Ceramics for construction

Victor C Li, *Associate Professor,* **Christopher K Y Leung**, *Graduate Research Assistant.*
Advanced Construction Materials Laboratory, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139

Abstract

The objective of this paper is to assess the suitability of ceramics as a construction material. Cost-performance comparison of ceramics and traditional construction materials shows that while ceramics is the more economical alternative in the long run for some special applications such as structures under fatigue loading or subject to severe environmental conditions, it is still too expensive to be widely used. With mass production and advances in processing technologies and toughening techniques, ceramics of further improved performance can be produced at lower cost in the future. It is believed that continued research in ceramics processing and toughening together with innovative ideas concerning the application of ceramics in construction can eventually bring about the widespread use of this high-performance material in the construction industry.

Introduction

The last two decades have seen innovative designs ranging from high technology structures to consumer goods being driven by advancements and exploitation of increasingly higher performance materials. In the consumer goods area, an excellent example is the use of plastics in hair dryers and vacuum cleaners, which results in compact, lightweight and lower production cost in comparison to the days when hair dryers and vacuum cleaners were made from steel. This change takes advantage of the easier molding and snap fitting made possible by advancements in structural plastics.

In the high technology arena, the practical design of the X-29 plane (which flies at transonic speed with exceptional maneuverability) with forward swept wings was made possible by the availability of fast real time computer processors and very strong and stiff fibre reinforced composite material which is used to make the wing spans. By different wing lay-ups, aero-elastic tailoring is possible to solve the problem of wing divergence(1).

One can find many other such examples which illustrate that innovative structural designs are often made possible by the availability of high performance materials. In the construction industry steel reinforcement made possible the design of concrete frame tall buildings. More recently the introduction of geotextiles open the way to improve design in various geotechnical systems(2).

Concrete has been in use in the construction industry for a long time and has proven to be a cheap and widely available material. Recent years have seen improvement in concrete properties. For example, compressive strength has gone up by several fold in certain high strength concrete(3). There are also several types of specialized concrete, eg MDF cement(4). However, the use of these concrete based material are not trouble free, and the improvements are still relatively limited. In contrast, high-performance ceramics (simply refer to as ceramics in the following) has several advantages over concrete:

1. Improved durability against freeze-thaw action, due to possibility of much better controlled porosity.
2. Improved durability against chemical (chloride, sulphate) attacks, as proper choice of ceramics could be inert to these chemicals.
3. Improved durability against mechanical wear due to ceramic hardness and wear resistance.
4. Higher elastic stiffness E, compressive σ_c and tensile strength σ_t , and modulus of rupture σ_f .
5. Higher dimensional stability in certain glass ceramics, resulting in reduction in thermal cracking related to temperature cycling.
6. Higher temperature resistance, which may be useful to prevent heat spalls, such as due to hot jet exhaust on airfield pavements from vertical take-off/landing aircrafts.

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Table 1 Unreinforced Ceramics

MATERIAL	E (GPa)	σ_c (MPa)	σ_f (MPa)	K_{1C} (MPam$^{0.5}$)	G_F (KJ/m^2)	TSR (K)
HIGH-PERFORMANCE CERAMICS						
ALUMINA (90-99% DENSE)	280-390	1500-3000	300-400	3-5	0.023-0.066	150
SILICON CARBIDE	410	2000	200-500	3-4	0.02-0.039	300
SILICON NITRIDE	310	1200	300-850	4	0.05*	500
GLASS/GLASS CERAMICS						
SODA GLASS	74	1000	50	0.7	0.003	84
BOROSILICATE GLASS	65	1200	90	0.8	0.003	280
LITHIUM ALUMINOSILICATE	83	1300	200	2	0.05*	>1000
CEMENTITIOUS MATERIALS						
CEMENT	20-30	50	7	0.4	0.01	<50
CONCRETE	30-40	50	7	0.2-2	0.1-0.2	<50
HIGH STRENGTH CEMENT (WITH 5-15% SILICA FUME)	34	100	12	<0.4	<0.01	Not Reported
DSP CEMENT	80	250		0.29*	0.001	Not Reported
WARM-PRESSED CEMENT	40	650	68 (σ_t)			Not Reported
MDF CEMENT	50	200	150	3.29	0.2-0.4	Not Reported

NOTE: K_{1C} OR G_F VALUES WITH (*) ARE ESTIMATED FROM THE OTHER VALUE THROUGH $EG_F = K_{lc}^2$

σ_c : COMPRESSIVE STRENGTH

σ_f : FLEXURAL STRENGTH

σ_t : TENSILE STRENGTH

TSR : THERMAL SHOCK RESISTANCE IS THE MAXIMUM DROP IN TEMPERATURE A CONSTRAINED PIECE OF THAT MATERIAL CAN SURVIVE

MDF : MACRO-DEFECT FREE

DSP : DENSIFIED SYSTEM WITH ULTRA-FINE PARTICLES DSP DIFFERS FROM SILICA FUME CEMENT IN THAT IT USUALLY CONSISTS OF A SUPERPLASTICIZER AS WELL

Some mechanical properties of three classes of materials-high performance ceramics, glass/glass ceramics and cementitious materials are shown in Table 1. The high performance ceramics and glass/glass ceramics show excellent E, σ_c, σ_f and TSR.

For the above reasons, ceramics could be considered a construction material with superior performance. Indeed, it has already been placed into operation (in a limited sense) in certain civil engineering structures. For example, the New York City Thruway toll booth approach lanes and exit ramps have used high alumina ceramic tiles, which have shown excellent durability performance over a fourteen-year period of use(5). Laboratory tests have also been carried out in the use of ceramics as a surface layer for concrete deck. Wheel loading fatigue tests have shown superior performance in withstanding mechanical wear(6).

In this paper, the suitability of ceramics as an advanced construction material is assessed. Potential markets for ceramics in the construction industry are first described. Then, cost-performance comparisons between ceramics and traditional construction materials for various applications are carried out. Such comparisons revealed that if applications are carefully chosen, ceramics can be a more economical alternative in the long run, though its initial cost is still too high for it to be widely used. To investigate the cost trend of ceramics when used in large volume in the construction industry, promises for reduction in ceramics cost through mass production and advances in technology are studied. Finally, research areas which can help to bring about the widespread use of ceramics in construction are identified and discussed. It is believed that continued research in ceramics processing and toughening technologies as well as innovative ideas that can fully exploit the advantages of ceramics may eventually lead to wide acceptance of ceramics as a construction material.

Potential markets and opportunities

The market for ceramics in the construction industry derives from the need to address current construction problems as well as to position for future innovative structural designs. Present construction problems include the wide spread infrastructural decay in the industrial world, which has been attributed to the exhaustion of material life for many concrete structures. The tremendous cost in rehabilitation (eg highway systems) create a market for materials with much longer life time and which requires minimal maintenance. Modern society also faces many unresolved engineering challenges such as containment of hazardous waste. Structures used in tackling such problems will demand high performance materials with better controlled microstructures.

In addition, certain specific environmental conditions may demand the use of ceramics over concrete, eg stiff lightweight thin member space

Table 2 Proposed applications for advanced ceramics in construction using three mechanisms of introduction (from Ref 7)

Mechanism	Applications
Simple Substitution	Road Pavement and Bridge Decks Fire Protection for Steel Pipe and Pipe Linings
Demanding Environments	Airfield Pavements (esp. those for Vertical Takeoff/landing Aircrafts) Walls for Engine Testing Facility and other High Heat Environment Structures in Marine or Severe Industrial Atmosphere Arctic, Offshore and Space Structures Vessels, Reactors and Conduits for High Purity and Hazardous Substances
Fundamental Changes in Construction	Self-monitoring Containment or Reactor (employing the ability of some ceramics to detect the presence of particular ions) Chloride Trapping Bridge Deck (some ceramics can trap chloride ions)

structures exposed to very large temperature fluctuations; pavements or platforms which may need to withstand high temperature from exhaust of jets or during launch of space shuttle; and for some ocean structures.

The mechanisms in which ceramics may be initially introduced into the construction market involves simple substitution of materials, applications in structures operating under demanding environments, and in the possibility of fundamental changes in construction (see Table 2). More thorough descriptions of these mechanisms can be found in Ref 7. With experience, the use of ceramics will filter down to much wider range of construction applications, particularly when the high performance/low maintenance requirement is appreciated by the user and operator of the facilities.

Cost-performance evaluation

Basic ideas

Despite the many technical advantages of ceramics, a limiting factor in its wide use as a construction material is the high cost in comparison to conventional cement and concrete. While it is generally recognized that ceramics have better mechanical properties than concrete but is also much more expensive, there is little attempt to do an actual cost-performance comparison between the two material to assess quantitatively whether the performance of ceamics is good enough to justify such a high cost. This kind of comparison is very important since it shows how much reduction in cost or improvement in performance is to be achieved if the more expensive material is to be competitive with the cheaper one.

The simplest technique of cost-performance evaluation is probably the one first suggested by Ashby(8). In this approach, cost and performance are considered together by looking at the cost of material required for a particular purpose. As an example, consider the simple case of a compression member. To carry a given compressive load, for fixed member length, the area of the member and hence the volume of material required is inversely proportional to the compressive strength (σ_c) of the material. Cost of the material is given by the product of the material volume, the relative density of the material (ρ) and its cost per unit weight (C). Hence, material cost for the compression member is proportional to $\rho C/\sigma_c$. A member with a smaller value of $\rho C/\sigma_c$ is thus more 'cost effective', that is, a lower material cost is paid to achieve the same structural purpose. Similarily, it can be shown that for members under other kinds of structural load, cost-performance of different materials can be compared through other parameters.

In Table 3, for different applications, the structural failure modes and parameters to be considered for cost-performance comparison are listed. For each application, the cost ratio for using ceramic over concrete is computed from the ratio of the values of the corresponding parameter for the two material. This ratio is tabulated in the last column of Table 3. In most of the applications, the values of cost and properties used for ceramics are those for Liquid Phase Sintered (LPS) Alumina. LPS Alumina is one of the most highly used high-performance ceramics and is among the least expensive in this class of material. In the last two applications, due to special performance requirements, more expensive ceramics have to be used. In the following sub-sections, implications for the various applications from the cost-performance comparison in Table 3 will be discussed.

Load-bearing members in normal building structures

From the first four rows of Table 3 it is quite obvious that in normal building

Table 3 Ceramic/concrete cost-performance comparison

Applications	**Structural Failure Mode**	**Parameter to be Considered**	**Ceramic for Comparison**	**Ceramic/Concrete Cost Ratio**
Beam/Slab	Flexural Failure of Plate	$C\rho/(\sigma_f)^{0.5}$	Alumina	123
Beam/Slab	Excess Deflection of Plate	$C\rho/(E)^{0.5}$	Alumina	289
Short Column	Crushing	$C\rho/\sigma_c$	Alumina	14
Long Column	Buckling	$C\rho/(E)^{1/3}$	Alumina	408
Rigid Pavement	Plate Bending on Elastic Foundation	$C\rho/(\sigma_f)^{0.5}$	Alumina	123
Pavement Surface	Excessive Wear	$C\rho/\sigma_c$	Alumina	14
Pavement Under Stress	Subcritical Crack Growth	$(C\rho)/$ (Pavement Life	Alumina	<<1
Pavement for Vertical Takeoff/ Landing Aircraft	Thermal Spalling	$C\rho/$(No of Thermal Impact to Failure)	Ratio may be <1 for some ceramics (refer to text for details)	
Chemical Tanks	Chemical Corrosion	$(C\rho)/$(Tank Life Under Corrosion)	Silicon Carbide	<<1

NOTES: (1) In the Table, the cost and properties of alumina are taken from Ref 24 for Liquid Phase Sintered Alumina and are listed as follows:- Cost (C):- \$20 per kg (\$20,000 per tonne)
Relative Density (ρ):- 3.55
Compressive Strength (σ_c):- 3000 MPa
Flexural Strength (σ_f):- 310 MPa
Young's Modulus (E):- 285 GPa

(2) Cost of Concrete is taken to be \$36 per tonne (from Ashby & Jones:- Engineering Materials 2, Pergamon Press, 1986). Relative Density of Concrete is 2.4. The mechanical properties of Concrete are tabulated in Table 1. In cases where a range of value is given, the middle value in the range is used.

structures, direct substitution of concrete beams and slabs with ceramics is probably not justified. It should be noted that we are comparing plain concrete with ceramics and the flexural strength of concrete can be improved by putting in steel reinforcements which will only lead to a small increase in its cost. The use of ceramics in columns may seem to be better justified. However, columns under pure compression are very rare as most columns are subjected to bending as well. Thus, we can conclude here that in structural parts where bending is the chief concern (which is, indeed, the case in many structural parts), direct substitution of concrete with ceramics (with today's price and technology) is not economically sound.

Rigid pavements

Rigid pavements are usually designed as a plate under bending on an elastic foundation[9]. As shown in Table 3, the ceramic/concrete cost ratio is over 100 for this case and if short term structural strength is the only consideration, the use of ceramics is clearly unjustified. However, compared with other structures (eg buildings), pavements show more severe deterioration during their lifetime and thus rehabilitation and replacement are often necessary. It has been calculated that replacing and rehabilitating existing pavements in the USA will cost four hundred billion US dollars in the next 15 years[10]. Therefore, the durability of a pavement (or the time taken for deterioration to become so severe that maintenance is required) should also be an important consideration.

Pavements can deteriorate in two major ways, surface wearing and subcritical crack growth under various loads leading eventually to spalling of the pavement. The cost-performance comparisons for these two failure modes may not be as obvious as those for normal building structures and hence will be discussed briefly in the following paragraphs.

The problem of surface wearing is first considered. Cost-performance comparison is made for concrete and ceramics as wearing layers. It is assumed that on top of a rigid pavement which is just thick enough to take the structural loads, a layer of concrete or ceramics is placed so maintenance would only be necessary when this upper layer is worn away. The cost-performance parameter in this case is simply (cost of material)x(rate of material removal). The rate of material removal can be obtained from wear theories. For a pavement, both adhesive wear (due to contact between wheel and pavement surface) and abrasive wear (due to a trapped particle between the wheel and the pavement surface) can take place.

For both mechanisms, the volume of material removed for a certain distance of contact is proportional to the actual area of contact which is given by P/H, where P is the applied load and H is the hardness of the material which is roughly three times its compressive strength σ_c(11,12). For adhesive wear, the volume removed is also proportional to a factor K, the probability for a piece of material under contact to come off. This factor depends on the actual nature of the two contact surfaces and has to be determined from experiments. Since no such experimental results are available for concrete and alumina, K is simply assumed to be the same for both materials. The cost-performance comparison parameter is then $C\rho/\sigma_c$. The ceramic/concrete cost ratio is 14 in this case, much lower than the ratio of 123 where ceramic is used to replace concrete in the whole pavement.

The deterioration of pavement through sub-critical growth of cracks is considered next. Spalling of pavement may be associated with the growth of cracks (formed by heaving of sub-soil or expansion of steel reinforcement due to corrosion) under various loads such as traffic or temperature loads. Assuming the governing failure mechanism to be fatigue crack growth, the relation between the rate of crack growth and the change of stress intensity due to the applied cyclic load is given by:-

$$(da/dN) = A\,(\Delta K_a)^n \qquad \ldots \text{eqn (1)}$$

where ΔK_a is the change in applied stress intensity, N is the number of cycles and A and n are material constants.

Line fitting of concrete fatigue test data from Ref 13 gives $A=10^{-24.3}$ and $n=3.15$ (EK_a in Pa $\sqrt{}$m and da/dN in m/cycle) for a R-ratio (ratio of minimum to maximum applied stress during a fatigue test) of 0.1. For alumina, fatigue test result in the form of eqn (1) is not available. Hence, result for stress corrosion (or static fatigue) from Ref 14 is employed. For stress corrosion, the relation between crack growth rate and applied stress intensity due to the static load is of the same form as eqn (1) except that K_a, the applied stress intensity is used in place of EK_a and da/dt is used instead of da/dN. For Alumina under static fatigue, $A = 10^{-150}$, $n = 21.76$. Actually, experimental investigations (15,16,17) have shown that the life time for alumina under cyclic fatigue is about 1 or 2 orders of magnitude lower than that under stress corrosion provided that the maximum applied load is the same in the two cases. The justification for using stress corrosion data in place of fatigue data for alumina here will be obvious after the life time for the two materials have been compared.

Assuming the frequency of the cyclic load is of the order of one Hertz and the same initial crack size in concrete and alumina pavements, the time for the crack to grow to a certain critical crack size (assumed to be the same for both materials; this underestimates the life of the alumina pavement, which is made of a tougher material (refer to Table 1, K_{IC} column) and thus can tolerate a larger critical crack size) can be obtained for both materials. Integration of eqn (1) reveals that for a crack to grow to a certain size, the time for crack growth in alumina is over 10^{30} times that in concrete, which means that the alumina pavement has a much longer life. Though we have used the stress corrosion data for alumina, which probably over-estimates its life by about 2 orders of magnitude, the large difference of over 30 orders of magnitude suggests that the ceramic/concrete cost ratio for this case is much lower than unity.

The implication is that if the life of the pavement is considered and if sub-critical crack growth due to traffic or temperature cyclic load is the major mechanism of deterioration, the use of ceramics (both for the whole pavement or for a surface layer) will be a more economical alternative in the long run.

Pavement for vertical take-off/landing aircraft

Vertical take-off/landing aircrafts have been developed by the US Navy. Vertical take-offs result in an exhaust blast from the engine onto the pavement with a temperature up to 1550°C (2800 °F). The pavement would then be subjected to a high temperature as well as a severe thermal shock. (The actual thermal shock, while being severe, is less than 1550°C and depends on the rate of heat transfer at the pavement surface.) Under such conditions, a concrete pavement will spall during each take-off(18) and thus have to be replaced each time.

In this case, a material with much better performance is clearly desirable. Several ceramics seem to be plausible candidates. Test results from Ref 19 show that a commercially available silicon nitride has a flexural strength of about 270 MPa (or 40 ksi) at temperatures as high as 1500°C. Its thermal shock resistance as obtained from a water quench test is 750°C (when cooled in air, the TSR is much higher as the heat transfer is not as rapid as that in water). Ref 20 mentioned that Hexacelsian, a glass-ceramic, can be used in high-performance applications at 1700°C. As a glass-ceramic, Hexacelsian is also expected to have good thermal shock resistance. Hot-pressed Aluminium Nitride has a flexural strength of 125 MPa at 1400°C and has been shown to survive rapid heating to 2200°C followed by rapid cooling without fracturing(21,22).

However, there is not enough data available from the literature to allow calculation of the actual life of any one of these materials under the 1550°C blast. Specimens of each ceramic should be tested under conditions simulating the actual blasts during take-off and if the number of thermal shocks the ceramic can withstand exceed the ceramic/concrete material cost ratio (which is probably over 3000), it can then be used as a more economical alternative to concrete.

Chemical tanks

Concrete is very vulnerable against acidic environments, especially sulphuric acid and other oxidizing acids. In chemical plants or for hazardous waste storage and disposal, tanks or holding ponds which can withstand acidic corrosion are very often required. Silicon carbide is essentially unaffected by both strong acids and strong alkalis(23). Thus, it can be used for holding chemicals. For this purpose, only a thin layer of silicon carbide on top of the concrete will be sufficient. (In current practice, glass linings are used, but glasses crack easily under temperature changes or small impacts.) The use of ceramic lining will increase the cost of the containment structure but its life against acidic corrosion is almost infinite (the lining is essentially uncorroded). Hence, in the long run, the use of ceramic is again justified.

Comments on the cost-performance comparisons

(1) From the above cost-performance comparisons, it is ob-

vious that the application of ceramics to construction has to be chosen with great care. In normal structures where concrete can satisfy performance requirement (eg buildings), the use of ceramics as a substitute is not economically sound. However, in cases where traditional material cannot perform well (eg chemical tank, pavement for vertical take-off) or where frequent repairs or replacements are anticipated (eg pavements), ceramics may be used as an alternative that is more economical in the long run.

(2) In the above cost-performance comparisons, only the material cost is being compared. The cost of material is only part of the total construction cost. If an inexpensive material like concrete is used, other costs such as labour costs and equipment costs can be much higher than material cost. If frequent maintenance is required, these other costs together with the indirect cost caused by the downtime in operation of the facility during maintenance, may sum up to an amount overwhelmingly larger than the cost of using a high performance material. If all these factors are considered (provided all these can be quantitatively assessed), the ceramic/concrete cost ratio would be reduced.

(3) While it has been shown that for some applications, the use of ceramics may be economically sound in the long run, the initial material cost for using ceramics is at the present orders of magnitude higher than that of using concrete. Hence, for the wide acceptance of ceramics in the construction industry, their costs must be significantly reduced. With mass production and advances in processing and materials engineering technology, cost reduction is an expected trend for commercial ceramics. The next section will focus on the various factors that can lead to reduction in ceramics cost when the material is applied to construction.

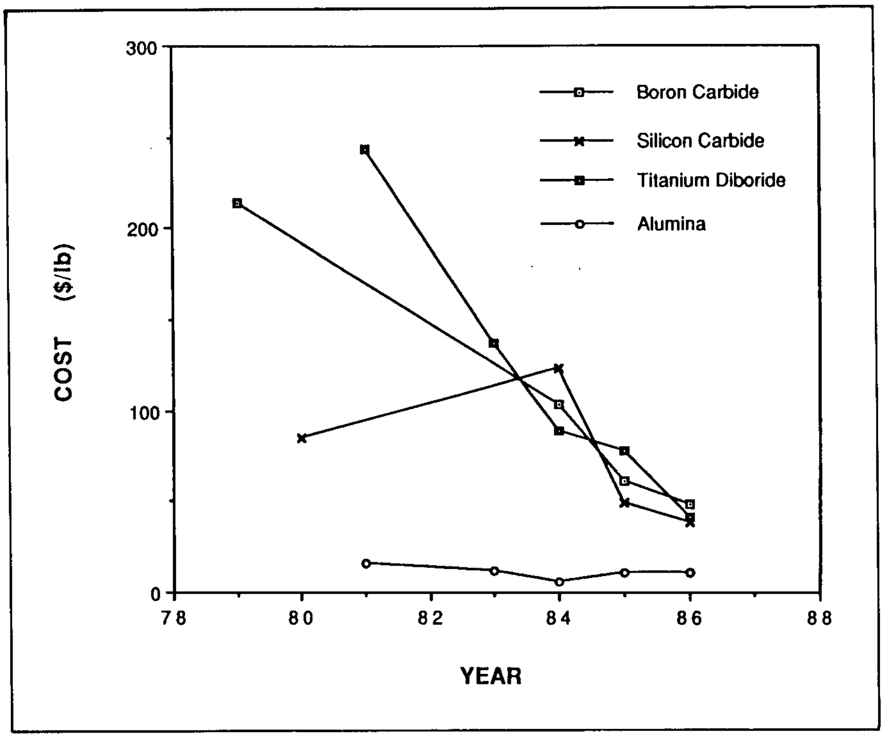

Fig 1 Cost trend of some Armour Ceramics (from Ref 24)

Promises for cost-reduction of ceramics

The high cost of ceramics is associated with the intricate processing cost, the low yield and low reliability of ceramic parts as well as the relatively small scale of production. However, it is expected that ceramics cost will reduce significantly when applied to construction because of the various factors discussed below.

Cost trend due to mass production

To be used in the construction industry, ceramics have to be produced in large volumes. Mass production usually can lead to a lower cost as fixed overhead (such as costs of equipment and plant) can then be shared over a larger volume of product. For example, Figure 1 shows the decreasing cost trend in several types of armour ceramics(24) as demand increases over the last few years. The cost of alumina (Al_2O_3) remains rather constant in the graph because of its rather constant demand in the ceramics market (note that the demand in armour industry only forms a small portion of the total alumina market).

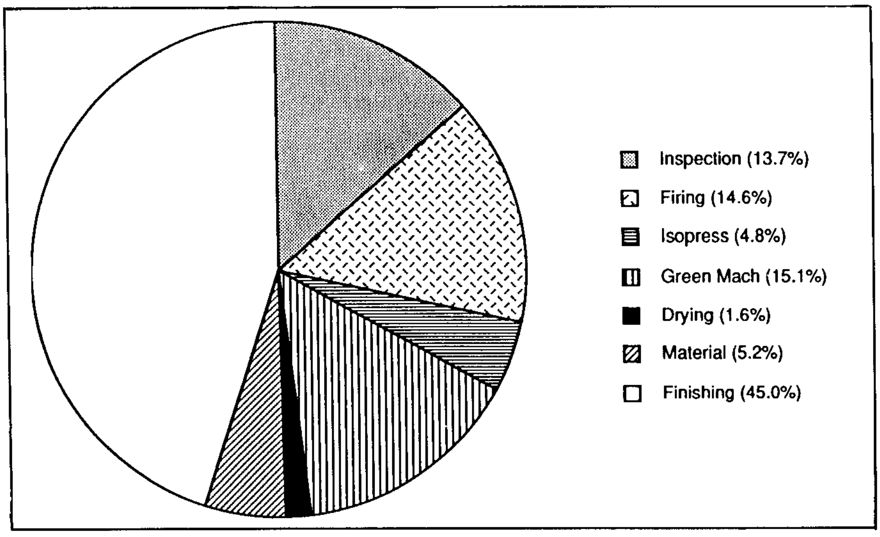

Fig 2 Cost distribution of SiC seals 5cm in diameter, assuming a \$2.90/kg powder and 40% yield (from Ref 25)

However, if alumina is used in construction, the huge increase in material demand will lead to a significant decrease in its cost. This is because with such a drastic change in production volume, the process for material production can be changed. The plant can now afford much more expensive equipment which is highly automated and has very reliable process control. These features can translate into significant reduction in cost through savings in labour and improvement in process reliability. A parallel trend in improving reliability in fabrication has already occurred in the electronic industry which made available increasingly lower cost electronic chip devices over the last decade.

Simple shape and high tolerance for construction parts

In most current applications, a significant proportion of the cost of a ceramic product is put into finishing and machining (Fig 2)(25), because of the importance of close tolerance. In civil engineering, tolerance is not an important issue. Relaxation in tolerance requirement can lead to a lower production cost (Fig 3)(25). Moreover, the complicated shape of most ceramic products makes powder compaction difficult and thus leads to a low yield of reliable parts. The simple shape of construction parts may enable a much higher yield. Fig 4(26) shows the significant reduction in cost with increasing yield. Therefore, we can expect that simple-shaped products for construction should cost less compared to current commercial ceramic products.

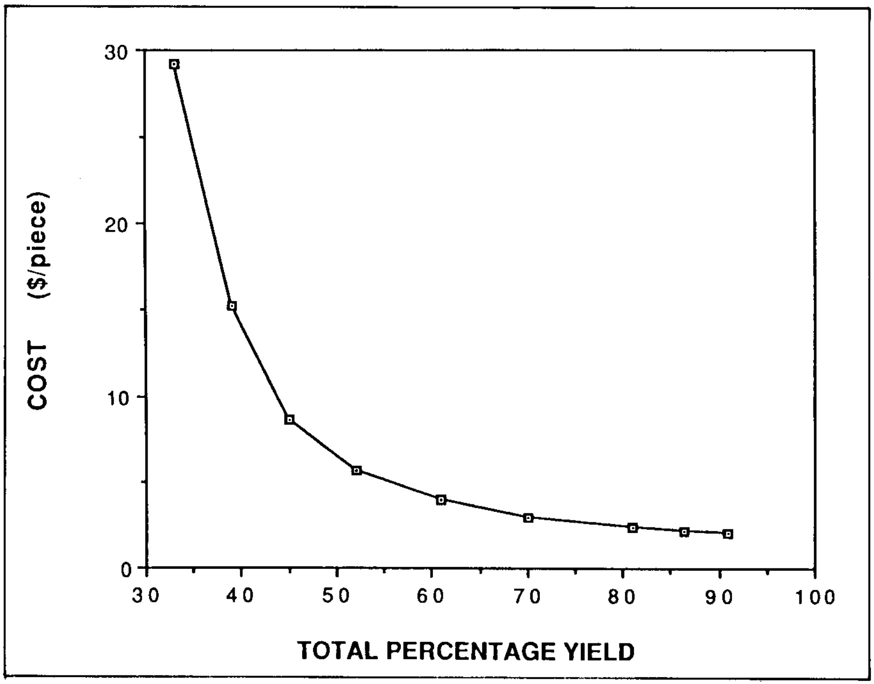

Fig 3 Cutting tool insert cost vs tolerance (from Ref 25)

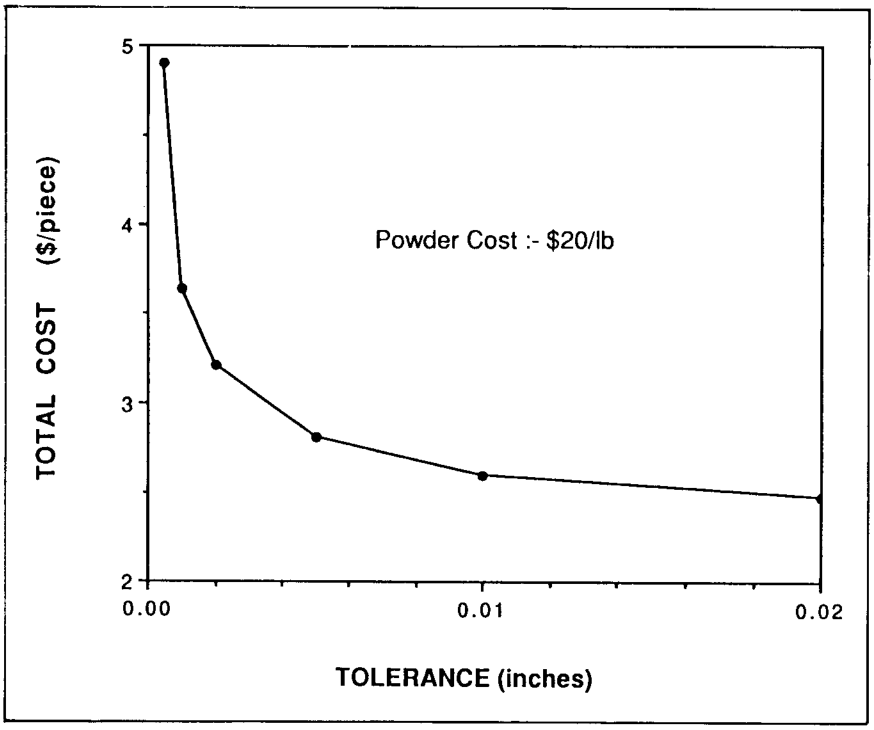

Fig 4 Silicon Nitride cutting tool insert cost vs total percentage yield for HIP/Sintering (from Ref 26)

Indirect savings due to the use of ceramics

Less material will be used in a structural component for a given design load, in taking advantage of the higher strength and stiffness of ceramics. This has a multiplying effect in that the dead-weight load of the structure will be lowered, thus reducing further the stresses in the supporting structural members. In some cases, we can take advantage of this to reduce part of the supporting structure. For example, the maximum span of a bridge between two piers is affected by the dead weight of the deck and girder. The use of ceramics, which allows a lighter deck and girder, enables the possibility of longer spans between piers. This implies that fewer piers are needed for the whole bridge which translates into possible saving and waterway transportation convenience.

By replacing concrete with ceramics, the weight of each structural part as well as the total weight of material to be handled are also reduced. This implies reduced cost in material transportation and less demand in the use of powerful construction equipment, which may lead to a reduction in the total construction cost.

Advances in ceramics technology

The above discussions have been concentrated on economical issues that should lead to reduction in ceramics cost. In fact, advances in ceramics technologies have made available various low temperature processing techniques(27) which can lead to a lower processing cost. Therefore, the implicit cost of ceramics will also be reduced. Research in the fracture behaviour of ceramics has resulted in a five-fold increase in fracture toughness of ceramics (from a maximum of 3·5 MPa$\sqrt{m}$ for unreinforced ceramics to over 20 MPa$\sqrt{m}$ for ceramics reinforced with continuous fiber) during the last two decades which translates into improved mechanical performance and reliability of the material.

Thus, it can be foreseen that through further research in the field, ceramics with further improved performance can be produced at lower cost. This will make ceramics more competitive as compared with traditional materials. In the next section, research challenges that can lead to further reduction of ceramics cost, improvement in ceramics performance as well as acceleration of the use of ceramics in construction will be discussed.

Challenges in ceramics research

The study of ceramics is a very large research field and here we will only concentrate our attention on research directly related to the application of ceramics in construction. These research may be divided into five major areas, described individually in each of the sub-sections below.

Researches in processing

Research emphasis is on the low temperature synthesis of ceramics. One of the main reason for the high processing cost of ceramics is the large demand of energy for high temperature processes. Various techniques for low temperature ceramic powder production have been successfully developed in the laboratory(27). Further research is required to develop these experimental techniques to production scale. More automation and better process control can lead to savings in labour cost and higher material yield. Research in robotics and computer-aided design with particular emphasis on ceramic processing should therefore be carried out.

Another research field in processing is the development of cost models for various processes. An initial attempt has been made by Rothman et al(25,26,28). With these cost models, the cost of material production through different processes as well as the final material cost related to factors such as material yield and material production volume can be quantitatively assessed. These models will be useful in the selection of processes as well as the estimation of cost trend when material is produced in large volume (such as application in construction) where no previous data can be used to extrapolate a reliable future cost trend.

Improvement of mechanical properties

While very strong, most ceramics are also very brittle, with fracture toughness ranging from 0.5 – 5 MPa$\sqrt{m}$. (Concrete has 0.1 – 0.2). At present there are five classes of toughening mechanisms (Table 4)(29). The most promising appears to be fibre reinforcement, which gives over 20 MPa$\sqrt{m}$. Also, fibre-reinforcement is more generally applicable as mechanisms like transformation toughening and micro-crack toughening only occur in some special ceramic systems. As a reference, structural steels range from 20-200 MPa$\sqrt{m}$. However, the technology trend is such that the toughness will continue to be improved over the next several years. It has also been shown that fibre reinforcement produces an R-curve behaviour, which in turn provides a higher material reliability measured by the Weibull Modulus(30).

With advantages discussed above, fibre-reinforced ceramics is probably the most prospective group of ceramic materials to be developed for use in construction. Thus, attention should be concentrated on the study of this group of material. Like other fibre-reinforced composites, the mechanical behaviour of fibre-reinforced ceramics is determined by fibre property, matrix property (governed by its microstructure), property of the fiber/matrix interface (or an interphase in some cases) as well as the residual stresses in the composite (formed when the composite is cooled down from its processing temperature as the fibre and matrix usually have different thermal expansion coefficients). Research on mechanical properties should thus be concentrated on the following aspects:-

(1) The understanding of how each of the above mentioned properties affect the behaviour of the composite and hence the development of a micromechanical model that can predict important mechanical properties of the composite such as its tensile, compressive and flexural strength as well as its toughness.

(2) The understanding of the effects of processing condition on matrix microstructures, fiber/matrix interfacial properties as well as residual stresses.

(3) The optimization of mechanical properties through tailoring of the interfacial properties and the residual stresses by optimizing processing conditions.

Table 4 Toughening Mechanisms in ceramics (from Ref 29)

Toughening Mechanisms	Material	Maximum Toughness (MPa$\sqrt{m}$)	Comments
Fibre Reinforced	LAS/SiC	>20	Steady - State - Cracking
	Glass/C	>20	
	SiC/SiC	>20	
Whisker Reinforced	Al_2O_3/SiC (0.2)	10	Amorphous Interphase
	Si_3N_4/SiC (0.2)	14	
Ductile Dispersion	Al_2O_3/Al (0.2)	>12	Steady - State - Cracking
	B_4C/Al (0.2)	>14	
	WC/Co (0.2)	20	
Transformation Toughened	PSZ	18	Nonlinear
	TZP	16	
	ZTA	10	
Microcrack Toughened	ZTA	7	
	Si_3N_4/SiC	7	

Performance evaluation of ceramics under severe conditions

Most initial applications of ceramics in construction are expected to be under severe conditions such as high thermal blast, large range of temperature cycling, heavy traffic or corrosive environment. Though ceramics are expected to perform much better than traditional materials, its actual performance under such conditions should be assessed through experiments simulating the actual service environments. The deterioration of ceramics under such conditions should be studied in detail to work out techniques for further improvement of ceramic properties under severe environments.

Development of new techniques in construction

To carry out actual construction with ceramics, new construction techniques have to be developed. Research issues include the joining of prefabricated ceramic parts, the possibility of in-situ processing of ceramics with good quality control and the application of ceramic layers on other construction materials (eg chemical tanks). Similar research has already been carried out on the joining of ceramics(31,32) and on the coating of ceramics on metals(33). These findings may be exploited in the research of ceramic construction components.

Innovative ideas in the application of ceramics in construction

Besides its use as a structural material, the full potential of ceramics should be exploited. New ideas that can use ceramics to full advantage should be developed. Two examples of such innovative ideas have been included in Table 2. The sensitivity of some ceramic materials to the presence of particular ions enables the use of such materials as chemical sensors. Containment for nuclear reaction or chemical reactions made of such a material can then serve the dual purpose of structural support and reaction monitoring.

The chloride-trapping ability of some ceramics can be made use of in pavements or bridge decks where chloride ions from de-icing salts can be trapped inside the ceramics to save vehicles and steel-reinforcements (if steel are still used with ceramics) from corrosion. Moreover, advances in photolithography techniques made possible the production of ceramics microsensors(34) with dimensions of the order of a millimeter. Sensors of such a small size can actually be carved (with laser beam) on the most heavily stressed regions of a critical ceramic structural member. The member would then become self-monitoring and can give warnings when its capacity is approached, thus eliminating the danger of a sudden collapse. Development of more new ideas of this kind can accelerate the introduction of ceramics into the construction industry.

Conclusion

While cost-performance comparison has shown that for some applications, the use of ceramics over concrete is actually more economical in the long run, the initial cost of ceramics is at present still too high for it to be widely used. However, during the past decade, we have witnessed the reduction in ceramics cost with volume produced, the increase in ceramics toughness through better understanding of toughening mechanisms as well as the success of processing techniques at increasingly lower temperatures. These are all encouraging facts which strongly suggest that in the future, ceramics with better performance can be produced at a much lower cost.

Continued research on processing and toughening of ceramics as well as research on special issues relating to construction are expected to gradually bring about the widespread use of ceramics in the construction industry.

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