Fatigue Failure Behavior of Al₂O₃–SiO₂ System Bricks under Compressive Stress at Room and High Temperatures

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The fatigue failure behaviors of high-alumina brick, agalmatolite brick and silica brick refractory materials were investigated at room temperature and high temperature. As a result, fatigue fracture lives at room temperature are almost the same with the order of high-alumina > agalmatolite > silica. In comparison with other inorganic materials, fatigue failure life in this work was slightly higher than that of silica glass and alumina ceramic.

At high temperatures, it should be noticed that fatigue failure lives of the agalmatolite and silica bricks showed significant increases at the temperatures over 1 473 K. On the other hand, the high-alumina brick showed slight increase. The behavior of strain rate at high temperatures proved that the strain rate of the silica brick mainly increased as a result of crack growth, while crack growth in the high-alumina and agalmatolite bricks increased as a result of creep deformation.

Moreover, the reason why fatigue fracture at high temperatures increased in the agalmatolite and silica bricks was examined in more detail. It was deduced that the longer fatigue fracture lives at high temperatures were related to the generation of a slight amount of liquid phase. The degree of how long fatigue fracture life would be, was estimated to be dependent on the wettability between the solid phase and liquid phase; poor wettability elongated fatigue fracture life.

KEY WORDS: fatigue fracture; high-alumina brick; agalmatolite brick; silica brick; stress; rupture mechanics; stress intensity factor.

1. Introduction

Refining equipment used in ironmaking and steelmaking, for example, the converter and hot metal ladle, etc. generally has a refractory lining structure comprising a wear refractory on the inner side of the vessel, overlaying a permanent refractory which is in contact with the outer steel shell of the vessel. When hot metal or molten steel is charged into a steelmaking vessel, the vessel is heated by the metal; conversely, when the metal is discharged, heat is radiated from the surfaces of the refractories and the steel vessel. As these charging/discharging processes are repeated, the wear refractories and safety brick undergo repeated and varying thermal stresses, which cause progressive cracking in the refractory materials, in some cases resulting in fracture. Refractories must possess adequate mechanical properties to tolerate periodical thermal stress. These types of damage are not short-term phenomena which occur instantaneously, but phenomena which develop progressively over an extended period of time. Thus, in order to estimate the period from crack initiation to fracture, it is necessary to investigate the relationship between continuous cyclical inputs and discharges of heat and fracture of refractories over a long-term span. Moreover, in order to improve refractory life, a detailed elucidation of the mechanism of crack growth under high temperature conditions is also required.

Generally, longer life can be obtained if materials which possess resistance to crack initiation and progress are used as refractories for steelmaking vessels. Two approaches to improving refractory properties are conceivable, that is, improvement of properties in order to reduce thermal stress, and improvement of properties which affect crack initiation and growth. The focus of most past studies was on reduction of thermal stress. The thermal expansion ratio and elastic modulus were regarded as the objects of discussion, and improvement of refractories progressed by controlling the elasticity modulus and coefficient of thermal expansion of the material. However, these studies did not examine the possibility that changes in the thermal expansion ratio might affect mechanical properties such as the modulus of rupture. Consequently, adequate consideration was not given to the effect of thermal stresses generated by cyclical heating and cooling on the modulus of rupture of refractory materials. As a result, information is not enough on how many repetitions of these thermal changes a refractory material can withstand before destruction.

Many studies of ceramics and concrete have investigated fatigue failure from the viewpoint of fracture behavior under periodical stress loading, but there have been very few studies on refractory technology. Therefore, as a first step, the authors investigated the crack growth behavior in refractory materials separately from the thermal expansion ratio and elastic modulus by conducting fatigue failure tests in which periodical stress was loaded directly on the
material, and evaluated the fatigue life of refractories under periodical stress. In previous research, the authors investigated the fatigue failure behavior of MgO–C brick under periodical stress at room temperature and high temperature. The relationship between fatigue failure behavior and thermal spalling fracture was examined based on the results of the fatigue failure test and rupture mechanics. It was found that a brick which had strength against dynamic fatigue failure also possessed excellent resistance against thermal spalling.\textsuperscript{14} Except for this research, few studies have been so far reported in connection with refractory technology.

The present study investigates the fatigue failure behavior of agalmatolite brick, high-alumina brick and silica brick under periodical compressive stress in room temperature and high temperature atmospheres, focusing on fired bricks containing mainly \( \text{Al}_2\text{O}_3 \) and \( \text{SiO}_2 \) without containing carbon. These refractories are used in the safety lining of steel-making vessels, and in coke ovens and hot stoves in the upstream process. The parameters which are related to thermal stress in refractory materials are the thermal expansion coefficient, elastic modulus, and Poisson’s ratio of the refractory material and the temperature difference due to heating.\textsuperscript{15} Since the fatigue fracture behavior and changes in refractory mechanical properties under periodical stress were unknown, stress was evaluated directly in this study.

2. Experimental Procedure

2.1. Fatigue Failure Test

Table 1 shows the chemical composition, phases, apparent porosities ratio, bulk density and mechanical strength of the agalmatolite brick, high-alumina brick and silica brick used in this study. Cubic specimens (20 mm × 20 mm × 20 mm) were used in all cases. Microstructure photographs of these samples are shown in Fig. 1. It was observed that several particles were sintered each other.

A schematic diagram of the experimental procedure is shown in Fig. 2. Cyclical compressive loading was applied to the specimens through the cylinder of the testing machine using the waveform shown in Fig. 2.

Compressive strength, defined as the static modulus of rupture under compressive loading, was measured in each

| Table 1. Chemical composition, phases and mechanical strength of materials used in this study. |
|-------------------------------------------------|-----------------|-----------------|-----------------|
| High Alumina brick | Agalmatolite brick | Silica brick |
| \( \%\text{Al}_2\text{O}_3 \) | 81.4 | 12.7 | 0.9 |
| \( \%\text{SiO}_2 \) | 18.4 | 86.3 | 95.4 |
| \( \%\text{CaO} \) | 0.1 | 0.6 | 0.3 |
| \( \%\text{MgO} \) | 0.1 | 0.4 | 2.4 |
| Phase (from XRD) | Corundum | Si\text{O}_2\text{(quartz)} | Si\text{O}_2\text{(cristballite)} |
| Mullite | Si\text{O}_2\text{(cristballite)} | Si\text{O}_2\text{(Tridymite)} |
| Apparent porosity (%) | 22.3 | 15.0 | 18.7 |
| Bulk density (g/cm\(^3\)) | 2.54 | 2.20 | 1.88 |
| Sample size | 20 mm × 20 mm × 20 mm |
| Compressive stress \( \sigma_c \) (MPa) | 1273 K | 101.0 | 177.6 | 41.1 |
| | 1473 K | 31.8 | 38.9 | 18.2 |
| | 1673 K | 9.3 |

Fig. 1. SEM images of high alumina brick (a), agalmatolite brick (b) and silica brick (c).

Fig. 2. Experimental apparatus for fatigue fracture test and loading pattern.
brick at room temperature and high temperature before the fatigue failure test. Table 1 also shows the compressive strength of each brick at the experimental temperatures, which were 298 K (room temperature), 1 273 K and 1 473 K in the case of the high-alumina brick and agalmatolite brick, and 298 K, 1 473 K and 1 673 K in the case of the silica brick. Compressive strength was evaluated by the following method. The static compressive load was given to each sample at the constant loading speed (0.5 mm/min), and Compressive strength was derived from the calculation method that the value of load when the sample was crushed divided by loading area. Fatigue failure tests were conducted by applying cyclical compressive loading under air atmosphere. The lower limit of compressive loading was a constant value of 10% of compressive strength ($\sigma_c$), while the upper limit of loading was changed from 70% to 100% of compressive strength ($\sigma_c$) with the loading frequency of 0.05 Hz. During the room temperature test, the dynamic elastic modulus of the sample was measured periodically after a certain number of repetitions (N) to investigate the progressive effects of cyclical loading (i.e., increase in ratio of cracks and pores) over the duration of the test. Here, the dynamic elastic modulus represents the modulus of elasticity in an adiabatic process. This property can be calculated from Eq. (1) by deriving the value of the sonic velocity propagated in the material from answering time measurement.\(^{16}\)

$$ E = \left( \frac{X}{t_s} \right)^2 \cdot \rho \quad (1) $$

where, $X$(m) is sample length, $t_s$(s) is answering time and $\rho$(kg/m$^3$) is bulk density.

2.2. Observation by Laser-scanning Microscope

Direct observation of high temperature phases in refractory was performed by using laser-scanning microscope. Silica brick was observed as a representative sample. A sample was crushed under 100 $\mu$m and powdered sample of 0.1 g was inserted into alumina crucible of which Pt plate was laid on the bottom. The size of alumina crucible was $\phi$8 mm–5 mm. After alumina crucible was set in the heating stage, the sample was observed during heating. Temperature elevating rate was set in 1 000 K/min from room temperature to 1 273 K, and 20 K/min from 1 273 K to 1 773 K, respectively. The atmosphere in the stage was filled in nitrogen.

3. Experimental Results

Figure 3 shows the relationship between the compressive stress ratio ($\sigma/\sigma_c$) and number of repetitions, that is, the S–N curve, for every brick at room temperature. Comparing at the same $\sigma/\sigma_c$, the high-alumina brick had a slightly longer fatigue fracture life and the agalmatolite brick had a shorter fatigue fracture life. But the difference in fracture life among these materials was not significant. Figures 4 and 5 separately show $E/E_0$ ($E_0$: the initial elastic modulus) for every brick in the compressive fatigue failure test. A decrease in the values means that the number of cracks, in other words, crack density, increased. As seen in Fig. 4, the decrease was more rapid in the agalmatolite brick than in the high-alumina brick. From Fig. 5, rupture occurred in a high-

Fig. 3. Relationship between compressive stress ratio and number of repetitions of loading for agalmatolite brick, high-alumina brick and silica brick in the experiments at room temperature.

Fig. 4. The changes of the ratio of dynamic elastic modulus to initial elastic modulus for agalmatolite brick and high-alumina brick in the experiments of compressive fatigue failure test.

Fig. 5. The changes of the ratio of dynamic elastic modulus to initial elastic modulus for agalmatolite brick and silica brick in the experiments of compressive fatigue failure test.
er range of the elastic modulus ratio in the silica brick. These figures show that the decrease in the dynamic elastic modulus, that is, crack generation or progress, is different from material to material.

Next, the high temperature fatigue failure behavior was investigated. Figure 6 shows $\sigma/\sigma_C$ versus $N$ for the high-alumina brick. Compared at each temperature, the fatigue fracture life at the same $\sigma/\sigma_C$ at 1 273 K seemed to be close to that at room temperature and increased slightly at 1 473 K. Figure 7 shows the same data for the agalmatolite brick. The fatigue fracture life at the same $\sigma/\sigma_C$ at 1 273 K was similar to that at room temperature but showed a large increase at 1 473 K. Figure 8, showing the data of the silica brick, tells us that obvious is significantly longer life with increasing temperature.

Figure 9 shows the trend of apparent strain in the vertical direction of the sample in the room temperature fatigue failure test of every brick. Apparent strain $\varepsilon$ was defined as shown in the following equation, where $h_0$ is sample height and $l$ is stroke length.

$$\varepsilon = \frac{h_0 - l}{h_0}$$

In the high-alumina brick and silica brick, apparent strain was substantially constant under cyclical compressive stress, whereas, apparent strain increased slightly in the

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Fig. 6. Relationship between compressive stress ratio and number of repetitions of loading for high alumina brick at room temperature, 1 273 K and 1 473 K.

Fig. 7. Relationship between compressive stress ratio and number of repetitions of loading for agalmatolite brick at room temperature and 1 473 K.

Fig. 8. Relationship between compressive stress ratio and number of repetitions of loading for silica brick at room temperature, 1 473 K and 1 673 K.

Fig. 9. Trend of apparent strain in vertical direction of sample during fatigue failure test at room temperature ((a) high-alumina brick, (b) agalmatolite brick and (c) silica brick).
agalmatolite brick. Figure 10 shows the same trend at the high temperatures indicating the gradual increase at the lower cycles with the rapid increase at higher cycles for every brick. This result suggests the possibility that, in addition to crack generation or crack growth, partial creep deformation takes place inside at high temperatures over 1 273 K.

4. Discussion

4.1. Fracture Dynamical Discussion of Refractory Material

Based on the observed relationship between $\sigma/\sigma_c$ and N, the fatigue fracture behavior was examined using rupture dynamics in order to compare the characteristics.\textsuperscript{16,17} The samples after fatigue fracture showed that cracks had mainly progressed in the direction perpendicular to the loading phase. The dynamic elastic modulus during the fatigue failure test was found to be decreased gradually, as shown in Figs. 4 and 5. From these results, the fracture mode was regarded as mode I, to which Irwin’s linear elastics theory is applicable.\textsuperscript{18}

It was assumed that an existing crack will progress gradually and in stable manner under cyclical compressive loading, and Paris’s law can be applied to the crack progress behavior. The rate of crack growth can be expressed by Eq. (3).\textsuperscript{16,17}

$$\frac{da}{dN} = C \left( \frac{\Delta K}{K_{ic}} \right)^n$$

where, $a$ is crack length, $N$ is number of cycles, $K_{ic}$ is fracture toughness, $C$ and $n$ are characteristic constants dependent on the material, and $\Delta K$ is the difference of the stress intensity factor expressed by Eq. (4).

$$\Delta K = K_{max} - K_{min}$$

Substituting Eq. (5) for Eq. (4), and the result was substituted for Eq. (3) further, the result of substitution was integrated, Eq. (6) was obtained finally.

$$\log \Delta \sigma = \frac{1}{n} \log N$$

When the results of the fatigue failure test shown in Figs. 5 to 7, that is to say, the difference of the maximum and minimum stress, $\Delta \sigma$, and the number of cycles to rupture, $N$, were substituted in Eq. (6), and a linear relationship between $\Delta \sigma$ and $N$ was assumed, the numerical constant $n$ could be obtained. Because this value was determined by conditions specific to the material and the atmosphere temperature and other experimental conditions, the index $n$ was compared and discussed for each experimental condition in this study.

As mentioned above, it is considered that the numerical index $n$ depends on the factors such as composition of the material, experimental temperature, environment and situation. The physical implication of the index $n$ is the degree of sensitivity to changes in the progress of the crack and in the stress intensity factor. It has been reported that smaller values of $n$ indicate a decrease in fatigue strength.\textsuperscript{4} In this study, the values of $n$ were compared for each experimental condition.

Table 2 shows the values of $n$ obtained from the results of the fatigue failure test of several refractory materials. The values of $n$ of the silica brick and agalmatolite brick showed large increases at high temperature. In particular, at 1 673 K,
the $n$ value of the silica brick was about five times larger than that at room temperature. On the other hand, the $n$ value of the high-alumina brick at room temperature was similar to that at 1 273 K and slightly increased at 1 473 K. The extent of the increase was not as much as that of $n$ of the silica brick.

Figure 11 shows the relationship between the index $n$ and the alumina content in bricks at room temperature along with $n$ values of silica glass$^{7,19-21}$ and alumina ceramic$^{3,5,6}$ as brittle materials. The $n$ values decreases as alumina content decreases. The values of $n$ obtained in this study were greater than that of silica glass and alumina ceramic, predicting that the Al$_2$O$_3$–SiO$_2$ system refractory evaluated in this study would display lower crack growth rate than that of an alumina ceramic.

4.2. Strain Behavior of Each Refractory

The creep deformation behavior of the Al$_2$O$_3$–SiO$_2$ system refractory was estimated at high temperatures applying constant compressive stress to the samples continuously. This will allow creep deformation to relate with strain behavior under dynamic fatigue stress. The solid lines in Fig. 12 show the change in apparent strain calculated by Eq. (2) in the vertical direction of the sample. The dotted lines in this figure show the average inclination of maximum strain change per the number of repetition at periodical loading applied to the sample (dotted lines) in the high temperature atmosphere (a) High alumina brick (b) Agalmatolite brick and (c) Silica brick).

It is considered that the cause of increasing strain rate includes two kinds of influences. One is the influence of creep deformation and another is influence of crack progress. From these results, it is considered that the strain rate increased as a result of crack growth in the silica brick because creep deformation behavior is not observed at high temperature. While it is presumed that the strain rate increased as a result of creep deformation in the high-alumina brick and agalmatolite brick.

The mechanism of creep in inorganic materials such as ceramic and refractories has been reported to be as a result of diffusion of the constituent components of the material.$^{16}$ Although some refractories may display creep behavior caused by crystal dislocation, few reports have examined this possibility. It has been reported that high temperature creep behavior is more pronounced if a small amount of liquid phase is formed between particles, for example, at grain boundaries.$^{16,22}$ In general, it has been argued that the formation of a liquid phase or glass phase has a comparatively large effect on the high temperature creep behavior of refractories, and the high temperature creep behavior associated with a liquid phase is influenced by physical properties of the liquid and solid phases, such as viscosity and wettability.$^{22}$ Based on the above results, the reason for significant increases in the fatigue failure life of the agalmatolite and silica bricks at high temperature will be discussed in the next section. Particularly, we focus on the relation to the property of wettability, which may be an influencing factor in creep or deformation behavior of refractories at high temperature.

4.3. Fatigue Fracture Behavior of Refractories at High Temperature

Figure 13 shows photographs of particles of the silica brick (fragments of the brick) taken with a laser-scanning microscope at high temperature. The particle shape did not change from room temperature to 1 273 K, over which softening occurred from the particle edge. A slight amount of
liquid phase partially formed at 1,673 K.

Figures 14(a), 14(b) and 14(c) show the calculated equilibrium phase composition as obtained by thermodynamic simulation (used with FACTSAGE) based on the chemical composition of the brick. Actual bricks consist of particles of various sizes as seen in Fig. 1 with probable heterogeneous distribution. Particularly minor components such as lime or periclase might be segregated. Equilibrium state can be, however, assumed in terms of chemical compositions by the following facts.

- Chemical composition of each brick was analyzed after randomly sampled. For high alumina brick, analyses of several portions proved that the compositions were mostly the same each other.
- High temperature XRD identified the solid phases same as those calculated by assuming equilibrium.
- The liquid phase ratio of 10.4 area% at 1,673 K, visually measured by Fig. 13, was in good agreement with the calculated value of 10.5 mass% realized in Fig. 14(c) considering that the area% was almost comparable to mass%.

A liquid phase was generated in the high-alumina brick over 1,313 K and in the agalmatolite brick over 1,358 K. In the silica brick, a liquid phase as much as 10% was generated at temperatures over 1,458 K. The calculated liquid phase ratio was 2.0–4.6% in the high-alumina brick, 1–3.7% in the agalmatolite brick and 6.7–11.7% in the silica brick. Small amount of liquid phase generated in the bricks at high temperature may play an important role in improved high temperature fatigue fracture life. Figures 15(a), 15(b) and 15(c) show the calculated composition of the liquid phase in each brick at high temperature. In the high-alumina brick, the liquid phase was calculated as an Al$_2$O$_3$–SiO$_2$–CaO system melt with Al$_2$O$_3$ content from 30–40% and SiO$_2$ content of 40%. In the agalmatolite brick and silica brick, the liquid phase was calculated as SiO$_2$ rich melt with SiO$_2$ content over 60%.

Table 3 shows the contact angles between Al$_2$O$_3$ or SiO$_2$ solid and Al$_2$O$_3$–SiO$_2$–CaO system liquid or SiO$_2$ liquid. It has been reported that the contact angle between Al$_2$O$_3$–SiO$_2$–CaO system liquid and Al$_2$O$_3$ solid is 40–60° implying good wettability. In contrast, the contact angle between SiO$_2$ rich liquid and Al$_2$O$_3$ solid is 140–150°, and that between SiO$_2$ rich liquid and Al$_2$O$_3$ solid is 130° at 1,473 K implying poor wettability.

From the results of the above discussion, the mechanism of improved high temperature fatigue fracture life in the high-alumina brick, agalmatolite brick and silica brick was deduced to be as follows. Acknowledging the qualitative nature of these conjectures, Fig. 16 shows the schematic diagram of behavior of refractory particles at high temperature when cyclical compressive stress is applied to the silica and agalmatolite bricks having poor wettability between their liquid and solid phase. Therefore, a very small amount of liquid phase with a sufficient thickness remains between the aggregate and the matrix. Due to poor wettability, this
liquid phase takes a spherical shape, allowing the liquid phase to absorb stress (by analogy, functioning like shock-absorbing rubber balls). When compressive stress is applied, this liquid phase relieves stress resulting in longer fatigue fracture life. It is also conjectured that the difference in the numerical index \( n \) of the silica brick and agalmatolite brick is due to the difference in the liquid phase ratio in these materials.

On the other hand, Fig. 17 shows the behavior of the high-alumina refractory particles at high temperature. In the high-alumina brick, the wettability between the liquid phase and solid phase is good. Therefore, a very small amount of liquid phase remains between the aggregate and the matrix in the form of a very thin film, which has less capacity to absorb stress than the others. In this case, the stress relieving capacity of the liquid phase is small, and therefore fatigue fracture life is not much improved.

Some reports discussing the fatigue mechanism\(^{25,26}\) have argued that refractories are strengthened by the presence of an \( \text{SiO}_2 \) system liquid phase that functions as a ligament across the surface in the wake region behind the crack. This liquid phase has a “bridging” effect, and the high viscosity of the liquid is effective in preventing crack propagation. However, calculations of high temperature viscosity do not necessarily support this conclusion. Figure 18 shows the calculated results of the viscosity\(^{27}\) of the liquid phase in each brick, as obtained from the calculated composition of the liquid phase shown in Fig. 15. The viscosity of liquid phase decreased when temperature elevated. Moreover, the viscosity of liquid phase in the high-alumina brick could be calculated to be the lowest in the three, and agalmatolite brick and silica brick could be calculated comparatively higher value (to be strictly, the viscosity in agalmatolite brick was a little higher than that in silica brick). We will
discuss the fatigue failure behavior at high temperature focusing on silica brick as follows. Comparing the numerical indexes of each brick at 1473 K (Table 2), a relationship between fatigue failure life and the strength of bridging by the liquid phase based on differences in viscosity cannot be denied. On the other hand, the calculated viscosity of the liquid phase in the silica brick is lower at 1673 K than at 1473 K. If the strength of the bridging effect is the predominant factor, the fatigue failure life of the silica brick should be lower at 1673 K than at 1473 K, but in fact, fatigue failure life is longer at the higher temperature. Moreover, when the shape of the liquid phase was inferred in terms of wettability between the liquid and solid phases, as shown in Table 3, the liquid is predicted to assume a spherical shape in cracks or pores between particles, in which case the liquid phase cannot play a bridging role.

Thus, in explaining the differences in the increased high temperature fatigue failure life of these materials, it can be concluded that fatigue failure life is influenced not only by the strength of bridging by the liquid phase, which is dependent on the viscosity of the liquid phase, but also by differences in the stress relieving behavior of the liquid phase, which is dependent on differences in wettability between the solid and liquid phases.

Nevertheless, many questions about high temperature fatigue fracture behavior in refractory materials remain to be answered. In the future, it will be necessary to clarify the mechanism of fatigue failure and analyze fatigue fracture behavior at high temperature.

5. Summary

The fatigue failure behaviors of high-alumina brick, agalmatolite brick and silica brick, which are used as refractory materials in steel manufacturing processes, were investigated at room temperature and high temperature. The results are shown in Table 4 and summarized as follows.

1. At room temperature, the high-alumina brick displays the highest fatigue fracture life among these bricks, followed by the agalmatolite brick and silica brick in that order. However, the differences among these materials are small. In comparison with other inorganic materials, fatigue failure life in this work was slightly higher than that of silica glass and alumina ceramic.

2. At high temperature, the fatigue fracture life of the high-alumina brick increased slightly in comparison with that at room temperature. In contrast, the fatigue fracture life of agalmatolite brick and silica brick showed large increases at 1473 K and higher temperatures.

3. At high temperature, it is considered that strain rate in the silica brick increases mainly as a result of crack growth. In contrast, a high temperature static stress test (creep test) revealed that crack growth in the high-alumina brick and agalmatolite brick is associated with creep deformation.

4. A thermodynamics simulation showed that small amounts of a liquid phase are generated in these materials above a certain temperature. It was deduced that the high temperature fatigue fracture behavior of these materials is related to the formation of the liquid phase, and furthermore, the increase in fatigue fracture life varies, depending on the wettability between the solid phase and liquid phase. Based on calculated differences in wettability, a mechanism by which the liquid phase performs a stress relieving function was proposed.

## Table 4. Summary in this study.

<table>
<thead>
<tr>
<th>Liquid phase at high temperature</th>
<th>Cause of strain rate increasing</th>
<th>Numerical index</th>
<th>Viscosity of liquid phase at 1473 K</th>
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<tbody>
<tr>
<td>Al2O3- SiO2-CaO</td>
<td>Creep</td>
<td>High (69 Pa·s)</td>
<td></td>
</tr>
<tr>
<td>SiO2 rich</td>
<td>Creep</td>
<td>Low (320 Pa·s)</td>
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<tr>
<td>SiO2 rich</td>
<td>Creep</td>
<td>High (230 Pa·s)</td>
<td></td>
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</tbody>
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### REFERENCES