Evaluation of Test Methods for Refractory Bricks: A Comparison and Validity Study of some Cold Crushing Strength Standards

Part 1: Procedure and Determination of Precision

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Measurement of cold compression strength (CCS) has only used over 100 years as a test method for characterizing refractory products. Although CCS describes in a limited way the performance of a refractory, it is widely used as a key parameter in data sheets and product definitions. Moreover, there are several different CCS standards, each with different influences, a circumstance leading to sometimes hardly comparable results which may cause complex trade issues.
For these reasons, a Task Force on Testing Methods and Standards of the World Refractory Association (WRA) has investigated precision data and the comparability of the main CCS standards. More than 1000 individual tests were performed by seven renowned laboratories on six different refractory grades. This work presents the statistically assured results. The standards ASTM C133 and ISO 10059-1 differ mainly in the load rate applied and the usage of an interlayer (packing) between the plunger and the test specimen. The results have shown that ASTM C133 gives on average around 24 % lower values, this is attributed to the use of the packing. The influence of the geometry of the test specimens (be it cylindrical or cubic) was also investigated and showed only a minor effect on the values. The precision data collected in this study have shown for both ASTM C133 and ISO 10059-1 a relative repeatability interval of around 20 %. Regarding reproducibility ASTM C133 performed slightly worse than ISO 10059-1 (40 % compared to 30 %). In a further step, the integration of the precision data and the comparative results into ISO/TC 33 for ISO 10059-1 will be proposed.

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1 Introduction

Although Cold Crushing Strength (or Cold Compressive Strength; CCS or σ) values provide only limited information on the performance of refractories, the property is commonly the straight choice to quickly assess the 'quality' of a refractory product. However, it must be underlined that only a correct combination of properties could assess the performance of a given refractory product and the lining made therefrom (1).
The mechanical resistance at the point of failure of a solid ceramic material at room temperature is known as its CCS. Its value results from dividing the applied force at failure, F, by the cross-sectional area, A, of the specimen tested:

$$\sigma = \frac{F}{A}$$

For ductile materials, the deformation at the point of failure is shown in stress-strain diagrams. Brittle materials (ceramics, refractories, concrete, glass) undergo a hardly measurable plastic deformation, the energy stored in the material under compression being released by catastrophic failure. The pressure (force/area) at which failure takes place is defined as the material's CCS.
The procedure to measure this value would appear uncomplicated. Throughout the years various procedures were developed with apparently small differences.
Testing can be basically performed either under lateral confinement (Fig. 1, left), or without lateral confinement at the specimen's top and bottom ends (Fig. 1, right). These two conditions reflect the type of contact between the end surfaces of the

refractory specimen and that of the testing machine plungers, a condition that is decisive for the CCS values measured and the fracture patterns obtained.

Without a cardboard packing between the specimen and the plunger, the top and bottom surfaces of the specimen are placed under lateral confinement (hampered transverse strain): they are fixed to the plungers of the testing machine and the material at the contact surface cannot "expand". As a result, at the top and bottom surfaces of the specimen the strain is nearly zero. Therefore, the highest strain would be produced at the middle of the specimen's length, causing it to fracture at ca. 45°. This laterally confined type of contact without packing does require a mean roughness of the steel plate plungers, transmitting the force, of Ra = 0,8–3,2 µm, and a Rockwell hardness of 58 HRC–62 HRC.

With a cardboard packing between the specimen and the plunger, the specimen top and bottom surfaces do not suffer lateral confinement. Therefore, the material at the contact surface with cardboard is squeezed to the sides evolving a shear tension on the surface of the specimen. Consequently, strain-caused cracks could appear roughly all over the length of the specimen, resulting in lower CCS values.

But packing – be it cardboard or rubber - could have an opposite influence on CCS if the preparation of the specimen is not good enough or the steel plates are uneven. Under these circumstances packing can have a compensating effect by avoiding stress peaks which would otherwise lead to lower strength values.

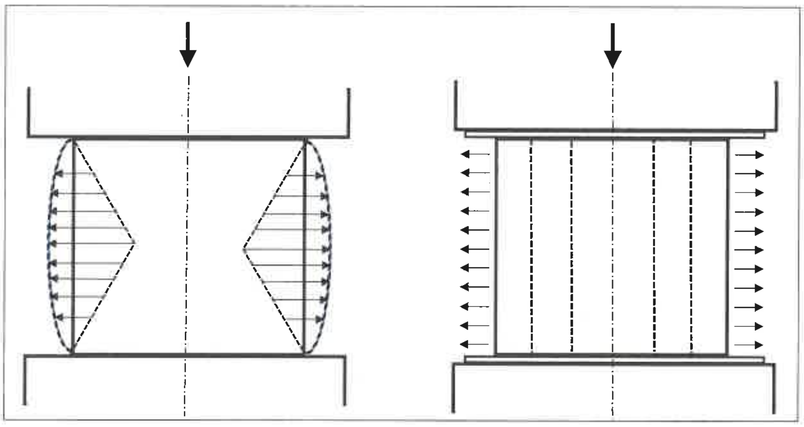

Fig. 1 Types of strain induction on a specimen during measurement of the Cold Crushing Strength (CCS)

Other influencing factors for the measurement of CCS are:

- the size and shape of the specimen,
- the direction of testing versus direction of pressing in fabrication,
- the presence of micro- and macro-cracks in the specimen,
- the surface condition of the specimen, and
- the load rate.

An overview on CCS values for various refractory materials is given in [2] and some detailed tests are also described in [3] and [4].

The state-of-the-art testing devices are hydraulic presses equipped with load cells in the axis of the force application, where the force speed is automatically controlled by proportional regulators. This avoids pressure pulses known in valve controlled old devices. New ones easily achieve the required accuracies, down to 1 % of the maximum force.

2 Objective: the comparison and establishment of correlations between standards ISO, EN (i.e.: DIN, etc), ASTM, and GB/T

CCS measurements have always been the subject of controversy. Unfortunately, there is not a single standard but several national and international ones (Section 2.1). They produce a significant scattering of results, admittedly up to 20 % standard deviation.

This is a foregone result of the heterogeneous structure of refractories, whose microstructure consist of grains and pores, each of different size and distribution. As a matter of fact, even small deviations in their production process – like the pressure applied during forming, the temperature distribution in the kiln during firing, etc. – may contribute to the inhomogeneity of the resulting material, and thus to the scattering of CCS measured values.

Tab. 1 Roundup of various international Cold Crushing Strength standards

Standard	Country	Sample Shape	Sample Size	Packing	Load Rate
ISO 10059-1	International	cylinder	50 mm or 36 mm	No	1,0 MPa/s
ISO 10059-2	International	cylinder or cube	cylinder 50 or 36 mm cube 75 mm or half standard brick	Yes 3–7 mm	1,0 MPa/s
EN 993-5	Europe	cylinder or cube	50 mm or 36 mm	No	1,0 MPa/s
ASTM C133-97	USA	cylinder or cube	51 mm	Yes 6,4 mm	0,2 MPa/s
GOST 4071.1-94	Russia	cylinder or cube	20–100 mm	No	1,0–2,0 MPa/s
JIS R2206 based on ISO 10059-1	Japan	cylinder	50 mm or 36 mm	No	1,0 MPa/s
JIS R2206-2 based on ISO 10059-2	Japan	cylinder or cube or half of a standard brick	cylinder 50 or 36 mm cube 75 mm or half standard brick	Yes 3–7 mm	1,0 MPa/s
IS 1528;4	India	cubes, cylinder or standard brick or half of a standard brick	50 mm or standard brick or half of a standard brick	No and Yes 3–7 mm	1,0 MPa/s
GB/T 5072-2008	China	cylinder	50 mm or 36 mm	No	1,0 MPa/s

Tab. 2 Properties of the investigated refractory bricks

Brick grade	Brick C	Brick S	Brick B	Brick A	Brick F	Brick R
Raw Materials	**magnesia carbon**	**magnesia spinel**	**bauxite**	**andalusite**	**fireclay**	**fireclay**
Density [g/cm³]	2,96	3,01	2,88	2,67	2,24	1,78
Porosity [%]	2,45	14,1	17,50	13,40	16,00	26,70
MgO [%]	95,50	88,10	0,10	0,10	0,25	0,35
Al_2O_3 [%]	1,10	10,5	82,80	61,10	41,.45	22,30
SiO_2 [%]	0,80	0,2	10,71	36,30	53,20	68,70
Fe_2O_3 [%]	0,70	0,50	1,50	0,80	1,40	2,00

Several CCS testing methods have been standardized, considering various possible influencing factors.,

2.1 Current international Cold Crushing Strength standards

A comprehensive summary of current CCS standards is given in Tab. 1.

The apparently simple determination of the CCS has been the subject of different standardized procedures, which results in significantly varying set of results. This becomes highly relevant or even confrontational when CCS values are given as guarantee between a refractory producer and the end user. But CCS measurements are also important for quality control purposes, for instance when used for evaluation of the homogeneity of a factory's refractory production, or when comparing different factories.

Finally, they are of outmost importance for designing and engineering technical installations, such as processing vessels for steel, aluminum, copper, cement, lime, glass, etc.. Values of CCS, together with some other parameters, such as refractoriness, thermal expansion, thermal conductivity, hot modulus of rupture, etc., are important for the calculation and layout of refractory linings worldwide.

3 Focus of the investigation

The focus of our investigation has been the evaluation of the most important influencing parameters on CCS testing.

Various types of refractory bricks grades, both basic and non-basic, covering a wide range of CCS values, from very high to low ones, were studied.

For each grade the evaluation has included several testing scenarios, those a priori considered having an influence on the dispersion of the CCS values measured, namely:

- Testing the influence of the testing standard employed: ASTM C133-97 (2021) and ISO 10059-1. The latter chosen as it is matchable with several other standards (Tab. 1).
- Testing within each brick and each laboratory separately (repeatability).
- Testing in different laboratories (reproducibility).
- Testing the influence of specimen shape (cylinder or cube) for each grade and each laboratory, as sample preparation for both standardized shapes is different.
- Testing the influence of load rate (0,2 and 1,0 MPa/s, respectively).
- Testing the influence of using packing or not.

The aim has been the determination of reproducibility and repeatability of standards, and to find systematic deviations that may be harmonized by a distinct factor to convert values from one standard into another.

4 Laboratories and materials

4.1 Laboratories

Seven internationally well-respected laboratories were selected for the investigations:

- Laboratories in Germany, Poland and Spain all specialized in measurements on refractory and ceramic materials.
- Refractory manufacturer's laboratories: in the United States of America, Great Britain, Austria (which also created the design, performed data preparation and statistical analysis) and in Germany (which also acted as coordinating laboratory).

4.2 Refractory brick grades

Six industrially, on hydraulic high-performance presses formed brick grades were selected to cover the whole range of dense refractory materials and expected material strengths, Tab. 3. Pure lightweight thermal insulation bricks were omitted from the investigation as they are not in the scope of the standards compared here.

4.3 Design of tests and sample description

4.3.1 General

To achieve significant and meaningful results, a sophisticated procedure was elaborated to determine possible correlations among the influencing parameters.

The population constituted by all samples was used to carry out:

- An interlaboratory tests for each standard method and brick grade (round robin test),
- A comparison of the tests carried out following ASTM C133-97 (onwards ASTM) and ISO 10059-1 (onwards ISO). The results obtained by each method were compared to those obtained for 50 mm cylinders tested according to ISO.

The Spanish laboratory and the two refractory manufacturers laboratories in Austria and Germany also carried out some additional tests intended for determining the influence of load speed on ISO Cylinders (1 MPa/s vs. 0,2 MPa/s) and the effect of packing on ISO Cylinders separately, and not only both together in the combinations defined by ASTM and ISO.

4.3.2 Sample preparation

All samples for the comparative tests were wet drilled and/or cut in a single laboratory, using the same equipment that was operated by one person. The final sample preparation was completed in each laboratory separately (cut/grind), so that the influence of sample preparation is as it is in real business.

For each refractory grade three bricks were selected from a higher initial population. In order to avoid deviations in CCS results that are caused by inhomogeneities typical for the brick production, bricks were selected according to fit in a 0,01 g/cm³ density interval.

From these three bricks, cylinders as well as cubes were prepared. The samples were dried immediately after cutting to prevent hydration (most important for basic bricks) or influence from the filling of pores with water.

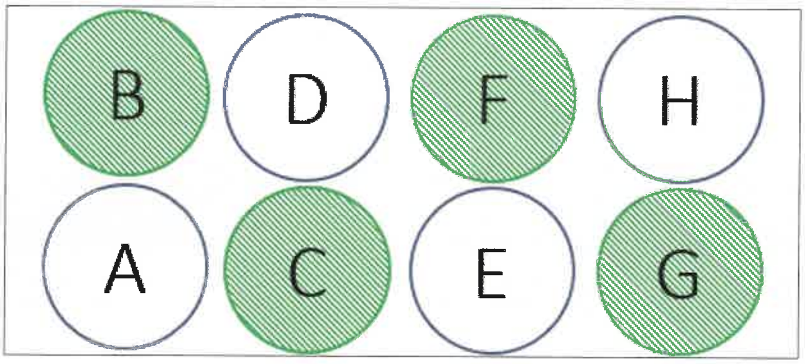

Fig. 2 Design pattern of specimens' extraction for comparison test for both: i) ASTM Cylinders and Cubes and ii) ISO Cylinders and Cubes

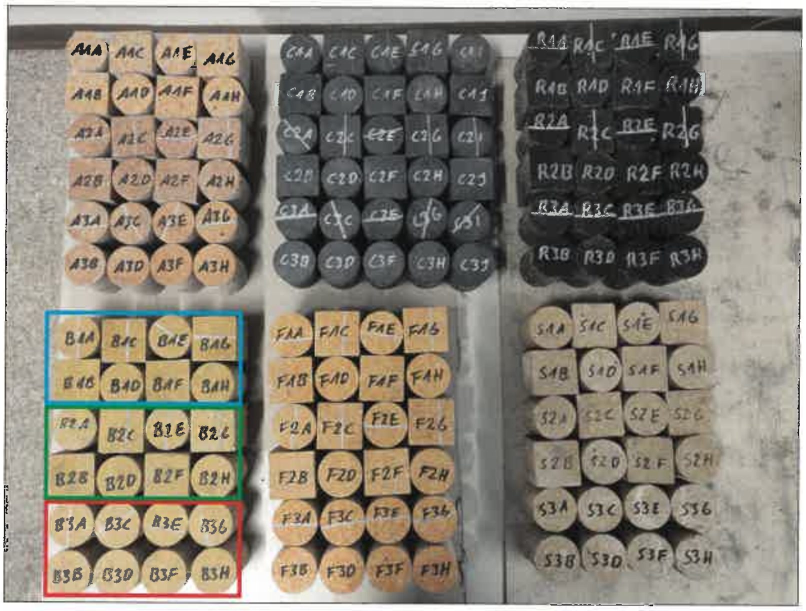

Fig. 3 General view of all specimens and brick grades tested in one laboratory: Blue square: batch of specimen for comparison of ISO Cylinder with ISO Cube; Green square: batch of specimen for comparison of ISO Cylinder with ASTM Cube; Red square: batch of specimen for comparison of ISO Cylinder with ASTM Cylinder

The sampling was designed to compare each type of test specimen and condition with that of the ISO cylinders taken as reference, Fig. 2.

- On brick #1: ISO cylinders (A, D, E, H) as reference for ISO cubes (B, C, F, G)
- On brick #2: ISO cylinders (A, D, E, H) as reference for ASTM cubes (B, C, F ,G)
- On brick #3: ISO cylinders (A, D, E, H) as reference for ASTM cylinders (B, C, F, G).

Fig. 3 shows a general overview of the samples for one laboratory. Each laboratory tested 144 specimens, making the total amount of specimens tested 1014 (for the magnesia carbon brick it was possible to cut 2 more samples out of the brick, which were used as additional statistical covering).

4.3.3 Coverage of CCS parameters by sample quantity.

The green marking in Tab. 3 shows the reference method used. In principle, a direct comparison was always calculated either per brick or twin cylinder to the refence method ISO Cylinder, which explains the very high number of measurement results.

5 Determination of precision (ISO 5725-2)

Based on the results of the interlaboratory study, the precision of the different tests methods was calculated according to ISO 5725-2.

Precision was evaluated under the following conditions:

- Repeatability: one equipment, tests carried out by one operator, with the same material in one laboratory, and
- Reproducibility: different equipment, carried out by different operators with the same material in different laboratory).

Trueness and hence the accuracy of the methods was not determined, because the test results depend on each method's parameters: geometry of the specimen and sample preparation, Tab. 4.

The precision data can include absolute and relative standard deviation for repeatability and reproducibility as well as repeatability and reproducibility itself for all grades separately.

To focus the overview only the relative repeatability and reproducibility interval are reported.

According to ISO 5725-1 the repeatability (r) reflects the closeness of agreement, that is, the maximum permissible difference due to the test error between two test results under repeatable conditions (ASTM C133). As such, two test results that do not differ by more than the repeatability interval will be from the same population. The reproducibility (R) has the same definition under reproducibility conditions.

As for reproducibility, the smallest relative repeatability interval was obtained under

Tab. 3 Number of CCS results analyzed for each influencing factor and specimen type

Evaluated Influencing Factors				Grade					
Packing	Shape	Load Rate [MPa/s]	Sum	A	B	C	F	R	S
Without (no)	Cube	1,0	227	28	28	63	28	28	52
	Cylinder	0,2	73	12	12	14	12	12	11
		1,0	828	108	108	216	108	108	180
With	Cube	0,2	226	28	28	62	28	28	52
	Cylinder	0,2	227	28	28	63	28	28	52
		1,0	74	12	12	14	12	12	12

Tab. 4 Precision data for the different methods and grades. The color marking indicates very good precision values in green and red the worst precision values in red

Method	Repeatability Interval	A Andalusite	B Bauxite	C Magnesia Carbon	F Fireclay	R Low density Fireclay	S Magnesia Spinel	All Grades
ISO_cyl	r [%]	18,4	18,1	14,7	14,4	13,9	27,6	17,9
ISO_cub	r [%]	19,0	18,3	20,6	15,8	20,3	36,2	21,7
ASTM_cyl	r [%]	27,7	23,8	18,9	17,6	16,3	25,4	21,6
ASTM_cub	r [%]	30,6	24,2	21,8	20,5	15,3	32,0	24,1
EN 993-5	r [%]	25,6		15,0				
ASTM C133	r [%]		12,2			5,9		
	reproducibility interval							
ISO_cyl	R [%]	30,9	23,7	21,1	26,7	15,9	33,9	25,4
ISO_cub	R [%]	43,0	43,4	30,7	46,2	27,2	46,0	39,4
ASTM_cyl	R [%]	46,9	48,9	25,3	32,3	30,5	37,9	36,9
ASTM_cub	R [%]	48,1	42,9	28,3	36,9	34,5	51,1	40,3
EN 993-5	R [%]	34,0		24,2				
ASTM C133	R [%]		45,0			18,1		

ISO conditions: cylinder shaped specimens, load rate 1,0 MPa/s without packing. This is possibly due to an easier sample preparation with drilling and cutting/grinding of two sides, more experience of the participating laboratories with cylinders, etc.

Fig. 4 reflects the differences due to the different test conditions as well as the high scatter of the single results. The highest scatter was observed for bricks with the highest CCS values, while lower values result in lower scattering.

5.1 Tests according to ISO 10059-1 with cylinders

The first evaluation of precision data summarizes the test parameter for the reference method ISO Cylinders without packing at a load rate of 1,0 MPa/s.

Half of all specimens of one brick were tested with these parameters. Therefore, much more results are available than from any other method

Tab. 5 gives an overview of the main precision data for ISO Cylinders. For example, for magnesia carbon bricks C 188 samples were tested. The mean value was calculated for all tested samples (188 results) excluding outliers. For this grade, 7 laboratories conducted the test, but one laboratory was an outlier (difference 7–>6). Next columns are the reproducibility interval and the repeat-

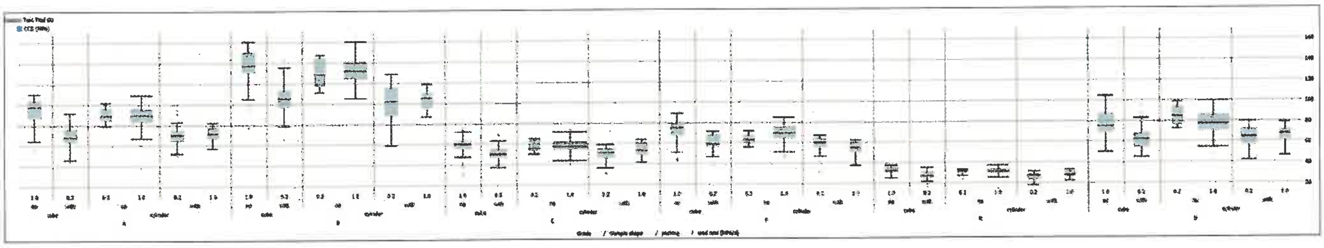

Fig. 4 Overview of all test results: one box contains 50 % of all tested results of all laboratories under the defined conditions, the area between the whiskers contains 95 % of all results performed under the defined conditions. This means that the narrower the whiskers, the lower the scatter and the better the precision, e.g., first box: grade A, shape: cube; without packing (no); load rate 1,0 MPa/s

Tab. 5 Basic table of the Interlaboratory Study (ILS) based on ISO Cylinders: all precision data for grades separately; all outliers eliminated

Grade	Number of Test Results	Number of Laboratories	Mean Value [MPa]	Reproducibility Interval [MPa]	Relative Reproducibility Interval [%]	Repeatability Interval [MPa]	Relative Repeatability Interval [%]
A	84	7	89,0	28,2	31,7	19,8	22,3
B	84	7	134,0	35,4	26,4	23,6	17,6
C	188	6	59,2	14,8	24,9	11,6	19,6
F	84	7	72,0	19,3	26,8	13,7	19,0
R	84	6	31,8	6,0	18,9	4,6	14,5
S	156	7	78,2	28,3	36,2	22,2	28,5

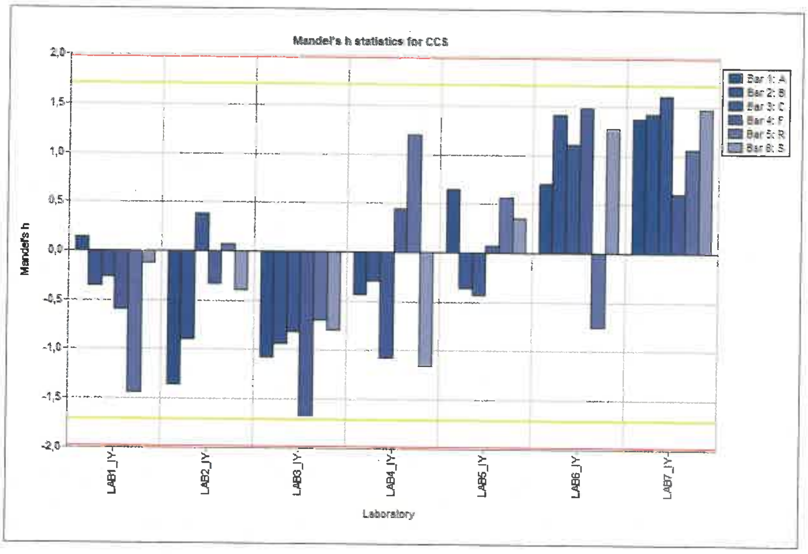

Fig. 5 **Mandel's h statistics for method ISO Cylinder**

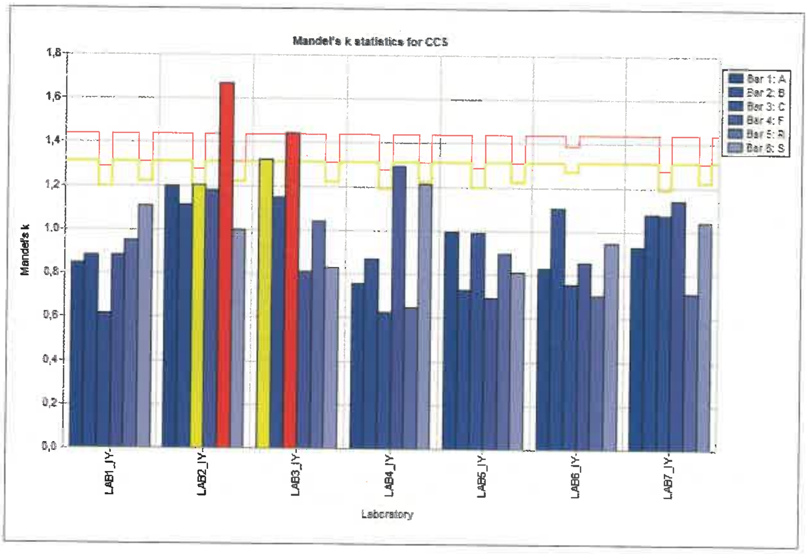

Fig. 6 **Mandel's k statistics for method ISO Cylinder**

ability intervals, also absolute and relative to the means. The intervals are more descriptive than other precision parameters like repeatability or standard deviation. Two single results under repeatability or reproducibility conditions should not differ more than these intervals. Otherwise, it is not the same sample, or the methods are different.

A graphical overview for comparison of mean values of all laboratories and grades are given by the two figures of Mandel's statistics, the h-statistics, and the k-statistics for the repeatability performance of each laboratory.

Both Mandel's h and k statistics are recommended by ISO 5725-2 (10) as well as ASTM E691 [11].

The bars are grouped by the laboratories and each bar represents the standardized results of each grade. The "h" statistics displays positive values for higher results than the mean of all laboratories vice versa. The "k" statistics displays the repeatability: bars, yellow or red, marking "significant" to "high" variations.

Fig. 5 shows that laboratories 6 and 7 measure predominantly higher values, while laboratories 1, 2, and 3 measure values which are generally lower than the overall mean value.

Laboratories 4 and 5 measure values which are around the mean value but show a wide scattering of values for the different brick grades. This is a sign for a non-systematic bias.

All laboratories are within the critical value. A systematic dependence on special brick grades is not obvious.

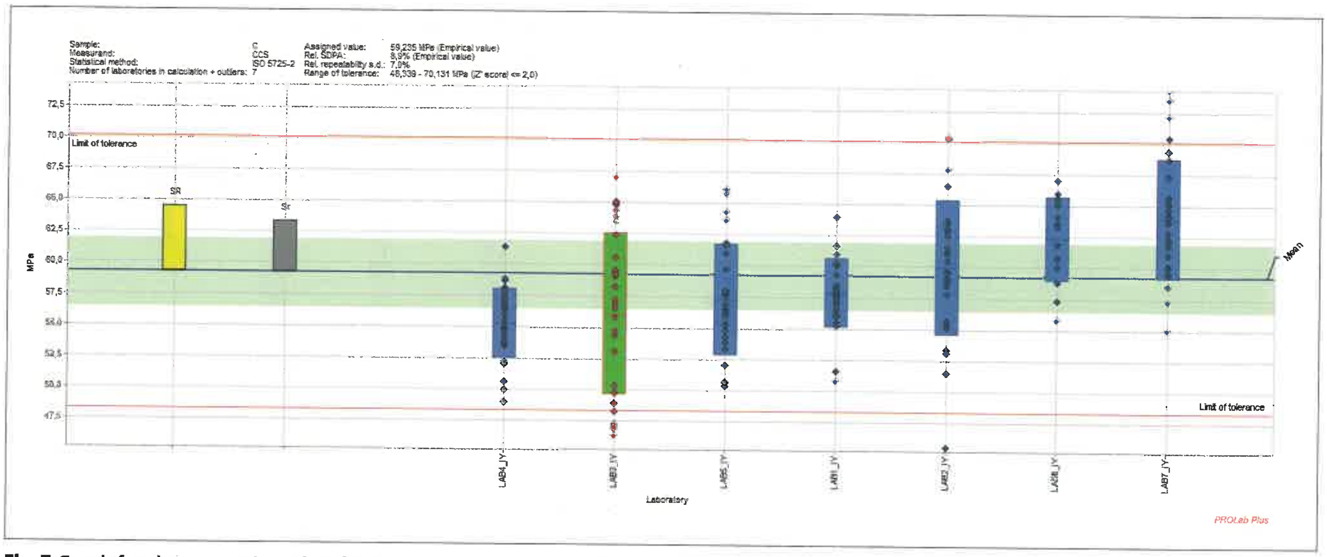

Fig. 7 **Graph for the magnesia carbon brick grade C with all single results of each laboratory grouped by laboratory**

For Mandel's statistics, red bar (a result which is significantly different to the other grades, samples and laboratories (it applies also for yellow bars)) is defined as outlier and erased for further calculations of the precision data. In this case, laboratories 2 and 3 are showing outliers (above the critical value), but only for some brick grades (lab 2: magnesia carbon brick C, low-den-

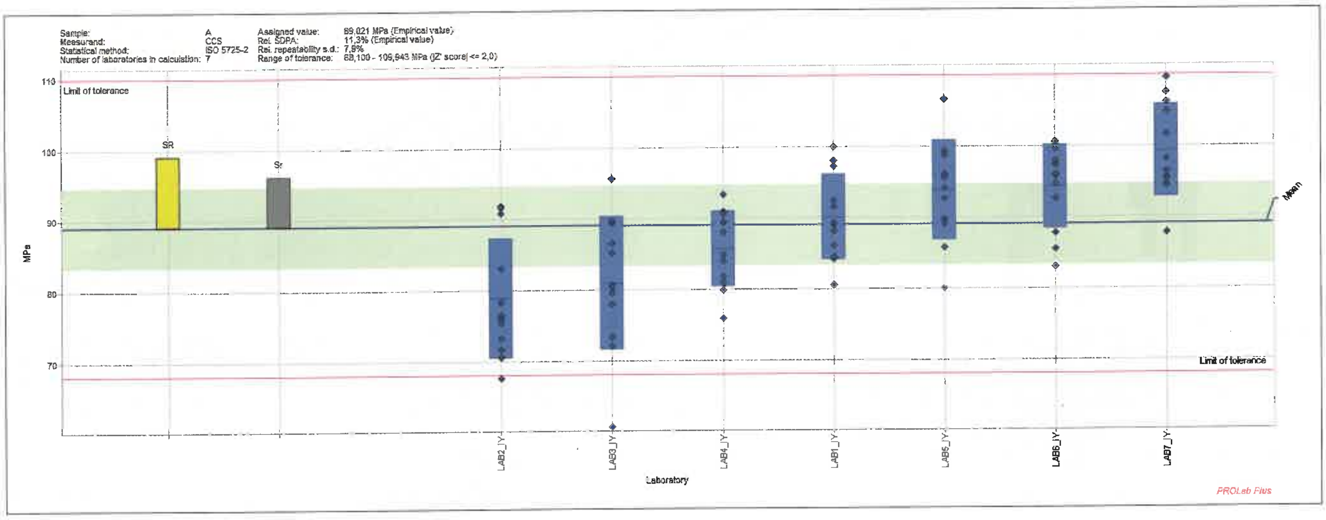

Fig. 8 **As Fig. 7 here for andalusite brick A**

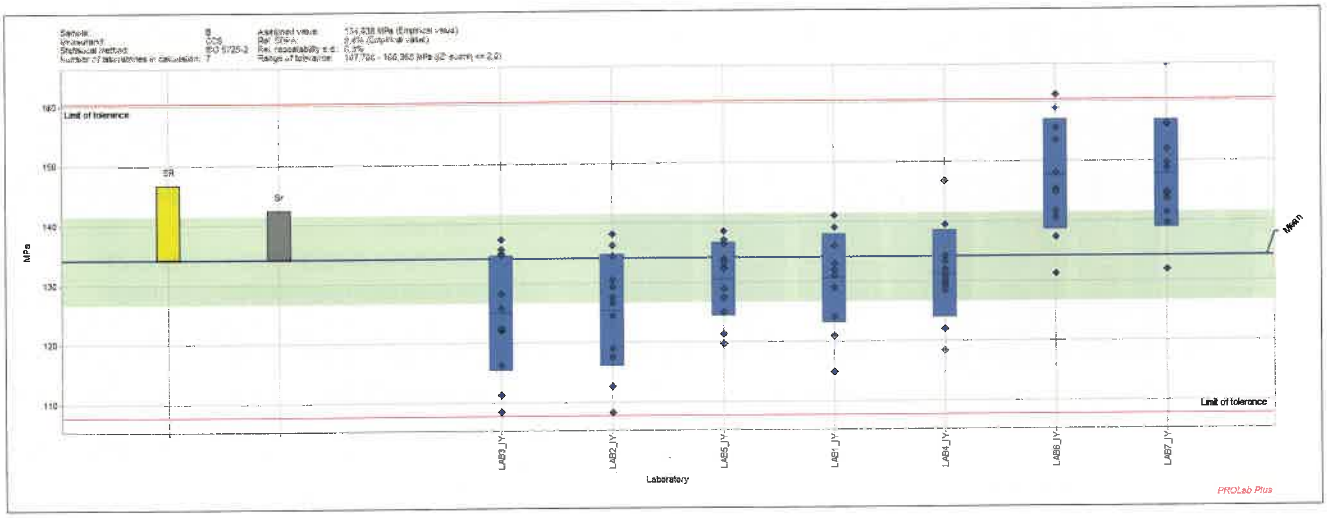

Fig. 9 **As Fig. 7 here for bauxite brick B**

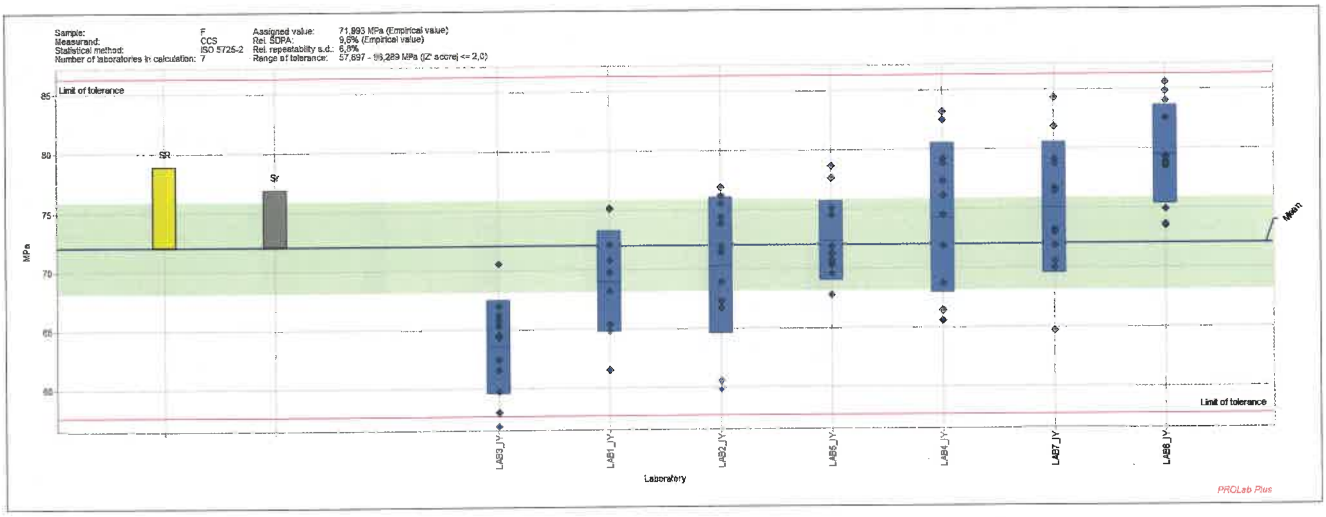

Fig. 10 **As Fig. 7 here for fireclay brick F**

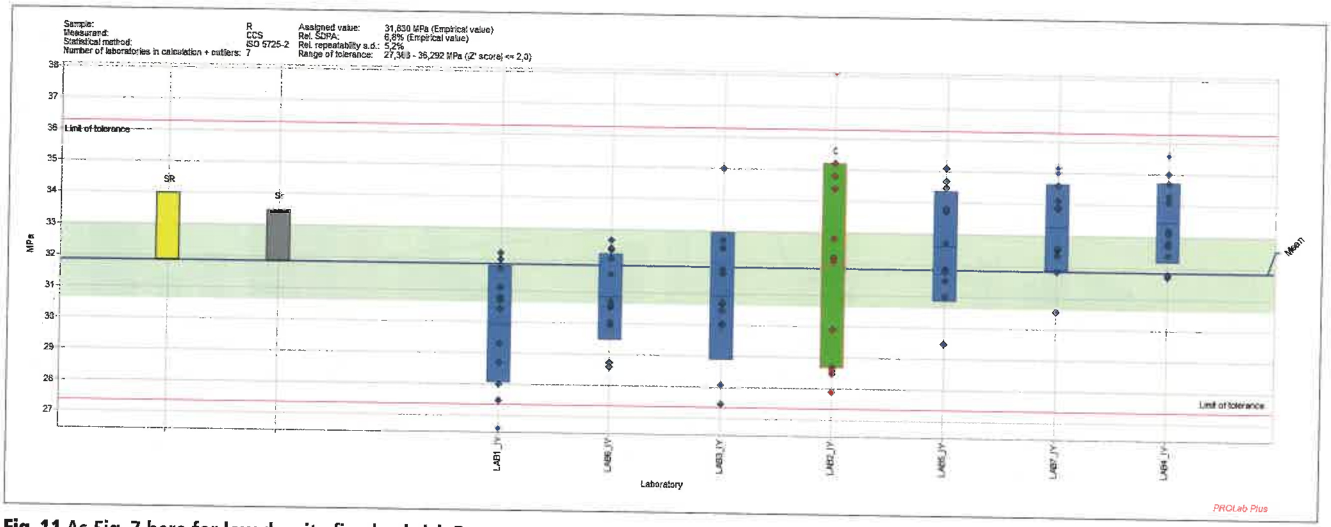

Fig. 11 As Fig. 7 here for low density fireclay brick R

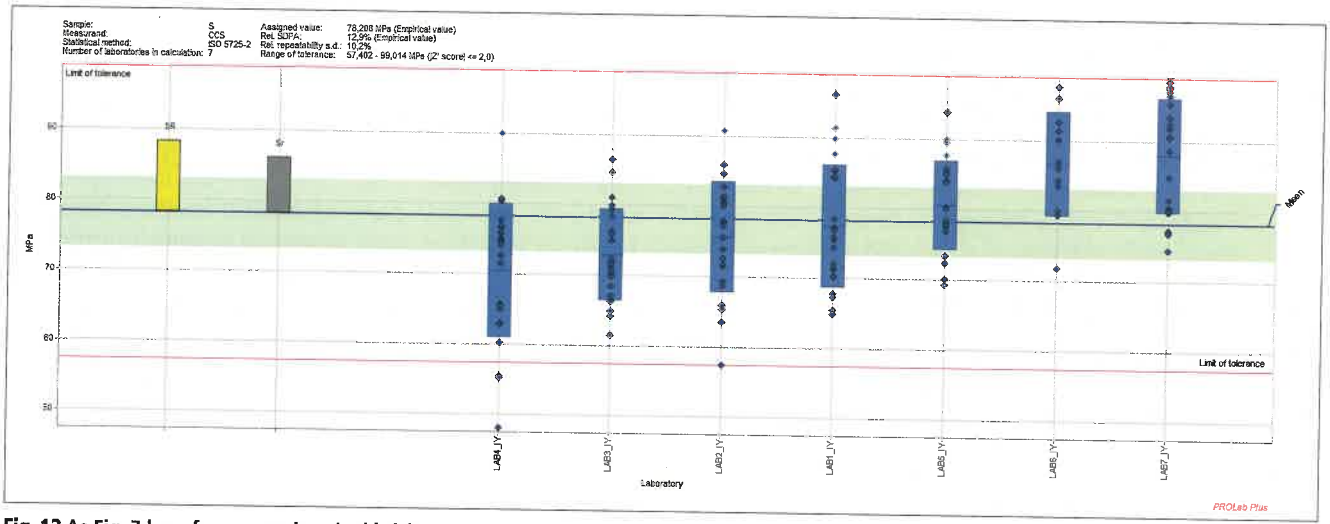

Fig. 12 As Fig. 7 here for magnesia spinel brick S

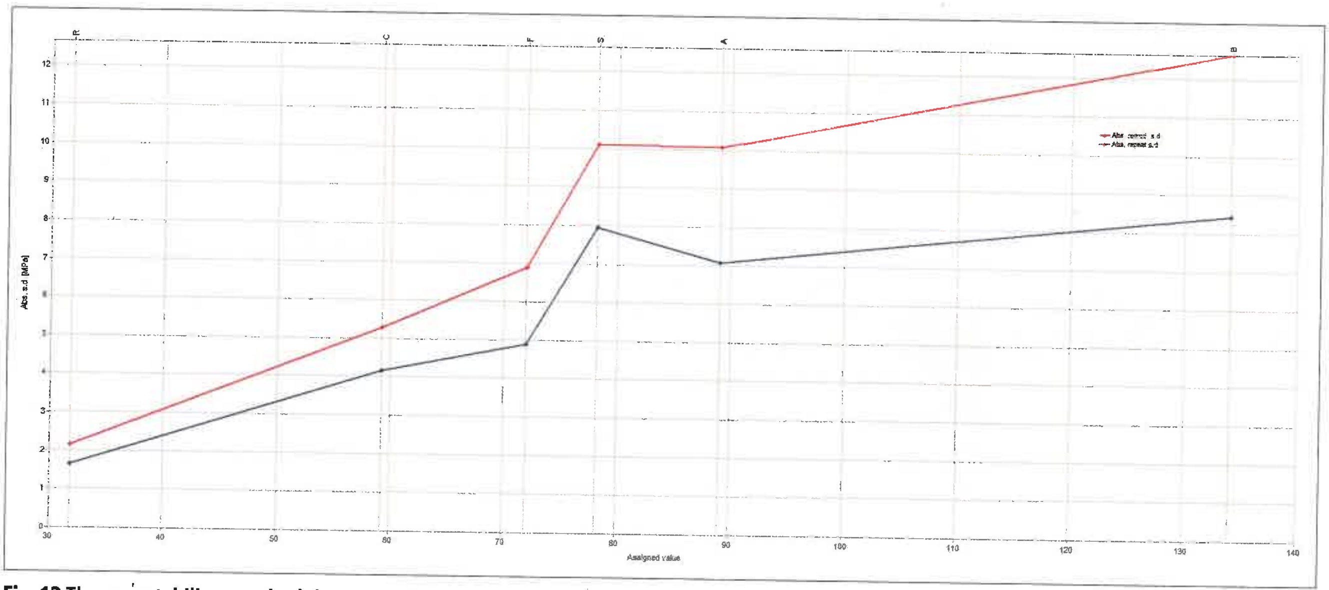

Fig. 13 The repeatability standard deviation [MPa] of the assigned values (CCS) increases with increasing absolute values of CCS and reproducibility standard deviation, respectively

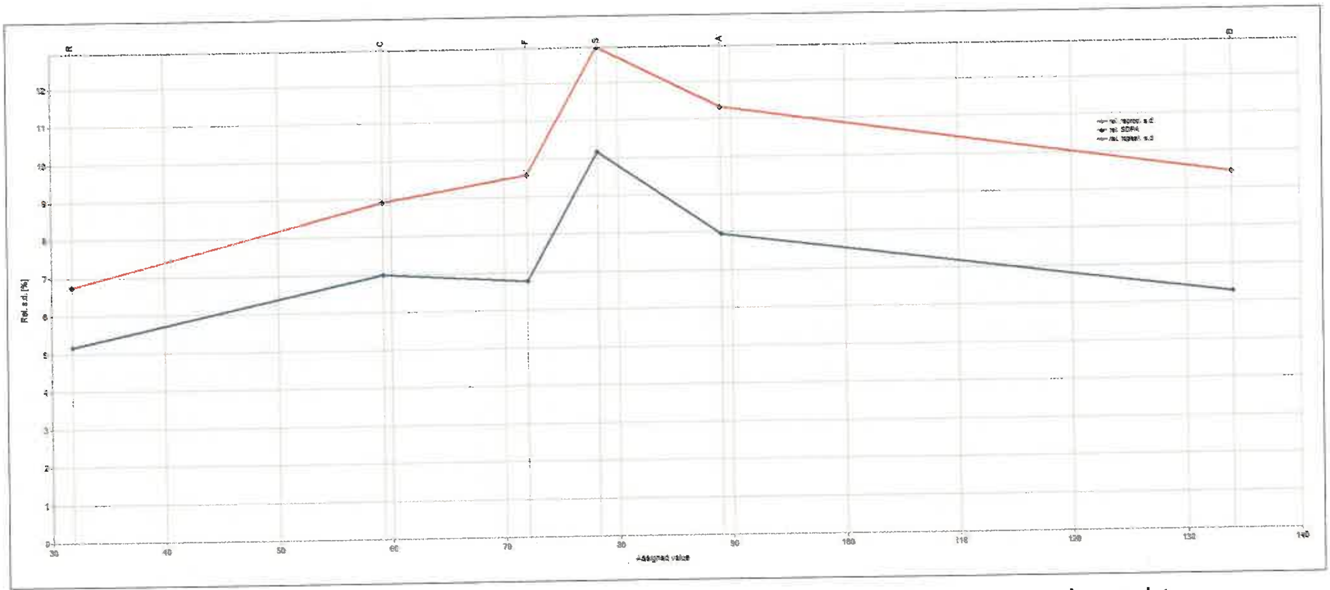

Fig. 14 **The relative repeatability standard deviation [%] of the assigned values (CCS) is approximately the same over the complete range of absolute CCS values and relative reproducibility standard deviation, respectively**

sity brick R; lab 3: andalusite brick A and magnesia carbon brick C), Fig. 6.

In Fig. 7, laboratory 3 red dots for magnesia carbon brick C show the single results and they show a high variation of the individual values. These results are eliminated for further precision calculation. The same applies for laboratory 2 and the low-density fireclay brick grade. The data for the other brick grades are given in Figs. 8 to 12. Figs. 13 and 14 show the relative and absolute standard deviation related to the absolute strength. Figs. 13 and 14 reflect, under repeatability and reproducibility conditions respectively, the dependency of scatter on grades. The

Tab. 6 **Basic table of the Interlaboratory Study (ILS) based on ISO Cubes: all precision data for grades separately; all outliers eliminated**

Grade	Number of Test Results	number of laboratories	Mean Value [MPa]	Reproducibility Interval [MPa]	Relative Reproducibility Interval [%]	Repeatability Interval [MPa]	Relative Repeatability Interval [%]
A	28	7	93,8	40,4	43,0	17,8	19,0
B	28	7	134,5	58,3	43,4	24,7	18,3
C	63	6	60,5	18,6	30,7	12,5	20,6
F	28	7	72,0	33,3	46,2	11,4	15,8
R	28	7	33,4	9,1	27,2	6,8	20,3
S	52	7	76,6	35,2	46,0	27,8	36,2

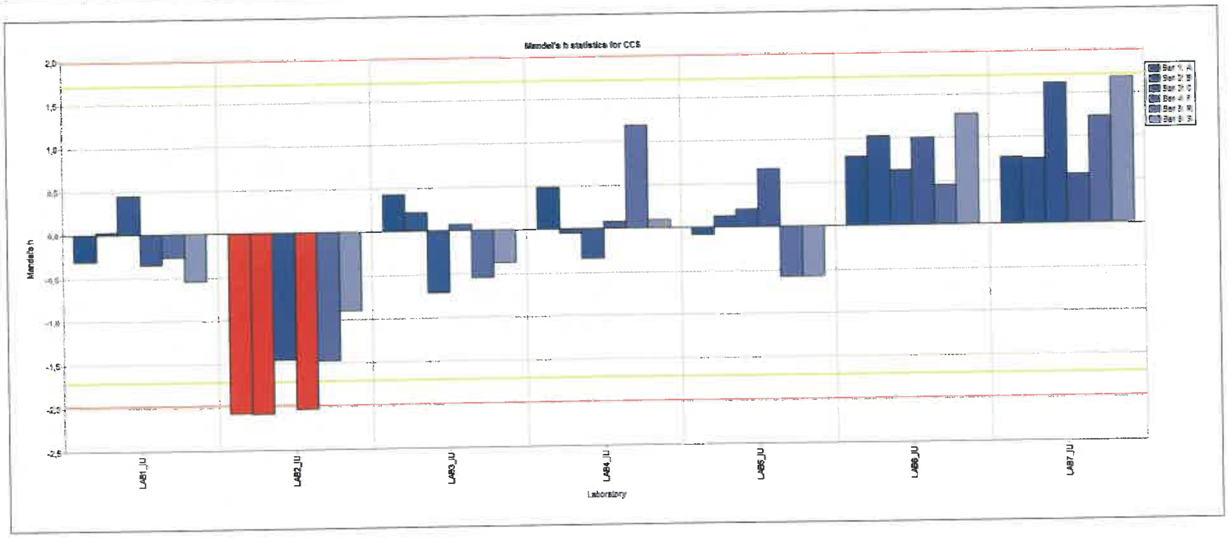

Fig. 15 **Mandel's h statistics for method ISO Cubes**

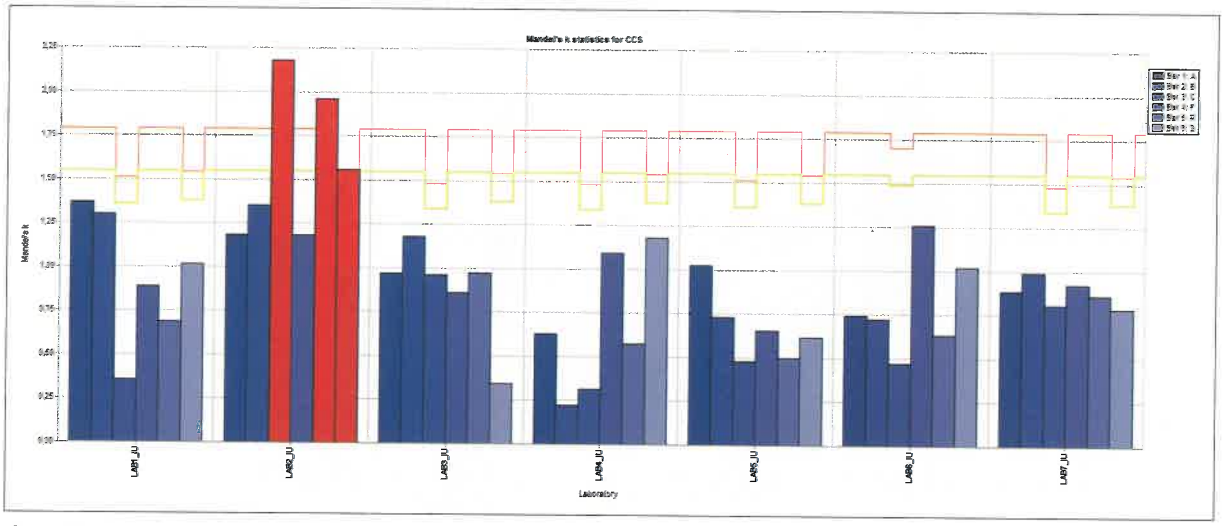

Fig. 16 Mandel's k statistics for method ISO Cubes

peaks in both diagrams are related to grade S (magnesia spinel), which showed some special effects throughout the investigations.

5.2 Tests according to ISO 10059-1 with cubes

The precision data summarizes the test parameter for the method ISO Cubes at a load rate of 1,0 MPa/s without packing, Tab. 6. Several values for laboratory 2 regarding cubes are outside of the critical value (andalusite, bauxite, and fireclay), Fig. 15, while all other values show a similar trend as for cylinders. Remarkably labs. 6 and 7 continue the trend of high Mandel's h values, which means they measure higher values than the mean of all laboratories. Significantly laboratory 2 had again too high scatter in their results.

For the geometrical parameter "cube" similar results as for "cylinder" are found also for Mandel's k. Laboratory 2 shows statistically differing results compared to the other ones, mainly for magnesia carbon, fireclay,

Tab. 7 ASTM Cylinders: all precision data for grades separately; all outliers eliminated

Grade	Number of Test Results	Number of Laboratories	Mean Value [MPa]	Reproducibility Interval [MPa]	Relative Reproducibility Interval [%]	Repeatability Interval [MPa]	Relative Repeatability Interval [%]
A	28	7	70,9	33,2	46,9	19,7	27,7
B	28	7	101,7	49,7	48,9	24,2	23,8
C	63	5	52,2	13,2	25,3	9,9	18,9
F	28	6	60,5	19,5	3,3	10,6	17,6
R	28	6	27,5	8,4	30,5	4,5	16,3
S	52	6	64,8	24,5	37,9	16,4	25,4

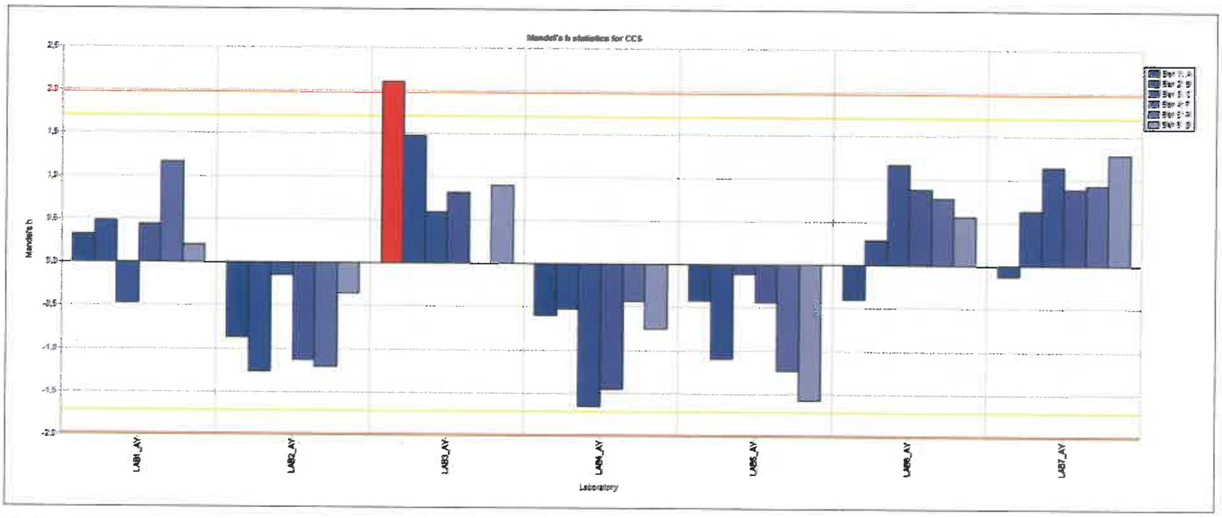

Fig. 17 Mandel's h statistics for method ASTM Cylinders

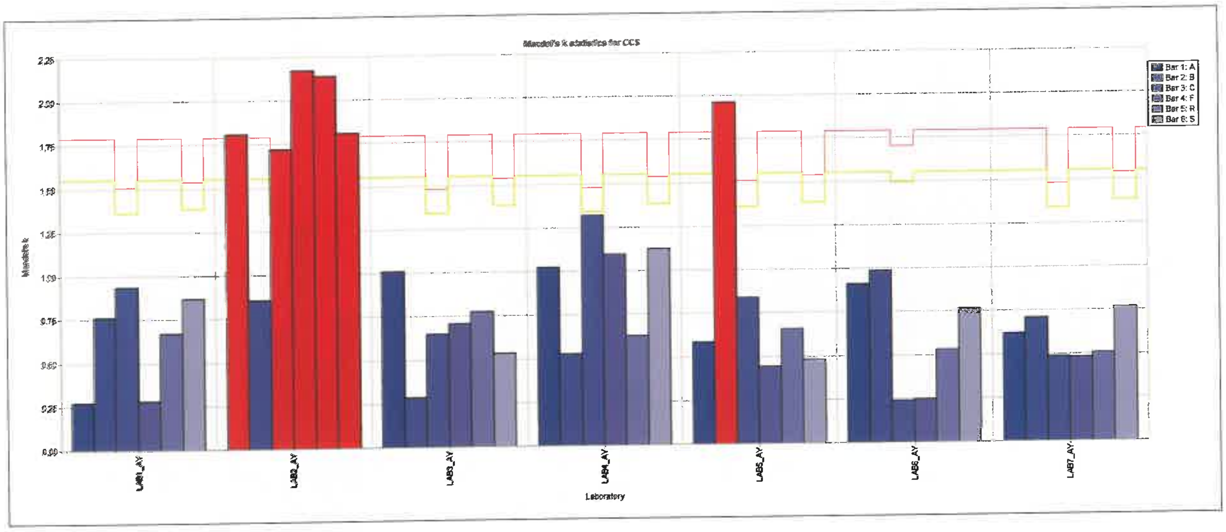

Fig. 18 Mandel's k statistics for method ASTM Cylinders

and magnesia spinel bricks, Fig. 16. Still, the other values of Mandel's k statistics are also higher, Figs. 18 and 20. It has to be noted that the outliers for Mandel's h and Mandel's k statistics affect different brick grades, still belonging to laboratories 2 and 3.

5.3 Tests according to ASTM C133 with cylinders

Tab. 7 and Figs. 17 and 18 summarize the precision data and test parameters for the method ASTM Cylinder tested at a load rate of 0,2 MPa/s with packing.

For ASTM cylinders the trend is like that of ISO. Laboratories 6 and 7 showed always values above the average. But contrarily to previous cases, laboratory 3 also showed high values.

Moreover, in this case also laboratory 2 showed significant effects on repeatability.

Tab. 8 Basic table of the Interlaboratory Study (ILS) of ASTM Cubes: all precision data for grades (samples) separately

Grade	Number of Test Results	Lmean value [MPa]	Reproducibility Interval [MPa]	Relative Reproducibility Interval [%]	Repeatability Interval [MPa]	Relative Repeatability Interval [%]
A	28	69,6	33,5	48,1	21,3	30,6
B	28	106,5	45,7	42,9	25,8	24,2
C	62	50,3	14,2	28,3	11,0	21,8
F	28	60,5	22,3	36,9	12,4	20,5
R	28	28,9	10,0	34,5	4,4	15,3
S	52	63,3	32,3	51,1	20,2	32,0

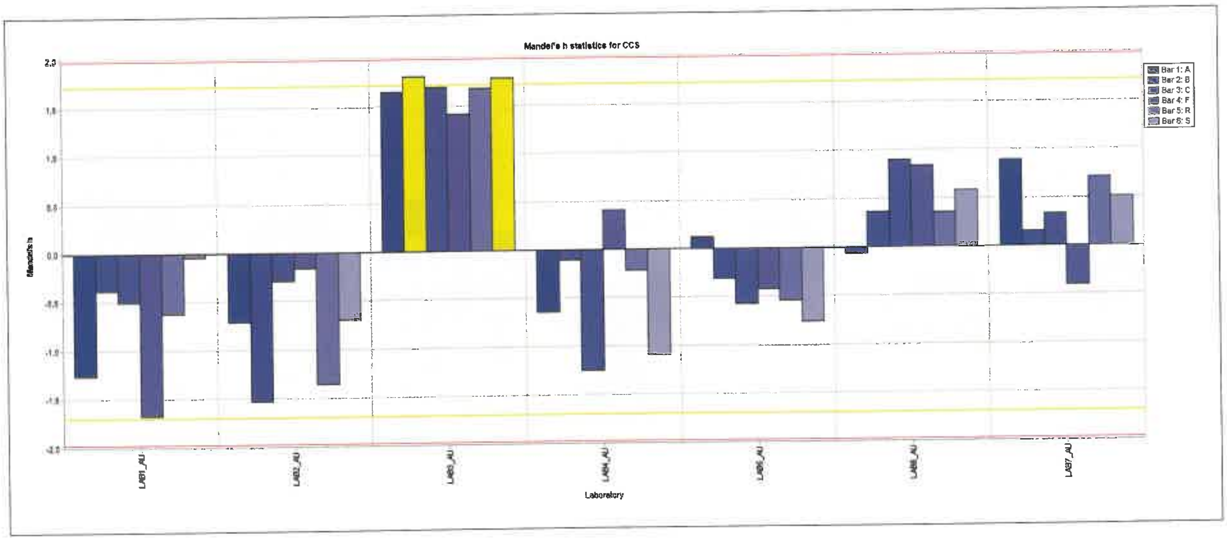

Fig. 19 Mandel's h statistics for method ASTM Cubes

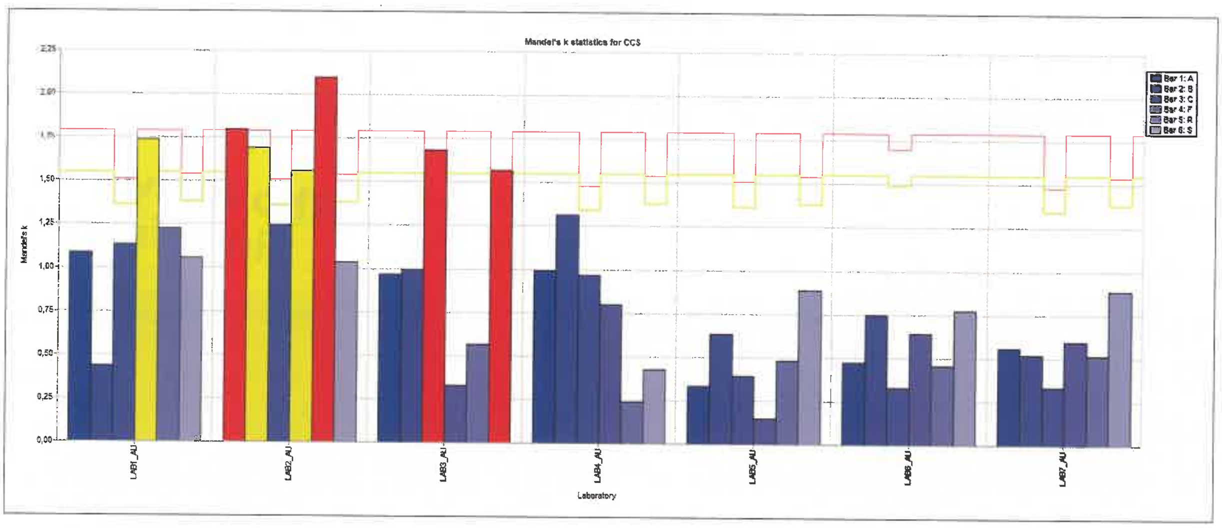

Fig. 20 Mandel's k statistics for method ASTM Cubes

5.4 Tests according to ASTM C133 with cubes

Tab. 8 and Figs. 19 and 20 summarize the precision data and test parameters for the method ASTM Cube testes at 0,2 MPa/s with packing.

ASTM Cubes also show the trends observed for the other parameters. Laboratory 3 shows higher values compared to lab. 6 and lab. 7, all others are still well below the average for Mandel's h and k statistics, Figs. 19 and 20.

Acknowledgement

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Remark from the editor:

Further chapters in the next issue will report on Determination of Precision and Special View on Brick Grades.

Part 2 will be published in refractories WORLDFORUM **15** (2023) [3] and the last part including references in refractories WORLDFORUM **16** (2024) [1].

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