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Recovered Carbon Black (rCB) as a sustainable alternative to traditional stabilisers: A comparative study on stabilisation of highly expansive subgrade soil

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ABSTRACT: Expansive soil is prevalent in more than 60 countries worldwide and poses a significant challenge to pavement and geotechnical engineers. Although various treatment methods have been developed and implemented with varying success rates, road agencies tend to apply chemical or combined chemical and mechanical treatments to minimise costs while increasing effectiveness. Lime and cement, with or without flyash, are identified as traditional stabilisers among road agencies worldwide. Recently, in Australia, especially in Queensland, triple blend (lime, cement, and flyash mix) stabilisation has become popular due to its proven success in expansive subgrade stabilisation. However, with growing global emphasis on sustainability and the shortage issues associated with these traditional stabilisers, exploring the reutilization of waste materials and industrial byproducts as alternatives has emerged as a popular research topic. Recovered Carbon Black (rCB) is a solid powdered product that is obtained through the pyrolysis process of end-of-life tyres. This study evaluated the performance of rCB as an alternative expansive subgrade stabilising material, aiming to address issues associated with chemical stabilisers and the rising environmental challenges posed by increasing tyre waste. To achieve the aforementioned objectives, highly expansive soil was stabilised with 6%, 10%, 14%, and 20% rCB mix proportions and tested for both soaked and unsoaked CBR, CBR swell, linear shrinkage, and constant volume swell pressure tests. Then, the experimental results were compared with the untreated test soil and with soil stabilised using lime, cement, and a triple blend in proportions of 6%, 10%, and 14%. All experimental results revealed significant improvements in rCB-stabilised expansive soil in terms of both strength and swell characteristics. Findings of this study suggested that utilising more than 14% of rCB can lead to better performance.

KEYWORDS: Expansive soil, Recovered carbon black, Swelling pressure, Subgrade stabilisation, Sustainability.

1 INTRODUCTION

Expansive soil is prevalent in more than 60 countries across all continents and poses significant damage to civil engineering structures due to seasonal variations in soil moisture that occur at shallow depths, typically up to 2-4 meters below ground level (Gedara and Udukumburage, 2024; Gallage *et al.*, 2024). The damage mechanism is termed cyclic shrink-swell movement. During the wet season, these soils expand in volume, while in the dry season they shrink back, and this cycle continues with the season change. The problem is more common in arid and semi-arid climatic regions, where frequent extreme wet and dry seasons occur, and higher evaporation rates are recorded than precipitation (Dushmantha *et al.*, 2025b; Jayalath *et al.*, 2024; Holland and Richards, 1982).

Lightweight structures, such as shallow foundations, irrigation structures, pavements, culverts, and shallow buried pipes, are highly vulnerable because they lack sufficient loads to counteract the swelling pressure exerted by the ground on which they are built (Klompmaker *et al.*, 2024). Expansive soil-related damages are associated with substantial financial losses, with estimated annual costs exceeding $15 billion in both the United States and China, and £400 million in the United Kingdom (Li *et al.*, 2014). It is well known that the rehabilitation costs of expansive soil damage exceed those of all other natural disasters combined.

Road infrastructures are more susceptible to this issue than any other type of infrastructure, especially pavements (Chan *et al.*, 2016; Dushmantha *et al.*, 2025a). The main reason is that the entire structure is directly exposed to all climatic interactions, and the stabilisation and/or construction of thick and wide pavement structures are not cost-effective for road authorities due to the higher land footprint, limited access to high-quality materials, a variable success rate of stabilisation methods, and climate change, among other factors (Udukumburage *et al.*, 2018; Gallage *et al.*, 2012). The most common damage mode to pavements is longitudinal cracks along the pavement edges, particularly beginning near the shoulders and subsequently appearing in the middle of the pavement with time (Gallage *et al.*, 2017). When these cracks appear, moisture infiltrates through these cracks, and all the pavement layers degrade exponentially, reducing the service life to only a few years (Dushmantha and Gallage, 2025; Dushmantha *et al.*, 2024; Gui *et al.*, 2022).

From the beginning of the 1950s, researchers, including pavement and geotechnical engineering professionals, explored various innovative design and stabilisation techniques to mitigate the expansive subgrade induced damages (Maheepala *et al.*, 2022; Ranasinghe *et al.*, 2025). As shown in Figure 1, the available subgrade stabilisation methods can be classified into three main categories. Mechanical methods primarily focus on physical soil modification without altering soil chemistry, while moisture methods aim to minimise soil moisture fluctuations and reduce subsequent volume changes (Fondjo *et al.*, 2021). Chemical and other material stabilisation methods are employed to modify soil composition and bind soil particles together, thereby increasing strength to counteract swelling pressure and reducing the swelling pressure of the stabilised subgrade layer itself. Lime, cement, and fly ash have been used as traditional stabilisers for several decades worldwide, although concerns have been raised regarding their scarcity and sustainability (Indraratna *et al.*, 2025). Furthermore, it is a well-known practice to apply different treatment types simultaneously to reduce costs and increase effectiveness. However, road authorities are still struggling with variable success rates across projects sharing similar conditions, highlighting the complexity of addressing the expansive soil problem.

Driven by increasing awareness of climate change and green philosophies, research on alternatives for traditional chemical stabilisers has increased rapidly over the past decade

(Gallage and Jayakody, 2023; Jayakody Arachchige *et al.*, 2012). Out of those efforts, the investigation of the potential use of waste materials from construction demolition, byproducts from various manufacturing industries, and giving a second life to end-of-life waste materials are most popular, as these options can simultaneously solve a series of environmental problems while improving expansive subgrades (Hung *et al.*, 2024; Clark *et al.*, 2018; Clark and Gallage, 2020). Recycled Concrete Aggregate (RCA), Ground Granulated Blast Furnace Slag (GBBS), plastic waste, burned sewage sludge, glass waste, and crumb rubber are only a few examples of non-traditional stabilisers (Indraratna *et al.*, 2025; Gallage and Jayakody, 2023). Although numerous studies have assessed the performance of waste material at the laboratory scale, only a limited number have advanced to field trials or large-scale construction applications.

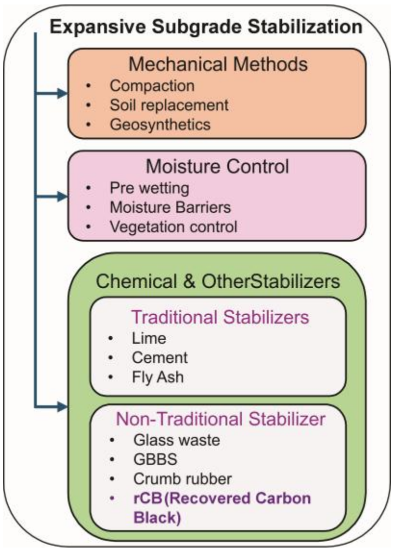

Figure 1. Expansive soil stabilisation methods.

The rapid development of the vehicle manufacturing industry has resulted in billions of tyres being produced annually, with a similar quantity being disposed of each year, creating significant environmental problems due to their non-degradability and bulkiness. These environmental issues, combined with the high availability of end-of-life tyres (ELT), have enabled the utilisation of tyre waste in meaningful applications, such as energy generation, and more recently, in the field of civil engineering.

Recovered carbon black (rCB) in powdered form is one of the primary materials obtained from end-of-life tyres (ELT) through the pyrolysis process, as illustrated in Figure 2. Other byproducts of this process include steel wires, pyrolytic gas, and oil. rCB is commonly used as a filler material in industries such as rubber, plastic, bitumen, and ink (Costa *et al.*, 2022; Norris *et al.*, 2023). Furthermore, increasing tyre waste and the advancement of pyrolysis technologies have enabled the use of rCB for civil engineering applications such as sustainable concrete production (Abdulfattah *et al.*, 2022), as an alternative to natural aggregate in asphalt production (Casado-Barrasa *et al.*, 2019), and as a stabilising material to improve weak subgrades (Kumar *et al.*, 2019). However, minimal studies have evaluated the suitability of rCB for expansive subgrade stabilisation. The performance of rCB in stabilising expansive subgrade soils, specifically in terms of one-dimensional swelling and unconfined compressive strength, was previously evaluated at the laboratory scale by Gedara *et al.* (2025).

Motivated by recent advancements in rCB production and growing sustainability concerns, this study evaluated the effectiveness of rCB as a sustainable alternative to traditional stabilisers currently used in Queensland, Australia. Accordingly, a comprehensive series of California Bearing Ratio (CBR) tests, swell pressure tests, and linear shrinkage tests were conducted on highly expansive soil treated with varying proportions of rCB, lime, cement, and a Triple Blend (TB) mixture comprising lime, cement, and fly ash (L:C:F).

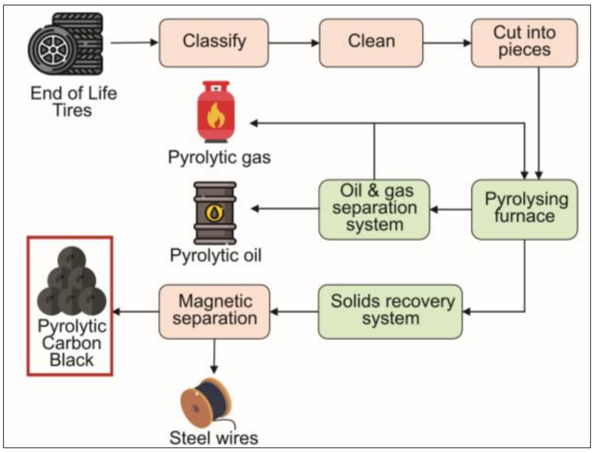

Figure 2. ELT pyrolysis process.

2 MATERIALS

The study used soil material from a pavement rehabilitation project site in the Toowoomba Region, Queensland, Australia. The soil properties are presented in the Table 1, while the particle size distribution curve is illustrated in Figure 3. According to the current Queensland guidelines, in line with the Austroads guidelines (Department of Transport and Main Roads, 2021a) the test soil is classified into the very highly expansive soil category.

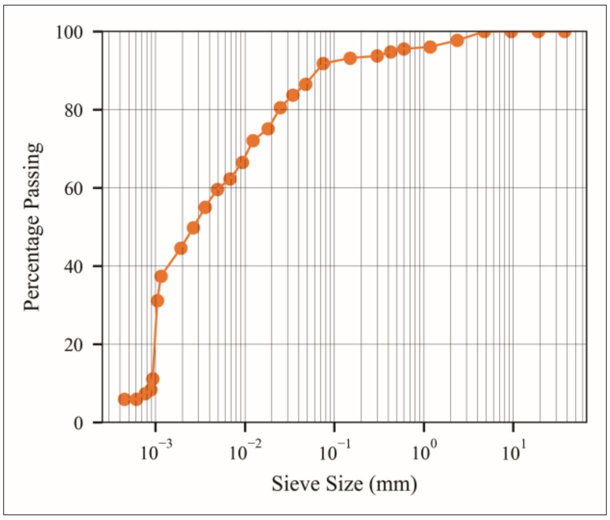

Figure 3. Particle size distribution curve of the test soil

As the key objective of this study is to evaluate the performance of rCB, commercially available rCB powder was used, with its properties and elemental composition detailed in Table 2 and Table 3, respectively. For comparison, commercially available hydrated lime [$Ca(OH)_2$] and general-purpose (GP) cement were also employed as conventional stabilisers. Additionally, a Triple Blend (TB) mixture comprising hydrated lime, cement, and fly ash in a 40:30:30 ratio was used as an alternative stabilising agent, as suggested by Queensland guidelines (Department of Transport and Main Roads, 2021b). The physical state of all four stabilisers used for the study is shown in Figure 4.

Table 1. Properties of the test soil

Parameter	Symbol	Value	Unit
Liquid limit	*LL*	105.3%	-
Plastic limit	*PL*	45.6%	-
Plasticity index	*PI*	59.7%	-
% Passing 0.425mm	-	94.8%	-
% Passing 75µm	-	91.8%	-
Weighted plasticity index	*WPI*	4503	
Linear shrinkage	-	25%	-
Free swell index	*FSI*	120%	-
Specific gravity	*SG*	2.62	-
Optimum moisture content	*OMC*	37.1%	-
Maximum dry density	*MDD*	1.253	g/cm^3
CBR swell (4-day, 4.5 Kg)	-	5.4%	-
CBR soaked (4 day, OMC & 97%MDD)	-	1.5%	-
CBR unsoaked (OMC & 97%MDD)	-	8.2%	-

Table 2. Properties of rCB

Property	Value
Specific Gravity	1.7 – 1.9
pH	6.7
Physical state	Dusty powder
Oduor	None to slight
Toxicology	Not determined

Table 3. Main elements and components of rCB (June, 2025)

Element	C	Na	Al	Si	S	K	Ca	Ti	Zn	Pb
Wt.%	93.56	0.36	0.16	2.34	1.41	0.07	0.11	0.12	1.78	0.09

3 EXPERIMENTAL PROGRAM

In this study, very high expansive soil was stabilised by four stabilisers, rCB, lime, cement, and TB, with different additive ratios. A comprehensive test series was performed, as tabulated in Table 4 to understand and assess the effect of rCB for minimising expansive behaviour.

Figure 4. Additives (a) rCB, (b) hydrated lime, (c)cement, and (d) TB

3.1 *CBR test series*

The CBR test series was conducted on expansive soil samples without stabilisers and those stabilised with rCB at mixing ratios of 6%, 10%, 14%, and 20%. CBR test was conducted following AS 1289.6.1.1:2014 (Standard Australia, 2017) to evaluate the strength improvement and 1-D swell reduction of soil stabilised by the rCB at both wet and dry conditions. The samples were prepared at 97%MDD and OMC as per the direction given in the QDTMR pavement design supplement (Department of Transport and Main Roads, 2021a). Accordingly, unsoaked CBR, soaked CBR and CBR swell tests were conducted for only five samples as listed in the Table 4. CBR soaked, and CBR swell tests were conducted simultaneously by the same sample at the end of the 4-day soaking period under 4.5kg of surcharge load.

Table 4. Experimental program

Additive Ratio	CBR Test (Soaked & Unsoaked)	CBR Swell Test	Linear Shrinkage Test	Swell Pressure Test
No additives	✓	✓	✓	✓
6% rCB	✓	✓	✓	✓
10% rCB	✓	✓	✓	✓
14% rCB	✓	✓	✓	✓
20% rCB	✓	✓	✓	✓
6% Lime	X	X	✓	✓
10% Lime	X	X	✓	✓
14% Lime	X	X	✓	✓
6% TB	X	X	✓	✓
10% TB	X	X	✓	✓
14% TB	X	X	✓	✓
6% Cement	X	X	✓	✓
10% Cement	X	X	✓	✓
14% Cement	X	X	✓	✓

3.2 *Linear shrinkage test series*

To assess the improvement of soil shrinkage due to stabilisation with additives, a linear shrinkage test series was conducted following the AS 1289.3.4.1:2008 (Standard Australia, 2008). Accordingly, linear shrinkage tests were conducted on fourteen samples as listed in the Table 4. 250 mm-long half-cylindrical moulds were used, and oven drying was performed on the samples after air drying.

3.3 *Swell pressure test series*

Several oedometer-based 1-D swell and swell pressure tests have been developed to assess the swelling potential of expansive soil, as well as to obtain design parameters required for pavement design (Udukumburage *et al.*, 2019; Udukumburage *et al.*, 2020). Swelling pressure is one of the key parameters that can be used to assess the improvement of any stabilised soil against the untreated soil. There are two types of swell pressure tests widely performed using the oedometers, namely the constant volume swell pressure test (CV) and the consolidation swell pressure test (CS) (Jayalath *et al.*, 2017; Nelson *et al.*, 2015). CV swell pressure test is performed by measuring the swell pressure required to maintain the inundated sample at a constant volume until the maximum swell pressure is reached. At this point, no further significant changes are observed. The CS swell pressure test involved allowing the sample to swell under a given inundation stress, then gradually increasing the load to return the sample to its initial position.

Since the ultimate goal of subgrade stabilisation in pavement design is to achieve a condition of zero movement, also referred to as a constant volume (CV) state, this study conducted CV swell pressure tests to compare the effectiveness of rCB with that of conventional stabilisers. Accordingly, 14 samples were tested following the ASTM D4546 test method C (ASTM, 2003). Sample tested at OMC, MDD, and inundation stress of 10 kPa. Tests continued for 3 days until the maximum swell pressure was reached. The oedometer apparatus is shown in Figure 5. The oedometer ring is 63.5 mm in diameter and 25.5 mm in height.

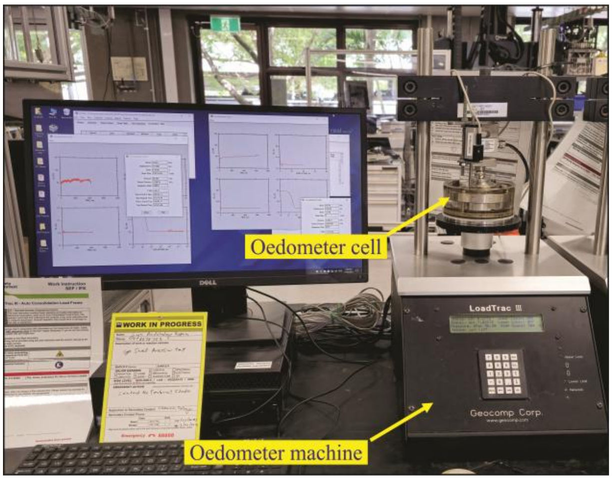

Figure 5. Oedometer test setup

4 RESULTS AND DISCUSSION

4.1 *CBR test series*

Comparison of CBR swell, soaked and unsoaked CBR results of rCB stabilised soils is shown in the Figure 6. Soaked CBR results exhibit a notable increase compared to the untreated sample, and the increasing trend is progressive with the rCB content increase. This trend can be attributed to the lower strength reduction of rCB under wet conditions compared to untreated expansive soil. Specifically, the sample stabilised with 6% rCB showed a 40% increase in soaked CBR, while the 20% rCB stabilised sample demonstrated a 127% improvement.

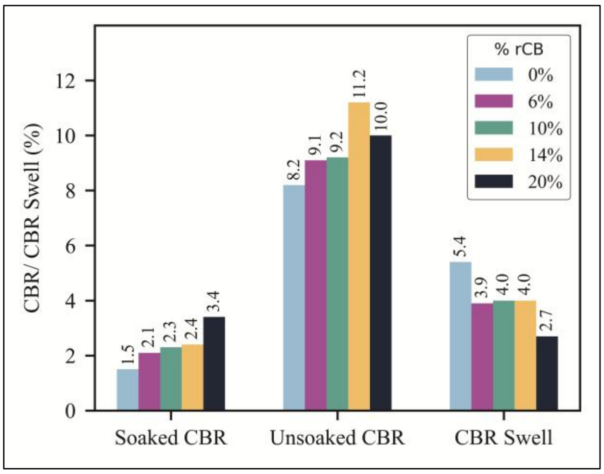

Figure 6. CBR and CBR swell test results

In contrast, the unsoaked CBR results showed relatively modest gains. The 6% and 20% rCB mixes recorded increases of only 11% and 22%, respectively. Interestingly, the peak unsoaked CBR was observed at 14% rCB content, showing a 60% improvement over the untreated soil, after which the strength declined. This reduction beyond 14% may be due to a shift in the particle size distribution (PSD) toward a finer gradation, which could negatively affect compaction and strength. Up to this point, the fine rCB particles may have enhanced the PSD and packing behaviour of the soil rCB mixture.

Furthermore, the 4-day CBR swell test results indicate about 4% swell for rCB-stabilised samples at 6%, 10%, and 14% rCB contents, which is only a slight reduction compared to the untreated sample with 5.4% swell. However, at 20% rCB content, the swell was significantly reduced by approximately 50% relative to the untreated value, indicating that higher rCB content offers significant improvements in swell control.

4.2 *Linear shrinkage test series*

Linear shrinkage results are shown in Figure 7, with the untreated soil exhibiting a significantly higher value of approximately 25%. All four additives, rCB, lime, cement, and TB, demonstrated a reduction in linear shrinkage with increasing mixing ratios. Notably, lime and cement achieved significant improvements, reducing shrinkage to below 5% at just 6% additive content. In contrast, rCB and TB resulted in shrinkage values of 17.2% and 10.4%, respectively, at the same mixing ratio.

However, results indicate that rCB was less effective at mitigating linear shrinkage than the other three stabilisers. Even at 20% rCB content, the linear shrinkage remained at 14%, which was still higher than the values achieved with just 6% of lime, cement, or TB. Among all additives, TB demonstrated the most pronounced reduction in shrinkage at higher mix proportions, reaching as low as 0.1% at a 14% mix ratio, outperforming both lime and cement at the same proportion.

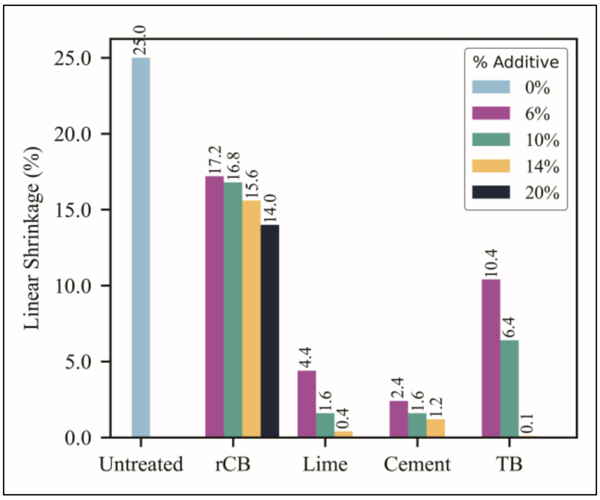

Figure 7. Linear shrinkage test results

4.3 *CV swell Pressure Test Series*

The results of the CV swell pressure tests for samples treated with rCB and TB over a three-day testing period are presented in Figure 8 and Figure 9, respectively. As shown in Figure 8, the swell pressure of both untreated and rCB-treated samples reached their peak on the first day and remained relatively stable thereafter, indicating minimal variation over time.

In contrast, Figure 9 illustrates a different behaviour for TB-stabilised samples. These specimens reached their initial peak swell pressure more rapidly and then gradually approached the inundation stress threshold of 10 kPa. This behaviour is attributed to the ongoing pozzolanic reactions enhanced by the presence of water, which contribute to continued strength development over time. Furthermore, once the swell pressure approached 10 kPa of inundation stress, the samples began to consolidate, resulting in a gradual volume reduction. Similar trends were also observed in samples stabilised with lime and cement-stabilised samples.

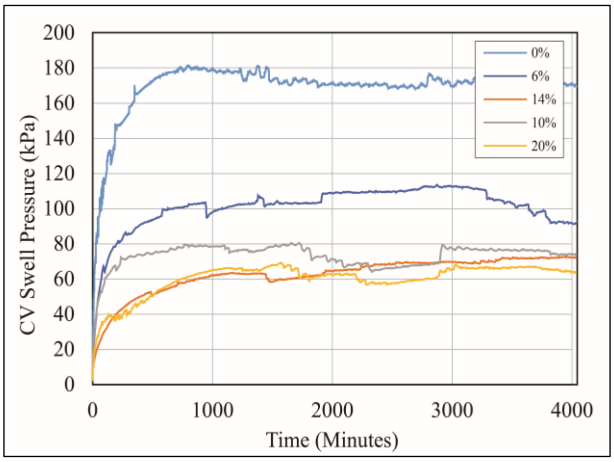

Figure 8. CV swell pressure test results of samples stabilised by rCB

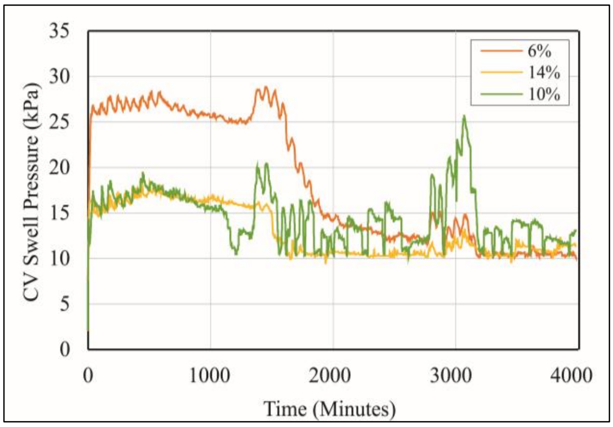

Figure 9. CV swell pressure test results of samples stabilised by TB

The maximum pressure recorded during the CV test for each specimen was taken as its CV swell pressure. A comparison of all four types of stabilisers is presented in Figure 10. Consistent with the trends observed in the CBR and linear shrinkage test results, the CV swell pressure decreased with increasing additive content for all stabilisers. In the 6% rCB treated sample, the swell pressure decreased to 113.4 kPa, representing a 38.3% reduction compared to the untreated soil. In contrast, the exact dosage of lime, cement, and TB achieved reductions exceeding 80%. rCB shows improved performance at higher dosages, particularly at levels above 10%. However, at 20% rCB content, the reduction reached only 62.5% relative to the untreated sample, remaining less effective than the traditional stabilisers.

5 ENVIRONMENTAL CONSIDERATIONS

Elemental analysis results in Table 3 clearly shows that rCB contains ~2% heavy metals (Zn, Pb) and 1.4% of sulphur compositions by weight. These elements are added during the tyre manufacturing process. Further, some studies discussed that rCB can contain carcinogenic polycyclic aromatic hydrocarbons (PAH) (Costa *et al.*, 2022). These are generally bound within the carbon matrix. Therefore, leaching under acidic or wet conditions could pose environmental concerns, such as potential contamination of surface water and groundwater. Especially areas with high rainfall or near water bodies. Furthermore, fine Particulate Matter (PMs) contained in the rCB can cause respiratory issues if not properly handled during field applications.

As rCB is relatively new in large-scale road construction, knowledge on its long-term performance, potential reuse of rCB-mixed soil, and environmental impacts is limited. Future investigations should focus on these critical aspects.

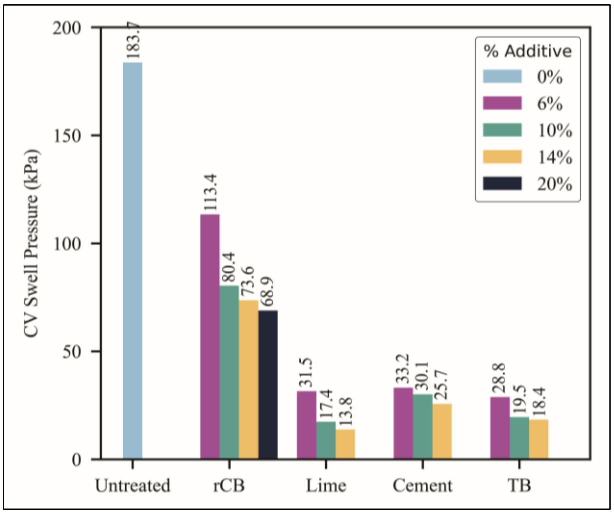

Figure 10. Summary of swell pressure test results

6 CONCLUSIONS

This study was undertaken to evaluate the potential of recovered carbon black (rCB) as a sustainable alternative for stabilising expansive subgrade soils, while also addressing the growing environmental issues of end-of-life tyre (ELT) waste. A comprehensive experimental program was conducted to assess the performance of rCB in comparison with traditional stabilisers: hydrated lime, cement, and a Triple Blend. Based on the findings of this study, the following conclusions can be drawn:

- There is a significant improvement in expansive soil stabilised with rCB, and performance increases with rCB content increases.
- rCB shows considerably lower performance compared to the traditional stabilisers. This observation can be attributed to the pozzolanic reaction of traditional stabilisers, while rCB is inert in reactions. Improvements in rCB samples are moreover due to the improvement of PSD and the replacement of expansive soil with inert materials.
- To achieve improved overall performance, rCB should be used at mixing ratios exceeding 14%.
- Further research is recommended to investigate the bonding mechanisms of rCB stabilisation through microscale analysis and evaluate the performance of soils treated with various combinations of rCB and traditional stabilisers.

7 ACKNOWLEDGEMENTS

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