# Sifting Through The Tailings

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# Presentation Outline

- Tailings Defined
- Tailings Dewatering—Thickening, Tailings Dam/Pond
- Historical Tailings Pond Example—Grizzly Gulch
- Option 1: Beneficiation of Tailings
- Option 2: Cement/Concrete
- Option 3: Bricks and Related Materials
- Option 4: Paste Backfill
- Option 5: Shotcrete
- Option 6: Dry Stacking
- Secondary Options
- Future Considerations
- Conclusions

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# Tailings

- Tailings are the product of a milling operation.
- It is estimated that ~10-14 billion tons of tailings are produced annually, with a total worldwide inventory of tailings estimated at 282 billion tons.
- The particle size distribution of mill tailings is quite variable, as it is dependent upon the size to liberate the desired mineral(s) from a given ore body (which is determined by the underlying geology of the ore body).
- Tailing particles are defined as <u>sand</u> (~2 mm-75 μm), <u>silt</u> (75-2 μm) and <u>clay</u> (< 2 μm) size particles.  These ranges are arbitrary and somewhat misleadingly named.

# Tailings

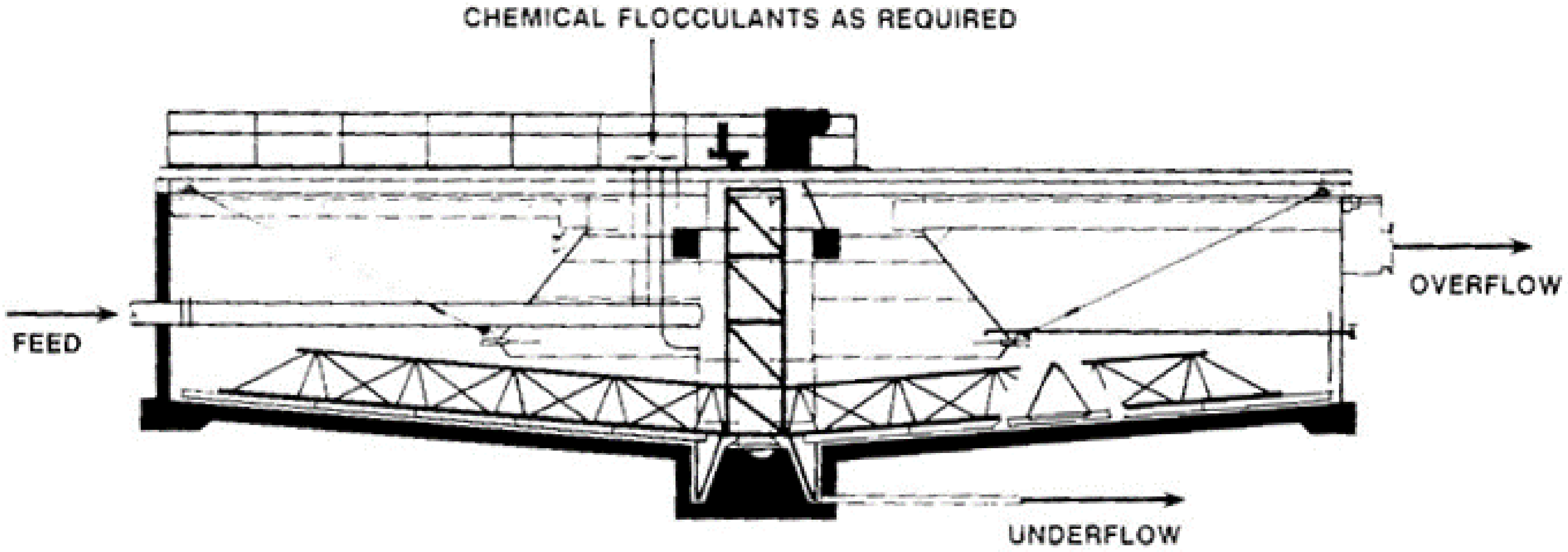
- Mineral grade decreases with time, and the desired minerals are more finely disseminated in the ore. Consequently, tailings size also tend to decrease in time.
- The chemical makeup of tailings is also quite variable and depends upon the ore body. Common gangue minerals include quartz ($SiO_2$), kaolinite ($Al_2Si_2O_5(OH)_4$), muscovite (mica) ($KAl_2(AlSi_3O_{10})(F,OH)_2$), montmorillonite ($(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$).
- Tailings also include gangue minerals from the predominant ore mineral type (e.g., sulfides (pyrite ($FeS_2$), arsenopyrite (FeAsS)), carbonates (calcite ($CaCO_3$)).

# Tailings

- One can also consider tailings from a prior large-scale ore treatment process.
- Examples in this category include: *a)* fly ash (minerals remaining after coal combustion (mainly metal (Si, Al, Fe) oxides), *b)* red mud (mainly oxides (Fe) minerals remaining after bauxite processing), and *c)* slag (glassy (amorphous) material (metal oxides) left after smelting and refining).

# Tailings (immediately after milling)

- Immediately after milling (e.g., after concentration of desired minerals by froth flotation) the tailings are usually in an aqueous slurry and contain ~60-80 wt% water.
- Dewatering of tailings occurs via thickening (add flocculant$).
- Thickening reduces the water (reused) content (< 50 wt% water).



# Initial Tailing Disposal

- Flocculated tailings are sent to an impound area called a tailings pond/dam.
- Tailings ponds are monitored for leakage (lined to ensure no ground water contamination), and to make sure they are of sound geotechnical design.
- The Brumadinho tailings dam failure in 2019 in Brazil released 12M $m^3$ of tailings and resulted in 270 deaths. Other issues: air-born dust, acid mine drainage (sulfide minerals). That failure and those issues has heightened industry awareness about the need for more sustainable options for tailings disposal (post tailings dam impoundment).

# Mineral Tailing Considerations

New Tailings*

Disposal

Repurpose

*assume all minerals of economic value have been recovered*

Old 'Historical' Tailings

Do Nothing

Reprocess or Repurpose*

*assume there are minerals of value that can be reclaimed or utilized*

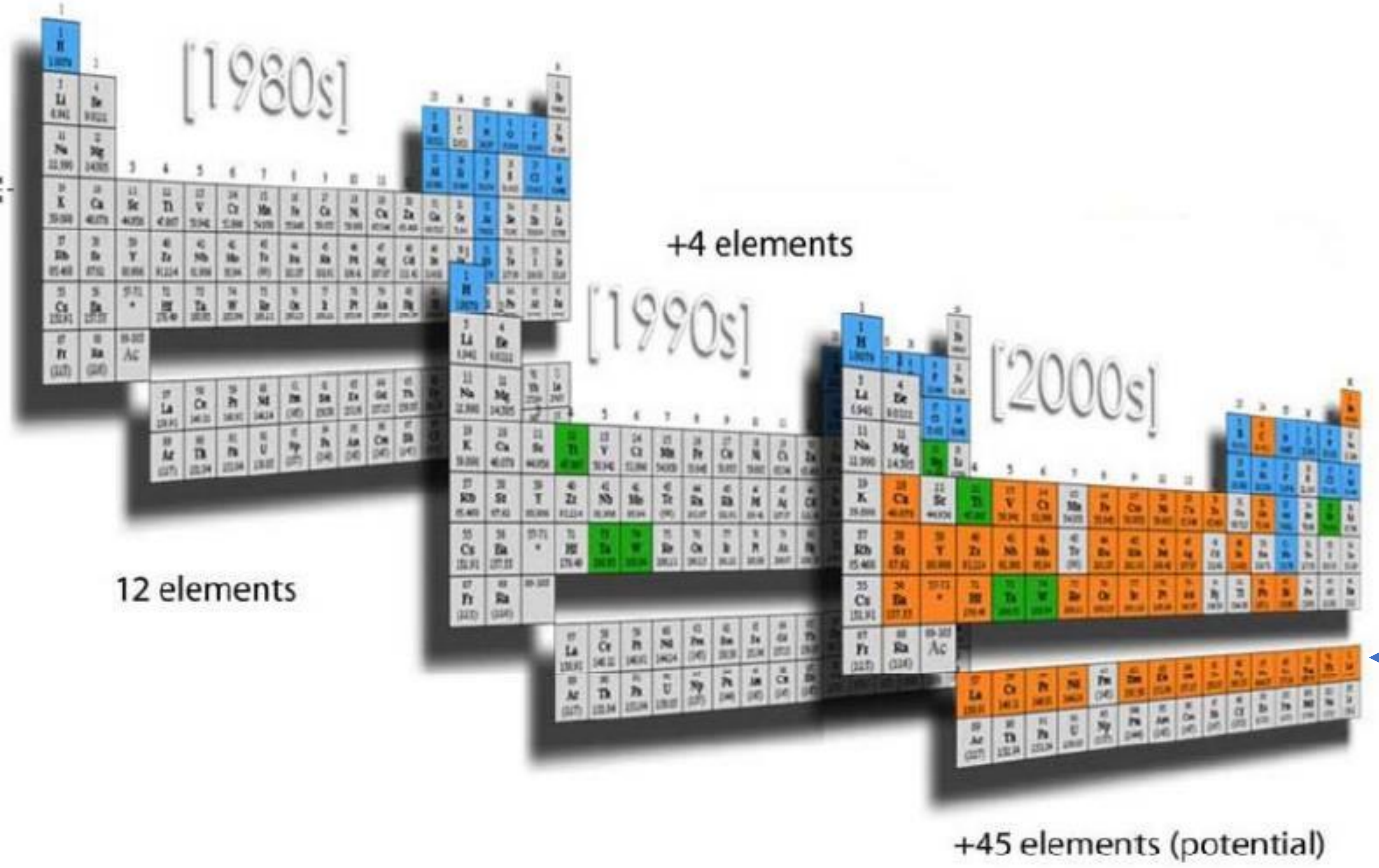
# Historical Tailings Dam Example

# Tailings Disposal (Grizzly Gulch Dam)

- Tailings impoundment from the former Homestake Gold Mine.
- Tailings were deposited between 1977 and 2002 (stopped mining).
- Contains roughly 40 million tons of tailings.
- Currently owned/managed by Barrick Gold (no reprocessing).

**Beach 1 at Grizzly Gulch**

# Historical Tailing Considerations




**Variety of Elements used Continues to Expand**

- electronics
- renewable energy
- defense
- automotive

**rare earth elements**

Source: National Research Council. (2008). *Minerals, critical minerals, and the US economy*. National Academies Press.

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# Option 1: Beneficiation of Tailings

- If permitting and economics are favorable historical tailings are quite amenable (already comminuted, beware of oxidation) to reprocessing (concentrating), followed by remediation/reuse of remaining tailings to current standards and requirements.
- Reprocessing usually follows standard mineral concentration methods (e.g., gravity, froth flotation, magnetic, electrostatic).
- A domestic example of this is the reprocessing of fly ash and the recovery of rare earth elements. Significant funding has been invested in this effort by the U.S. Department of Energy.

# Option 2: Cement/Concrete

## What is Portland Cement?

(1) comminute the minerals (e.g., limestone ($CaCO_3$), iron ore ($Fe_2O_3$), silica/quartz ($SiO_2$), kaolin ($Al_2Si_2O_5(OH)_4$)), (mineral feed based upon local ores/feeds (need source of Ca, Fe, Si, Al), fly ash (common) and mix,

(2) heat the prepared mix in a kiln to react to form cement "clinker",

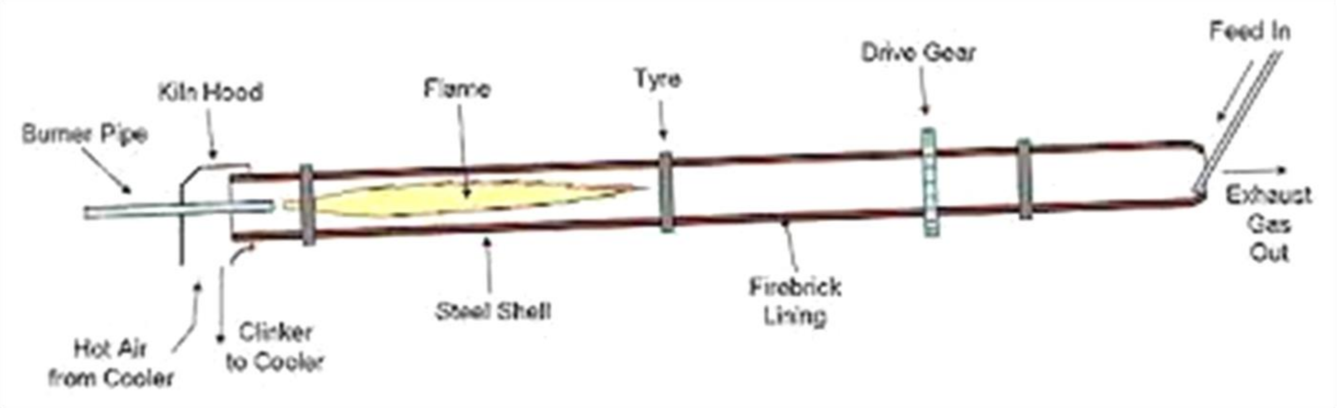
(3) mix the clinker, with ~5% of gypsum ($CaSO_4 \cdot 2H_2O$) to allow storage/transport,

(4) cement clinker is mixed with water and aggregate (large (sand, silt size) mineral particles, added for strength, fly ash (commonly added, acts as a **pozzolan**)) on site to form concrete, and

(5) water causes the cement to become workable and then harden (set) into final concrete.

# Option 2: Cement/Concrete

## Firing/Calcining of Cement




- Kiln (1300-1450 °C) (beware of sulfides) is used to chemically react the feed minerals mix to form cement (clinker).
- Cement consists of four main compounds listed in order of their importance: β-dicalcium silicate (β-$Ca_2SiO_4$), tricalcium silicate ($Ca_3SiO_5$), tricalcium aluminate ($Ca_3Al_2O_6$), and calcium aluminoferrite ($Ca_2AlFeO_5$). (need for minerals that contain Ca*, Si, Al, Fe).

# Option 3: Bricks & Related Materials

- A classic U.S. Bureau of Mines (USBM) Report of Investigation from 1971 demonstrated the potential to produce bricks from mill tailings (*ROI 7527, Dry-Pressed Building Bricks from Copper Mill Tailings*).
- However, the USBM research required the added beneficiation step (froth flotation) for removal of pyrite.
- Sulfide (e.g., pyrite) and carbonate minerals present are problematic to traditional brick production because of the release of $SO_{2(g)}$ and $CO_{2(g)}$ at temperatures greater than ~400°C. The gas causes cracking of the bricks.

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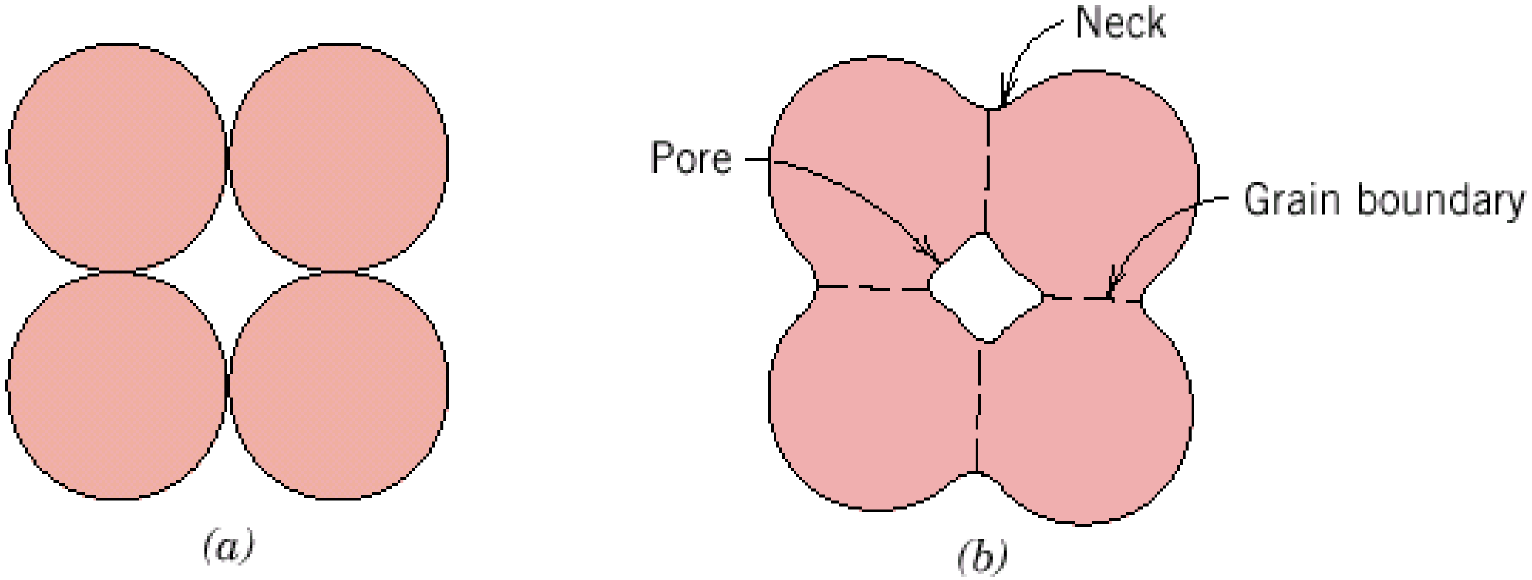
# Option 3: Bricks & Related Materials

## Sintering of Clay-based Ceramics




- Most bricks are clay-based and include kaolin and quartz. Other common minerals include metal oxides, mica and feldspar.
- Bricks are formed by creating a mineral paste to form the brick, drying (green body) and then firing to a high temperature (>1000°C) to cause sintering (and chemical reactions) between particles.

# Option 3: Bricks & Related Materials

## Firing/Sintering Reactions

**Table 6.1.** Firing and cooling a kaolinitic clay

| °C | *Firing* |
|---|---|
| 15° to 110° | Remaining water (dampness due to humidity of atmosphere) evaporated |
| 110° to 250° | Plastic clays lose adsorbed water. (Montmorillonite loses its '$nH_2O$') |
| 250° to 500° | Dry kaolinite, $Al_2Si_2O_5(OH)_4$ |
| 500° to 650° (maximum at 550°) | Kaolinite is dehydroxylised |
| 573° | Any free quartz present has α–β change |
| 550° to 900° | Clay is probably 'metakaolin' ($Al_2O_3$, $2SiO_2$), with increase of pores and of overall volume. 'Dry' sintering begins |
| 900° upwards | Recrystallisation begins |
| 950° upwards | Sintering helped by liquid. Contraction. Vitrification begins. Any micas present are dehydroxylised |
| 1000° upwards | Mullite begins to appear |
| 1050° upwards | Micas decomposing to mullite and liquid |
| 1150° upwards | Cristobalite begins to crystallise from the liberated silica. Mullite increasing in quantity and crystal size. Liquid increasing in quantity |
| 1200° to 1300° | Vitrification complete. Cristobalite and other free silica progressively dissolving in the liquid. All the alumina has now either become mullite or joined the liquid phase |

| °C | *Cooling* |
|---|---|
| 1300° to 1000° | Body is pyroplastic |
| 1000° to 15° | Body is a solid |
| 700° to 600° (variable) | Annealing range of glaze, i.e. glaze is in a plastic state |
| 600° to 15° | Glaze is a solid |
| 573° | Any remaining quartz has β–α change |
| 270° to 200° | Cristobalite has β–α change |

**Mullite** ($3Al_2O_3 \cdot 2SiO_2$) is a constituent of ceramics, and high-temperature insulating and refractory materials.

Cardew, M. *Pioneer Pottery.* 3rd ed., St. Martin's Press, 1969.

- Sintering occurs at temperatures less than $T_m$ because of the reactive nature (atomic diffusion) of fine particles (-200 μm (sand, silt, clay)) that are in close contact. In general, smaller particles with asperities (sharp morphology) tend to sinter more easily than larger particles.
- Resulting microstructure can be quite complex.
- Brick formation requires a capital and energy intensive kiln. Rule of thumb—markets should be < 500 miles from site.

# Option 4: Paste Backfill

- Paste Backfill (or Cemented Paste Backfill) involves using mill tailings to fill (and reinforce) underground mine cavities.
- The use of paste backfill has become more commonplace and emerged as a viable option for tailings disposal in the mid-1990s. Its adoption requires understanding and control of paste rheology (avoid pipeline clogging).
- The solids (flocculated tailings and solid chemical additions) are typically 70-85 wt%, with water representing 15-30 wt% of the paste. (paste is a non-Newtonian fluid)
- Common additions to the paste include cement and a plasticizer.

# Option 4: Paste Backfill

- Cement (e.g., Ordinary Portland Cement) addition (~3-7 wt%) serves as a paste binder, and after curing gives structural integrity to the final product (avoid liquefaction, encapsulate leachable sulfides).
- Cement as a binder opens the door to possible ancillary additions such as plasticizers (polycarboxylates) and superplasticizers to control rheology, reduce amount of cement and adjust curing time.
- Cement accounts for ~75-80% of backfilling cost. Lower cost pozzolanic additions such as fly ash and slag are often considered to reduce cost.

# Option 4: Paste Backfill

- Other considerations include careful control over the thickener solid/liquid ratio, and control of tailings particle size.
- Rule of thumb—at least 15% of the fines should be -20 μm (silt/clays), aids in flow behavior. However, excessive fines leads to higher cement consumption.
- The capital costs of a paste plant and pumping can be quite significant.
- Technology is most easily implemented in green field operations (allows simultaneous design of thickening/paste systems).

# Option 5: Shotcrete

- Shotcrete involves using dry ingredients (cement, sand, aggregates) with compressed air and the addition of water just before the mixture impacts a reinforced (e.g., rebar) wall surface.
- The shotcrete flows around a reinforced wall and cures in place to give the wall added structural integrity.
- Tailings have been investigated to replace the fine aggregate component in the shotcrete.
- The tailings composition (e.g., sulfides) and size distribution can negatively impact shotcrete performance, and requires careful consideration with shotcrete mix design.

# Option 6: Dry Stacking

- Dry Stacking technology emerged in the 2000s.
- Rather than using just thickening large-scale vacuum and pressure filters are used to dewater tailings (allows greater water reclamation and reuse compared to thickening).
- Modern vacuum and pressure filters are quite accommodating of tailings that have a wide particle size distribution (including high 'clay' content).
- The tailings filter cake (~80-85 wt% solids, 50-75 %, ($V_w/V_v$ x100% saturation)) that can be transported (conveyer, truck) and 'dry' stacked to give above ground geotechnical support.

# Option 6: Dry Stacking

- Geotechnical concerns include: liner under stack, stack shear strength, stack height, resistance to liquefaction, drainage, water seepage (leaching of sulfides).
- The dry stacked tailings are often covered with native soils and vegetation.
- Some underground operations use a combination of paste back filling and dry stacking to accommodate both above and below ground operations.

**Angloamerican La Coipa, Chile**

# Some Secondary Options

- Extenders (Cu tailings) in paints (imparts strength).
- Pigments (Fe tailings) in paints (imparts color).
- Stone paper (fine ground calcium carbonate (~80 wt%) heated (~100 - 200$^{o}$C) with ~18% of high-density polyethylene) can form an eco-friendly paper.
- What keeps tailings from being used for some applications??
  - Drying/heating (e.g., sintering of ceramics) costs
  - Transportation costs
  - Mining waste regulations
  - Lack of innovation, awareness

# Future Consideration: Bricks

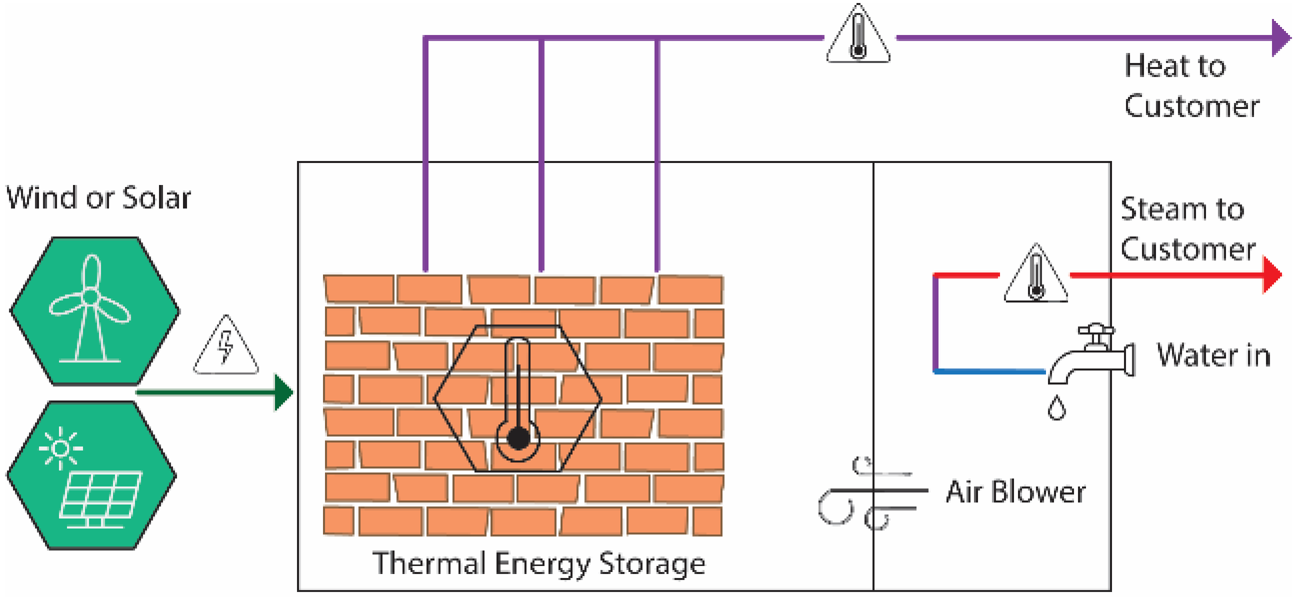
> Prior to 1900, brick plants were in nearly all of the towns along the Missouri River and in the Black Hills region. These used local material. As soon as cheaper lumber became generally available, these companies shut down.

- Bricks used to be a primary construction material. Perhaps it is time to reconsider their utility (e.g., low-cost housing in remote locations, adjacent mining operations).
- A big challenge with brick processing is that worldwide coal is used to fire kilns----accounts for ~500 x $10^6$ tons of $CO_{2(g)}$ emissions (1% of global emissions).

**Solar Powered Kiln**

# Future Consideration: Bricks

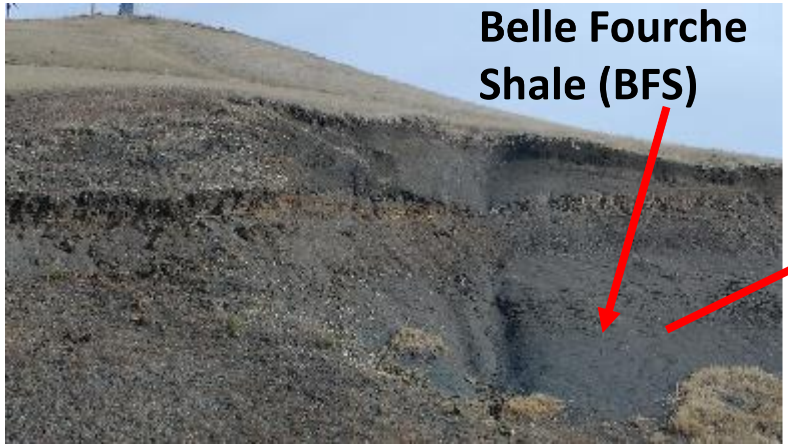
- Bricks might have an addition important use---thermal energy storage (bricks serve as a heat battery).




- **Rondo Thermal Energy Storage:** https://www.rondo.com
- **Brenmiller Thermal Energy Storage**: [https://bren-energy.com/](https://bren-energy.com/)

# Future Consideration: Indigenous and Local Materials

- Local deposits (e.g., mine site shales etc.) might have value as an amendment material such as a natural pozzolan for paste backfill.
- Other secondary sources such as waste paper and glass might be useful amendment materials (e.g., Rapid City, SD).

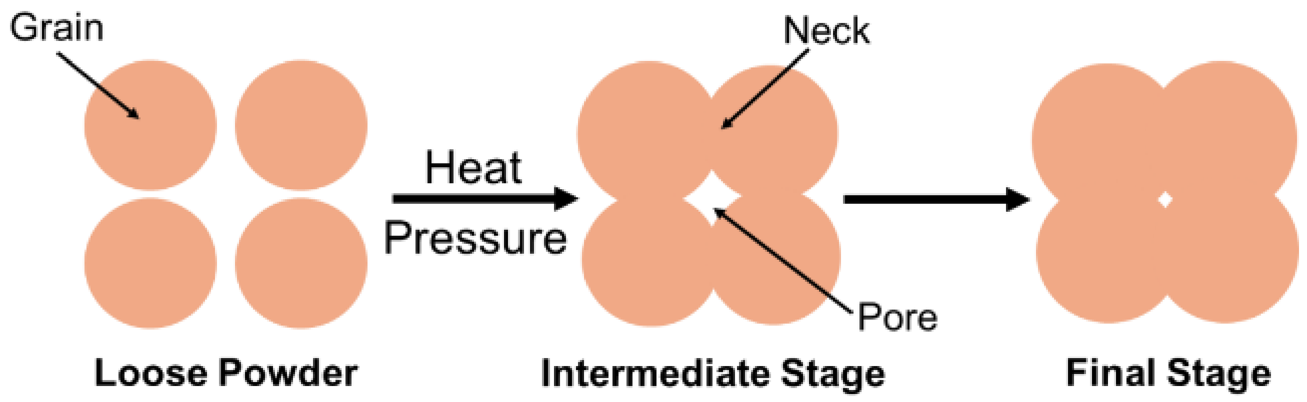




# Future Consideration: Cold Sintering

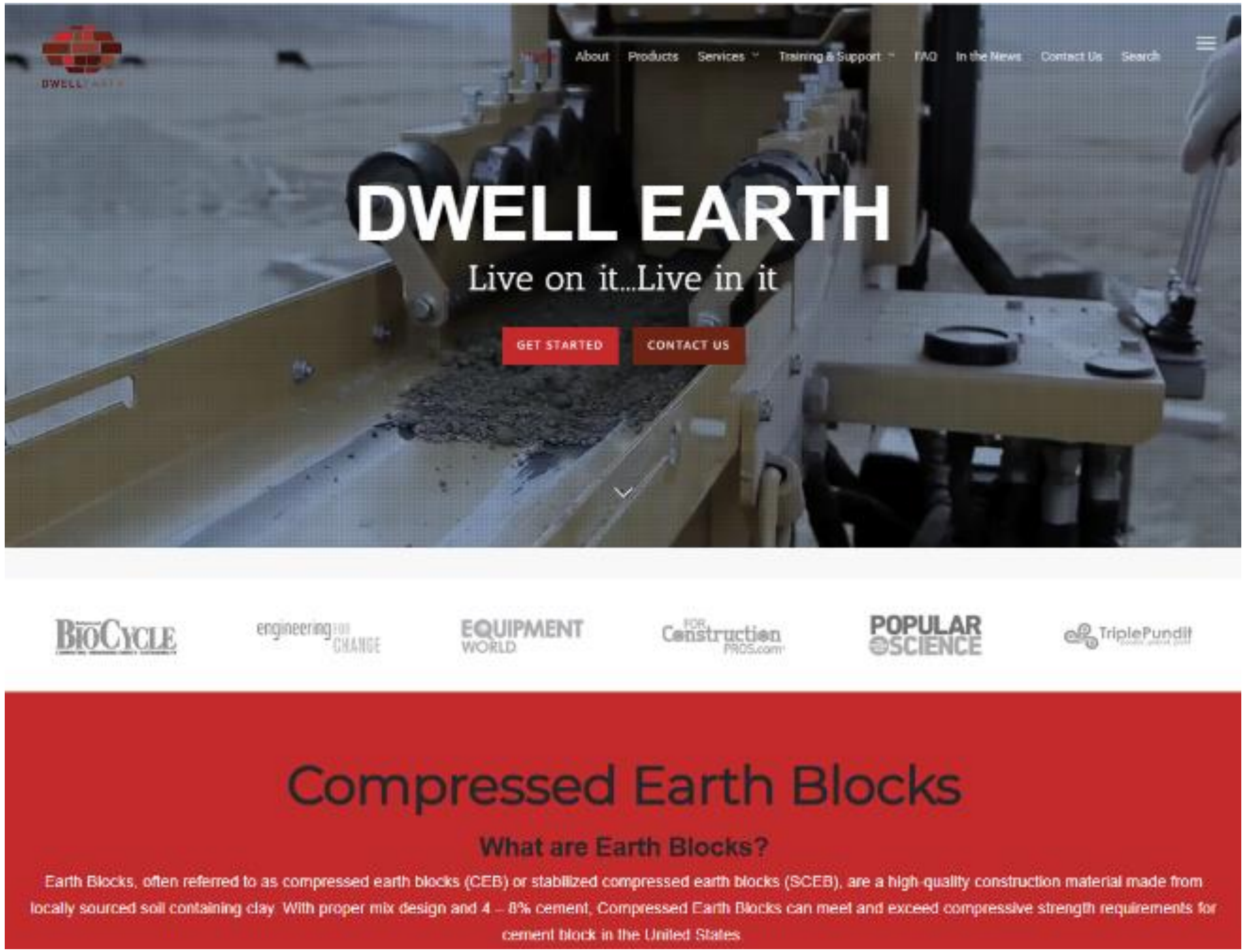
- Many of the disposal/reuse options require cement (+1300ºC processing) or high temperatures (sintering, 1000ºC).
- Low temperature processing or reduction in cement would reduce unwanted gas production (e.g., $CO_2$, $SO_2$).
- 'Cold Sintering' might offer an alternative processing route (proof of concept, limestone, Belle Fourche Shale).

**Cold Sintering** - Fusing powdered material at a relatively low temperature (< 400°C) and pressure in the presence of a transient liquid that aids in the dissolution/precipitation process.




# Future Consideration: Compressed Earth Blocks

- Compressed Earth Blocks (CEBs)?
- Kit supplied—to allow you to determine if your soil composition (need clay) and particle size are adequate to produce CEBs.
- If your soil is adequate add 4-8% cement and press the brick (at room temperature).




https://dwellearth.com/

# Conclusions

- Mill tailings are both a tremendous waste product and a tremendous potential resource.
- Processing options are quite varied (beneficiation, cement, ceramics, paste backfill, shotcrete, dry stacking), and highly dependent upon the original ore body from which the tailings are derived.
- Future opportunities for tailings processing include use of indigenous materials, secondary waste sources and cold sintering.

# Selected References


- Grasso, Salvatore, et al. "A Review of Cold Sintering Processes." *Advances in Applied Ceramics* 119.3 (2020): 115-143.
- Tailings Info. La Coipa, Region III, Chile South America, https://www.tailings.info/casestudies/lacoipa.htm
- United States Geological Survey, “Belle Fourche Shale”, https://mrdata.usgs.gov/geology/state/sgmc-unit.php?unit=SDKb%3B0
- Kessinger, S., Green, K., Petersen, J., and Kellar, J. J. (2023). Characterization, Processing and Performance of Belle Fourche Shale for Ceramics. *Mining, Metallurgy & Exploration*, *40*(5), 1631-1638.
- Thrift, C., Stuber, B., Petersen, J., Jin, J. and Kellar, J. J. (to appear 2025). Amending and Processing Indigenous Shale for Improved Ceramic Performance.
- The Brick Industry Association: Technical Notes on Brick Construction, 2006, www.gobrick.com
- Lupo, J, and Hall, J., Dry Stack Tailings—Design Considerations, AMEC Earth and Environmental, Englewood, CO.
- Davies, M., Filtered Dry Stacked Tailings—The Fundamentals. Proceedings Tailings and Mine Waste 2011, Vancouver, BC, 2011.
- Yowa, G.G., Influence of Pozzolans and Plasticizer on the Performance of Paste Backfill in Underground Mines, M.S. Thesis, Geotechnical Engineering, James Cook University, 2020.
- Rondo Thermal Energy Storage: https://www.rondo.com
- Brenmiller Thermal Energy Storage:  https://bren-energy.com/

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