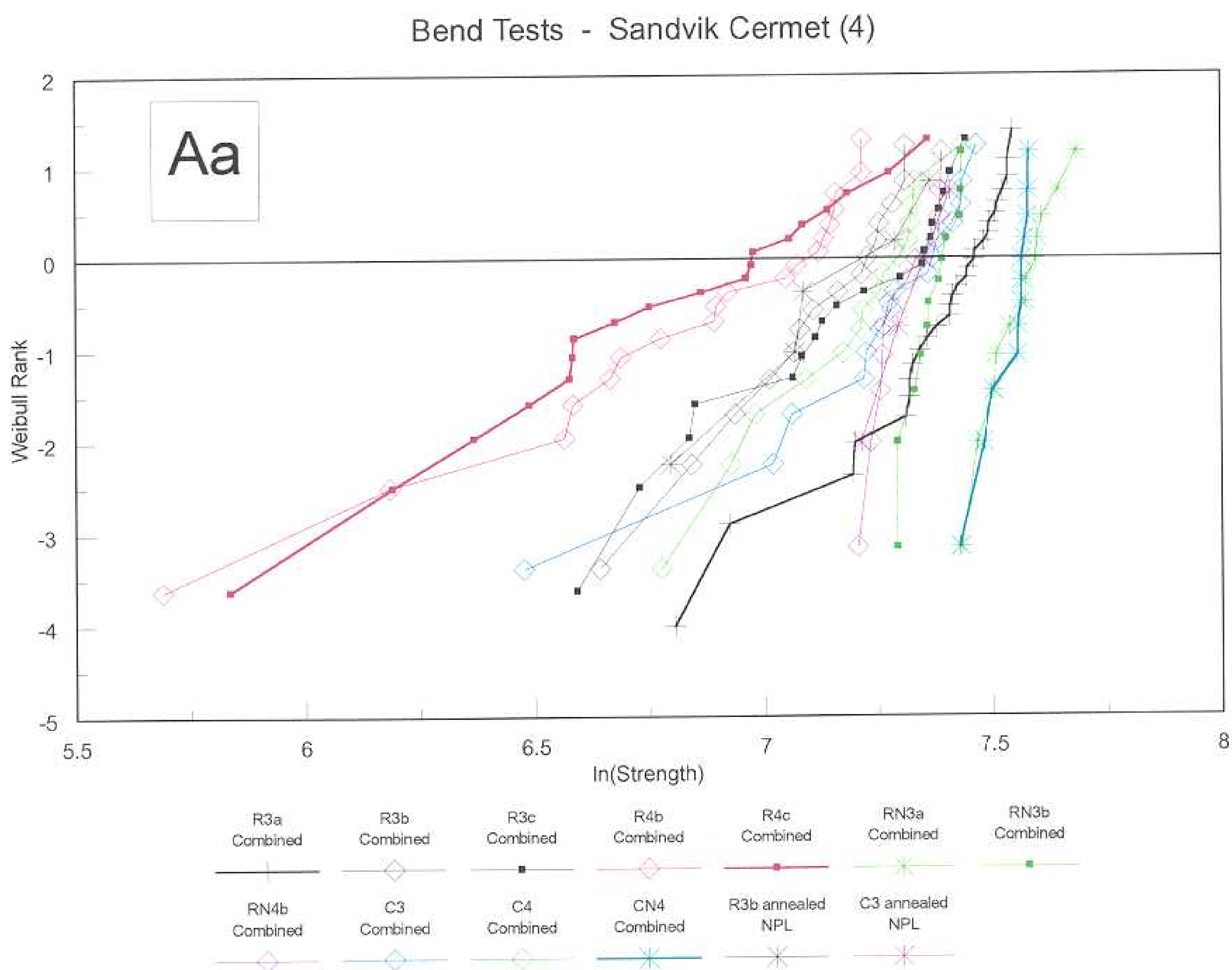
Results Comment Sheet

Sandvik Coromant - Category (5) Ti(C,N) Cermet

PLOT SEQUENCE

A	-	Complete set of all strength values.
Aa	-	Complete set, different laboratories combined.
1	-	Standard tests, ISO type B (R3a).
1a	-	Combined R3a.
2	-	3 pt rectangular tests; R3a, R3b, R3c.
2a	-	Combined R3a, R3b and R3c.
3	-	4 pt rectangular tests, compared with standard ISO type B; R3a, R4b, R4c.
3a	-	Combined R3a, R4b and R4c.
4	-	3 pt vs 4 pt tests; R3b, R3c, R4b, R4c; not including R3a.
4a	-	Combined 3 pt vs 4 pt tests; R3b, R3c, R4b and R4c.
5	-	Round testpieces, compared with standard R3a; (C3, C4 and R3a).
5a	-	Combined C3, C4 and R3a.
6	-	3 pt rectangular and round; R3b, R3c and C3; not including R3a.
6a	-	Combined C3 compared with R3b and R3c combined.
7	-	4 pt rectangular and round, R4b, R4c and C4.
7a	-	Combined C4 compared with R4b and R4c.
8	-	Notched rectangular testpieces; RN3a, RN3b and RN4b.
8a	-	Combined notched testpieces; RN3a, RN3b and RN4b.
9	-	Notched round compared with combined notched rectangular; CN4 and RN3a, RB3b and RN4b.
9a	-	Combined notched round compared with combined notched rectangular; CN4 and RN3a, RN3b and RN4b.


Bend Tests - Sandvik Cermet (4)
A
Weibull Rank
2
1
0
-1
-2
-3
-4
5.5
6
6.5
7
7.5
8
ln(Strength)
R3a Kennametal
R3a CERMeP
R3b NPL
R3b Sandvik
R3c NPL
R3c BAM
R4b NPL
R4b Sandvik
R4c NPL
R4c BAM
RN3a NPL
RN3a Sandvik
RN3b NPL
RN3b BAM
RN4b NPL
RN4b Sandvik
C3 NPL
C3 BAM
C4 NPL
C4 Sandvik
CN4 NPL
CN4 BAM
CN4 sandvk
R3b annealed NPL
C3 annealed NPL

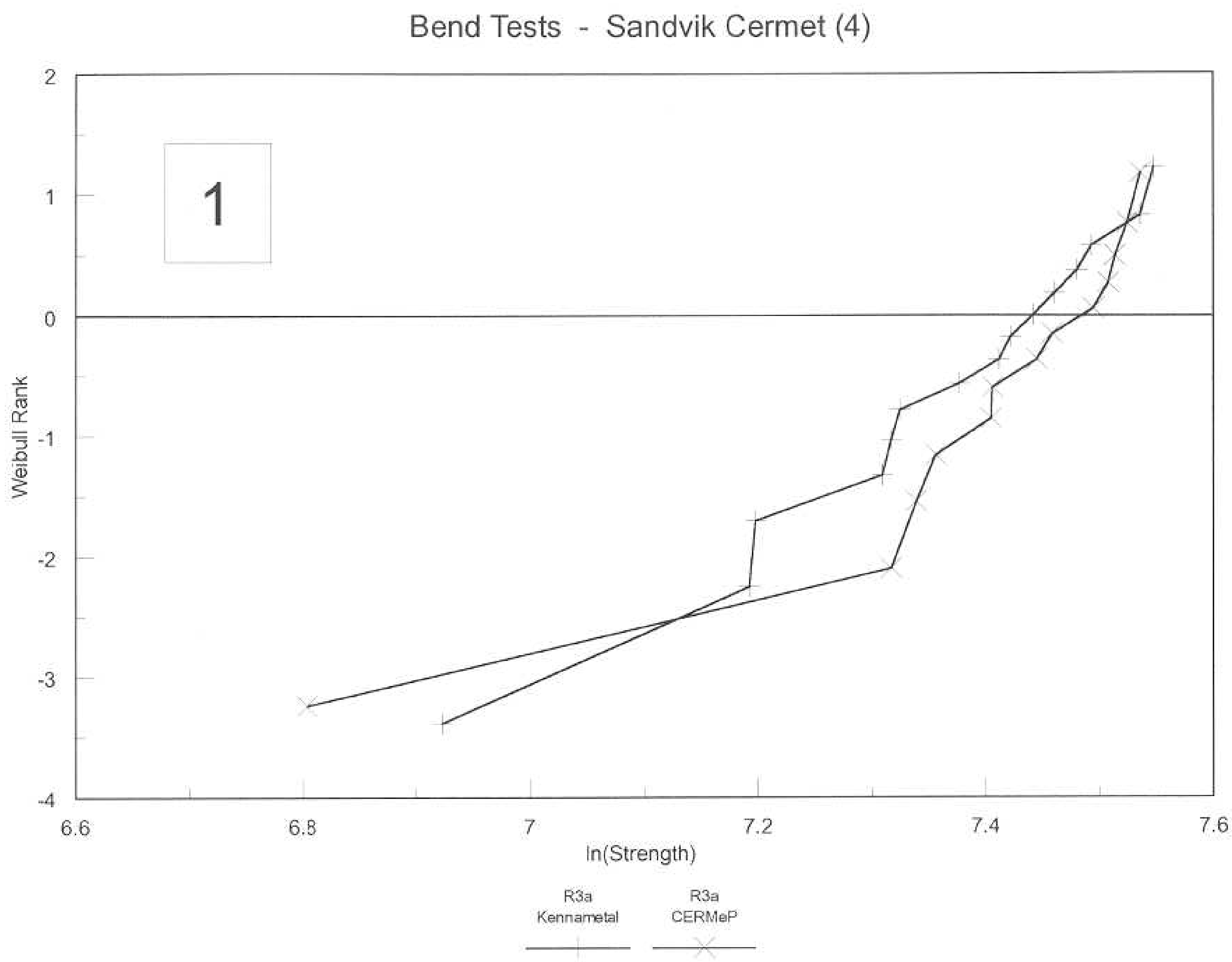


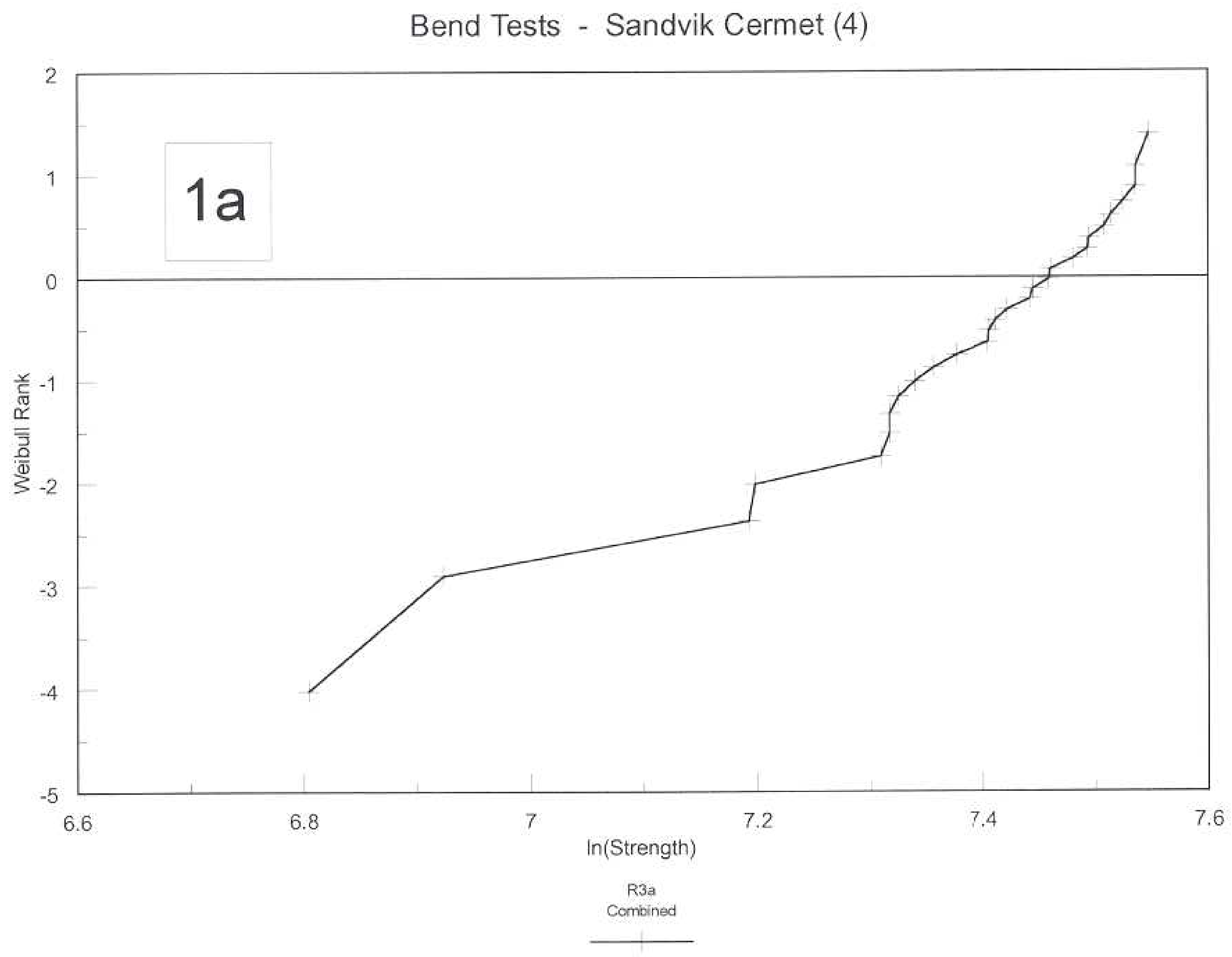
Bend Tests - Sandvik Cermet (4)
Aa
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
5.5
6
6.5
7
7.5
8
ln(Strength)
R3a Combined
R3b Combined
R3c Combined
R4b Combined
R4c Combined
RN3a Combined
RN3b Combined
RN4b Combined
C3 Combined
C4 Combined
CN4 Combined
R3b annealed NPL
C3 annealed NPL

WEIBULL RESULTS SET

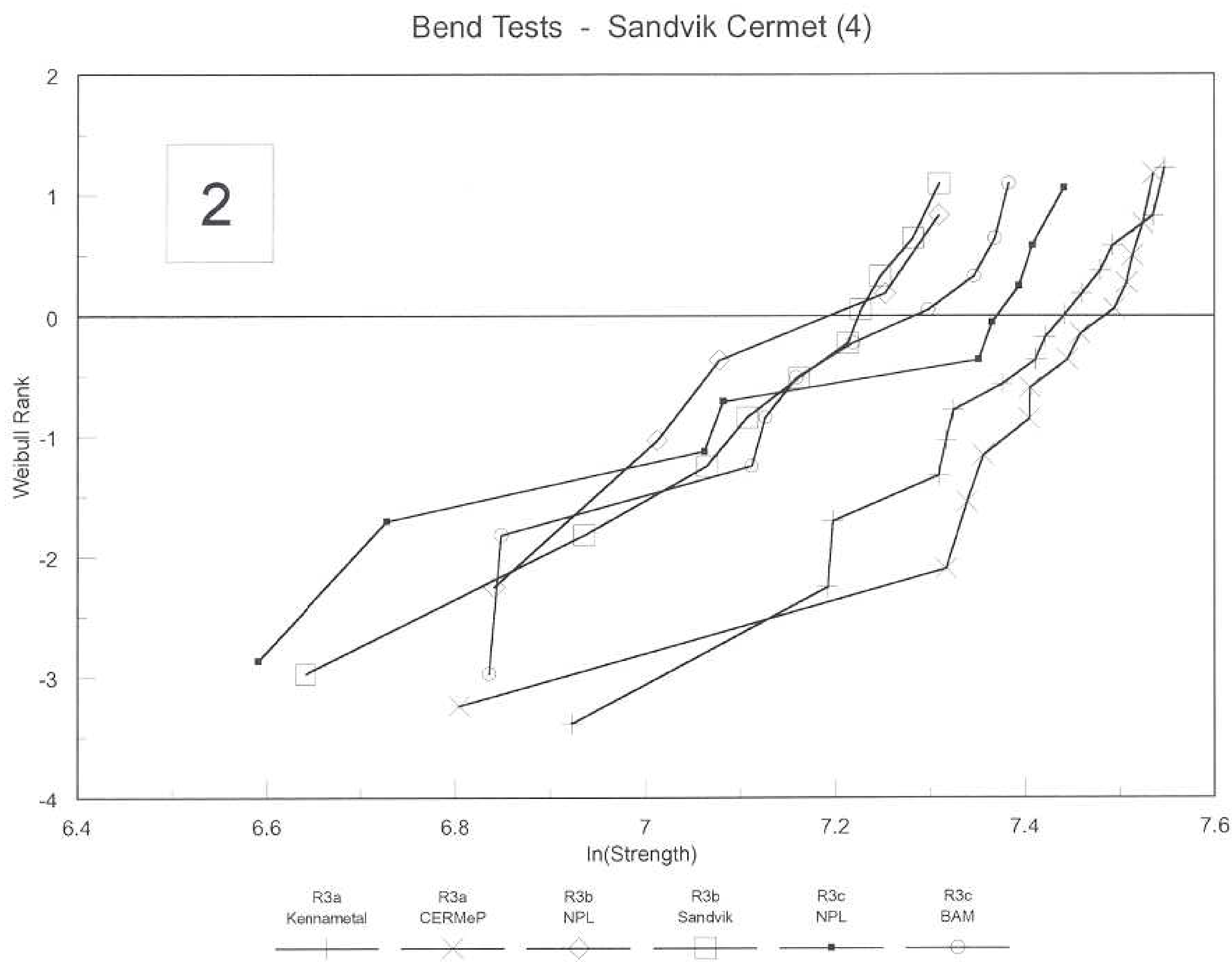
(5) SANDVIK COROMANT

Ti(C,N) Cermet

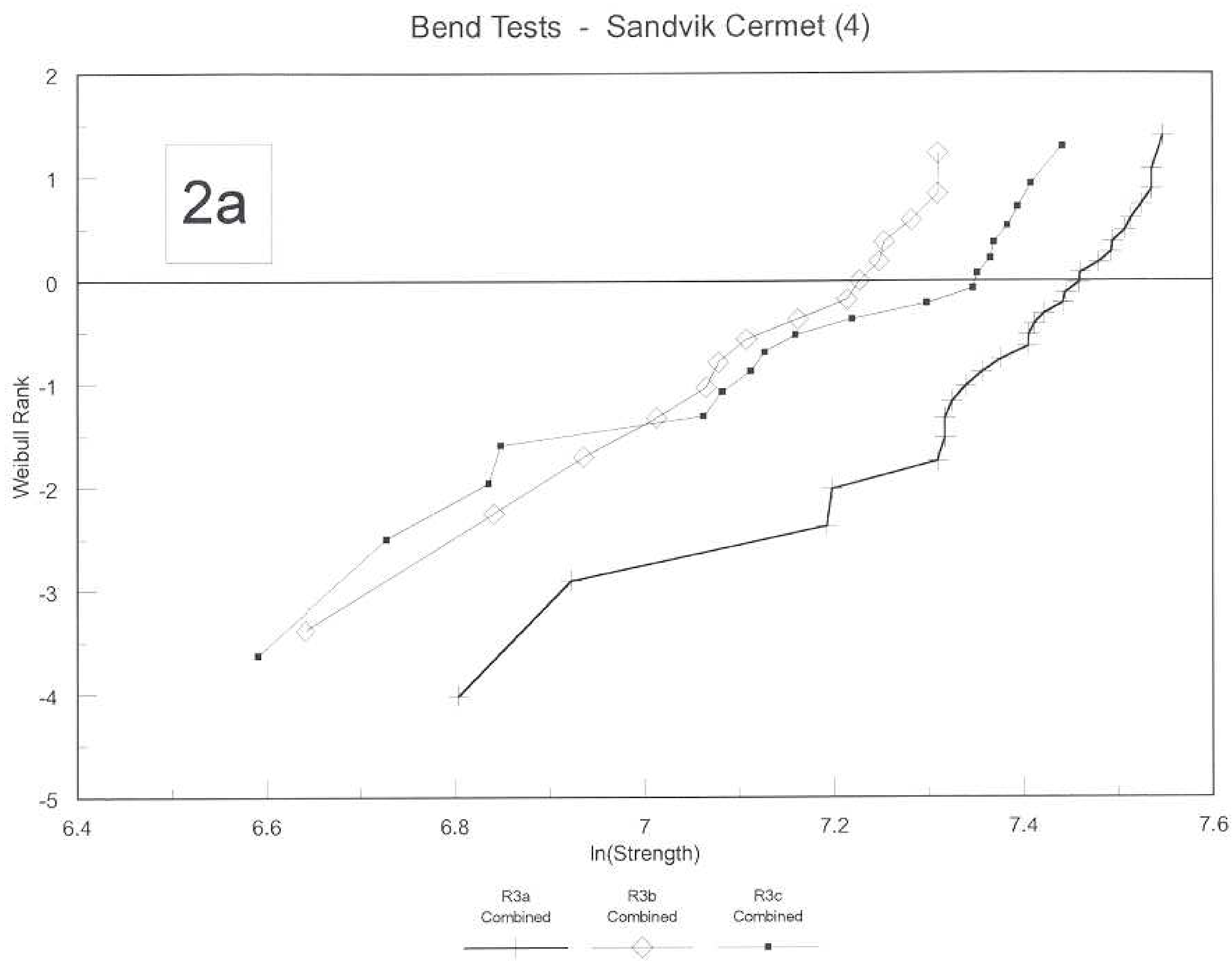

Bend Tests - Sandvik Cermet (4)
1
Weibull Rank
2
1
0
-1
-2
-3
-4
6.6
6.8
7
7.2
7.4
7.6
ln(Strength)
R3a Kennametal
R3a CERMeP

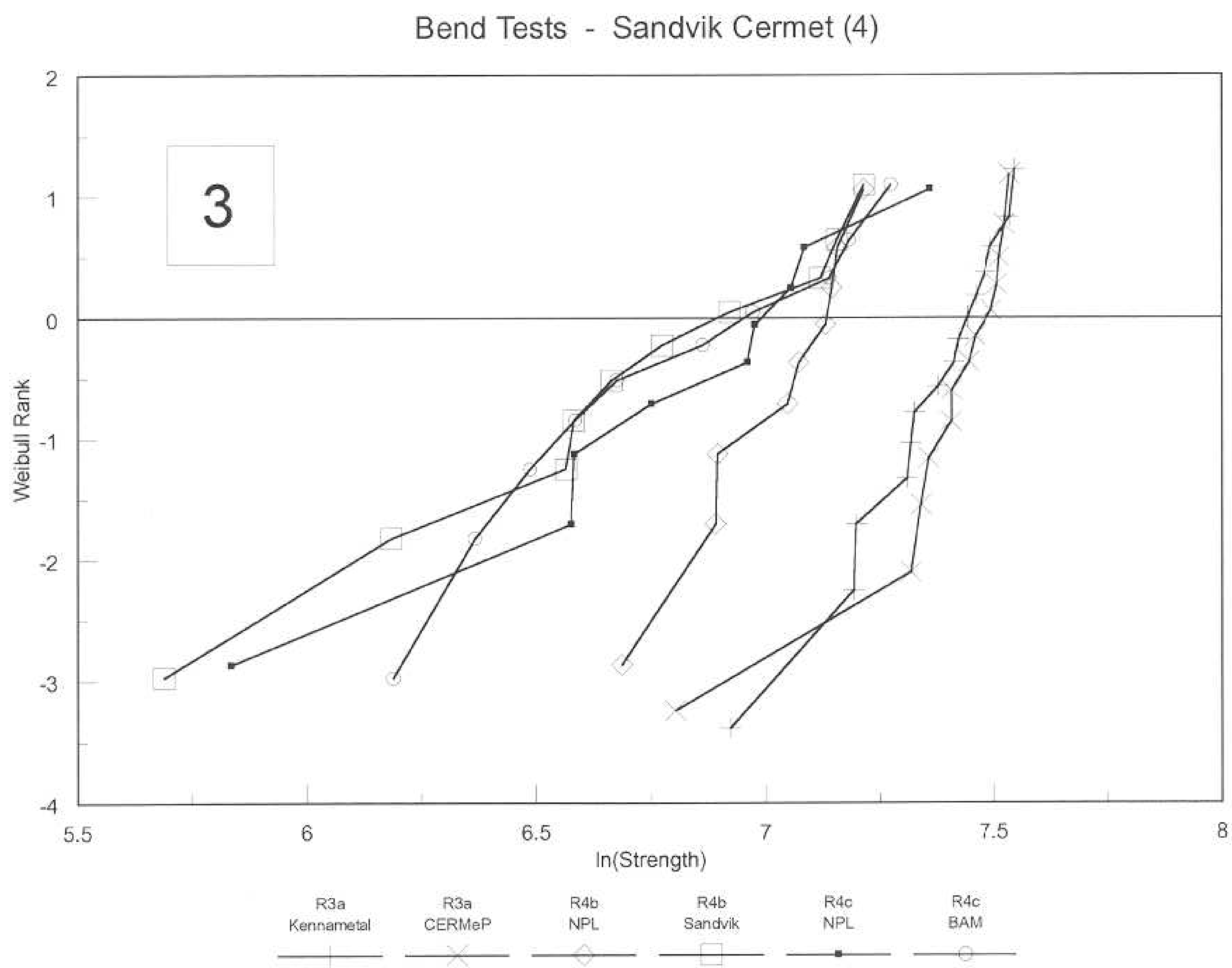


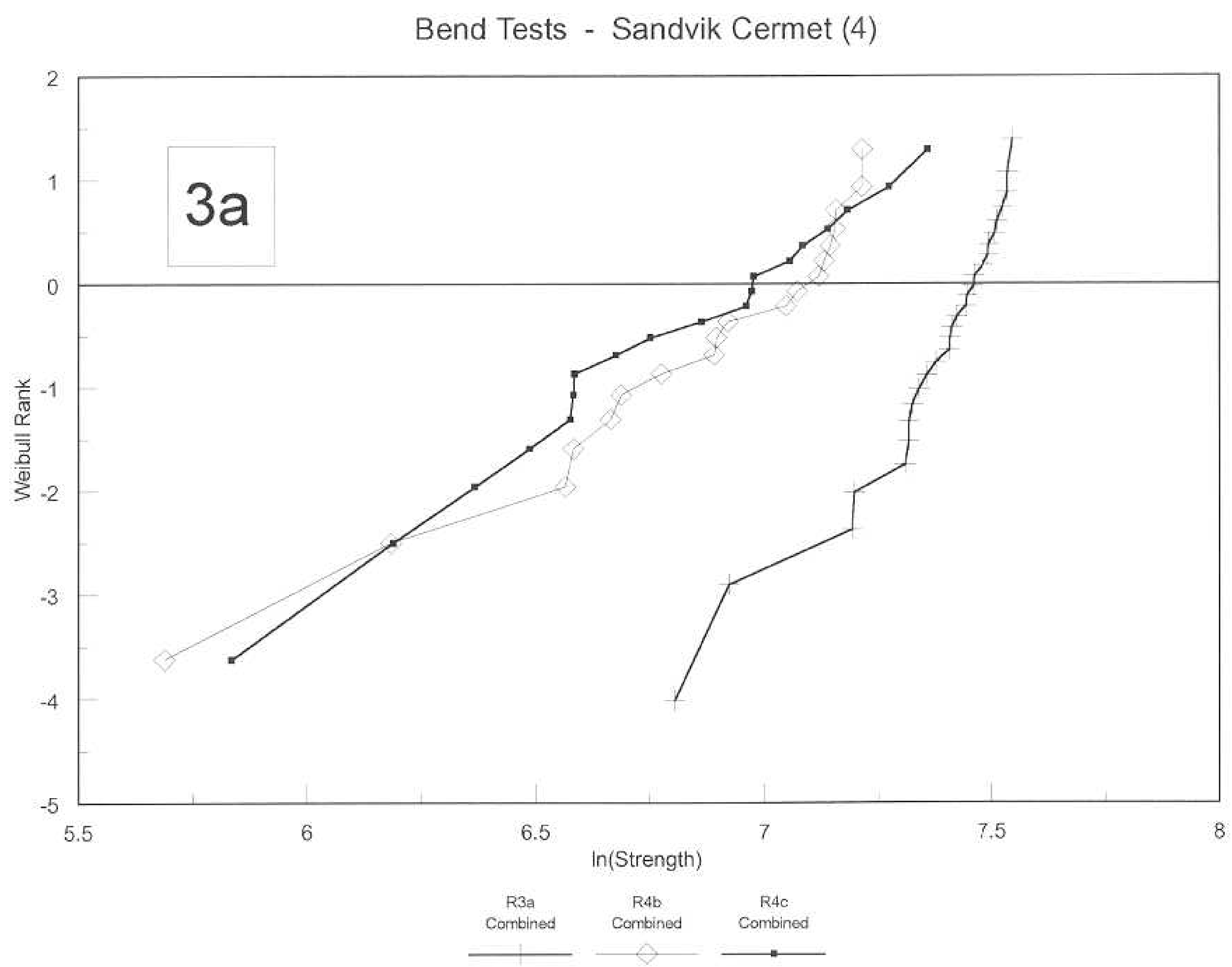
Bend Tests - Sandvik Cermet (4)
1a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
6.6
6.8
7
7.2
7.4
7.6
ln(Strength)
R3a
Combined

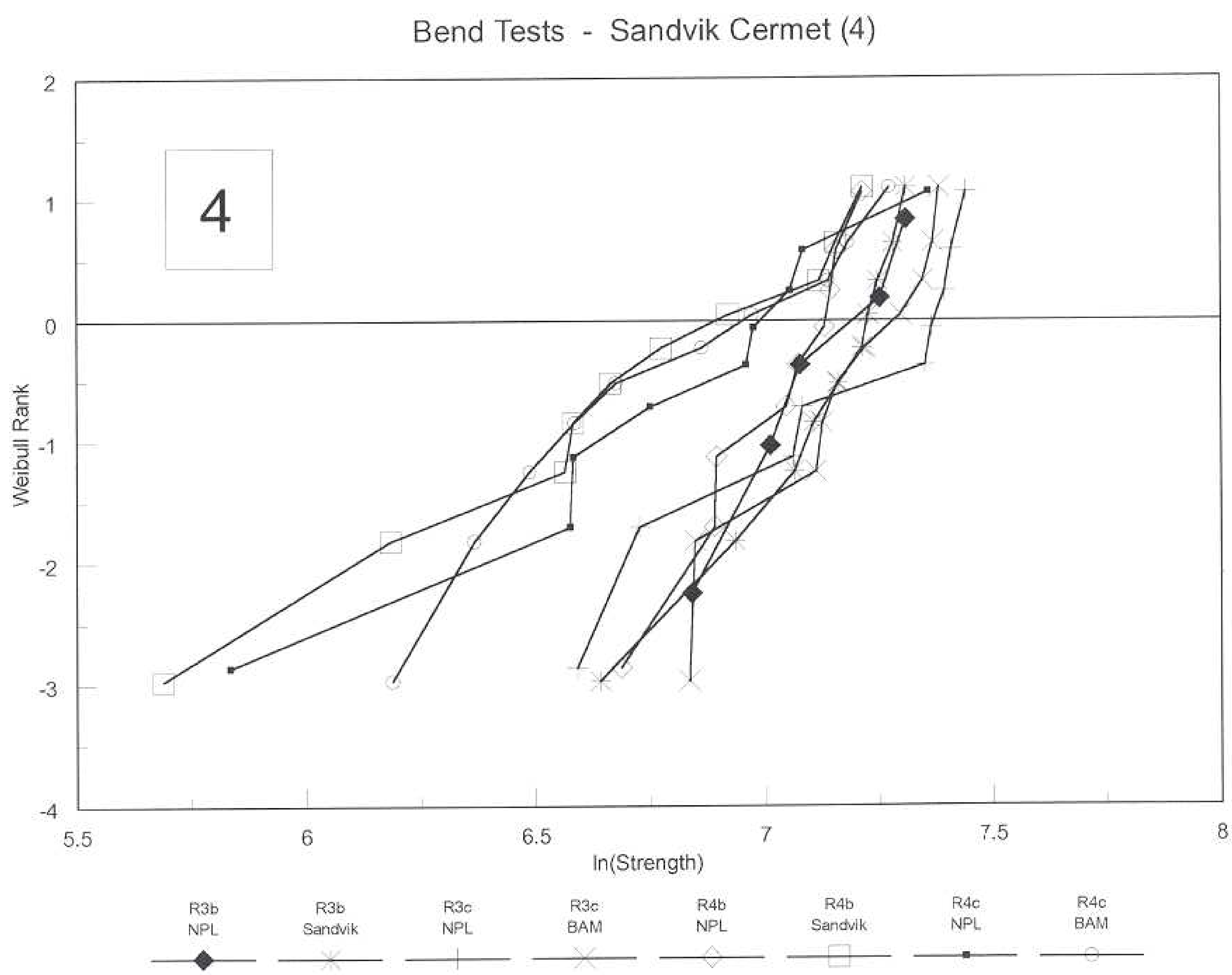


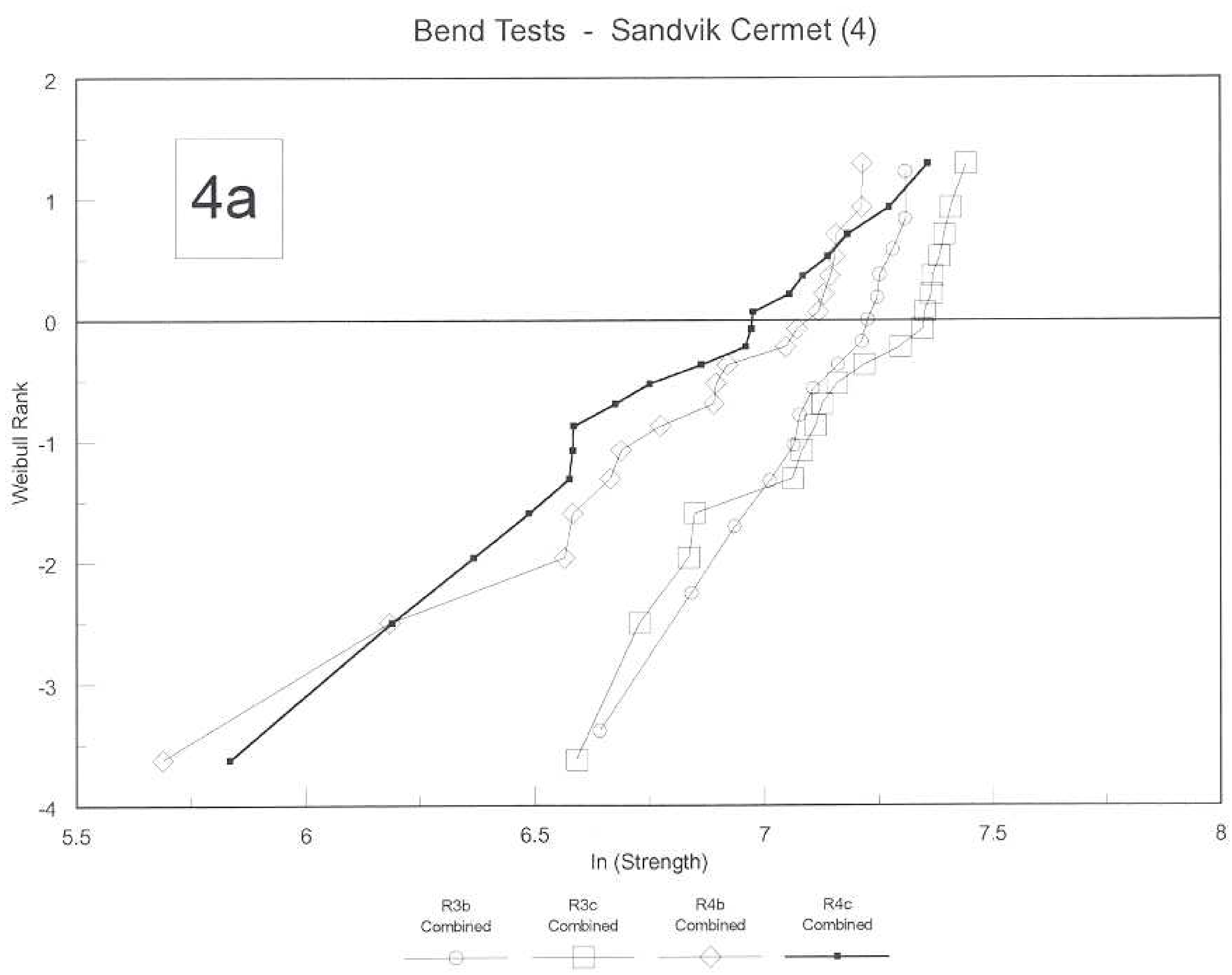
Bend Tests - Sandvik Cermet (4)
2
Weibull Rank
2
1
0
-1
-2
-3
-4
6.4
6.6
6.8
7
7.2
7.4
7.6
ln(Strength)
R3a Kennametal
R3a CERMeP
R3b NPL
R3b Sandvik
R3c NPL
R3c BAM


Bend Tests - Sandvik Cermet (4)
2a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
6.4
6.6
6.8
7
7.2
7.4
7.6
ln(Strength)
R3a Combined
R3b Combined
R3c Combined

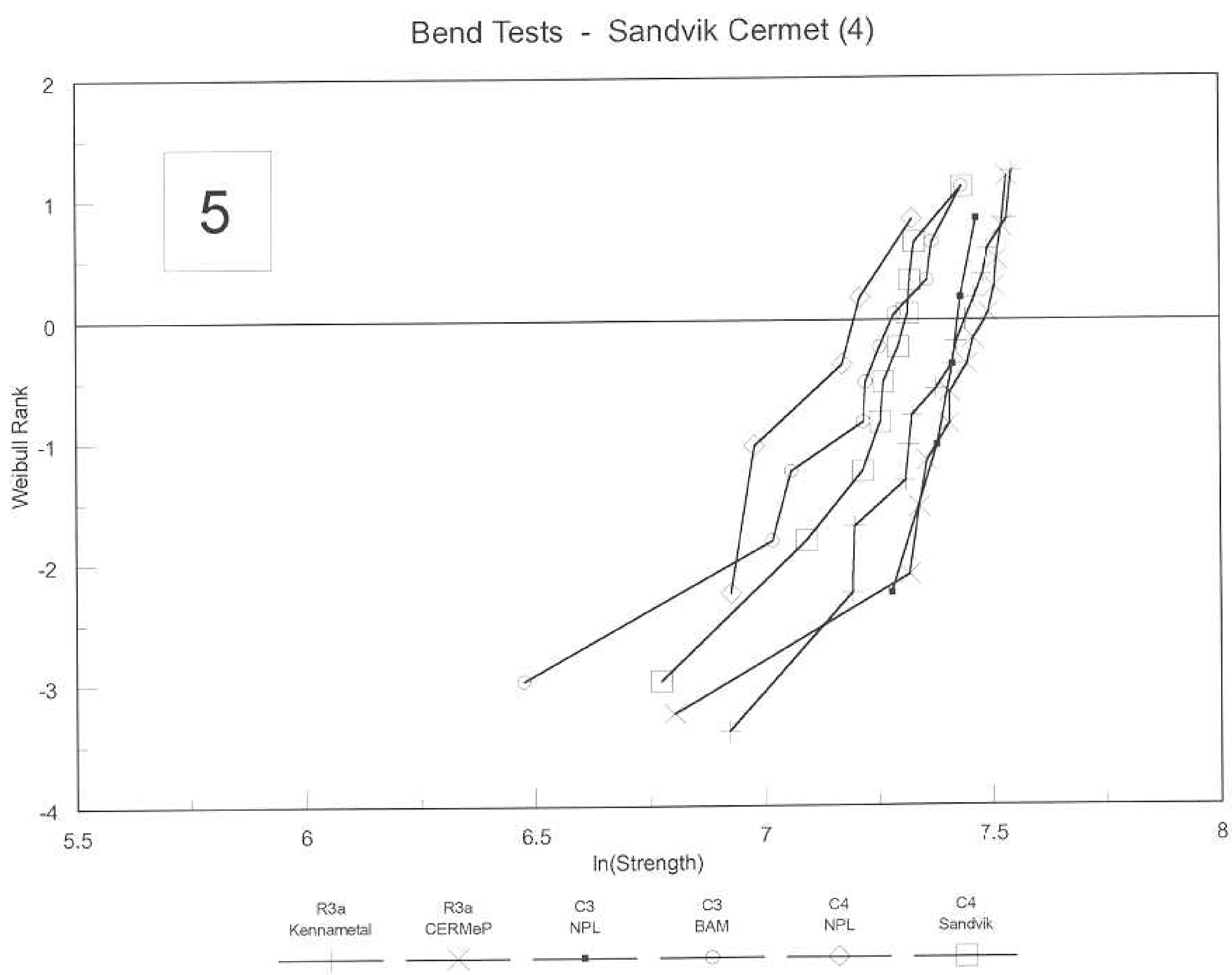

Bend Tests - Sandvik Cermet (4)
3
Weibull Rank
2
1
0
-1
-2
-3
-4
5.5
6
6.5
7
7.5
8
ln(Strength)
R3a Kennametal
R3a CERMeP
R4b NPL
R4b Sandvik
R4c NPL
R4c BAM

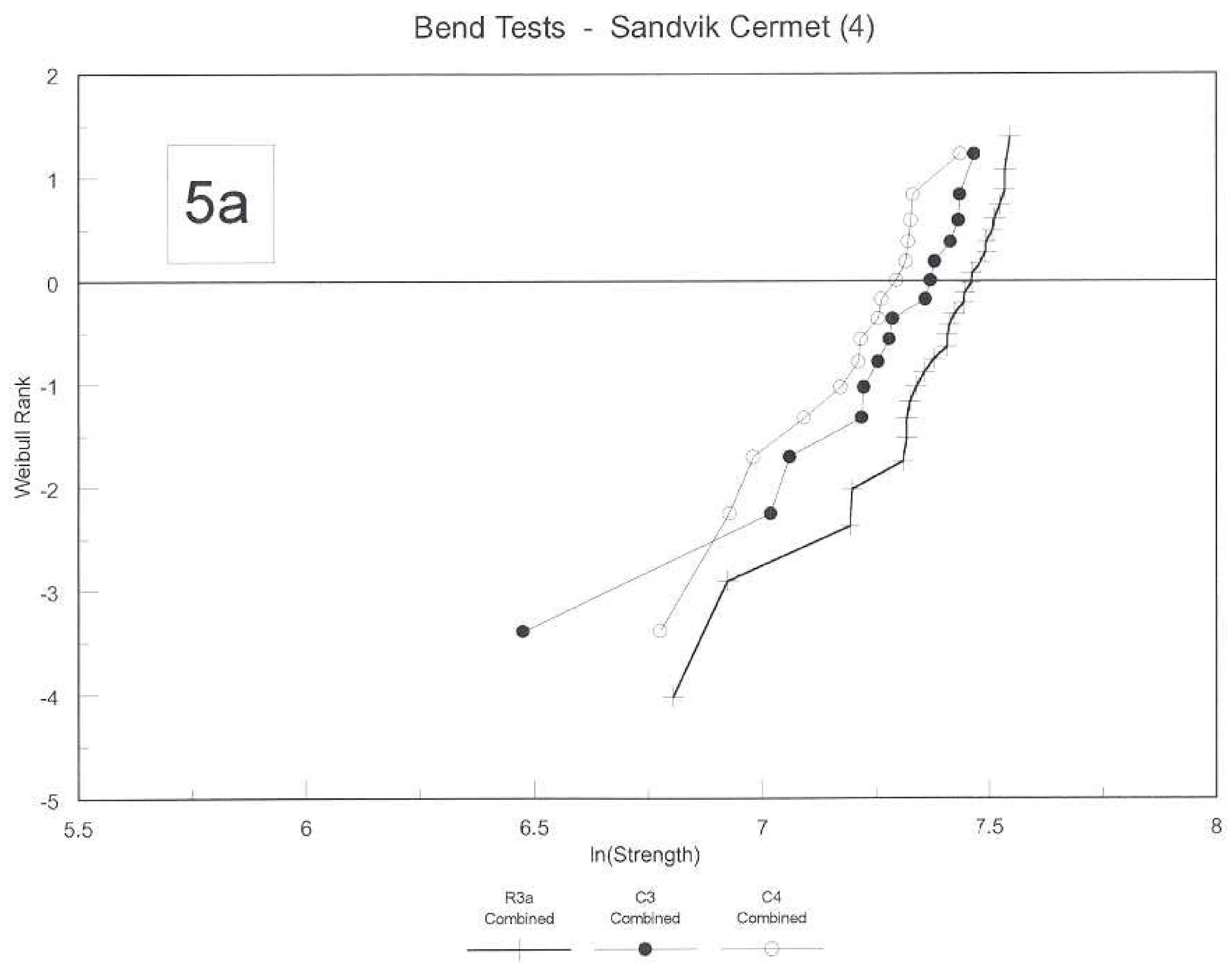

Bend Tests - Sandvik Cermet (4)
3a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
5.5
6
6.5
7
7.5
8
ln(Strength)
R3a Combined
R4b Combined
R4c Combined


Bend Tests - Sandvik Cermet (4)
4
Weibull Rank
2
1
0
-1
-2
-3
-4
5.5
6
6.5
7
7.5
8
ln(Strength)
R3b NPL
R3b Sandvik
R3c NPL
R3c BAM
R4b NPL
R4b Sandvik
R4c NPL
R4c BAM



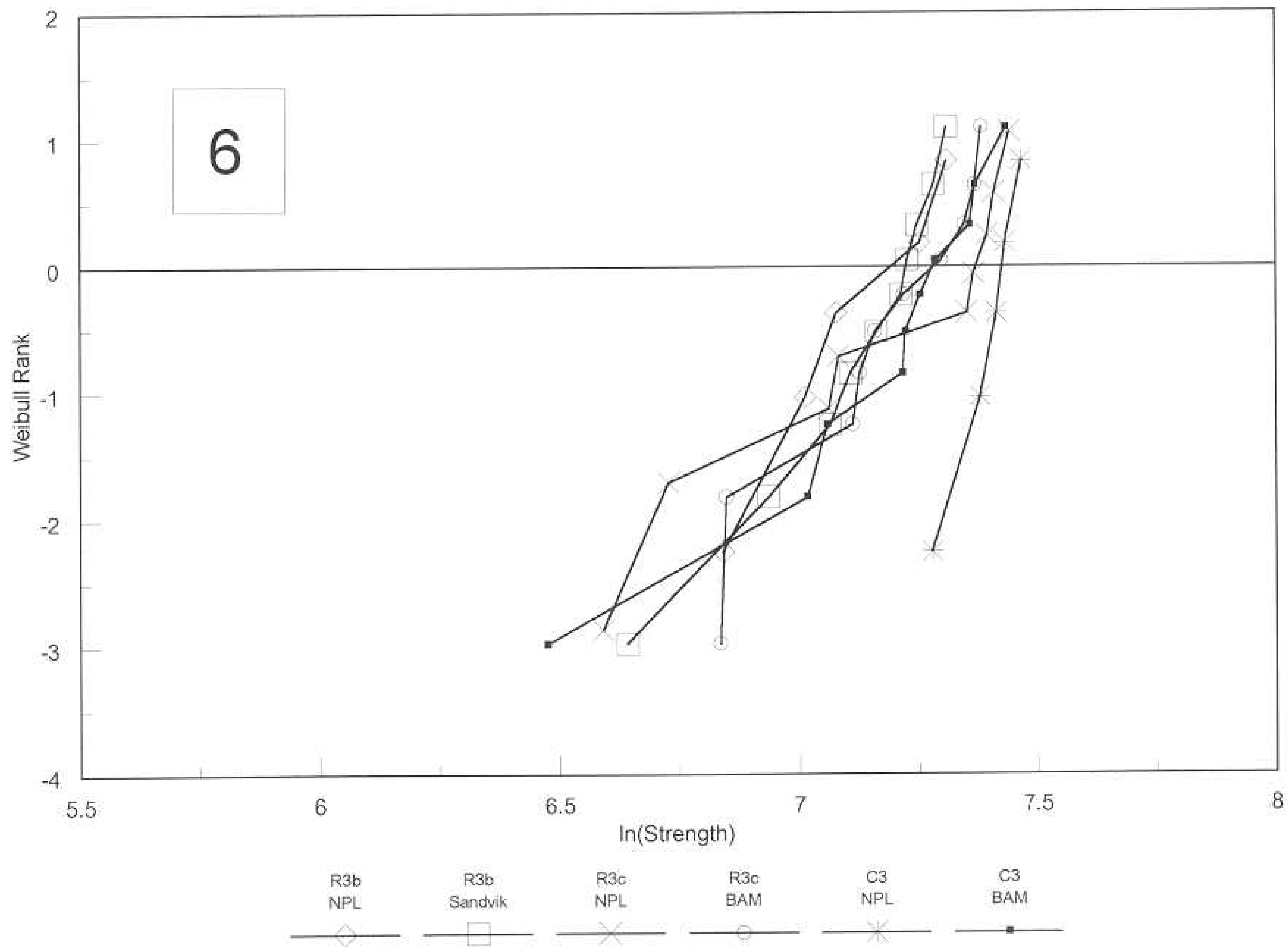
Bend Tests - Sandvik Cermet (4)
4a
Weibull Rank
2
1
0
-1
-2
-3
-4
5.5
6
6.5
7
7.5
8
ln (Strength)
R3b Combined
R3c Combined
R4b Combined
R4c Combined


Bend Tests - Sandvik Cermet (4)
5
Weibull Rank
2
1
0
-1
-2
-3
-4
5.5
6
6.5
7
7.5
8
ln(Strength)
R3a Kennametal
R3a CERMeP
C3 NPL
C3 BAM
C4 NPL
C4 Sandvik

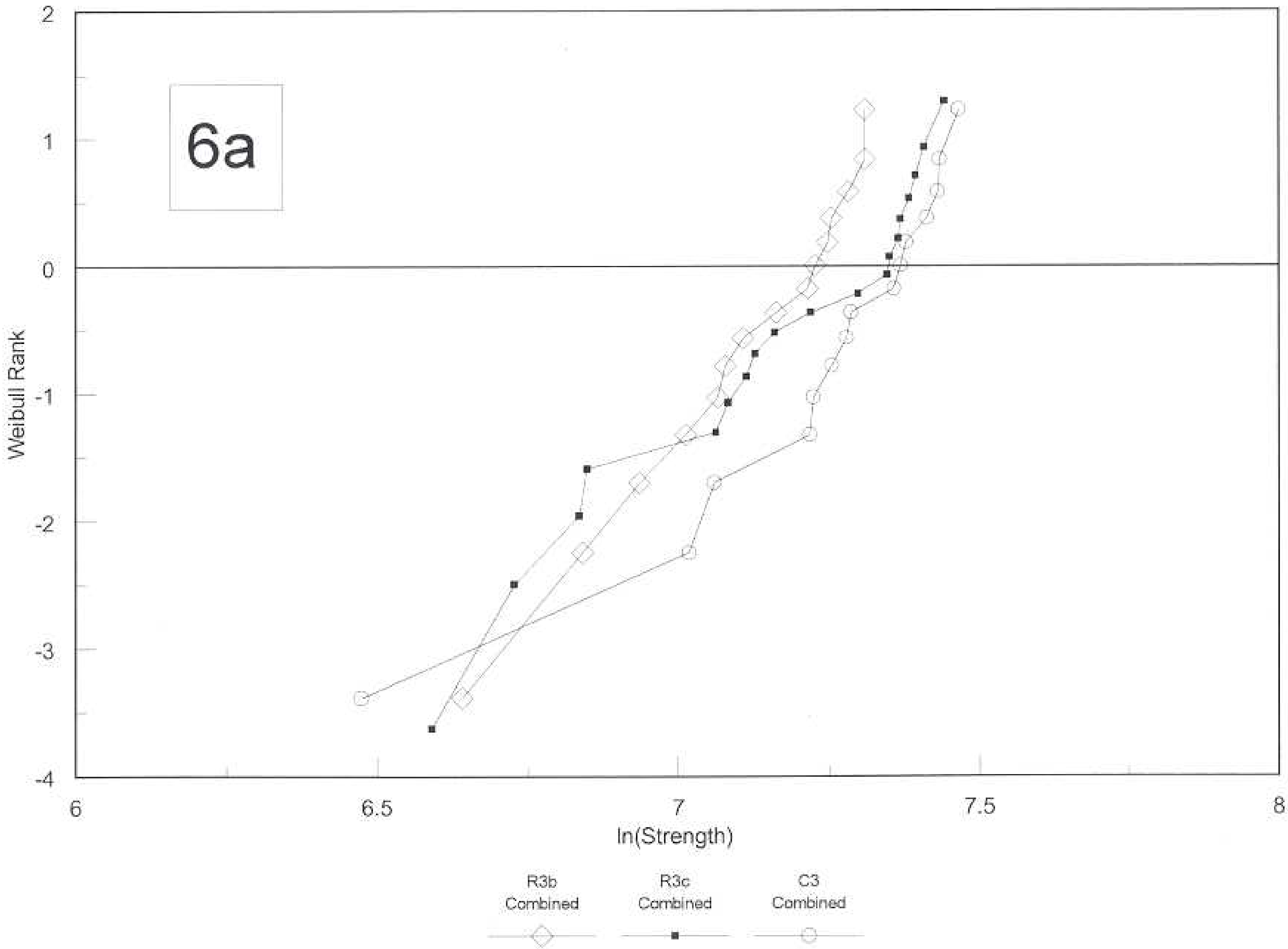


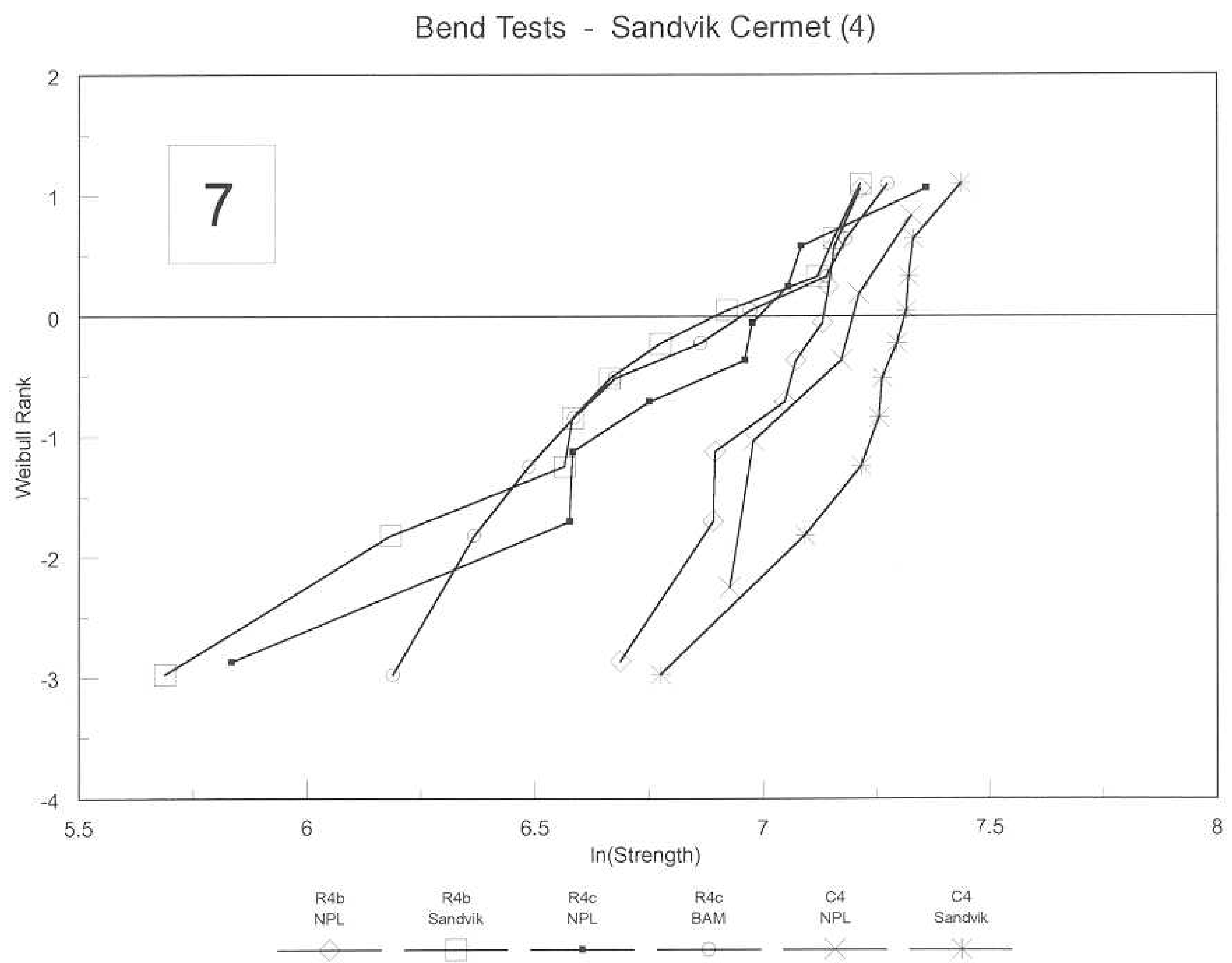
Bend Tests - Sandvik Cermet (4)
5a
Weibull Rank
2
1
0
-1
-2
-3
-4
-5
5.5
6
6.5
7
7.5
8
ln(Strength)
R3a Combined
C3 Combined
C4 Combined

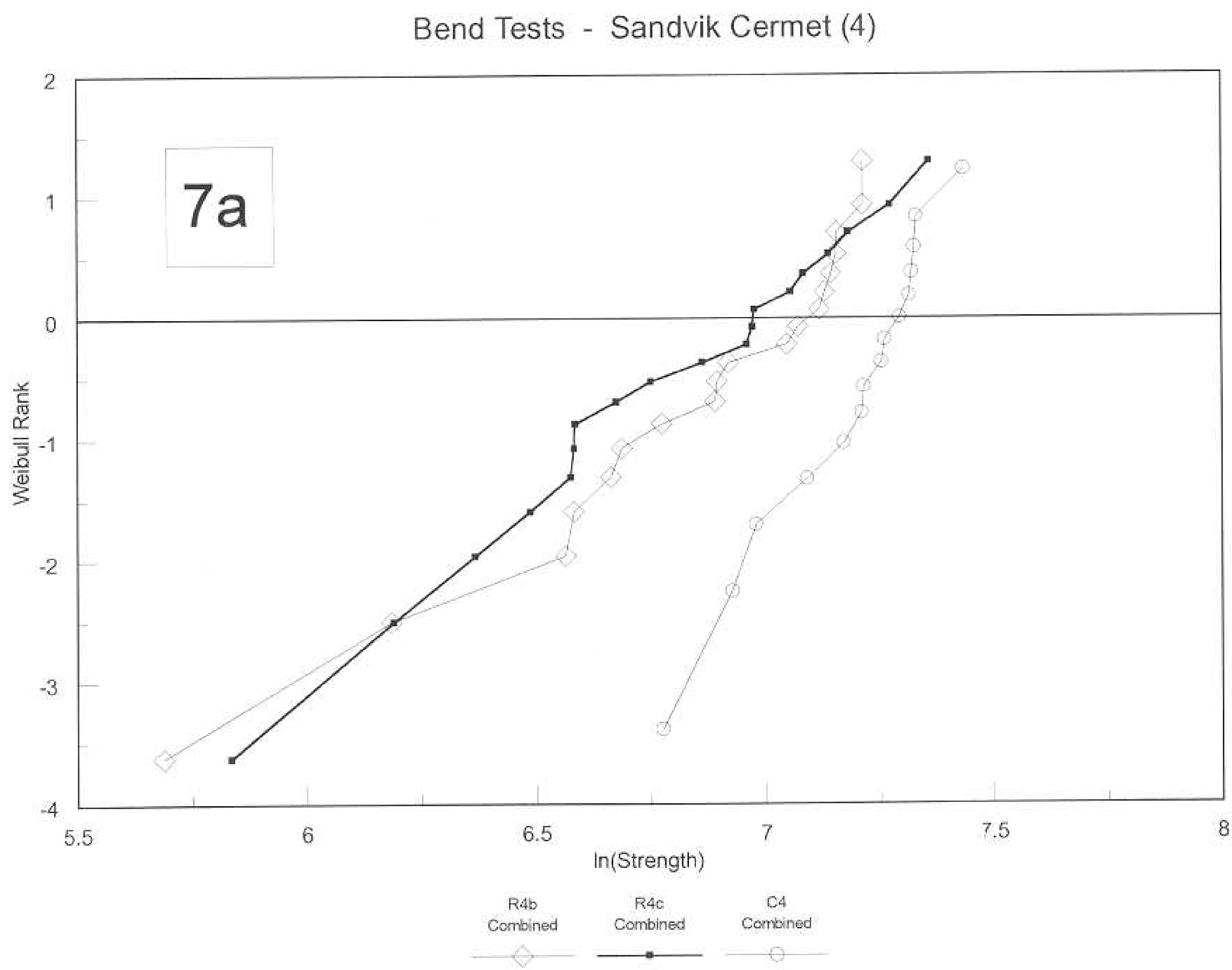
Bend Tests - Sandvik Cermet (4)

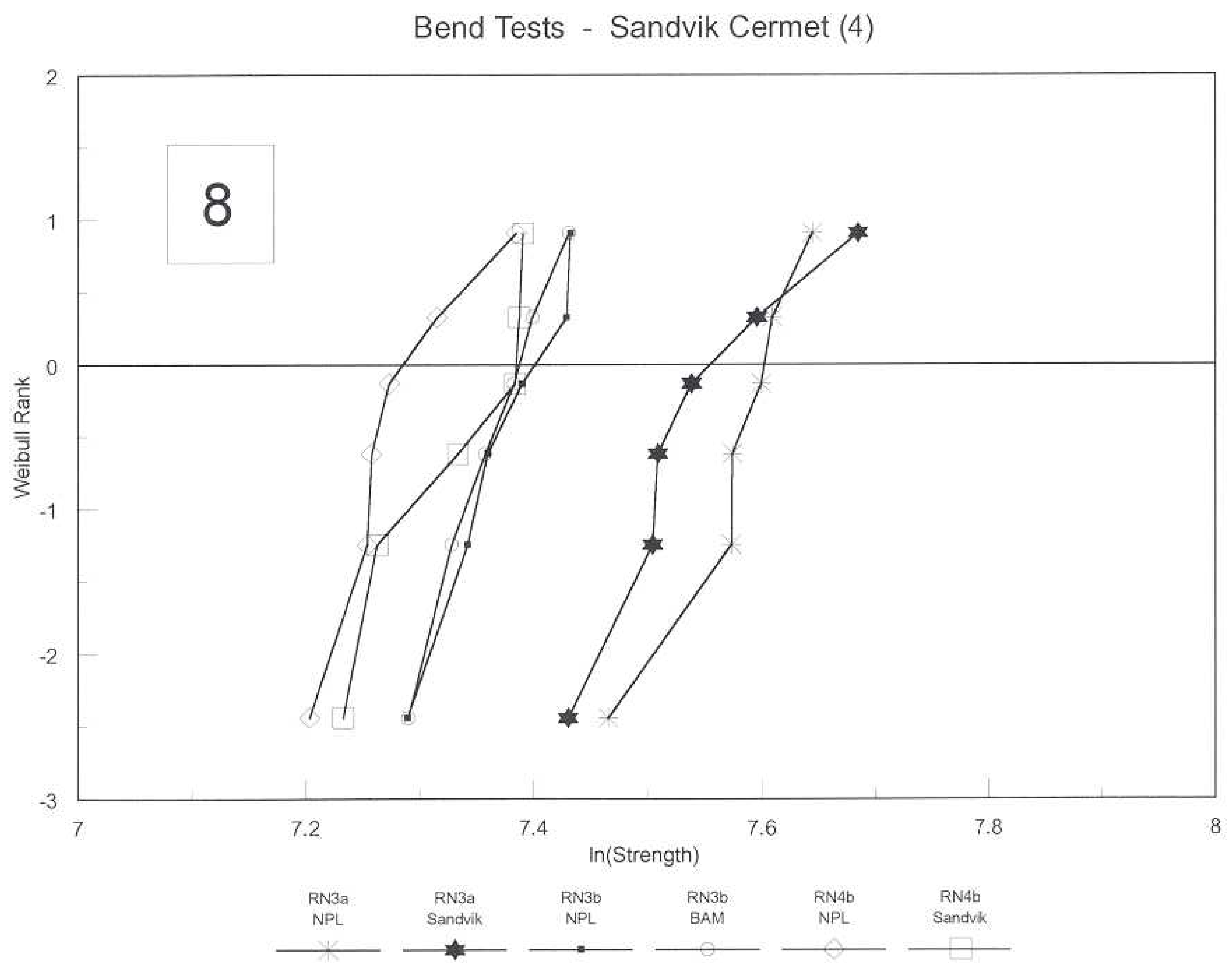


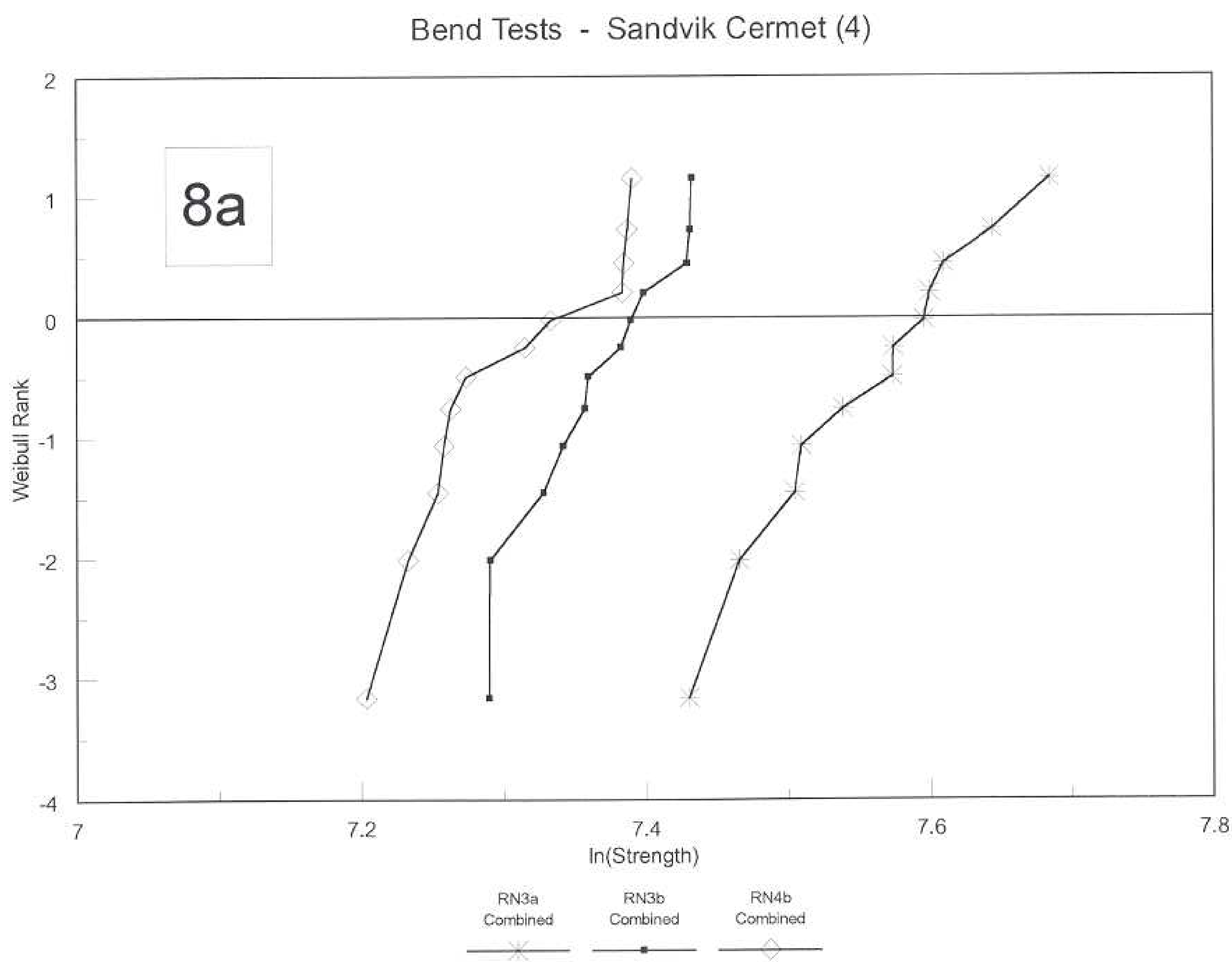
Bend Tests - Sandvik Cermet (4)



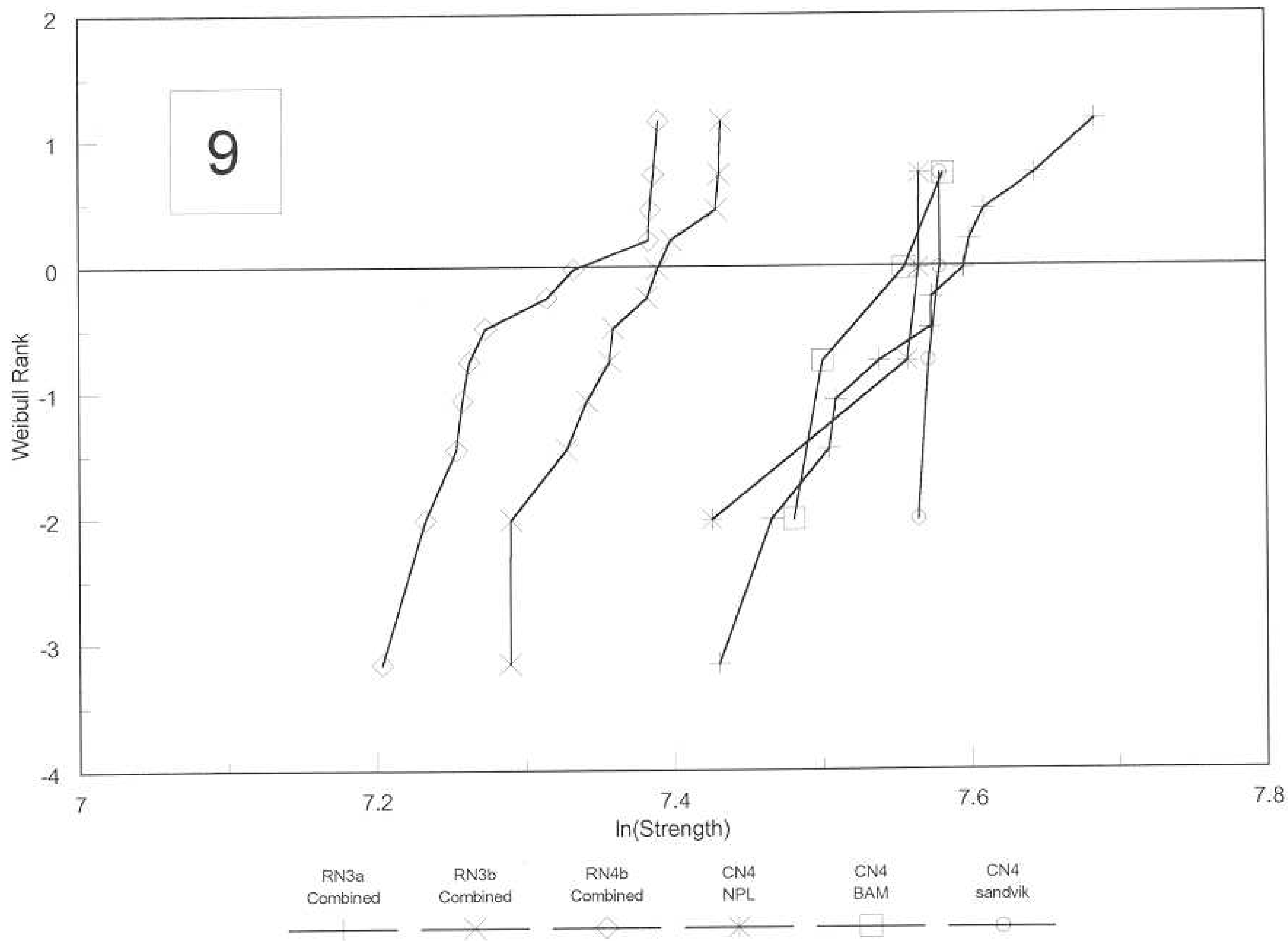

Bend Tests - Sandvik Cermet (4)
7
Weibull Rank
2
1
0
-1
-2
-3
-4
5.5
6
6.5
7
7.5
8
ln(Strength)
R4b NPL
R4b Sandvik
R4c NPL
R4c BAM
C4 NPL
C4 Sandvik

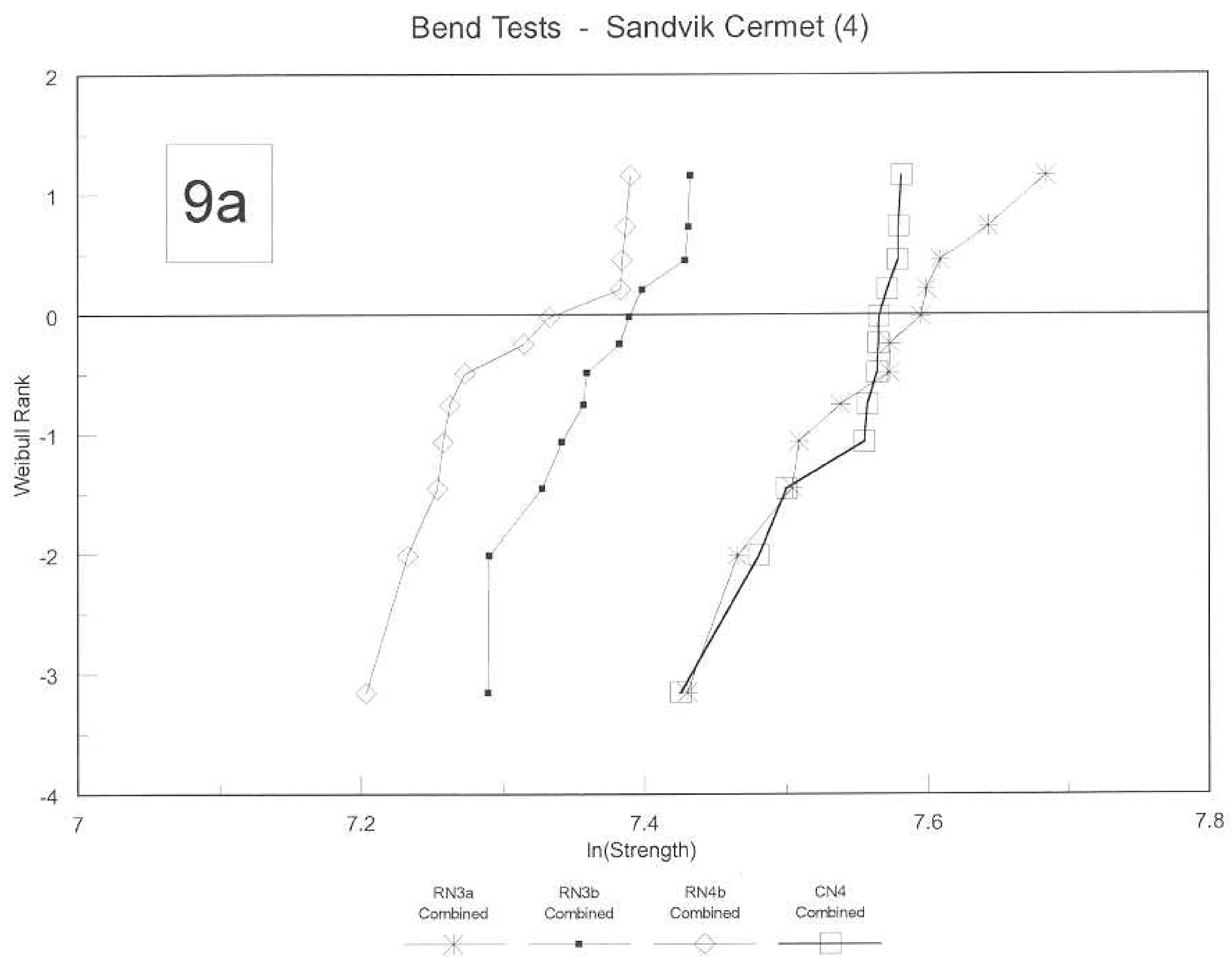

Bend Tests - Sandvik Cermet (4)
7a
Weibull Rank
2
1
0
-1
-2
-3
-4
5.5
6
6.5
7
7.5
8
ln(Strength)
R4b Combined
R4c Combined
C4 Combined


Bend Tests - Sandvik Cermet (4)
8
2
1
0
-1
-2
-3
Weibull Rank
7
7.2
7.4
7.6
7.8
8
ln(Strength)
RN3a NPL
RN3a Sandvik
RN3b NPL
RN3b BAM
RN4b NPL
RN4b Sandvik


Bend Tests - Sandvik Cermet (4)
8a
Weibull Rank
2
1
0
-1
-2
-3
-4
7
7.2
7.4
7.6
7.8
ln(Strength)
RN3a Combined
RN3b Combined
RN4b Combined

Bend Tests - Sandvik Cermet (4)





Bend Tests - Sandvik Cermet (4)
9a
Weibull Rank
2
1
0
-1
-2
-3
-4
7
7.2
7.4
7.6
7.8
ln(Strength)
RN3a Combined
RN3b Combined
RN4b Combined
CN4 Combined

WEIBULL RESULTS SET

(6) SANDVIK COROMANT

Medium/Coarse, WC/Co

HARDMETAL BEND TESTS

Results Comment Sheet

Sandvik Coromant - Category (6) Med/Coarse WC/Co Hardmetal

PLOT SEQUENCE

A - Complete set of all strength values.

Aa - Complete set, different laboratories combined.

1 - Standard tests, ISO type B (R3a).

1a - Combined R3a.

2 - 3 pt rectangular tests; R3a, R3b, R3c.

2a - Combined R3a, R3b and R3c.

3 - 4 pt rectangular tests, compared with standard ISO type B; R3a, R4b, R4c.

3a - Combined R3a, R4b and R4c.

4 - 3 pt vs 4 pt tests; R3b, R3c, R4b, R4c; not including R3a.

4a - Combined R3b, R3c, R4b and R4c.

5 - Round testpieces, compared with standard R3a, C3, C4 and R3a.

5a - Combined C3, C4 and R3a.

6 - 3 pt rectangular and round; R3b, R3c and C3; not including R3a.

6a - Combined C3 compared with R3b and R3c combined.

7 - 4 pt rectangular and round R4b, R4c and C4.

7a - Combined C4 compared with R4b and R4c.

8 - Notched rectangular testpieces, RN3a, RN3b and RN4b.

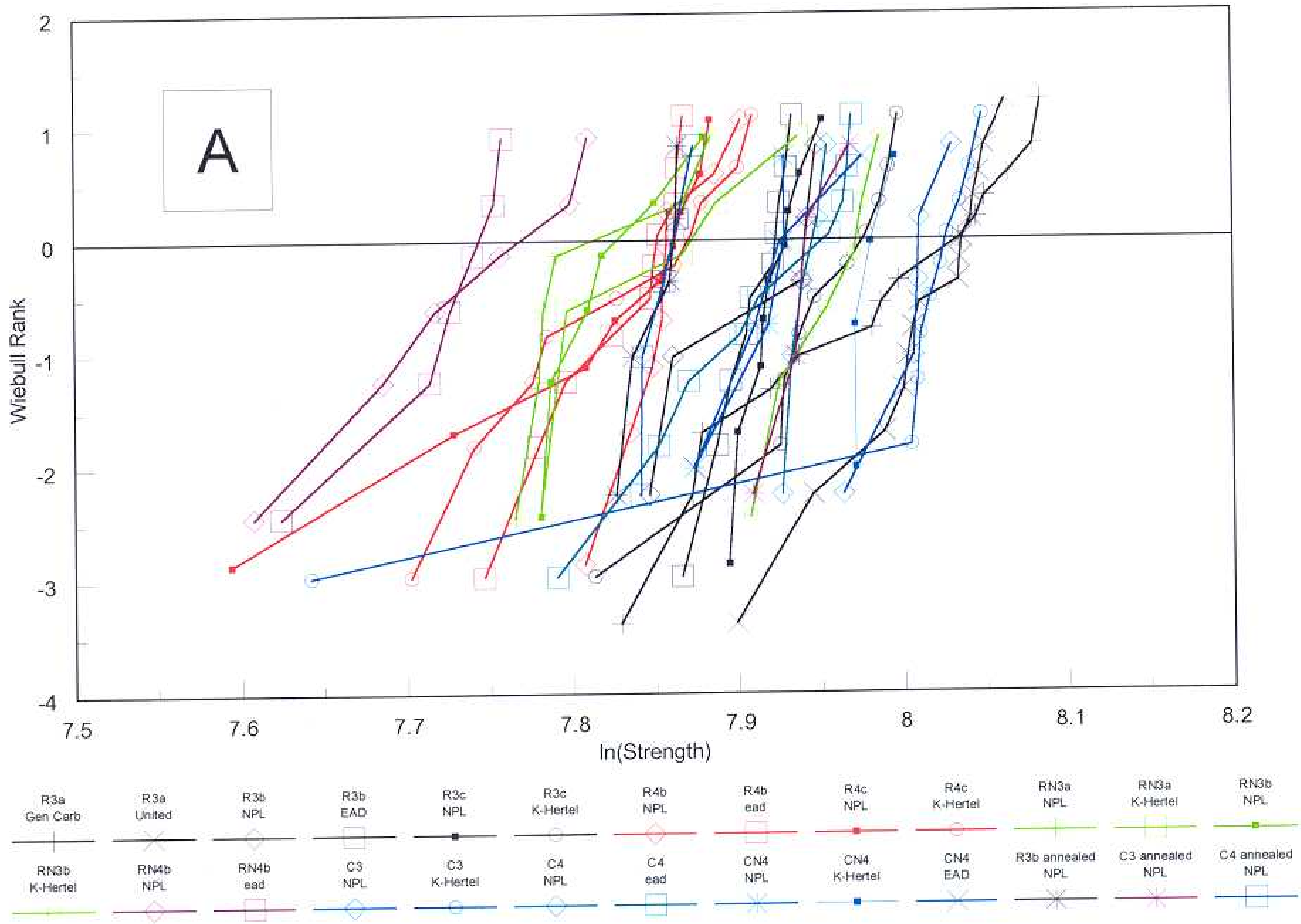
8a - Combined notched testpieces; RN3a, RN3b and RN4b.

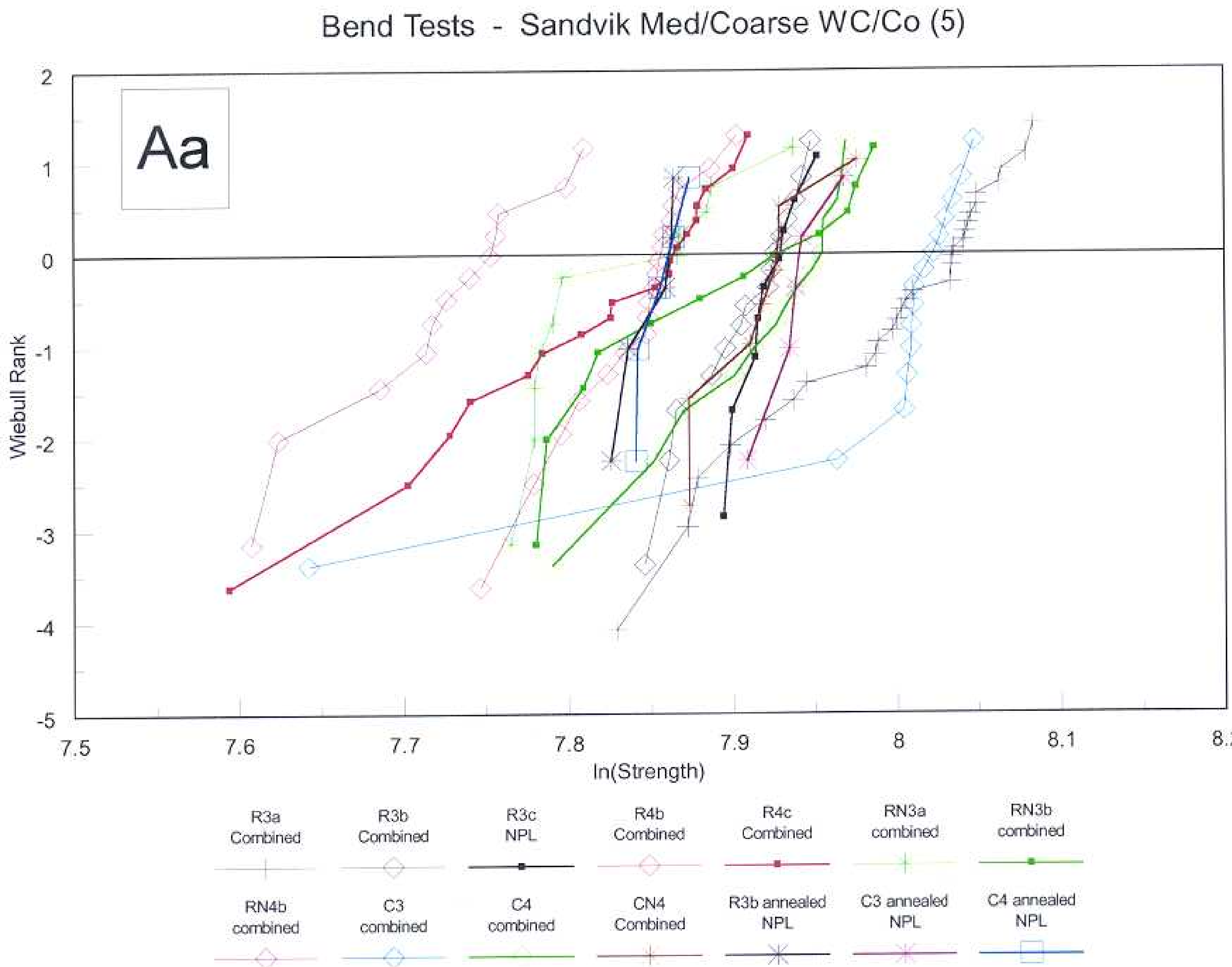
9 - Notched round compared with combined notched rectangular; CN4 and RN3a, RB3b and RN4b.

9a - Combined notched round compared with combined notched rectangular; CN4 and RN3a, RN3b and RN4b.

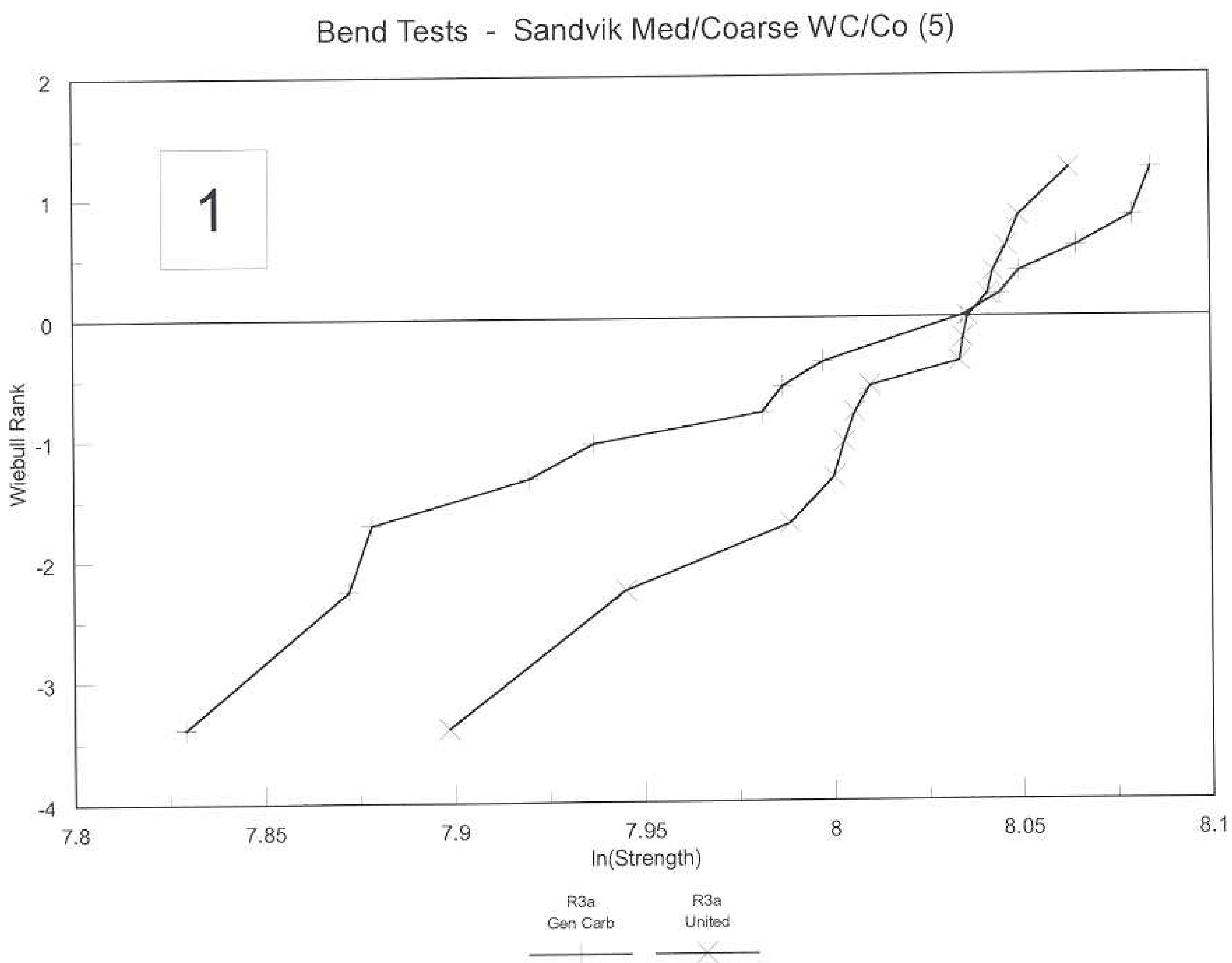
*NB *There was good agreement between laboratories except for the R3c, CN4 and RN3b K-Hertel results which were high. These have been excluded from the combined plots.*

Bend Tests - Sandvik Med/Coarse WC/Co (5)

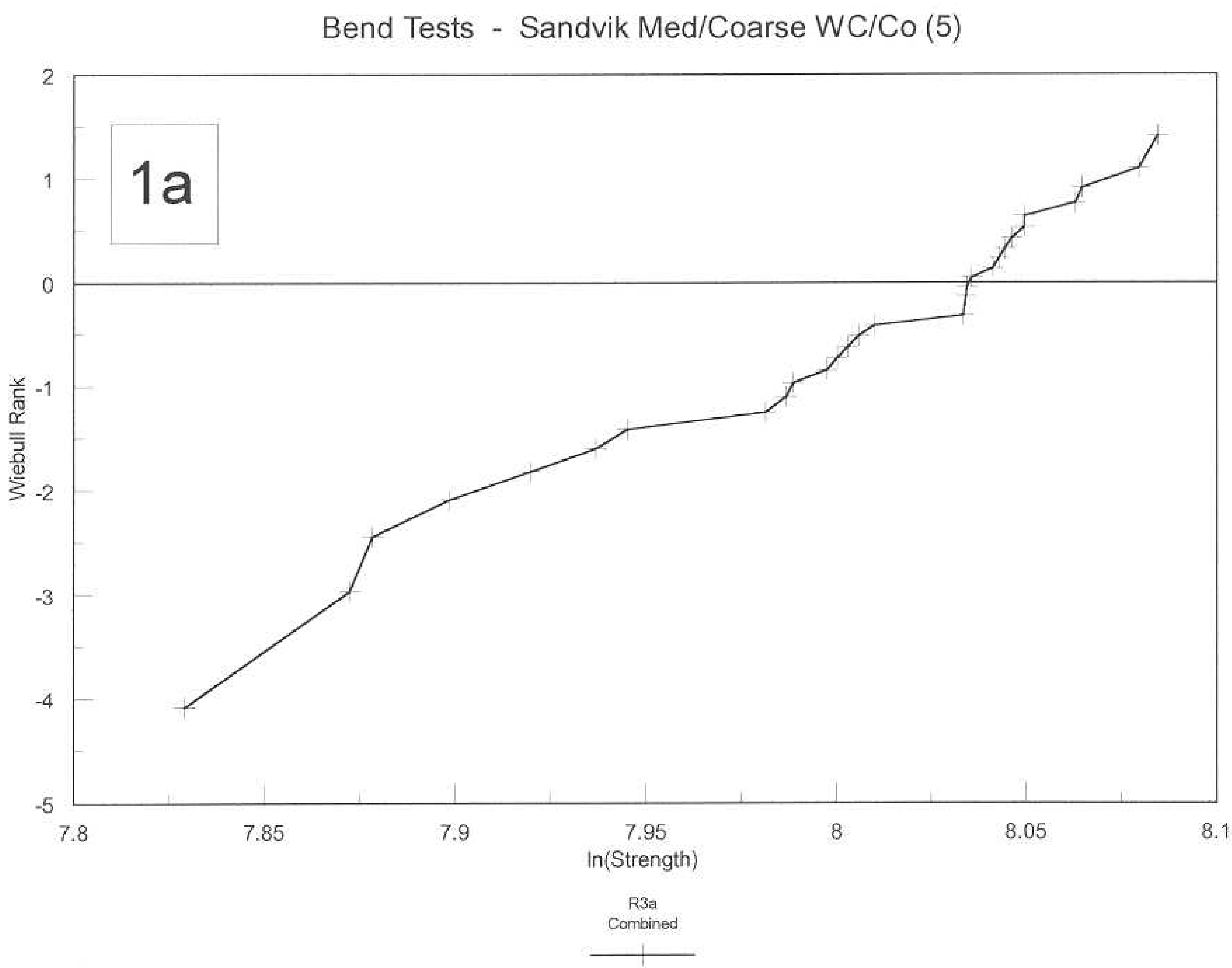


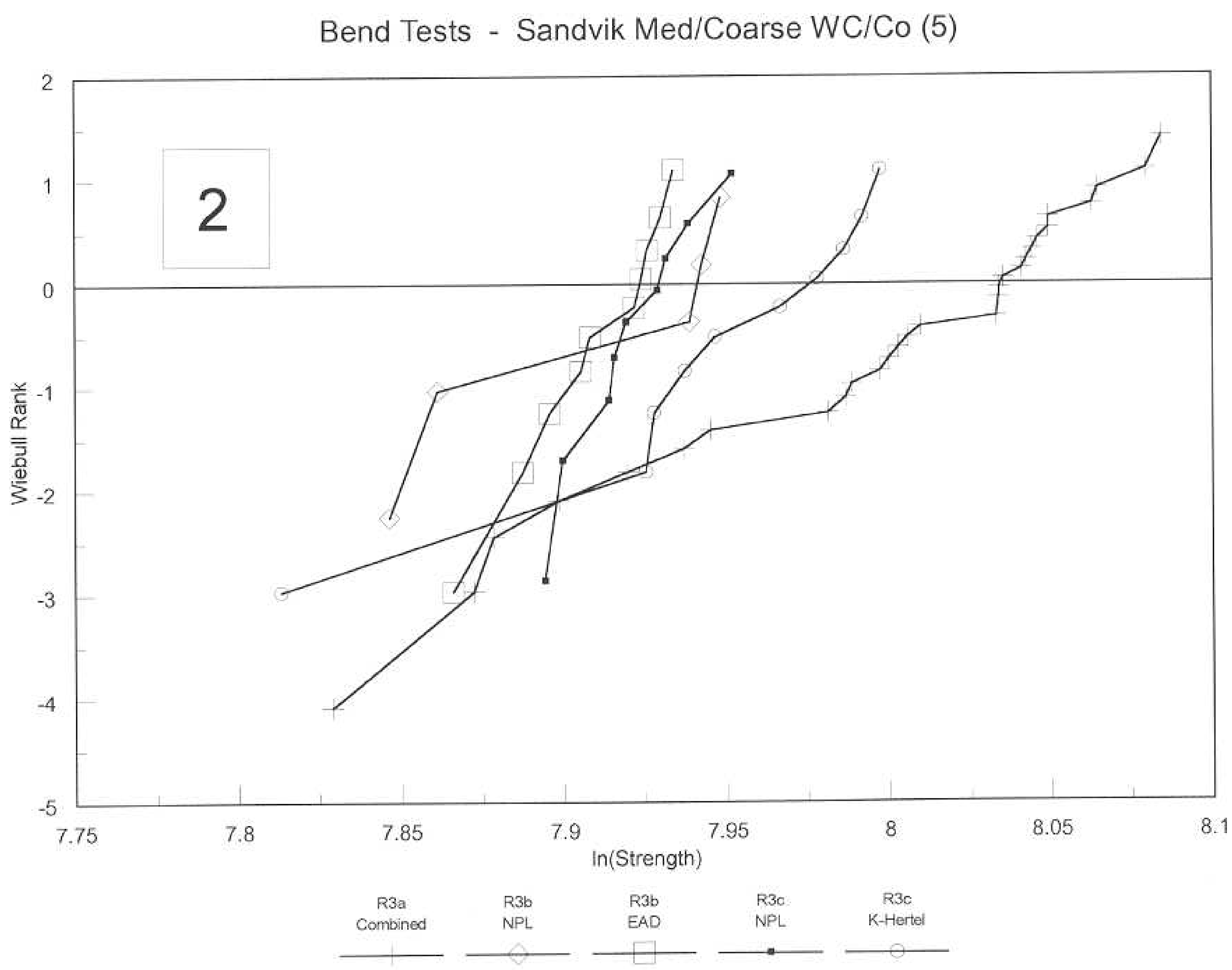


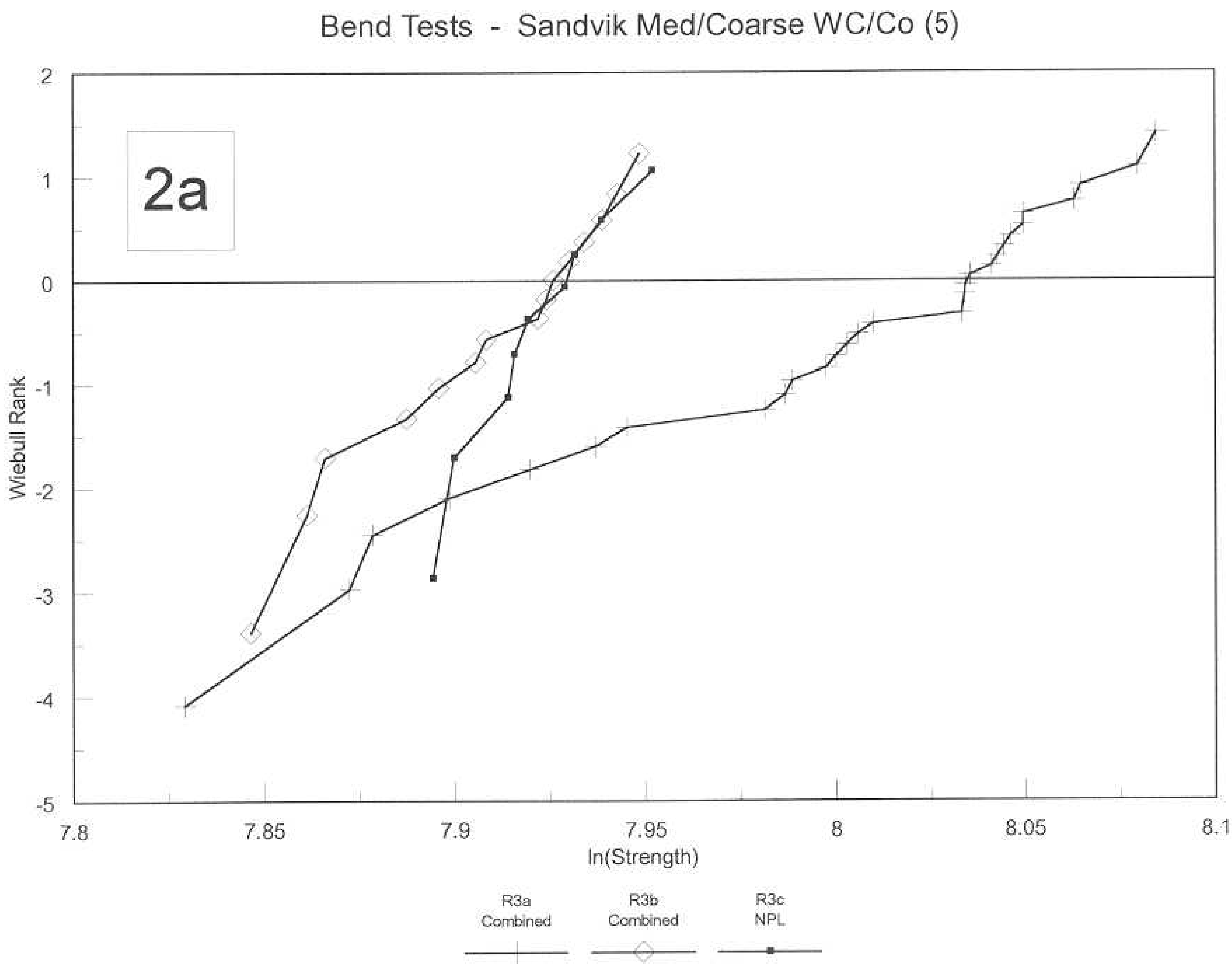
Bend Tests - Sandvik Med/Coarse WC/Co (5)
Aa
Wiebull Rank
2
1
0
-1
-2
-3
-4
-5
7.5
7.6
7.7
7.8
7.9
8
8.1
8.2
ln(Strength)
R3a Combined
R3b Combined
R3c NPL
R4b Combined
R4c Combined
RN3a combined
RN3b combined
RN4b combined
C3 combined
C4 combined
CN4 Combined
R3b annealed NPL
C3 annealed NPL
C4 annealed NPL



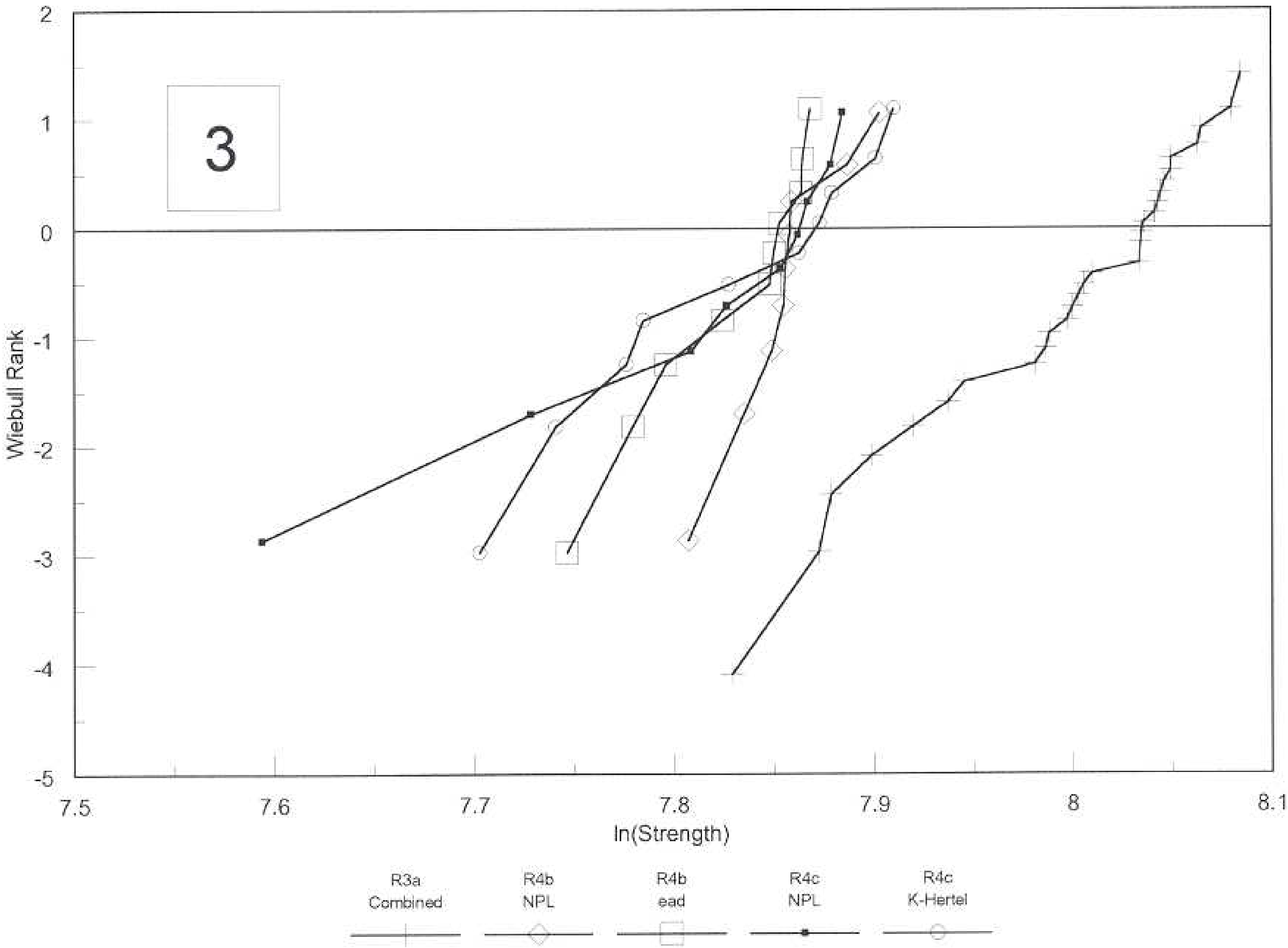
Bend Tests - Sandvik Med/Coarse WC/Co (5)
1
Wiebull Rank
2
1
0
-1
-2
-3
-4
7.8
7.85
7.9
7.95
8
8.05
8.1
ln(Strength)
R3a
Gen Carb
R3a
United


Bend Tests - Sandvik Med/Coarse WC/Co (5)
1a
Wiebull Rank
2
1
0
-1
-2
-3
-4
-5
7.8
7.85
7.9
7.95
8
8.05
8.1
ln(Strength)
R3a
Combined

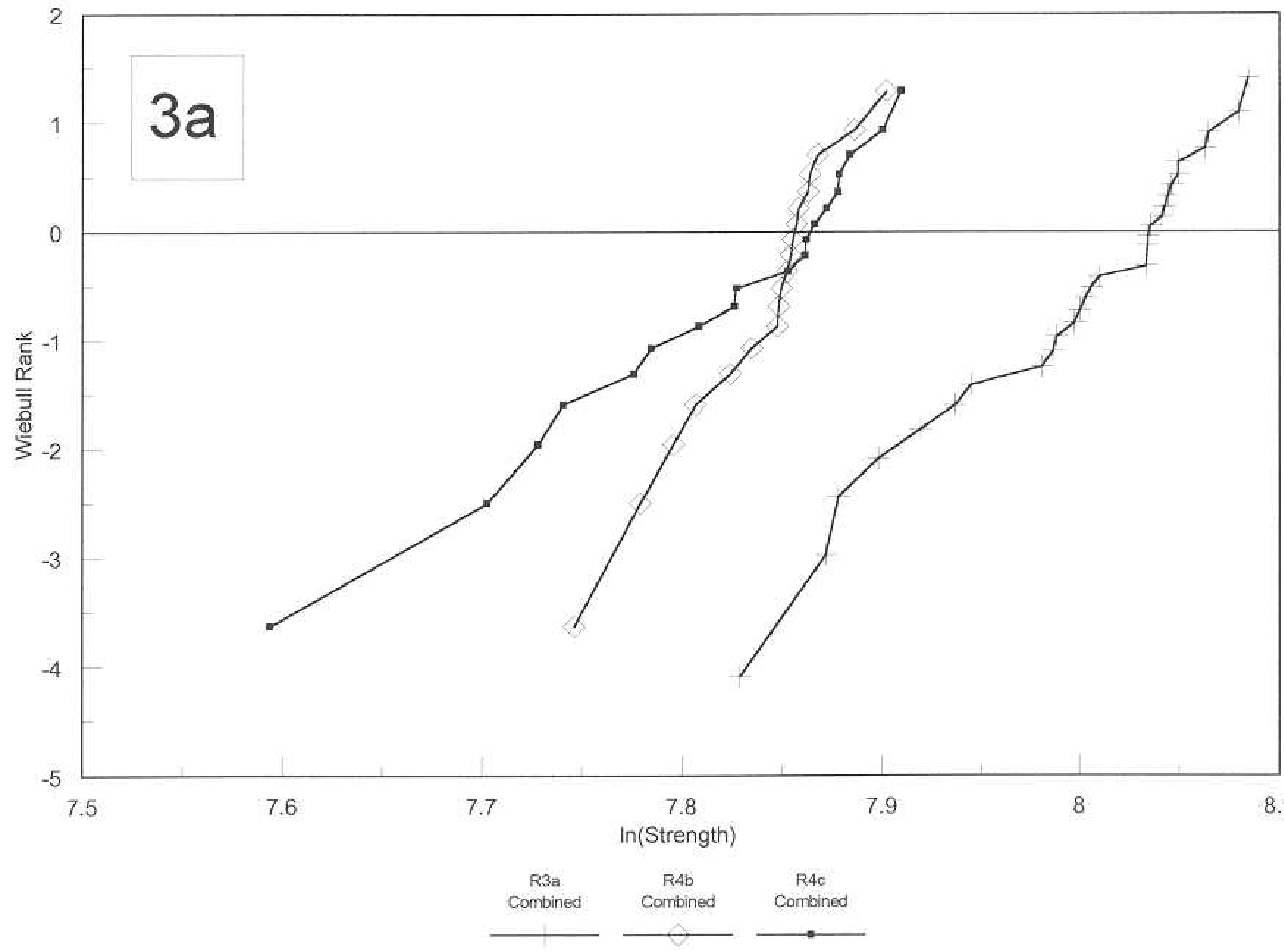

Bend Tests - Sandvik Med/Coarse WC/Co (5)
2
Wiebull Rank
2
1
0
-1
-2
-3
-4
-5
7.75
7.8
7.85
7.9
7.95
8
8.05
8.1
ln(Strength)
R3a Combined
R3b NPL
R3b EAD
R3c NPL
R3c K-Hertel


Bend Tests - Sandvik Med/Coarse WC/Co (5)
2a
Wiebull Rank
2
1
0
-1
-2
-3
-4
-5
7.8
7.85
7.9
7.95
8
8.05
8.1
ln(Strength)
R3a Combined
R3b Combined
R3c NPL

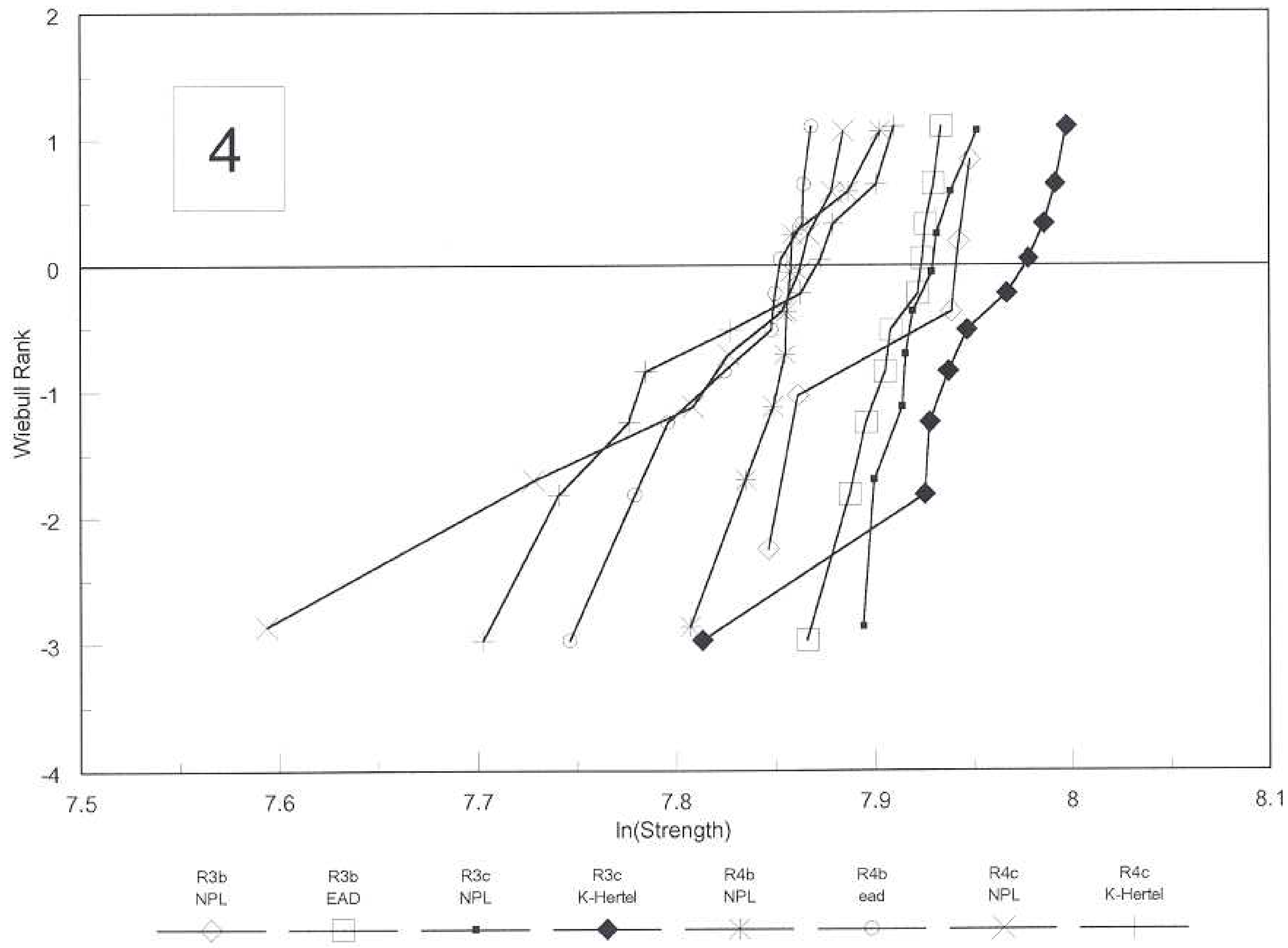
Bend Tests - Sandvik Med/Coarse WC/Co (5)

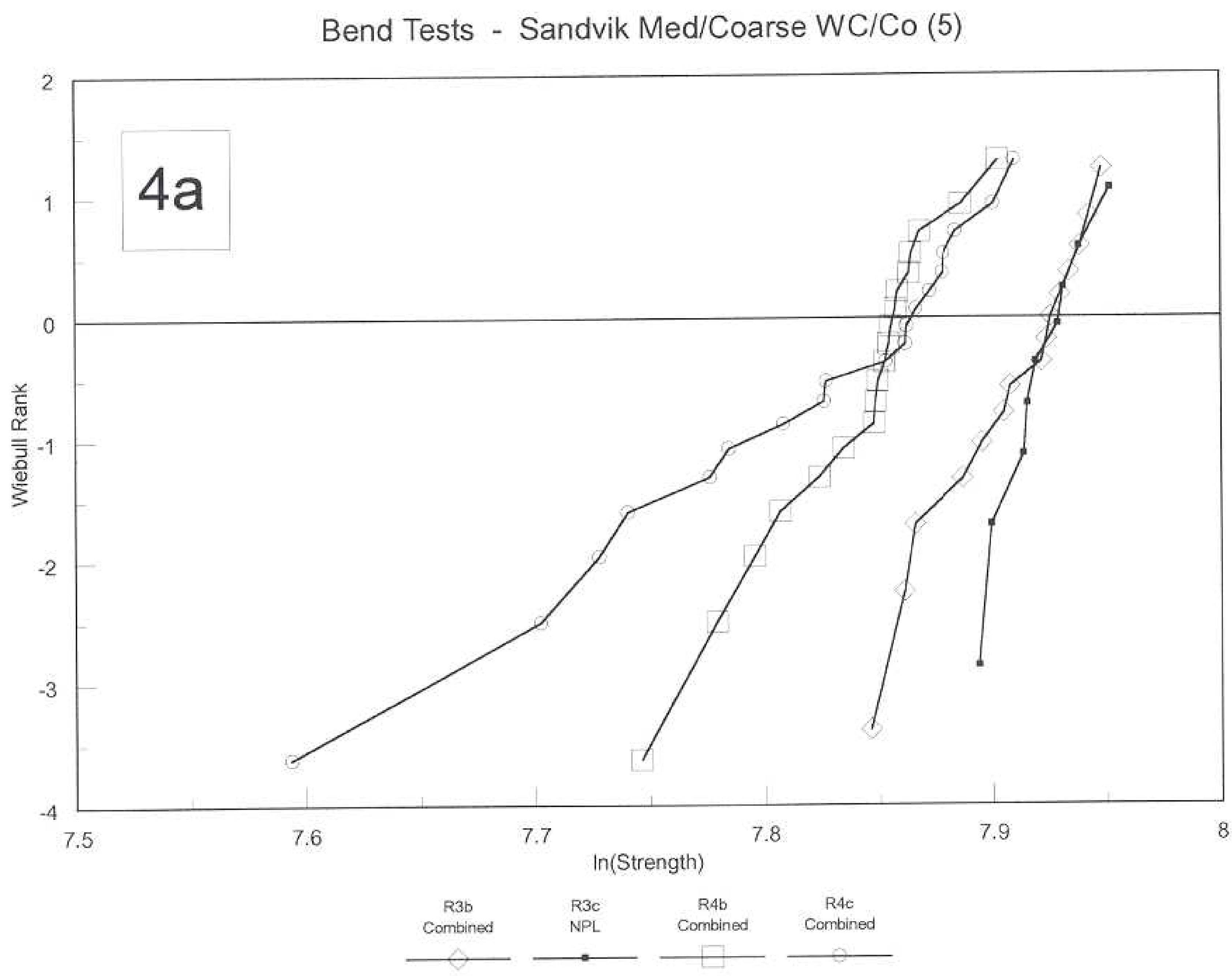


Bend Tests - Sandvik Med/Coarse WC/Co (5)

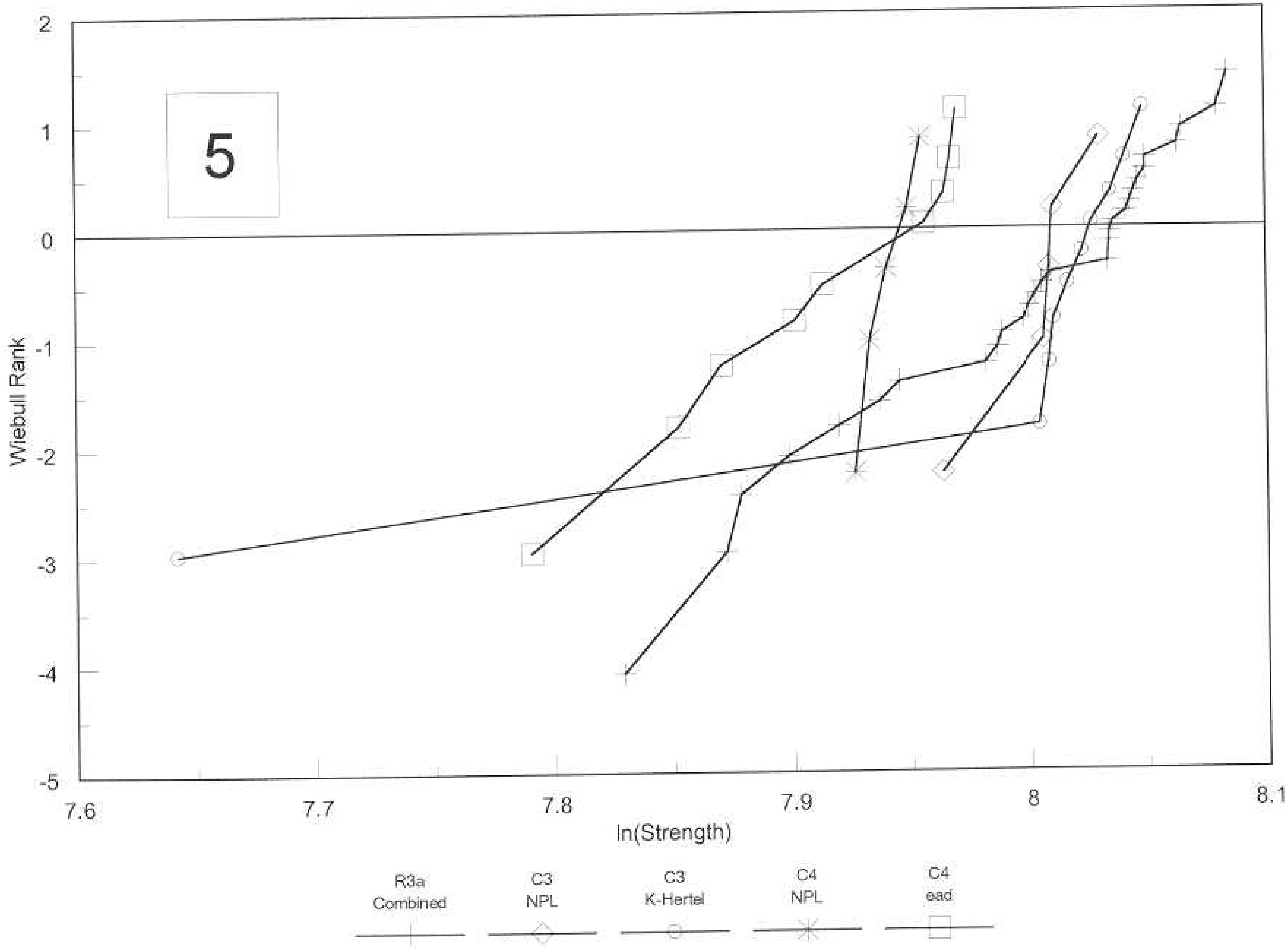


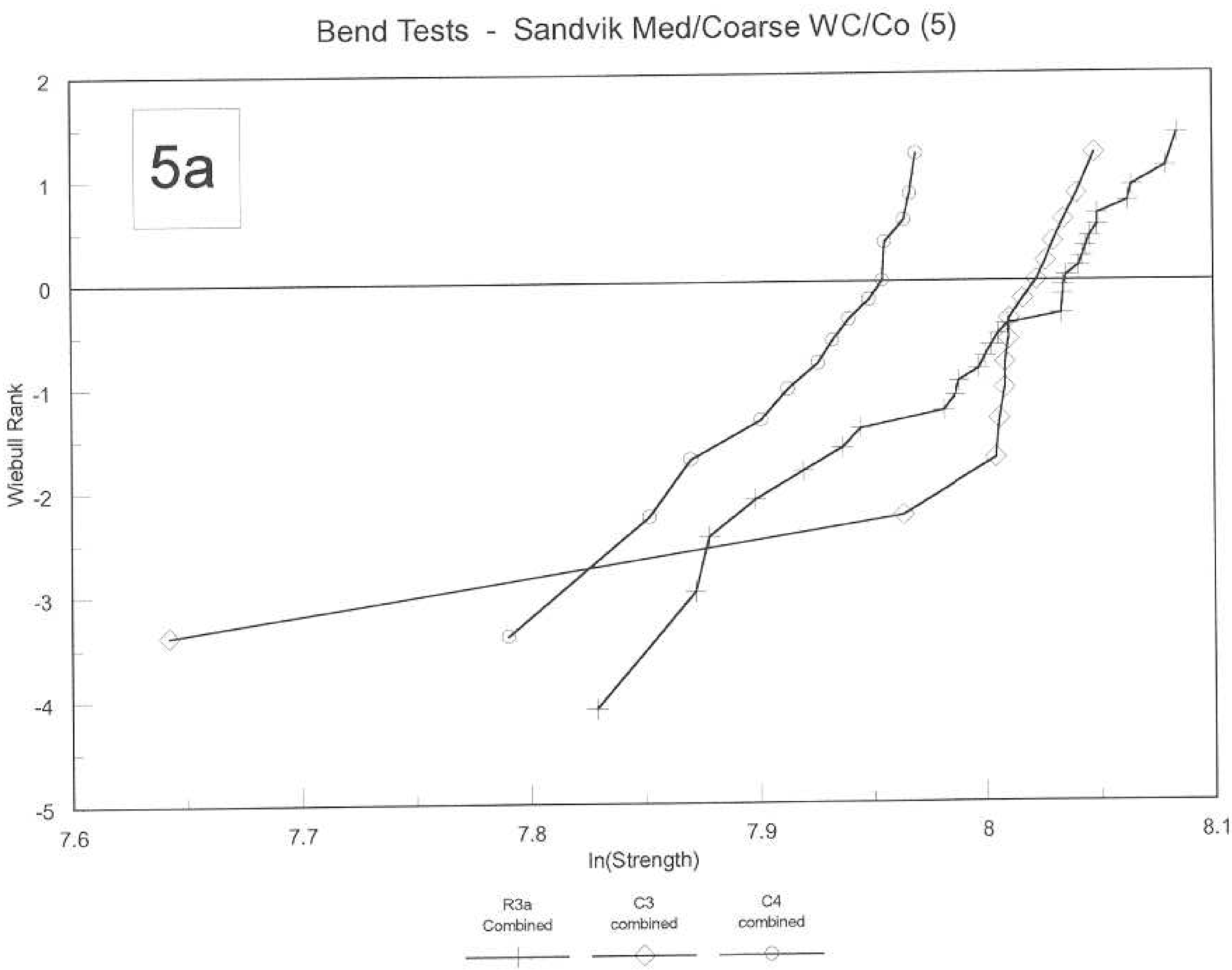
Bend Tests - Sandvik Med/Coarse WC/Co (5)




Bend Tests - Sandvik Med/Coarse WC/Co (5)
4a
Wiebull Rank
2
1
0
-1
-2
-3
-4
7.5
7.6
7.7
7.8
7.9
8
ln(Strength)
R3b Combined
R3c NPL
R4b Combined
R4c Combined

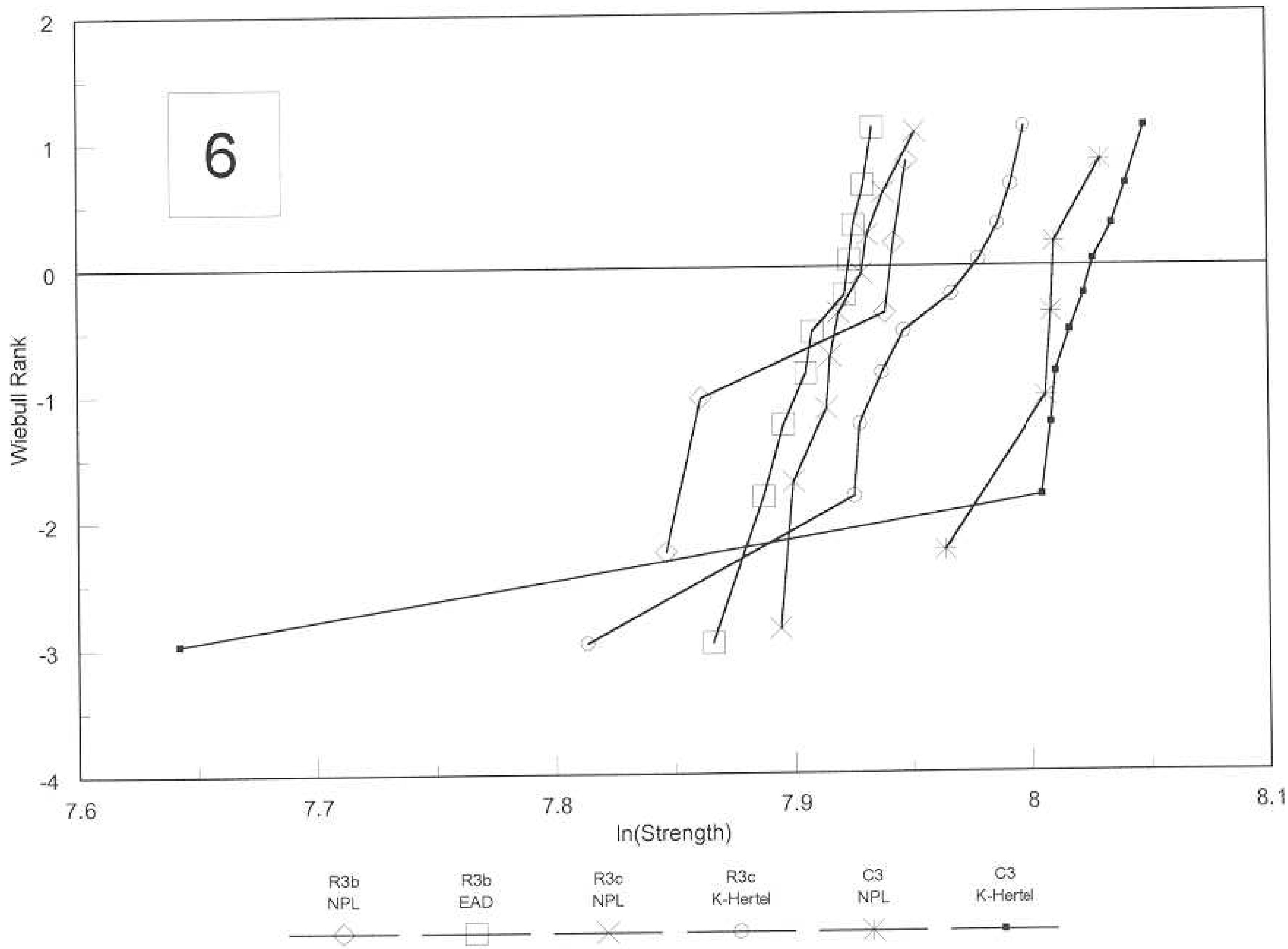
Bend Tests - Sandvik Med/Coarse WC/Co (5)

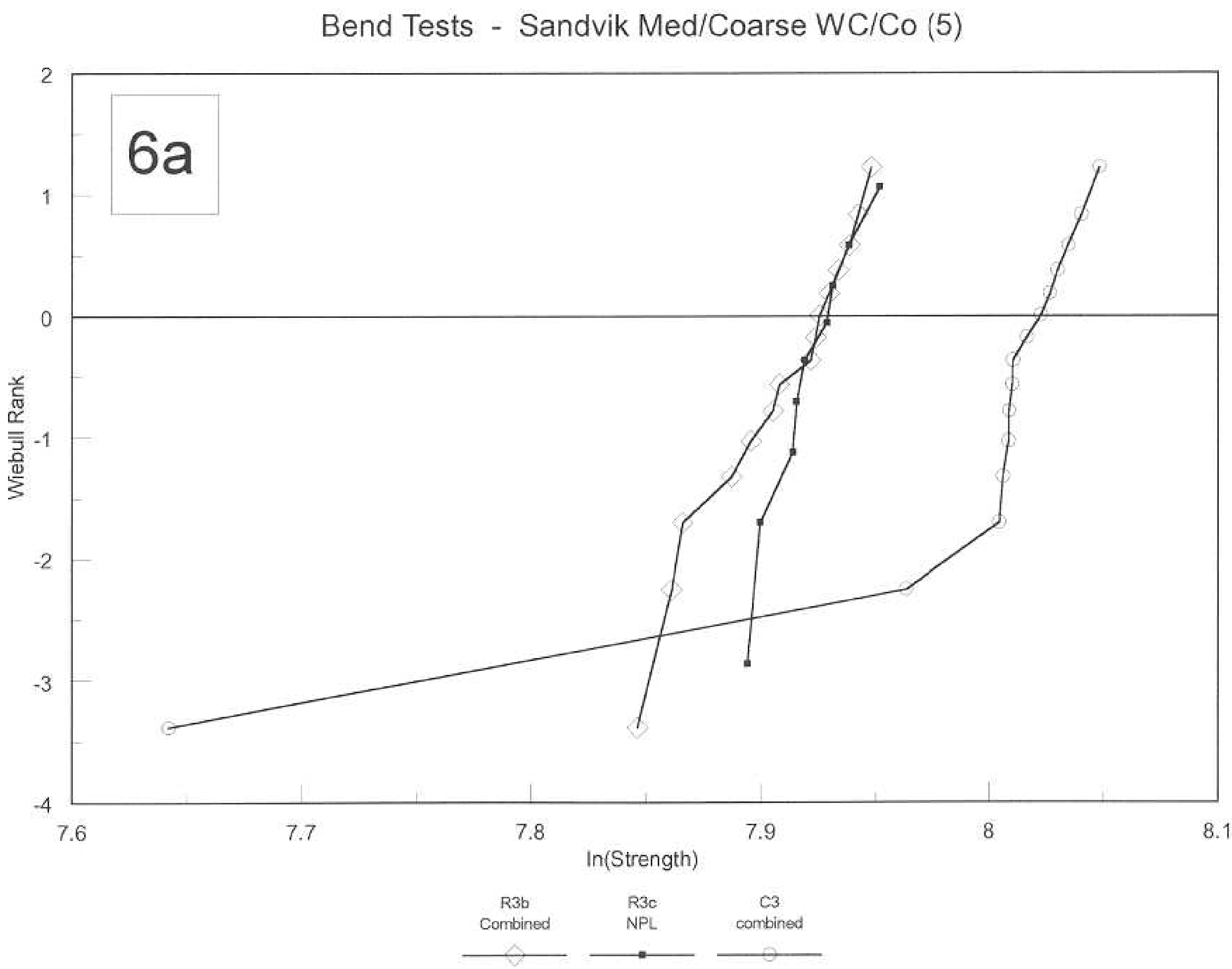




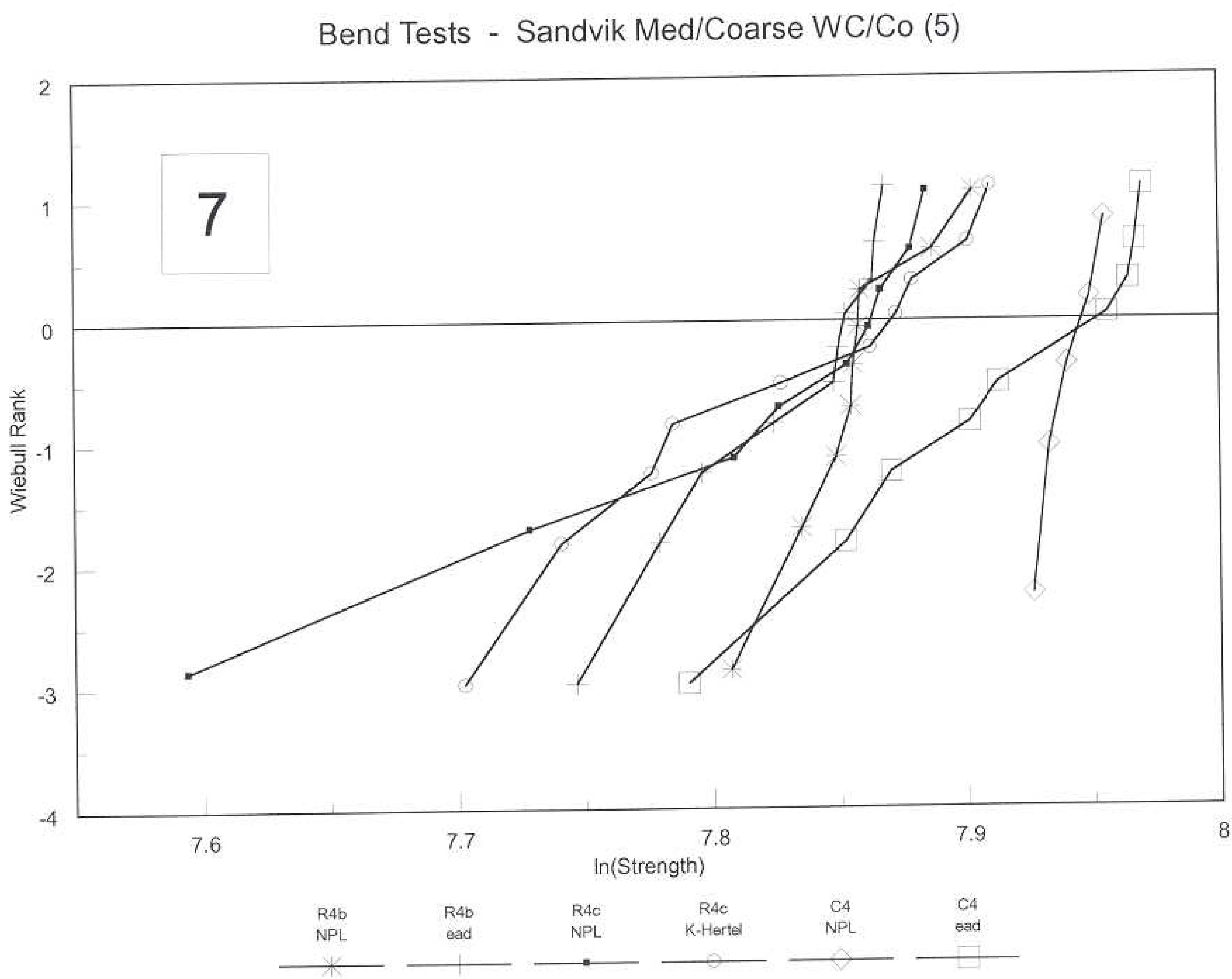
Bend Tests - Sandvik Med/Coarse WC/Co (5)
5a
Wiebull Rank
2
1
0
-1
-2
-3
-4
-5
7.6
7.7
7.8
7.9
8
8.1
ln(Strength)
R3a Combined
C3 combined
C4 combined

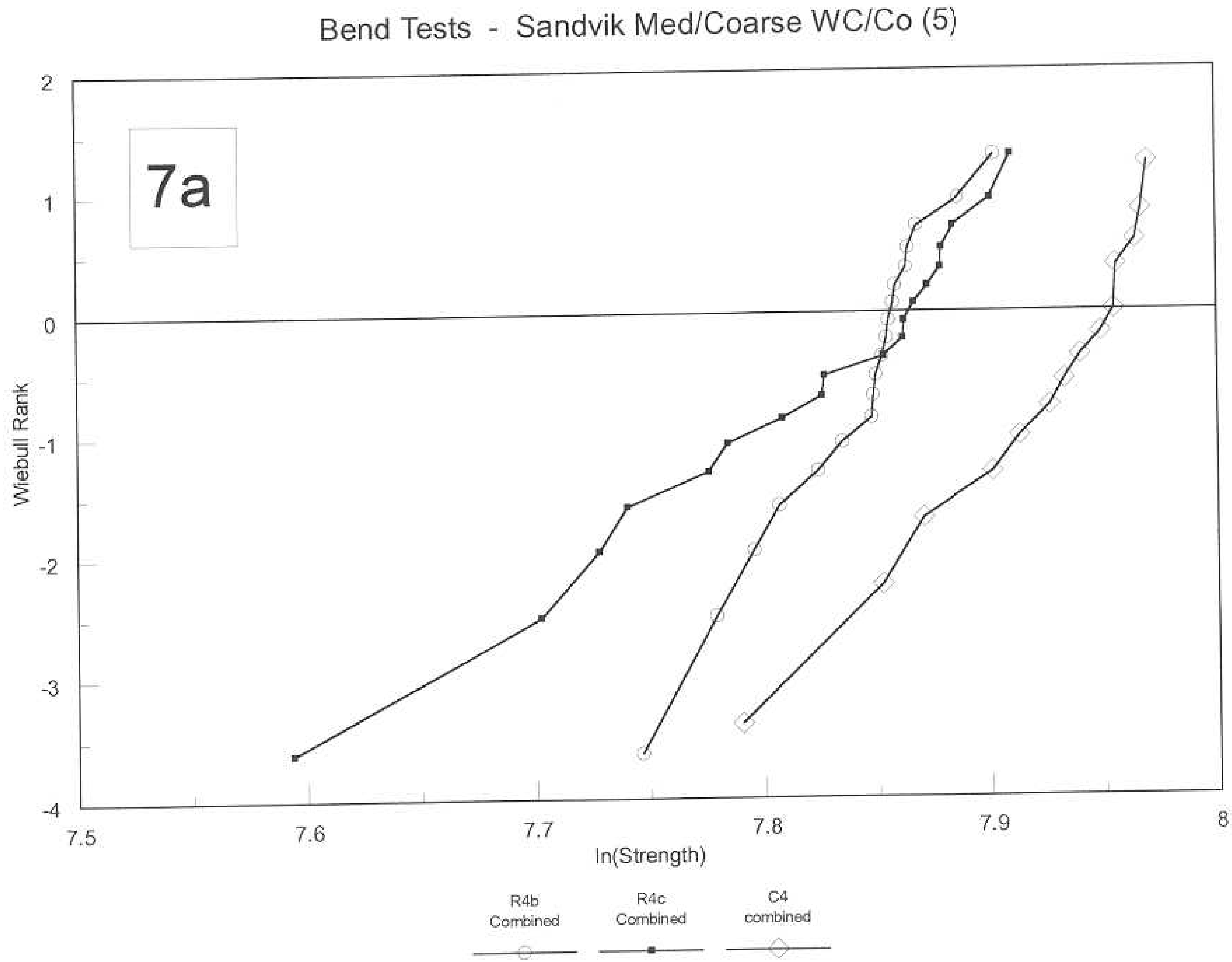
Bend Tests - Sandvik Med/Coarse WC/Co (5)



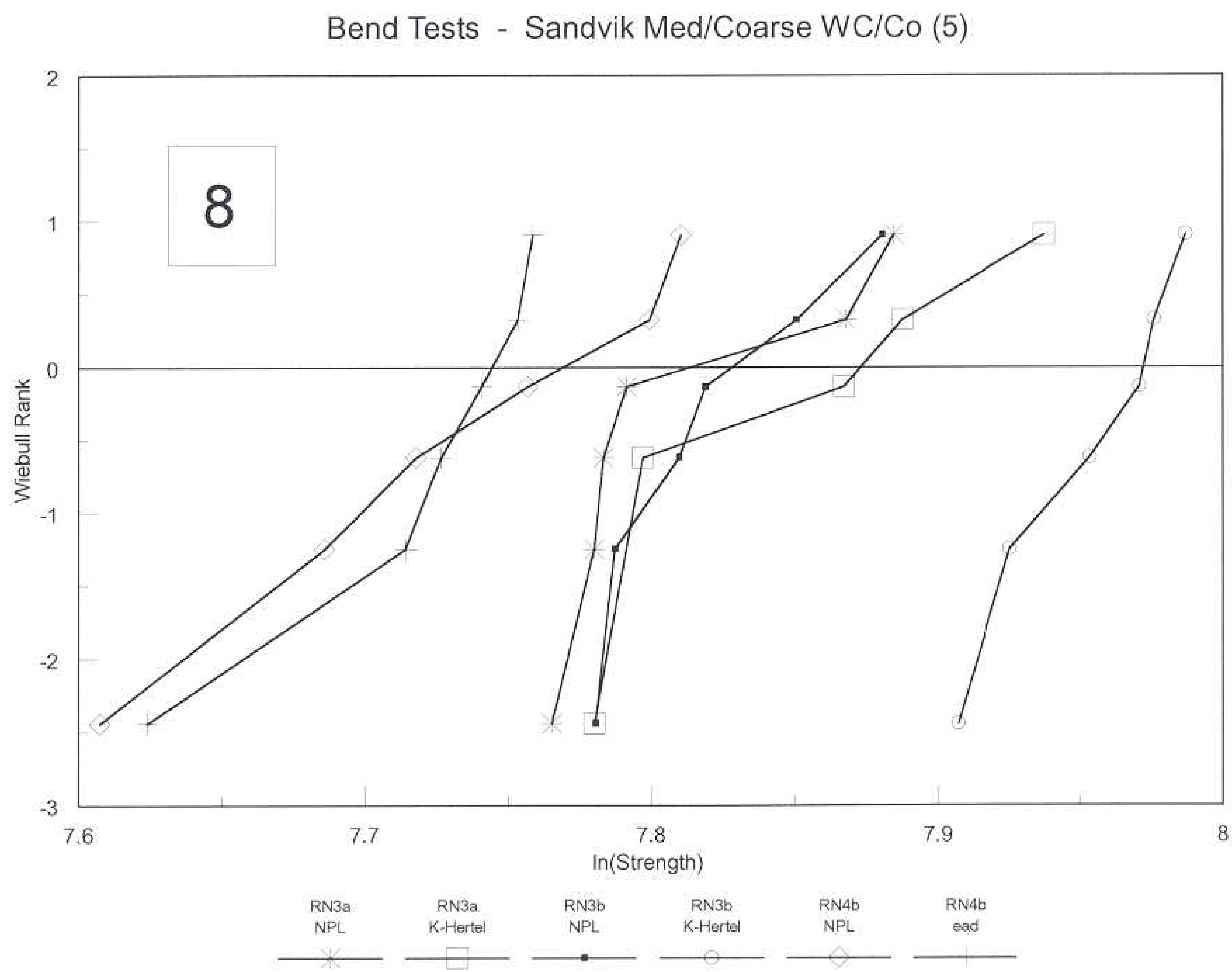


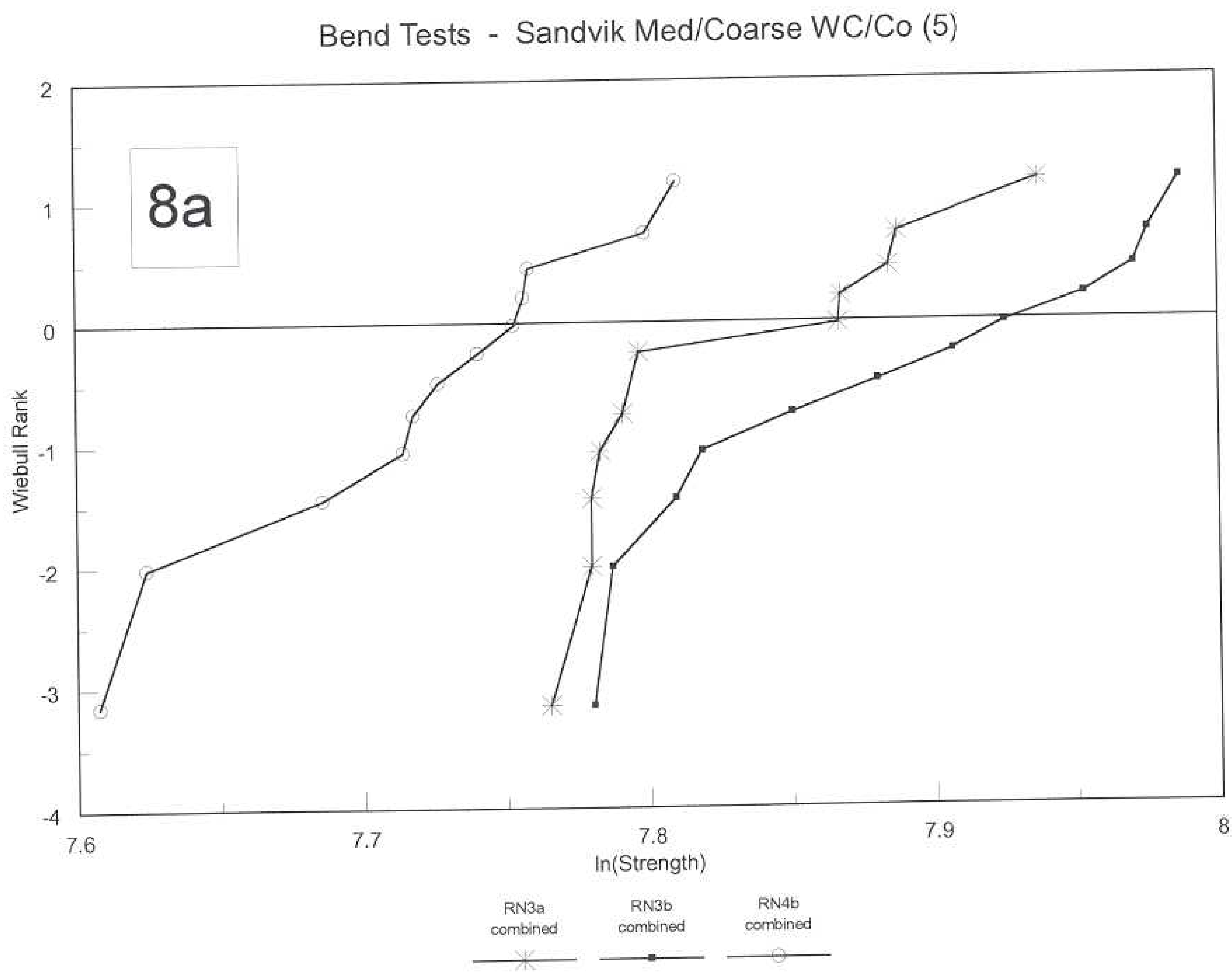
Bend Tests - Sandvik Med/Coarse WC/Co (5)
6a
Webull Rank
2
1
0
-1
-2
-3
-4
7.6
7.7
7.8
7.9
8
8.1
ln(Strength)
R3b
Combined
R3c
NPL
C3
combined

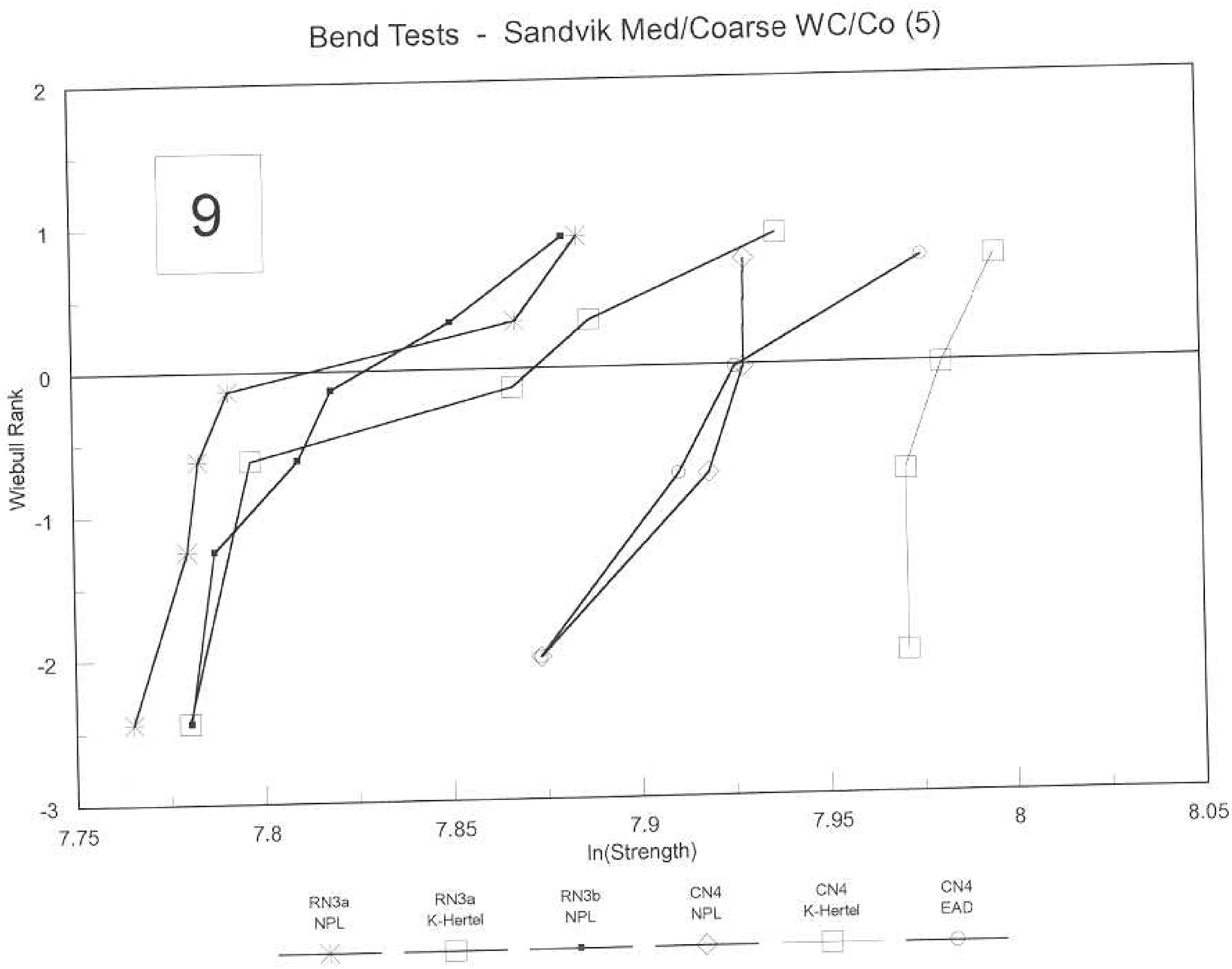

Bend Tests - Sandvik Med/Coarse WC/Co (5)
7
Wiebull Rank
2
1
0
-1
-2
-3
-4
7.6
7.7
7.8
7.9
8
ln(Strength)
R4b NPL
R4b ead
R4c NPL
R4c K-Hertel
C4 NPL
C4 ead



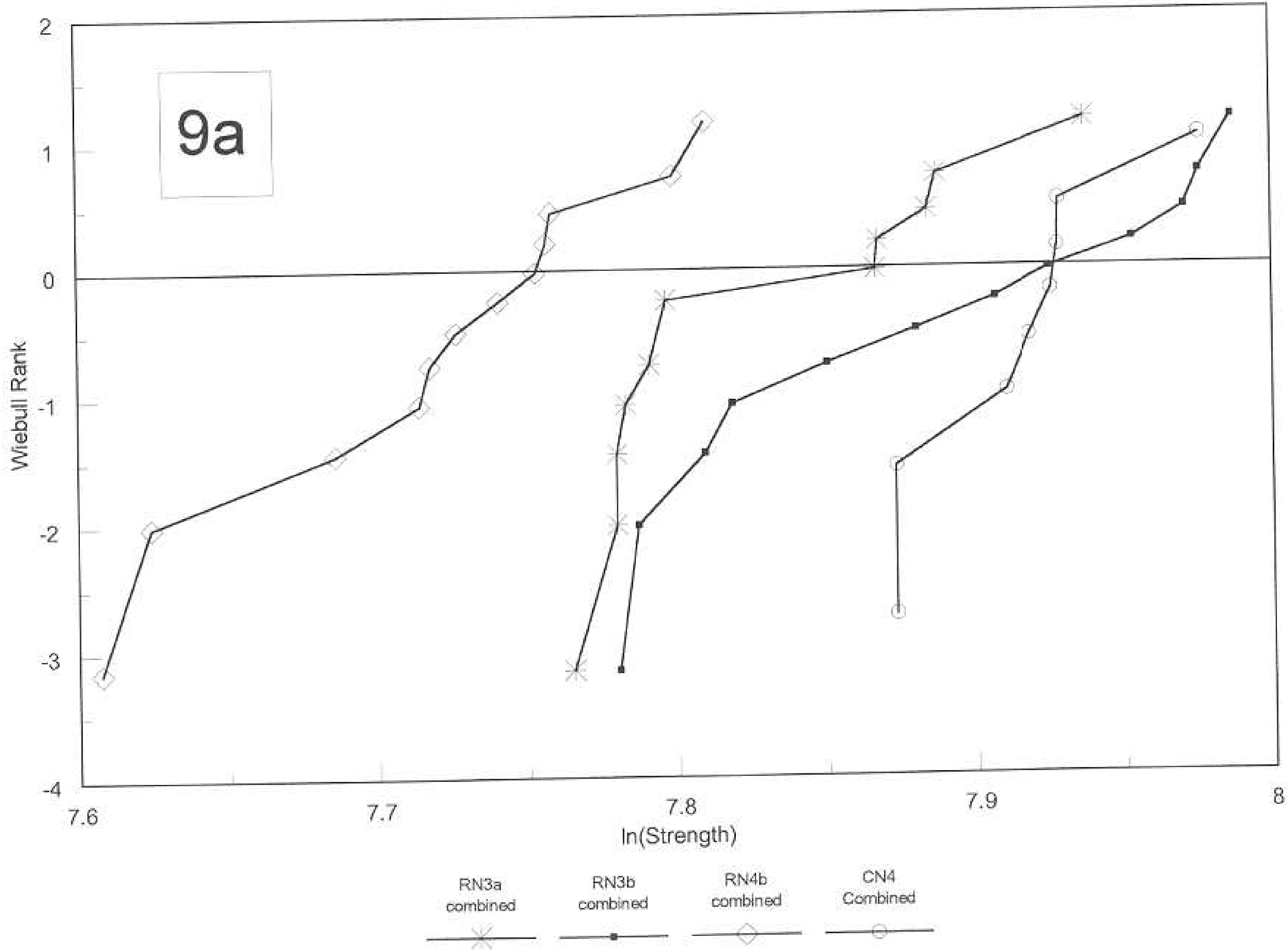
Bend Tests - Sandvik Med/Coarse WC/Co (5)
7a
Wiebull Rank
2
1
0
-1
-2
-3
-4
7.5
7.6
7.7
7.8
7.9
8
ln(Strength)
R4b Combined
R4c Combined
C4 combined


Bend Tests - Sandvik Med/Coarse WC/Co (5)
8
Wiebull Rank
2
1
0
-1
-2
-3
7.6
7.7
7.8
7.9
8
ln(Strength)
RN3a NPL
RN3a K-Hertel
RN3b NPL
RN3b K-Hertel
RN4b NPL
RN4b ead


Bend Tests - Sandvik Med/Coarse WC/Co (5)
8a
Wiebull Rank
2
1
0
-1
-2
-3
-4
7.6
7.7
7.8
7.9
8
ln(Strength)
RN3a combined
RN3b combined
RN4b combined


Bend Tests - Sandvik Med/Coarse WC/Co (5)
9
Wiebull Rank
2
1
0
-1
-2
-3
7.75
7.8
7.85
7.9
7.95
8
8.05
ln(Strength)
RN3a NPL
RN3a K-Hertel
RN3b NPL
CN4 NPL
CN4 K-Hertel
CN4 EAD

Bend Tests - Sandvik Med/Coarse WC/Co (5)



WEIBULL RESULTS SET

(7) BOART LONGYEAR

Coarse, WC/Co

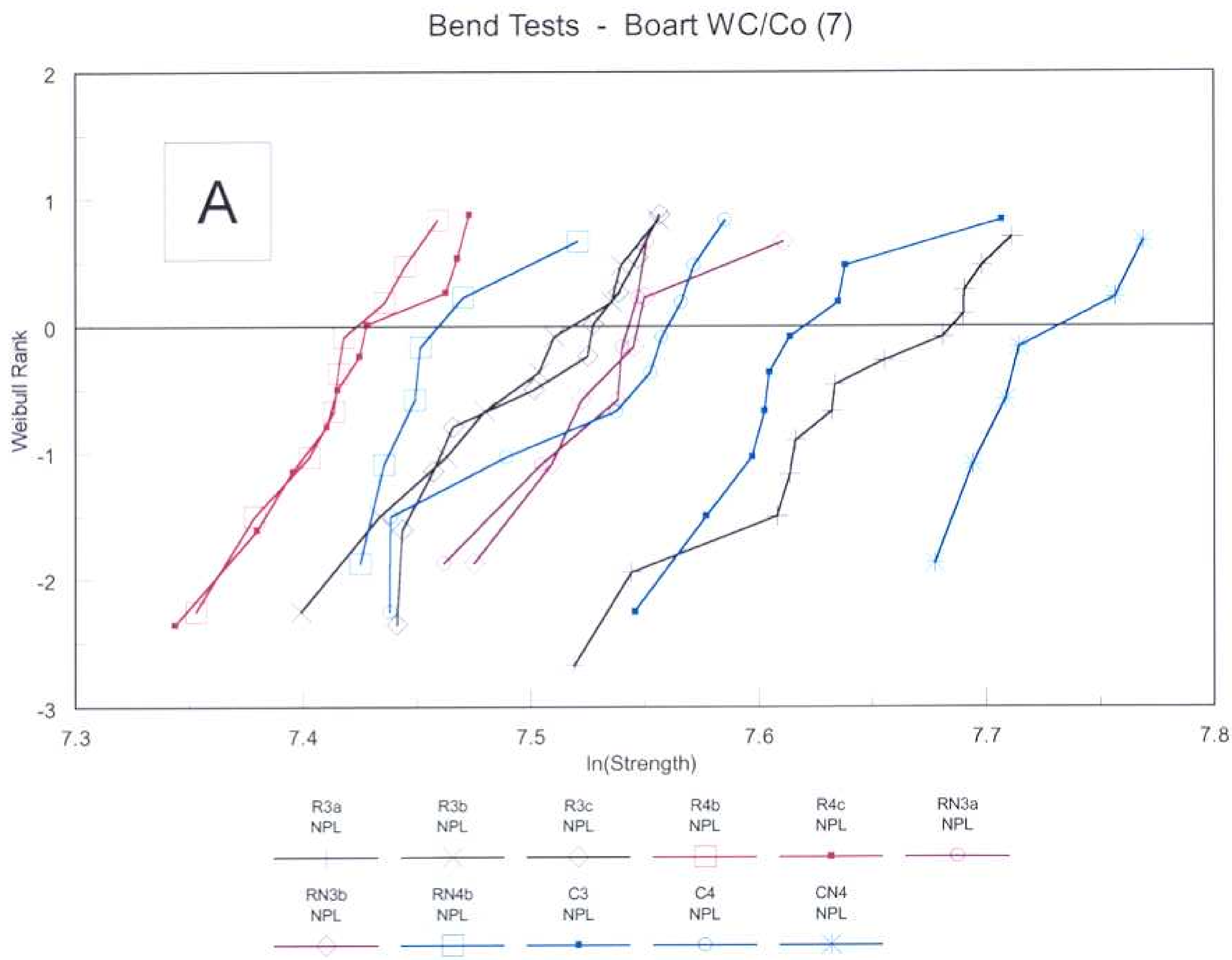
HARDMETAL BEND TESTS

Results Comment Sheet

Boart Longyear Category (7) Coarse WC/Co Hardmetal

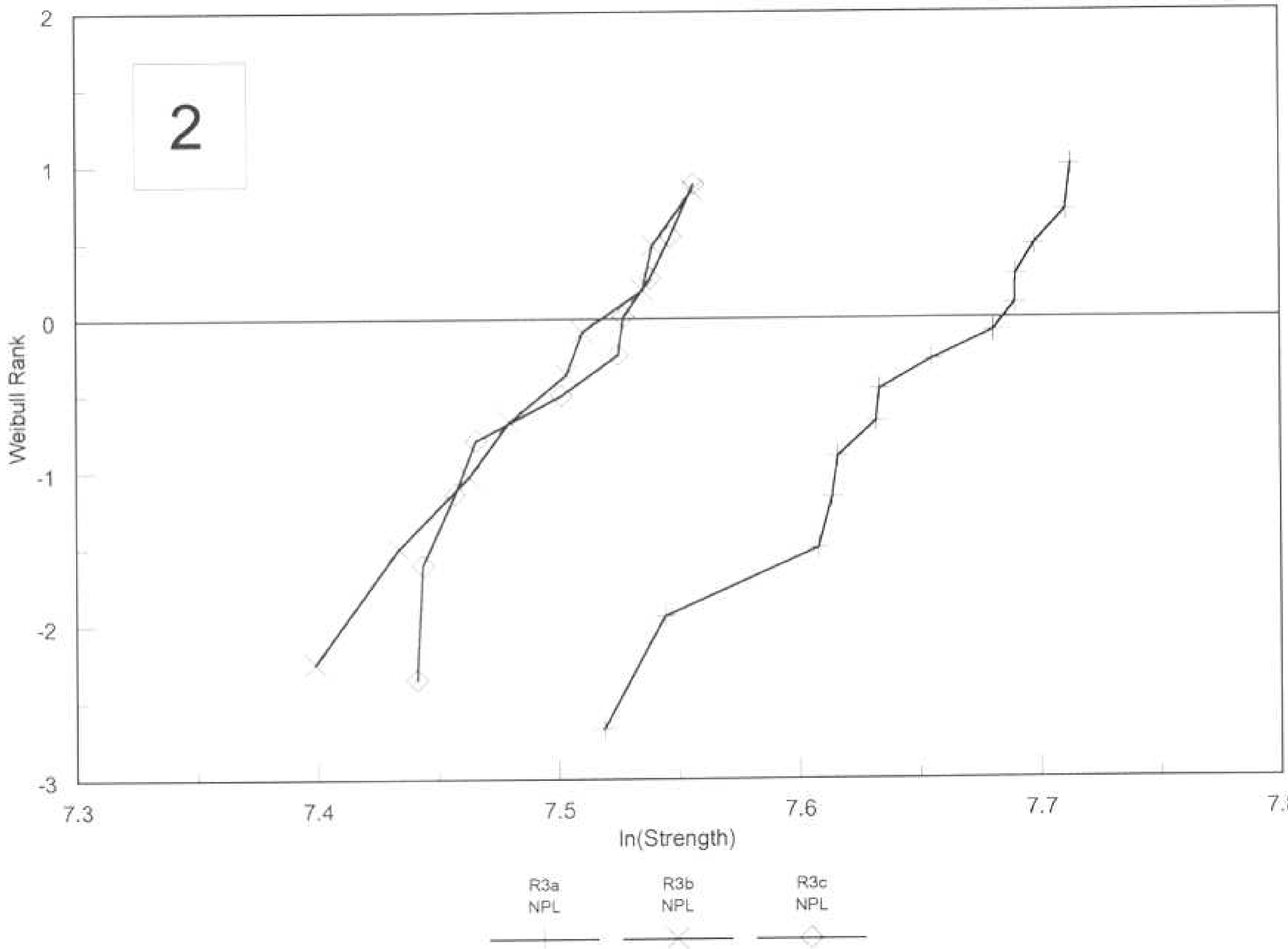
PLOT SEQUENCE

A	-	Complete set of all strength values.
2	-	3 pt rectangular tests, compared with ISO Type B, R3a, R3b, R3c.
3	-	4 pt rectangular tests, compared with standard ISO type B; R3a, R4b and R4c.
4	-	3 pt vs 4 pt tests; not including R3a, R3b, R3c, R4b, R4c.
5	-	Round testpieces, compared with standard R3a, C3, C4 and R3a.
6	-	3 pt rectangular and round, R3b, R3c and C3; not including R3a..
7	-	4 pt rectangular and round, R4b, R4c and C4.
8	-	Notched rectangular testpieces, RN3a, RN3b and RN4b.
9	-	Notched round compared with notched rectangular; CN4 and RN3a, RB3b and RN4b.

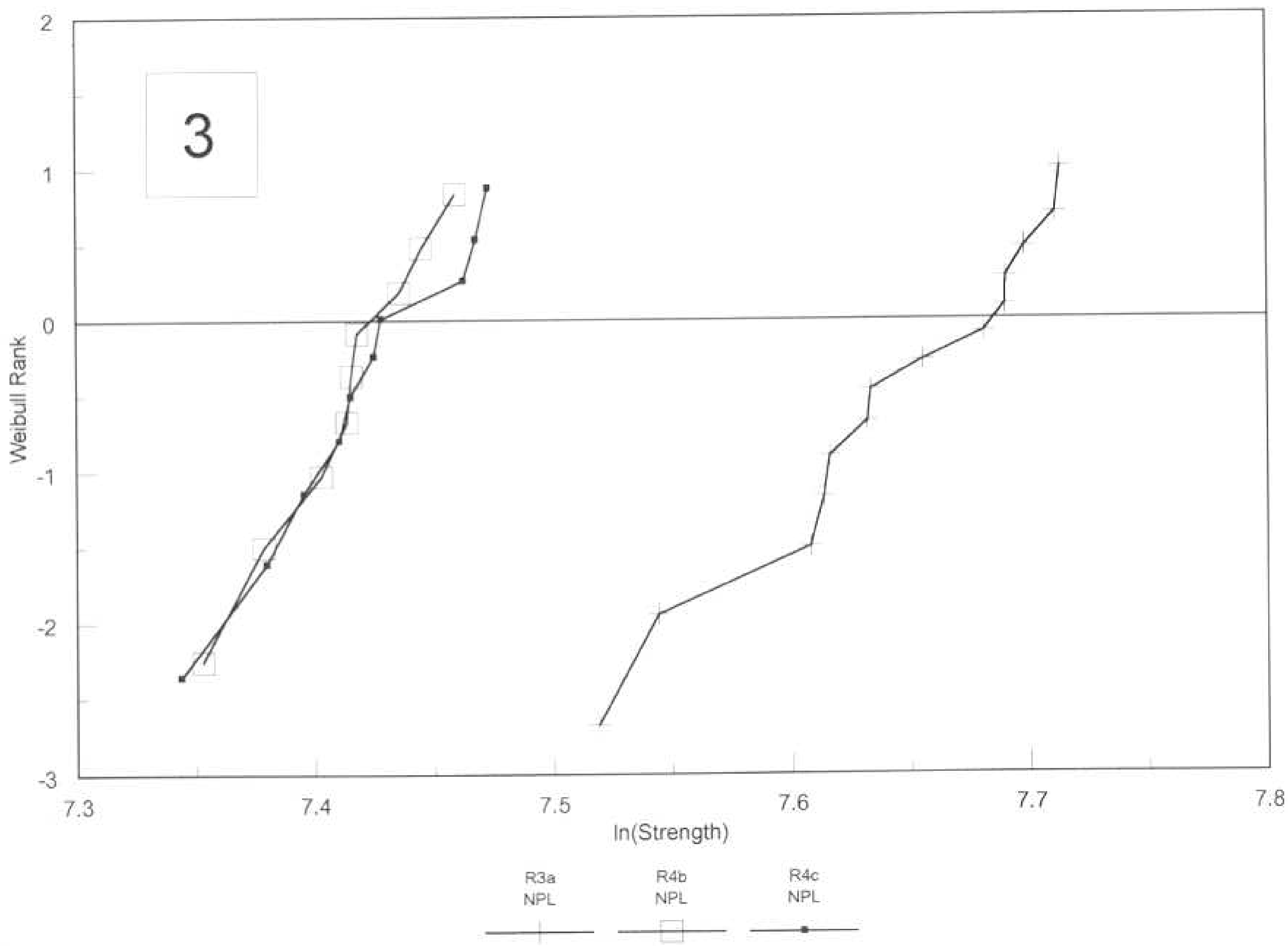


Bend Tests - Boart WC/Co (7)
A
Weibull Rank
2
1
0
-1
-2
-3
7.3
7.4
7.5
7.6
7.7
7.8
ln(Strength)
R3a NPL
R3b NPL
R3c NPL
R4b NPL
R4c NPL
RN3a NPL
RN3b NPL
RN4b NPL
C3 NPL
C4 NPL
CN4 NPL

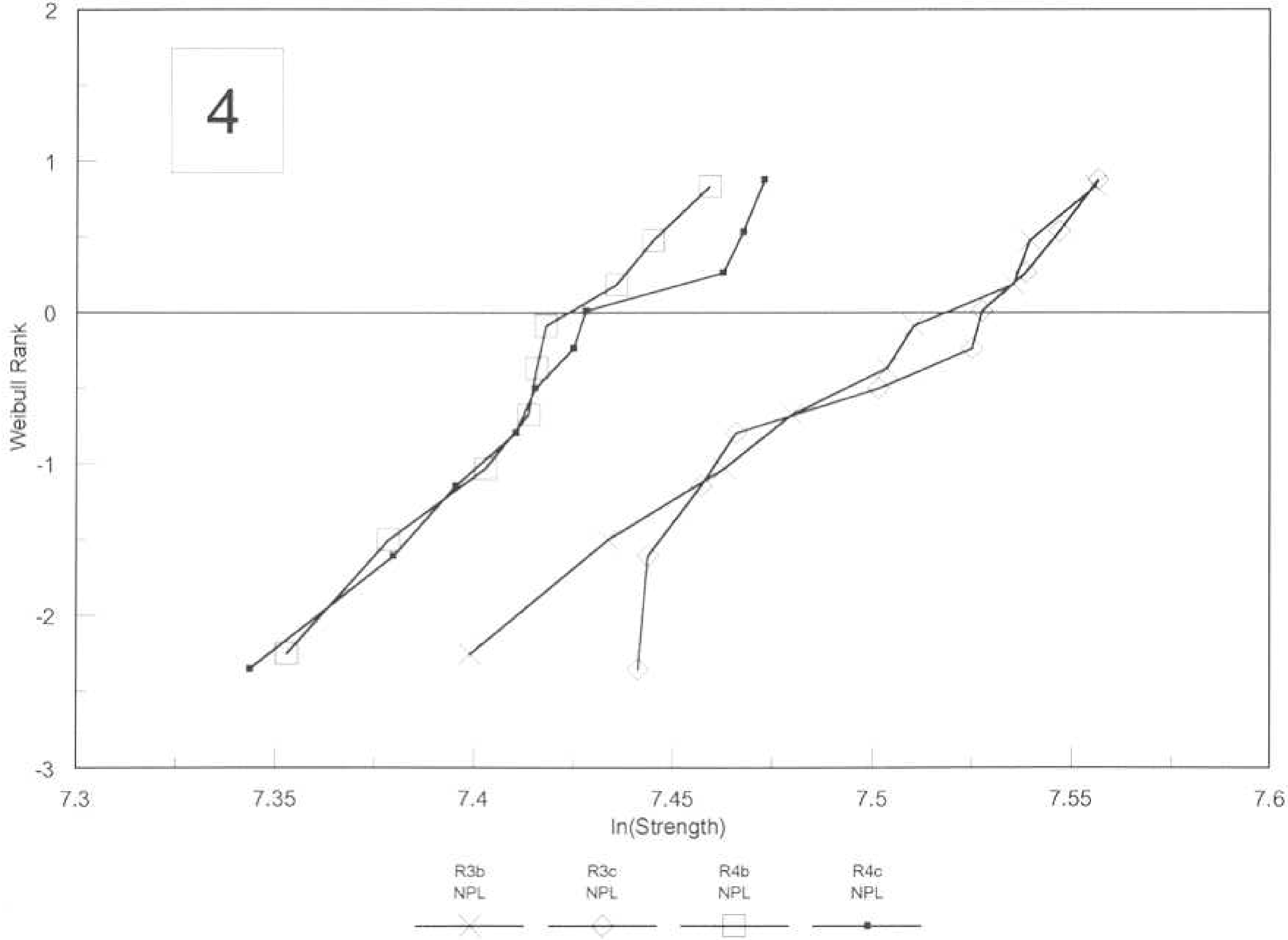
Bend Tests - Boart WC/Co (7)

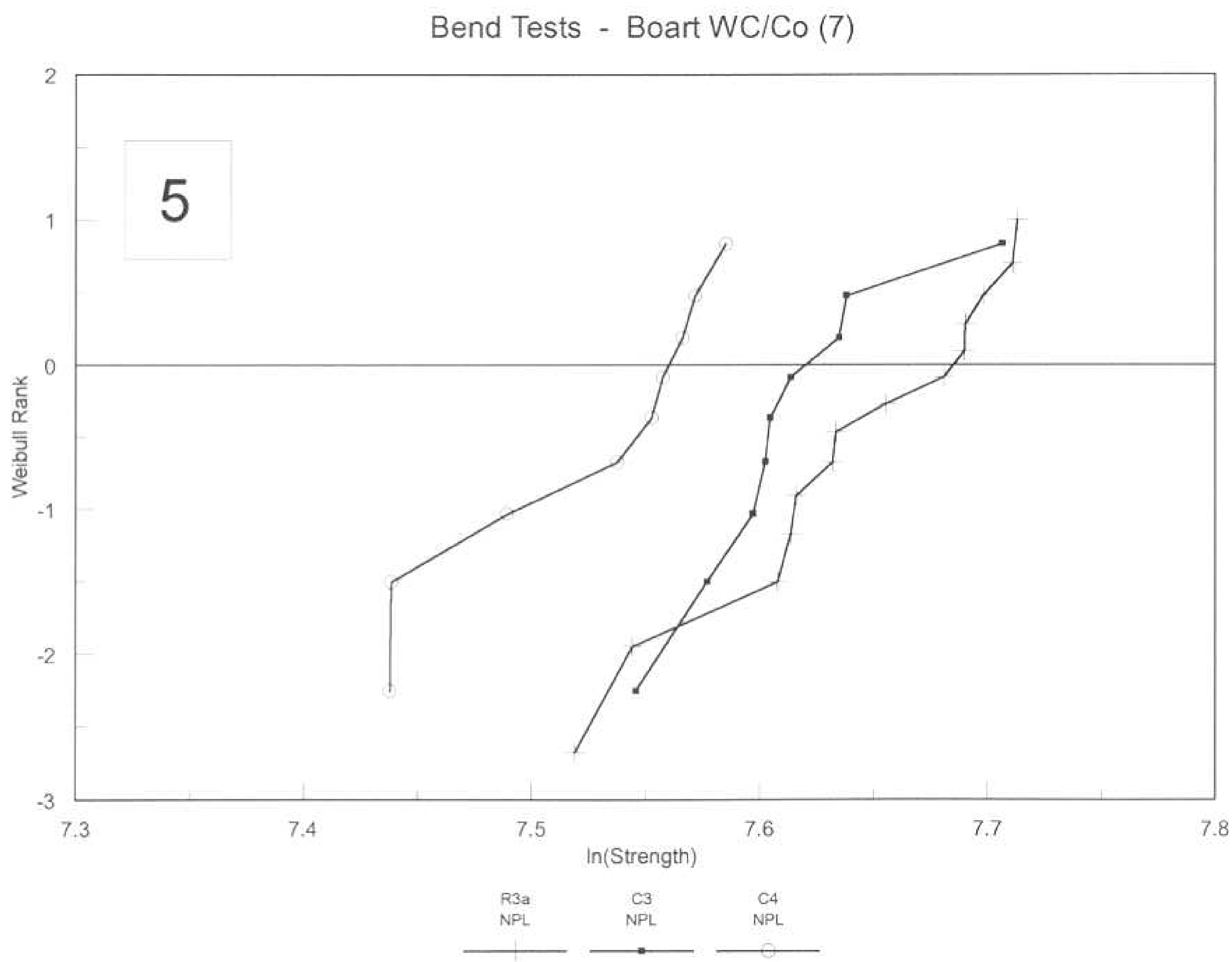


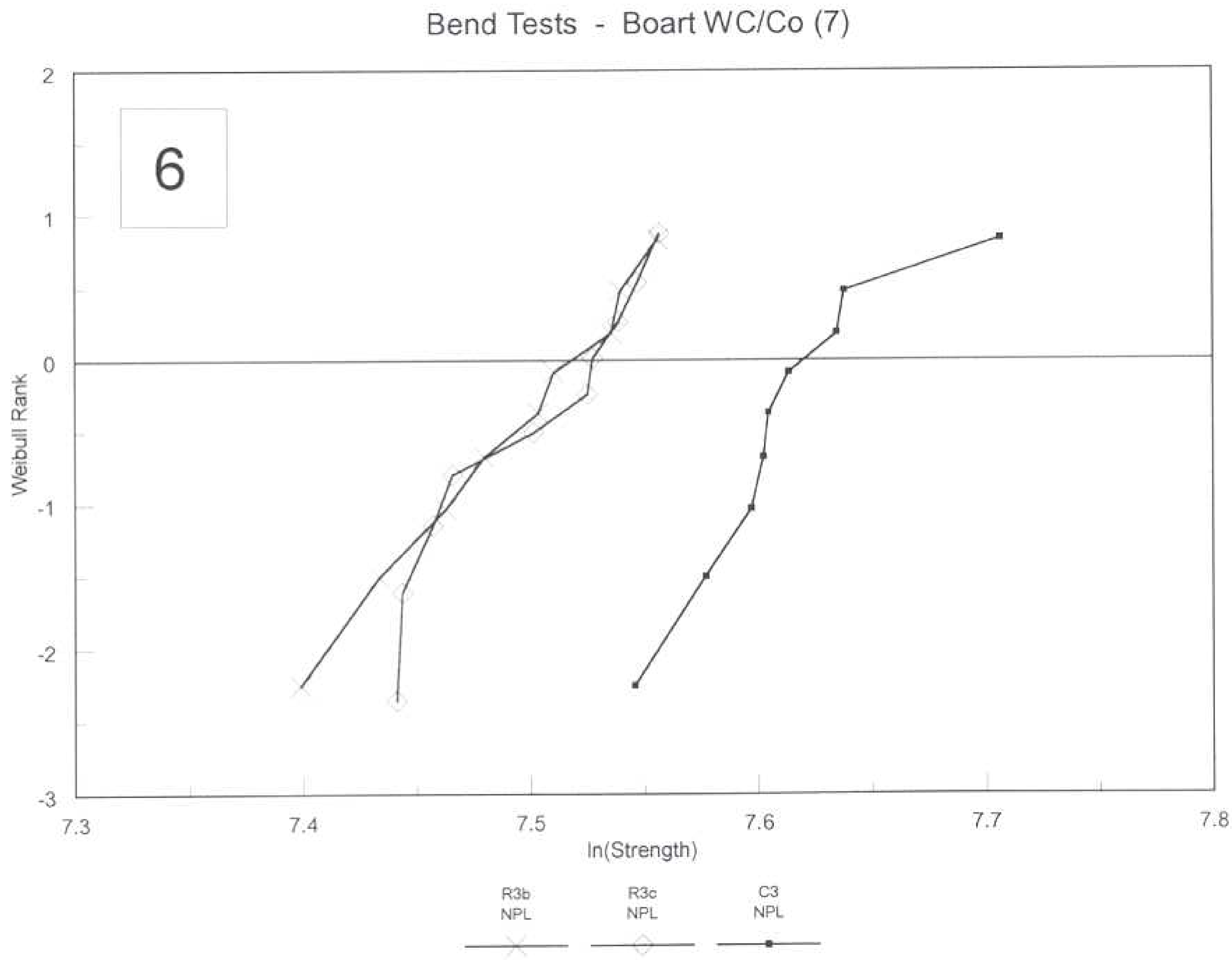
Bend Tests - Boart WC/Co (7)

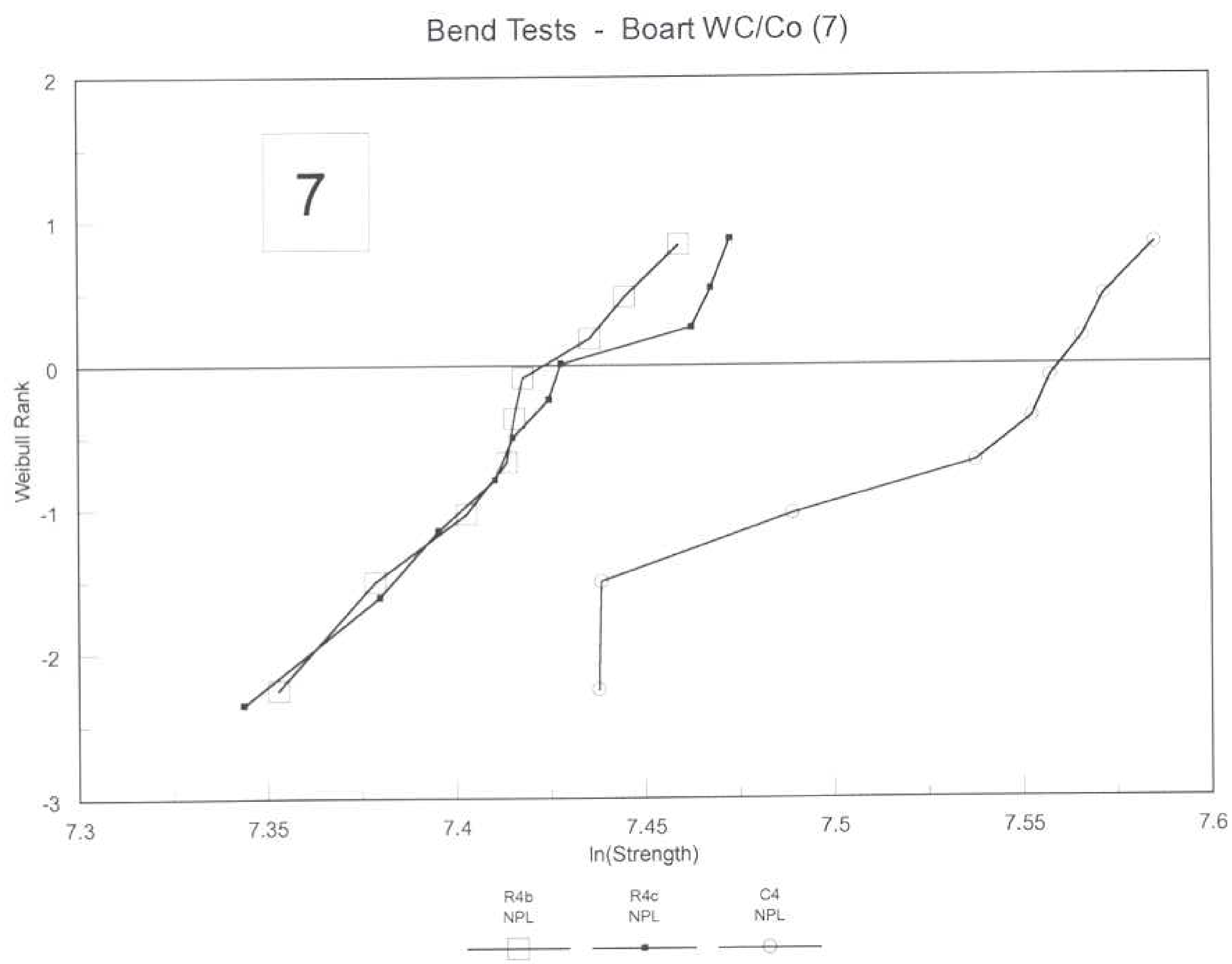


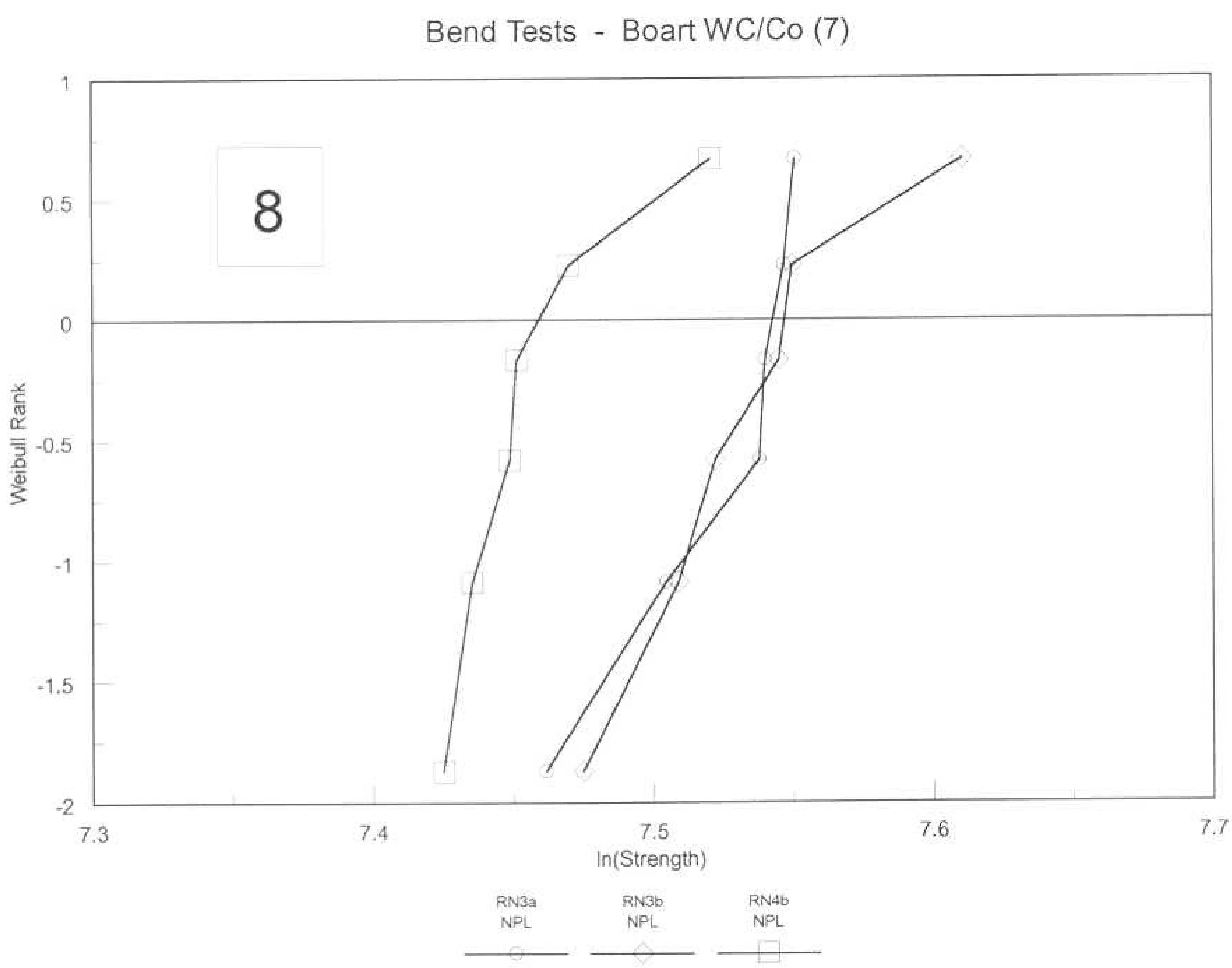
Bend Tests - Boart WC/Co (7)

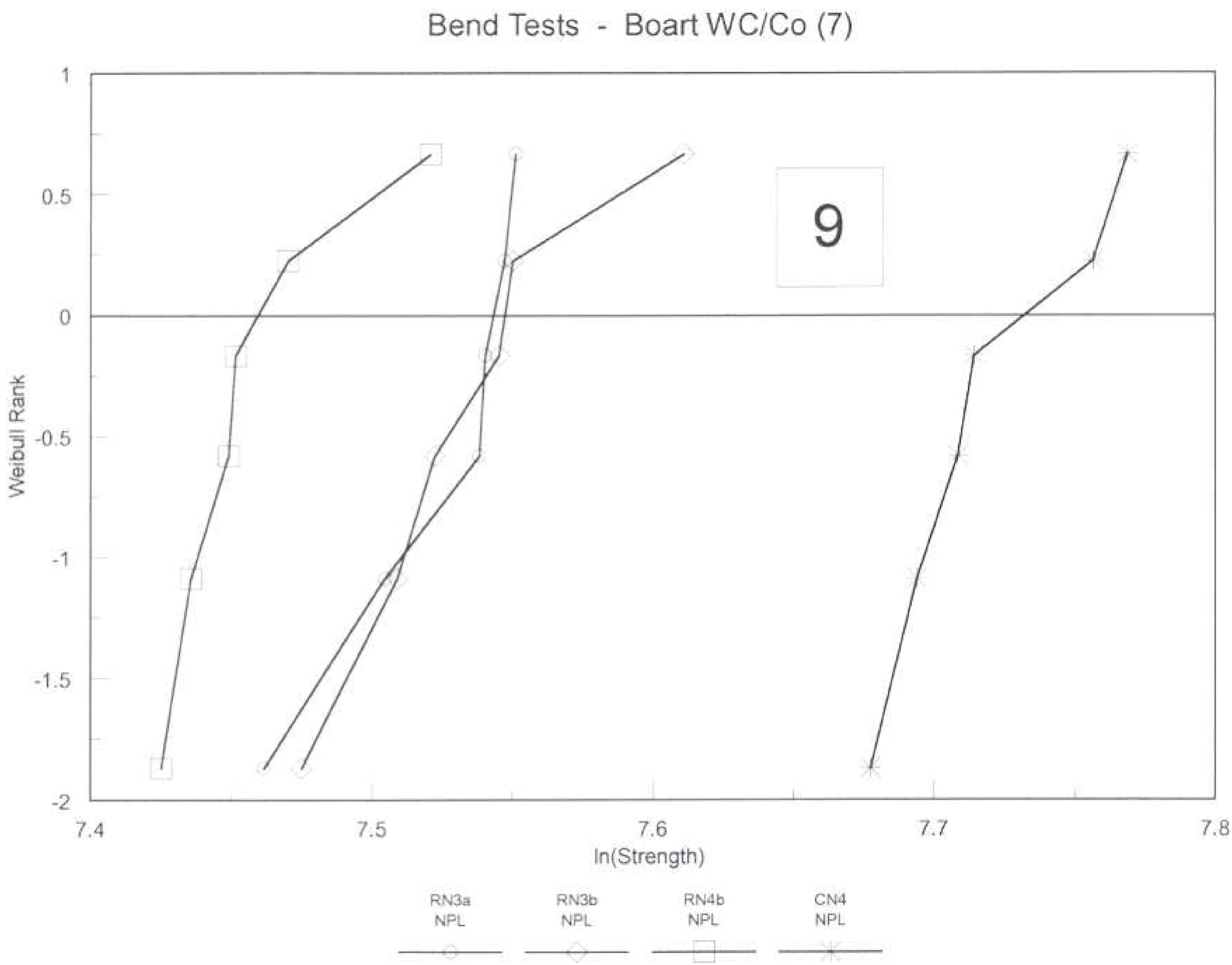



Bend Tests - Boart WC/Co (7)
5
Weibull Rank
2
1
0
-1
-2
-3
7.3
7.4
7.5
7.6
7.7
7.8
ln(Strength)
R3a NPL
C3 NPL
C4 NPL


Bend Tests - Boart WC/Co (7)
6
Weibull Rank
2
1
0
-1
-2
-3
7.3
7.4
7.5
7.6
7.7
7.8
ln(Strength)
R3b
NPL
R3c
NPL
C3
NPL


Bend Tests - Boart WC/Co (7)
7
Weibull Rank
2
1
0
-1
-2
-3
7.3
7.35
7.4
7.45
7.5
7.55
7.6
ln(Strength)
R4b NPL
R4c NPL
C4 NPL


Bend Tests - Boart WC/Co (7)
8
Weibull Rank
1
0.5
0
-0.5
-1
-1.5
-2
7.3
7.4
7.5
7.6
7.7
ln(Strength)
RN3a NPL
RN3b NPL
RN4b NPL


Bend Tests - Boart WC/Co (7)
9
Weibull Rank
1
0.5
0
-0.5
-1
-1.5
-2
7.4
7.5
7.6
7.7
7.8
ln(Strength)
RN3a NPL
RN3b NPL
RN4b NPL
CN4 NPL