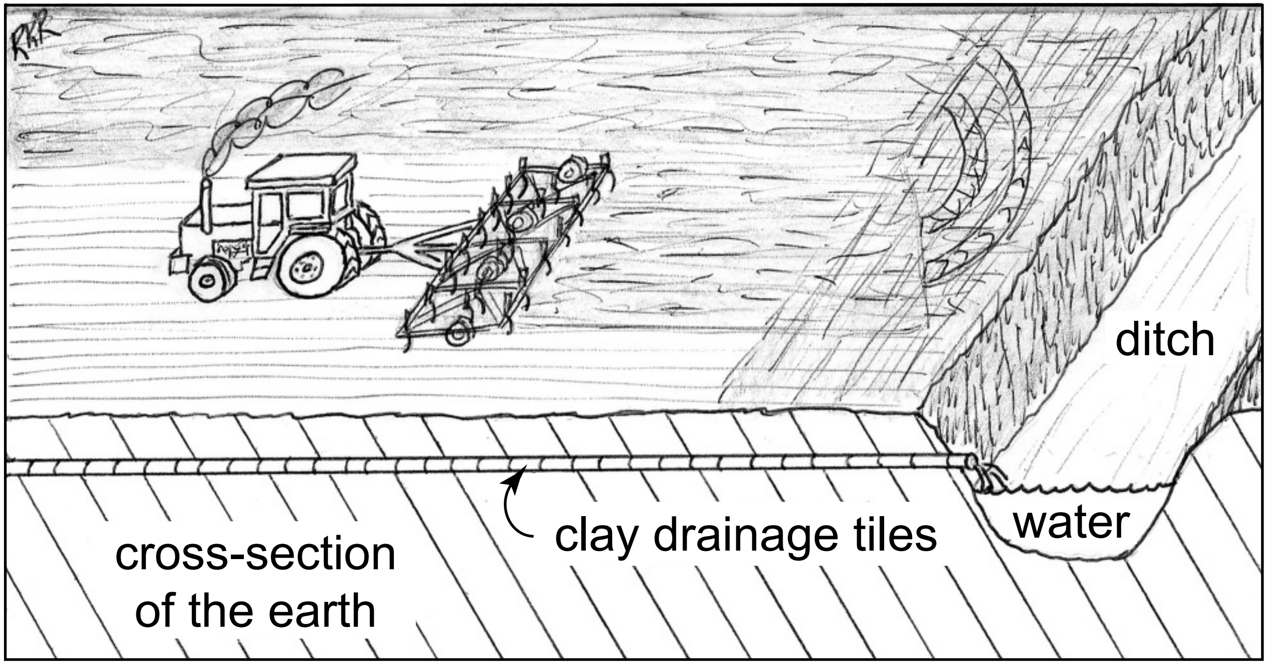
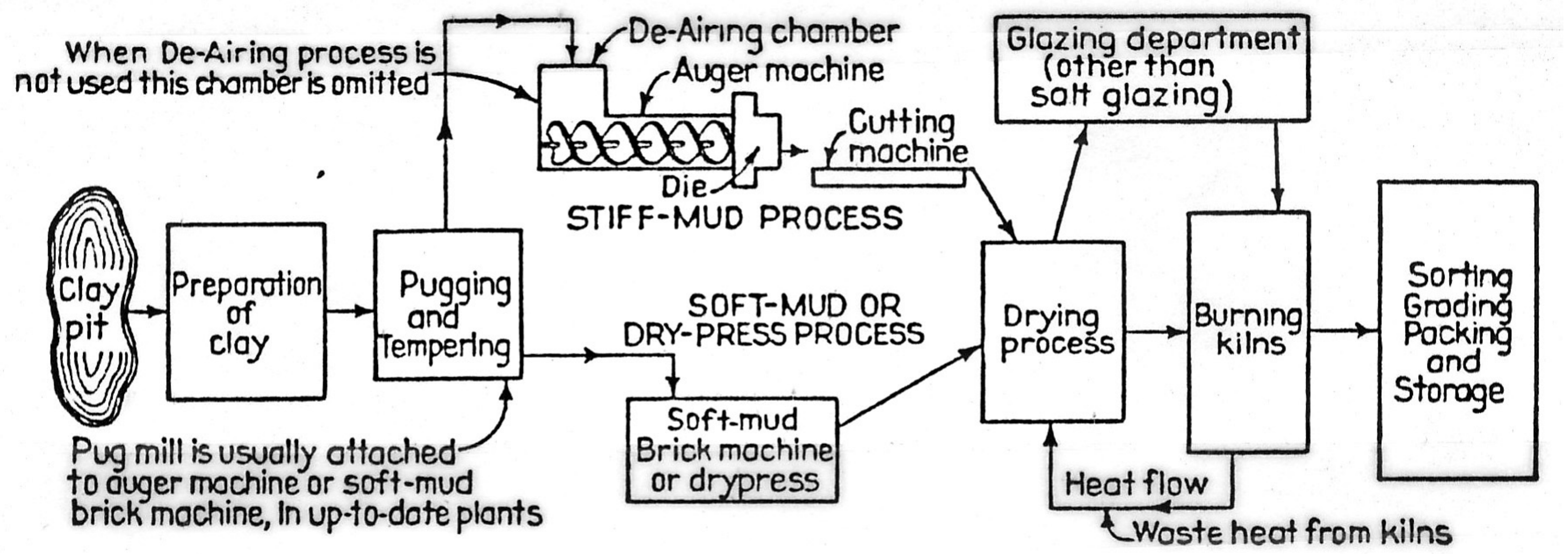
Fracture Analysis of a Clay Drainage Tile



- In agricultural drainage systems many clay tiles remain in use after up to 100 years.
- New drainage systems use corrugated PVC piping.

Clay Drainage Tile Manufacturing

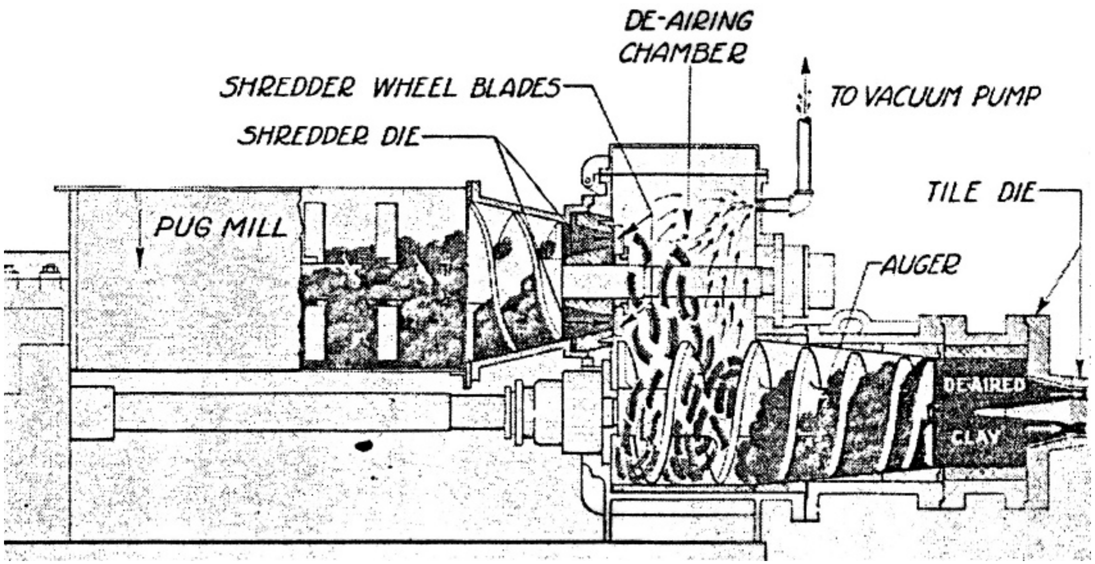
- Earliest drainage tile shaped on a potter's wheel (4000 BC).
- First American mass production in 1875 (New Jersey), reaching Indiana (location of tile in this study) by 1885.

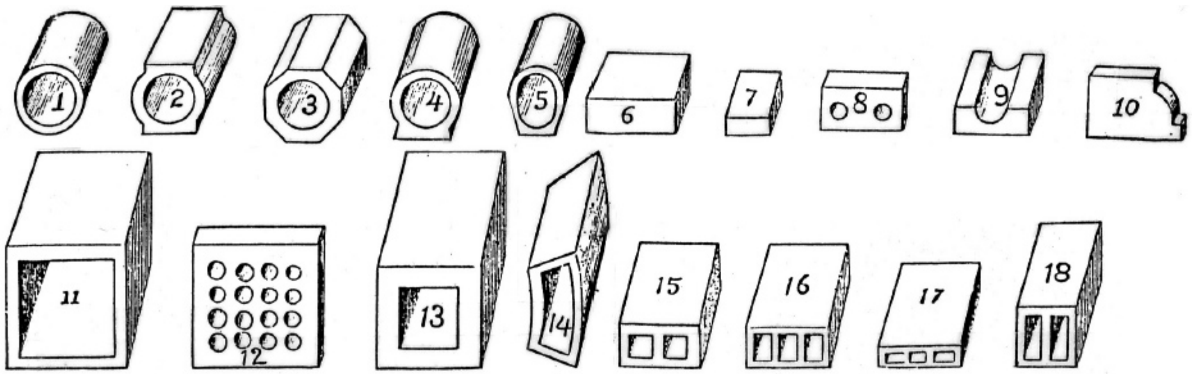


Adapted from: H.C. Plummer, *Brick and Tile Engineering Handbook of Design*, Structural Clay Products Institute, Washington, DC, 1950.

Clay Drainage Tile Manufacturing

- Shapes formed by "stiff-mud" extrusion.





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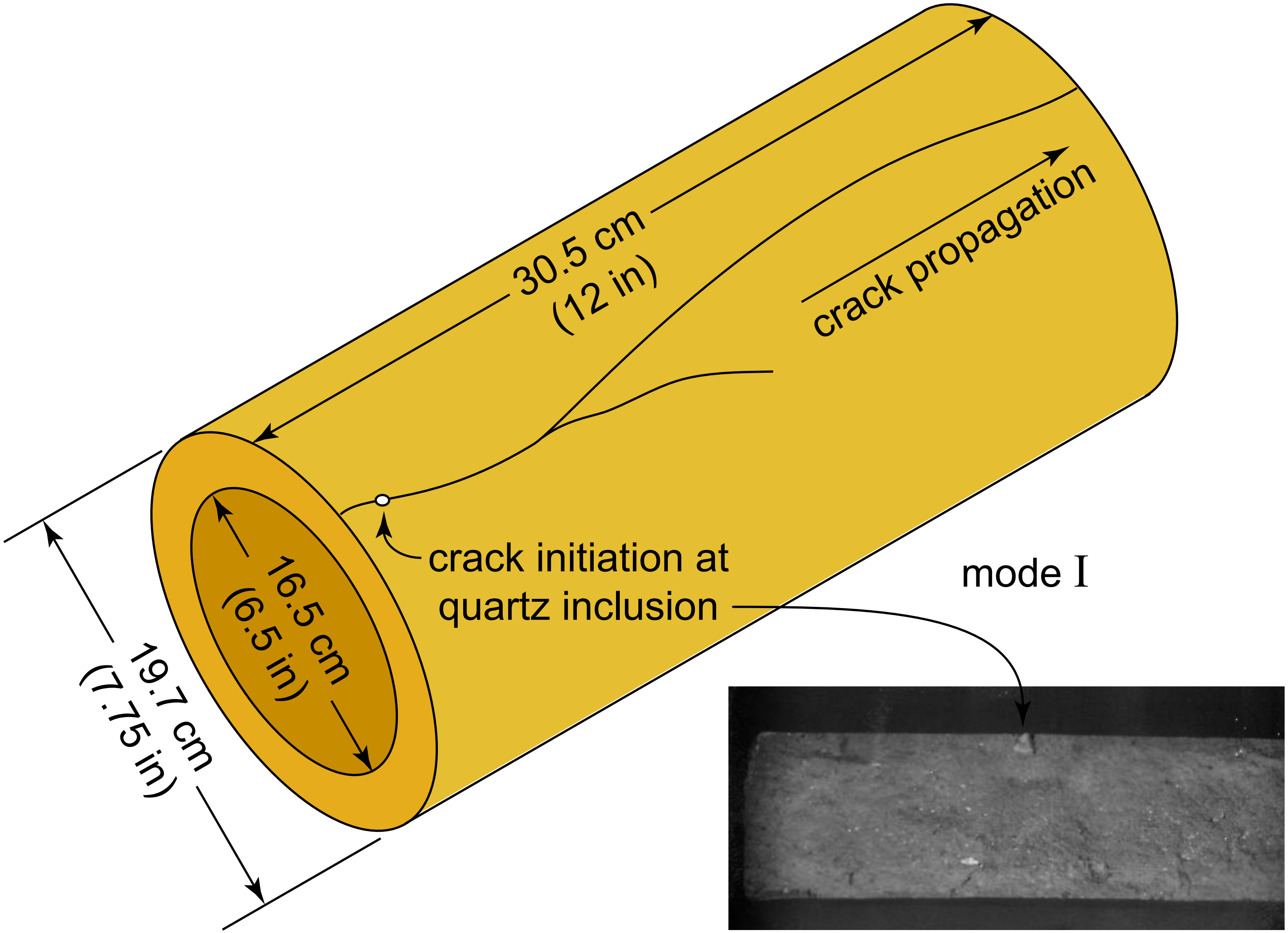
Fracture Analysis Objectives

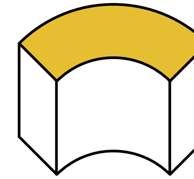
- Determine the typical cause(s) of fracture in clay drainage tiles.
- Provide an educational case study for the fracture of brittle materials.

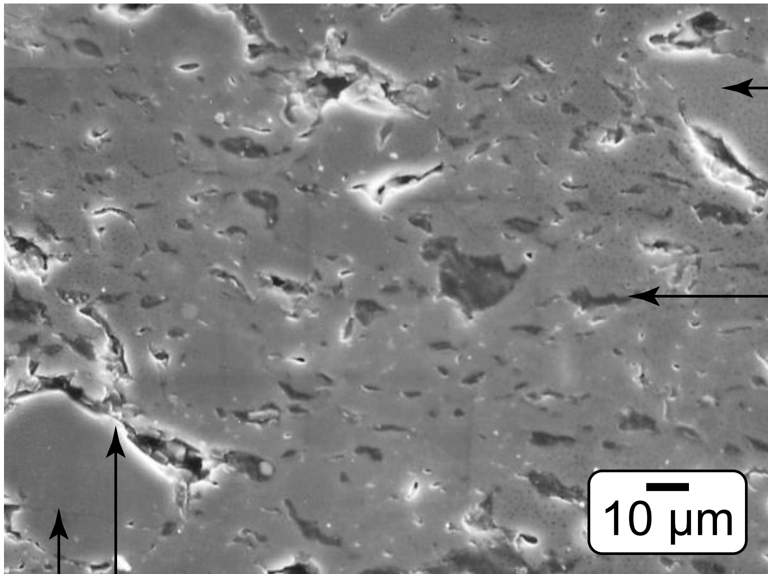
(Given the success of corrugated PVC piping as a replacement, proposed design modifications are unnecessary.)

Fractured Clay Drainage Tile



Clay Microstructure





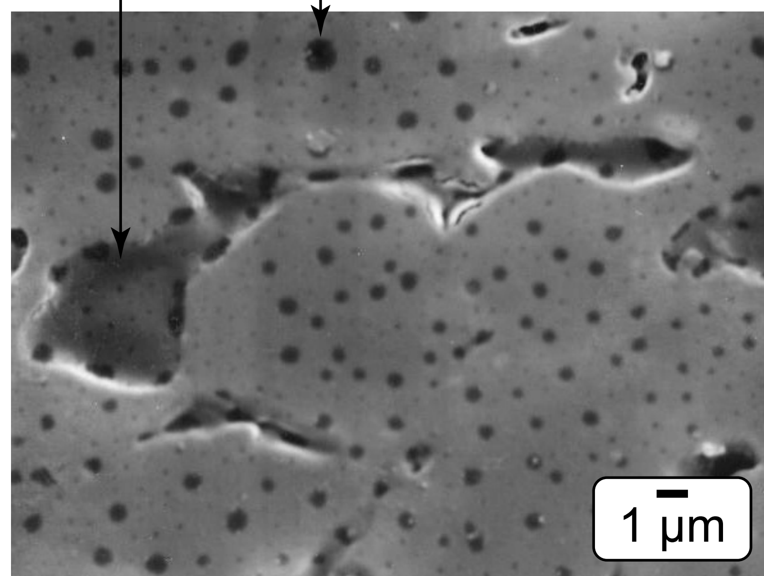
silicate matrix

porosity (≈22%)
- micro vs. nano
- texture

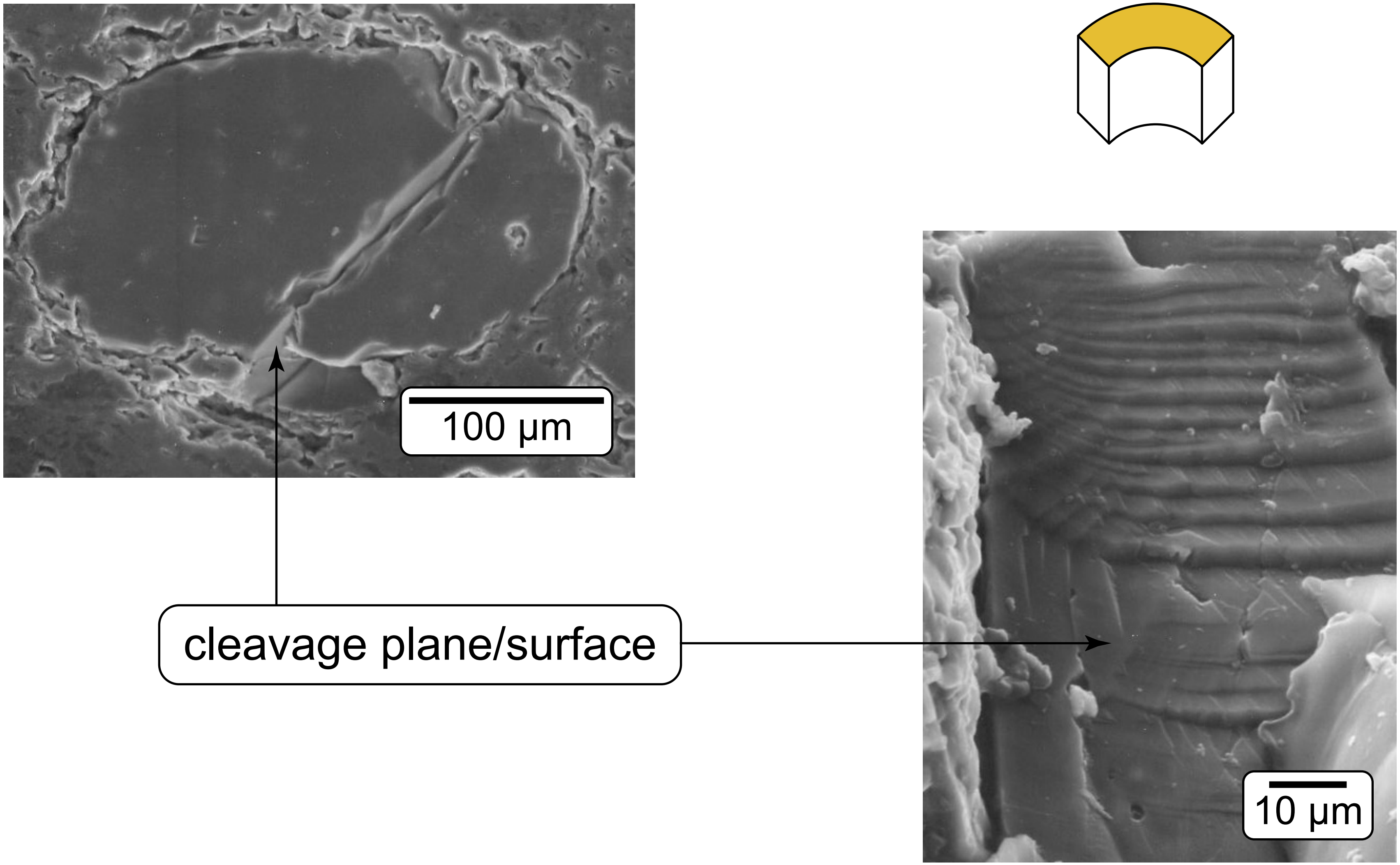
composition:
71.5 at% Si
15.4 at% Al
6.3 at% Fe
4.3 at% K
1.6 at% Ca
0.7 at% Ti

microcracks

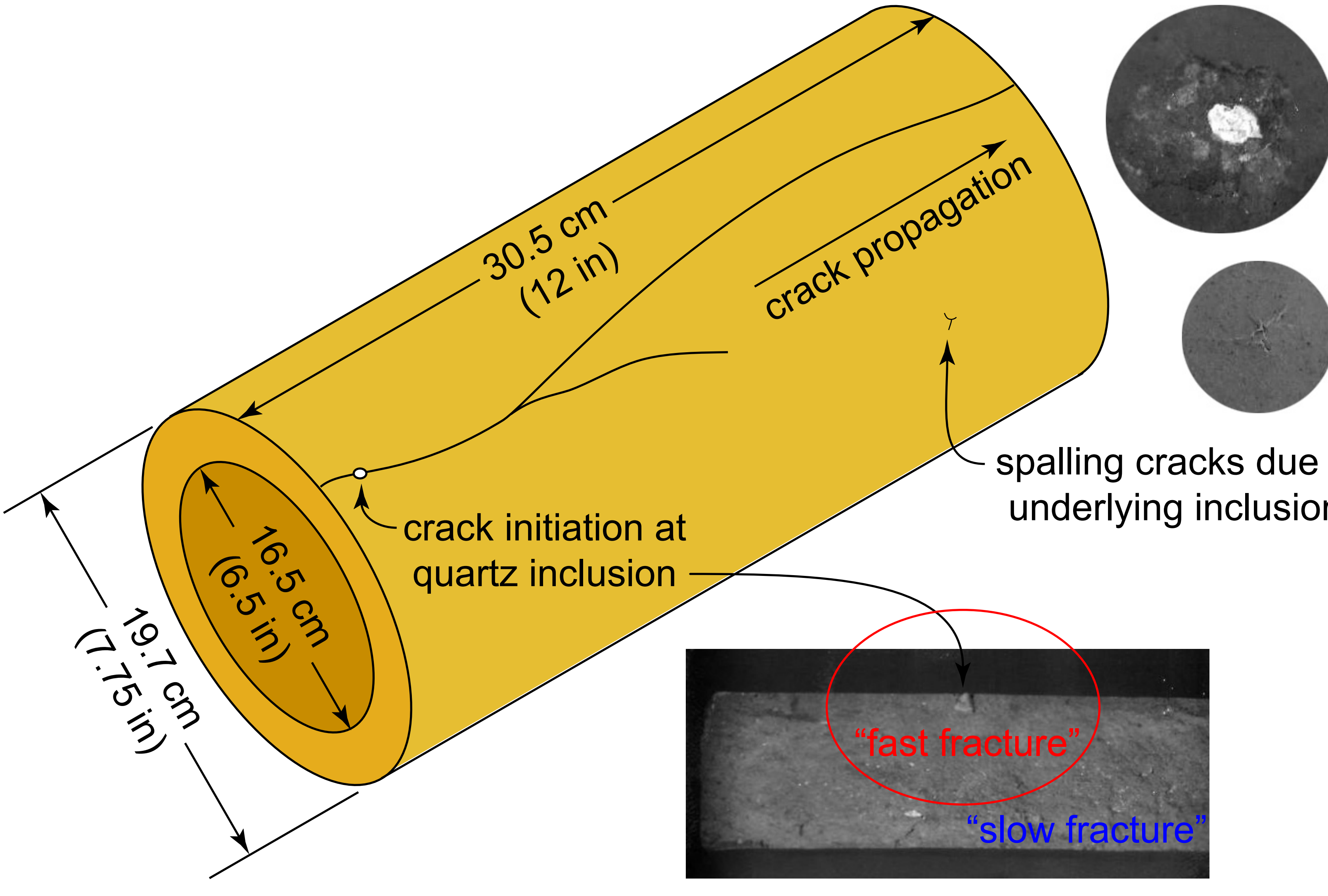
inclusions (crystalline)
- white - quartz (SiO_2)
- black - hematite (Fe_2O_3)
- orange - clay (silicate)



Cleavage of Quartz Inclusions



Fractured Clay Drainage Tile

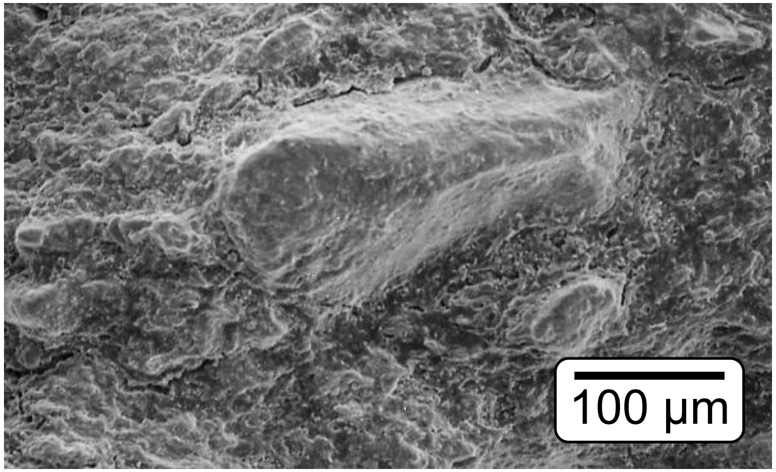


Fracture Surface

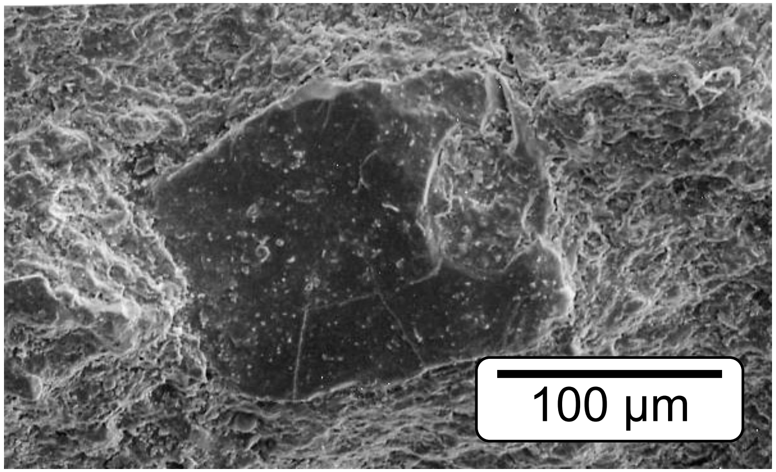
"slow fracture" or crack propagation

- greater surface roughness
- large number of inclusions
- microcracking

pullout of inclusions



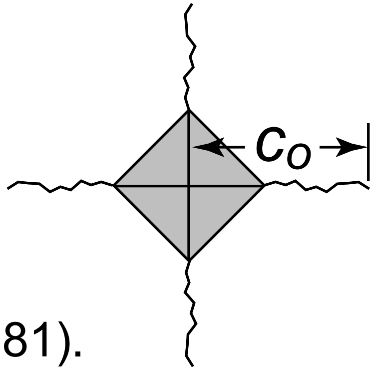
cleavage of inclusions



Fracture Toughness (K_{Ic}) Measurement

Using Vickers microhardness indentations:

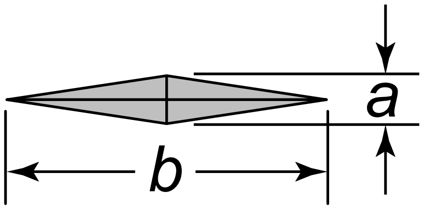
$$K_{Ic} = 0.16(E/H)^{1/2}(P \cdot c_o^{-3/2})$$



G.R. Anstis *et al.*, *J. Am. Ceram. Soc.*, **64** [8] 533-538 (1981).

Using Knoop microhardness indentations:

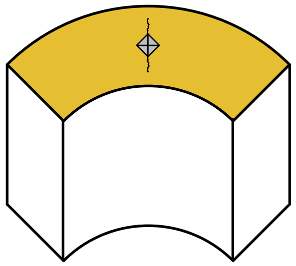
$$E/H = \frac{0.45}{(0.14 - a/b)}$$



$$KHN = P/(0.07028 \cdot b^2)$$

D.B. Marshall, *J. Am. Ceram. Soc.*, **65** [2] C175-176 (1982).

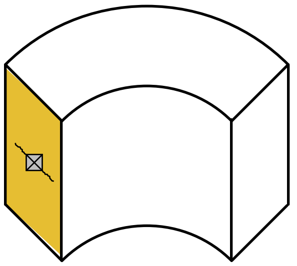
Fracture Toughness (K_{Ic}) Measurement



KHN = 153 ± 15 Kg/mm^2

E/H = 16.7 ± 7.3

K_{Ic} = 2.2 ± 0.2 MPa·m$^{1/2}$



KHN = 158 ± 23 Kg/mm^2

E/H = 15.5 ± 6.5

K_{Ic} = 2.2 ± 0.6 MPa·m$^{1/2}$

Estimation of Failure Stress

Crack Initiation:

inclusion assumed as elliptical crack, a = 2 mm, 2c = 3 mm

$$K_{Ic} = \frac{1.12 \cdot \sigma \cdot (\pi \cdot a)^{1/2}}{(3\pi/8) + (\pi/8)(a^2/c^2)} = 2.2 \pm 0.2 \text{ MPa} \cdot \text{m}^{1/2}$$

$$\sigma = 46 \pm 4 \text{ MPa}$$

Crack Propagation:

through center crack, 2a = 30 mm, w = 30.5 cm

$$K_{Ic} = f(a/w) \cdot (w/\pi \cdot a)^{1/2} \cdot \sigma \cdot (\pi \cdot a)^{1/2} = 2.2 \pm 0.2 \text{ MPa} \cdot \text{m}^{1/2}$$

$$f(a/w) = [(\pi \cdot a/4w) \cdot \sec(\pi \cdot a/2w)]^{1/2} \cdot [1 - 0.025 \cdot (a/w)^2 + 0.06 \cdot (a/w)^4]$$

$$\sigma = 12 \pm 1 \text{ MPa (or less)}$$

Possible Failure Mechanisms

1) Crushing of tile from forces above ground.
2) Thermal expansion/contraction of clay.
3) Thermal expansion mismatch of matrix and inclusions.
4) Freezing of water inside tile.
5) Freezing of water inside clay.

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1) Crushing of tile from forces above ground.

- Tile unlikely to remain intact.
- Mode I crack expected to initiate on inner surface.

Therefore, unlikely to be the cause of failure.

Possible Failure Mechanisms

2) Thermal expansion/contraction of clay.

- Plane theory of thermoelasticity for a thick-walled tube.

  A.P. Boresi, *Elasticity in Engineering Mechanics*, Prentice-Hall, 1965.

- $E \approx 23$ GPa measured from hardness and E/H ratio.

- $E = 24.8$ GPa, $\nu = 0.05 - 0.1$

  H.C. Plummer, *Brick and Tile Engineering Handbook of Design*, Structural Clay Products Institute, Washington, DC, 1950.

- If $\Delta T \leq 10°C$, $\sigma \leq 10$ MPa.

Therefore, likely to contribute to crack propagation but unlikely to be the cause of crack initiation.

Possible Failure Mechanisms

3) Thermal expansion mismatch of matrix and inclusions.

$\alpha_{quartz} = 13.0 \cdot 10^{-6}$ °C^{-1} $\alpha_{clay} = 5.36 \cdot 10^{-6}$ °C^{-1}

$\Delta T \approx$ 1100°C (post-firing)

Therefore, likely the cause of spalling cracks on the tile surface but unlikely to be the cause of failure.

4) Freezing of water inside tile.

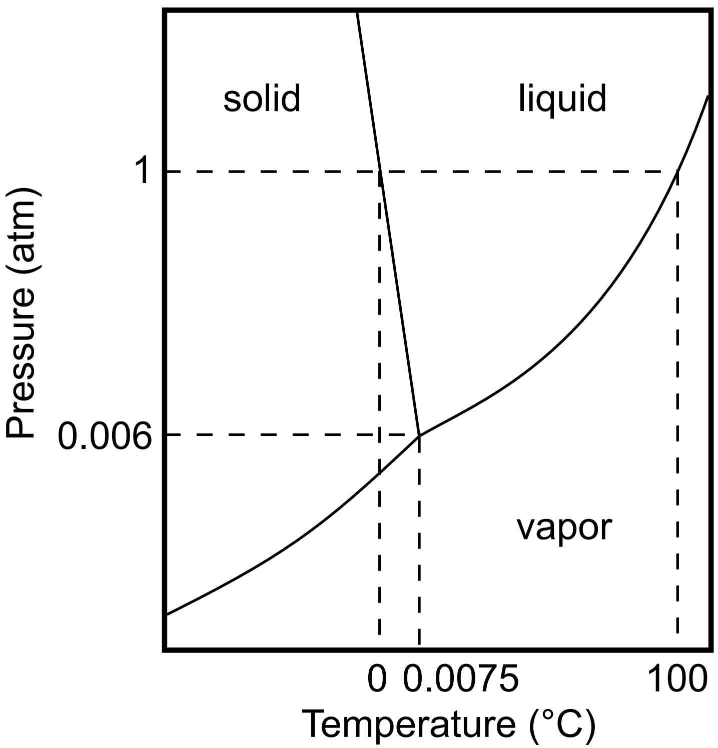
- Tiles are gradually sloped to allow drainage.
- Tiles are placed below the frost line (≈ 36 in).

Therefore, unlikely to be the cause of failure.

Possible Failure Mechanisms

5) Freezing of water inside clay.

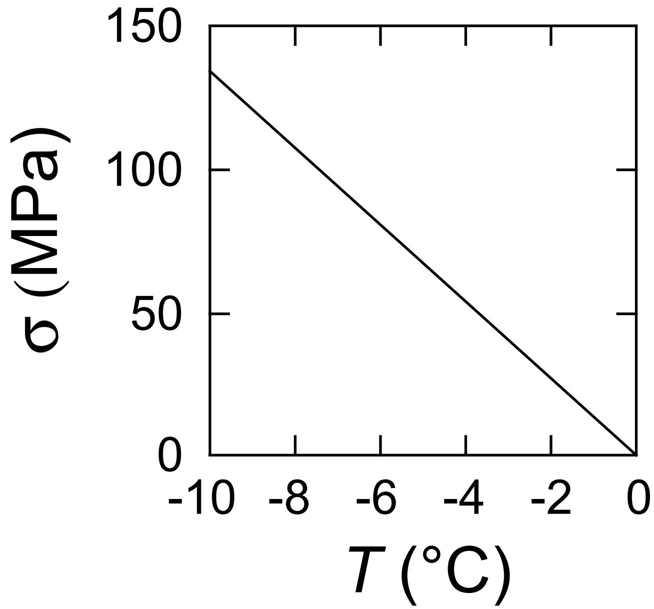
- $p(T) = -132.5 \cdot T + 1$ (atm)
- If pore considered a thick walled pressure vessel, $\sigma_{max} = p(T)$.

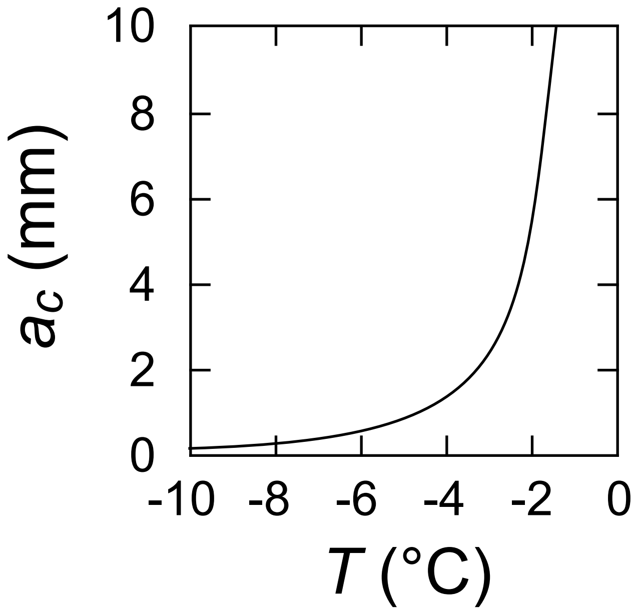


Possible Failure Mechanisms

5) Freezing of water inside clay.

- $K_{Ic} = (2/\pi)\cdot\sigma(T)\cdot(\pi\cdot a_c)^{1/2} \approx 2.2\ \mathrm{MPa}\cdot\mathrm{m}^{1/2}$





Therefore, likely to be the cause of crack initiation and contribute to crack propagation.

Summary

1) Freezing water inside pores or cracks in the clay was the only source able to generate the stresses necessary for crack initiation.

2) A crack initiated at a quartz inclusion on the outer surface of the tile. The inclusion acted as a pore that was open to water via spalling cracks due to differential thermal contraction after firing.

3) Crack propagation continued due to continued freezing of water in the crack and/or cyclic thermal stresses.