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

Part 3: Focus on Brick Grades

G. Urbanek, H.-J. Klischat, M. Miranda-Martinez

Cold crushing strength (CCS) is a standard test method for measuring refractory products mechanical resistance which is mentioned in nearly all data sheets. However this measurement, although theoretically quite simple, often produces a wide variety of results which may be cause for discussions between refractory producers and refractory users. A statistical evaluation of precision data and the comparability of different CCS standards was carried out by the Task Force "Testing Methods and Standards" of the World Refractories Association. The exercise involved the work of seven laboratories and the application of Mandel's statistics to all the results and materials tested. The study showed not only the differences between applying standards ASTM C133 and ISO 10059-1 to the same set of samples, but also the influence of each testing parameter and some dependencies based on material specific characteristics. For instance, a higher scatter of values (higher standard deviation) was observed with increasing CCS values. Also, some specific effects may be assigned to each material microstructural characteristics, for instance, in magnesia-spinel bricks, the presence of microcracks does influence the strain field within the specimens. In the case of fireclay bricks, loading rate related effects were observed, which are attributed to the presence of an abundant glassy phase. Furthermore, CCS values for all brick grades were affected by laboratory specific measurement conditions, in some cases these resulted in lower measured values. In conclusion, it would be highly desirable that the standards: ISO 10059 (dependant of ISO/TC 33) and ASTM C133, reflect more statistical data incorporating CCS reference values for different refractory grades. A suggestion is therefore made for the revision of standard ISO 10059-1 with the incorporation of precision data, a guidance for the conversion of data between test methods, some suggestion about the number of tests specimens and an even more precise advice for preferred drilling schemes.

8 Introduction

Although Cold Compression Strength values (CCS) describe the performance of a refractory product only in a limited way, CCS is widely used as reference parameter in data sheets and product definitions. The Task Force on Testing Methods and Standards of the World Refractory Association (WRA) has investigated not only the precision data and comparability of the different CCS standards, [12–13], but has also extensively tested six different types of refractory brick materials. Measurements were performed according to standards ASTM C133

Gerhard Urbanek
RHI Magnesita, Austria

Hans-Jürgen Klischat
Refratechnik Cement, Germany

Manuel Miranda-Martinez
Idonial Technological Center, Spain

World Refractories Association
Brussels, Belgium

Peer reviewed by Prof. Olaf Krause, University of Applied Sciences, Koblenz, Germany

Corresponding author: *G. Urbanek*
E-mail: Gerhard.Urbanek@RHIMagnesita.com

WRA Technical Working Group on "Cold Crushing (=Compressive) Strength"

Keywords: cold crushing strength, standards, interlaboratory study, refractory brick strength, ASTM, LSO

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

and ISO 10059-1. These two standards differ mainly in the load rate applied and the use or not of a packing layer between the plunger and the test specimen. The results obtained in the investigation have shown that ASTM C133 gives, on average, around 24 % lower CCS values, a result which is attributed to the use of the packing. The influence of test specimen geometry, either cylindrical or cubic, was also investigated, and showed only minor effects on measured CCS values.

It was also the intention of the study to check how material microstructure influences CCS measurements. Brick grades of different nature were tested. These included magnesia-carbon, magnesia-spinel, bauxite, andalusite, fireclay and insulation fireclay bricks. A recommendation for the revision of the ISO 10059-1 would be to include references of several refractory grades. The proposed revision would also include guidelines about precision data, number of specimens to be tested and drilling schemes.

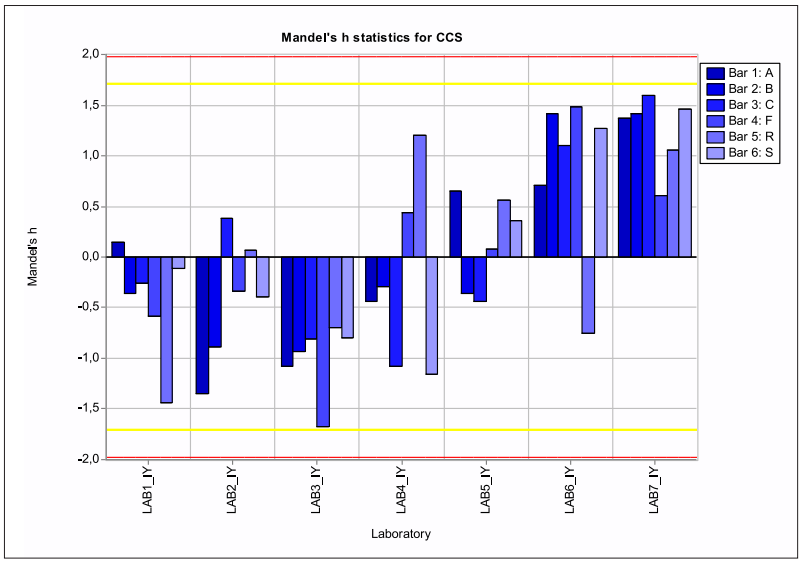

Fig. 29 Mandel's h statistics for method ISO cylinder (equates Fig. 5 in [12])

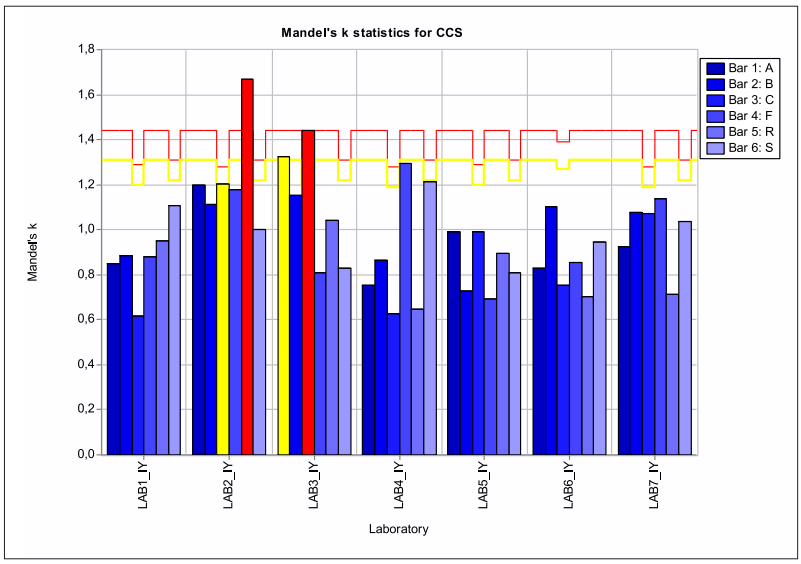

Fig. 30 Mandel's k statistics for method ISO cylinder (equates Fig. 6 in [12])

8.1 Materials and test procedures

Basic and non-basic refractory bricks grades, covering a wide range of CCS values, were tested in the study. The chemical analysis, density and porosity characteristics of the magnesia-carbon (C), magnesia-spinel (S), bauxite (B), andalusite (A), fireclay (F), and lightweight fireclay (R) bricks investigated are shown in Tab. 2 [12].

For each grade several testing scenarios suspected to have an influence on the dispersion of the CCS values were tested. These were:

- influence of the testing standard employed, both ASTM C133-97 (2021) and ISO 10059-1,
- repeatability: testing within each brick and each laboratory separately,
- reproducibility: testing in different laboratories,
- influence of specimen shape: cylinder or cube,
- influence of load rate: at both 0,2 and 1,0 MPa/s and, finally,
- influence of using packing or not.

Due to the expected high scatter of results of interlaboratory testing, Mandel's statistics were used to detect outliers and systematic differences between laboratories. The specific analysis used have comprised:

- h-statistics for comparison of mean values of all laboratories and grades, used in order to determine the consistency of interlaboratory tests and to confirm if a laboratory is an outlier;

and

- k-statistics to check the repeatability performance of each laboratory by comparing the standard deviation of a laboratory with the average of the standard deviation of all laboratories. Mandel's statistics are recommended both by ISO 5725-2 (3) and ASTM E691 (4).

9 Focus on each brick grade

Although all data gathered in the study have been analysed, a closer look was placed on the results obtained for each refractory material grade. And, in that specific case, the evaluation, based on Mandel's statistics, was carried out only on the results for ISO cylinders.

9.1 Magnesia-carbon brick (C)

Magnesia-carbon bricks are manufactured from fused magnesia aggregates and graphite. Graphite is constituted by plate-like grains which during the pressing of the bricks tend to get aligned. This effect influences all their properties, including CCS.

The CCS measurements on ISO cylinders showed that Laboratories 6 and 7 produced the highest values, while Laboratory 3 measured the lowest ones, Fig. 29.

Laboratory 3 was characterised by a high standard deviation, exceeding the lower tolerance limit, which is ±2 standard deviations from the mean value of all laboratory results, Fig. 6 [12]. Lab 3 scatters between C 47–67 MPa and this includes the differences between bricks, not only the scatter within one brick.

The measurements on ISO cubes showed a different picture, Fig. 31. While laboratories 6 and 7 still show the highest values, Laboratory 2 showed unacceptable low values and a high variation. The remainder presented intermediate values with a low scatter of results. Remarkably, the tolerance limit for cubes was significantly higher than for cylinders, Fig. 32.

Measurements on ASTM cylinders resulted in a very high scatter of values for Laboratories 2 and 5, while laboratories 6 and 7 measured again the highest values and showed a low standard deviation, Figs. 33, 34. Surprisingly, on ASTM cubes Laboratory 3 got the highest results but also a very high scatter, even exceeding the tolerance limit, Figs. 35, 36. All other measured values were unremarkable, except Laboratory 2 which shows a scatter which is significantly too high.

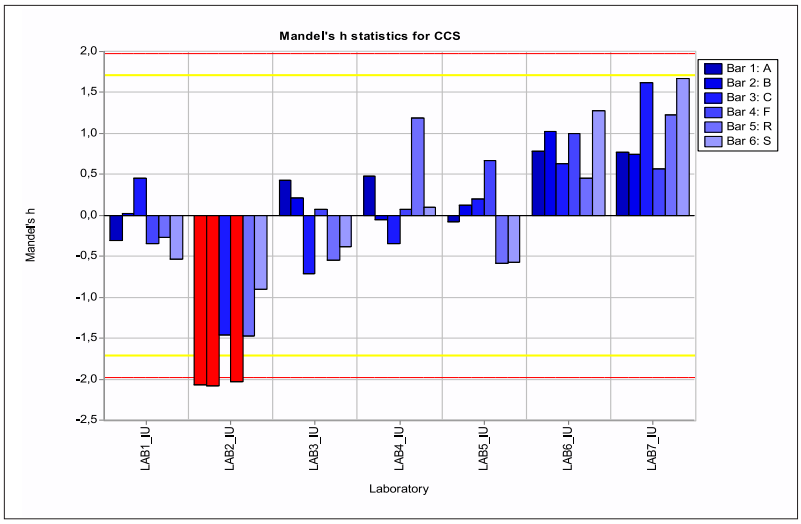

Fig. 31 Mandel's h statistics for method ISO cubes (equals Fig. 15 in [12])

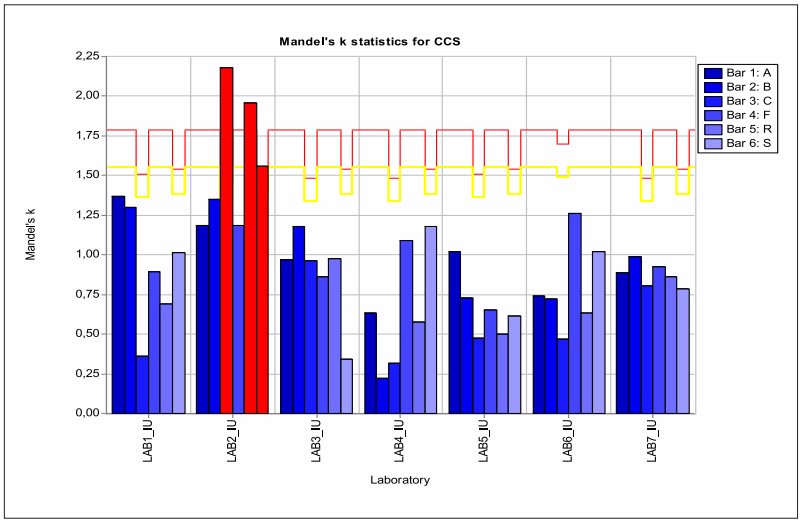

Fig. 32 Mandel's k statistics for method ISO cubes (equals Fig. 16 in [12])

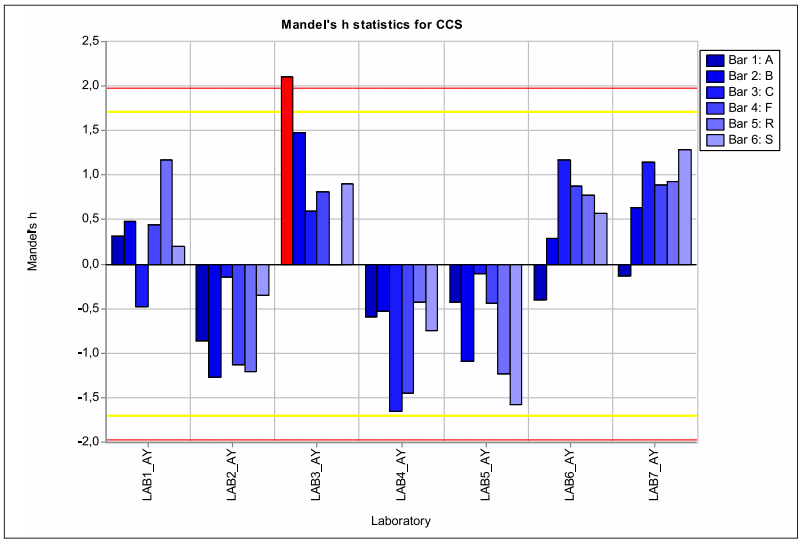

Fig. 33 Mandel's h statistics for method ASTM cylinders (equals Fig. 17 in [12])

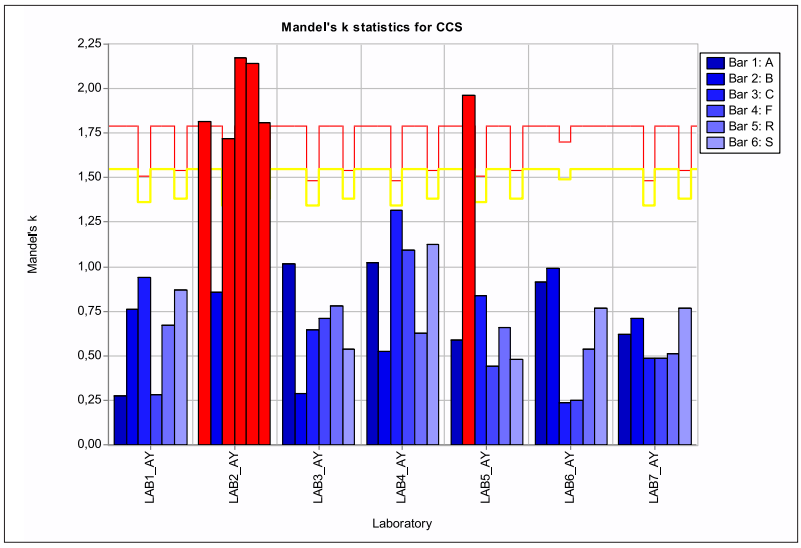

Fig. 34 Mandel's k statistics for method ASTM cylinders (equals Fig. 18 in [12])

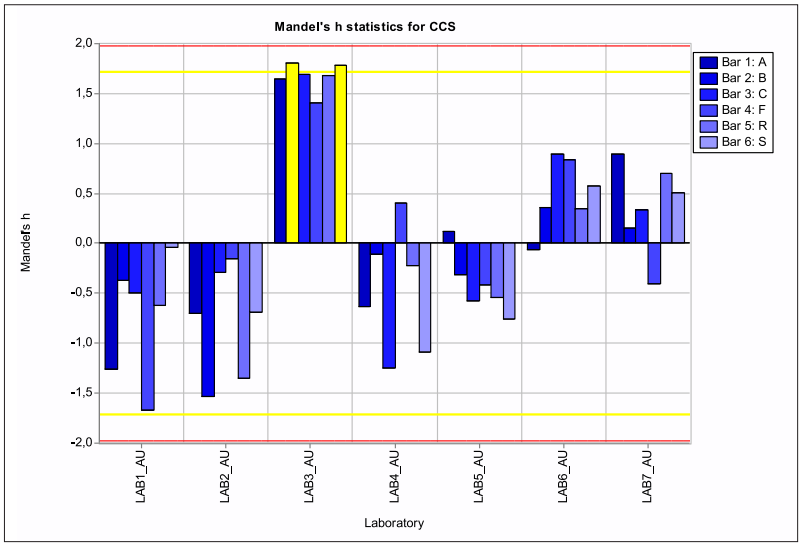

Fig. 35 Mandel's h statistics for method ASTM cubes (equals Fig. 19 in [12])

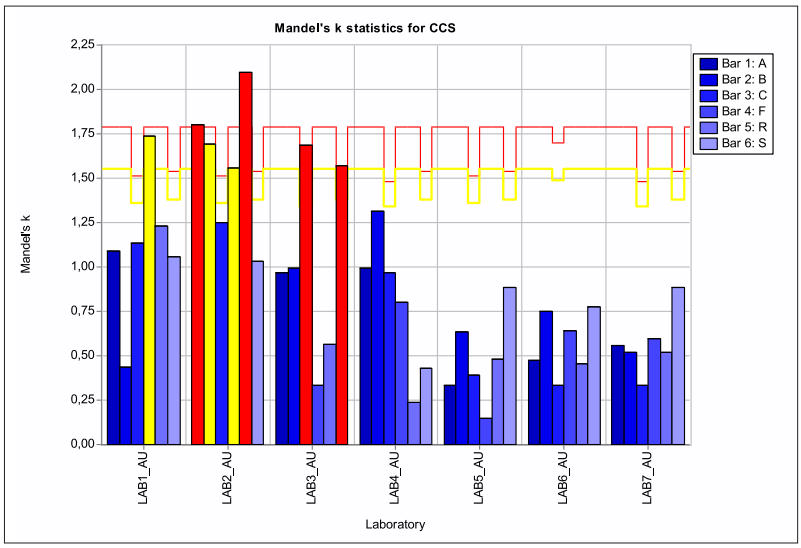

Fig. 36 Mandel's k statistics for method ASTM cubes (equals Fig. 20 in [12])

As a result, for the MgO-C bricks there was no systematic dependence on the CCS measurements. Laboratories 6 and 7 measured the highest values, while all other laboratories sometimes measured values with a very high standard deviation, exceeding or undercutting the tolerance limits, but this could not be assigned to a specific laboratory.

Therefore, an immediate cause assignment to the material's properties is not obvious. The tolerance limits for ISO measurements were tighter for cylinders than for cubes. ASTM measurements showed no difference between shapes.

9.2 Magnesia-spinel brick (S)

Magnesia-spinel bricks are characterised by the presence of two main mineral phases:

- magnesia as the main component, which has a high resistance to basic metallurgical slags and liquid cement clinker, and
- magnesia-alumina spinel, whose presence produces a so-called "microcrack system" in the overall microstructure of the material, reducing for instance its Young's modulus.

The CCS data measured were evaluated for statistical relevance to determine the influence of this well-known microcrack system on the stability and reliability of the results of CCS testing.

The data regarding the measurements on ISO cylinders showed a low scattering, characterised by a lower standard deviation and no excess over the tolerance limits, Figs. 29, 30. However, Laboratories 6 and 7 measured higher values than the rest. Few outliers were observed for Laboratory 4, even with the highest standard deviation, Fig. 12, [12].

The data for ISO cubes showed a similar trend, values of all laboratories are within a small range, and therefore all data can be rated as reliable. The tolerance limits are depending on the amount of results (for ISO cylinders 3 × 4 samples were used, for the others 4 samples were used), so the tolerance limit for cubes is significantly higher than for cylinders, Fig. 31. Laboratory 2 shows a higher scatter of values.

Data from ASTM cylinders confirmed these findings, except for the fact that Laboratory 2 showed a high scattering of values, and Laboratory 5 values in a close range, but not very pronounced. In this case, La-

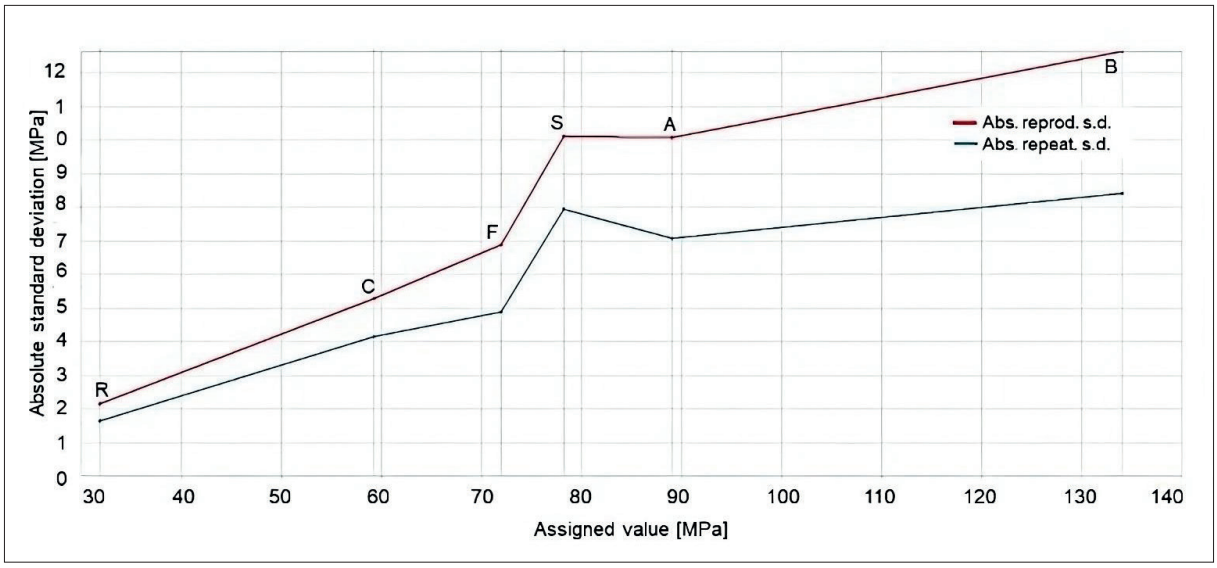

Fig. 37 **Increase of repeatability standard deviation with increase of absolute CCS values and reproducibility standard deviation, showing an anomaly for magnesia-spinel bricks (equals Fig. 5 in [12])**

boratory 3 showed the high values found in the Laboratories 6 and 7, Fig. 33.

The results were confirmed for ASTM cubes, Fig. 35. Regarding Fig. 37, the influence of the microcrack system has to be considered as an influence on the brick behaviour.

For magnesia-spinel bricks no further systematic dependence of the values was observed, other than the anomaly in repeatability standard deviation. ISO produced higher values than ASTM. Cylinders gave tighter tolerance limits only in the case of ISO cylinders, but ASTM showed no significant difference. Laboratories 6 and 7 measured the highest values. Therefore, an assignment of CCS testing biases to material properties is not obvious.

9.3 Bauxite brick (B)

Bauxite bricks are composed of calcined bauxite and the addition of a small amount of bonding clay. In the study this type of bricks were phosphate bonded (through the formation of alumina phosphate), in addition a ceramic bond results from their sintering at high temperatures, producing very high CCS values, which have been the highest in the context of this study.

The results for ISO cylinders showed values within the tolerance limit for all laboratories, Fig. 9, (12). Considering the high strength values of the material, the scattering did not increase, remaining stable below 10 %. Again, Laboratories 6 and 7 measured the highest CCS values.

This was confirmed for Mandel's h and k statistics on ISO cubes, except that for Laboratory 2 that produced lower values, Figs. 31, 32.

ASTM measurements gave lower values compared to ISO. For ASTM cylinders, Laboratory 5 was characterised by low CCS values and high scattering of the standard deviation, Figs. 33, 34. Laboratory 2 also gave low CCS values, Fig. 33.

In the case of ASTM cubes, Laboratory 3 gave significantly higher CCS values than all other laboratories, while laboratory 2 gave significantly lower values than all other laboratories, accompanied by a high scattering of the standard deviation Figs. 35, 36.

9.4 Andalusite brick (A)

Andalusite bricks are composed of natural andalusite with the addition of a small quantity of bonding clay. In this case, the bricks were also phosphate bonded in addition to the ceramic bond resulting from sintering at high temperatures, which results in higher strengths. The results should therefore be comparable to those of bauxite bricks, although on a lower strength level.

The results for ISO cylinders showed for all laboratories values within the tolerance limit, although strength levels were very different between laboratories. They increase from 78 MPa to 99 MPa, but very consistently with typical standard deviations, Figs. 29, 30.

This could be a hint for a systematic influence of the testing conditions. Laboratory 2 measured again the lowest values, but at a similar level as Laboratory 3. Again, Laboratories 6 and 7 produced the highest ones.

This was confirmed by the measurements on cubes were, with the exception that Laboratory 2, all values measured were significantly below the lower tolerance limit, Fig. 31, 32, confirming the results which were obtained for bauxite bricks.

The values for cubes were well below the ones for cylinders.

For measurements on ASTM cylinders, all laboratories measured similar strength values, close to 68 MPa, except laboratory 3, for which all measured values were above the upper tolerance limit, Figs. 33, 34.

The findings were confirmed for ASTM cubes, Figs. 35, 36. The highest values measured by Laboratory 3, but within the tolerance limits. Due to a much higher scatter of the values, the tolerance limits for cubes were much wider than for cylinders, confirming the findings for MgO-C bricks from the same laboratory.

9.5 Fireclay brick (F)

Fireclay bricks, a classical refractory material, is composed of fired refractory clay ("chamotte") and the addition of a small amount of bonding clay. In this case, the bricks were also phosphate bonded, which in addition to the ceramic bond resulting from sintering at high temperatures, pro-

duces higher strengths when compared to phosphate-free products. They are homogeneous in their composition and its microstructure contains mullite, cristobalite, aluminium phosphate and glassy phase.

As opposed to the other grades, the tolerance limits and the standard deviations for the different laboratories were less pronounced. All standard deviations are below 6,5 MPa. Laboratories 6 and 7 produced again the highest CCS values, but not far apart from the other laboratories, Fig. 29. A clear explanation for this behaviour is not obvious, since fireclay bricks also consist of several mineral phases (mullite, glass phase, cristobalite), which would theoretically result in a behaviour as diverse as that found for the other brick grades.

All other values for ASTM and ISO cube measurements confirm the already known results. Laboratory 2 still producing the highest scatter of results, Fig. 34.

Fireclay bricks show some influence of the load rate, see Tabs. 13, 14, [13] especially when a packing layer is used. This is possibly due to the presence of a substantial quantity of amorphous glass phase. A low load rate results in a significantly higher strength values compared to the other brick grades, although the packing layer transforms the compressive stress into a tensile one, Fig. 1, [12].

Without packing, the strength values were lower compared to the other brick grades. The load rate showed some influence on the CCS values of Fireclay bricks, possibly due to the presence of a glassy phase and its mineral phase composition (mullite, glass phase, cristobalite) in this type of brick, although a priori its behaviour should have been comparable to that of the other brick grades tested.

9.6 Low density fireclay brick (R)

The low-density unburnt fireclay bricks are composed of a lightweight porous fireclay with the addition of a small amount of clay and phosphate, which develops binding without a firing process. They are homogeneous in their composition, and their microstructure consists of mullite, cristobalite, aluminium phosphate and a glassy phase. Due to their high porosity, the expected strength values would be much lower when compared to the rest of the bricks in this study.

The standard deviation of low-density fireclay bricks was, as for fireclay bricks, comparatively small. Laboratory 2 showed the highest scatter of results, Fig. 29. Laboratory 6 did not measure the highest values for this brick grade, while Laboratory 7 again measured higher values than most other. The results were roughly confirmed by ISO cube measurements, but with a higher scatter of values, Figs. 31 and 32. This high scatter contributes also to the comparatively higher limits of tolerance.

These results were also valid for measurements according to ASTM, both cubes and cylinders, Figs. 33–36. Laboratory 2 showed the highest scatter (although below the lower limit of tolerance).

The behaviour of fired fireclay bricks regarding load rate was not reproduced for low density fireclay bricks possibly since the amount of glassy phase developed during firing is missing. Therefore, a higher amount of crystalline phase is a substantial influence on cold crushing strength behaviour.

9.7 Discussion of results

The results from Section 6.1.1, [13], were confirmed for all brick grades investigated: measurements on ASTM cylinders always resulted in lower CCS values when compared to ISO cylinders.

Regarding Section 6.4, where the load rate is discussed, there were no significant differences, except for the bauxite brick B, the magnesia-carbon brick C, and the fireclay brick F. Here, a strong negative impact is observed for a lower load rate. According to theory, a higher load rate would result in a higher strength, as the distribution of stresses cannot follow fast enough the application of force. Only magnesia-spinel bricks showed a different behaviour, possibly due to the preexisting microcrack system present in its structure, which may dissipate some of the stresses, resulting in the higher CCS values for lower load rates. The content of amorphous phase may be responsible for the extreme behaviour of fireclay bricks, more prone to catastrophic failure.

Surprisingly a packing layer turned these results around. Fireclay bricks showed higher CCS values when exposed to lower loading rates, while magnesia-spinel bricks showed lower strengths when exposed to lower load rates. As the state of the stress distribution is known to be completely changed by the cardboard packing (Fig. 1, [12]), these two brick grades seemed to be most extremely affected. The fireclay bricks' glassy phase may deal better with the tensile stresses, while the microcracks of the magnesia-spinel bricks seem to enable a spread of the stresses in the structure resulting in a lower strength value.

Magnesia-carbon and bauxite bricks did not show any specific trend. Their CCS measured values were within the statistical variation. But obviously, there is an impact of their microstructure on the influence of the load rate, which may be investigated furthermore with an extended amount of measurements and thus an even better statistical validation.

In general, the influence of the specimens' shape showed higher values for cubes than for cylinders, Section 6.6, [12], Although this cannot be explained in terms of the specific type of material behaviour, andalusite bricks and fireclay bricks showed the biggest differences, while magnesia-spinel brick showed the lowest. An explanation for the latter might again be the structure micro-cracking produced by the different coefficients of thermal expansion of magnesia and spinel during brick firing, which might be the reason for a stress distribution in the microstructure leading to lower values for cubes. The results were confirmed by paired samples, showing a similar effect in these two brick grades. Although similarly bonded, the effect is less pronounced for bauxite (B) and fireclay bricks (F).

Therefore, the nature of bonding may influence CCS measurements, since:

- andalusite, bauxite and fireclay bricks, grades A, B, C and F, were phosphate and ceramic co-bonded,
- magnesia-carbon was resin bonded,
- the low-density brick, grade R, was chemically bonded, and
- magnesia-spinel brick, grade S, was purely ceramic bonded, and generates a microcrack system.

Determination of strength properties measured on twin samples confirmed these data: Cubes showed higher values than cylinders and the amount of lower values is less than for ISO cylinders (Fig. 23, [13´], This confirms the simulation study results in [3]. The effect for andalusite bricks (A) is even higher than for magnesia-spinel brick grades (S). The

influence of scattering still has to be considered (standard deviation).

10 Conclusion

Most CCS influencing factors evaluated showed a high degree of interdependency to the refractory material grade. Still, a priori, such direct influence of the material's microstructure to the scattering of values was not obvious.

Pure ceramic bonded magnesia-spinel behaved differently than the other brick grades tested, most probably due to its special microstructure, where an intentionally created microcrack system also reduces Young's modulus. These microcracks are produced by the thermal expansion mismatch between magnesia and spinel, resulting in a stress and strain pattern within these bricks which is ultimately considered responsible for their unique and different behaviour. All other grades, be it chemically/ceramic bonded or resin bonded (magnesia-carbon brick), differ from the results for magnesia-spinel bricks.

The glassy phase in fireclay bricks, and to a lesser degree in bauxite and andalusite bricks, also seems to influence the scatter of CCS values recorded and the behaviour during testing under different influencing parameters.

When compared to those obtained by ISO 10059-1, measurements according to ASTM C133 always resulted in lower CCS values. The use of a packing layer also showed a significant influence, always reducing CCS values for all grades and standards. The explanation would be the conversion into tensile stresses of the compressive stress applied to the specimen, Fig. 1 [12].

Influences of load rate and specimen geometry were less pronounced. Some brick grades showed higher CCS values when tested at faster load speed, but some others showed lower values; the explanation may again be on the microstructure of each brick grade.

Microstructure also influences the results for the two investigated shapes: cylinders and cubes, as there is also a significantly different strain distribution in the samples, although the effect is small (approx max 4 % in average). Finally, measurements on twin samples did produce more reliable results than those of absolute median values.

Tab. 23 Overview of all mean differences based on twin ISO cylinders to ISO cubes and to ASTM cylinders and cubes

	Grades (Difference on Twins) [%]						
Grade	**All**	A	B	C	F	R	S
ASTM cube	**–20,6**	–34,8	–26,3	–15,9	–21,7	–9,9	–22,6
ASTM cyl.	**–23,4**	–36,1	–38,9	–17,4	–23,8	–12,6	–27,2
ISO cube	**3,9**	8,5	2,9	4,7	5,5	3,5	–1,0

Tab. 24 Significance and relevance of parameters load rate, specimen shape, and packing

	Median Brick	Twin Sample	Practically
Load rate (0,2–1,0 MPa)	not significant	significant (~4 %)	not relevant
Shape (cube-cylinder)	not significant	significant (~4 %)	not relevant
Packing (with-without)	**Significant**	**Significant (24 %)**	**Relevant**

From Tab. 23, higher values (except for magnesia spinel bricks) of cubes can be derived. Insulating fireclay bricks R show lower differences regarding ASTM values. Bauxite and andalusite bricks show the highest deviations, possibly due to their higher absolute strength values. For industrial purposes, the highest relevance is the influence of the presence of a packing. The other influences are of minor importance, but relevant for scientific reasons, Tab. 24.

11 Recommendation for ISO 10059-1

As of now, ISO standard 10059-1 for cylinder shape and a load rate of 1,0 MPa/s performed without packing does not include precision data and there is no recommendation for the number of specimens to be tested for one sample.

The study has shown that packing influences significantly the results of the tests. It is believed that packing should compensate for point loads, but it drastically changes the stress state in the specimen, so the application of a packing should be dismissed.

An outcome of these investigations is the recommendation of revising ISO 10059-1 in order to include:

- the sets of precision data obtained in this investigation,
- the conversion between the test methods (Fig. 26, [13], Tab. 23), so that there are less discussions regarding CCS values stated in datasheets,
- the number of specimens for one sample (n=4) and
- a recommended drilling schema.

Remark from the editor:

This is the last part of the serial including references published by the Technical Working Group on "Cold Crushing (=Compressive) Strength" of the World Refractories Association (WRA), Brussels/BE.

For part 1 please see refractories WORLDFORUM **15** (2023) [2] pages 56–67 and for part 2 refractories WORLDFORUM **15** (2023) [3] pages 55–63 [12, 13].

References

[1] Jarvis, D.A.: Refractories testing and the significance of chemical and physical characteristics. Part 2: The physical properties of refractory materials. refractories WORLDFORUM **13** (2021) [3] 15–18

[2] Konopicky, K.; Lohre, W.: Die Kaltdruckfestigkeit feuerfester Baustoffe. Tonind. Zeitung **80** (1956) 299–292

[3] Sharma, V.: Influence of sample geometry and contact properties on cold crushing strength. Master thesis, Montanuniversität Leoben, 2014

[4] Czechowski, J.; et al.; Investigating the factors that influence the cold crushing strength results of shaped refractories. XVI International Scientific Conference "Refractory materials: manufacture, methods of testing, application", Wista-Jawornik, Poland, May 20–22, 2015

[5] ISO 10059-1:1992-02 Dense, shaped refractory products; determination of cold compressive strength; part 1: referee test without packing

[6] EN 993-5:2019-03 Prüfverfahren für dichte geformte feuerfeste Erzeugnisse – Teil 5: Bestimmung der Kaltdruckfestigkeit; Deutsche Fassung EN 993-5:2018 (Methods of test for dense shaped refractory products – Part 5: Determination of Cold Crushing Strength)

[7] GB/T 5072-2008 Refractories – Determination of cold compressive strength

[8] ASTM C133-97 (reapproved 2021) Cold Crushing Strength and Modulus of Rupture of Refractories

[9] Majdic, A.; Hagemann, L.; Lichomski, H.: Einfluss der Güte der Probekörperdruckflächen und der Druckplattenrauheit auf Mittelwert und Streubreite der Kaltdruckfestigkeit feuerfester Steine (The influence of the quality of the specimen surface and the roughness of the pressure platens on the mean value and the dispersion in the cold-crushing-strength test of refractory bricks). Tonind.-Zeitung **97** (1973) [9] 237–243

[10] ISO 5725-2: 2019-12 Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method

[11] ASTM E691:2022 Standard practice for conducting an interlaboratory study to determine the precision of a test method

[12] Urbanek, G.; Klischat, H.-J.; Miranda-Martinez, M.: Evaluation of test methods for refractory bricks: A comparison and validity study of some cold crushing strength standards. Part 1. refractories WORLDFORUM **15** (2023) [2] 56–67

[13] Urbanek, G.; Klischat, H.-J.; Miranda-Martinez, M.: Evaluation of test methods for refractory bricks: A comparison and validity study of some cold crushing strength standards. Part 2. refractories WORLDFORUM **15** (2023) [3] 55–63