Review

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Trends in Refractories R & D Overseas

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Abstract

Global steel production has grown to 1.8 billion tons, and the importance of refractories to support high-temperature equipment is increasing. As a result of investigating R & D trends in refractories overseas, universities and public research institutes in Europe and China are actively conducting basic research on refractories and application development in cooperation with refractory companies. Education in undergraduate and graduate schools and training of engineers are being actively promoted. Large-scale research programs have been set up with various financial supports from the EU, each government and several foundations. Recent topics at international conferences on refractories include the development of high-purity, high-functionality unshaped refractories based on MgO and SiO_2, evaluation of thermomechanical properties of large lining walls, and basic research on numerical simulation. New technology development and application on measurement, analysis, and evaluation were presented.

1. Introduction

Steel demand has been increasing mainly in developing areas such as Asia and India and the annual production of refractories for steel is more than approximately 25 million tons. The refractory unit consumption in global steel production has been decreasing to 10–20 kg/ton-steel. This means that the steel production technologies, material technologies for refractories, and technologies for using them have advanced significantly.

Japan had been leading the world in refractory technologies. However, it cannot necessarily be said that the full momentum has been retained at present. It is essential to understand the overseas trends when considering the current and future Japanese refractory technologies. This paper introduces institutions that made presentations at the meeting of the Unified International Technical Conference on Refractories held at Yokohama in October 2019 (UNITECR 2019) along with details of the presentations and other information.

2. Refractories Demand

The global crude steel production in 2018 is considered to be approximately 1.8 billion tons: China produced approximately 900 million tons and India produced a little over 100 million tons, followed by Japan with the production of approximately 100 million tons. When assuming that the refractory unit consumption in the global crude steel production is 15 kg/ton-steel, the quantity used by refractories is assumed to be approximately 27 million tons/year. When assuming that the ratio of refractories for steel is 65%, the total refractory production is assumed to be approximately 42 million tons/year. **Figure 1** shows the refractories demand analogized in reference to the values in 2013 estimated by the Freedonia Group (the annual increasing rate was assumed to be approximately 3%).[1] In 2016, the refractories demand in the Asia/Pacific area was overwhelmingly high at approximately 33 million tons/year; that in Europe was approximately 6 million tons/year; that in North America was approximately 3 million tons/year; that in Africa/the Middle East was approximately 2 million tons/year; and that in South America was also approximately 2 million tons/year. The total was approximately 46 million tons/year. Although these values are only an estimation, the total global refractory production and total demand in recent years is considered to be about 45 million tons/year.

Among the demand of approximately 33 million tons/year in the Asia/Pacific area, China is estimated to account for approximately 24 million tons/year. In Asia, Africa, the Pacific area, and the Middle East, the infrastructure development will be continuously expanded in the future. Therefore, the demand for steel, cement, and glass is likely to increase and refractory production will also increase.

Although it is difficult to obtain accurate data for refractory production in China, according to Semler,[2] the refractory production in China in 2012 was close to 28 million tons in one report.

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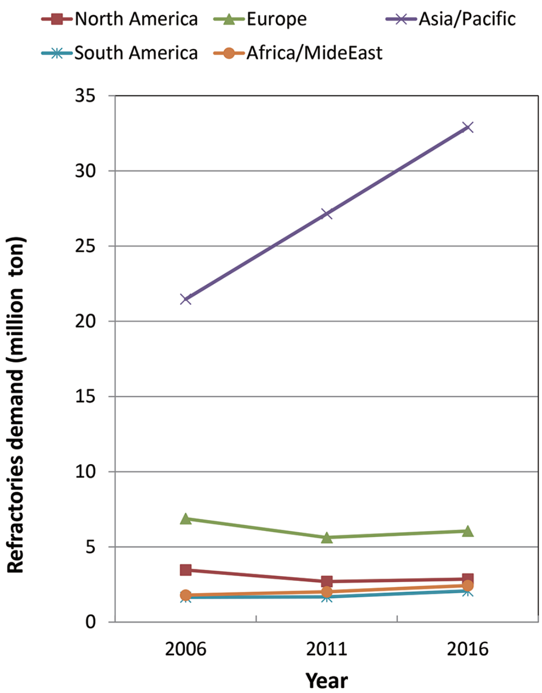

Fig. 1 Refractories demand in the world

In recent years, large-scale refractory manufacturers have often merged and it is said that the top 10 or so companies have approximately 20 to 25% of the global market share. Examples of such higher-ranking leading companies include: RHI Magnesita (Austria), Vesuvius PLC (U.K.), Krosaki Harima Corp., Shinagawa Refractories Co., Ltd., Saint-Gobain Performance Ceramics & Refractories (France), Imerys SA (France), Calderys (France), Posco Chemical Co., Ltd. (South Korea), Chosun Refractories Co., Ltd. (South Korea), Morgan Advanced Materials (U.K.), and HarbisonWalker International (U.S.). Semler[2)] reported that in 2012, 150 Chinese refractory manufacturers (companies belonging to the China Refractory Industry Association) accounted for approximately 37% of the global refractory production.

3. Major Overseas Refractory R&D Institutions

Among the 238 preprints for UNITECR 2019, 97 reports include overseas universities and/or public research institutions as the authors. Meanwhile, 20 reports include Japanese universities and public research institutions as the authors. In addition, among the 160 preprints for UNITECR 2017 (held at Santiago, Chile), 74 reports include overseas universities and/or public institutions as the authors, while no reports include Japanese universities/public institutions. In Japan, unfortunately the number of universities and public institutions that engage in the research and development of refractories has decreased significantly. Meanwhile, overseas universities and public institutions—especially those in Europe, China, and Brazil—have been researching and developing refractories actively. The universities and public institutions that participated in UNITECR 2019 were investigated.

3.1 Germany

3.1.1 European Centre for Refractories (ECRF)

The center determines the themes regarding refractories in Europe, makes approaches to related authorities, develops programs for funding and awarding, and manages standardization activities. The center uses its own evaluation equipment to support refractory manufacturers in Germany and Europe, contributing to upgrading the position of the refractory industry by adjusting education, training, research, and development and strengthening the networks. The center also utilizes public funds (e.g., European Structural Fund for Regional Development).

The center has been cooperating with many universities, public research institutions, and companies in addition to the European Refractories Producers Federation. The center is located in Höhr-Grenzhausen, Germany, on the same premises as the Deutsches Institut für Feuerfest und Keramik GmbH (DIFK). The center is adjacent to the west school building of Koblenz University of Applied Sciences.

3.1.2 DIFK GmbH (Deutsches Institut für Feuerfest und Keramik GmbH)

DIFK owns many high-grade test systems for chemical, physical, mineral, and high-temperature properties to measure, analyze, and evaluate materials. DIFK functions as an independent test institute and always preserves its neutrality and reliability. In order to determine accurately-reproducible characteristic values, the institute has specially developed equipment and professional engineers. For example, the institute can evaluate the performance of a material while changing the mineral composition in a high-temperature corrosive environment where mechanical stress is also applied.

The institute also aids customers in collecting and preparing samples based on their requests. It has been closely cooperating with ECRF, Verband der Deutschen Feuerfest Industrie, and Forschungs-Gemeinschaft Feuerfest.

3.1.3 Koblenz University of Applied Sciences (Hochschule Koblenz)

Koblenz University of Applied Sciences (formerly Fachhochschule Koblenz or FH Koblenz) is a public university in Land Rheinland-Pfalz. The current university was founded in 1996. Höhr-Grenzhausen has a long history of education in ceramics. The roots of the material engineering faculty and glass/ceramics faculty go back to the 19th century. Craft pottery and ceramics have taken deep root in this area thanks to the high-quality plastic clay mined in Westerwald. This university has an engineering faculty and laboratory that focus on material science and engineering of glass and ceramics in its west campus. It has been cooperating with DIFK and ECRF.

3.1.4 Technische Universität Bergakademie Freiberg Institute of Ceramic, Glass and Construction Materials (Technische Universität Bergakademie Freiberg Institut für Keramik, Glas- und Baustofftechnik)

As its name “Bergakademie” (Academy of Mines) suggests, this university has specialized in mineral resources for more than 250 years. The university started researching silicate engineering around 1903 and providing education in ceramics and cement for engineers. The name was changed to Technische Universität Bergakademie Freiberg Institut für Keramik, Glas- und Baustofftechnik in 2002 after several changes, including the Institute of Ceramics and Institute of Silicate Technology. The university is located in Freiberg and has approximately 50 researchers at present.

3.1.5 RWTH Aachen University (Rheinisch-Westfälische Technische Hochschule Aachen)

The technical university’s school buildings are not gathered in one campus; they are scattered in the center of Aachen. The Aachen Institute of Mineral Engineering under the university has been evaluating and developing fireproof materials for more than 45 years. During the period, the application of high-quality oxides and non-oxide synthetic raw materials to refractories has advanced. The development of performance refractories has been accelerated due to the expansion of the steel industry, demand for waste incinerators, and innovation in coal gasification processes. The Aachen Institute of Mineral Engineering engaged in the development of new evaluation technologies for assessing the compatibility and reliability of fireproof materials under severe service conditions, and it developed evaluation technologies conforming to various standards, such as DIN, EN-DIN, ISO, ASTM, AFNOR, and BS. The university also developed non-standard test methods to simulate special operation conditions. The Aachen Institute of Mineral Engineering has a ceramics & fireproof material department and a glass & ceramics synthetic material department.

3.1.6 FAU Erlangen-Nurnberg (Friedrich-Alexander Universität Erlangen-Nürnberg)

The university was established in Bayreuth by Friedrich von Brandenburg-Bayreuth in 1742 and relocated to Erlangen in 1743. In 1961, the university merged with the Nuremberg College of Economics and Social Sciences (Nürnberger Hochschule für Wirtschafts- und Sozialwissenschaften) established in 1919 in Nürnberg and "Erlangen-Nürnberg" was added to the university name. In 1966, the faculty of engineering was set up in Südgelände (south campus) in Erlangen. The university is the second largest in Bavaria.

3.2 France

3.2.1 Multidisciplinary Research Laboratory in Systems Engineering, Mechanics, Energy (PRISME Laboratory) (Université d'Orléans Laboratoire Pluridisciplinaire de Recherche en Ingénierie des Systèmes, Mécanique, Énergétique)

The University of Orléans established by Pope Clement V in 1306 is one of the oldest universities in Europe. In the 1960s, the campus was established in the southern part of Orléans and since then the university has been advancing and expanding at Centre-Val de Loire.

The PRISME Laboratory consists of the University of Orléans and the National Institute of Applied Sciences Center Loire Valley (INSA-CVL). The fluid, energy, combustion, and propulsion (FECP) department of the PRISME Laboratory has been conducting research in the transportation (automobile and aviation) sector and energy system (e.g., combustion, energy materials, and high-temperature materials) sector. The PRISME Laboratory has 90 researchers including 22 professors, 10 postdoctoral researchers, 52 students in the doctoral course, and 11 technical staff members.

3.2.2 CEMHTI and the University of Orléans: Extreme Conditions and High Temperature Materials and Irradiation (Le CEMHTI et l'Université d'Orléans: Conditions Extrêmes et Matériaux Haute Température et Irradiation)

CEMHTI has contracted with the University of Orléans. It includes 1) a science faculty, 2) Institut Universitaire de Technologie (IUT; a two-year vocational university that provides the diplôme universitaire de technologie [DUT]), and 3) teachers and researchers of Polytech' Orléans. CEMHTI has been engaging in projects across areas and nationwide projects. Its main research targets are as follows: Transparent (glass) ceramics and fireproof ceramics/fireproof materials (corrosion, property evaluation, and application); use of NMR (structure and dynamics); energy and raw materials for molten salt; energy and nano-porous materials for environments; and optics and thermal engineering for materials. CEMHTI has ion beam application equipment, high-resolution solid and high-temperature NMRs, and high-temperature evaluation facilities as its main experimental facilities.

The high-temperature platform (HITEM) of CEMHTI develops high-temperature and ultra-high temperature materials (3 000°C) through the development of original equipment specific for property evaluation. The platform has been working to measure temperature without contact, observe macroscopic properties in situ, observe the structure and dynamics of solids and ultra-high temperature fluids in situ, and develop measuring and heating devices by fully using its tools and high-level skills. Example systems that the platform has are listed below:

- Dilatometer that measures up to 1 700°C in combination with high-resolution cameras that measure deformation
- Flotation system (3 000°C) in combination with high-speed imaging (1 000 images/second)
- System that measures the electric conductivity of solids and fluids (1 Hz to 1 MHz, 1 650°C)

3.2.3 University of Limoges Institute for Ceramics Research (Université de Limoges Institut de Recherche sur les Céramiques [IRCER])

IRCER researches materials for ceramics processes and surface treatment processes. IRCER has approximately 200 staff members in the building of the European Center for Ceramics, Limoges (Centre Européen de la Céramique, Limoges). In addition, IRCER is a partner of the Sigma-Lim Laboratory of Excellence (XLIM laboratory; an interdisciplinary research institution at multiple geographical sites). Example keywords for IRCER are as follows: Ceramics; biomaterials; ecomaterials; materials for which the microstructure and structure have been controlled; materials for which the porosity has been controlled; materials and deposits of nanostructure; high-temperature materials; energy and materials for environments; information technologies and materials; solid-state chemistry; crystal chemistry; ceramics processes; and surface treatment processes (e.g., plasma, flames, CVD, and laser abrasion).

3.2.4 Superior National School of Industrial Ceramics (École Nationale Supérieure de Céramique Industrielle [ENSCI])

The foundation of ENSCI was a national ceramics school established in Sèvres in 1893 and it became its present form in 1950. In 2017, ENSCI was combined with the Superior National School of Engineers of Limoges (École Nationale Supérieure d'Ingénieurs de Limoges [ENSIL]). ENSCI is a public institution for higher education to develop technical engineers for process engineering from powder to finished products and forming of nonmetallic mineral materials. ENSCI has been closely cooperating with the economic and industrial circles and has entered into more than 30 agreements or partnerships with overseas universities, laboratories, and companies. In the last year of the three-year training, students stay overseas at least once. ENSCI is located in the facility of the European Center for Ceramics, Limoges in Ester Technopole located in the northern part of Limoges. It is assumed to be in the same building as the University of Limoges Institute for Ceramics Research (IRCER).

3.3 China

3.3.1 Wuhan University of Science and Technology

The original school was established in 1958 as the Wuhan Institute of Metallurgy to provide education as a unit of the faculty. In 1995, the school merged with the Wuhan Iron and Steel Institute, Wuhan Architecture College, and Wuhan Medical School of Metallurgy belonging to the former Ministry of Metallurgy to establish the Wuhan Metallurgy University of Science and Technology. In 1998, the Chinese government reformed the higher-education management system nationwide. As a result, the university name was changed to the Wuhan University of Science and Technology in 1999 as one of the first schools constructed jointly by the central government and local governments. Currently, the university has three campuses in Qingshan, Huangjia Lake, and Hongshan. The number of undergraduates is more than 24000 and students in the doctorate course and graduate students total more than 6000.

In 2016, the university set up 1) a college that the Hubei government owns, 2) the State Key Laboratory in Refractory Materials and Metallurgy, which is the university's first state key laboratory, and 3) the National and Local Joint Engineering Research Center for High Temperature Materials and Furnace Lining Technology, which is the university's first national engineering research center. The university proposes energy-saving measures and provides services such as pilot testing, demonstration, engineering, and technical consultation. In addition, the university has been cooperating with more than 30 leading-companies. As joint research centers, the university set up the Wuhan University of Science and Technology Yixing Ceramics and Refractory Research Institute and the Wuhan University of Science and Technology Zibo Refractory Engineering Research Institute.

3.3.2 Sinosteel Luoyang Institute of Refractories Research Co., Ltd. (LIRR)

When the institute was established under the direct control of the Ministry of Metallurgy in 1963, it was the only large-scale general research institution in the refractory sector in China. Currently, it is a national company that develops, produces, and sells raw materials for refractories, refractory products, energy-saving materials, superhard materials, testing devices, and high-temperature devices. It also tests the performance of refractories and develops metallurgical and industrial furnaces. The institute located in Luoyang, Henan also houses the National Engineering Research Center for Refractories and the National High-tech Industrialization Base for Special Refractories, mainly acting as a manufacturer of materials. As a manufacturing section, the institute manufactures more than 60000 tons of synthetic materials and high-quality refractories annually. The institute has more than 400 technical engineers and more than 100 doctors, masters, and higher-grade engineers at the professorial level. The R&D center has research workstations for postdoctoral researchers. In the 45 years since the foundation, the research institute has engaged in more than 300 national scientific technology development plans and scientific technology research projects in the fireproof material sector.

However, once the institute started producing and selling refractories, it became a rival to other refractory manufacturers and thereby it may have lost its neutrality as a research and development institution.

3.3.3 Henan University of Science and Technology

The Henan University of Science and Technology located in Luoyang, Henan, is one of the key universities in Henan along with Henan University and Zhengzhou University. The Henan University of Science and Technology has 23 faculties such as science, engineering, agriculture, medical science, economics, and pedagogy. The number of school personnel is 1700 and that of students is 27000 including 1000 graduate students. The university has four campuses in Xiyuan, Jinghua, Zhoushan, and Kaiyuan. It was founded in 1952 as the Beijing Stretching Machine Technical School and relocated to Tianjin in 1953 to merge with the Tianjin Automobile Industry School. It then became the Tianjin Automobile Industry Stretching Machine Technical School by reorganization, and the name was then changed to the Tianjin Stretching Machine Production School. In 1956, it was relocated to Luoyang, Henan, and renamed as the Luoyang Stretching Machine Production School. In 1982, the name was changed to the Luoyang Institute of Technology. In 2002, it merged with the Luoyang Higher Medical School and Luoyang Agricultural Higher School to become the Henan University of Science and Technology.

The material science and engineering faculty has a high-temperature material laboratory. In order to support the high-temperature industry—metallurgy industry, in particular—the university mainly researches new synthetic fireproof materials, amorphous refractories, heat-resistant industrial ceramics, and application technologies for high-temperature materials. It actively conducts industry-university cooperative research to accelerate commercialization. The Henan Polytechnic University (Jiaozuo, Henan) is a different university.

3.3.4 Zhengzhou University

The university founded in 1956 assimilated the Zhengzhou Teacher's College in 1961, Huanghe University in 1991, and Henan Physical Education School in 1992. In 2007, it merged with the Zhengzhou University of Technology and Henan Medical University to become the current form of Zhengzhou University.

Zhengzhou University is a national key university selected for the "211 Project," which is directly controlled by the Education Department and jointly controlled by the Henan provincial government. The high-level general university has various departments, including the department of science, engineering, medical science, literature, history, philosophy, law, economics, and management. The university has more than 51000 undergraduates, more than 19000 graduate students, and more than 2500 overseas students from 98 countries.

The high-temperature material laboratory under Zhengzhou University established in 2000 is a key laboratory to research high-temperature functional materials. It includes a structural laboratory, high-temperature performance laboratory, and high-temperature simulation laboratory. The high-temperature material laboratory also researches mechanisms in which refractories are damaged in high-temperature furnaces. The university aims to become an R&D center for high-temperature functional materials in China and promotes the advancement of refractory technologies and the development of the refractory industry.

3.3.5 University of Science and Technology Beijing

The Beijing Institute of Iron and Steel Technology, a public university, was established in 1952 as a result of the merger of the following schools: School of Computer and Communication Engineering; Department of Metallurgy, Peiyang University; Department of Metallurgy, Tangshan Railway College; Beijing Institute of Technology, Department of Metallurgy, Iron and Steel Machinery; Department of Metallurgy, Northwestern Polytechnical University; Department of Metallurgy, Shanxi University; and Department of Metallurgy, Tsinghua University. In 1988, the name was changed to the University of Science and Technology Beijing. The university has approximately 27000 students and approximately 3000 school personnel.

The School of Materials Science and Engineering covers the inorganic material sector. It researches, designs, and develops structural ceramics, special refractories, inorganic functionality materials, and energy materials. The Institute for Advanced Materials and Technology includes an inorganic nonmetal material section and a powder metallurgy and advanced ceramics research section. In addition, the State Key Laboratory for Advanced Metals and Materials was set up in 1999.

3.3.6 Education on refractories at universities in China[3)]

In China, nine universities listed below have a refractory laboratory or a regular course on refractories: Anhui Univ. of Technology, Hebei Polytechnic Univ., Henan Univ. of Science and Technology, Northeastern Univ., Univ. of Science and Technology Beijing, Univ. of Science and Technology Liaoning, Wuhan Univ. of Science and Technology, Xi'an Univ. of Architecture and Technology, and Zhengzhou Univ. It is said that the number of undergraduates is approximately 1 500 and that of graduate students is approximately 200. China is thus a country that supplies the most refractory engineers and researchers in the world.

3.4 Brazil

3.4.1 Federal University of São Carlos (Universidade Federal de São Carlos [UFSCar])

The public university founded in 1968 and located in San Carlos, São Paulo in Brazil, has approximately 16 000 students and 1 000 professors and researchers. Professor Victor C Pandolfelli at the Department of Materials Engineering is renowned due to his active research activities.

3.5 Research institutions and universities that are conducting research on refractories in other countries

3.5.1 Catholic University of Leuven (Katholieke Universiteit Leuven)

The university established in 1425 has many programs in English and accepts many students from other countries—mainly from Europe due to its location. The university is a leading member of the Coimbra Group,[*1] which is an organization that promotes a cooperative framework between universities, the levels of which are internationally acknowledged as high. It is also the only Belgian member of the League of European Research Universities,[*2] which was set up in 2002 as a league of key research universities in Europe. It focuses on the exchange of students within the EU.

3.5.2 Swansea University

The university was set up in 1920 as the fourth college of the University of Wales. The university has approximately 19 000 students in the faculties and graduate school. The engineering courses were set up in 1920 and in 2001, all the engineering sections were merged to become the College of Engineering. It was relocated to the Bay Campus in 2015. Currently, the university has five engineering buildings and experimental laboratories with an area of 30 000 m^2. It includes the Institute of Structural Materials (ISM), which has the Technology Centre for Rolls Royce materials testing, and the Energy Safety Research Institute (ESRI). In addition, the university has the Materials Research Centre (MRC), the Systems and Process Engineering Centre (SPEC), and the Zienkiewicz Centre for Computational Engineering (ZCCE) as strategic technology centers.

3.5.3 Institute of Ceramics and Glass (ICV) belonging to the Higher Council for Scientific Research (CSIC) (Institute de Ceramica y Vidrio Agencia Estatal Consejo Superior de Investigaciones Científicas [ICV-CSIC])

ICV located in Madrid, Spain, is one of 130 centers belonging to the Higher Council for Scientific Research (CSIC). The R&D projects conducted at the institute are funded by the Spanish National Research Plan, the EU Framework Program, and local programs. ICV closely cooperates with the industries in Spain, and the source of funds based on contracts with private companies is also important. The institute transfers high-level scientific knowledge to the production sector to provide new applications in the ceramics and glass sectors, aiming at effective development. ICV holds courses, workshops, and seminars for students, researchers, and engineers in cooperation with the Faculty of Science of the Autonomous University of Madrid (Universidad Autónoma de Madrid [UAM]). The management head office of the nonprofit Spanish Ceramic Society is located in the same building as ICV, aiming at promoting scientific technologies for ceramics and glass.

3.5.4 AGH University of Science and Technology (Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie)

The Polish national university with the head office in Krakow was established in 1919. The technical university has approximately 27 000 students and approximately 1 800 school personnel. It exchanges students with various universities in Europe and other areas in the world and conducts many cooperative studies with companies in various sectors. "AGH" stands for "Akademia (academy)," "Górniczo (mining)," and "Hutnicza (metallurgy)." It used to be known by the name of the "Mining Academy in Krakow." The university has laboratories for researching rock properties and stone products, buildings and ceramics materials, structural analysis, transportation and techniques for materials, geochemistry, and vibroacoustics.

3.5.5 Institute of Ceramics and Building Materials, Refractory Division in Gliwice, Poland (Instytut Ceramiki i Materiałów Budowlanych [ICiMB])

In 1951, the Institute of Silicate Technology was established. In 1953, the Institute of Refractory Materials was established in Gliwice, and in 1954, the Institute of Mineral Building Materials was established in Opole. In 2010, the Research and Development Center for the Concrete Industry was added to become the Institute of Ceramics and Building Materials. The institute has the Glass and Building Materials Division in Kulakov, the Material, Process and Environmental Engineering Division in Opole, and the Refractory Materials Division in Gliwice. The institute has been closely cooperating with other academic centers including the AGH University of Science and Technology in Krakow and the Warsaw University of Technology to conduct cooperative research projects.

3.5.6 Ukrainian Research Institute of Refractories named after A.S. Berezhnoy (Украинский научно-исследовательский институт огнеупоров им. А.С.Бережного, АО)

The research and production organization established in 1927 develops domestic fireproof materials and reduces imports substantially. During the Second World War, the institute contributed to the production of refractories from raw materials from the Urals and the enhancement of steel refining capacity. After that, it worked to develop corundum, zirconia, chromium oxides, ceramics fiber, and unshaped refractories, etc. It has developed a vibration forming technology for refractories and manufactures large high-quality products. It is located in Kharkov.

3.6 Other institutions that supported the research and development presented at UNITECR 2019

(1) University of Leoben (Montanuniversität Leoben) (Austria)
(2) TU (Technical University) Vienna (Technische Universität Wien) (Austria)
(3) Technical University Graz (Technische Universität Graz) (Austria)
(4) University of Bonn (Universität Bonn) (Germany)
(5) University of Poitiers (Université de Poitiers) (France)

[*1] The Coimbra Group was originally established in 1985 and became a formal European league of universities in 1987 by adopting a charter. The number of member universities is 39. The head office is in Brussels, Belgium. The name comes from a city in Portugal.

[*2] To participate in the League of European Research Universities, universities must have conducted many high-quality academic studies. The league was started by 12 universities in 2002. The number of member universities in 2015 is 21. The head office is in Leuven, Belgium.

(6) Imperial College London (ICL) (U.K.)
(7) Kingston University (KUL) (U.K.)
(8) University of Exeter (U.K.)
(9) University of Oulu (Oulu yliopisto) (Finland)
(10) University of Coimbra (Universidade de Coimbra) (Portugal)
(11) University of Minho (Universidade do Minho) (Portugal)
(12) McGill University (Canada)
(13) University of Connecticut (UConn) (U.S.)
(14) The New York State College of Ceramics (NYSCC) at Alfred University (U.S.)
(15) University of Sao Paulo (Universidade de São Paulo [USP]) (Brazil)
(16) Argentine Steel Institute (Instituto Argentino de Siderurgia) (Argentina)
(17) Seoul National University (SNU) (South Korea)
(18) Yonsei University (South Korea)

According to Semler,[2] regarding education on refractories at universities in the U.S., although 14 programs were available at 14 universities in the 1960s, in 2013, the number was only two at two universities.

4. Research and Development Networks

Overseas universities and research institutions often obtain funding from their governments and various foundations. Students go abroad to present their papers at UNITECR with financial support, which contributes to the development of researchers and engineers in the refractory sector. At overseas universities, students and graduate students have been seriously working on refractories as their themes. In Japan, it is no exaggeration to say that almost no universities have regular courses and lectures on refractories. There is a considerable difference in the education and research on the base technologies that support the high-temperature industry between Japan and overseas. This section shows some networks that support research and development overseas with reference to the acknowledgments of the papers presented at UNITECR 2019.

4.1 Federation for International Refractory Research and Education (FIRE)

This global network of academic institutions and companies (manufacturers, users, and other service providers) working in the refractory sector is a nonprofit organization consisting of universities and private companies and controlled by the board of directors. It is funded by the membership fees of the member companies and donations from institutions.

The 10 academic institutions participating in the FIRE are listed below.

- University of Leoben (Montanuniversität Leoben) (Austria)
- Federal University of São Carlos (Universidade Federal de São Carlos) (Brazil)
- Seoul National University (South Korea)
- Wuhan University of Science and Technology (China)
- Superior National School of Industrial Ceramics – Limoges (École Nationale Supérieure de Céramique Industrielle – Limoges) (France)
- University of Orléans, Extreme Conditions and High Temperature Materials and Irradiation (CEMHTI), French National Centre for Scientific Research (CNRS) (Polytech'Orléans - Orléans CEMHTI-CNRS) (France)
- RWTH Aachen (Germany)
- TU (Technical University) Freiberg - Institute of Ceramic, Glass and Construction (Germany)
- Nagoya Institute of Technology (Japan)
- University of Missouri-Rolla (U.S.)

The supporting companies are listed below.

- TENARIS Siderca (Argentina)
- TATA Steel Ceramics Research Centre (India)
- RHI Magnesita (Austria)
- IMERYS - Minerals for Refractories Imerys Refractory Minerals (France)
- Kerneos (France)
- Elkem AS, Materials (Sweden)
- Almatis, inc. (U.S.)
- Pyrotek (U.S.)
- Calderys Center for Abrasives and Refractories Research & Development (France)
- Alteo Alumina (France)
- Saint Gobain (France)
- POSCO Technical Research Laboratories (South Korea)

The main purpose of the FIRE is to educate engineers for the future. It is necessary to develop young engineers who can develop, design, implement, and manage complicated refractory products with values added in order to optimize the entire life cycle of refractories. The FIRE aims to become a cross-border international research and industrial consortium through multi-partner research programs.

4.2 Advanced Thermomechanical Multiscale Modelling of Refractory Linings (ATHOR)

ATHOR stands for Advanced THermomechanical Multiscale MOdelling of Refractory Linings. ATHOR may be a part of the Marie Skłodowska-Curie Action European Training Network–Innovative Training Network (ETN ITN). ATHOR is an innovative, cooperative, and interdisciplinary project that ties together seven academic institutes and eight private companies as partners. The ATHOR network supports the FIRE's initiative and provides combinations of research and training.

The seven academic institutions are listed below.

- University of Limoges (France)
- AGH University of Science & Technology (Poland)
- RWTH Aachen (Germany)
- Montanuniversität Leoben (University of Leoben) (Austria)
- University of Orléans (France)
- University of Minho (Portugal)
- University of Coimbra (Portugal)

The eight private partner companies are listed below.

- Altéo Alumina – Gardanne (France)
- Imerys Refractory Minerals – Villach (Austria)
- RHI-Magnesita (Austria)
- Pyrotek Scandinavia AB – Ed (Sweden)
- Saint-Gobain – Cavaillon (France)
- TataSteel – Ijmuiden (Netherlands)
- FIRE – Montréal (Canada)
- Safran (France)

The ATHOR network develops leading-edge modelling techniques and experimental technologies that match refractories in order to achieve reliable calculation and measurement in service temperature ranges. The network also develops engineering technologies in the material science and numerical simulation sectors to use such technologies to design stronger and more reliable refractory linings.

4.3 Example funds

The examples of funds other than FIRE and ATHOR that were

found in the acknowledgments of the papers presented at UNITECR 2019 are listed below.
(1) German Federation of Industrial Research Associations (AiF)
(2) Federal Ministry of Economics and Technology (BMWi)
(3) German Research Foundation (DFG)
(4) Financial support by the Austrian Federal Government
(5) European Union's Horizon 2020 research and innovation program
(6) Important projects by the National Natural Science Foundation of China
(7) China Scholarship Council

5. Latest Trends in the Research and Development of Refractories

The trends based on the papers presented at UNITECR 2019 were investigated. Regarding materials, unshaped refractories were often targeted. It was found that many authors focused on bonding structure and grain properties and aimed at developing high-functionality unshaped refractories by drawing on the properties of MgO, SiO_2, and other compounds.

Regarding the control of microstructure, researchers tried to improve the properties of refractories by fabricating target plate-like products during firing by adding catalytic compounds and nanoparticles.

In the production of ultra-low carbon steel, the development of low-carbon refractories was accelerated. By controlling the structure of matrices and chemical compounds that had properties of both ceramics and metal, also by advancing the bonding system, researchers tried to dramatically improve the thermal shock resistance even when carbon was reduced or eliminated.

To use refractories as large linings, numerical analysis and simulation of properties of materials in hot working, structural mechanics as linings, and stress that occurred due to thermal changes are essential, and thereby basic research results were reported by many authors mainly in Europe.

Some authors reported their research on the physical property measurement, analysis, and evaluation of refractories from new perspectives.

5.1 Unshaped refractories

Table 1 lists the examples of interesting reports on unshaped refractories.

5.1.1 Unshaped MgO refractories

Plate-like brucite made by hydrating MgO is used as binders through adjusting the dehydration process. The authors had been developing cement-free bonding (A-1). Refractories with higher strength in hot working, higher heat resistance, and higher corrosion resistance had been developed by reducing microsilica used as MgO castable binders and by adding synthetic MgO-SiO_2-H_2O binders (A-2). Bonding structure to fully use the properties of MgO in basic unshaped refractories is expected to be developed.

5.1.2 Unshaped SiO_2 refractories

It is expected that when castables for which amorphous fused silica is used are heat-treated in advance, the maintenance factor of the dynamic Young's modulus may be higher than that of normal silica bricks and thereby they may deteriorate less, even after thermal shock tests are repeated (A-3). Quartz and microsilica were used as raw materials for unshaped vibration forming. Cement-free 96%-silica castables to which the sol-gel method is applied are expected (A-4). Demand for high-purity silica refractories for coke ovens and high-temperature hot stoves is increasing. For large refractories and complicated-shaped refractories, in particular, the use of unshaped, precast, and heat-treated castables is considered.

5.1.3 Effect of grain shape for unshaped refractories

The impact of splintered and cubic grains on explosion was studied in the coarse grain region. The results show that the interlocking property of cubic grains is weak, and they tend to explode (A-5). Splintered and cubic grains were applied to unshaped refractories for steel ladles in the coarse grain region to test the durability. As a result, splintered coarse grains have higher cohesive power and durability (A-6).

5.2 Microstructure

Table 2 lists the examples of interesting reports on microstructure.

The effects of additives with catalyst functions were studied in the fabrication of Al_2O_3-C in sialon bonding. Adding Fe_2O_3 formed plate-like β-sialon in the matrix, and it enhanced the strength and improved the strength maintenance factor after thermal shock tests (B-1).

The use of nanoalumina formed plate-like CA_2 and CA_6 during firing, and they improved the mechanical properties and significant-

Table 1 Topics for refractory castables

No.	Title	Author
A-1	14-B-15 Assessment of a New Magnesia-based Binder Concept for Refractory Castables[4]	IMERYS, Paris, France
A-2	14-E-18 Optimization of Magnesia Castables by Introduction of Pre-synthesized Magnesium Silicate Hydrate[5]	Wuhan Univ. of Science and Technology, Univ. of Exeter
A-3	14-E-11 The Influence of Crystallisation on Thermal Shock Behaviour of a Fused Silica Refractory Castable Concrete[6]	RWTH Aachen Univ., Ceramics Research Centre, Tata Steel, IJmuiden, the Netherlands
A-4	14-E-12 Newly Developed Low Cement and Cement-free Castables Based on Silica[7]	P-D Refractories CZ a.s. Czech Republic
A-5	14-B-17 Splintered versus Cubic Grains in High Alumina Castables–Part I: Examination of the Impact of the Particle Shape on the Explosion Resistance[8]	Hochschule Koblenz, Forschungsgemeinschaft Feuerfest e.V. at the European Centre for Refractories, INISMa, Institut Interuniversitaire des Silicates, Belgium
A-6	14-B-19 Splintered versus Cubic Grains in High Alumina Castables–Part III: Assessment of the Failure Tendency in the Wear Lining of a Modelled Steel Ladle Using the Drucker-Prager Failure Criterion[9]	Forschungsgemeinschaft Feuerfest e. V., Hochschule Koblenz, INISMa Institut Interuniversitaire des Silicates, Mons, Belgium

ly enhanced the thermal shock resistance (B-2).

5.3 Low-carbon refractories

Table 3 lists the examples of interesting reports on low-carbon refractories.

In clean steel production, the carbon content in refractories is demanded to be lower. The authors tried to replace part of graphite with a phase of Ti-MAX (chemical compound with properties of both metal and ceramics). The results show that oxidation and dissolution of Ti_3AlC_2 work to suppress rapid oxidation of graphite at eroded interfaces. However, an adverse effect due to cubical expansion was considered (C-1).

Nanocarbon was added to MgO-C to study the catalytic action of Ni and metal Al in the carbonization process of phenolic resin. As a result, MgO whiskers and spinel whiskers formed, the microstructure was improved, and the modulus of rupture, strain to fracture, and thermal shock resistance were improved (C-2). Means in which minute quantities of nanocarbon grains and hybrid graphite black were added to form whiskers and needle compounds in the matrices during heating of resin binders to improve the properties had been studied before.[10]

Carbon-free unburned alumina-magnesia bricks for ladle metal lines to be applied to ultra-low carbon steel were developed. An original binder system was used. After they were heat-treated at 180°C, they showed the same mechanical properties as those of fired products. The new bricks show more excellent performance under operation conditions of ladles than that of fired bricks (C-3).

5.4 Mechanical properties and numerical analysis

Table 4 lists the examples of interesting reports on mechanical properties in hot working and numerical simulation.

The discrete element method (DEM) was used to simulate the fracture mechanism of refractories that were pseudo-continuum media that would show brittle behavior and crack branching. Considering existing cracks, the quasi-brittle behavior of fireproof ceramics and decrease in the brittleness can be reproduced on the microscale (D-1).

The DEM shows the discontinuity of materials and may link the microstructure to its macroscopic behavior. As a result, the similarity between the model and experiment for measuring the Young's modulus and Poisson's ratio was more than 90%. This method is expected to be an effective tool to clarify the mechanical behavior of

Table 2 Topics for microstructures

No.	Title	Author
B-1	15-A-11 Effect of Catalysts on Mcrostructure and Thermo-mechanical Properties of Al_2O_3-C Refractories[11]	Wuhan Univ. of Science and Technology
B-2	15-A-21 Mcrostructure and Phase Evolution of Corundum-Spinel Based Castables Containing Nano Phases[12]	Wuhan Univ. of Science and Technology, Zhejiang Zili Corp. Ltd, China

Table 3 Topics for law carbon and carbon free refractories applied to ultra law carbon steel

No.	Title	Author
C-1	14-B-16 The Application of Ti-Max Phase in Low Carbon Refractories and Elucidating Its Related Role[13]	Wuhan Univ. of Science and Technology, Univ. of Exeter
C-2	14-C-15 Improved Mechanical Properties and Thermal Shock Resistance of Low Carbon MgO-C Refractories via the Catalytic Formation of Nanocarbons and Ceramic Bonding Phases[14]	Wuhan Univ. of Science and Technology
C-3	14-D-18 Refractory without Carbon for the Production of Ultra-low Carbon Steels[15]	Usiminas, Brazil, RHI Magnesita, Brazil

Table 4 Topics for thermomechanical properties and numerical simulations

No.	Title	Author
D-1	14-A-14 Numerical Modeling of Wedge Splitting Test by Discrete Element Approach: Flat Joint Contact Model[16]	IRCER laboratory, Centre Européen de la Céramique, France
D-2	15-D-2 Discrete Element Modeling–A Promising Method for Refractory Application[17]	Federal Univ. of São Carlos, Univ. of São Paulo, Tata Steel R&D, IJmuiden, The Netherlands
D-3	14-E-16 Modeling of Nonlinear Behavior at High Temperature of Refractory Masonries Without Mortar[18]	Univ. Orléans, Univ. Tours, INSA-CVL, LaMé
D-4	14-E-17 Thermomechanical Modelling of Refractory Mortarless Masonry Wall Subjected to Biaxial Compression[19]	Univ. Orléans, Univ. Tours, INSA-CVL, LaMé
D-5	15-C-11 Thermomechanical Behaviour of an Alumina Spinel Refractory for Steel Ladle Applications[20]	Univ. of Limoges, IRCER, Centre Européen de la Céramique, Limoges, Univ. of Poitiers, Institut Pprime, Univ. of Orléans, Laboratoire de Mécanique
D-6	15-E-17 Matrix Design in High Alumina Refractory Castables–Part II: Assessment of the Brittle-ductile Transition Temperature and Ways to Influence It[21]	Forschungsgemeinschaft Feuerfest e. V. at the European Centre for Refractories, Hochschule Koblenz, Institute of Ceramics and Building Materials, Refractory Division, Gliwice, Poland

refractories and can be used for research on unshaped refractories (D-2).

Mortarless masonry linings of steel ladles show nonlinear mechanical behavior at high temperatures. The creep law of the Bingham-Norton's rheological model (BNM) was used to model isotropic viscoelastic behavior. It is targeted to use the method for ladle simulation to show changes in the stress in various segments of lining to time (D-3).

A 3D thermomechanical model was developed to analyze the effects of closure and reopening of the joints on the mechanical behavior of mortarless masonry walls. Since the pattern of the joint changes as the joint of linings is gradually closed, the mechanical behavior becomes orthotropic anisotropy and nonlinear. After the load is removed, usually the final thickness of the joint is thinner than the original thickness and permanent deformation occurs in both directions (D-4).

The authors created a numerical model for microstructure and thermomechanical properties under operation conditions of ladle linings to which alumina spinel refractories were applied. The model shows nonlinear behavior at 1200°C. Acoustic emission, ultrasonic, uniaxial tensile testing, and the mechanical testing method proposed by the researchers in Brazil were used to study changes in the Young's modulus during heat treatment, hysteresis, etc. The thermal shock resistance increased due to the existence of minute cracks and microstructure (e.g., high-temperature viscous phase) (D-5).

High-temperature wedge splitting testing was performed to calculate the energy of rupture of high-alumina unshaped refractories. When more fine grains are used for a matrix, the specific fracture energy tends to increase at high temperatures and thereby the application may work to enhance the ductility of unshaped refractories at high temperatures (D-6).

5.5 Measurement, analysis, and evaluation

Table 5 lists the examples of interesting reports on measurement, analysis, and evaluation.

The authors used, in place of 1D tensile and compressive creep tests, integrated digital image correlation (I-DIC), in which a mechanical test method proposed by the researchers in Brazil was combinedly used, to understand the mechanical properties of refractories at high temperatures. This method is promising since the number of tests required to evaluate material properties can be reduced and the accuracy can be maintained at a fairly high level (E-1).

Under thermal cycle conditions, the authors evaluated castables by measuring the Young's modulus, mechanical damping, and acoustic emission. The results show that castables with a greater quantity of sub-micron spinel grains exert more excellent damping capacity at high temperatures and that enhancement of the stress relaxation capacity improves the thermal shock resistance. The temperature dependence of the Young's modulus affects the thermal shock resistance significantly (E-2).

The authors used in-situ hyperspectral Raman imaging (HSRI) to study the mineral reaction and changes in the structure. HSRI at high temperatures is a strong tool to clarify the sintering reaction. The tool can detect phases in a small quantity in addition to metastable phases. It can also distinguish different polymorphs, offering another advantage (E-3).

Radar signals detect free water in solid materials very sensitively. They can detect the behavior of water (e.g., bound water and hydrated water) released due to the heating of unshaped refractories for which the separation temperature varies in a nondestructive and noncontact way (E-4).

6. Conclusions

(1) Many overseas universities and public research institutions participate in the research and development of refractories actively. Research institutions mainly in Germany and France and in many other countries (e.g., Brazil) cooperate with other institutions and conduct basic research with public funding and financial support from foundations. Students and graduate students often go to other countries to present their research results. Academia gives serious consideration to research on refractories.

(2) Many Chinese universities have been researching and developing refractories. The number of students is quite large and many advanced research facilities are provided. Their importance is acknowledged as state key laboratories and they have high-temperature material laboratories and engineering research centers for furnace lining technologies. China's annual steel production is 900 million tons and the annual refractory production (including refractories for application other than steel) is more than 25 million tons. These numbers indicate that China has been intensely working on refractory technologies.

(3) Universities and public research institutions often target basic technologies in their research and development. Various companies cooperate on common technologies. This may also be because a single company cannot complete research and development on its own due to limitations on the human resources and funds.

(4) As the trend of the refractory technologies presented at UNITECR 2019, it seems that the development of high-functionality unshaped refractories and basic research on understanding and evaluating thermomechanical properties of large

Table 5 Topics for measurement, analysis and evaluation

No.	Title	Author
E-1	16-E-4 Creep Characterization of Refractory Materials at High Temperatures Using the Integrated Digital Image Correlation[22]	Univ. Orléans, Univ. Tours, INSA-CVL, LaMé
E-2	16-E-8 Alumina-Spinel Castables under Thermal Cycling Conditions–In Situ Characterisation[23]	RWTH Aachen Univ., IRCER - Univ. of Limoges, RHI Magnesita, Leoben, Imerys Aluminates, Paris
E-3	16-E-14 Hyperspectral Raman Imaging: A Powerful Tool for Time-, Space-, and Temperature-resolved in Situ Studies Using the Example of the CaO-SiO_2-System[24]	Hochschule Koblenz, Univ. Bonn
E-4	16-E-15 Radar Based Investigation of the Decomposition of Hydrate Phases in Calcium Alumina Concrete[25]	Hochschule Koblenz

linings to enhance their reliability have been steadily conducted.

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13) ibid. 14-B-16, 2019, p. 69–73
14) ibid. 14-C-15, 2019, p. 109–112
15) ibid. 14-D-18, 2019, p. 162–165
16) ibid. 14-A-14, 2019, p. 23–26
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19) ibid. 14-E-17, 2019, p. 202–205
20) ibid. 15-C-11, 2019, p. 419–422
21) ibid. 15-E-17, 2019, p. 605–608
22) ibid. 16-E-4, 2019, p. 896–899
23) ibid. 16-E-8, 2019, p. 912–915
24) ibid. 16-E-14, 2019, p. 937–940
25) ibid. 16-E-15, 2019, p. 941–944

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