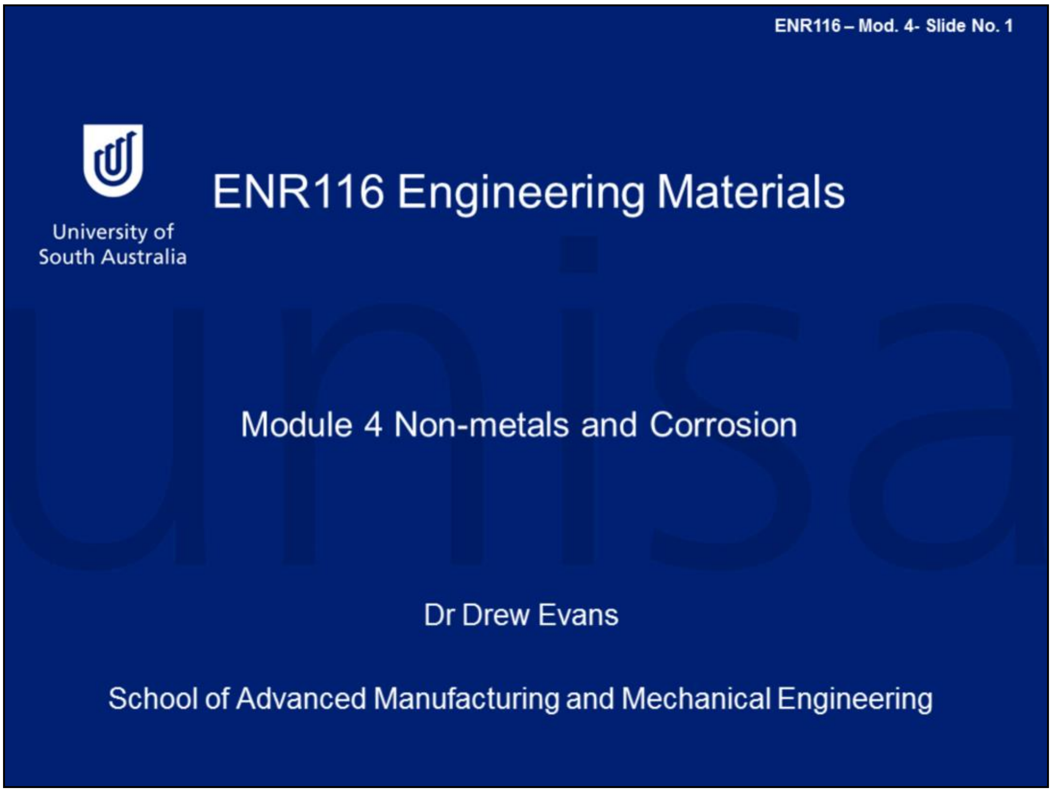

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# ENR116 Engineering Materials

## Module 4 Non-metals and Corrosion

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- My name is Drew Evans, and welcome to Module 4 of ENR116 Engineering Materials – Non-Metals and Corrosion

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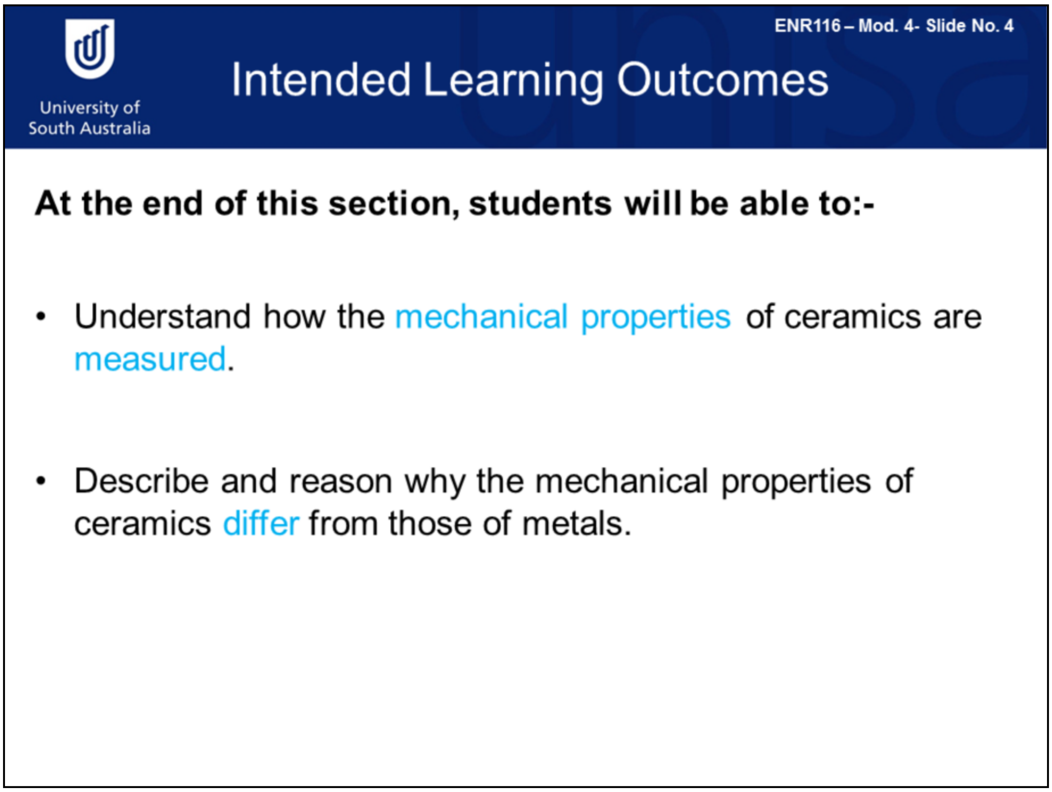
# Ceramic mechanical properties

- This presentation will cover the mechanical properties of ceramics



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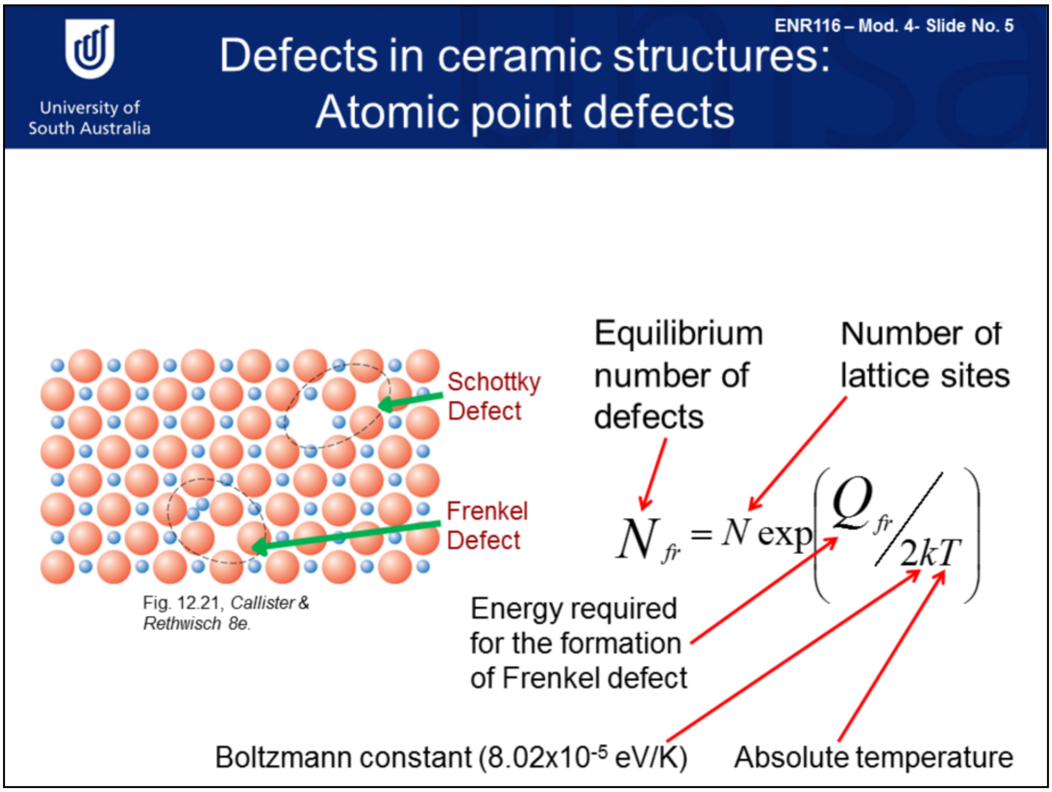
# Intended Learning Outcomes

**At the end of this section, students will be able to:-**

- Understand how the mechanical properties of ceramics are measured.
- Describe and reason why the mechanical properties of ceramics differ from those of metals.

- By the end of this presentation, you should be able to:
    - Understand how to measure the mechanical properties of ceramics
    - Describe and reason why ceramics have different mechanical properties from metals



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## Defects in ceramic structures: Atomic point defects

Fig. 12.21, *Callister & Rethwisch 8e.*

$$N_{fr} = N\exp\left(Q_{fr}/2kT\right)$$

Equilibrium number of defects

Number of lattice sites

Energy required for the formation of Frenkel defect

Boltzmann constant (8.02x10$^{-5}$ eV/K)

Absolute temperature

- Before exploring the mechanical properties of ceramics, it is important to briefly discuss some of the aspects of a ceramic that could impart influence on the ceramic compounds properties
- The first aspect for discussion relates to atomic point defects
- These are point defects in the atomic structure of the ceramic, and can exist as either missing atoms or additional atoms
- The atoms in a ceramic compound are considered as ions, either cations or anions
- Based on this, if there are atoms missing, the overall neutral charge must be maintained
- This means, in a ceramic compound where the cation and anion have the same charge magnitude,
    - if a cation is missing from the structure,
    - then either an anion must also be missing to balance the charge or
    - an extra cation must exist elsewhere in the structure
- When a cation is missing from one position, but an extra cation resides elsewhere in the structure, this is termed as a Frenkel defect
- When a cation is missing from one position, and an anion is also missing, this is termed as a Schottky defect
- The equilibrium number of both defects increases with temperature in a similar manner to vacancies in a metal
- Nfr is the equilibrium number of Frenkel defects at a given

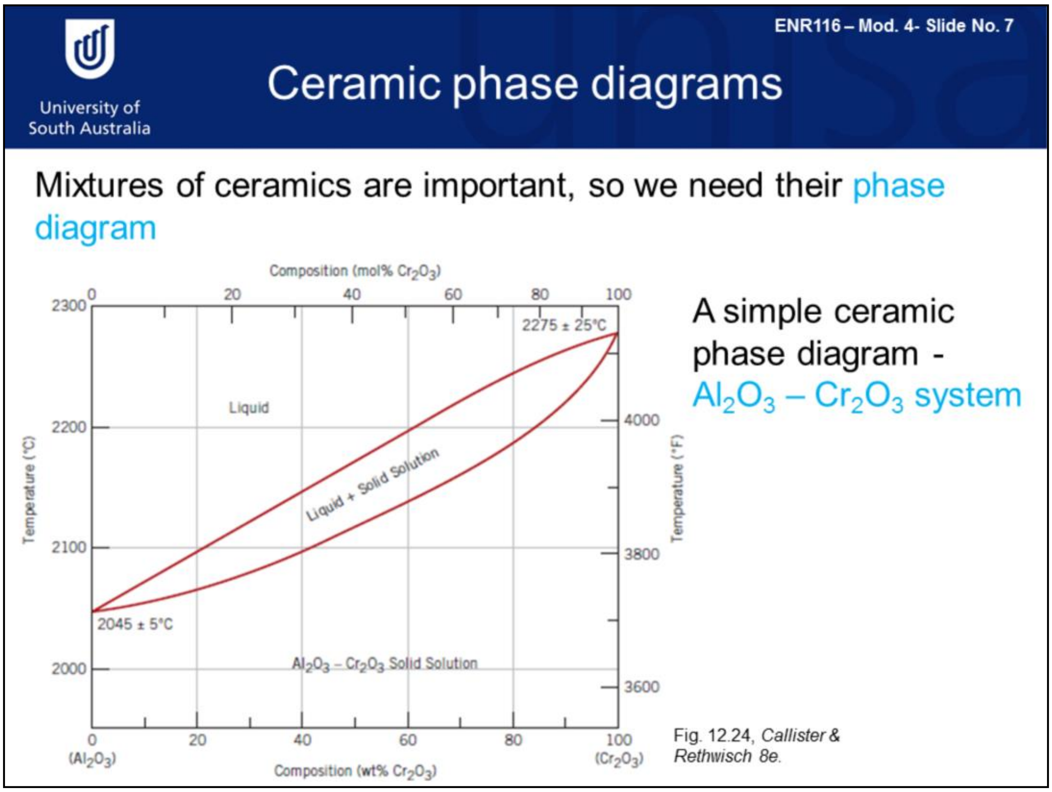
temperature T

- The parameter N is the total number of lattice sites, k is Boltzmann constant, and Qfr is the energy required to form each Frenkel defect
- The denominator of two arises from the number of atoms involved in the defect, i.e. a cation and anion
- This equation is equally valid for Schottky defects in an AX ceramic compound, where Qs is used instead of Qfr, as it represents the energy required to form each Schottky defect

# Impurities

Substitution impurity replaces the host atoms in the structure

- Another aspect for consideration is the presence of impurities in the ceramic compound
- Substitutional impurities are atoms that substitute the host atoms in the ceramic crystal structure
- Based on the impurities charge, it will substitute for either the host cation or host anion
- Importantly, the substitution of the impurity still requires the charge neutrality of the ceramic compound to be maintained
- The following is an example using sodium chloride
- Firstly, what if the impurity is calcium which has a charge of 2+
- Because it is a cation, it will substitute the host cation of sodium
- Also, because of its charge of 2+, it will substitute for two sodium atoms which each have a charge of 1+
- In this case this leads to a vacancy at one of the cation positions within the ceramic crystal structure
- On the other hand, what if the impurity was oxygen which has a charge of 2-
- Because it is an anion, it will substitute the host anion of chlorine
- Similar to the calcium impurity, the 2- charge on the oxygen leads to it substituting two chlorine atoms to maintain charge neutrality
- This now leads to an anion vacancy at one of the anion positions within the ceramic structure



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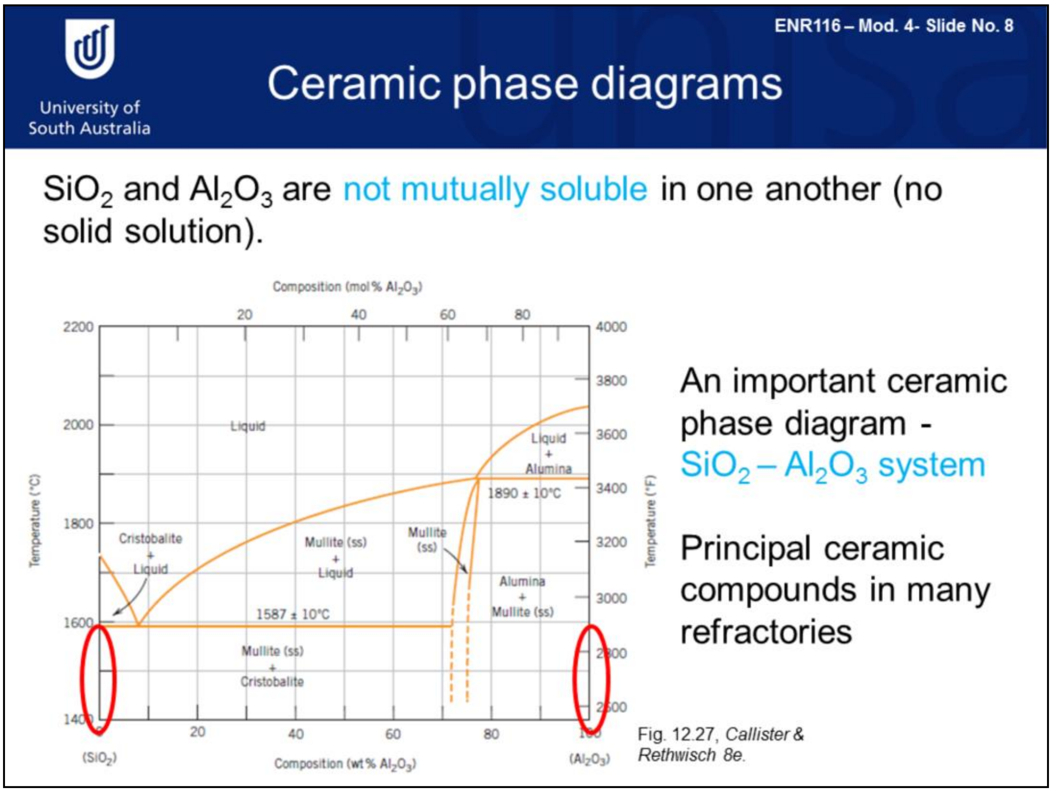
# Ceramic phase diagrams

Mixtures of ceramics are important, so we need their phase diagram

A simple ceramic phase diagram - $Al_2O_3 – Cr_2O_3$ system

Fig. 12.24, *Callister & Rethwisch 8e.*

- In many applications the ceramic compound will be a mixture of two ceramic materials
- The reasons for this might be to obtain certain physical or chemical properties, for manufacturing considerations, or safety related matters
- With this in mind, it is important to appreciate how ceramic materials mix together
- In a similar manner to metals, mixtures or ceramic compounds can be described by using a Phase Diagram
- An example of a simple ceramic phase diagram is that for the Al2O3 – Cr2O3 system
- This simple phase diagram arises from the complete solubility of the two elements in each other at all compositions, making it comparable to the Isomorphous Binary Phase Diagram for metals
- The solid solution in this example occurs because the Al and Cr can substitute for each other in the crystal structure
- This arises from the same charge for both Al and Cr and similar ionic radii, and hence the crystal structures for Al2O3 and Cr2O3 are the same



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# Ceramic phase diagrams

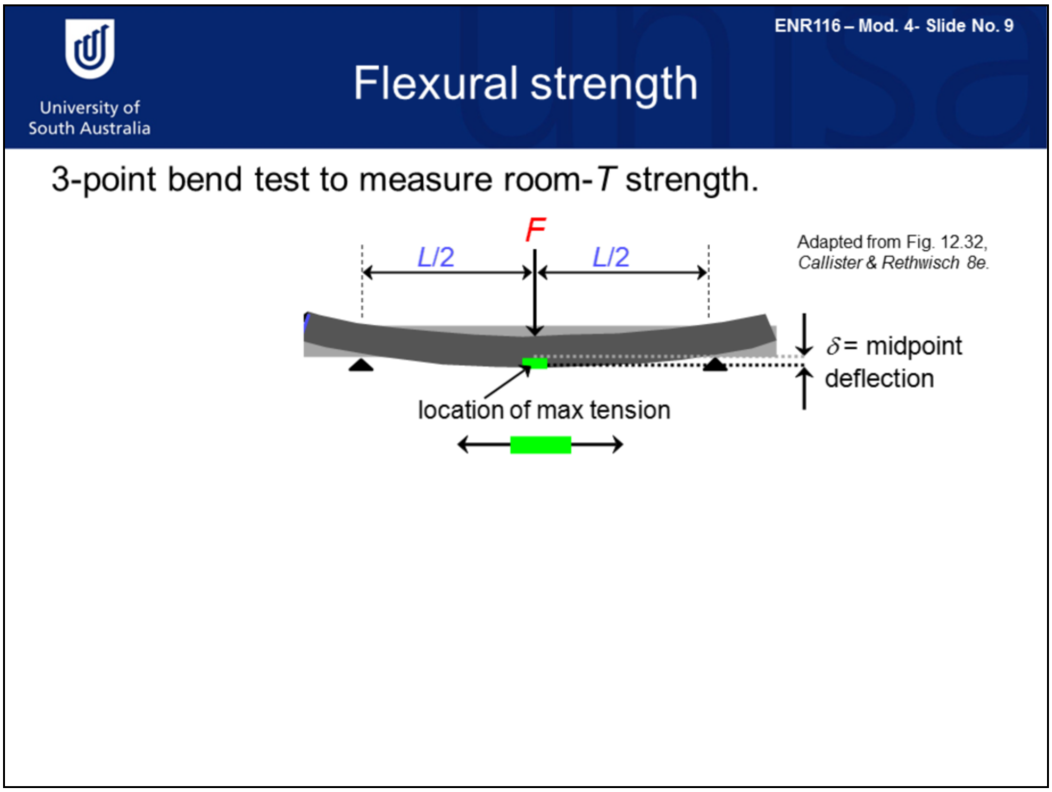
$SiO_2$ and $Al_2O_3$ are not mutually soluble in one another (no solid solution).

An important ceramic phase diagram - $SiO_2 – Al_2O_3$ system

Principal ceramic compounds in many refractories

Fig. 12.27, *Callister & Rethwisch 8e.*

- To demonstrate the complexity that some ceramic phase diagrams can have, the SiO2 – Al2O3 system is presented
- The complexity in this phase diagram arises from the fact that the ceramic compounds being mixed are not mutually soluble in each other
- This is demonstrated by the lack of terminal solid solutions at both extremes in the Composition of the phase diagram
- A lot of discussion surrounds the phase diagrams for mixtures of various ceramic compounds
- To understand more about different ceramic phase diagrams, section 12.7 of the course text is recommended as a good starting point



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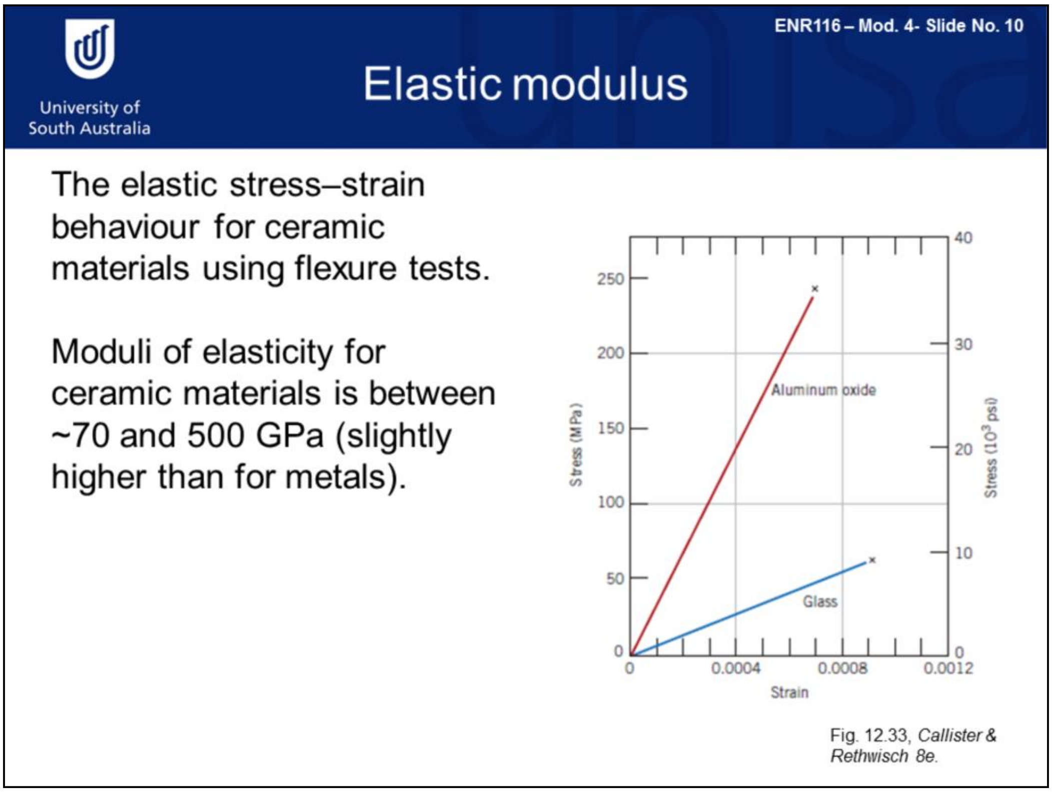
# Flexural strength

3-point bend test to measure room-$T$ strength.

Adapted from Fig. 12.32, *Callister & Rethwisch 8e.*

- Unlike metals, the stress-strain behaviour of a brittle ceramic is not determined from the tensile test
- There are several reasons for this,
    - In practice it is difficult to prepare the required geometry of the test samples
    - Also, in practice it is difficult to mount the test sample in the tensile testing device without damage
    - And finally, the ceramics fail after small applied strains, making it difficult to accurately measure the material response
- To measure the mechanical properties of the ceramic compound, a 3-point bend test is commonly employed
- This test is used to determine the flexural strength by bending the ceramic until it fractures
- The geometry of the ceramic compound test sample is a long rod which is either rectangular or circular in cross section
- This test sample is placed across two points, and then loaded from the top with a known force at the mid-point between the two resting points
- As the sample bends, the top surface is placed under compression and the bottom surface is placed under tension
- For ceramic compounds, their compressive strength is approximately an order of magnitude greater than their tensile strength
- This means that tensile failure of the ceramic test sample will be

observed before it any compressive failure
- In this light, it is reasonable to state that the 3-point bending test can replace the tensile test for ceramic materials
- In an experiment, when the sample fractures the applied load is recorded, and depending on the geometry of the test sample, one of two equations is used to calculate the flexural strength
- Examples of the flexural strength of some different materials is present here
- For more examples, table 12.5 from the course text is recommended



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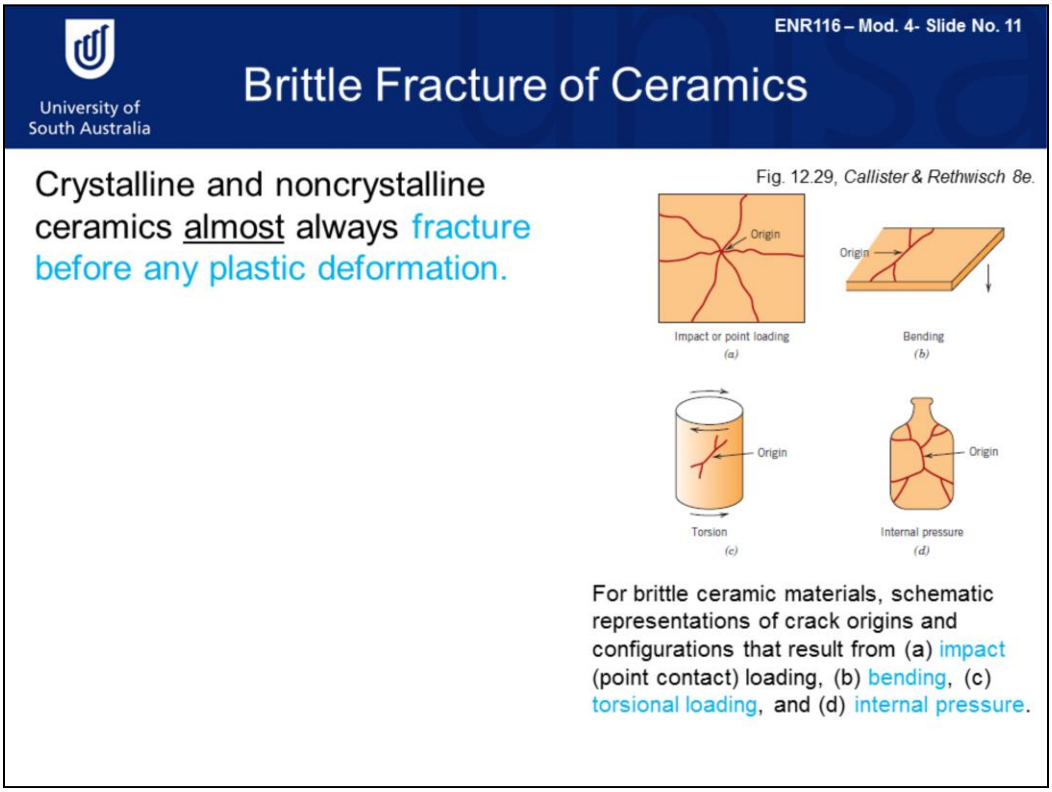
# Elastic modulus

The elastic stress–strain behaviour for ceramic materials using flexure tests.

Moduli of elasticity for ceramic materials is between ~70 and 500 GPa (slightly higher than for metals).

Fig. 12.33, *Callister & Rethwisch 8e.*

- Using the 3-point bending test, the elastic stress-strain behaviour for the ceramic compounds can be studied,
- A linear relationship between stress and strain is observed, which is similar to the stress-strain behaviour of metals using the tensile test
- The slope of this linear response is the elastic modulus
- Ceramic compounds typically have elastic moduli of between 70 and 500 GPa



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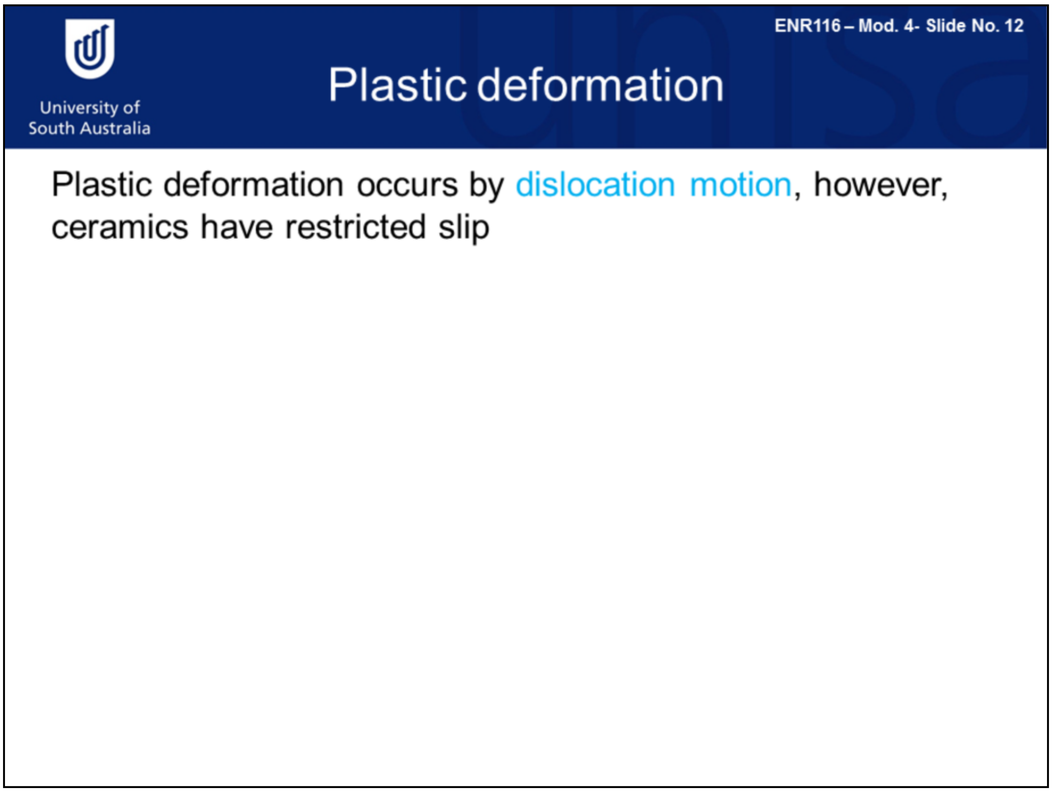
## Brittle Fracture of Ceramics

Crystalline and noncrystalline ceramics almost always fracture before any plastic deformation.

Fig. 12.29, *Callister & Rethwisch 8e.*

For brittle ceramic materials, schematic representations of crack origins and configurations that result from (a) impact (point contact) loading, (b) bending, (c) torsional loading, and (d) internal pressure.

- Almost all ceramic compounds will transition from the elastic region of the stress-strain behaviour to fracture, at room temperature
- No plastic deformation is observed, as tensile failure occurs before the onset of plastic deformation
- Brittle fracture occurs from the formation and propagation of cracks through the cross section of the ceramic compound
- The cracks propagate perpendicular to the applied load
- In practice, any flaws present in a ceramic structure will act as stress raisers, which increases the magnitude of the applied stress for a given load
- The raise in the applied stress leads to fracture at loads less than those predicted by theory



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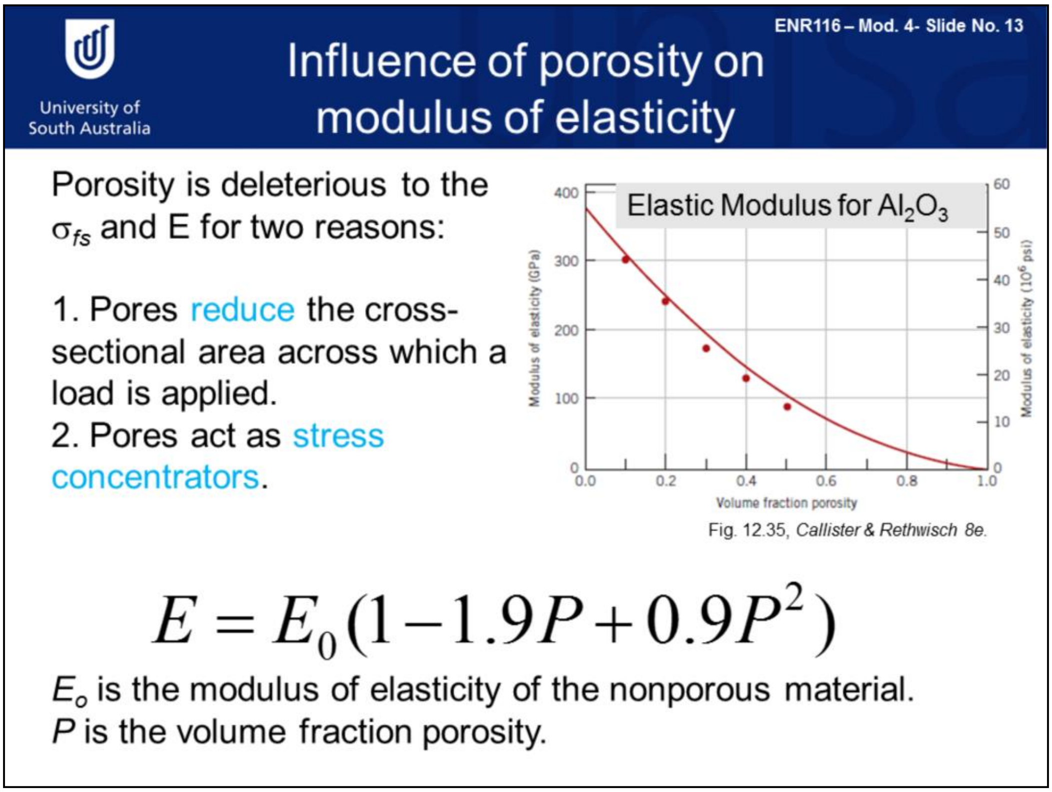
## Plastic deformation

Plastic deformation occurs by dislocation motion, however, ceramics have restricted slip

- The lack of plastic deformation in ceramic compounds is an important point to discuss
- Plastic deformation occurs via the motion of dislocations, or slip within the crystal structure
- In crystalline ceramic compounds the interatomic bonding is predominantly ionic in character, and the structure is made up of cations and anions
- For slip to occur, like charged atoms would have to come into close proximity with each other
- Due to electrostatic repulsion between like charges, this acts to restrict slip within the structure
- When the bonding character is covalent in character, slip is also restricted
    - This occurs because covalent bonds are relatively strong
    - There are limited numbers of slip systems
    - And dislocation structures are complex
- The restriction or inhibition of slip mechanisms is the reason why ceramic compounds are hard and brittle



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# Influence of porosity on modulus of elasticity

Porosity is deleterious to the $\sigma_{fs}$ and E for two reasons:

1. Pores reduce the cross-sectional area across which a load is applied.
2. Pores act as stress concentrators.

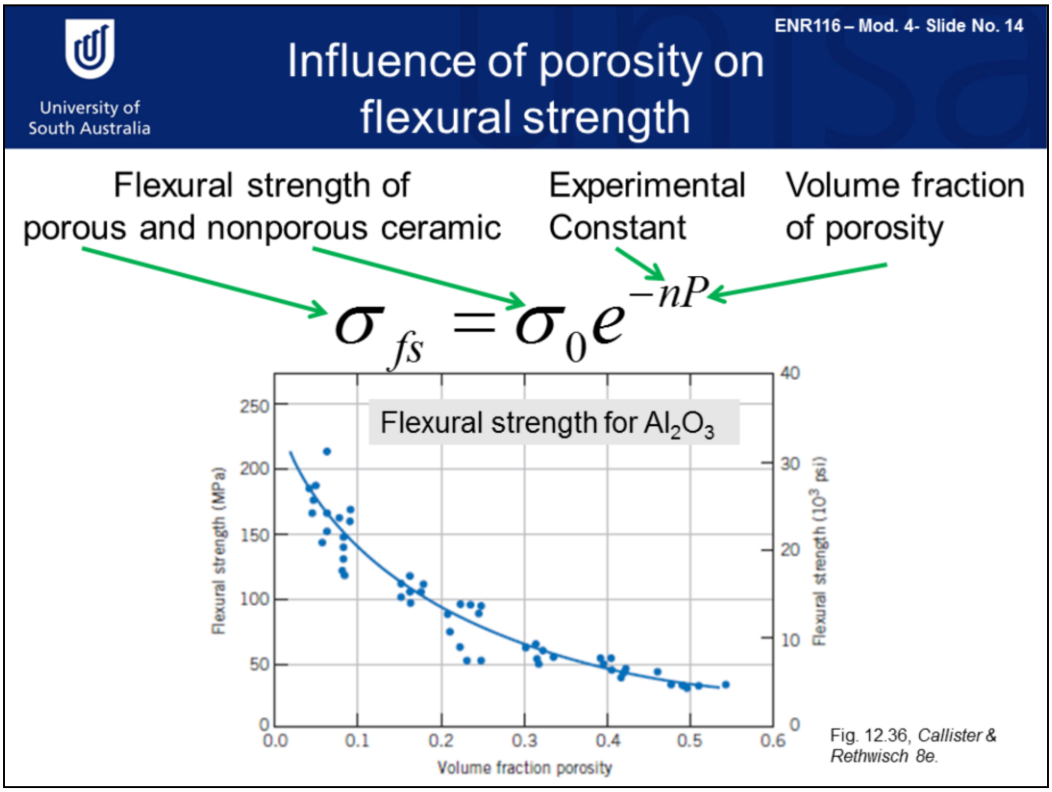
Elastic Modulus for $Al_2O_3$

Fig. 12.35, *Callister & Rethwisch 8e.*

$$E = E_0(1-1.9P+0.9P^2)$$

*E*$_o$ is the modulus of elasticity of the nonporous material.
*P* is the volume fraction porosity.

- When using ceramic compounds in practical applications, their process of forming can lead to pores or void space within the ceramic structure
- While post-processing steps are employed in an attempt to remove these voids, in most cases some level of porosity will exist within the ceramic compound
- The residual porosity has a deleterious effect on the flexural strength and elastic modulus of the ceramic compound
- These pores reduce the cross sectional area over which the applied load acts, and they concentrate the resulting stress
- The effect of porosity on the elastic modulus can be described by the volume fraction of the porosity and the elastic modulus of the non-porous compound



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# Influence of porosity on flexural strength

Flexural strength of porous and nonporous ceramic

Experimental Constant

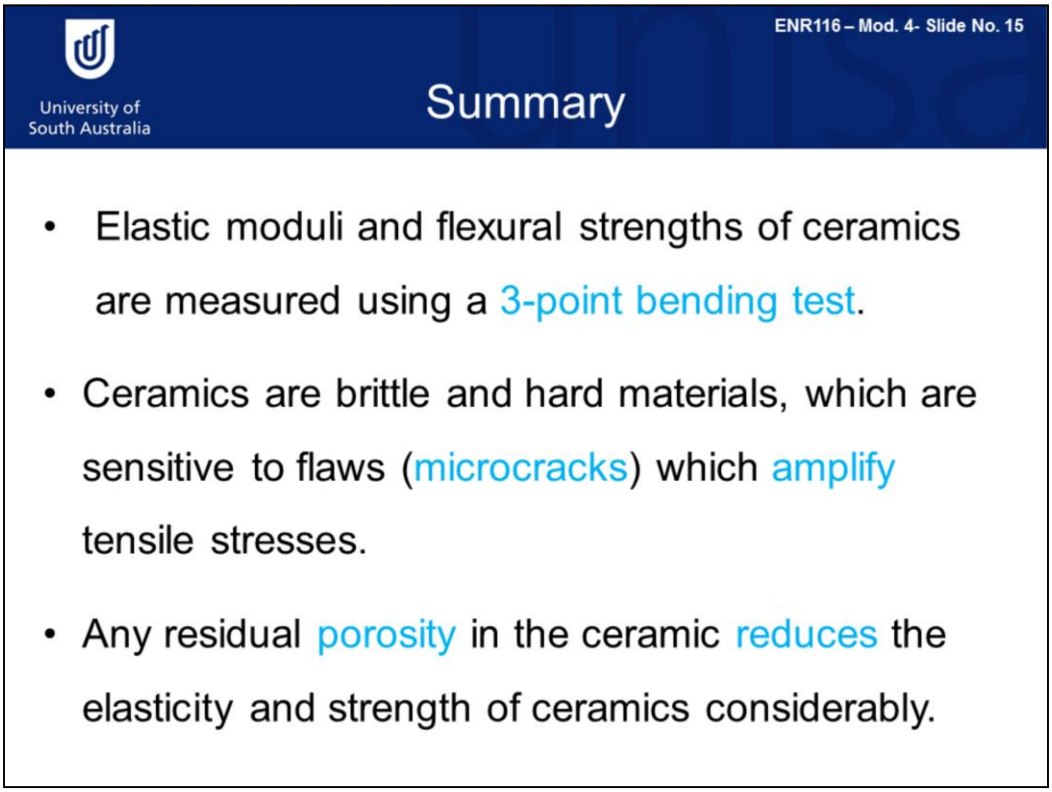
Volume fraction of porosity

$$\sigma_{fs} = \sigma_0 e^{-nP}$$

Flexural strength for $Al_2O_3$

Fig. 12.36, *Callister & Rethwisch 8e.*

- The influence of porosity is more pronounced when discussing the flexural strength
- A porosity of 10 vol% will generally decrease the flexural strength to around 50% of the non-porous ceramic compound
- While the elastic modulus and porosity are related through a second order polynomial equation, the flexural strength and porosity are related through an exponential decay
- This captures the fact that the flexural strength decreases quite rapidly with porosity compared to the elastic modulus



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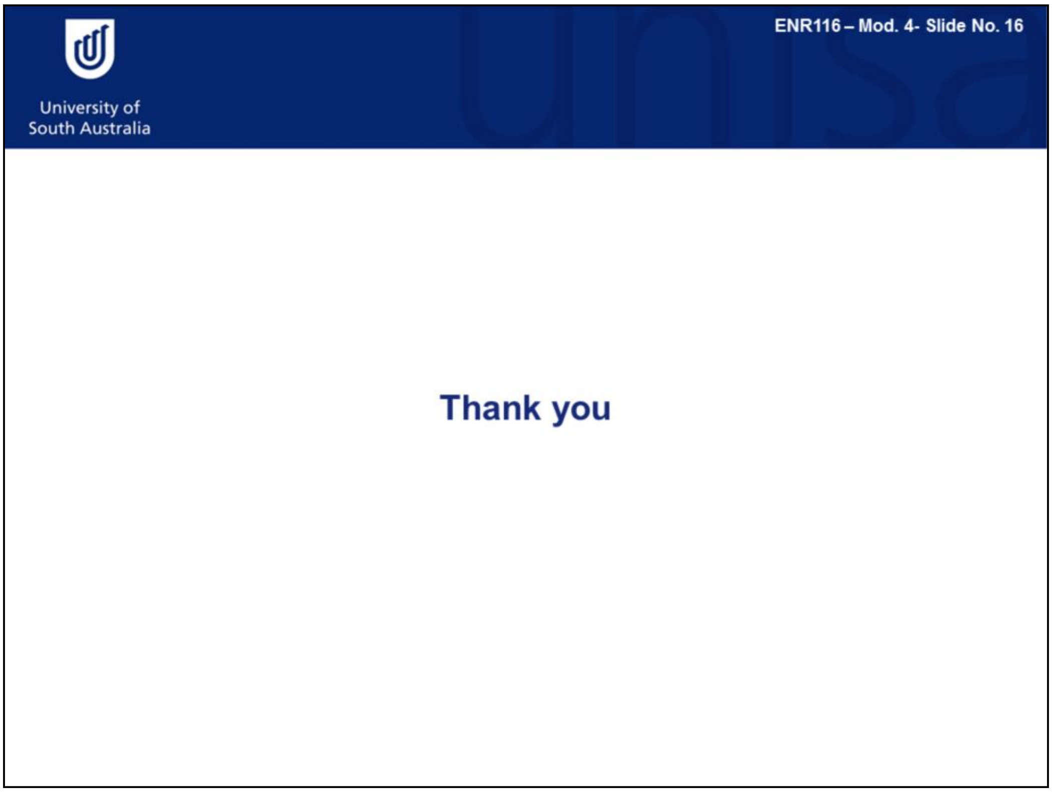
## Summary

- Elastic moduli and flexural strengths of ceramics are measured using a 3-point bending test.
- Ceramics are brittle and hard materials, which are sensitive to flaws (microcracks) which amplify tensile stresses.
- Any residual porosity in the ceramic reduces the elasticity and strength of ceramics considerably.

- In summary,
  - The three point bending test is used to determine the elastic moduli and flexural strength of ceramic compounds
  - Ceramics are brittle hard materials that are sensitive to flaws or microcracks which amplify the tensile stresses
  - Any residual porosity in the ceramic after forming has a deleterious effect on its mechanical properties



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**Thank you**

- This concludes the presentation on the mechanical properties of ceramics
- If you have any questions or desire further clarification please post a question or comment on the ENR116 Discussion Forum
- For further reading please consult the course text, specifically Chapter 12