

Mechanical Strength of Silicon Carbide Bonded with Iraqi Clays

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Abstract

Two types of Iraqi clays (Kaolin and Bentonite) were used in bonding process with different weight percentage (5%, 10%, 15%, 20%, and 25%) and with different particle size from clays and silicon carbide.

The specimens were formed by using low biaxial pressing and two types of internal lubricants (sodium silicate and the carbon paste) to increase the specimen's cohesion. These specimens were sintered at various temperatures of (1100°C, 1200°C, 1300°C, and 1400°C).

Increasing of clay percentage leads to decreasing the porosity. But it leads to increase mechanical properties (compressive strength, diametrical strength and bending strength). Also, the effect of particle size on all properties is studied together with sintering temperature. All mechanical properties (when bonded SiC with bentonite) are higher than kaolin bonded SiC.

Keywords: silicon carbide; kaolin; bentonite; compressive strength; diametrical strength; bending strength

المتانة الميكانيكية لكاربيد السيليكون المربوط بأطيان عراقية

الخلاصة

استعمل نوعان من الطين العراقي مختلفين في التكوين المعدي، هما الكاولين و البنتونايت، وتم إضافتهما إلى كاربيد السيليكون وبنسب وزنية طينية متغيرة: 5%, 10%, 15%, 20%, 25% وبمحجفين حبيبين مختلفين. استخدم في عملية الربط نوعين من مواد الربط الداخلي هما سيليكات الصوديوم و معجون الكربون(Carbon Paste)، شكلت العينات باستخدام الكبس المحوري ثم لبدت العينات بدرجات حرارية متباعدة: 1100°C, 1200°C, 1300°C, 1400°C.

تبين أن زيادة نسبة إضافة الطين تؤدي إلى تناقص المسامية. أما الخصائص الميكانيكية (متانة الانضغاط، متانة الكسر و متانة الانهاء) فقد ازدادت جميعها مع زيادة نسبة الطين لكلا النوعين، وأن جميع الخصائص الميكانيكية كانت أعلى في حالة إضافة البنتونايت بالمقارنة مع إضافة الكاولين. أيضاً تأثير الحجم الحبيبي ودرجة حرارة التلبيد على جميع الخصائص درست في هذا البحث.

Introduction

Clay-bonded silicon carbide has a high thermal conductivity and low thermal expansion, which gives it excellent thermal shock resistance.

Clay-bonded silicon carbide is composed of roughly 73 to 77% SiC, 17 to 21% Al₂O₃, and 4 to 6% SiO₂. Silicon carbide also offers high strength at elevated temperatures. The

maximum use temperature of silicon carbide is limited to 1350 °C in oxidizing atmospheres due to the oxidation of SiC to SiO₂. Silicon carbide is a superb choice when thermal shock resistance is needed in highly reducing atmospheres that will degrade fused silica, cordierite or mullite.[1]

The strength of SiC based refractory kiln furniture is influenced primarily by the bonding phase. In the case of clay-bonded material the strength of the body increases up to 900 °C to 1000°C, followed by a rather rapid decrease, with minimum strength at the top temperature of usual ceramic firing [2].

The key to understand the mechanical properties of ceramics is the Griffith theory for failure of brittle materials. Ceramics are extremely brittle and, therefore, extremely sensitive to the presence of any sort of flaw on the surface or in the bulk of the ceramic.[3]

The propagation of cracks through the cross sectional of brittle material is in a direction perpendicular to the applied load.

The measured fracture strengths of ceramic materials are substantially lower than that predicted by theory from interatomic bonding forces [4].

Strength and Compressive Strength

For compressive stresses, there is no stress amplification associated with any existent flaws. For this reason, brittle ceramics display much high strengths in compression than in tension (on the order of a factor of 10), and they are generally utilized when load conditions are compressive [4].ASTM C773 was used as

standard to test the compressive strength for cylindrical ceramic specimens, and the compressive strength is calculated from the relation:

$$\text{Compressive Strength} = \frac{F}{A} \text{ (MPa)} \quad \dots\dots(1)$$

Where F : total load on the specimen at failure (N), A : Cross section area of the specimen (mm²).

Tensile testing of ceramics is not only time consuming but it is also expensive to fabricate the specimens. Therefore, the easier-to-handle transverse bending or flexure test is commonly used for determining the strength of ceramics [5].

Motivated by a desire to use compressive forces to induce tensile failures, as well as the necessity to study surface area and volume effects, engineers have devised a number of ingenious in direct tension test. One of these methods is diametrical compression; this method is plagued by the common problem of precise machining of difficult – to – machine materials. Loading configuration is an important factor in the diametrical compression disk. The stress distribution should be independent of length, provided a uniform compression stress applied. However, friction stress, as well as non uniform stresses, ordinarily results at contact points.

The simple theory describing the stress distribution under a uniform diametric load on a disk-shaped specimen predicts a uniform tension field at the center of the disk:

(Diametrical Strength)

$$\sigma_D = \frac{2F}{\pi D t} \quad \dots(2)$$

where F is the applied load (N), D is the disk diameter and t is the thickness of disk. The stress field in the transverse direction is highly dependent on the width of load application and becomes highly compressive. The disk test has therefore been used to attempt to study biaxial stress failure response [6].

Bending Strength

In ceramic materials, the conventional tensile test cannot be used because of the problems of preparing suitable test pieces and effectively holding them in the test machines. The materials are in the forms of beams and bent by three-point bending, the term flexural strength or modulus of rupture is used for the surface stress in the beam when breaking occurs. For a rectangular cross-section beam, The maximum stress that is happening on the surface with three-point loading is:

$$\text{Flexural Strength} = \frac{3FD}{2bd^2} \quad \dots(3)$$

where, (b) is the breadth of the section and (d) its depth.[7] Flexural strength values for materials tend to be about twice their tensile strength values. Because cracks and flaws tend to close up in compression, brittle materials tend to be much stronger in compression than tension [8].

During bending, a specimen is subjected to both compressive and tensile stresses [4]. Although bending strength is independent of the orientation of the test specimen, higher values are obtained in the pressing direction [5].

Experiment

Preparation of SiC-Clay System

Powder processing technologies are used generally in manufacturing of ceramics, because of their high melting point, producing hard and brittle ceramic components. [9].

The starting materials used for this work were a commercial α -SiC powder, produced by Struers Company (impurity 99.5%) with two particle sizes, the first is coarse powder ($10 \mu\text{m} < D < 38 \mu\text{m}$) and second is fine powder ($D < 10 \mu\text{m}$).

White Kaolin and bentonite (Iraqi raw materials) have been used as a bonding material. These raw materials were supplied by "State Company of Geological Survey and Mining". The composition of raw materials is shown in table (1).[10]

The coarse powder ($53 \mu\text{m} < D < 63 \mu\text{m}$) of clays was mixed with coarse SiC powder and fine powder ($D < 38 \mu\text{m}$) of clays was mixed with fine SiC powder. The clays raw materials were added to α -SiC in different weight percentage of clay (5%, 10%, 15%, 20%, and 25%). The powder mixture was ball-milled in methanol for 24 hr to insure homogeneity. [11]

Sodium silicate was added to SiC-Clay component with amount 0.05 g to one gram of SiC-Clay with density 1.35 g/cm^3 . The green compact specimens with sodium silicate have high cohesion after drying in oven at 50°C for 24 hr. The second type of binder is carbon paste, was added in amount of 0.1g to each 1g of (SiC -Clay).

The composition of all Samples is shown in table (2).

Results and Discussion

Green compact specimens have high homogeneity and exact uniform dimensions with ease in press process and the specimen slides inside the mold, but the coherence of the specimens is smaller than sodium silicate. The carbon paste lubricant disintegrates (during heating treatment at temperature below the sintering temperature) leaving the specimen without any binder except the clay. Therefore, the clay binds SiC powder during sintering in liquid phase, which is generated at high temperature and penetrates around SiC particles.

Porosity: Open porosity was determined by using *Archimedes Method* using distilled H₂O.[8]

Fig. (1a) shows the porosity decrease exponentially with kaolin additions. Also, the porosity decreases with the sintering temperature increase and it decreases slightly with decreasing particle size as the densification of the fine powder is larger than that of coarse powder which leads to a decrease in vacancies.

These results are consistent with previous results for silicon carbide additions to the clay raw materials.[12]

Porosity increases for SiC-Clay specimens when formed with carbon paste (Fig. 1b) compared with sodium silicate addition, because the intervacancies are caused by carbon paste that leaves the specimen during firing. Also, the liquid phase doesn't appear at 1200°C but appears at 1400°C and leading to clearly decrease in the porosity.

Generally, the porosity of SiC-Bentonite specimens is lower than SiC-Kaolin, because of lower

melting point for bentonite. This leads to emergence of the liquid phase at low temperature, consequently; slip among the boundary particles and closure of the intervacancies. Fig. (1c) shows the particle size effect isn't clear (especially in small addition of clay at 1100°C) it becomes clearer at 1200°C. This parameter (particle size) is not effective at high additions (15%, 20%, 25%), because these high additions lead to increase in the liquid phase, consequently, the porosity is stable at low values. Also, the porosity is increased with the addition of carbon paste (internal lubricant), especially, at 1100°C (Fig. (1d)), but it is reduced in a large amount at the firing temperature of 1300°C, clearly, when bentonite is added, the porosity near to lowest value and close to zero at 25% bentonite addition.

Compressive Strength: The compressive strength was increased with clay content and firing temperature , also decreased with particle size (Fig. 2a). It is noticed the strength becomes constant at the higher additions of kaolin at the temperature 1200°C. At firing temperature of 1400°C, increase in kaolin addition leads to increase in the strength of ceramic products linearly, because of the bigger amount of liquid phase resulted from mullite and cristobalite, besides the silicon oxide layer generated from silicon carbide oxidation. The particle size effect starts from the porosity disappearance, because the great effect of porosity on mechanical properties. Therefore the results demonstrate, that the fine particle size specimens have higher mechanical strength than the coarse particles and this becomes clearly at

high percentage of additives (more than 20%).

The porosity increases when carbon paste internal lubricant is added to the specimens, leading to decrease in the mechanical properties (Fig. (2b)). With bentonite additions, generally; the specimens have high mechanical strength in comparison with kaolin additions specimens, due to large liquid phase with further bentonite addition (Fig. 2c). The mechanical strength decreases when carbon paste is added and sintering at 1100°C, 1300°C comparing with sodium silicate (Fig. (2d)). Generally, the compressive strength changes with clay additions as quadratically.

Bending Strength: *Bending Strength* increasing with clay addition increase but in a linear form (Fig. 3(a, b, c, d)), except for kaolin bonded SiC with carbon paste at 1200°C due to high porosity that makes the strength stable at high additions (over 20%). The change in the bending strength with factors such as clay percentage, sintering temperature, particle size and the type of internal lubricant is similar to compressive strength behavior.

Diametrical Strength: In case of *diametrical strength*, it is noticed the strength behavior with clay addition percent is similar to the compressive and bending strength (Fig. 4(a, b, c, d)) and in comparison with bending; the diametrical strength is slightly more than bending because part from influent force in diametrical is granted to compressive at contact point besides the large part for tensile strength. Also the failure speed in bending is larger than diametrical, because the crack propagates to long distance in diametrical fracture in comparison

with bending. Therefore, the diametrical test is better when the effect of crack propagation is calculated as a result of thermal stress. Fig. 8 shows the shapes of fractures of the specimen after diametrical strength test, where we note that the multi and long paths of cracks increase the fracture strength of brittle materials.

Conclusions

- ♦ Type of clay (kaolin, bentonite) and type of binders (carbon paste, sodium silicate) effective on properties of SiC-Clay system, from where, the amount of liquid phase that's resulting from firing process.
- ♦ Good mechanical strength
- ♦ From the comparison between bending strength and compressive strength results, one concludes the compression is greater than bending, where compressive strength \approx 5 bending strength. Therefore the tensile strength is smaller than compressive strength.
- ♦ High strength of green compact for Kaolin and bentonite bonded SiC with Na – Silicate make those mixtures uses excellently to manufacture mortars for laying SiC bricks also for patching.
- ♦ If there is necessity to use SiC-Clay materials for structural applications at low temperature, SiC-Bentonite ensure that. They have good mechanical properties with compressive strength ranging from 80 to 160 MPa, also, the bending strength from 10 to 30 MPa.

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Table1: Chemical analysis of raw materials

Oxide Raw material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O	Loss on ignition %
Kaolin ¹	47.34	36.37	0.63	2.2	0.12	0.08	0.31	0.53	12.42
Bentonite ²	55.31	14.62	5.71	1.17	3.43	3.31	1.11	0.72	14.62

1 Wadi Al-Hussainiat, Western Desert-Iraq

2 Traifawi, Western Desert, 35 km to the South of H3-Iraq

Table 2: Compositions of specimens (Key specimens).

Specimen NO.	SiC wt %	Particle Size (μm)	Kaolin wt %	Kaolin Particle Size (μm)	Bentonite wt %	Bentonite Particle Size (μm)
1	95		5			
2	90		10			
3	85	10 < D < 38	15			
4	80		20			
5	75		25			
6	95		5			
7	90		10			
8	85	D < 10	15			
9	80		20			
10	75		25			
11	95				5	
12	90				10	
13	85	10 < D < 38			15	53 < D < 63
14	80				20	
15	75				25	
16	95				5	
17	90				10	
18	85	D < 10			15	D < 38
19	80				20	
20	75				25	

((Note: all specimens were mixed with Na-Silicate and carbon paste and sintered at temperatures: 1200,1400 °C for SiC-Kaolin Specimens ,1100,1200 °C for SiC-Bentonite with Na-Silicate specimens and 1100,1300 °C for SiC-Bentonite with carbon paste specimens)).

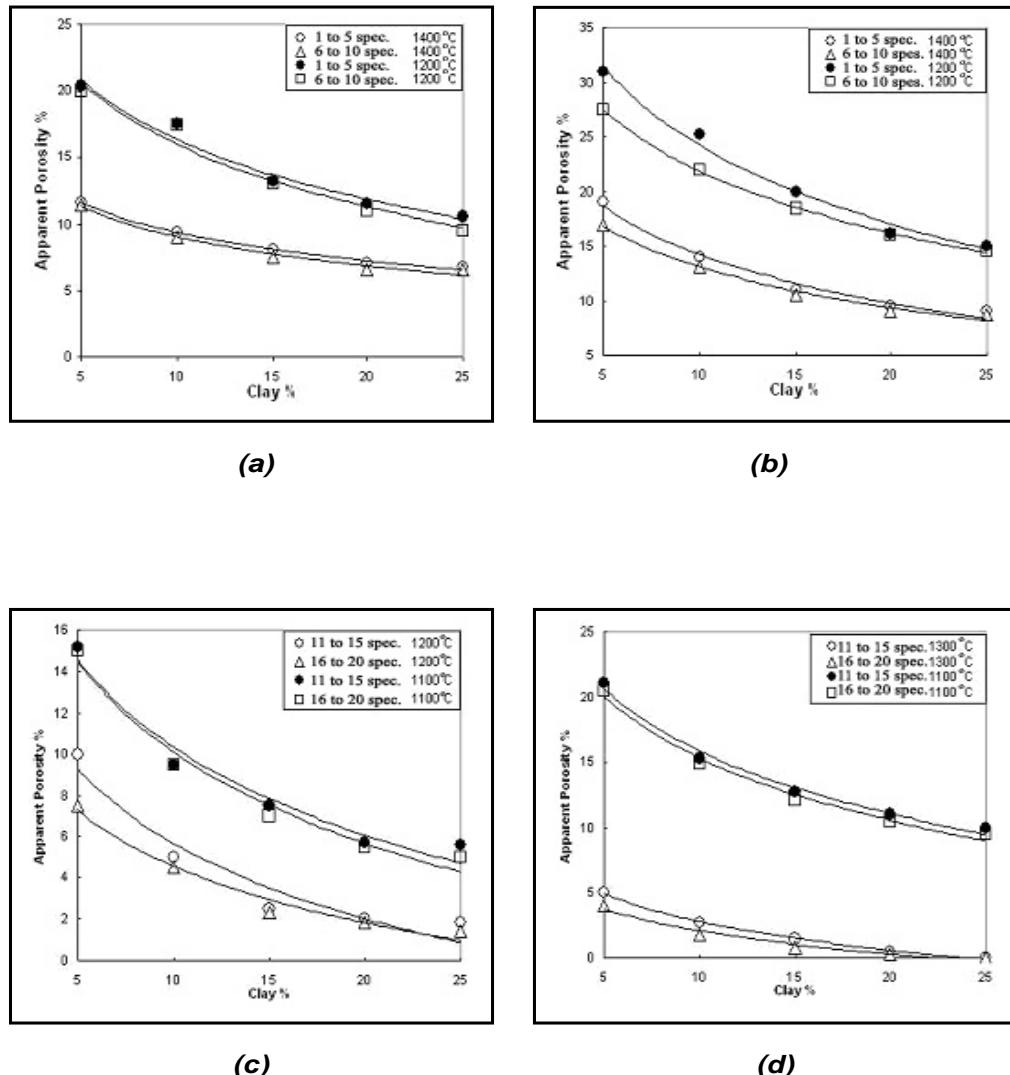


Figure 1: Effect of clay percentage addition, particle size and sintering temperature on apparent porosity. (a) SiC-Kaolin with Na-Silicate specimens.(b) SiC-Kaolin with Carbon Paste specimens.(c) SiC-bentonite with Na-Silicate specimens.(d) SiC-bentonite with Carbon Paste specimens.

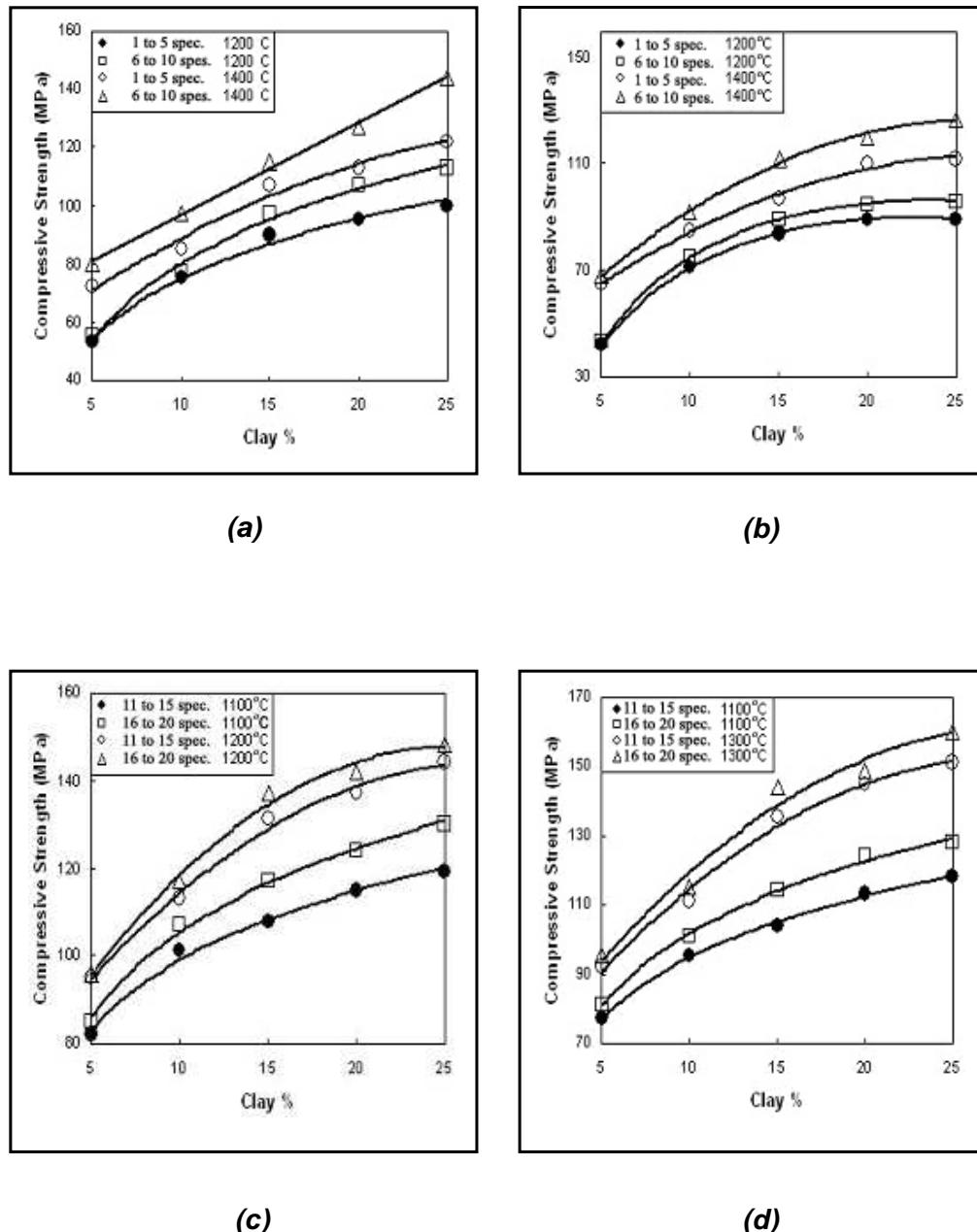


Figure 2: Effect of clay percentage addition, particle size and sintering temperature on compressive strength. (a) SiC-Kaolin with Na-Silicate specimens.(b) SiC-Kaolin with Carbon Paste specimens.(c) SiC-Bentonite with Na-Silicate specimens.(d) SiC-Bentonite with Carbon Paste specimens

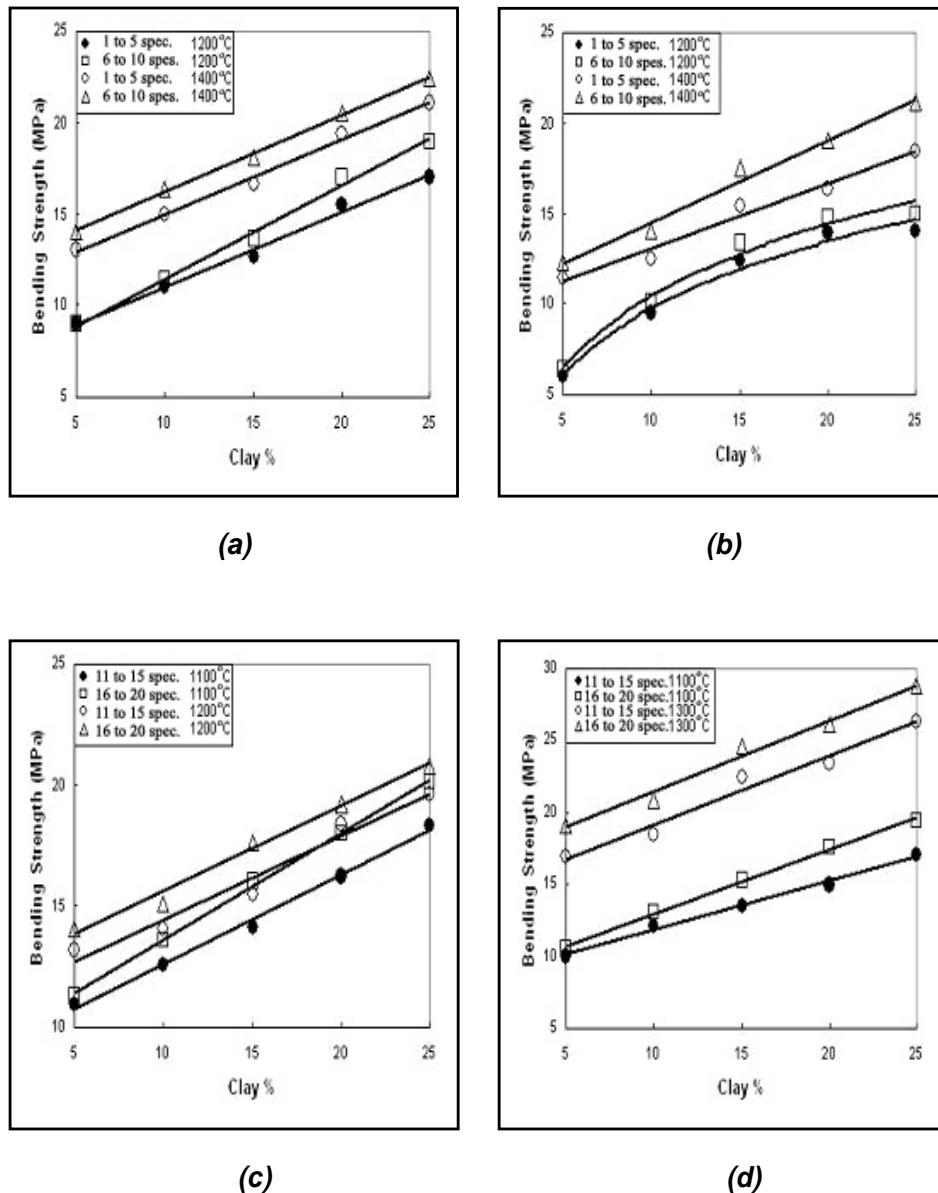
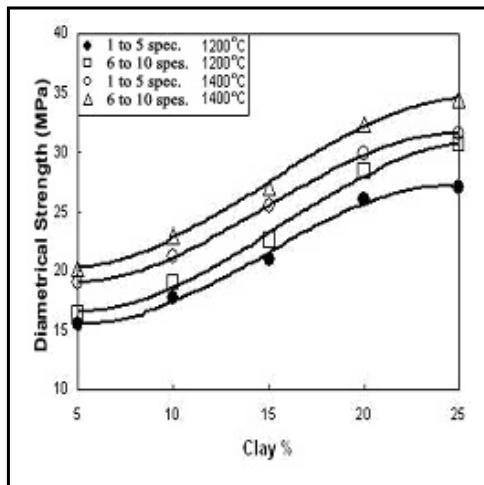
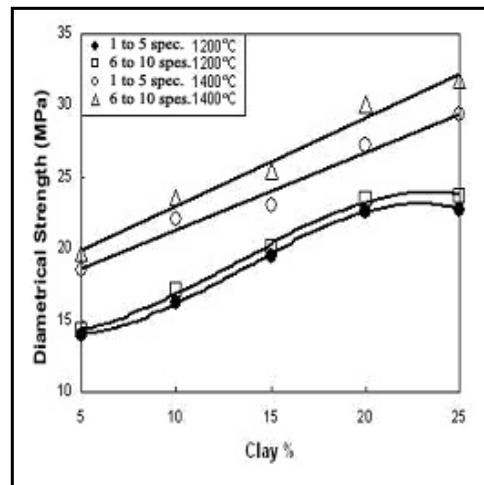


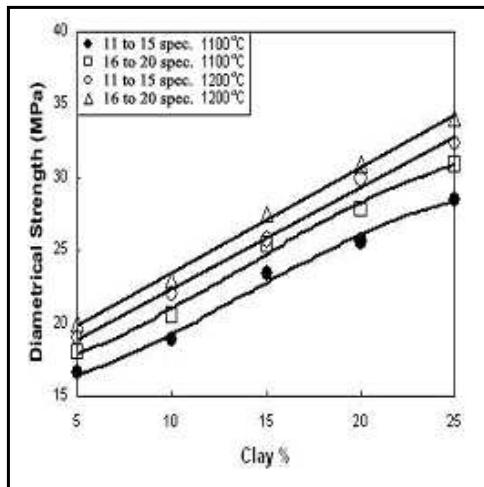
Figure 3: Effect of clay percentage addition, particle size and sintering temperature on bending strength. (a) SiC-Kaolin with Na-Silicate specimens.(b) SiC-Kaolin with Carbon Paste specimens.(c) SiC-Bentonite with Na-Silicate specimens.(d) SiC-Bentonite with Carbon Paste specimens



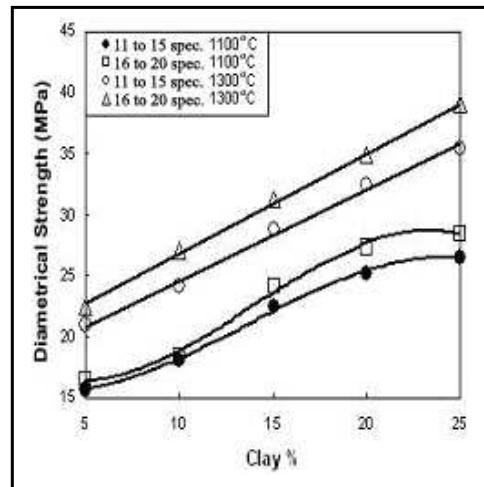
(a)



(b)



(c)



(d)

Figure 4: Effect of clay percentage addition, particle size and sintering temperature on diametrical strength. (a) SiC-Kaolin with Na-Silicate specimens.(b) SiC-Kaolin with Carbon Paste specimens.(c) SiC-Bentonite with Na-Silicate specimens.(d) SiC-Bentonite with Carbon Paste specimens

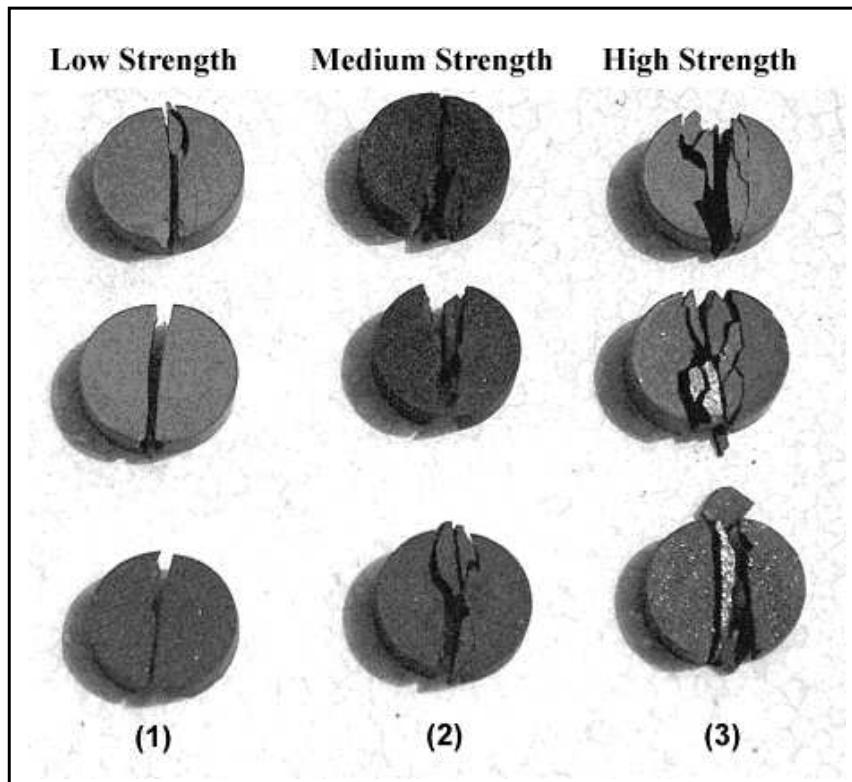


Figure 5: The broken specimens when diametrical loaded is applied for specimens with carbon paste: (1) specimen:10 at 1200°C , (2) specimen:10 at 1400°C , (3) specimen:20 at 1300°C .