

Optimizing the Bond Performance of Stainless-Steel Bars in CAC-Based Refractory Castables under Elevated Temperatures

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Abstract:

Forty years ago, calcium aluminate cement (CAC) based refractory castables were invented specifically for the metallurgical and petrochemical industries. These castables have exhibited exceptional mechanical resistance even when heated above 1000 °C. Due to the combination of temperature and mechanical loads, these materials can withstand compression stresses without structural reinforcement. This study is part of a research project aimed at developing composite materials that can withstand high temperatures and are suitable for protecting building structures from fire and explosions. However, for this application, structural reinforcement is necessary, and the problem of bond performance becomes crucial under high temperatures. Continuing the pull-out test campaign [<https://doi.org/10.3390/jcs7120485>], this study investigates the bonding performance of austenitic stainless steel ribbed bars in refractory castables after high-temperature treatments. This investigation includes three chamotte-based refractory materials, i.e., conventional castable (CC), medium cement castable (MCC), low cement castable (LCC), and one low cement bauxite-based castable (LCB). The first three material compositions were designed to achieve a cold compressive strength of 100 MPa, undergoing curing at 110 °C. In contrast, the LCB material was engineered to reach a cold compressive strength of 150 MPa following the same curing process. The castables have different material compositions, with CC containing 25 wt% of CAC and MCC containing 12 wt% of CAC; LCC and LCB contain 7 wt% of CAC but differ in used aggregate. The testing process involved a 110 °C reference and four treatment temperatures: 400 °C, 600 °C, 800 °C, and 1000 °C. Results showed that the ribbed stainless-steel bars formed a reliable bond with the high-performance castable, making it a promising material for high-temperature applications. However, the bonding efficiency, expressed in the deformation energy terms, is not proportional to the compressive strength that describes the object for further optimization.

Keywords: refractory castables, stainless steel bar, pull-out tests, heat treatment, cold compressive strength, deformation energy.

1 Introduction

Refractory castable with calcium aluminate cement (CAC) is commonly used in the thermal equipment linings of the energy industry [1]. This castable type is easy to manufacture on-site by mixing refractory aggregate with CAC, offering several technological advantages, including easy blending, convenient shaping, and high mixture stability [1,2]. The conventional castables, incorporating CAC with aluminum oxide not exceeding 40% and aggregates with low Al₂O₃ content, are more cost-effective than medium- and low-CAC content castables with expensive mixture components. The on-site manufacturing ability of conventional refractory materials further increases the economic benefits [2,3]. Conventional castables have

drawbacks because of the loss of mechanical properties after exposure to temperatures ranging from 800 °C to 1100 °C. This effect is caused by various interactions, such as the dehydration of the binder and the recrystallization of cement minerals at high temperatures [4]. As a result of these processes, the CC strength may decrease by up to half compared to its initial mechanical properties. Despite this limitation, CAC-based refractory castable is still used in specific industrial applications where resistance to high temperatures is required and mechanical properties are not critical. Antonovich et al. [5] found that adding SiO₂ micro-particles to castable enhances its compressive strength up to three times more than the conventional one without these additives. Wöhrmeyer et al. [6] observed that this modification improves the mechanical properties and enhances the refractory materials' thermal and abrasion resistance. Additionally, the microscale silica/alumina activation process enhances castables' strength and sinterability temperature compared to traditional alternatives [7].

Refractory castables and ordinary Portland cement-based concretes have apparent similarities despite physical differences. Both materials are composed of inorganic oxides and used for structural purposes [8]. The reinforcement principles also define a common feature of these materials, though research on refractory materials focuses on corrosion problems [9]. Stainless steel can solve the corrosion problem [10], and fiber reinforcement is a typical solution. However, studies of refractory materials with bar reinforcements are rare. Andión et al. [11] investigated the corrosion resistance of stainless steel bars. Bareiro et al. [12] conducted a thorough experimental program that included panel three-point bending and pull-out tests. The aim was to determine how fiber shape and elevated temperature affect the mechanical performance of refractory castables. However, to the Authors' knowledge, there is no investigation into the bond performance of steel bars in refractory castables. Nevertheless, this information is critical for developing reliable numerical models and efficient building structures. In particular, refractory material components can ensure the building's integrity during fire and explosion incidents.

Continuing the pull-out test campaign [13], this study investigates the bonding performance of austenitic stainless steel ribbed bars in refractory castables after high-temperature treatments. The pull-out tests employ the setup developed by Chu & Kwan [14]. This investigation includes four refractory materials: conventional castable (CC), medium cement castable (MCC), low cement castable (LCC), and low cement bauxite castable (LCB). The first three castable compositions were designed to achieve a cold compressive strength of 100 MPa, undergoing the typical curing at 110 °C. In contrast, the LCB material was engineered to reach a cold compressive strength of 150 MPa. The testing process involved a 110 °C reference and four treatment temperatures: 400 °C, 600 °C, 800 °C, and 1000 °C. The pull-out deformation energy determines the bonding effect, and the energy and compressive strength ratio expresses the bonding efficiency.

2 Test program: Materials and methods

The previous results [13] demonstrate the efficiency of the ribbed stainless-steel bars in forming a reliable bond with refractory castables, making it a promising material for high-temperature applications. Thus, this study employing the same 8 mm ribbed bars (considered in [13]) focuses on the compressive strength effect on the bonding performance. The reference [13] describes all the mechanical characteristics of these bars. So, this test campaign includes three chamotte-based refractory materials, i.e., CC, MCC, and LCC, designed for the 100 MPa cold compressive strength, and one bauxite-based LCB, developed for the 150 MPa strength. The castables have different material compositions, with CC containing 25 wt% of CAC and MCC containing 12 wt% of CAC; LCC and LCB contain 7 wt% of CAC but differ in used aggregate. So, in addition to deflocculants and micro-silica, all the castables (except for LCB) include 2.5 wt% of finely ground quartz sand; MCC and LCC compositions have 5% and 25 wt% of reactive aluminum; LCB contains 21 wt% of a clinker G50 and 42 wt% of Bauxite. **Table 1** describes the material proportions of all castables. The ordinary CC was produced using CAC ISTR 40 (I40, CALUCEM, Germany). The MCC, LCC, and LCB materials used CAC GORKAL 70 (G70, GÓRKA CEMENT, Poland). **Table 2** describes the chemical composition of CAC provided by the manufacturers. To prepare the refractory castables, the dry components were mixed for 5 minutes in a Hobart mixer, followed by water addition and another 5 minutes. The amount of water added was determined using the ASTM C0860-15R19 ball-in-hand test method.

Table. 1 Mix proportions of refractory castables (wt%)

Sample name	CAC		QS	MS	RA	BOS 145		G50	Bauxite		FS20	FS30	NT	Water
	I40	G70				0-0.14	0-5		0-1	1-3				
						mm	mm		mm	mm				
CC	25	–	2.5	2.5	–	10	60	–	–	–	–	0.1	–	8
MCC	–	12	2.5	3	5	12	65.5	–	–	–	0.1	–	0.1	7.5
LCC	–	7	2.5	5	25	–	60.5	–	–	–	0.1	–	0.1	6.5
LCB	–	7	–	5	25	–	–	21	21	21	0.1	–	0.1	6.5

Note: CAC = calcium aluminate cement; MS = micro-silica; QS = milled quartz sand; RA = reactive alumina; BOS 145 = milled (0–0.14 mm) and crushed (0–5 mm) chamotte filler, also known as a fire clay; G50 = crushed clinker filler 0-5 mm (GORKAL 50); FS30 and FS20 = a polycarboxylate ester-based deflocculants; NT = deflocculant, anhydrous sodium tripolyphosphate Na₅P₃O₁₀.

Table. 2 The chemical composition of CAC (wt%)

Component	ISTRA 40 (I40)	GORKAL 70 (G70)
Al ₂ O ₃	37–42	69–71
CaO	36–40	28–30
Fe ₂ O ₃	13–18	<0.3
SiO ₂	≤6	<0.5
MgO	<1.5	–
SO ₃	<0.4	–
Na ₂ O + K ₂ O	–	<0.5

This investigation uses the pull-out test setup designed by Chu & Kwan [14], as **Fig. 1a** shows. The pull-out tests were conducted on refractory samples prepared with 8 mm ribbed bars of austenitic stainless 304 steel (**Fig. 1b**) containing 18% chromium and 8% nickel. The testing process involved a 110 °C reference and four treatment temperatures, i.e., 400 °C, 600 °C, 800 °C, and 1000 °C. **Fig. 1c** shows the pull-out test setup. The testing apparatus for pull-out tests was an electromechanical machine H75KS (TINIUS OLSEN, UK) with a 75 kN capacity and a position measurement accuracy of ±0.01%. The bar was loaded in tension with a 2 mm/min rate in a deformation-control manner. To measure the tension reaction with 0.5% precision, a 50 kN load cell was used. Additionally, two 50 mm linear variable displacement transducers (LVDT) measured the relative displacement of the bar with 0.02% precision. **Fig. 1a** shows the LVDT positions; further analysis employs the average value of their readings. The readings from all devices, including the LVDTs and the load cell, were acquired every second through the signal processing device ALMEMO 2890-9 equipped with a workstation computer for acquiring and processing the data.

The preparation and treatment (curing, drying, heat treatment) of the samples were carried out according to the requirements of the LST EN ISO 1927-5:2013 standard [15]. The castables were removed from the form after 72 h of curing at 20 ± 1 °C. After that, they were dried for 72 h at 110 ± 5 °C using a 2.0 kW drying camera. After that, the samples were heated for 5 h at the target temperatures using a 3.4 kW furnace with an electronic controller (UMEGA, Lithuania). The heating rate was 2.5 °C/min to 700 °C and 5.0 °C/min for temperatures ranging from 700 °C to 1000 °C. The density and cold compressive strength (CCS) of the refractory castable 70 mm cube samples were determined following LST EN ISO 1927-6:2013 standard [16]. The CCS tests were conducted on the same cube samples using the ALPHA 3-3000 S testing machine (FORM + TEST SEIDNER & CO., GmbH, Germany). The density was estimated as the weight-to-volume ratio. The tests were conducted in two stages: the first stage analyzes the CCS effect on the bond performance of the refractory castable at the reference 110 °C; the second stage considers the bond characteristics after the heat treatment at 400 °C, 600 °C, 800 °C, and 1000 °C. Thus, the mechanical tests employed equal numbers of cube samples (four) for CCS and pull-out tests. So, the test program employed 40 (20 CCS and 20 pull-out) samples of CC, MCC, and LCC, and 7 (4 CCS and 3 pull-out) specimens of LCB for the reasons described in Section 3.1.

In addition to the mechanical tests, the present analysis employed the X-ray fluorescence (XRF) and X-ray diffraction (XRD) techniques to investigate the reasons behind the bonding mechanisms after the treatments at 800 °C and 1000 °C. The XRF technique helps identify the chemical composition of specimens after high-temperature treatment. It excites the atoms of a material with high-energy X-rays, causing them to emit fluorescent X-rays characteristic of their elemental makeup. The XRD equipment deciphers atomic and molecular configurations in crystalline substances. This process is akin to utilizing detailed blueprints for discerning structural intricacies within materials. To employ the above methods, selected concrete samples underwent an initial crushing process using a sledgehammer. Special care was taken to crush small pieces from the interior of the cubes while preventing the outer layer from mixing with the rest of the parts. Subsequently, the manually crushed samples were further reduced into smaller pieces as much as possible using a hammer. The processed samples were then placed in a specialized bowl with steel balls and subjected to rotation in a 2L planetary ball milling machine for 20 minutes. This machine is designed explicitly for fine-grinding and preparing small-volume high-tech material samples. After this grinding process, the resulting mixture was extracted and sieved through a 63 μ ISO-3310.1 sieve. The processed material was compressed in $\varnothing 37 \times 3$ mm cylinders using the hydraulic TP20 press (HERZOG MASCHINENFABR GMBH & CO., Germany) and examined with a wavelength-dispersive XRF spectrometer ZSX PRIMUS IV (RIGAKU, Japan) equipped with Rh target, end window, and a 4 kW X-ray tube. For calibration purposes, the XRD samples were blended with a standard of anatase (a 99.8% purity titanium oxide) with a mass ratio of 10 parts of the sample to 1 part of anatase. The peak heights in all diffractograms were standardized to ensure that the intensity of the central peak of anatase ($2\theta = 25.28^\circ$) was consistent across all diffractograms. This standardization allows for a fair comparison of the compounds by considering their relative intensities. The amounts of compounds were determined based on the strength of the primary peaks. The samples underwent analysis using a DRON-7 (BOUREVESTNIK, Russia) diffractometer with Cu-K α radiation ($\lambda = 0.1541837$ nm). Experimental conditions included a voltage of 30 kV, a current of 12 mA, and scanning the 2θ diffraction angle from 4° to 60° at intervals of every 2 seconds with an incremental increase of 0.02° .

The microstructure analysis for four small samples was performed using a scanning electron microscope (SEM) JSM-7600F (JEOL, Tokyo, Japan). The study was conducted at an accelerating voltage of 4 or 10 kV. Secondary electrons were utilized for image formation. Before the examination, a layer of electrically conducting material was applied to the specimen surfaces using a QUORUM Q150R ES device from (QUORUM TECHNOLOGIES LTD., Germany).

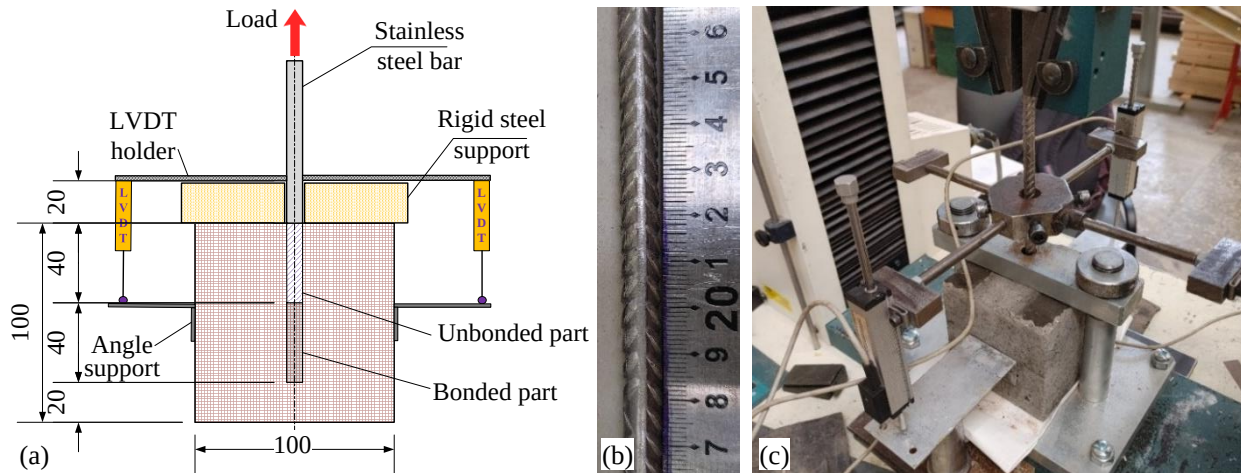


Fig. 1 Pull-out test: a) testing scheme; b) an 8 mm reinforcement bar; c) test setup.

3 Discussion of the test results

3.1 Stage 1: The CCS effect on the bond performance of reference (unheated) samples

The first analysis stage involves all castables' compression and pull-out samples, investigating the strength effect on the bond performance. The reference samples (cured at 110°C) determine the analysis object; the cold compressive strength (CCS), pull-out deformation energy, and normalized deformation energy (regarding CCS) define the analysis parameters. **Fig. 2** shows the compression and pull-out test results. The CCS test results (**Fig. 2a**) demonstrate the adequate design of the mix proportions for achieving the target strength value with a slight overperformance of CC, MCC, and LCC test samples. The standard deviation obtained for four samples determines the wickers on the diagram. Still, these results were obtained for the 70 mm cubes and will be reduced for the standardized 150 cube samples.

The pull-out test results expressed in terms of the load-displacement diagrams (**Fig. 2b**) define three characteristic aspects. *First*, the pull-out failure was the result of all tests. That makes the test results representative of the analysis of the bonding mechanisms because of the concrete resistance mechanisms. This situation aligns with the previous study [13] and results from the relatively smooth shape of the stainless-steel bars (**Fig. 1b**) regarding the typical construction steel reinforcement. *Second*, all the pull-out samples demonstrate comparable ultimate bond resistance. This output is surprising considering the differences in the compressive strength (**Fig. 2a**). *Third*, the substantial scatter and differences in the shape of the diagrams shown in **Fig. 2b** do not ensure the quantitative comparison of the test outcomes. To overcome the above limitation, this study employs the pull-out deformation energy, i.e., the area beneath the load-deformation diagram. The 15 mm displacement u (the vertical dashed line in **Fig. 2b**) limits the deformation energy assessment area. **Fig. 3a** shows the corresponding deformation energy assessment results. The LCC outperforms the alternative castables designed for the 100 MPa CCS. However, the LCB does not represent a significant statistical difference (expressed by the wickers overlapping) because of the substantial scatter. As previously (i.e., **Fig. 2a**), the standard deviation determines the wickers length. **Fig. 3b** demonstrates the deformation energy normalizing results in the CCS regarding improving comparison adequacy. In this case, the extraordinary bonding performance of LCC becomes statistically significant. This outcome leads to two conclusions:

- 1) The pull-out tests demonstrate significantly different bond performance despite the nominally identical strengths of the CC, MCC, and LCC refractory materials (**Fig. 2a**). This outcome ensures hypothesizing the chemical composition effects predominating the bond resistance over the CCS.
- 2) The LCB's relatively high compressive strength (regarding alternative castables, **Fig. 2a**) does not allow for improvement in bond performance. This observation strengthens the above impression of the materials-affected bond-resistance mechanisms. On the other hand, the LCB composition did not demonstrate sufficient bonding performance. Therefore, it is not included in a further experimental program that investigates the effects of temperature on bonding resistance.

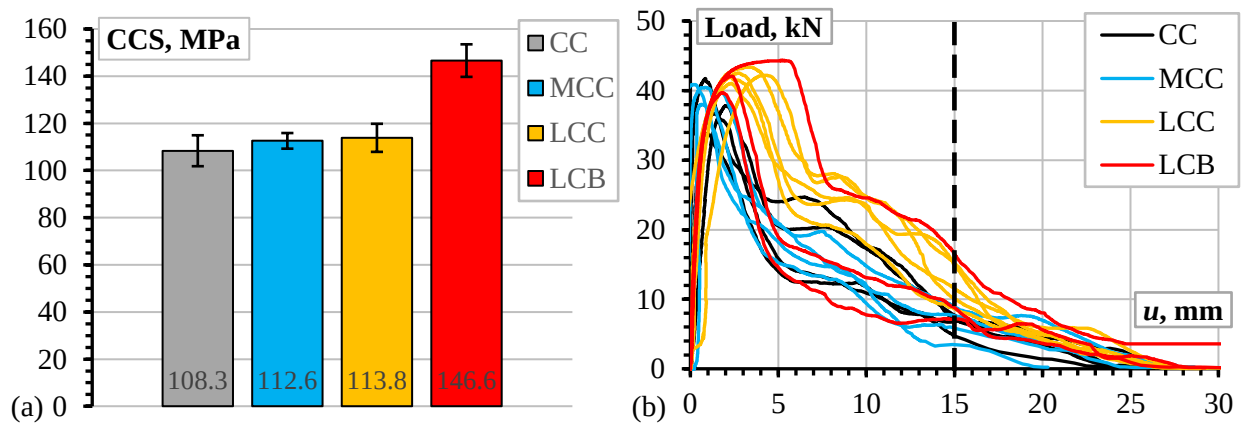


Fig. 2 The mechanical test results of reference (unheated) samples: a) the cold compressive strength; b) the pull-out load-displacement diagrams.

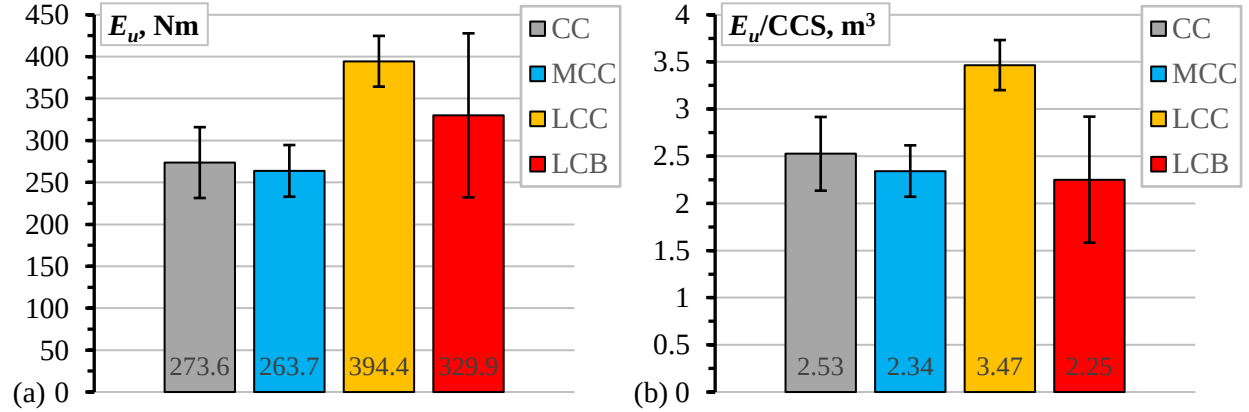


Fig. 3 The pull-out energy assessment results: a) the deformation energy; b) the deformation energy normalized by CCS.

3.2 Stage 2: The temperature treatment effect on the bond performance of CC, MCC, and LCC

The testing philosophy has remained the same as it was at the first testing stage except for the additional heat treatment stages at four target temperatures, i.e., 400 °C, 600 °C, 800 °C, and 1000 °C. In other words, the reference results (without heat treatment) of the CC, MCC, and LCC samples used for the comparative analysis at this stage came from the previous stage and did not change. So, **Fig. 4** shows the compressive test results. The LCC demonstrates a remarkable tendency for CCS increase, with the average strength reaching 170 MPa after the 1000 °C treatment. On the contrary, the compressive strength of CC and MCC does not change substantially, varying between 90 MPa and 115 MPa. This result was expected from the previous investigations [13,17]. However, the pull-out test results demonstrate a different trend.

Fig. 5a shows the pull-out deformation energy estimation results corresponding to the 15 mm displacement in the same manner as **Fig. 3a**. These tests were conducted after the heated specimens were cooled in the laboratory for at least one day. The LCC bond performance significantly outperforms the considered counterparts. Still, this outcome is expected from the strength increase (**Fig. 4**). To estimate the significance of the relationship between the CCS and deformation energy E_u , **Fig. 5b** shows the normalized energy values regarding the corresponding strength values (**Fig. 4**). The remarkable transformation in the LCC bond resistance emerges after 800 °C and 1000 °C treatments when the relative bond efficiency of MCC overtakes the LCC results (**Fig. 5b**), which becomes the object of following analysis.

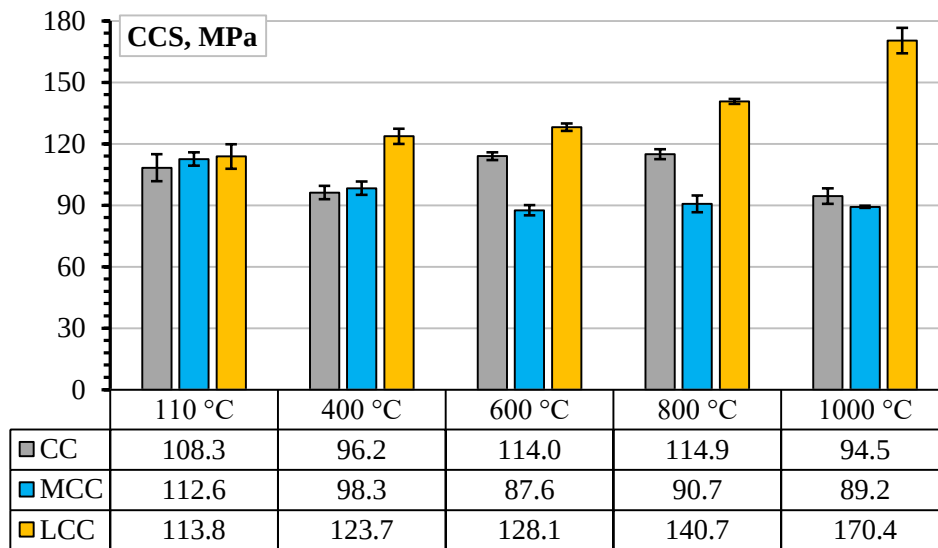


Fig. 4 The CCS test results after treatment at different temperatures.

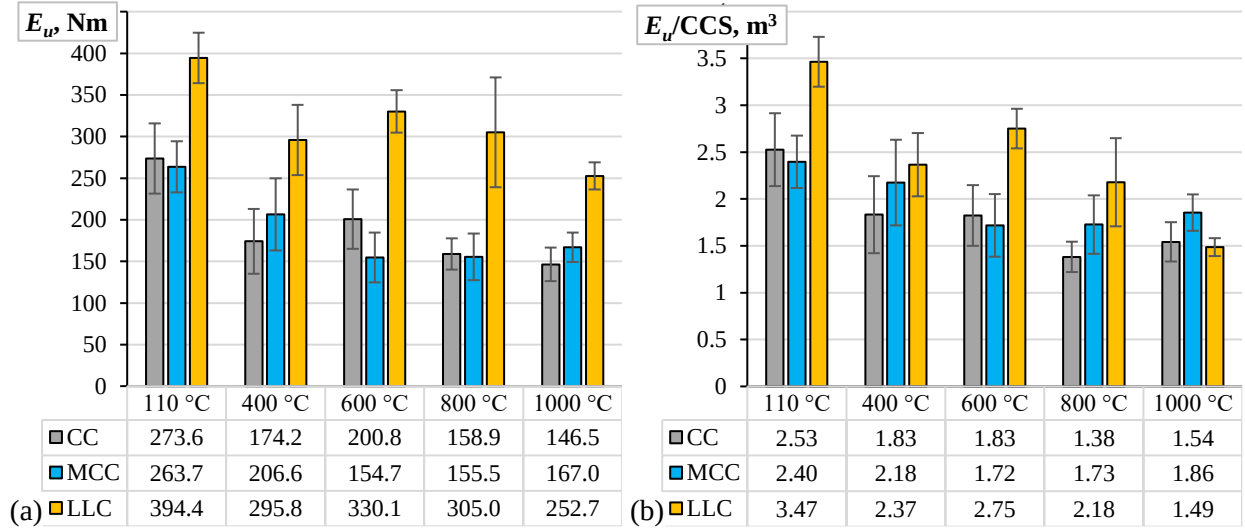


Fig. 5 The pull-out energy assessment results after heat treatment: a) the deformation energy; b) the deformation energy normalized by the corresponding CCS.

3.3 The detailed transformation analysis of the MCC and LCC bond performance

This section employs XRF, XRD, and SEM tools to analyze chemical and structural transformations in the refractory castables after the 800 °C and 1000 °C treatments to explain the bond transformations observed in **Fig. 5b**. **Table 3** shows the XRF chemical composition analysis results, which is independent on the temperature treatment. The LCC sample demonstrates a substantial aluminum oxide (Al_2O_3) content of 56.9 wt% alongside a silica (SiO_2) content of 32.4 wt%, suggesting a superior refractory capability suitable for high-temperature applications. The MCC sample exhibited slightly lower alumina levels at 49.8 wt% but a higher silica presence at 37.0 wt%, potentially affecting its thermal resistance and mechanical strength differently from LCC. The CC sample, however, presented the lowest alumina content at 41.4 wt% and a higher silica content at 34.6 wt%, which diminished its refractoriness and thermal durability. Thus, the analytical results underscore the LCC composition as potentially the most favorable for high-temperature applications, attributed to its optimal alumina content. At the same time, the MCC offers a viable alternative with a balanced composition. Meanwhile, due to its compositional constraints, the CC appears less suited for the most demanding thermal environments.

Tables 4 and **5** demonstrate the XRD analysis results normalized in the added titanium oxide regard. All castables show mineral content changes when the temperature increases from 800°C to 1000°C. This indicates that temperature significantly affects the crystal structure and phase composition of materials. In particular, the MCC 800 and MCC 1000 have more significant amounts of Mullite than the CC and LCC variants. The level of corundum is the highest in the MCC 1000 sample, indicating a phase transformation or heating process that favors the formation of corundum at high temperatures in MCC. The LCC samples at 800 °C and 1000 °C show different reactions to high temperatures than CC and MCC.

Table. 3 The XRF analysis results (wt%)

Component	CC	MCC	LCC
Na ₂ O	0.163	0.221	0.209
MgO	0.941	0.835	0.581
Al ₂ O ₃	41.4	49.8	56.9
SiO ₂	34.6	37.0	32.4
K ₂ O	0.612	0.699	0.645
CaO	10.8	4.35	2.73
TiO ₂	1.46	1.17	1.06
Fe ₂ O ₃	5.22	1.54	1.24

In particular, the CC and MCC specimens demonstrate an increase in corundum when elevating the temperature from 800 °C to 1000 °C (compare the results of **Tables 4** and **5**); however, LCC possesses a slight reduction of this component. The mineral composition directly affects the mechanical properties, thermal resistance, and durability of castables; for example, an increase in the mullite and corundum concentration can improve the strength and thermal stability of the castable [18]. The pull-out test results (**Fig. 5b**) indicate that the corundum and ΣN mineral concentrations seemingly more significantly affect the bond performance than CCS, determining the object for further research.

Table. 4 XRD identified mineral components after 800 °C treatment

Name	Anorthite 28.02°	Mullite 26.26-30°	Gehlenite 31.38-42°	Corundum 35.15-18°	Tridymite 21.68-70°	TiO ₂ 25.32-34°	Quartz 26.62-66°	ΣQ	ΣN
CC	0.00	367	37.6	238	230	440	249	479	643
MCC	0.00	370	26.6	386	309	440	162	470	780
LCC	0.00	295	7.45	493	217	440	372	589	795

Table. 5 XRD identified mineral components after 1000 °C treatment

Name	Anorthite 28.02°	Mullite 26.26-30°	Gehlenite 31.38-42°	Corundum 35.15-18°	Tridymite 21.68-70°	TiO ₂ 25.32-34°	Quartz 26.62-66°	ΣQ	ΣN
CC	53.2	351	135	254	248	440	196	444	792
MCC	58.5	359	36.7	628	254	440	179	433	1082
LCC	0.00	249	14.0	415	188	440	298	485	677

Note: ΣQ = sum of quartz + tridymite; ΣN = sum of anorthite + mullite + gehlenite + corundum.

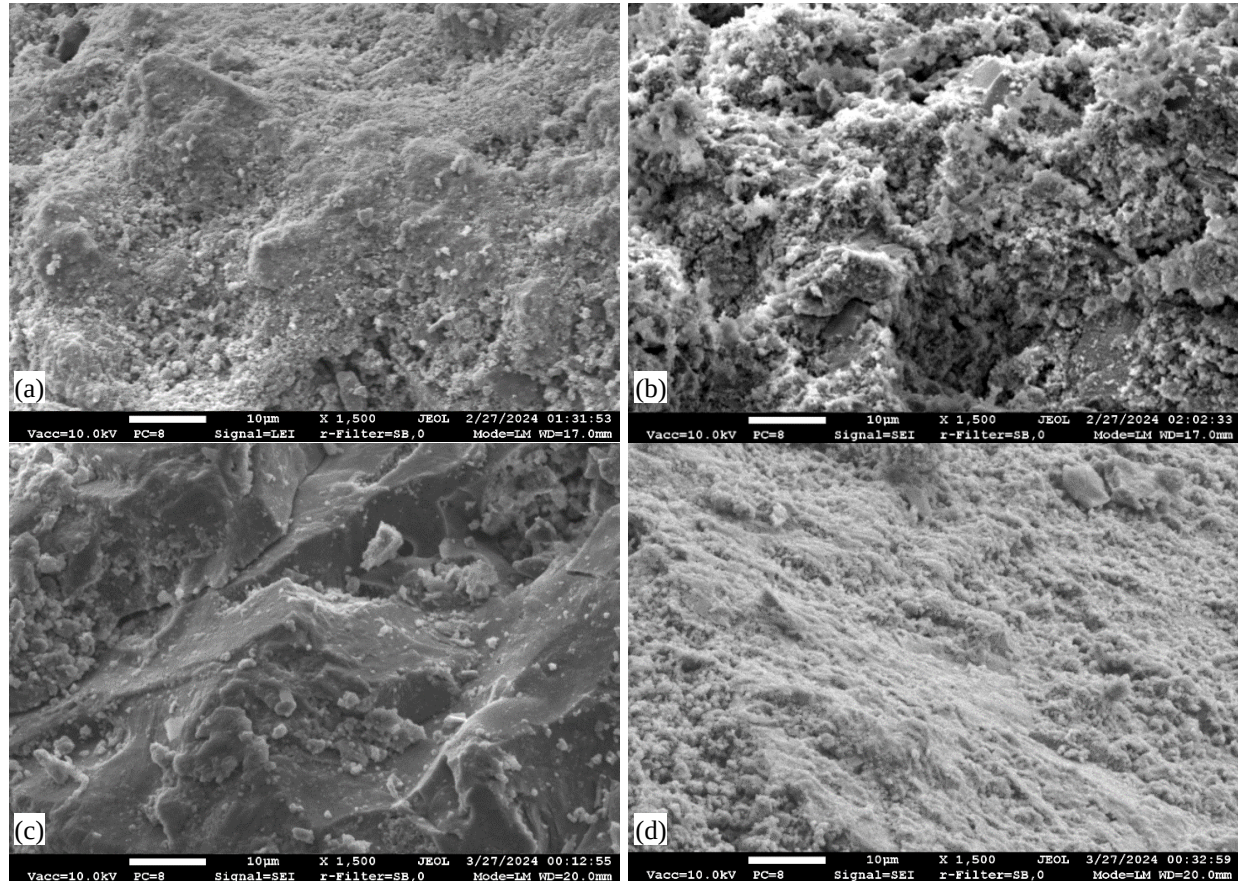


Fig. 6 The SEM analysis results at $\times 1500$ magnification: a) and b) MCC treated at 800 °C and 1000 °C; c) and d) LCC treated at 800 °C and 1000 °C.

Fig. 6 shows the microstructure transformation of MCC and LCC after treatment at 800 °C and 1000 °C. The qualitative material structure changes are apparent. This observation is consistent with our X-ray diffraction results, which showed increased corundum content in the MCC 1000 °C sample. The formation of different minerals at higher temperatures may have contributed to filling some pores, increasing the concrete density, and potentially improving bond performance. This finding would agree with what was reported in previous studies on refractory materials. The formation of different minerals, such as anorthite, mullite, and corundum, in the material can result in improved mechanical properties, including increased strength and deformation capacity [18,19].

Choosing castables for industrial applications would depend on thermal resistance, mechanical strength, and durability requirements. It would also be based on balancing cost and performance under less demanding conditions. Thus, the materials prices of the castables determined in March 2024 define the following expenses of the considered castables for a ton of dry mixture: CC = 507 €, MCC = 623 €, LCC = 733 €, and LCB = 1040 €. In normal (unheated) conditions, these castables may virtually provide 0.540, 0.423, 0.538, and 0.317 pull-out deformation energy per Euro (Nm/€). However, the test results demonstrate the limited effect of CCS on the bond performance, which describes the object for further research.

4 Conclusions

This experimental study investigates the bonding performance of austenitic stainless steel ribbed bars in refractory castables after high-temperature treatments, investigating the relationship between the cold compressive strength (CCS) and the pull-out deformation energy. This investigation includes four refractory materials: conventional castable (CC), medium cement castable (MCC), low cement castable (LCC), and low cement bauxite castable (LCB). These refractory materials were designed for particular CCS but had different calcium aluminate cement (CAC) content and demonstrated different bonding performance even after temperature treatments. The obtained results ensure reaching the following conclusions:

- 1) Despite nominally identical CCS of CC, MCC, and LCC samples in normal conditions (without the heat treatment), the pull-out tests demonstrate significantly different bond performance of these castables, suggesting that the chemical composition may have a more significant effect on bond resistance than compressive strength.
- 2) The LCC samples treated at 800 °C and 1000 °C demonstrated substantial transformation of the deformation energy and CCS ratio, which was not apparent in the CC and MCC specimens. The comparative scanning electron microscopy (SEM) analysis of LCC and MCC samples demonstrates apparent micro-structure differences because of heating. The X-ray diffraction (XRD) analysis identified the opposite mullite and corundum concentration tendencies in LCC and MCC materials. The latter minerals may increase strength, but the experiments demonstrate that the mullite and corundum concentrations seemingly more significantly affect the bond performance than CCS, determining the object for further research.
- 3) Industrial applications of refractory castables consider thermal resistance, mechanical strength, and durability requirements as essential factors, balancing the cost and performance under less demanding conditions. For instance, the prices of castable materials in this study estimated on March 2024 determine the approximate expenses for a ton of dry mixture as follows: CC = 507 €, MCC = 623 €, LCC = 733 €, and LCB = 1040 €. Under normal (unheated) conditions, the castables can provide an average of 0.540, 0.423, 0.538, and 0.317 pull-out deformation energy per Euro (Nm/€). Still, the operating temperature range would determine the optimal choice of the material.

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