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Characterisation of the geomechanical properties of cemented paste backfill for design

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Abstract

This paper documents an investigation that has been conducted into the influence of pulp solids and cement content on the unconfined compressive strength (UCS), modulus and tensile strength of cemented paste backfill. A laboratory testing program has been conducted that includes in excess of 500 tests to provide a series of relationships that consider:

1. *Pulp solids to provide density values*
2. *Binder contents to provide UCS values*
3. *UCS values to provide laboratory and in situ modulus values*
4. *UCS values to provide direct tension values.*

In relation to the modulus, existing literature has been used to relate laboratory-scale tests to field-scale values that are able to account for the enhanced mixing during placement underground, higher in situ curing temperatures and consolidation within the stope due to the increasing overlying fill mass during curing (Thompson et al. 2012). Direct tension values have been measured directly via a bespoke method that has been modified based on a technique outlined in Guo et al. (2022) and Pan & Grabinsky (2021). While there are many studies that propose relationships for cemented paste backfill that characterise density, UCS and modulus, none are completed on such an extensive database or provide direct tension values over such a broad range. The relationships presented provide guidance for pre-feasibility or optimisation studies associated with cemented paste backfill.

Keywords: *cemented paste backfill, geomechanical testing, direct tension, modulus, unconfined compressive strength*

1 Introduction

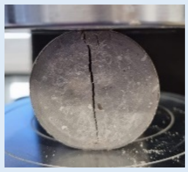
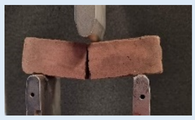
Due to the unique nature of each mine site, the characteristics of cemented paste backfill (CPB) may vary significantly between operations due to tailings mineralogical and mechanical properties, particle size distribution, length of reticulation circuits, pressure difference between the surface batch plant and underground point of placement, size of excavations and sequence of exposure. As such, batch design and optimisation studies should consider both strength and rheology. However, during pre-feasibility or optimisation studies associated with CPB, a comprehensive laboratory testing program is not always achievable due to limited access to filter cake and time and cost considerations. This paper documents a mechanical laboratory testing program conducted on a range of CPB that include variations in pulp solids content and binder content to relate the outcomes to strength and stiffness properties. These relationships can be used to help identify design parameters that can be optimised in the laboratory.

In general, slump can be managed through the addition of super-plasticisers that are commonly included to increase pulp solids (strength) while maintaining a suitable slump (Yang et al. 2018; Zhang et al. 2018). No additives have been used in this study.

2 Laboratory testing

CPB samples were mixed in small-scale batches in the laboratory using a commercial 9L Apuro Planetary mixer. Upon placement in their moulds, they were individually sealed and cured under zero effective stress at a temperature of 23° and minimum humidity of 50% for 28–29 days. Samples were tested based on the standards provided in Table 1. A loading rate of 0.5 mm/min was applied to each sample to induce failure.

Table 1 Summary of applied testing standards

Test	Standard	Specimen dimensions	Specimen
Unconfined compression strength	ISRM Suggested Method for the Complete Stress-Strain Curve for Intact Rock in Uniaxial Compression (Fairhurst & Hudson 1999)	50 mm diameter 100 mm height	
Splitting tensile strength	SM for Determining the Tensile Strength of Rock Materials (ISRM 2007)	50 mm diameter	
Flexure/three-point bending	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) (ASTM International 2015)	40 mm width 120 mm length	
Direct tension strength	A New Method for Direct Tensile Testing of Concrete. Journal of Testing and Evaluation – modified after (Alhussainy et al. 2019)	25 mm diameter 50 mm height[1]	

[1] Length of neck and not entire sample – see Figure 5

2.1 Density

CPB is comprised of filter cake, water, binder and air. To be considered CPB and not hydraulic fill, CPB has a higher solids content and uses the full mill tailings particle size distribution (Slade 2010). The density of CPB samples tested in the laboratory has been calculated based on the volume of the sample and its weight prior to testing after 28 days curing. The density can be directly related to pulp solids which is a measure of the total solids (filter cake and binder) within the paste mix, as shown in Figure 1.

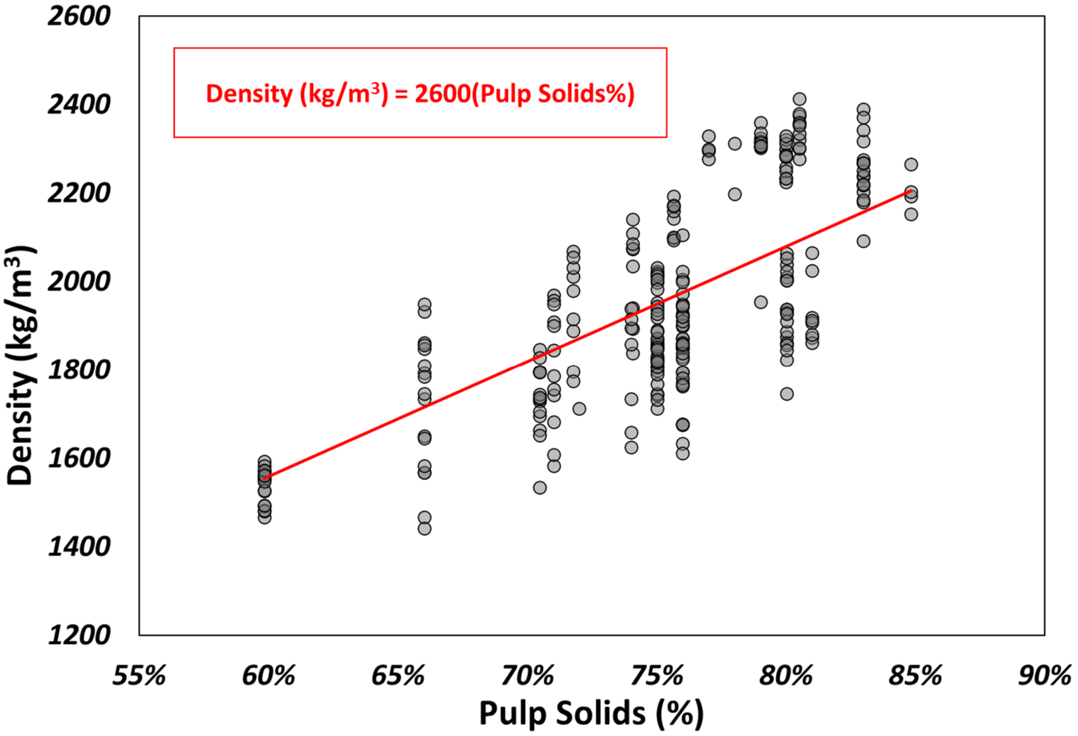


Figure 1 Relationship between pulp solids and density based on laboratory testing results

The relationship between pulp solids and density after 28 days curing is described by Equation 1:

$$Density\ (\text{kg/m3}) = 2{,}600\ (pulp\ solids\ \%) \tag{1}$$

where pulp solids include the binder and filter cake proportions and is expressed in decimal % (e.g. 0.6 = 60%) according to Equation 2:

$$Pulp\ Solids(\%) = \frac{Binder(kg) + Dry\ Tailings(kg)}{Binder(kg) + DryTailings(kg) + Water(kg)} \tag{2}$$

The accurate characterisation of the density of a CPB is important since it will influence the stresses within the stope. It is also understood that the density of CPB may change during curing due to the hydration and drainage conditions within individual stopes.

2.2 Unconfined compressive strength

The characterisation of the mechanical strength response of CPB is usually designated by its unconfined compressive strength (UCS) since this value is specified from exposure stability analyses (Sainsbury & Urie 2007) and can be measured easily onsite for quality assurance and control (Johnson et al. 2015; Le Roux et al. 2005). The UCS can be directly related to binder content through Figure 2 and the relationship presented in Equation 3.

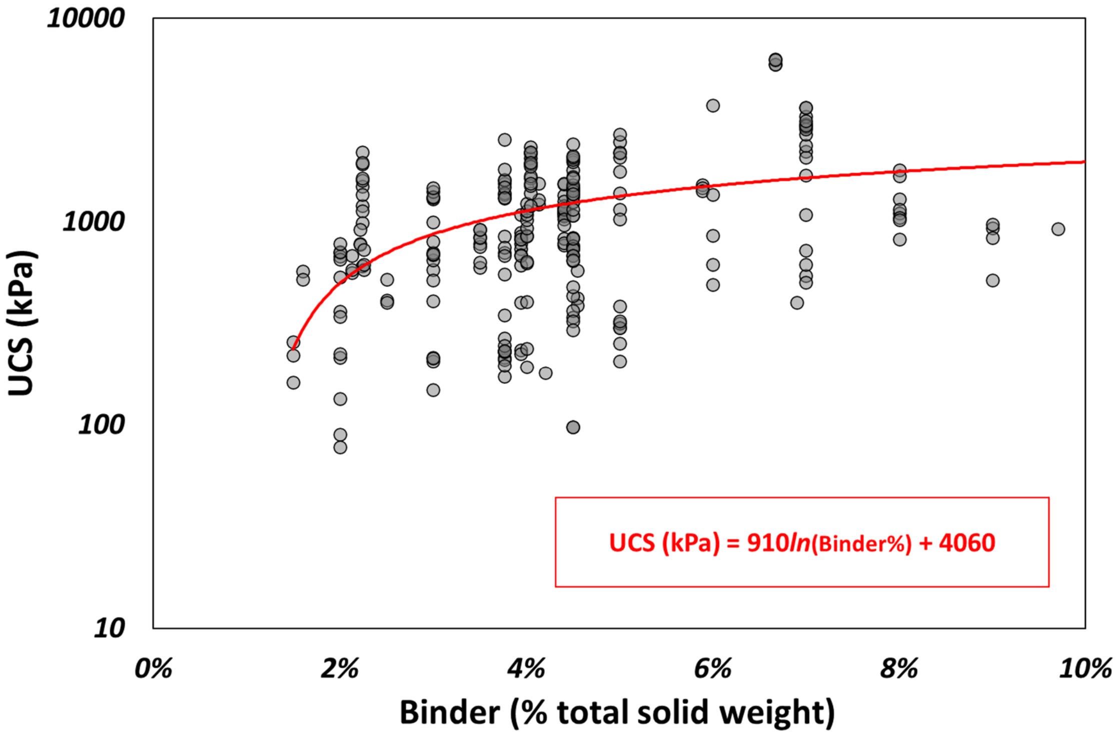


Figure 2 Relationship between binder and UCS

$$UCS\ (kPa) = 910\ln(Binder\%) + 4060 \quad (3)$$

The binders considered in this study include slag, fly ash and Portland cement. No additives have been used to enhance the strength. The UCS is utilised to determine cohesion and friction values and an indicator the tensile strength of the CPB.

2.3 Elastic modulus

Many operations using CPB have moved away from the concept of a high strength 'plug' and low strength fill mass body. Because paste becomes stiffer and more brittle with increasing strength, a high strength plug can often yield and crack under minor rock mass convergence well before a softer, more ductile paste (Figure 3). Closure strains reported at various mining operations range from 5–15% (Grabinsky et al. 2022). In these instances, a typical 8 m high 'plug' is still normally required as a means to limit the horizontal pressure applied to the barricades, but this does not need to have a strength greater than what is required for short-term vertical exposure.

Figure 3 Example of damage to stiff cemented paste backfill due to moderate drive closure

The modulus of the CPB has been determined in the laboratory via two traditional techniques (Tangent 50% and Secant 100%) and presented in Figure 4. In situ results are also presented that have been compiled based on data from published sources (Raffaldi et al. 2019; Le Roux et al. 2005; Seymour et al. 2017; Williams et al. 2001). A relationship with the UCS is proposed for each modulus value and is presented in Equations 4, 5 and 6.

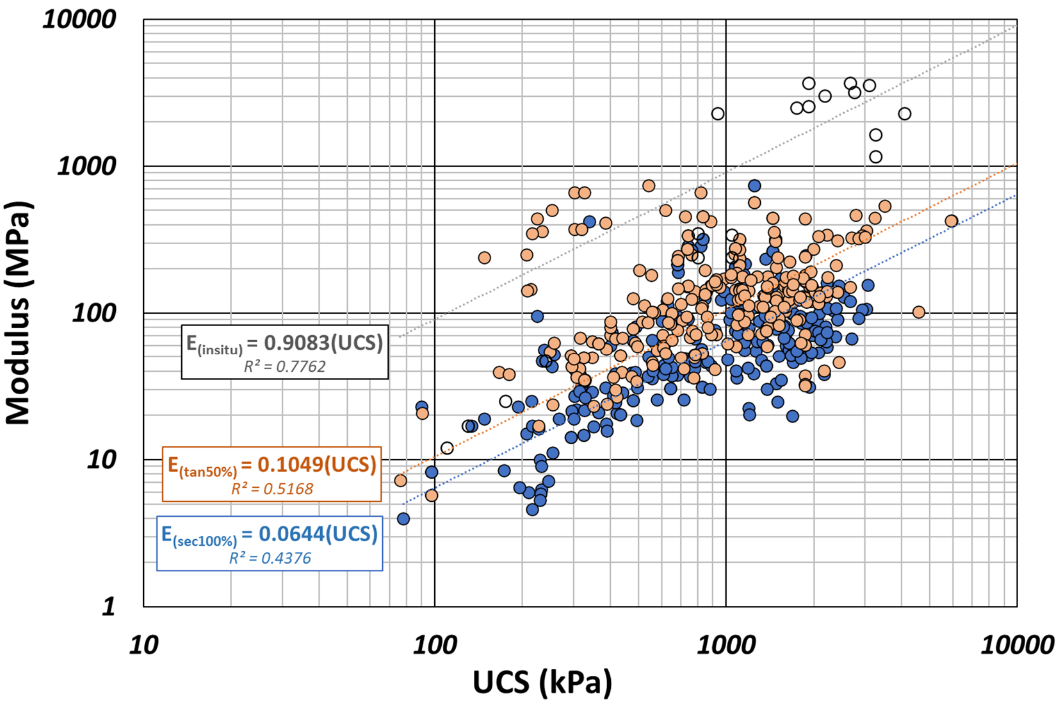


Figure 4 Relationship between unconfined compressive strength (UCS) and modulus. In situ results are compiled based on data from published sources (Raffaldi et al. 2019; Le Roux et al. 2005; Seymour et al. 2017; Williams et al. 2001)

$$E_{(sec100\%)} = 0.0644(\text{UCS}) \quad (4)$$

$$E_{(tan50\%)} = 0.1049(\text{UCS}) \quad (5)$$

$$E_{insitu} = 0.9083(\text{UCS}) \quad (6)$$

where E is determined in MPa and UCS is defined by kPa.

When the laboratory measured values are compared to field determined values for the same UCS, it is observed that the laboratory values are 7–12% (secant and tangent, respectively) the field measured values. The greater in situ modulus when compared to laboratory measured modulus has previously been attributed to due to enhanced mixing underground, higher curing temperatures, consolidation within the stope by (Thompson et al. 2012).

2.4 Tension

Tension responses of brittle materials are routinely measured using three-and-four point bending, Brazilian splitting and direct tension testing (Chen et al. 2014). Both the bending and splitting tests are easy to perform but provide indirect measurements of tension and are shown to provide responses that do not match with direct tension results at UCS strengths (Pan & Grabinsky 2023). Previous studies have shown that these indirect tension measurements overestimate the true values by 120–300% (Jones & Sainsbury 2023; Packulak et al. 2022). As such, the direct tension test is the most obvious measurement method, but they are difficult to perform through conventional approaches (ISRM 2007) due to the varying performance of bonding agents and delicate nature of CPB specimens. For this reason, few studies have been completed that measure the direct tensile strength test of CPB (Grabinsky et al. 2022; Pan & Grabinsky 2023).

To quantify the variance in the results of each of the tension testing procedures (splitting, bending, direct), a series of samples have been conducted on the same CPB batch mixes for comparison.

The direct tension response has been established based on the direct measurement procedure documented by Guo et al. (2022) and Pan & Grabinsky (2021). Moulds, modified after Alhussainy et al. (2019), have been printed in a Fortus 450mc production system with front and back pieces cut from 2 mm perspex to provide transparency. A bespoke tension bracket has been utilised to load the sample as presented in Figure 5.

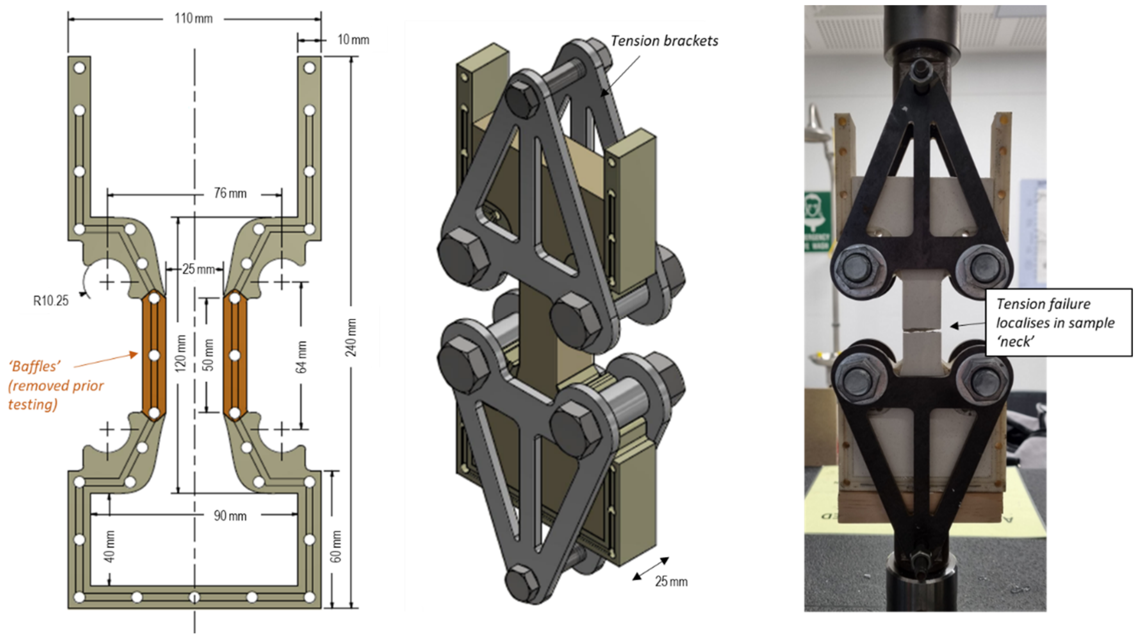


Figure 5 Direct tension mould assemblage and application

The results of the direct and indirect (splitting and bending) tension testing on CPB are provided in Figure 6.

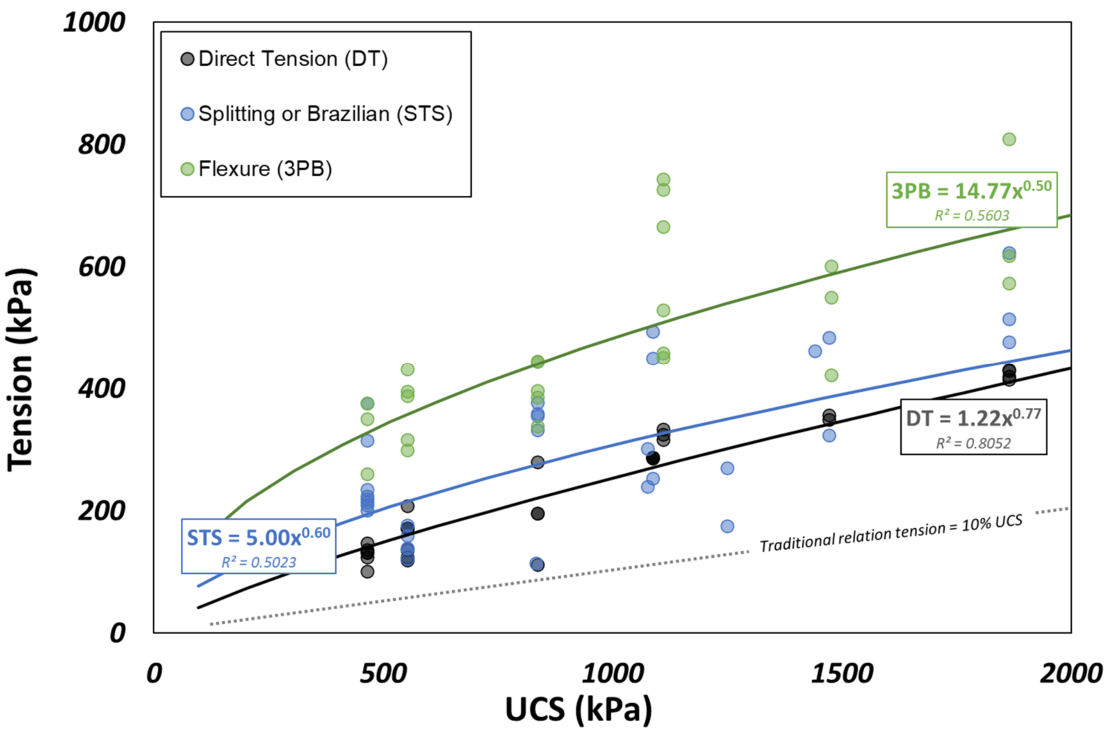


Figure 6 Comparison of measured direct and indirect tension values cemented paste backfill with a measured UCS less than 2 MPa

The measured direct tension values are lower than both the indirect measured values. The direct tension relationship with UCS is proposed and presented in Equation 7.

$$Direct\ tension\ = 1.22(\mathrm{UCS})^{0.77} \tag{7}$$

The relationship with UCS for all the measured tension values are significantly greater than those reported for rock ~10% the UCS (Jones & Sainsbury 2023).

While bending and splitting test method may be appropriate for stronger and stiffer geo-materials, the results suggest a changing mode of failure in the indirect methods at this low (2 MPa) strength.

The differences in the tension results are a product of the testing environments:

- In less stiff materials, a splitting sample is prone to deformation (compression) prior to failure. As the sample deforms (flattens), the sample is no longer subjected to a point load and the surface area in contact with the loading ram is increased. The increase in the surface area of the loading area on the sample no longer reflects a splitting/tensile failure mechanism (Figure 7a).
- Immediately at the point of loading in a three-point bending experiment, a less stiff material is prone to deformation (compression). Since geo-materials usually exhibit a higher compressive strength than tension strength, the method no longer reflects a purely tensile mechanism. Furthermore, in less stiff geo-materials, the sample may be prone to sagging prior to rupture. Both of these geometrical changes in the sample affect the dimensional values of L and d in the flexural strength equation that are not accounted for (Figure 7b).

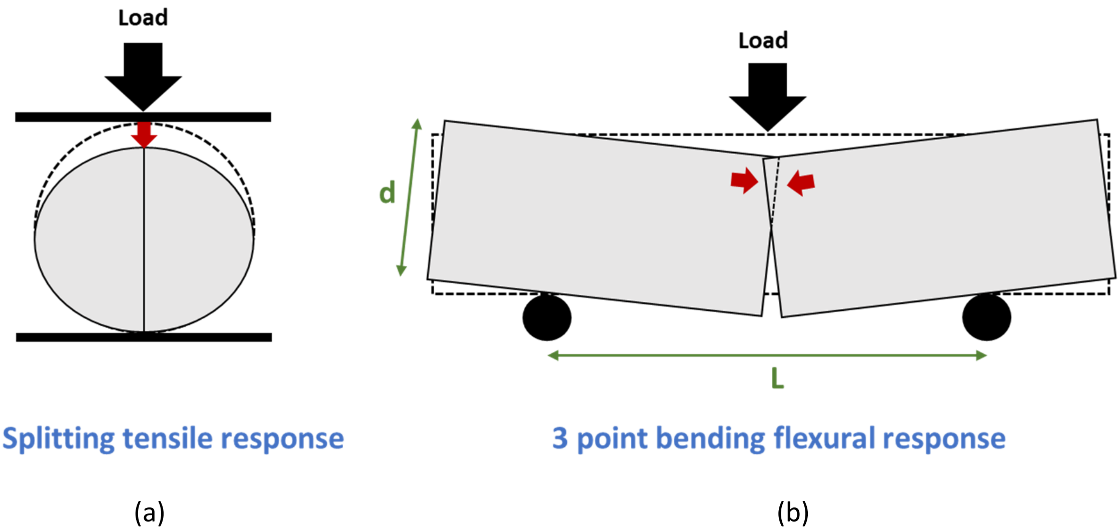


Figure 7 Comparison of the failure modes associated with direct and indirect tension test methods

While the average of the splitting tensile strength results is only marginally greater than the direct tension results, significant scatter in the splitting tensile strength is observed which suggests it is not a reliable method for tension at these low stiffness and strengths. Flexure strength results are more consistent but clearly overestimate the strength and cannot be considered a reliable measure of direct tension unless a correction factor is applied. Pan & Grabinsky (2023) also note that the ratio of the direct tension:UCS also changes during curing. Younger age samples usually provide higher tension:UCS ratios.

3 Conclusion

The relationships for CPB presented in this paper are in no way definite but provide some guidance on the selection of paste properties in lieu of geomechanical laboratory testing. The relationships provide a link between solid content and binder addition in relation to density and UCS. The UCS can be used to determine strength and stiffness parameters for exposure stability analyses (and vice versa). Of note is the relationship between the laboratory derived and in situ modulus values. The presentation of the tension testing results provide a basis for the selection of an appropriate testing method and the outcome that applying rock-related empirical relationships to CPB (e.g. tension = 10% UCS) may be under-estimating the response of the material and require unnecessary additional binder addition. The measurement of bending and splitting responses of CPB does not reflect a true tensile strength response.

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