On Refractories' High Performance and High Cost-Effectiveness, based on new practices in China

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What does High Performance mean?

High properties

High behavious

High efficiency **High durability** **High reliability** **High availability**

Representativeness of HP

Criteria for HP

- Properties data
- Application result
- Acceptance by market
- P/C

HP $\begin{cases} \textbf{Low cost} \\ \\ \textbf{High P/C ratio} \end{cases}$

Key properties determining service performance!

How to achieve a high P/C？

- **Greatly enhancing performance at edged up cost:**
- **P↑↑, cost ↑**
- **Enhancing perf. at original cost : P.↑, cost ~**
- **Equiv. performance at lower cost: P. ~, cost ↓**
- **Enhancing performance at reduced cost: P. ↑, cost↓**

P/C ↑

Approaches to high performance and high cost-effectiveness

- **Nano-sized effect**
- ***In-situ* effect**
- **Engineered materials and pores**
- **Combination/assemblage effect**
- **Reuse of used refractories**
- **more scientific methods (big data, computer-aid design & simulation, etc.)**

Challenges of nano-sized effect that refractories are facing

- **Major advantages：** **High dispersiveness**

  High reactivity

  Special microstructure

- **Major difficulties：**

  Poor dispersibility and high cost

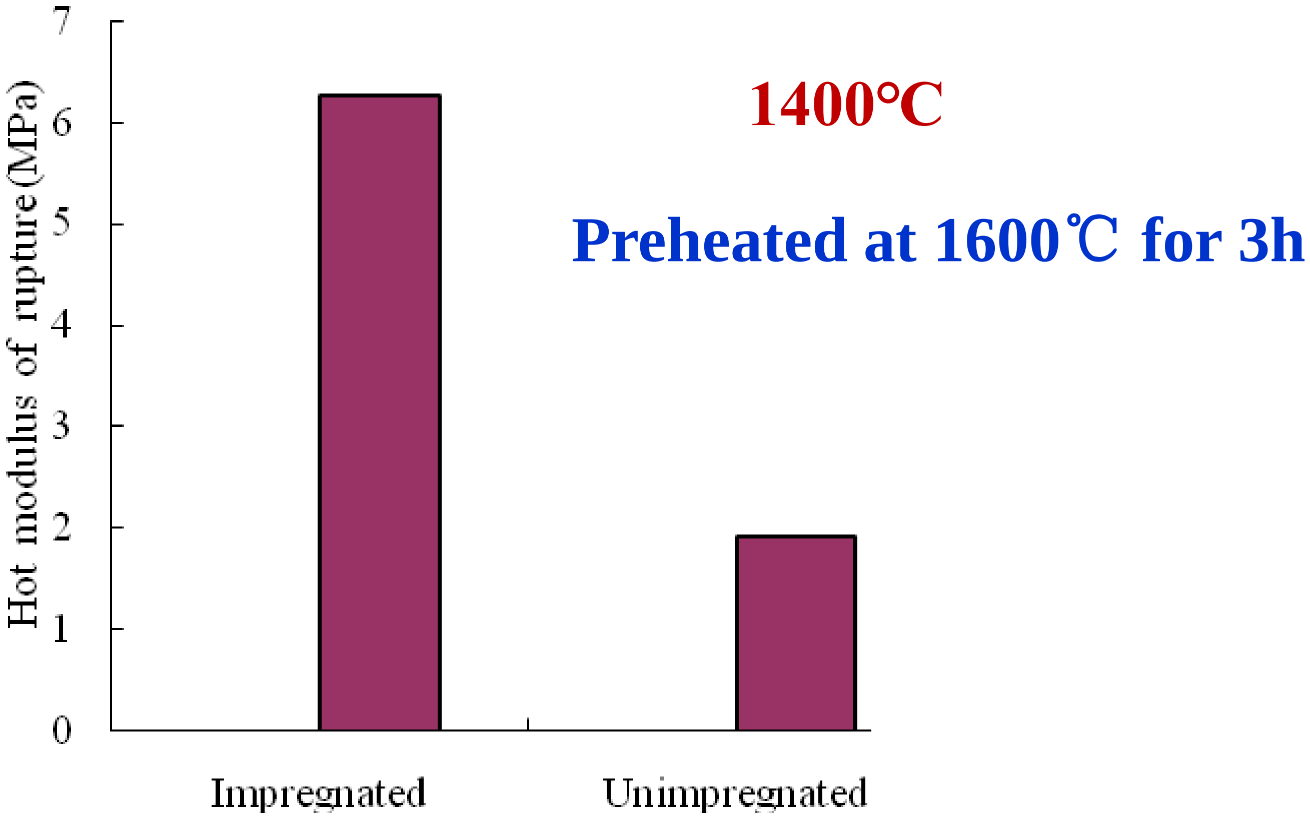
- **Cost-effective approaches to nano-sized effect:**

  Sol-gel

  Precursor

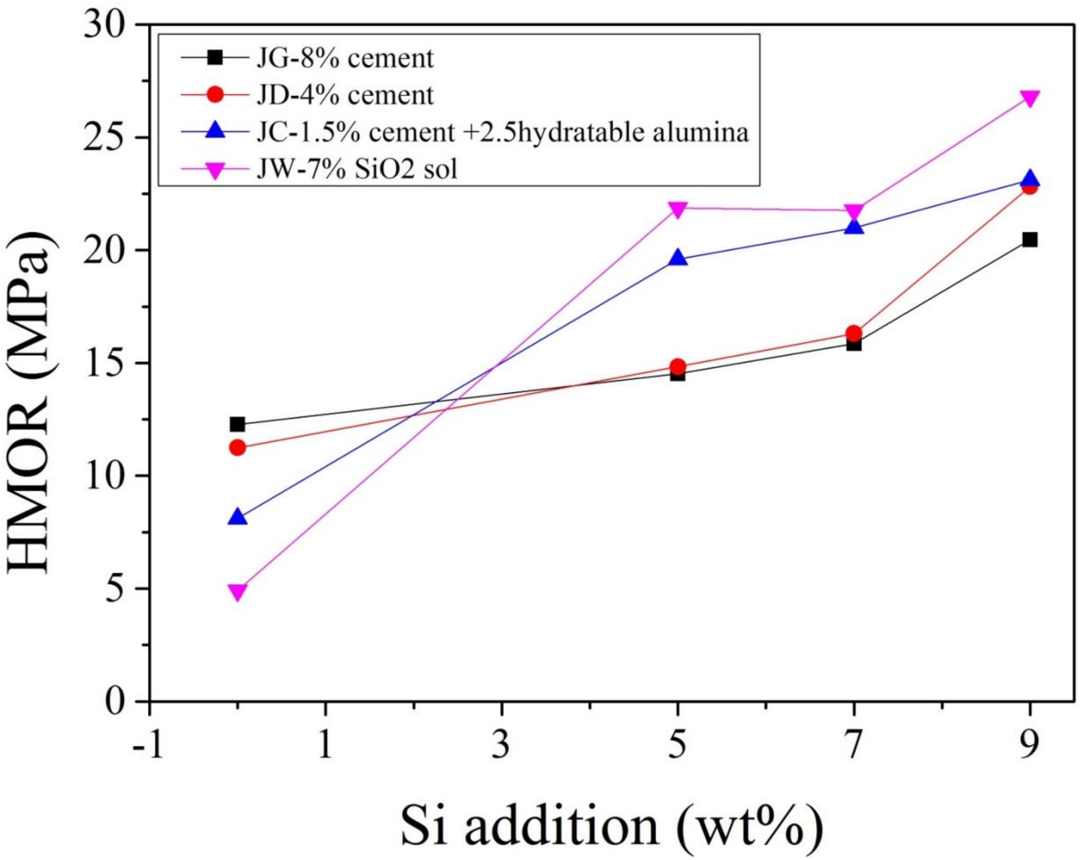
  Gaseous phase as reactant

Nano-sized effect by liquid salt impregnation



Effect of magnesium sulfate impregnation on HMOR of Al_2O_3 based castable

Nano-sized effect by gaseous reaction



Four binding systems:

- Medium cement
- Low cement
- Ultralow cement
- Silica sol-gel

Hot strength enhancement of anchor brick by nitridation

Nitrided at1450℃ for 9h

Test: 1300℃×0.5h, carbon embedding

Si↑ → HMOR↑

CaO↓ → ΔHMOR↑

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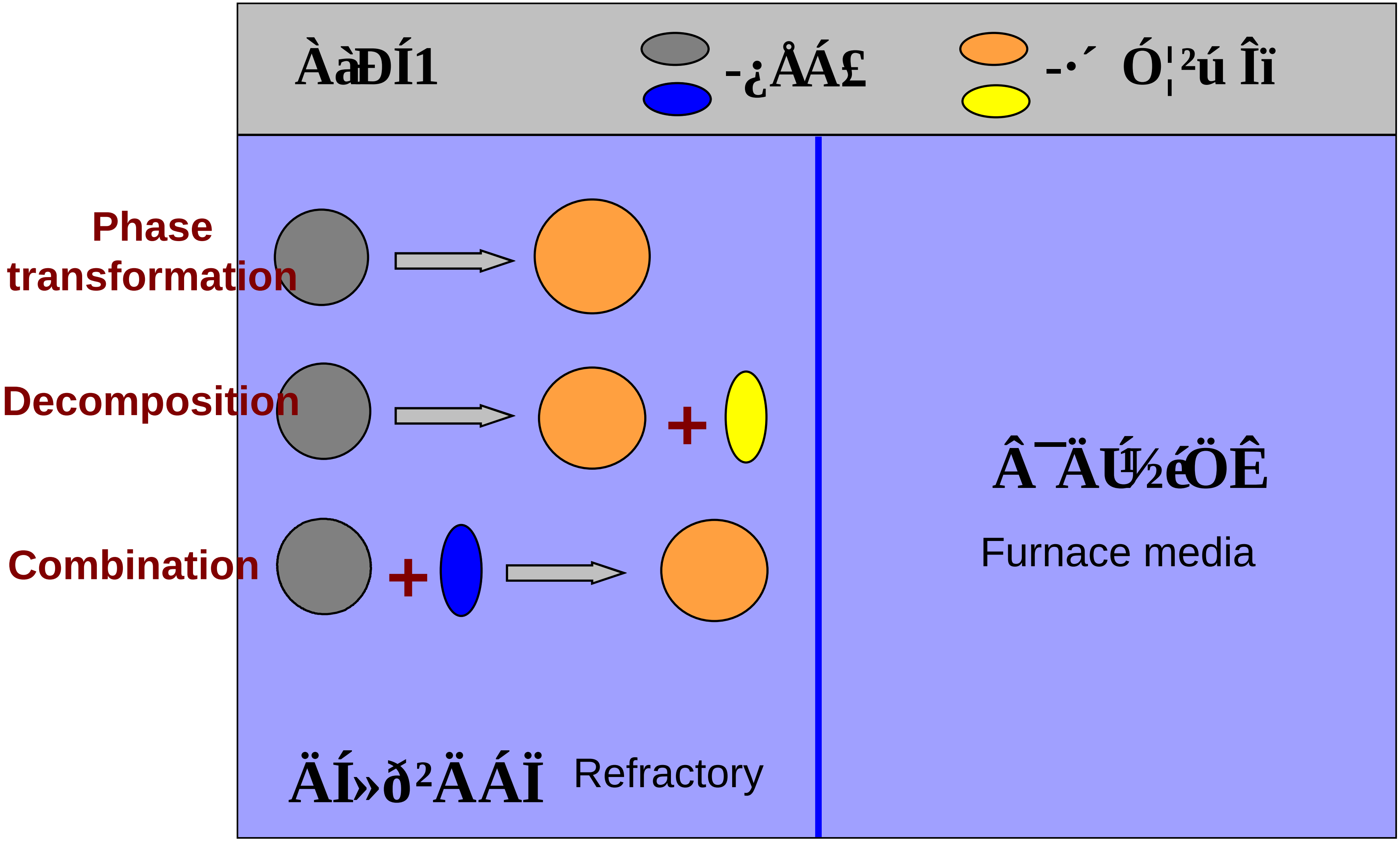
“*In-situ* refractory” Concept

“*Tn situ* refractory” may be defined as the in use product(s) of reaction within a refractory system or between the refractory and furnace contents leading to improved refractory behaviour.

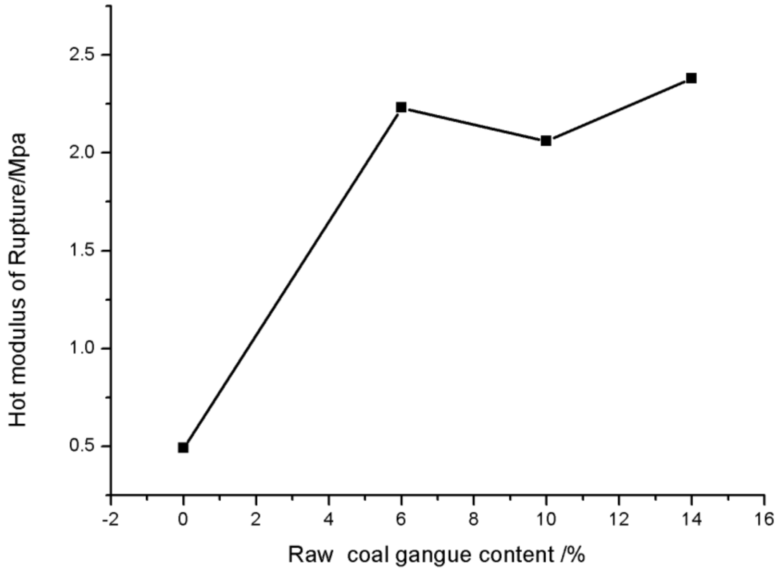
Key point： The reaction occurs “in use”; The reaction and the reaction product are beneficial.

- W. E. Lee and R. E. Moore. The evolution of *in situ* refractories in the 20th century. 1998, J. Am. Ceram. Soc., 81(6)， 1385-1410.
- R. E. Moore and M. Karakus, *In-Situ* refractories used in the containment of molten iron and steel: Strategies for their development, Proc. of the 4th International Symposium on Refractories, March 24-28, Dalian, China, 2003， 134-143.

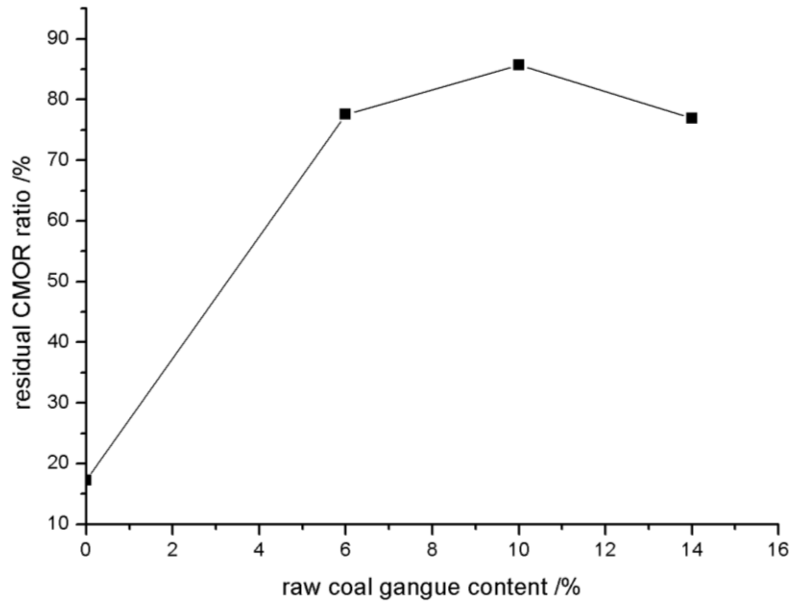
Schematic of *in situ* refractory: Type1



Application of raw coal gangue in aluminosilicate castable

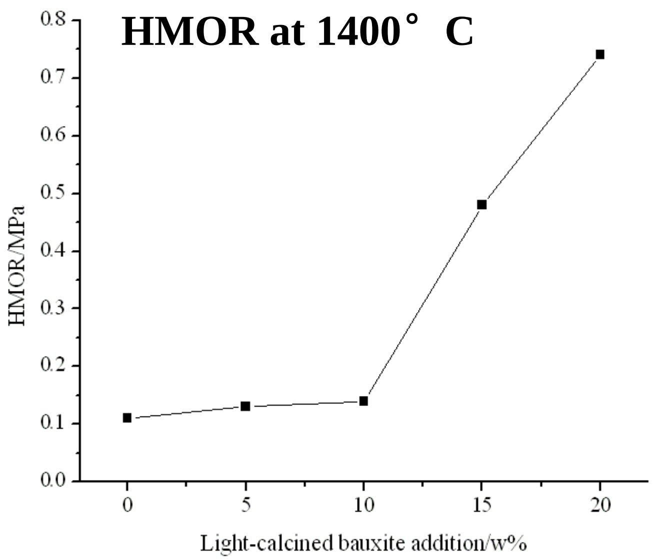


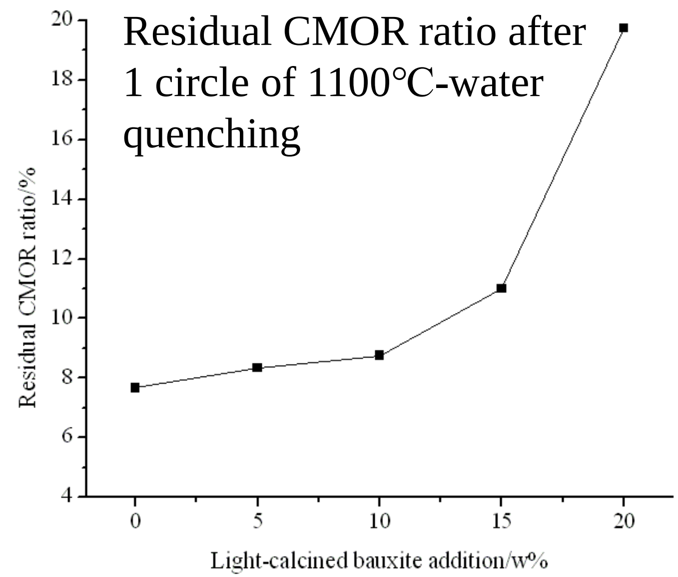
HMOR at1400℃

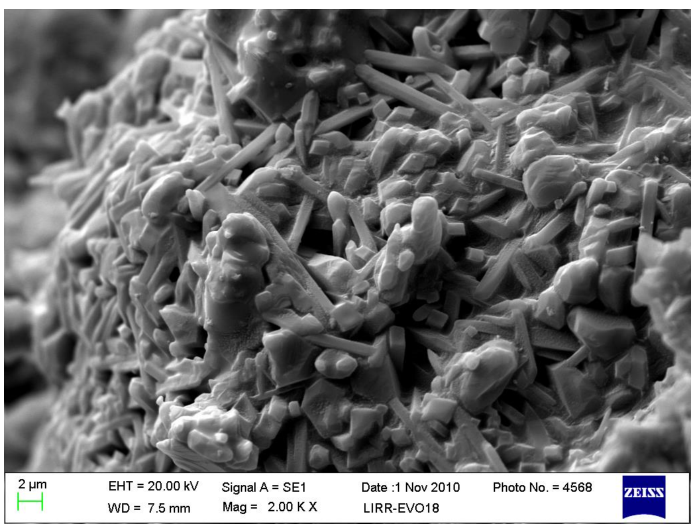


Residual CMOR ratio after 1 circle of 1100°C-water quenching

Application of light-calcined bauxite in aluminosilicate castable

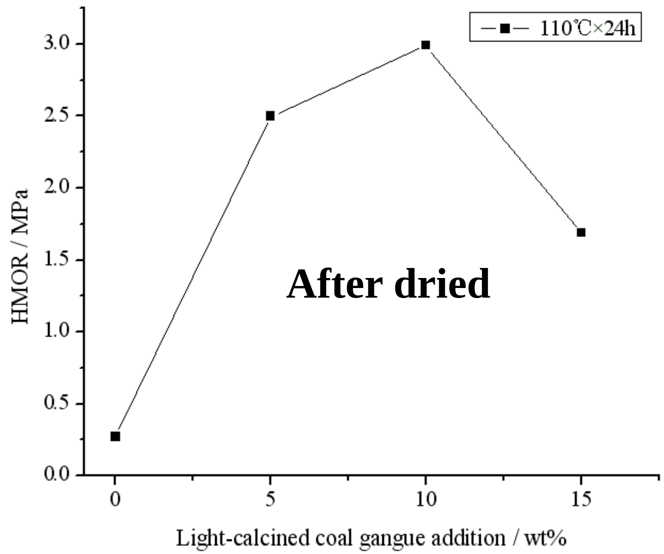


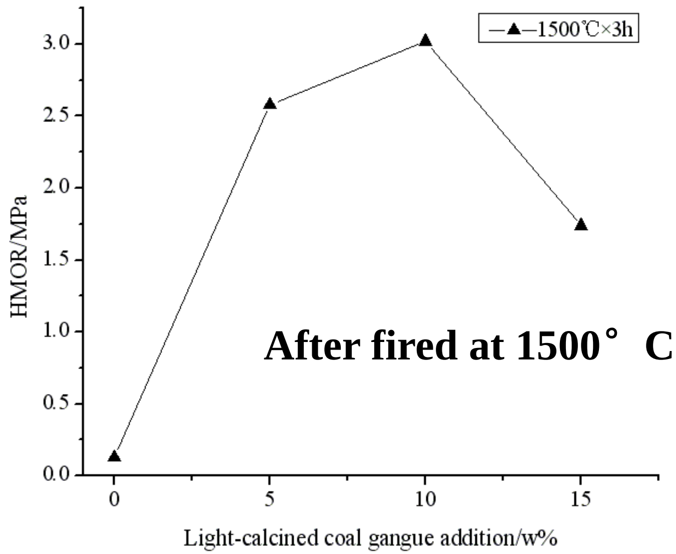


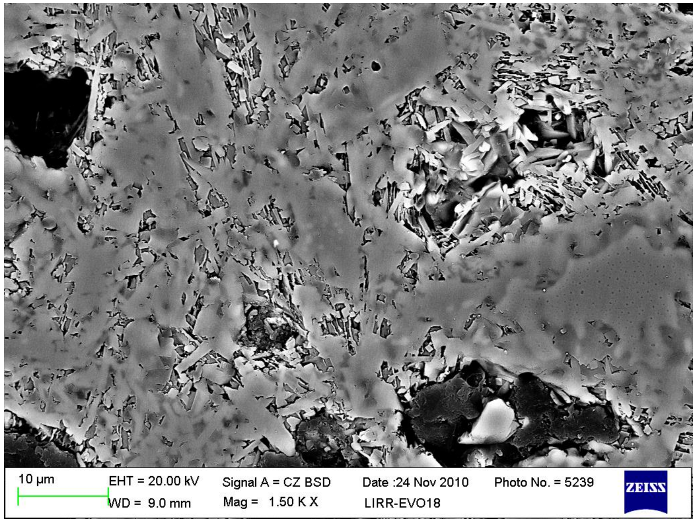


CB-20，fired at 1500℃ for 3h

Application of light-calcined coal gangue in aluminosilicate castable







Microstructure featured by *in situ* mullite can exist for long.

CG-10，fired at 1500℃ for 3h

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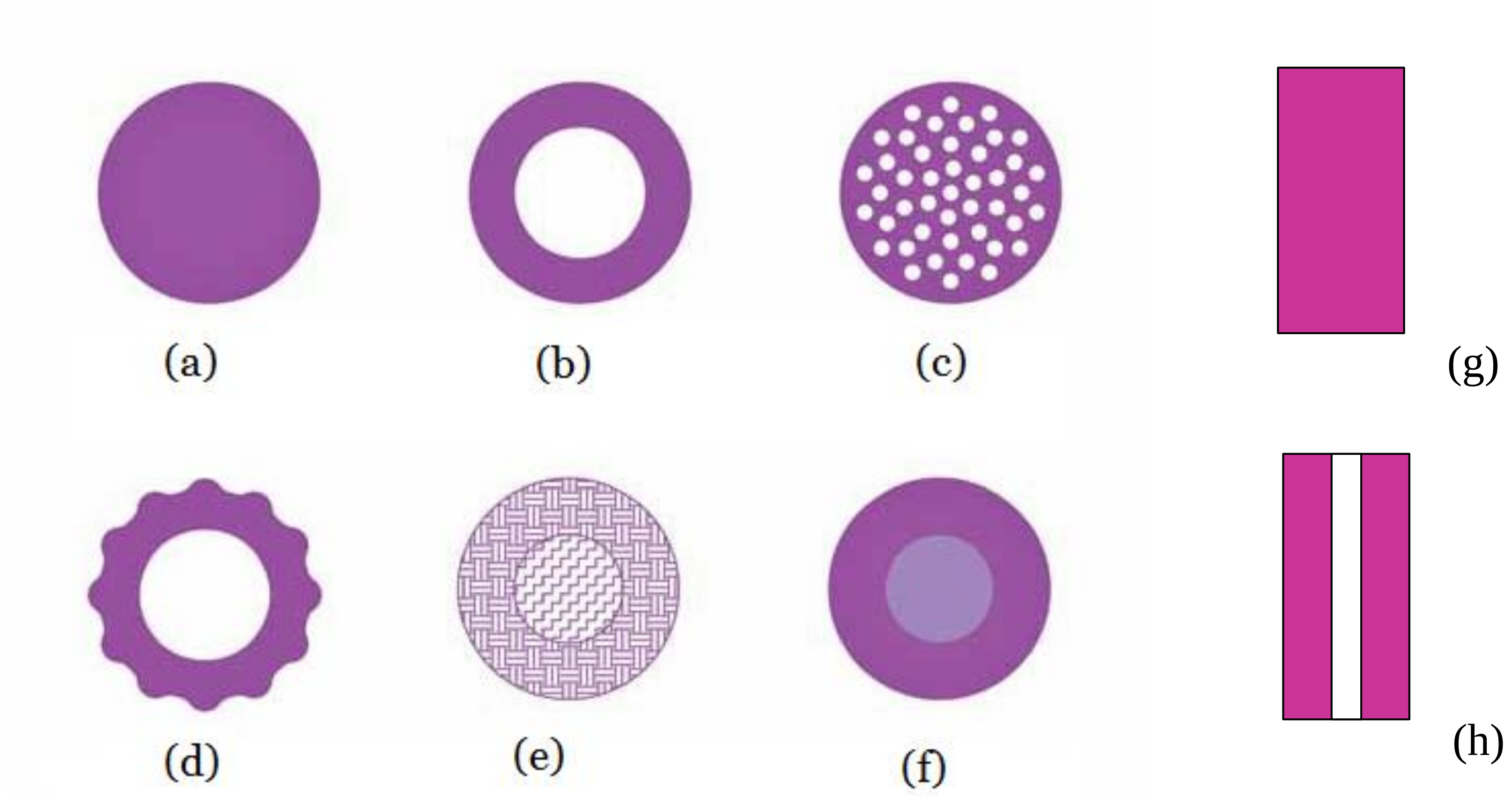
What does “engineering aggregate” mean?

Aggregates engineering refers to a working system, including **design, customization, properties testing, evaluation of their performances** in refractory products and **adoption of them** for desired purposes. Design and customization of engineered aggregates are implemented by **specially designed and controlled shape, surface features, chemical and phase compositions and their distribution as well as microstructures inside and on the aggregate surface**.

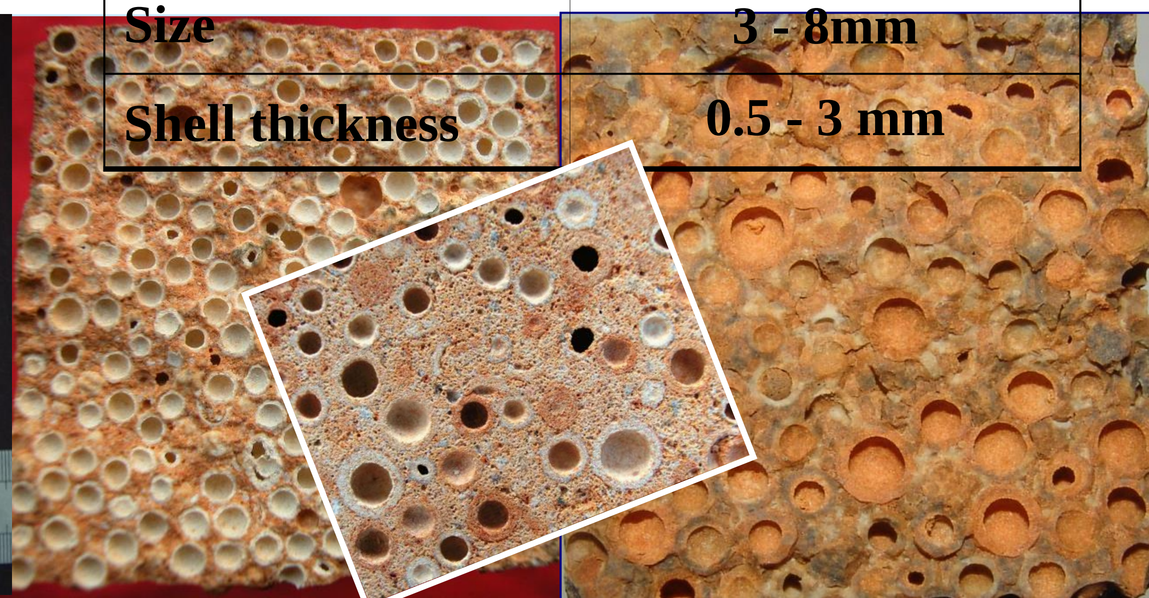
Proposed designs of engineered aggregates



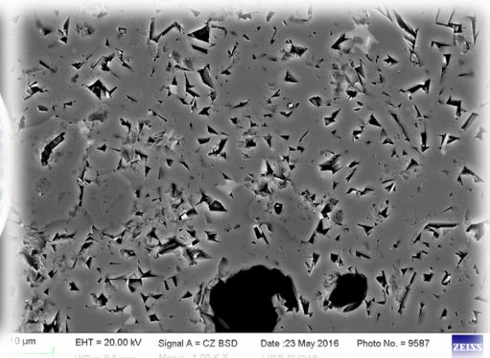
(a) solid sphere; (b) hollow sphere; (c) porous sphere;
(d) sphere with rugged surface; (e) core–shell sphere with different textures between core & shell; (f) core– shell sphere with different chemical compositions between core & shell; (g) columnar/rod aggregate; (h) hollow column/ tube aggregate.

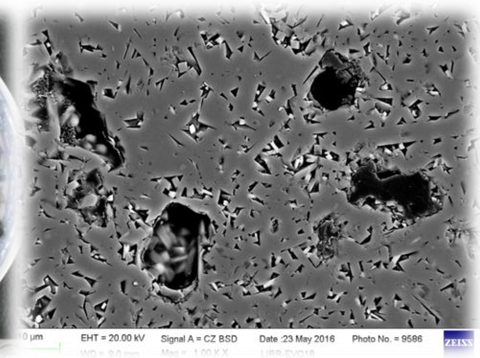
Mullite based hollow balls

Al_2O_3	55 - 60 %
K_2O+Na_2O	≤1.0%
Packing density	0.68 - 0.76 g/cm^3
Refractoriness	≥1770°C
Cylindrical compress strength	2.2 - 2.8 MPa
Size	3 - 8mm
Shell thickness	0.5 - 3 mm



Normally crushed bauxite
vs
spherical bauxite



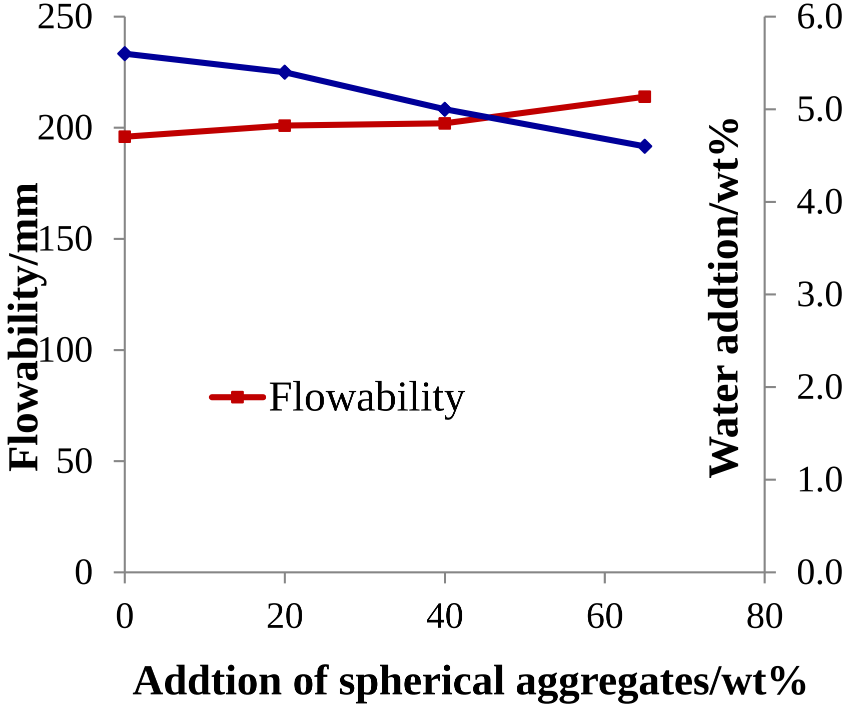


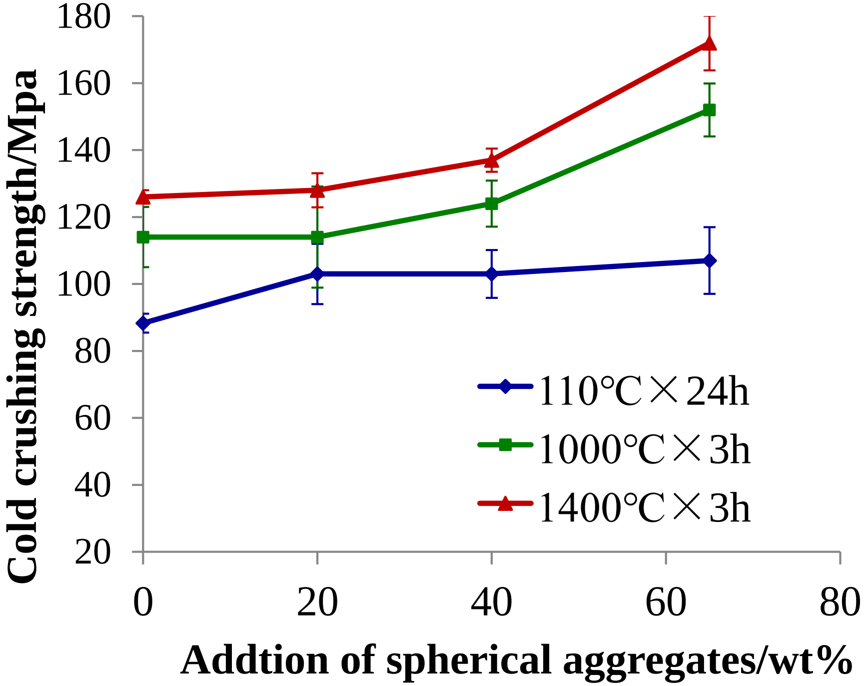
Conventional

Spherical

Aggregate	Al_2O_3%	SiO_2%	BD (g/cm^3)	WA(%)
Spherical	64.9	29.7	2.73	2.6
Spherical	64.77	28.09	2.78	2.5
Conventional	69.00	26.53	2.81	1.8
Conventional	67.64	27.29	2.80	1.5

Effect of spherical aggregate addition on flowability and CCS





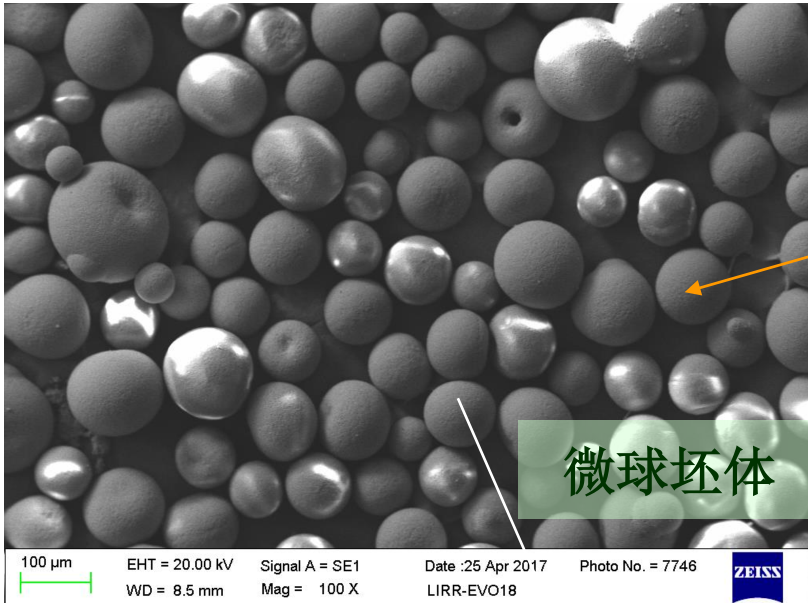
Spherical agg.↑ → Water demand↓， Flowability↑

Spherical agg.↑ → CCS↑

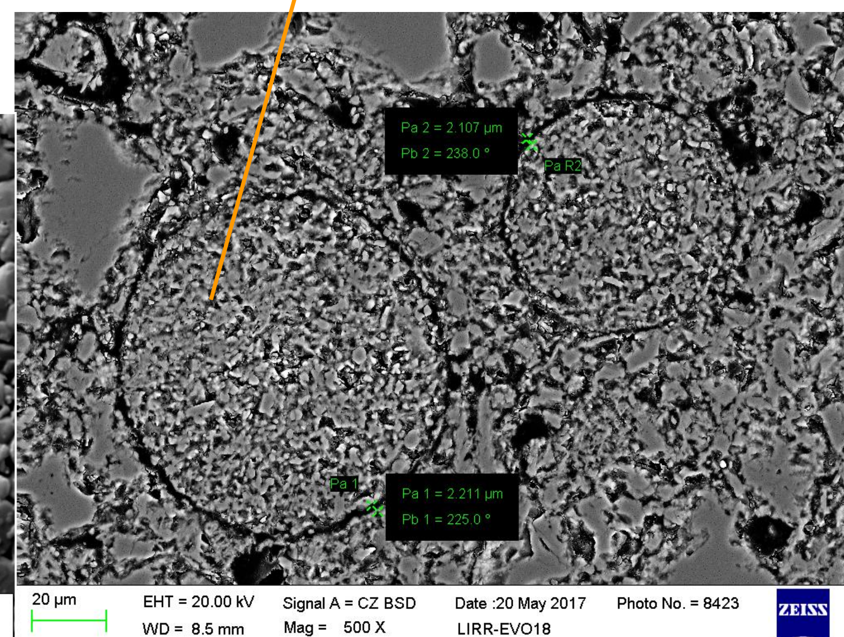
Stress dissipative aggregate — Alumina micro-spheres

Agglomorated alumina untrafines

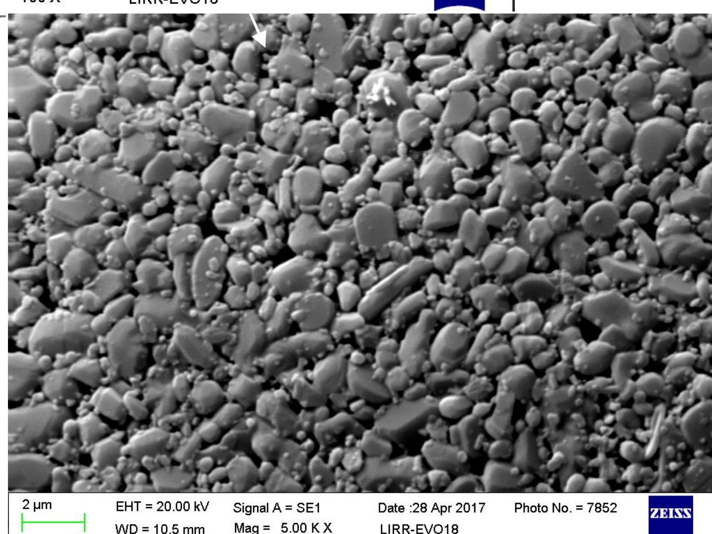
Diameter: ~100μm



In a castable fired at 1550°C for 3h



Fired at 1600°C for 30min



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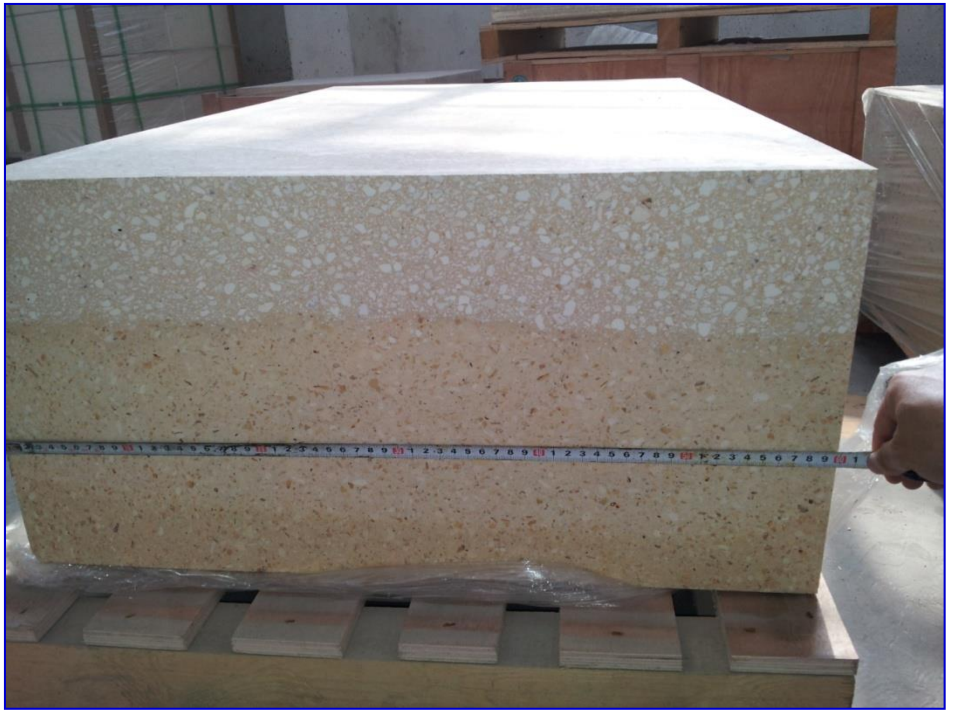
Two-layer brick for hot metal ladle lining

Multi-layer brick for cement kiln

Combined precast shape of castables

QM45-1.8 Micro-pored mullite



Pre-cast block combined with dense and LW castables

Application: back lining of tin bath bottom in glass industry

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Reuse of recycled refractories is also an effective way to obtain good cost effectiveness, with the target of equivalent or even better service performance, while significantly reduced cost.

More applications of big data

- Determine the dominated factor(s) among many
- Better evaluation and control of quality and quality consistency

More applications of computer-aid design and simulation

- Simulating temperature field and stress state
- Developing “low-energy state” and “toughened” refractory products

Concluding remarks

- High performance of refractories must gear to practical situations and requirements with as much as possible high cost effectiveness.
- The approaches to improved service performances under the premise of possibly low cost are more worthy of efforts.
- Six suggested approaches to high performance and high cost-effectiveness deserve to be actively tried and practiced.
- Fusion development by adopting ideas and approaches of other disciplines are encouraged and is believed to bring about more vitalities to R & D, manufacture and application of modern refractories.

Thanks！