

**Project Summary**  
**[Ground improvement using demolition wastes as semi-rigid inclusion columns]**



<b>Administration</b>	
Lead researcher	Dr. Farshid Maghool; Prof. Arul Arulrajah; Youli Lin (PhD candidate)
Contact details	fmaghool@swin.edu.au; aarulrajah@swin.edu.au; youlilin@swin.edu.au
University	Swinburne University of Technology
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The project team would also like to acknowledge the technical staff in the Advanced Geotechnical Laboratory and Smart Structural Laboratory (for their help with experimental testing), the Materials Research Laboratory (for their support on chemical and microstructure characterisation of samples), and the Workshop of Swinburne University of Technology for their professional assistance with the fabrication of steel mould for conducting the large-scale fully-instrumented prototype testing in this project.

## Abstract

This project systematically evaluated the suitability of using recycled concrete aggregate (RCA) as unbound and lightly-bound semi-rigid ground inclusion columns. To achieve this aim, extensive experimental studies and fully-instrumented prototype laboratory equipment were conducted and developed. Final findings compared the performance of the new product with the performance of the conventional natural granular materials used for the construction of ground inclusions to meet existing VicRoads specifications (target strength of 1.034 MPa of stabilised ground inclusion columns for ground improvement work). Geopolymers were used as low-carbon binders to produce novel semi-rigid inclusion columns aiming to improve the performance and mechanical properties of stone columns installed in highly plastic soils. Evaluation of semi-rigid column inclusions' strength with respect to different material compositions and curing conditions were carried out, and the optimal mixture design was proposed for such application. Characterisation of samples of various mixtures using optical and scanning electron microscopy to understand how the binding mechanism formed with the RCA and geopolymer binders. In addition, the behaviour and performance of the proposed semi-rigid inclusion column system were further examined under cyclic loading conditions to simulate the dynamic moving traffic loads imposed on the stone column system.

The experimental results demonstrated that RCA possesses comparable engineering properties to that of the conventional natural aggregates, and is qualified to be used in a wide range of geotechnical applications without any environmental impacts. Fly ash (FA) and ground granulated blast furnace slag (S)-based geopolymers are suitable low-carbon binders for stabilising RCA as semi-rigid inclusion columns for ground improvement work, and the optimal mixture design that meets the strength requirement is RCA + 5%(FA+S). The experimental results from cyclic loading tests evidenced that stabilising RCA by geopolymer as semi-rigid inclusion columns is a cost-effective and simple solution to improve the load-carrying capacity of the ground inclusion columns, and able to reduce the permanent strain of inclusion columns for more than 89.5% under cyclic loading as compared to conventional unbound stone column system. In addition, the fully-instrumented prototype test results demonstrated that stabilised semi-rigid inclusion column possesses a comparable drainage function to the conventional unbound stone column to dissipate the accumulated pore water pressure under loading conditions.

The usage of RCA as a natural aggregate substitution in stone column applications provides a feasible end-of-life option to transfer landfill waste into usable material. In view of the upcoming road and other infrastructure projects in Australia, the benefits from the cost and environmental savings from using RCA as ground inclusions in future projects are significant.

## 1. Industry Problem, Needs and Relevance

Natural aggregates are one of the predominant raw materials used in civil infrastructure projects. Over-exploitation and massive consumption of natural aggregate resources by the construction industry have depleted their reserves and skyrocketed their price. The ground improvement industry has been keen to explore substitution backfill materials due to the shortage of natural aggregate resources typically used to construct stone columns.

On the other hand, the generation of construction and demolition (C&D) wastes worldwide reached more than 3 billion tonnes annually until 2012, and RCA is the predominant stream of C&D waste (Akhtar et al. 2018). The increasing scarcity of natural resources and the soaring cost of waste disposal to landfills highlight the urgency of recycling and finding new ways to reuse RCA. Recycling and subsequent reuse of RCA will reduce the demand for scarce virgin natural resources as well as reduce the significant quantities of this waste material currently destined for landfill (Disfani et al. 2011).

In Australia, soft soils are widespread in the coastal region, with a typical undrained shear strength ( $c_u$ ) of 15–80 kPa depending on the depth. The undesirable characteristics of soft soils, such as low shear strength, high compressibility and moisture content, place severe geotechnical constraints and make it necessary to adopt a proper ground improvement method to meet the required engineering properties for construction (Lin et al. 2022). The installation of stone columns is one of the most popular ground improvement techniques. Typically, the use of conventional unbound stone columns for ground improvement work is generally suitable for soft soil strata with an undrained shear strength above 15 kPa. However, when the shear strength falls below this threshold, the effectiveness and performance of stone columns are significantly diminished due to the insufficient lateral confining pressure provided by the surrounding soil (Lin et al., 2022). In the past years, researchers and geotechnical engineers have always been seeking simple and cost-effective solutions to improve the mechanical properties of ground inclusion columns installed in highly plastic soils.

## 2. Project Purpose, Objectives, and Impact Pathways

The objective of this project is to evaluate the usage of recycled concrete aggregates (RCA) as unbound and lightly-bound semi-rigid ground inclusion columns.

Nine million tonnes of demolition concrete are produced in Australia annually. This project aims to evaluate their usage as an alternative material in ground inclusions for ground improvement projects. This project involved extensive laboratory testing and the development of fully-instrumented laboratory prototype equipment to evaluate the performance of RCA as an alternative aggregate for ground inclusion columns.

This project was undertaken in several stages:

1. Define the resource and the market of RCA and geopolymers in ground improvement projects
2. Comprehensive laboratory testing to evaluate physical, geotechnical and geo-environmental properties of the RCA for usage as ground inclusions
3. Perform advanced geotechnical tests on unbound and lightly-bound RCA with geopolymers
4. Cost analysis of the final product, as compared to the usage of conventional quarry materials
5. Promote and develop necessary training for the sustainable usage of RCA in unbound and semi-rigid ground inclusion columns
6. Engage the potential partner in utilising the new product in their future projects



Figure 1. Physical appearance of RCA from stockpiles in Australia.

### 3. Project Methodology and Key Activities

This research project investigated the feasibility of stabilising RCA by fly ash and ground granulated blast furnace slag-based geopolymers as semi-rigid inclusion columns to resolve practical challenges of the stone columns in terms of the shortages in suitable granular backfills for its construction. In addition, another aim of this project was to optimise the performance of stone columns installed in very soft soils. To achieve the aim of this project, extensive experimental studies and fully-instrumented large-scale prototype laboratory equipment were undertaken and developed. Final findings compared the performance of the new product with the performance of the conventional materials used for construction of stone columns to meet existing VicRoads specifications. The methodology and key activities of the research project includes:

1. Literature review and background review of the usage of RCA and geopolymers in ground improvement projects
2. Identify the resources, quantities, cost, and location of the required materials
3. Comprehensive laboratory tests to evaluate the suitability of RCA as an alternative granular backfill in stone column applications in terms of its engineering and environmental properties
4. Using fly ash and ground granulated blast furnace slag-based geopolymers as low-carbon binders for the stabilisation of RCA as semi-rigid inclusion columns
5. Evaluation of semi-rigid column inclusions' strength with respect to different material compositions and curing conditions
6. Characterisation of samples of various mixtures using optical and scanning electron microscopy to understand how the binding mechanism formed with the RCA and geopolymer binders. The microscopy image will also be able to reveal the weak joint where failure mode after the compressive strength test
7. Determination of an optimal mixture with the lowest binder contents for stabilising RCA as semi-rigid column inclusions, whilst satisfying the minimum target strength requirement for ground improvement work
8. Fully-instrumented large-scale laboratory stone column prototype testing to assess the performance of semi-rigid inclusion columns under both static and dynamic loadings

## 4. Key Results, Deliverables, Description of Outputs and IP

The outcomes of this project demonstrated the viability of using RCA for natural aggregate substitution as unbound and lightly-bound semi-rigid stone columns for ground improvement. The outcomes of this project also outlined the potential usage of RCA in other geotechnical applications (such as road base and subbase material, or rigid pavement). The project deliverables (refer to the key activities) mentioned in the previous section of this report were all completed successfully. The experimental test results demonstrated that:

1. RCA possesses comparable engineering and environmental characteristics to that of the natural aggregates, and can be used as a sustainable alternative in stone column applications
2. FA and S-based geopolymers are suitable low-carbon binders for stabilising RCA as semi-rigid inclusion columns for ground improvement work
3. The target strength requirement of stabilised columns for ground improvement work is 1.034 MPa (Puppala et al. 2008), and the optimal mixture design that meets the strength requirement is RCA + 5%(FA+S)
4. Compared with the conventional unbound stone columns, lightly-bound semi-rigid stone columns can effectively improve the load-carrying capacity of the ground inclusion columns, and reduce the permanent strain of inclusion columns for more than 89.5% under cyclic loading
5. Stabilised semi-rigid inclusion column possesses a comparable drainage function to that of the conventional unbound stone column, to dissipate the accumulated pore water pressure under loading
6. Increased cyclic loading frequency, in general, resulted in a greater settlement and higher accumulated pore water pressure values

The outputs of this project include journal and conference articles published in internationally-reputable journals. Other project outputs include the developed novel technology, the semi-rigid inclusion column system for ground improvement work, and the proposed optimal mixture design for such an application (optimal mixture: RCA + 5%(FA+S)).

Figure 2 illustrates the schematic of newly proposed reinforcing technique in this project, a novel semi-rigid inclusion column system for ground improvement of soft soils.

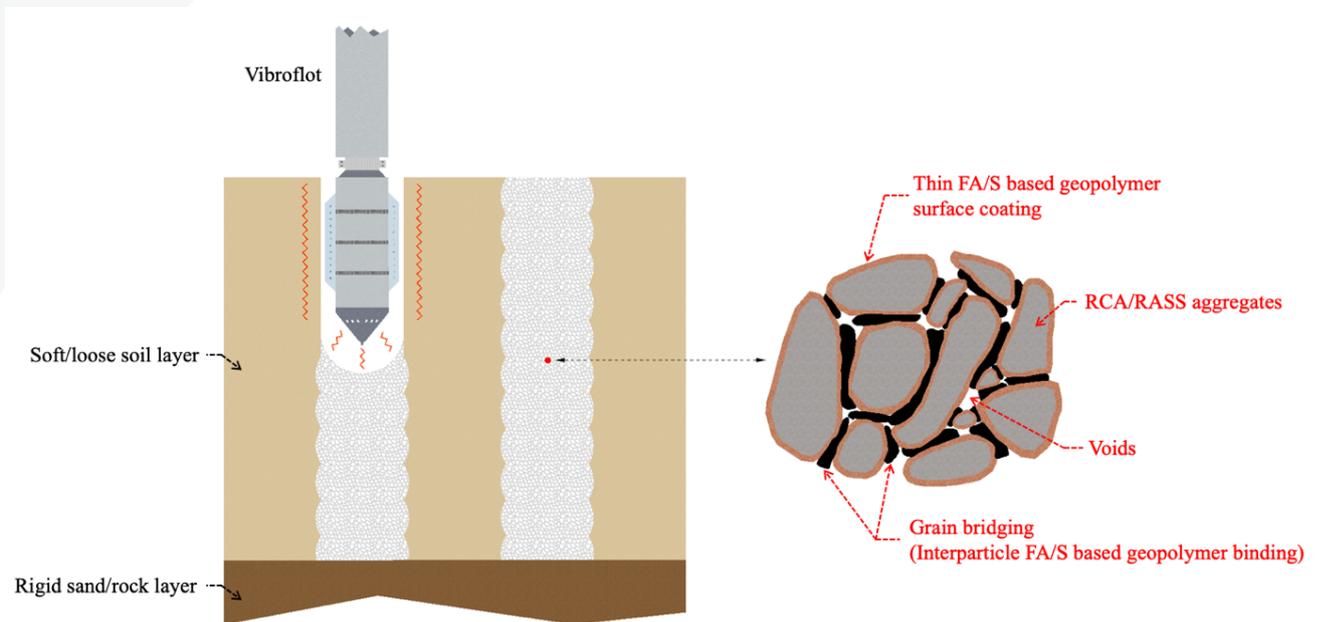


Figure 2. Schematic of a geopolymer-stabilised semi-rigid inclusion column system.

Figures 3 to 5 show the unconfined compressive strength (UCS) of two-part geopolymer stabilised RCA as semi-rigid column inclusions. Based on the experimental results plotted below, all of the two-part geopolymer stabilised RCA mixtures meet the minimum strength requirement of 1.034 MPa of stabilised columns for ground improvement work. With due consideration to the economic and environmental reasons, the proposed optimal two-part geopolymer stabilised RCA mixture is RCA + 5%(FA+S), with a fixed  $\text{Na}_2\text{SiO}_3:\text{NaOH}$  ratio of 70:30 and a liquid alkaline activator to precursor ratio of 0.4.

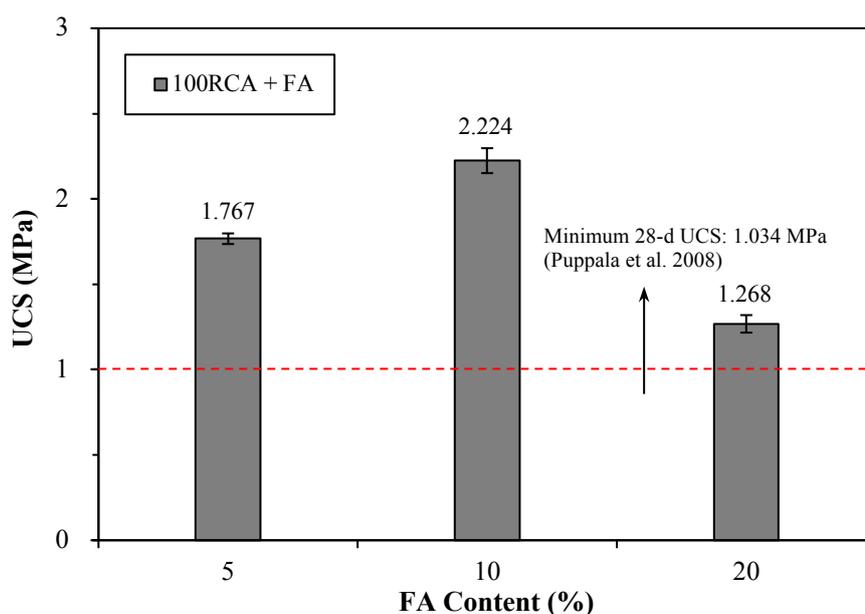


Figure 3. UCS of FA-based two-part geopolymer stabilised semi-rigid column inclusions.

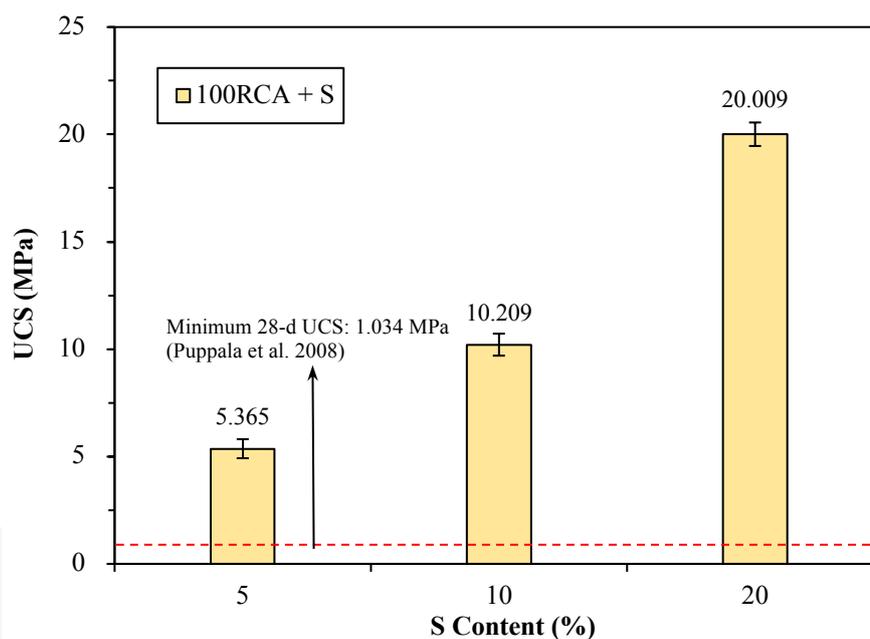


Figure 4. UCS of S-based two-part geopolymer stabilised semi-rigid column inclusions.

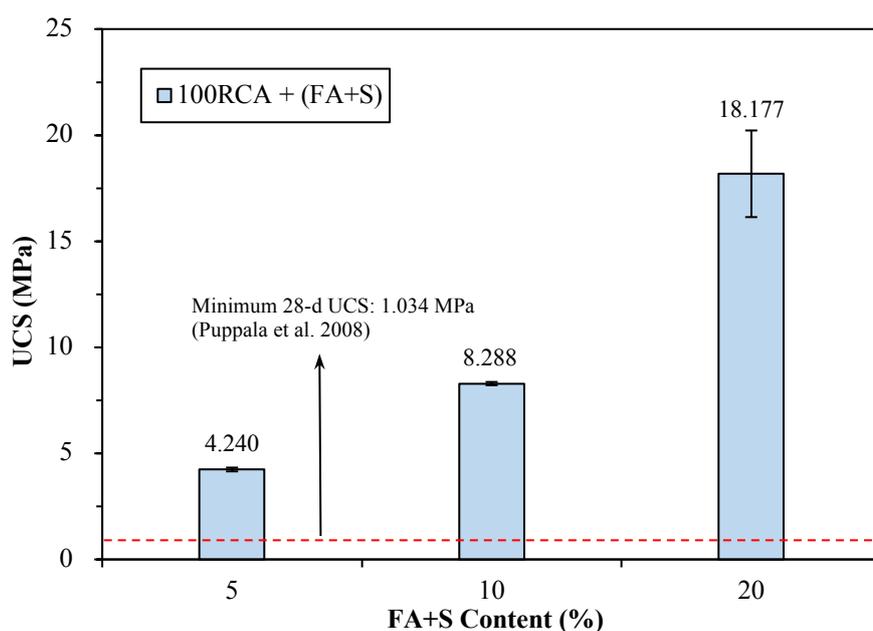


Figure 5. UCS of (FA+S)-based two-part geopolymer stabilised semi-rigid column inclusions.

Figure 6 shows the physical appearance of two-part geopolymers stabilised RCA as semi-rigid ground inclusion columns.

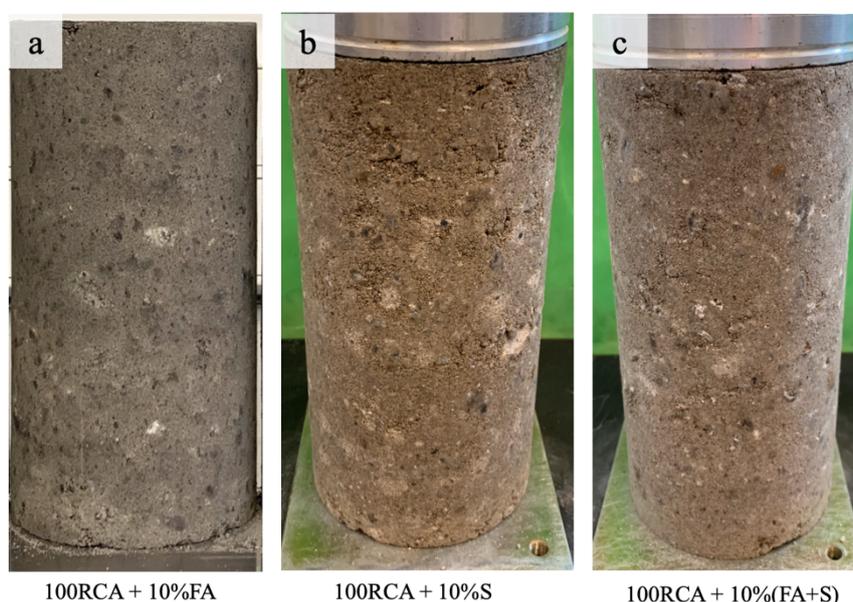


Figure 6. Stabilised-RCA products by two-part geopolymers as semi-rigid column inclusions: (a) stabilised by addition of 10% FA-based geopolymer, (b) stabilised by addition of 10% S-based geopolymer, and (c) stabilised by addition of 10% (FA+S)-based geopolymer

Figures 7 to 9 show the UCS of one-part geopolymer stabilised RCA as semi-rigid column inclusions. As shown below, most of the one-part geopolymer stabilised RCA mixtures meet the minimum strength requirement of 1.034 MPa of stabilised columns for ground improvement work. With due consideration to the economic and environmental reasons, the proposed optimal one-part geopolymer stabilised RCA mixture is RCA + 5%(FA+S) with a solid activator to precursor ratio of 0.1.

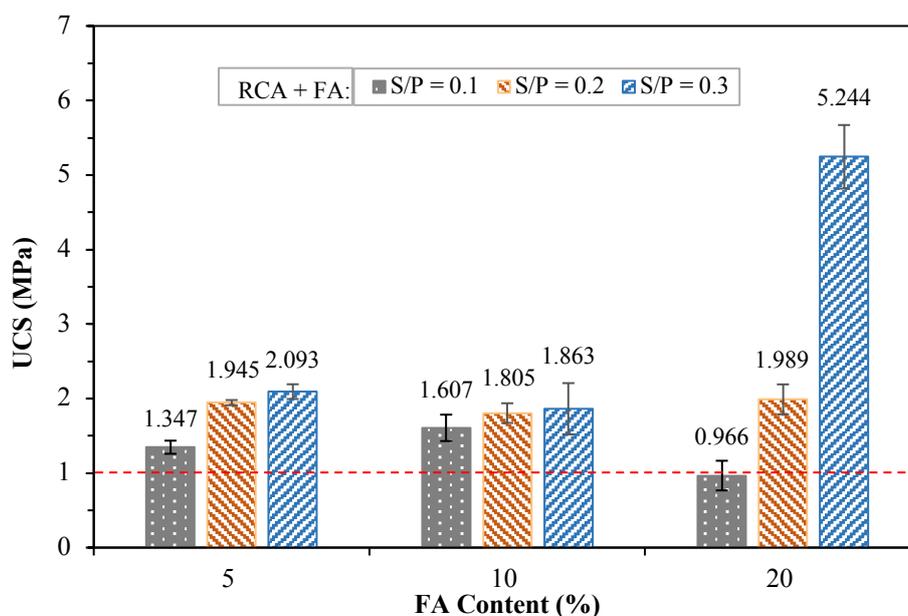


Figure 7. UCS of FA-based one-part geopolymer stabilised semi-rigid column inclusions.

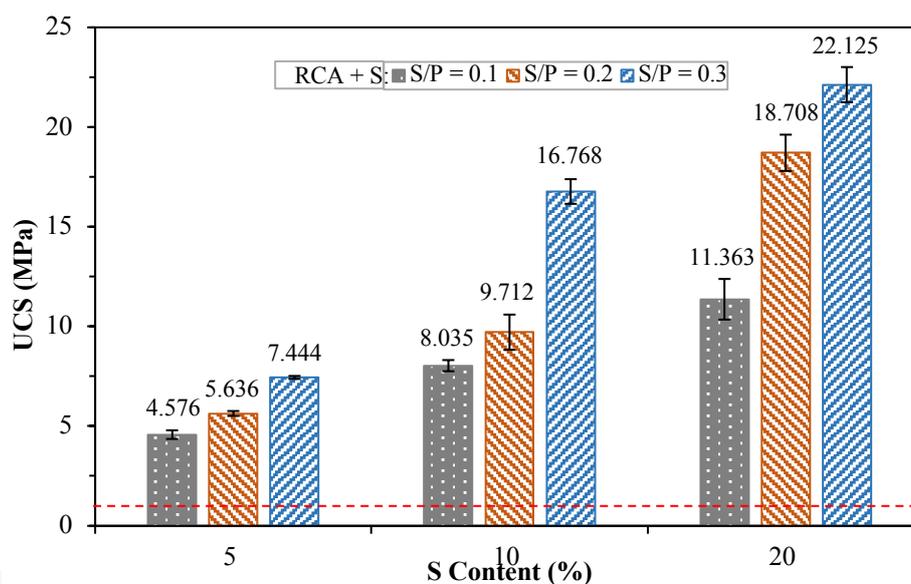


Figure 8. UCS of S-based one-part geopolymer stabilised semi-rigid column inclusions.

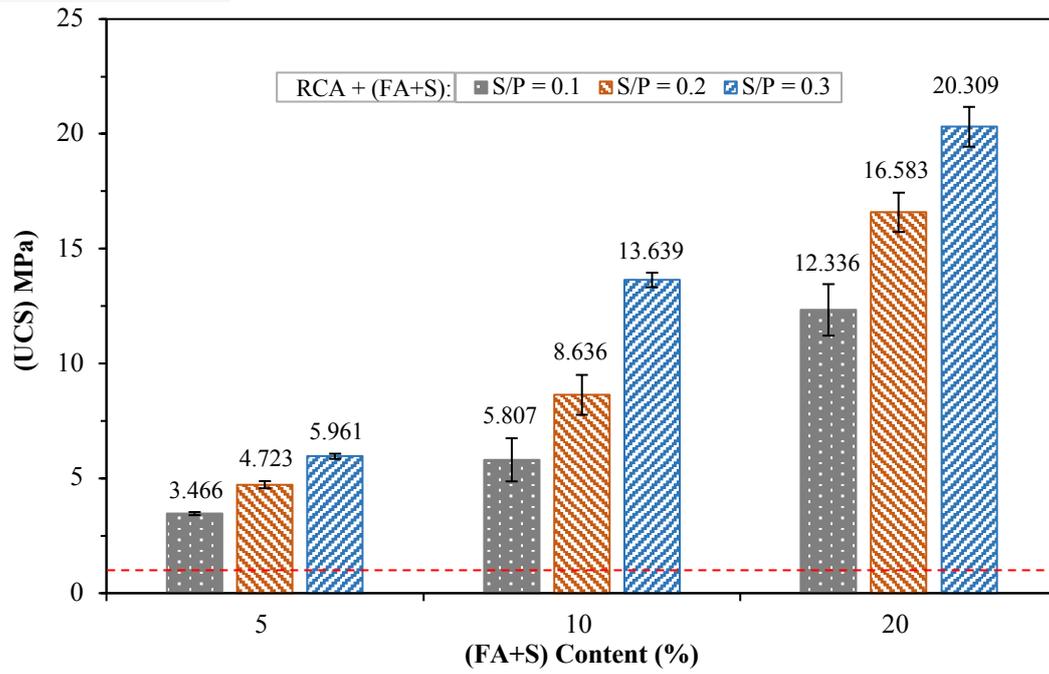


Figure 9. UCS of (FA+S)-based one-part geopolymer stabilised semi-rigid column inclusions.

Figure 10 (a) shows the scanning electron microscopy (SEM) image of conventional unbound ground inclusion (mixture: unbound RCA). As depicted in Figure 10 (a), the RCA particles are in an unbound state, and in such case, the load-carrying capacity of a conventional unbound stone column is derived from the lateral confining pressure provided by the surrounding soil. While Figure 10 (b) demonstrates the SEM image of stabilised semi-rigid ground inclusion (mixture: RCA + 5%(FA+S)). The RCA particles were covered and interlocked by the gel products after alkali activation of 5%(FA+S) geopolymer. As a result, the stabilised semi-rigid ground inclusion is much more robust than the conventional unbound stone column in terms of its mechanical properties.

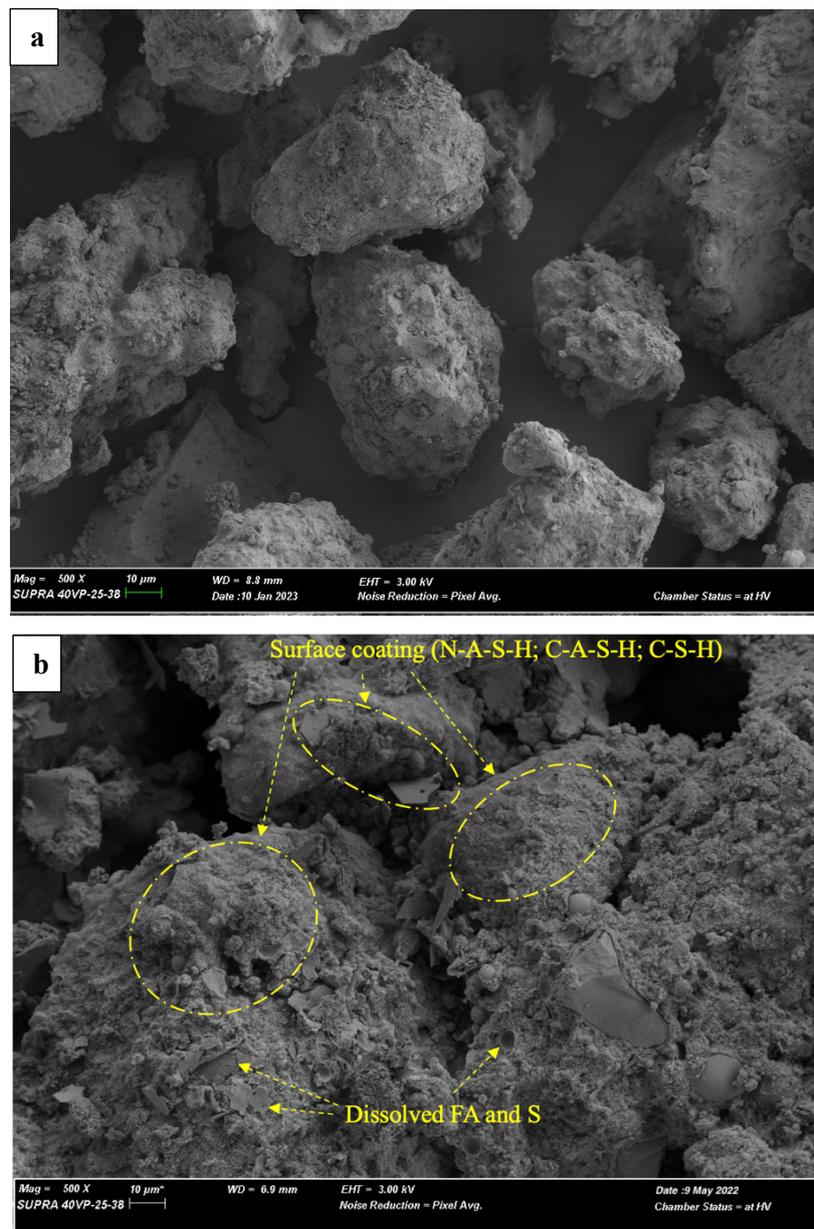


Figure 10. scanning electron microscopy images: a) conventional unbound ground inclusion (mixture: unbound RCA), and b) optimal mixture of stabilised semi-rigid ground inclusion (mixture: RCA + 5%(FA+S)).

The repeated load triaxial (RLT) tests were conducted on unbound RCA and optimal stabilised RCA mixture to simulate the cyclic moving traffic loads imposed on the ground inclusion column system. Figure 11 compares the RLT permanent deformation results between unbound RCA, and optimal one-part geopolymer stabilised RCA mixture: RCA + 5%(FA+S), under different curing conditions. It was found that stabilising RCA with as low as 5% alkali-activated (FA+S) one-part geopolymer binder reduced permanent deformation by more than 89.5%, compared to conventional unbound stone columns (unbound RCA).

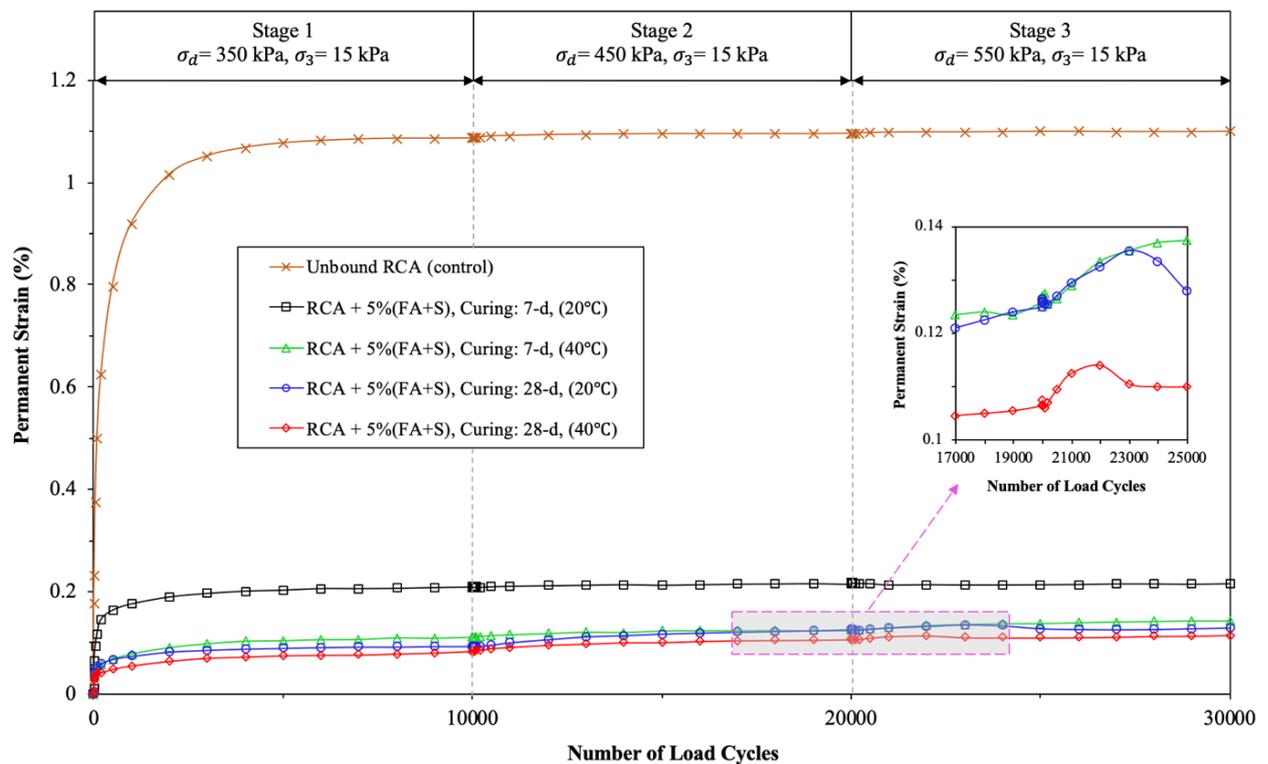


Figure 11. Comparison of RLT permanent deformation results between unbound RCA and one-part geopolymer stabilised RCA + 5%(FA+S) mixture under different curing conditions.

To conduct the large-scale fully-instrumented prototype testing in this project, the software drawings of the large-scale prototype were first developed. Figure 15 shows the schematic 3D view of a large cylindrical mould used for the test. The large cylindrical mould was then fabricated by the Swinburne workshop according to the drawing. Figure 16 demonstrates the locations of earth pressure cells (EPC) and pore water pressure transducers (PPT) installed during the tests to monitor the performance of ground inclusion columns under static and cyclic loading conditions. Figure 14 depicts the setup of fully-instrumented large-scale laboratory stone column prototype testing. The large-scale prototype tests were undertaken on a conventional unbound stone column (mixture: unbound RCA), and the optimal one-part geopolymer stabilised RCA semi-rigid stone column (optimal mixture: RCA + 5%(FA+S)). The cyclic loading schemes consist of four different loading stages. For each loading stage, 15,000 repetitions of cyclic load were applied. Two different cyclic loading frequencies were carried out for the prototype testing, as illustrated in Figures 12 and 13.

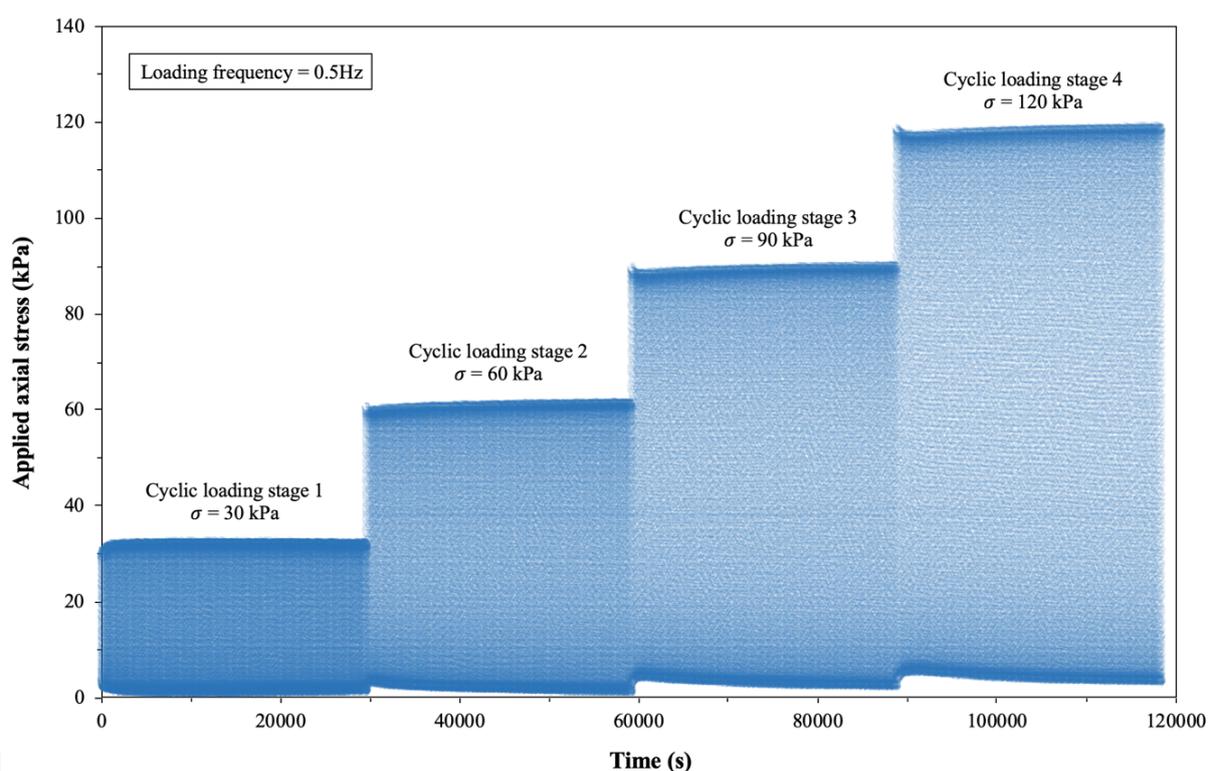


Figure 12. cyclic loading scheme at loading frequency of 0.5Hz.

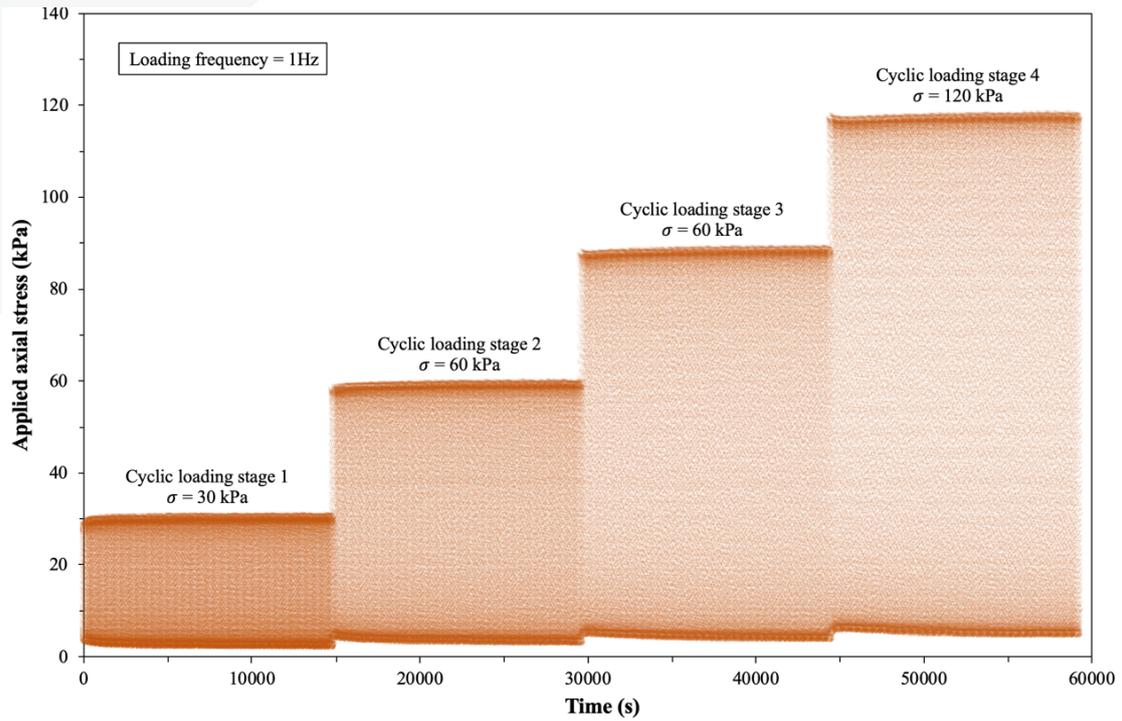


Figure 13. cyclic loading scheme at loading frequency of 1Hz.

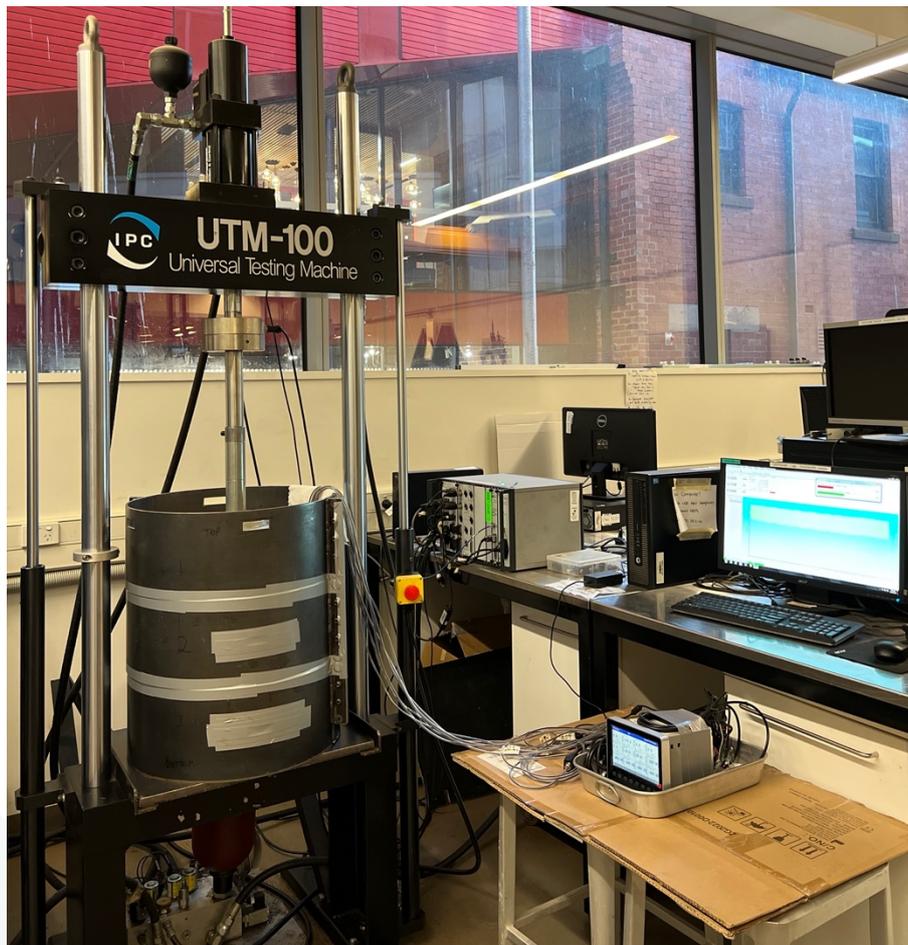


Figure 14. setup of fully-instrumented large-scale laboratory stone column prototype testing.

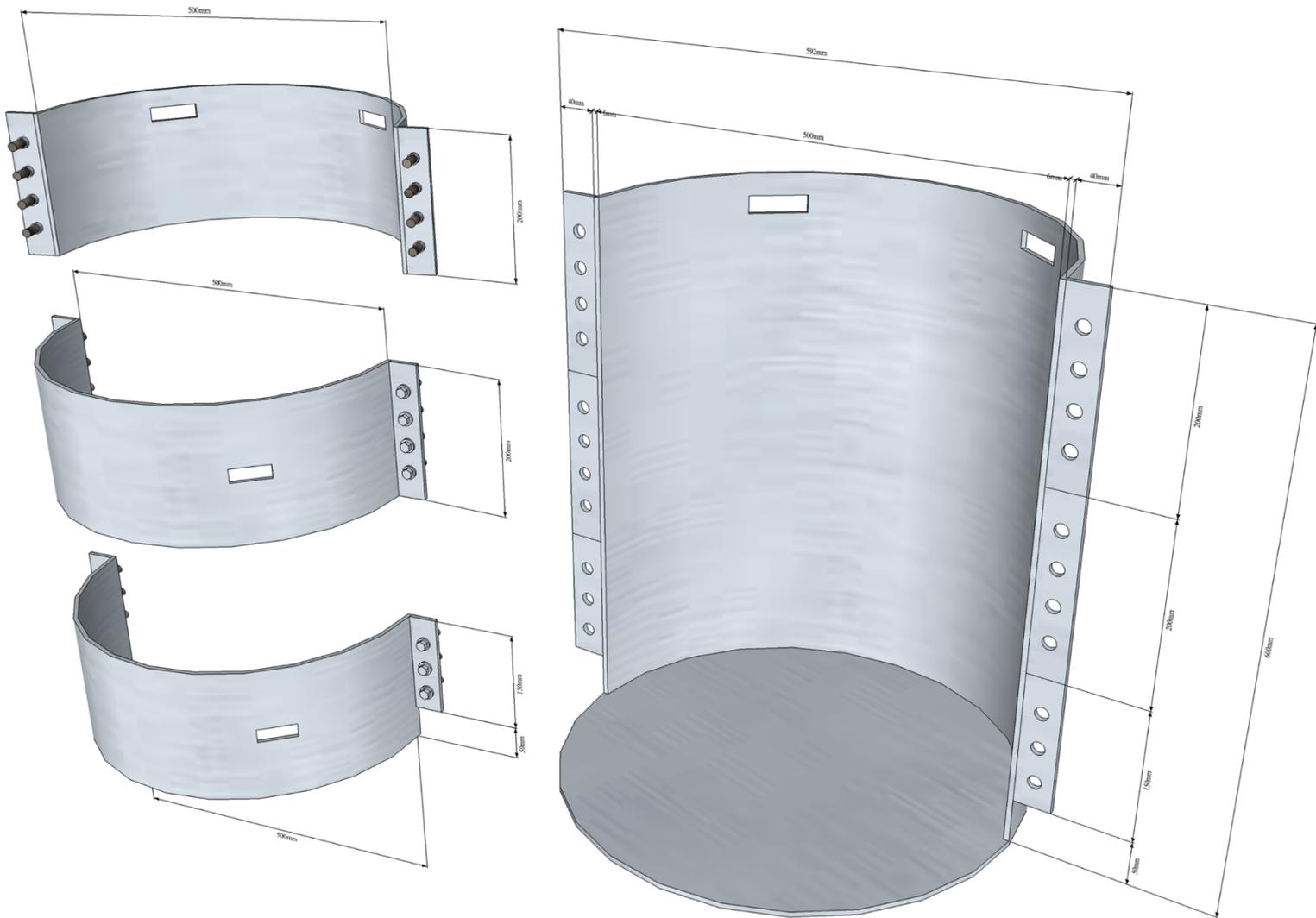


Figure 15. Schematic 3D view of laboratory prototype cell design.

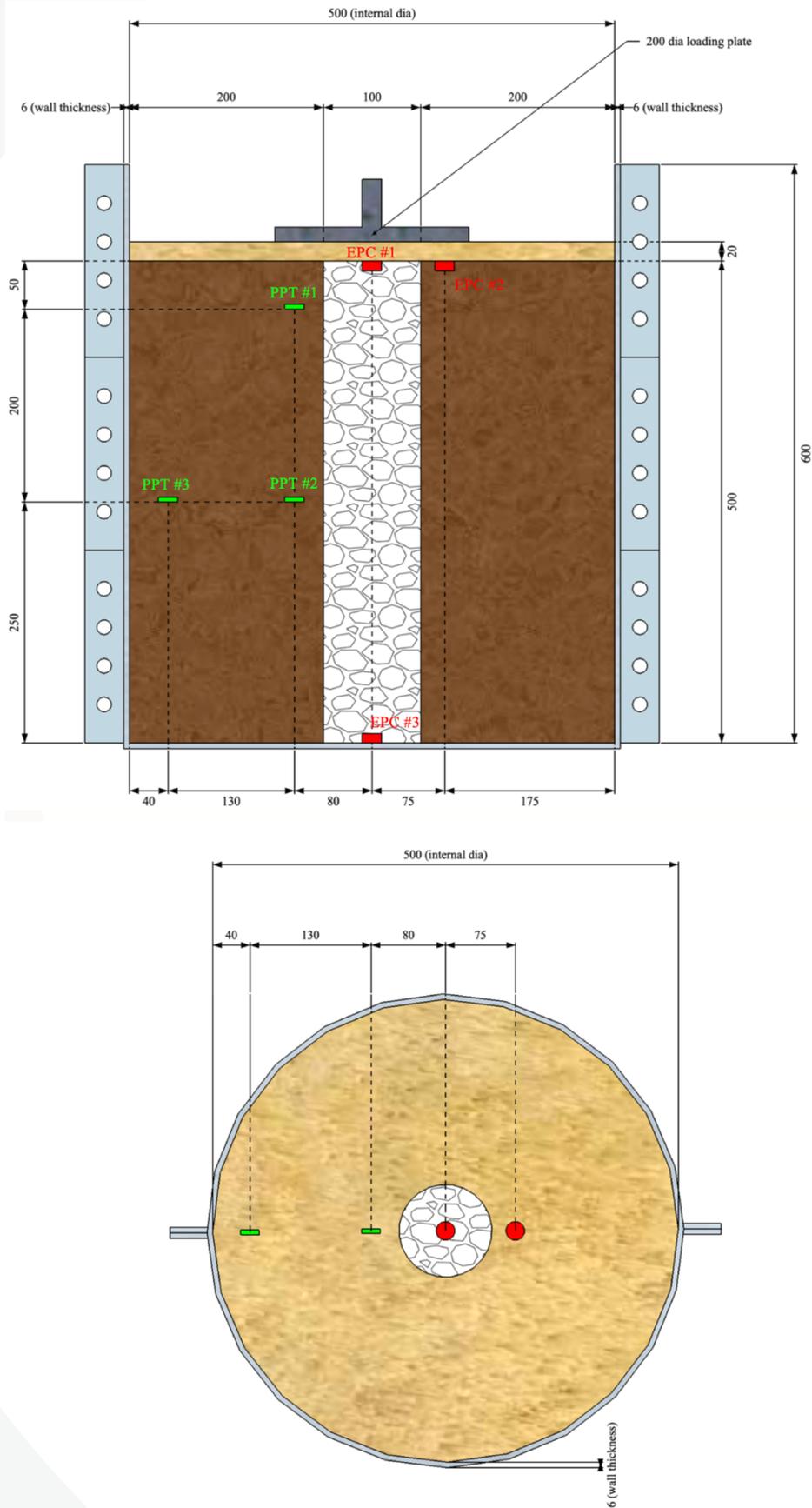


Figure 16. Schematic 2D view of laboratory prototype cell design.

Figures 17 to 18 show the settlement behaviour of conventional unbound and semi-rigid stone column systems under cyclic loading with different loading frequencies (0.5Hz and 1Hz). Based on the experimental results, it is found that stabilising RCA as semi-rigid ground inclusion can effectively reduce the settlement of ground inclusion under cyclic loading with a same magnitude of axial stress. For a loading frequency of 0.5Hz, stabilising RCA as semi-rigid ground inclusion reduced the accumulated settlement of the stone column by more than 80% at the end of the loading cycle, compared to the conventional unbound stone column. While for loading frequency of 1Hz, settlement of the stone column was reduced by 74.6% after stabilisation of column inclusions as compared to the conventional unbound stone column. In addition, it is found that the settlement of ground inclusion columns was increased with increasing the cyclic loading frequency with the same magnitude of axial stress.

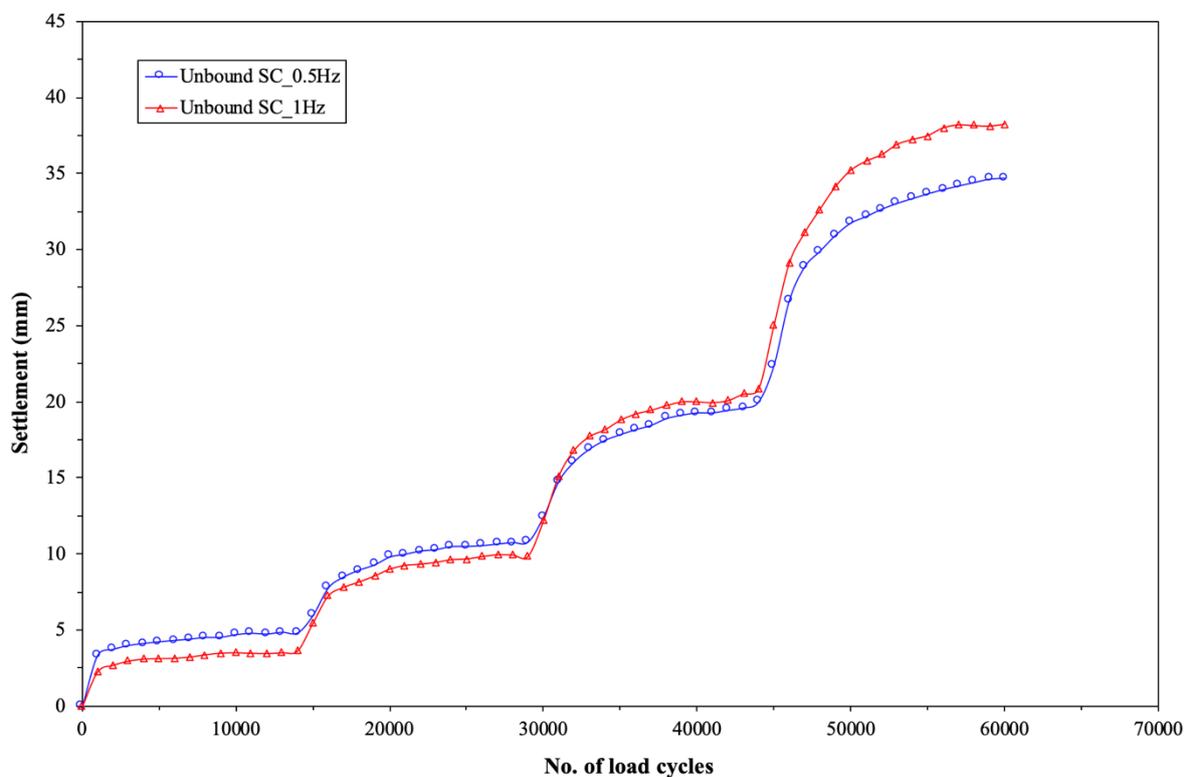


Figure 17. Settlement behaviour of conventional unbound SC under cyclic loading with different loading frequencies (0.5Hz and 1Hz).

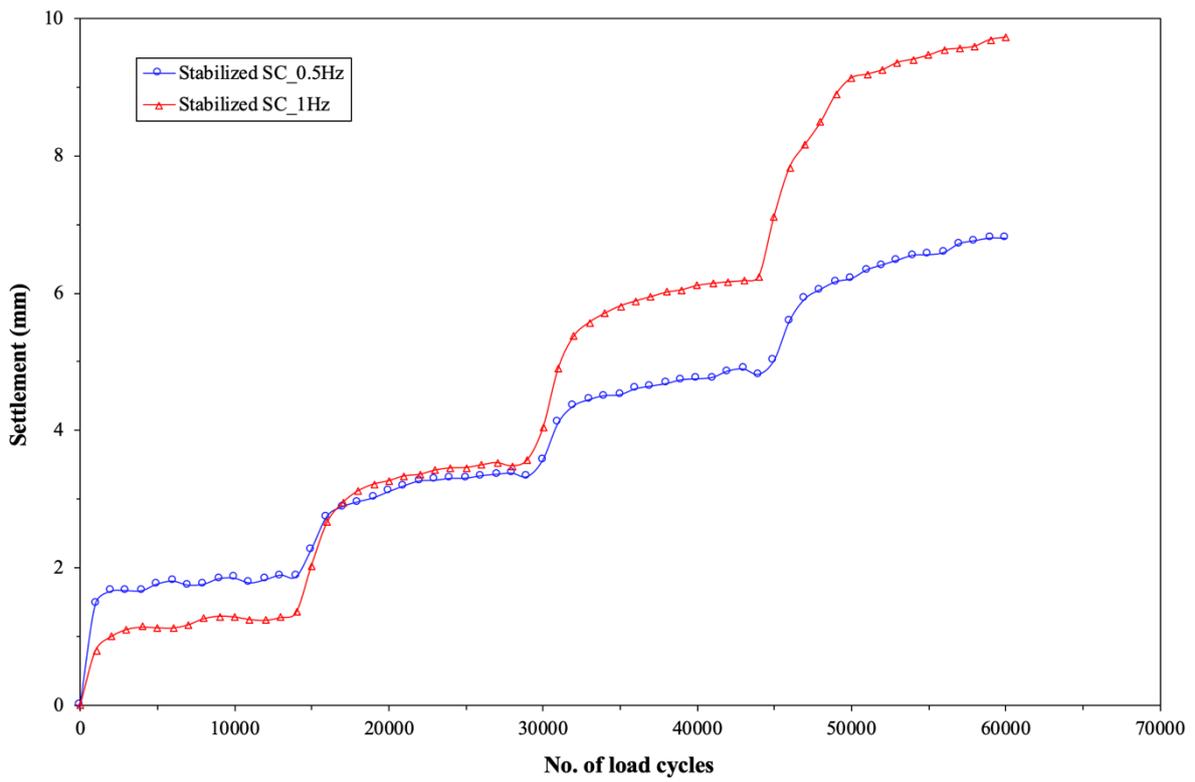


Figure 18. Settlement behaviour of stabilised SC under cyclic loading with different loading frequencies (0.5Hz and 1Hz).

Figures 19 and 20 show the pore water pressure accumulation and dissipation behaviours of conventional unbound stone column improved clay bed under cyclic loading, with different loading frequencies (0.5Hz and 1Hz). While Figures 21 and 22 illustrate the pore water pressure accumulation and dissipation behaviours of semi-rigid stone column improved clay bed subject to the same loading scheme. Based on the experimental results, it is evidenced that the accumulated pore water pressure recorded by PPT at different locations of semi-rigid stone column improved clay bed were much lower than the conventional unbound stone column one, as more axial stress was taken by ground inclusion column instead of clay bed. In addition, the stabilised semi-rigid inclusion column exhibits a comparable vertical drain function to that of the conventional unbound stone column for ground improvement works on soft soils. Moreover, it was also found that increasing the cyclic loading frequency from 0.5Hz to 1Hz, in general, resulted in higher pore water pressure accumulation on stone column improved clay bed.

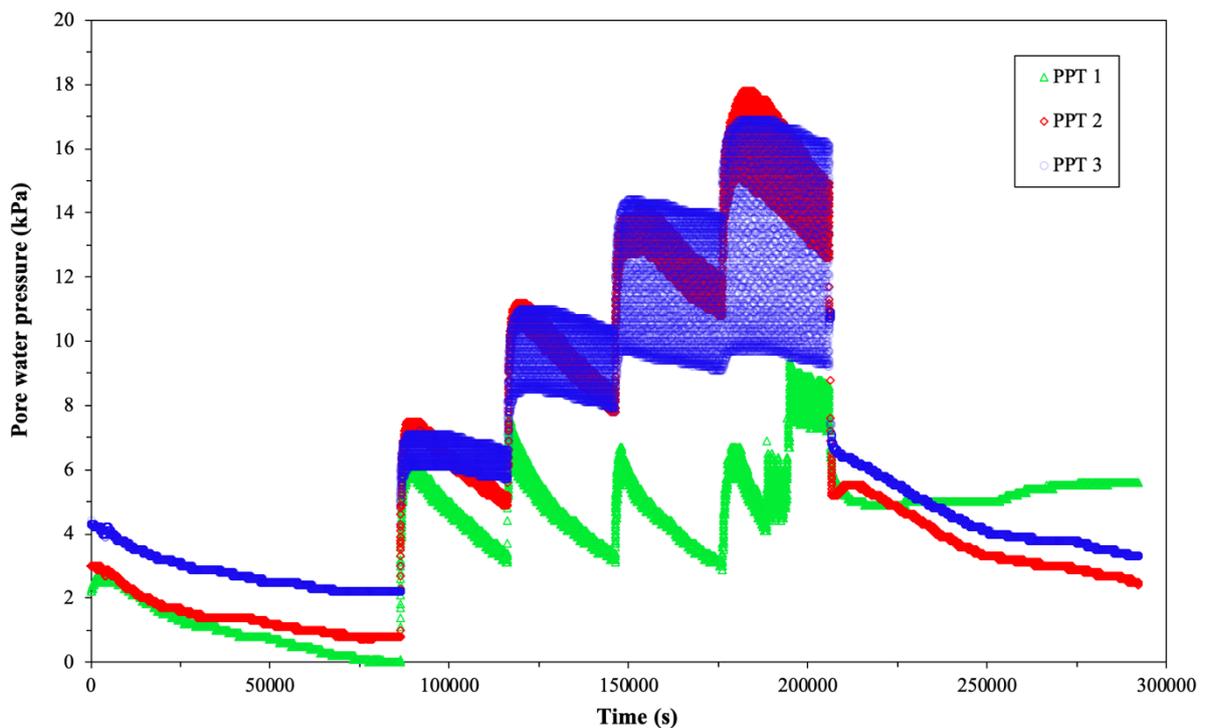


Figure 19. Pore water pressure accumulation and dissipation behaviours of conventional unbound SC improved clay bed under cyclic loading (loading frequency = 0.5Hz).

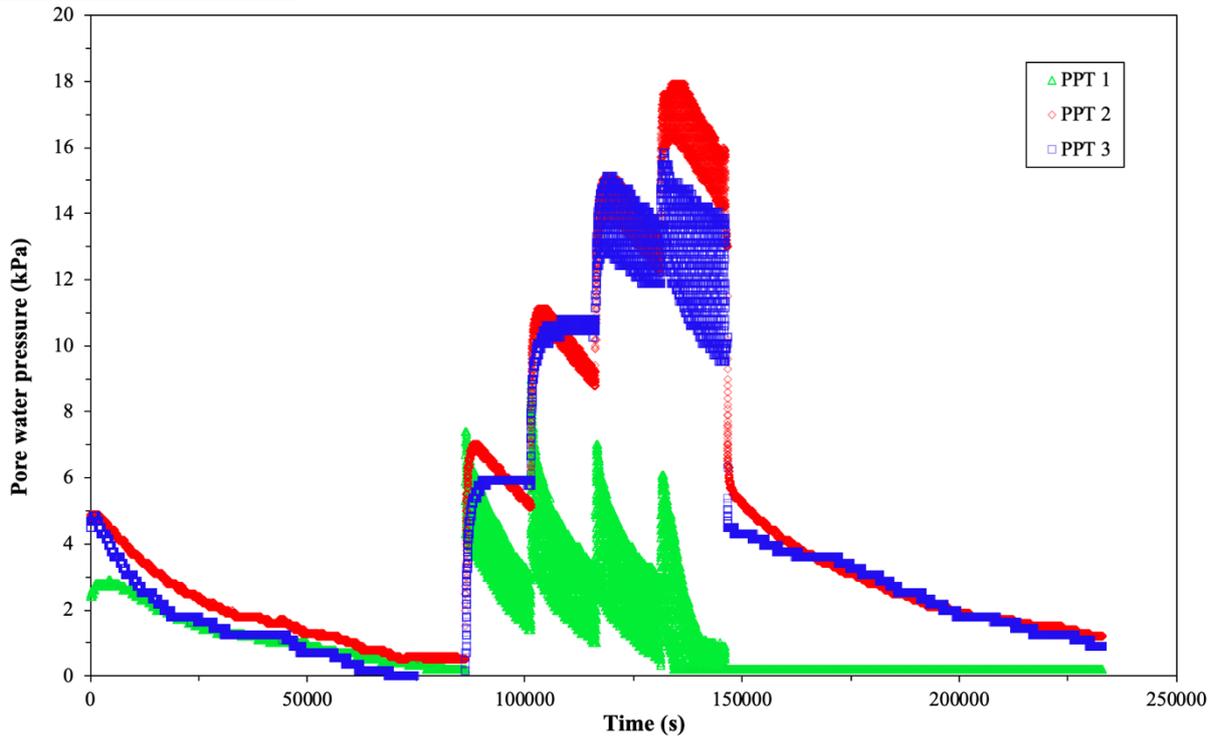


Figure 20. Pore water pressure accumulation and dissipation behaviours of conventional unbound SC improved clay bed under cyclic loading (loading frequency = 1Hz).

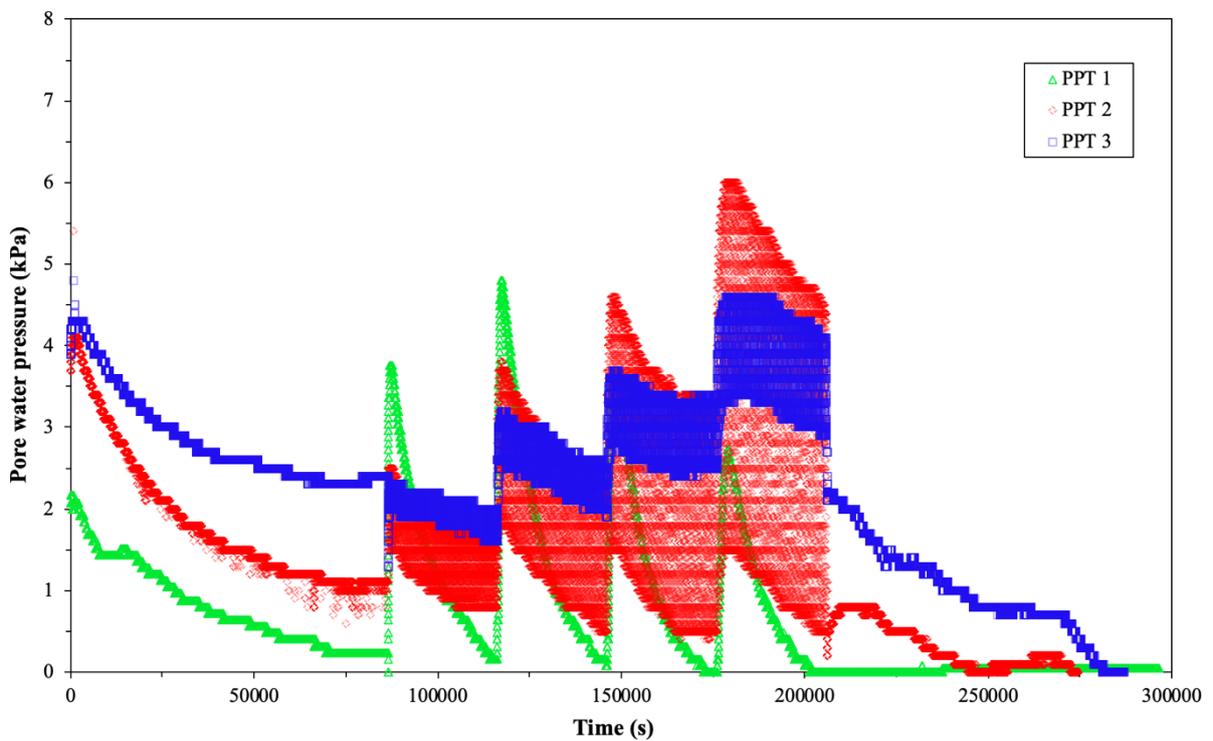


Figure 21. Pore water pressure accumulation and dissipation behaviours of stabilised SC improved clay bed under cyclic loading (loading frequency = 0.5Hz).

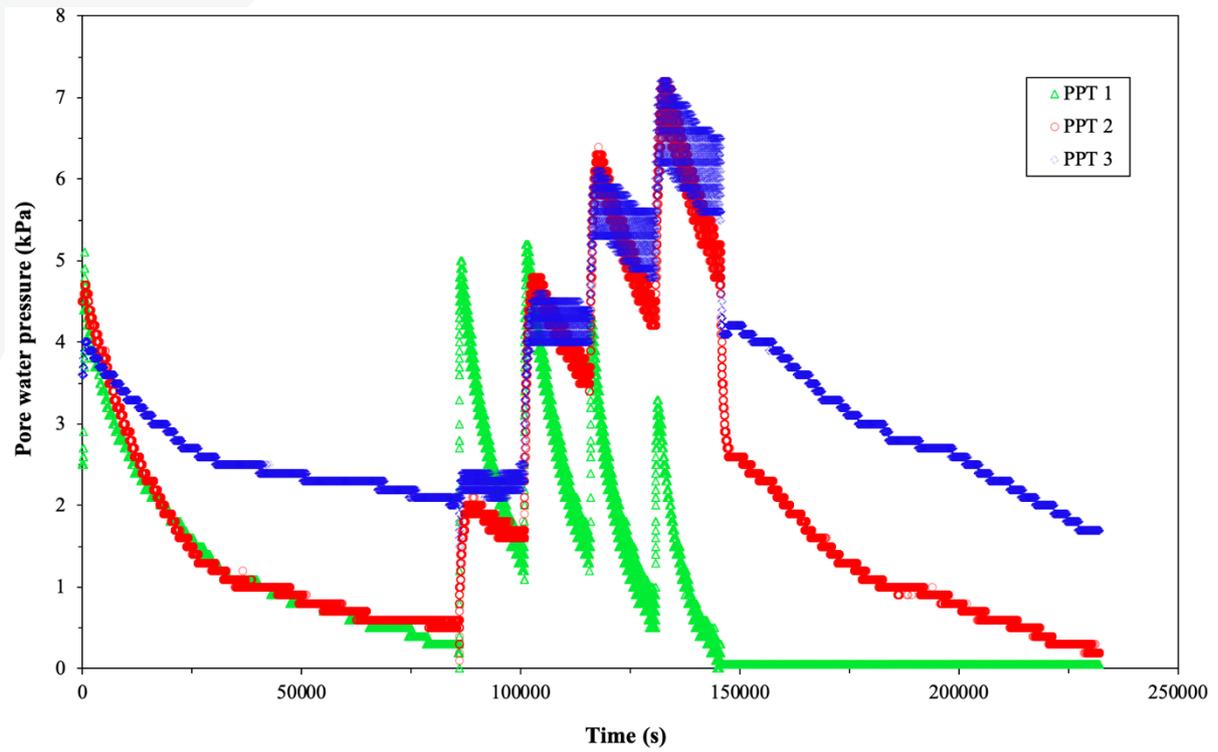


Figure 22. Pore water pressure accumulation and dissipation behaviours of stabilised SC improved clay bed under cyclic loading (loading frequency = 1Hz).

## 7. Conclusions, Implications and Recommendations

Comparing the engineering and environmental properties of unbound RCA to natural aggregates provides satisfactory evidence that RCA met existing VicRoads specifications for usage in a wide range of geotechnical applications, and is qualified as alternative backfill material in ground inclusion column. The developed novel semi-rigid inclusion column system, achieved by stabilising RCA with fly ash and ground granulated blast furnace slag-based geopolymers, is an efficient, economical and environmentally-friendly solution to improve the performance and mechanical properties of stone columns installed in very soft soils. The optimal mixture design that meets the strength requirement of 1.034 MPa for ground improvement work is: RCA + 5%(FA+S).

The cyclic loading experimental results evidenced that the semi-rigid ground inclusion produced by optimal mixture (RCA + 5%(FA+S)) can effectively enhance the load-carrying capacity of the ground inclusion column, and the permanent strain of the inclusion column was reduced by more than 89.5% under cyclic loading compared to the conventional unbound stone column.

Furthermore, the fully-instrumented prototype tests demonstrated that stabilised semi-rigid inclusion column possesses a comparable drainage function to the conventional unbound stone column, allowing to dissipate the accumulated pore water pressure effectively under loading conditions, accelerate the consolidation and reduce the post-construction settlement of stone column improved ground.

The outcome of this research project will provide implications for geotechnical engineers, researchers and government bodies who focus on ground improvement of soft soils and solid waste recycling. Using RCA for natural aggregate substitution in stone column application offers a viable option for valorising and reutilising such waste materials, ultimately supporting the conservation of natural resources and promoting a shift toward a circular economy.

It is recommended to conduct more laboratory trials of this new product (RCA) for its potential usage in a broader range of geotechnical applications. Furthermore, future research can focus on incorporating other construction and demolition wastes with RCA, such as recycled brick and recycled glass, as semi-rigid column inclusions.

## 8. Education and Training

For the commercialisation of such new product and technology, it is crucial to provide comprehensive training for the safe usage, handling, and mixing of the geopolymer and RCA materials. Additionally, proper safety regulations must be established to promote the sustainable use of the final product. This essential training can be effectively delivered through various means, such as journal or conference publications, attending seminars, or presenting at conferences.

Moreover, educating professionals about the new product (RCA) and technology (semi-rigid inclusion column system) can be accomplished through university-related subjects. For instance, at the Swinburne University of Technology, the master unit CVE80007 Geotechnical Design, delivered by Professor Arul Arulrajah, offers an excellent platform for educating future engineering professionals about these innovative advancements.

## 9. Next Steps – Commercialisation & Impact Plan

Demand for more sustainable construction materials is driving demand for the reuse of demolition concrete. Additionally, the cost of traditional quarry materials is increasing as their supply reduces. The commercial benefits of this project are significant.

RCA is available at various recycling sites at the cost of \$16/tonne, compared to a quarry stone which costing \$30/tonne, this translates to almost a 50% cost savings per tonne. There is currently, nine million tonnes of RCA disposed of in Australian landfill per annum. This makes the market size for this project \$126 M per annum, which does not account for the escalating price of quarry materials. If ground inclusions of 1 m diameter are installed at spacings of 2 m x 2 m, usage of RCA as ground inclusions will translate to a cost savings of up to \$1.1 M/km. This revenue and margin equate to using up to 78,000 tonnes of RCA for construction of a typical road comprising a 20m width over a length of 1 km, requiring ground improvement of problematic soils to depths of 10m. It is expected that its adoption will double each year on a compounding basis. The commercial opportunities of this project will also extend to recycling companies.

In addition to this project's commercial benefits, carbon savings of up to 65% with the usage of recycled products can be expected compared to quarry materials. This is significant in view of upcoming road and other infrastructure projects in Australia that will benefit from the cost and environmental savings from the potential usage of RCA as ground inclusions.

## 10. Project Team

<b>Team member</b>	<b>Position</b>	<b>Personnel type</b>	<b>Organisation</b>
<b>Dr. Farshid Maghool</b>	Senior Engineer & Geotechnical Laboratory Manager	Project Lead	Swinburne University of Technology
<b>Prof. Arul Arulrajah</b>	Professor of Geotechnical Engineering	Project Lead	Swinburne University of Technology
<b>Youli Lin</b>	PhD candidate	Researcher	Swinburne University of Technology

## 11. Publication List

### Journal Publications

1. Lin, Y., Maghool, F., Arulrajah, A. and Horpibulsuk, S. (2023). “Alkali activation of recycled concrete and aluminum salt slag aggregates for semi-rigid column inclusions”, *Construction and Building Materials*, Vol. 366, 130106.
2. Lin, Y., Maghool, F., Arulrajah, A. and Horpibulsuk, S. (2021). “Engineering characteristics and environmental risks of utilizing recycled aluminum salt slag and recycled concrete as a sustainable geomaterial”, *Sustainability*, Vol. 13, 10633.
3. Lin, Y., Maghool, F., Arulrajah, A. and Horpibulsuk, S. “Cleaner semi-rigid column inclusions containing recycled concrete aggregate stabilized by one-part geopolymer”. (In preparation).

### Conference Publications

4. Lin, Y., Maghool, F., Arulrajah, A. and Horpibulsuk, S. (2023). “Recycled concrete aggregate as a sustainable construction material: engineering and environmental consideration”, *Concrete Institute of Australia’s 31<sup>st</sup> Biennial National Conference on Resilient and Sustainable Concrete: Breaking Down Barriers*, Perth, Australia. (Full paper accepted on 26<sup>th</sup> May 2023)
5. Lin, Y., Maghool, F., Arulrajah, A. and Horpibulsuk, S. (2023). “Environmental impact of recycled crushed concrete and aluminium salt slag as used in civil infrastructure construction”, *2<sup>nd</sup> International Conference on Construction Resources for Environmentally Sustainable Technologies*, Fukuoka, Japan. (Full paper accepted 1<sup>st</sup> Mar 2023)

## 12. Acronyms and Abbreviations

C&D	Construction and demolition
$C_u$	Undrained shear strength
EPC	Earth pressure cell
FA	Fly ash
RCA	Recycled concrete aggregate
PPT	Pore water pressure transducer
S	Ground granulated blast furnace slag
SC	Stone column
UCS	Unconfined compressive strength
(FA+S)	Fly ash plus ground granulated blast furnace slag at fixed FA:S ratio of 50:50

## 13. References

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