

Paste fill stiffness investigation

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SUMMARY: When conducting a backfill test campaign based on the selected mining method, there are various types of tests that are usually conducted to understand the in-situ behaviour of the material when placed underground. The unconfined compressive strength (UCS) and modulus of elasticity are the two most commonly measured parameters when dealing with a cemented paste fill material. However, when dealing with complex ore bodies or extraction techniques, additional testing, including triaxial and consolidation can be required to better understand the material's behaviour when exposed to a sustained ground load. This is of particular interest in yielding or closing ground conditions. The modulus of elasticity results, measured by conducting a UCS test, provides information on the strength of the material and the ability to resist deformation under load when the fill is exposed vertically and horizontally. However, when dealing with long term stability and support, it is important to understand the stiffness of the material and how it will resist deformation when exposed to different loading conditions when confined.

This paper will present selected triaxial and consolidation test data for a range of material blends, considerations that defined the testing program, and the nature of the tests performed. Conclusions will be presented as to the significance of the selected testing methodologies on the results obtained and their applications for industry.

Keywords: unconfined compressive strength, triaxial, backfill, modulus of elasticity and modulus of stiffness

1 INTRODUCTION

Before commencing with a backfill test campaign, it is important to understand how the backfill will be used and how it should perform. Key to the selection of a backfill type, other than the well established commercial drivers, is an understanding of how the material is required, or expected to behave within the proposed mining method or application. It is also important to develop a material testing program to support the engineering and project development process. Such a program must give consideration to the material available for backfill, the mining methodology and the anticipated ground conditions, including the development of vertical and/or horizontal ground stresses that may influence the backfill, and against which the backfill performance specifications must be developed.

The data presented within this paper are derived from a large, multi-phased test work program undertaken by Paterson & Cooke in its Cape Town laboratory. The project requirements for backfill included:

- Bulk mining extraction methods,
- High ore body extraction ratios,

Table 1. Test matrix.

Number	Constituted mixture	Concentration	Water/Cement ratio	Cement addition
1.1	75SN/25TA	75%/m	4.76/1	7%
2.1	60SN/40TA	71%/m	5.83/1	7%
3.1	60SN/20TA/20TB	76%/m	4.51/1	7%
3.2	50SN/30TA/20TB	74%/m	5.02/1	7%
4.1	50SN/40TA/10TB	72%/m	5.56/1	7%
4.2	40SN/40TA/20TB	71%/m	5.83/1	7%
5.1	60SN/20TAC/20TB	81%/m	3.35/1	7%
5.2	60SN/5TA/15TAC/20TB	80%/m	3.57/1	7%
5.3	60SN/10TA/10TAC/20TB	79%/m	3.81/1	7%

- Modest mining horizons extending up to 800 m below surface, and
- A rockmass with a tendency for convergence or closure.

As a consequence of the above project conditions, it was necessary to investigate a backfill not only with a target strength, but also a target stiffness, and indeed the stiffness target predicated the backfill strength specification, it being the more onerous condition. The anticipated sustained vertical and horizontal loading forecasts for the project indicated a target stiffness in the order of 100 MPa.

The project was able to consider a number of component backfill products, including two tailings types and an imported sand product. Further more, the option to cyclone one of the tailings products was also available for consideration. In order for the test work program to adequately investigate and develop a backfill product to meet these criteria, the following tests were considered for this test program:

1. Material properties tests,
2. Rheology tests,
3. Unconfined compressive strength and modulus of elasticity tests,
4. One-dimensional consolidation testing and
5. Unconsolidated-Undrained triaxial tests.

1.1 Test matrix

Table 1 presents the test matrix and mix reference. The following abbreviations are used:

- SN: Sand
- TA: Tailings A
- TAC: Tailings A Cycloned
- TB: Tailings B

Development of this test matrix followed a number of previous test campaigns which enabled iteration and refinement of the mix designs towards attaining the target specification.

2 MATERIAL PROPERTIES TESTS

2.1 Solids density

The solids density of the samples was determined using a helium pycnometer, which measures the skeletal solids density. Table 2 presents the measured solids densities.

Table 2. Solids densities.

Sample reference	Solids density (kg/m ³)
Tailings A	2654
Tailings A cycloned	2641
Sand	2753
Tailings B	2495
Cement	3015

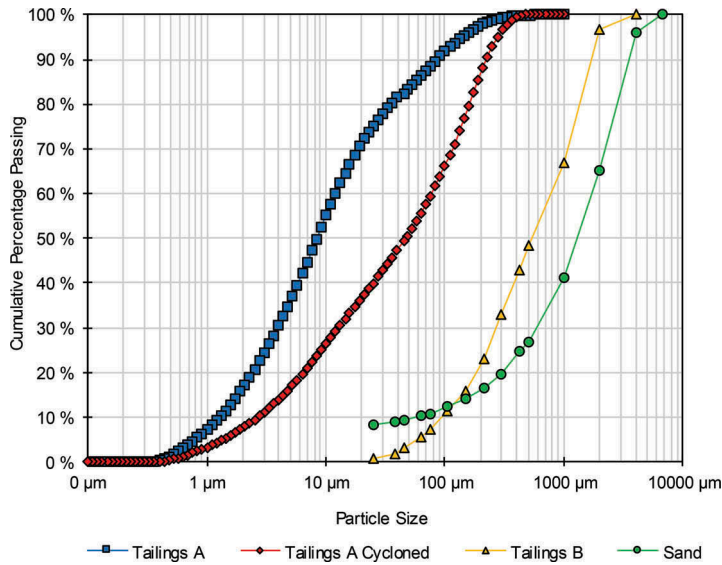


Figure 1. Particle size distributions.

2.2 Particle size distributions

The particle size distributions (PSD) of the as-received materials were determined by wet sieving and laser diffraction. Figure 1 presents the measured PSD data.

2.3 Cement quality

A CEM III/B 32.5 N cement was supplied for the test work. Before commencing with the test work, cement mortar tests, according to EN 196-1:2005 Edition 2, were carried out to determine the quality of the cement. The 28-day results showed a compression strength of 34.8 MPa which exceeds the minimum required compressive strength of 32.5 MPa indicating that the cement complied with the standard requirements.

3 RHEOLOGY TESTS

An Anton Paar Rheolab QC rotational viscometer was used for the test work. The slurries were tested and analysed according to the infinite bob and cup method described by Chhabra & Richardson (1999). The data were analysed by applying the Bingham plastic model which is a two-parameter model describing the slurry rheology.

Figure 2 shows the rheogram for the various mixes. The data show that the yield stress varies from ~120 to ~260 Pa for the various constituted mixes.

4 UNCONFINED COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY TESTS

4.1 Cement addition and water/cement ratio

The percentage cement addition and water/cement ratio are calculated using the following formulas:

$$\text{Percentage cement} = \frac{\text{mass of cement}}{\text{mass of solids} + \text{mass of cement}} \quad (1)$$

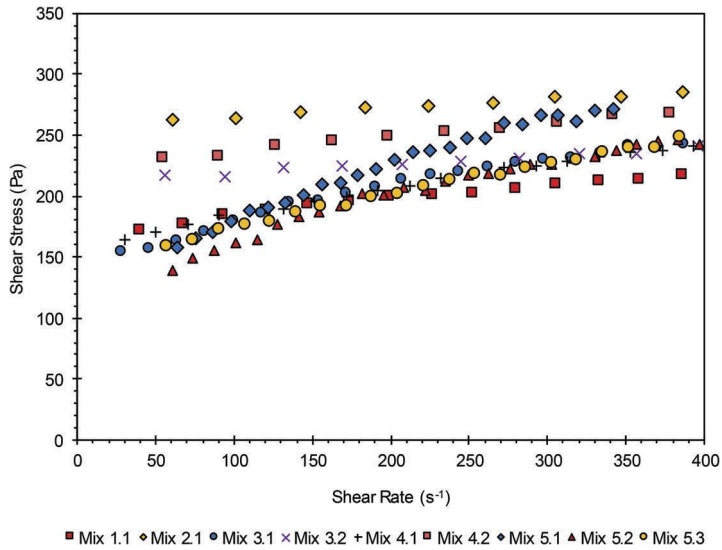


Figure 2. Rheogram for Mixes 1.1 to 5.3.

$$\text{Water : Cement Ratio} = \frac{\text{mass of water}}{\text{mass of cement}} \quad (2)$$

4.2 Test results

Table 3 shows a summary of the w/c ratio at which the mixes were constituted, the cylinder (fill) density, the UCS and the modulus of elasticity. Figure 3 shows the UCS and modulus of elasticity test results versus the constituted mixtures. The data show that the mixes with a w/c ratio lower than 5/1, yield the highest results in terms of UCS and modulus of elasticity. Also evident from the data is that the proportionality between UCS and modulus of elasticity is not uniform, confirming the assertion that the different material blends, and importantly, the associated changes in overall particle size distribution of the final mixture, influence the geomechanical response of the backfill.

Table 3. UCS and modulus of elasticity test results.

Mix Number	Water/Cement Ratio	Cylinder Density (kg/m ³)	28 Day UCS (kPa)	28 Day Modulus of Elasticity (MPa) ¹
1.1	4.76/1	1927	2212	341
2.1	5.83/1	1845	2067	333
3.1	4.51/1	1923	2369	140
3.2	5.02/1	1859	2686	327
4.1	5.56/1	1712	1085	84
4.2	5.83/1	1786	1696	119
5.1	3.35/1	2024	3025	366
5.2	3.57/1	2009	2928	336
5.3	3.81/1	1955	2851	322

¹Secant modulus based on 25 and 75% of UCS.

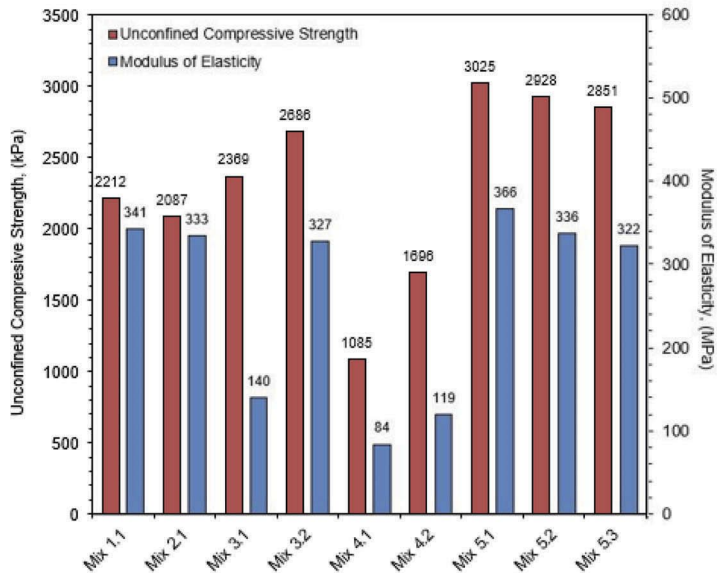


Figure 3. Unconfined compressive strength and modulus of elasticity vs mix number.

5 ONE-DIMENSIONAL CONSOLIDATION TESTS

One-dimensional consolidation tests are conducted at axial loading pressures ranging from 10 to 25000 kPa to simulated ground load conditions which is based on the mining plan. For this particular test work program, the maximum axial load considered was 6400 kPa. Figure 4 and Figure 5 show the axial stress versus axial strain and void ratio versus axial stress respectively. The axial stress versus axial strain data indicates that the voids are compressed up to an axial stress of 800 kPa. This is evident as an exponential increase in the stress versus strain is seen, where a more linear relationship is seen at axial stress values above 800 kPa.

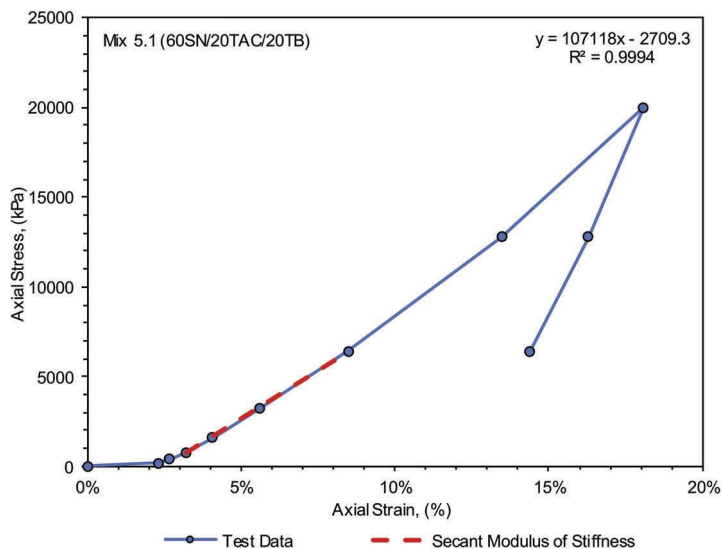


Figure 4. Axial Stress vs Axial Strain for Mix 5.1.

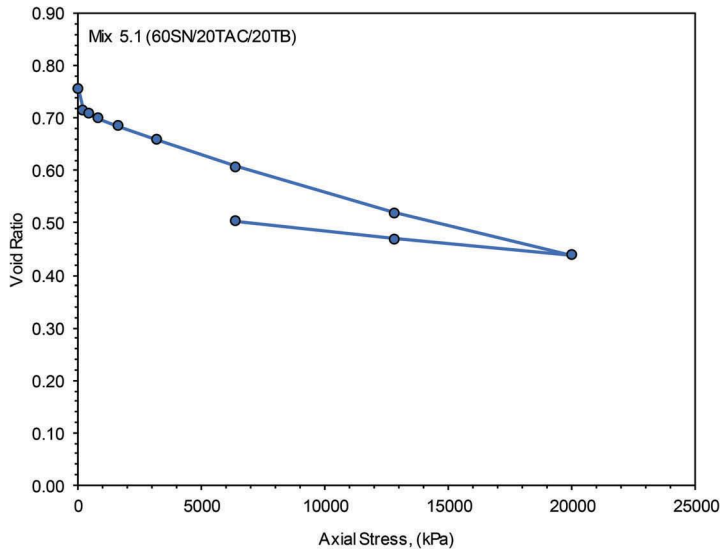


Figure 5. Void Ratio vs Axial Stress for Mix 5.1.

Table 4. Secant modulus of stiffness results.

Mix Reference	Water/Cement Ratio	Axial Stress Range (kPa)	Secant Modulus of Stiffness (MPa)
1.1	4.76/1	800 – 6400	59
2.1	5.83/1		54
3.1	4.51/1		69
3.2	5.02/1		67
4.1	5.56/1		36
4.2	5.83/1		46
5.1	3.35/1		107
5.2	3.57/1		106
5.3	3.81/1		92

Table 4 and Figure 6 show the average modulus of stiffness results for each mixture, with Figure 7 showing the change in void ratio at different axial loads for each mixture. As seen from the UCS and modulus of elasticity test results, the lower the water/cement ratio and subsequent denser fill, the higher the starting void ratio which results in a higher modulus of stiffness.

6 UNCONSOLIDATED-UNDRAINED TRIAXIAL TESTS

Table 5 and Figure 8 present the unconsolidated-undrained triaxial results. Mix series 3 and 5 yield the highest results in terms of effective cohesion, thus aligning with the UCS results presented earlier. The effective angle of friction varied from 18° at the lowest to 39° at the highest.

7 CONCLUSIONS

This paper presents the results of a series of tests conducted using various blends of materials in order to determine the mixture with the highest modulus of stiffness. The main conclusions are as follows:

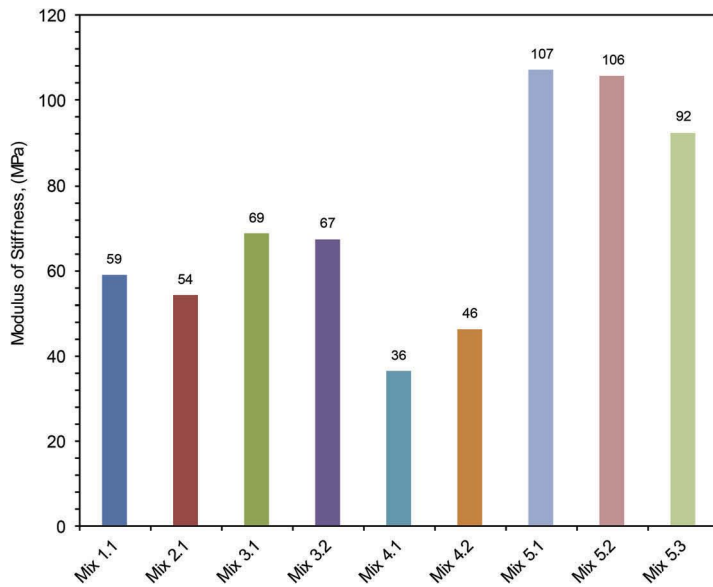


Figure 6. Modulus of stiffness vs mix number.

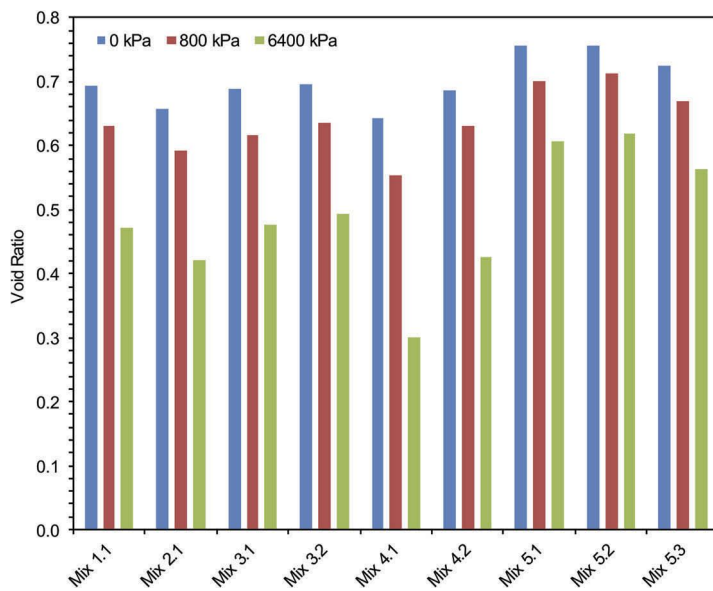


Figure 7. Change in void ratio at different axial loads vs mix number.

1. Before commencing with any test work, it is important to understand what type of mining plan is to be used and what the purpose of the backfill should be, as well as how the host rock will behave under loading conditions. Once this has been established, the test work program should be developed to measure the required parameters in order to ensure that the backfill will meet the requirements. These parameters can vary from the UCS and

Table 5. Unconsolidated-undrained triaxial test results.

Mix Reference	Water/Cement Ratio	Effective Cohesion c'	Effective Angle of Friction ϕ'
1.1	4.76/1	680 kPa	26.5°
2.1	5.83/1	710 kPa	18.0°
3.1	4.51/1	850 kPa	24.5°
3.2	5.02/1	835 kPa	23.0°
4.1	5.56/1	223 kPa	29.0°
4.2	5.83/1	487 kPa	29.0°
5.1	3.35/1	658 kPa	37.0°
5.2	3.57/1	804 kPa	33.0°
5.3	3.81/1	820 kPa	31.0°

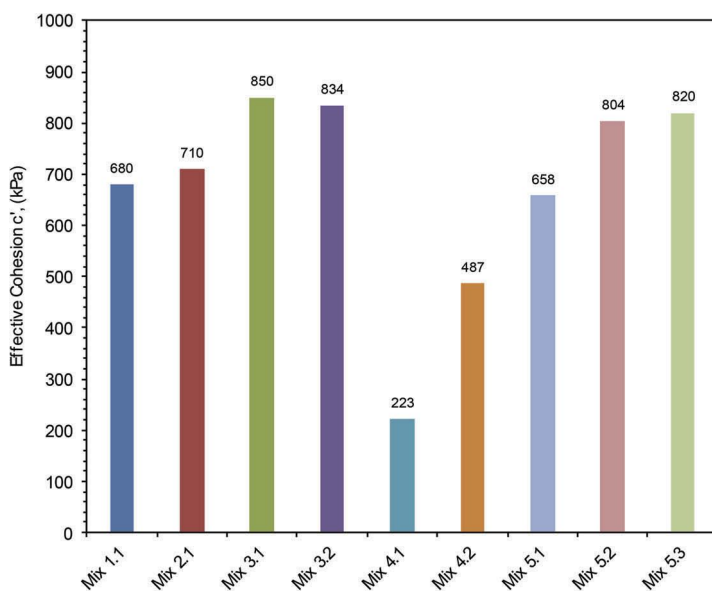


Figure 8. Effective cohesion versus mix number.

- modulus of elasticity (understand how the backfill will behave when vertically exposed) to the modulus of stiffness (long term stability and support).
- The tests data indicated that the mix series five yielded the highest results in terms of UCS, modulus of elasticity and modulus of stiffness. The starting void ratios for these mixes were above 0.7 where all the other mixes were below 0.7. At an axial load of 6400 kPa, the void ratios for these mixes were only compressed to above 0.55, where all the others were compressed to below 0.50.
 - The unconsolidated-undrained triaxial test results indicated that very similar effective cohesion results were measured for the majority of the mixes, except for mix series four. Mix series five had the highest effective angle of friction of above 31° compared to the other mixes where effective angles of friction of 29° and lower were recorded.

Overall the test work program sought to obtain a mix design that could deliver a stiffness in excess of 100MPa. Through the test work program, the data were able to substantiate that mix series 5 provided the best opportunity to attain this, and it is notable that this mixture contained the lowest fines content and returned the highest in-situ density of all the mixes prepared.

ACKNOWLEDGEMENT

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