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Pavement stabilisation of municipal wastes using foamed bitumen and supplementary binders

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Foamed bitumen stabilisation (FBS) is widely used to enhance durability, moisture resistance, and road flexibility while reducing cracking. Addressing knowledge gaps in its application with recycled materials can expand their usage in road construction. This study focused on stabilising mixes of 50% recycled concrete aggregate (RCA) and 50% fine recycled glass (RG) using foamed bitumen (FB). Recycled toner aggregate (RTA) and geopolymers derived from ground granulated blast furnace slag (S) and fly ash (FA) were evaluated as potential alternatives to conventional secondary binders, such as Portland cement for FBS of recycled material blends. To assess the performance of RTA, a fixed 3% FB dosage was combined with varying RTA amounts (1%–4%). Geopolymers including FA, S, and (FA + S) at dosages of 10%, 20%, and 30% by mass of RCA and RG blend were tested alongside 3% FB for their stabilising effectiveness. FB-stabilised samples with RTA initially failed the indirect tensile modulus tests, but their performance improved significantly after extended curing. The blend incorporating geopolymers, RCA + RG + 3% FB + 20% (FA + S), met local road authority standards. These results demonstrate the potential of sustainable secondary binders for the stabilisation of RCA and RG mixtures in road construction.

Keywords: foamed bitumen/geopolymers/ground improvement/pavement geotechnics/recycled material/recycled toner aggregate/waste toner powder aggregate

Introduction

With the growing emphasis on building environmentally sustainable roads, the construction industry is increasingly focusing on the reuse of construction and demolition (C&D) waste. Governments worldwide are promoting sustainability by encouraging the reduction, reuse, and recycling of all types of waste to decrease the consumption of natural resources. In 2022–2023, Australia generated approximately 26.8 million tonnes of C&D waste and 1.36 million tonnes of glass waste. The resource recovery rate for C&D waste reached 84%, yet 16% still ended up in landfills without reuse. Similarly, while the recycling rate for glass waste remained constant at 61%, 39% of this material was landfilled (Pickin *et al*., 2024). Recycled concrete aggregate (RCA) is a primary product derived from C&D waste. While some glass containers can be recycled back into new glass products, others cannot, which complicates waste disposal efforts. Fine recycled glass (RG) has found wide application in road construction, where it serves as a sustainable alternative to natural sand. Numerous studies have been conducted to evaluate the suitability of various recycled materials for road construction, aiming to prevent C&D waste from going to landfill (Arulrajah *et al*., 2014, Alnedawi *et al*., 2021; Maghool *et al*., 2021).

A widely accepted practice in Australasia is the stabilisation of granular pavement materials and underlying soils. This process involves the mechanical incorporation of reactive agents to enhance the materials' properties (Browne, 2020). Traditional pavement stabilisation often uses high cement content, resulting in a stiff, fully bound base layer prone to shrinkage cracks. Although slower-setting additives are now used to reduce stiffness, the focus on achieving high unconfined compressive strength (UCS) values still leads to cracking issues (Ramanujam *et al*., 2007). A variety of research studies have explored the performance of stabilised recycled materials using a range of chemical stabilisation methods (Senanayake *et al*., 2022; Mohammadinia *et al*., 2017; Maghool *et al*., 2022). According to a research, the key stabilisation additives that help prevent fatigue cracking are lime–fly ash (FA), emulsion with cement, and foamed bitumen (FB) (Ramanujam and Jones, 2007).

Bitumen stabilisation is achieved by mixing bitumen, either as foam or emulsion, with granular materials, either in a plant or through in situ stabilisation. The purpose of bituminous stabilisation is to add cohesion to non-plastic materials or to reduce the moisture sensitivity of cohesive materials to enhance their stability and mechanical properties (Austroads, 2019). FB is created by injecting a small amount of cold, finely misted water into hot penetration grade bitumen within an expansion chamber. This process temporarily lowers the viscosity of the bitumen, allowing it to mix effectively with aggregates at ambient temperature and existing moisture levels (Jenkins *et al*., 2000). Foamed bitumen stabilisation (FBS) is considered more flexible than other stabilisation treatments, with the aim of creating a road pavement that is strong, flexible, and impermeable. A study indicated that FBS is a cost-effective alternative to traditional cement, lime stabilisation methods (Saleh, 2007). Research conducted using the Accelerated Pavement Testing Facility demonstrated that natural granular material stabilised with 1.2%–2.8% FB and 1% cement exhibited better performance, with reduced rutting, compared to stabilisation using only cement (1%) or only FB (2.2%) (Gonzalez *et al*., 2009).

In earlier study, the performance of these FB-stabilised blends of RCA, which were mixed with RG, recycled plastic, and reclaimed asphalt pavement (RAP) was assessed through experimental testing. The results showed that indirect tensile strength, UCS, and California bearing ratio (CBR) values decreased with increasing RAP, RG, and recycled plastic contents. Compared to unbound blends, the FB-stabilised mixtures showed improved resistance to permanent deformation, attributed to the combined effects of FB and the filler, hydrated lime (Maghool *et al*., 2022). In a separate investigation, FA and asphalt emulsion were utilised to create a stabilised mixture of marginal crushed rock, with the objective of enhancing the mechanical performance of low-grade materials for use as a sustainable pavement base. Compared to cement-stabilised crushed rock with a comparable UCS, the FA asphalt emulsion stabilised mixture demonstrated superior flexural strength, indirect tensile strength, resilient modulus, and fatigue life under indirect tensile loading, while also exhibiting a reduced carbon footprint (Yaowarat *et al*., 2021).

A study examined the flexural fatigue behaviour of FB-stabilised crushed rock mixtures under varying conditions, including temperature, bitumen content, secondary binders, density, and moisture levels, with the goal of creating a more robust design method for FB-stabilised pavements. The findings revealed that the flexural fatigue life of FB-stabilised beams improved as density and bitumen content increased but declined with rising temperature and moisture content (Pitawala *et al*., 2022). Research revealed that FB-stabilised materials exhibited significant behavioural changes with even a one-degree variation from the initial test temperature. It is essential to account for temperature variations in both mix and pavement designs involving these materials. The same study demonstrated that the FB-stabilised mixture exhibited a significant increase in resistance to failure and elastic modulus after an extended curing period (Dal Ben *et al*., 2014). A study comparing field constructed and laboratory manufactured FB-stabilised beams revealed that field samples were less sensitive to temperature and frequency changes than their laboratory counterparts (Pitawala *et al*., 2021.). A study demonstrated that the FB-stabilised mixture, composed of 50% crushed rock and 50% RAP, exhibited strong rut resistance, even with the high proportion of recycled content. Laboratory wheel tracking tests conducted on the field material at an elevated temperature of 60°C also confirmed its excellent rut resistance (Bodin *et al*., 2020).

Research evidence supports the use of waste toner, and geopolymers as a secondary binder in asphalt mixtures; but evidence of its application as a secondary binder for stabilising base or subbase pavement materials is limited. A study found that a mixture of residual toner powder and 10% calcite served as a good bitumen additive, enhancing the material's application properties (Vucinic *et al*., 2013). Studies have shown that incorporating waste toner into asphalt binder enhances its stiffness, decreases moisture susceptibility, and reduces its potential for pumping. The inclusion of waste toner reduced the workability and moisture-induced damage resistance of asphalt mixtures, while improving their resistance to rutting (Huang *et al*., 2021). In one example, adding waste toner to pavement aggregate led to workability issues, including challenges with rolling and flaking caused by insufficient adhesion (Solaimanian *et al*., 1998).

Geopolymers offer a sustainable alternative to traditional cementitious systems, providing comparable mechanical properties while reducing environmental impact compared to Portland cement (Duxson *et al*., 2007). Numerous studies have been conducted on FA and ground granulated blast furnace slag (S)-based geopolymer stabilisation of pavements containing RCA, crushed brick, RAP, and other recycled materials. These studies demonstrated that S-based geopolymer stabilisation achieved higher compressive strength compared to FA-based geopolymer stabilisation (Doan *et al*., 2024; Mohammadinia *et al*., 2016). However, limited research has focused on the use of FA and S geopolymers as secondary binders in FBS. In a study, S-based geopolymer was used as a secondary binder for in situ FBS of 100% RAP. The results showed that incorporating S-based geopolymer led to a significant improvement in tensile strength and also caused a notable reduction in moisture resistance (Barisoglu *et al*., 2023). In a separate study, 0%–5% FA was intended for use as a filler in the FBS of a crushed rock and crushed limestone mix. However, preliminary investigations revealed that FA did not enhance the mechanical strength of the mix and functioned only as a mineral filler to support gradation (Jitsangiam *et al*., 2011). Existing literature explaining current trends in FBS, including geopolymer stabilisation, is summarised in Table 1.

This study investigated the stabilisation of mixes containing RCA and RG using 3% FB, supplemented with alternative secondary binders such as 1%, 2%, 3%, and 4% recycled toner aggregate (RTA) and 10%, 20%, and 30% geopolymers S, FA and (FA + S) by mass of RCA and RG blend. The strength and stiffness properties of the stabilised blends were assessed in the laboratory

Table 1. Summary of literature on current trends in FBS of recycled materials on pavements

Author	Research objectives	Recycled materials utilised	Key findings and associated advantages	Key findings and associated challenges
Maghool *et al*., 2022	Evaluate strength and deformation of FB-stabilised waste materials	RCA, RAP, RG, and recycled plastic	FB and hydrated lime mixtures showed improved deformation resistance due to synergistic effects	Higher RAP, RG, and recycled plastic contents reduced strength
Bodin *et al*., 2020	Study deformation of FBS materials and effects of RAP increase	50% RAP with crushed rock	Minimal pavement surface deformation and low rates of deformation under accelerated loading in both early-life and cured states	Adding 50% RAP raised deformation rate but stayed below the control asphalt at similar temperatures
Doan *et al*., 2024	Evaluate one-part FA and S geopolymers for stabilising C&D aggregates	RCA, crushed brick and RAP	Strength gains occurred at 0.1 activator ratio for CB and RCA, and 0.05 for RAP, exceeding traditional geopolymers Longer curing improved one-part geopolymer strength more than higher temperatures	Low fine contents notably reduced strength, especially at 10% precursor dosage
Mohammadinia *et al*., 2016	Investigate geopolymer-stabilised C&D materials using FA and S with varied activator-to-binder ratios	RCA, crushed brick and RAP	Geopolymer stabilisation was most effective for RCA, with S binders giving higher strength than FA binders	Crushed brick had low strength, with 7-day curing and additives showing little improvement
Barisoglu *et al*., 2023	Evaluate cold-recycled FB mixes with 100% RAP for base layers	100% RAP	S-based geopolymer boosted tensile strength, and all active fillers improved moisture resistance by 30%–35%	Adding S-based geopolymers with FB didn't raise wet indirect tensile strength but reduced moisture sensitivity

through a series of UCS, CBR, and indirect tensile modulus (ITM_r) tests.

Materials and methods

This study evaluated the potential of stabilising blends of 50% RCA and 50% fine RG using FB. The FBS process involved adding supplementary cementitious secondary binders, such RTA, which derived from waste toner and post-consumer recycled soft plastics and geopolymers made from industrial waste products such as S and FA.

As an initial step in this research, the geotechnical properties of unbound RCA and RG mixes were obtained. Figure 1 shows the unbound RCA and RG mixture and the blending apparatus. A modified Proctor compaction test was performed on unbound RCA and RG mixtures to obtain the relationship between moisture content and dry density of the blends (SA, 2017). Particle size distribution (PSD) test was performed for both unwashed and washed unbound blends (SA, 2009). For PSDs, the requirements of the local road authority (LRA), VicRoads, were adhered to, as correct distribution is important for improving compaction, enhancing load-bearing capacity, increasing durability, and optimising permeability. The Los Angeles (LA) abrasion test was conducted on the coarser fraction of the unbound blend to assess the hardness of the source material (ASTM, 2006). The flakiness index test was conducted on the unbound blend to measure the proportion of elongated or flaky particles, which aids in improving pavement compaction and stability (SA, 1999).

It is important to ensure that the foaming characteristics of FB are sufficient to adequately coat the fine particles with bitumen. In this study, the characteristics of Class 170 bitumen, the expansion ratio and half-life, were determined based on parameters established in previous research (Maghool *et al*., 2022). The expansion ratio quantifies the ratio of the maximum volume attained by FB to its initial volume prior to foaming. The half-life, on the other hand, refers to the time required for the FB volume to decrease to half of its maximum value (Austroads, 2017a). An increase in water content raises the expansion ratio value while reducing the half-life value. Conversely, lower water content results in highly viscous FB, leading to a lower expansion ratio value. Higher water content decreases viscosity, thereby increasing the expansion ratio value. A longer half-life allows the mixture additional time before settling occurs. Guided by prior research (Maghool *et al*., 2022) and supported by economic and environmental considerations, the optimal FB parameters listed in Table 2 were selected for stabilising mixtures containing 50% RCA and 50% RG.

In the second phase of the research, tests were conducted to determine the strength and resilient modulus characteristics of stabilised blends consisting of 50% RCA and 50% RG, with FB and varying contents of RTA as secondary binders. The Austroads test

Figure 1. (a) Unbound RCA and RG mixture. (b) Blending apparatus

Table 2. Optimum FB parameters for C170 bitumen (Maghool *et al.*, 2022)

Parameters	Set value
Optimum foaming moisture content: %	3.0
Optimum foamed bitumen content: %	3.0
Foaming agent: %	0.5
Air pressure: bars	5
Water pressure: bars	6
Bitumen temperature: °C	175–180

method, AGPT/T302, was followed for mixing materials for FBS (Austroads, 2017b). The FB was created using the Wirtgen WLB 10S machine, which is depicted in Figure 2. The formation of FB mixes involved injecting hot bitumen, together with a specified amount of cold water and compressed air, into a mixer containing the RCA and RG blend. An optimal FB content of 3.0% was chosen and applied throughout all testing phases. The application of 3% FB in pavement stabilisation is widely adopted, supported by substantial prior research (Halles *et al.*, 2009). This proportion typically provides adequate coverage of the fines and sand particles within the pavement material, ensuring an optimal balance between the layer's stiffness and flexibility. RTA was incorporated as an active secondary binder in quantities of 1%, 2%, 3%, and 4% by mass of RCA and RG blend to promote uniform dispersion of FB within the mixture. A 0.5% foaming agent was added to enhance the properties of the FB. In this phase, a blend containing a traditional secondary binder, cement (C), in the composition RCA + RG + 3% FB + 2% C, was used as the control. The optimum moisture content (OMC) and maximum dry density (MDD) were obtained for all five blends, including the control, using the modified Proctor compaction test (SA, 2017). The CBR tests were conducted under soaked conditions to evaluate the strength of the above mentioned five mixtures (SA, 2014). UCS tests were conducted on stabilised samples cured at 20°C and 40°C, each for a duration of 3 days (SA, 2008). The ITM$_r$ tests were conducted on the same blends to determine the ITM$_r$ values at three conditions: initially after 3 h of drying at room temperature, after 3 days of drying with curing at 40°C, and after 3 days of drying with curing at 40°C, followed by 10 min of soaking prior to testing (SA, 1995). During ITM$_r$ testing, a cyclic vertical compressive load was added in alignment with the vertical diametral plane, and horizontal displacements were recorded at the midpoint of the horizontal diameter (Austroads, 2019). The specimens were compacted using a standard Marshall mould, applying 50 blows per side. Testing began with five initial load pulses to measure the seating force, followed by an additional five cycles to evaluate the resilient modulus, using peak force and horizontal deformation data. Figure 3 illustrates the ITM$_r$ test sample along with the testing setup. The resilient modulus was obtained from Equation 1 (Austroads, 2017c):

Figure 2. Laboratory-scale apparatus used to create FB

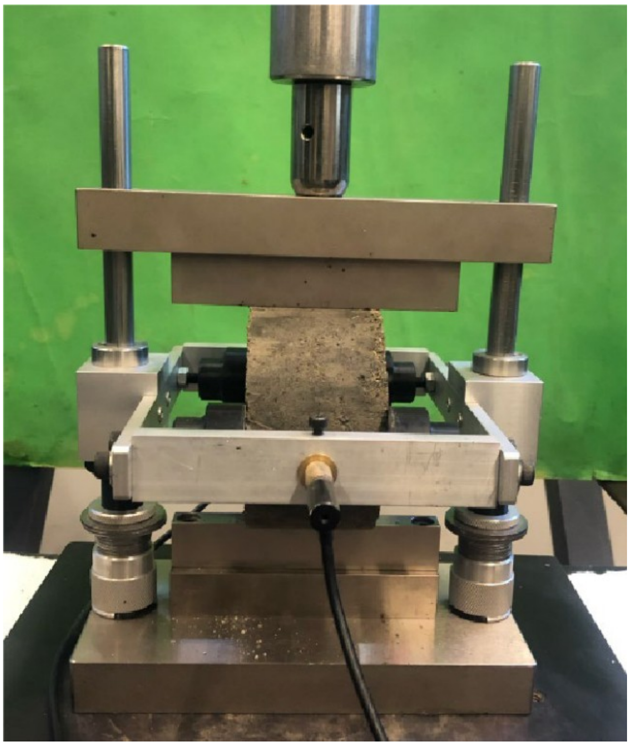


Figure 3. ITM_r testing setup and sample

1. $E = P(v + 0.27)/Hh_c$

where P represents the peak load, v is Poisson's ratio (assumed to be 0.4), H denotes the recovered horizontal deformation, and h_c is the average height of the specimen.

In the third stage of the research, tests were conducted to determine the strength and stiffness characteristics of stabilised mixtures composed of RCA and RG, with 3% FB and varying contents (10%, 20%, and 30%) of geopolymers as sustainable secondary binders. Figure 4 presents the physical appearance of FB material along with the secondary binder materials FA and S used in this study. Commercially available class F FA, S, and a 50:50 blend of FA and S were utilised as solid precursors (P) in the alkali activation process for geopolymer production. A liquid alkaline activator (L), consisting of a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions, was utilised to facilitate the alkali activation of FA, S, and the (FA + S) blend. For effective strength development and practical application, the optimal concentration of NaOH solution is reported to range between 8 and 12 mol. In this study, a concentration of 8 mol was selected, considering both economic and safety considerations (Hanjitsuwan *et al*., 2014, Rattanasak et al., 2009, Arulrajah *et al*., 2018). The Na_2SiO_3 solution used in this study was a commercially available D-grade liquid Na_2SiO_3 with a molar ratio of 2. Based on previous studies, the optimal ratios for strength development in alkali-activated FA and S were found to be 70:30 for Na_2SiO_3:NaOH and 0.4 for L/P, and the same ratios were adopted for this study (Lin *et al*., 2023). In this stage, nine mixtures – RCA + RG + 3% FB + 10%, 20%, and 30% FA; RCA + RG + 3% FB + 10%, 20%, and 30% S; and RCA + RG + 3% FB + 10%, 20%, and 30% (FA + S) – were evaluated using modified compaction, CBR, UCS, and ITM_r tests. Figure 5 presents the sequential testing procedure adopted in this study, illustrating the various material compositions and the laboratory tests conducted under different conditions across different stages.

Results and discussion

The 50% RCA and 50% RG unbound blend was considered the parent material for the series of stabilisation tests conducted for this research. The OMC and MDD of the unbound mixture were 9.22% and 2.081 t/m^3, respectively, and the compaction curve is presented in Figure 6. The LA abrasion value for the recycled material source was 26, the flakiness index of the material was 13, and both values met the LRA's requirements for base and subbase materials (Vicroads, 2018; Vicroads, 2017a). PSD analyses were performed for both washed and unwashed unbound blends. The

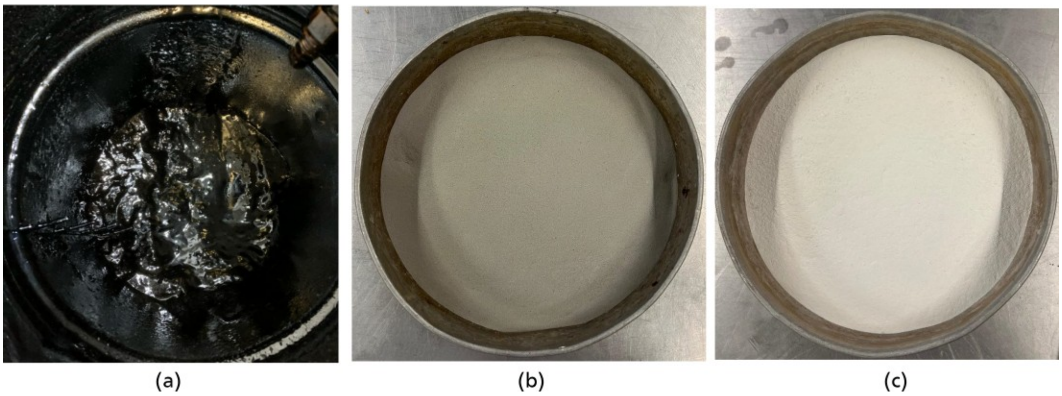


Figure 4. (a) Foamed bitumen. (b) Fly ash, and (c) slag used in testing

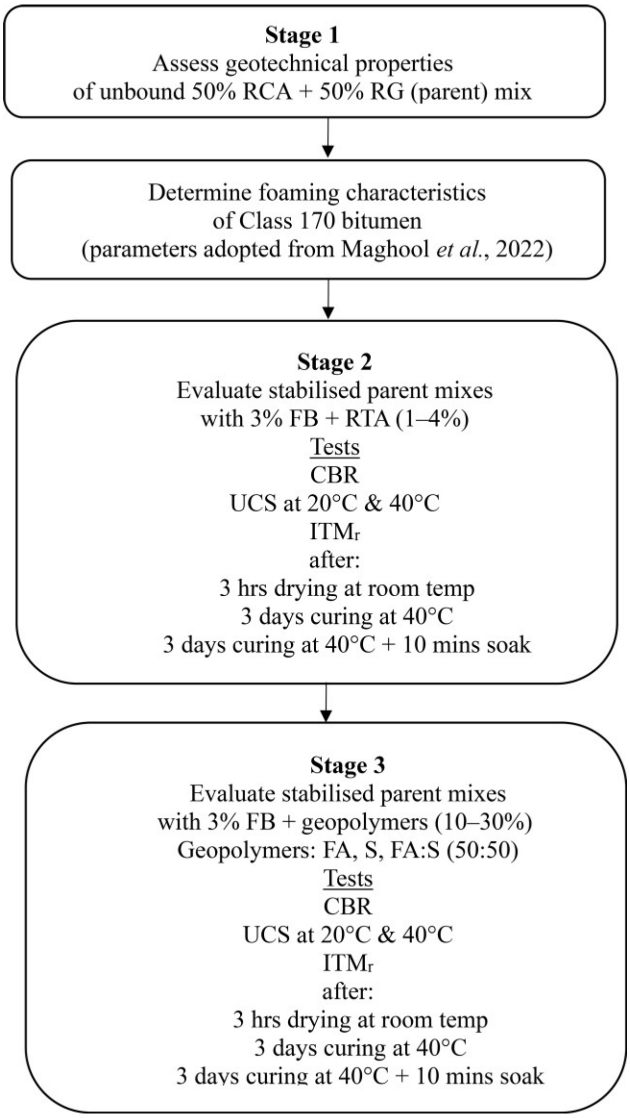


Figure 5. Stages of laboratory testing

results, along with the LRA recommended grading envelope for upper and lower subbase materials, are presented in Figure 7. The grading of the unwashed blend, which was most relevant to the research, fell within the allowable grading envelope (Vicroads, 2017a). Accordingly, the unbound blend of 50% RCA and 50% RG met the necessary LRA requirements for FBS.

Four FB-stabilised blends, utilising RTA as a secondary binder, were evaluated to assess their strength and stiffness for potential application in road construction. The results, presented in Table 3, were compared against a control blend in which 2% cement served as the secondary binder for FBS. As the RTA content increased, both the OMC and MDD decreased, as shown in Figure 8. The CBR values of the RCA + RG + 3% FB + 1% RTA and RCA + RG + 3% FB + 2% RTA blends were both 81%, which marginally met the LRA requirements for use in base and subbase applications. A previous investigation on comparable unbound RCA + RG mixes reported CBR values ranging from 116% to 147% (Maghool *et al.*, 2021). The LRA's Code of Practice specifies that recycled materials used in base or upper subbase layers must achieve a minimum CBR of 80%. In contrast, the Earthworks Specification allows values as low as 6% for materials used in capping, verges, structural fill, or select fill. Although blends containing more than 2% RTA did not meet the requirements for base or upper subbase layers, they demonstrated improved suitability for use in general fill applications (Vicroads, 2017a; Vicroads, 2015). However, unlike modulus, the CBR is an empirical value that does not directly correlate with any fundamental engineering property and is generally considered an indirect measure of shear strength. UCS tests were performed on FB-stabilised RCA and RG blends with varied RTA secondary binder contents, cured at temperatures of 20°C and 40°C for a period of 3 days, with the results, including those of the control blends, illustrated in Figure 9. Similar to the CBR results, UCS values decreased with increasing RTA content at both curing temperatures. In comparison to the control blend containing cement as the secondary binder, the blends incorporating RTA exhibited 90%–94% lower UCS values after 3 days of curing at 20°C, and 69%–77% lower UCS values after 3 days at 40°C. Meanwhile, the blends cured at 40°C exhibited a strength increase ranging from 13% to 24%. However, in pavement stabilisation, elevated UCS values result in increased stiffness, which can lead to issues with cracking.

ITM$_r$ tests were conducted on the control blend (RCA + RG + 3% FB + 2% C) after 3 h of drying at room temperature, 3 days of drying and curing at 40°C, and 3 days of drying and curing at 40°C followed soaking, as shown in Table 3. According to the LRA

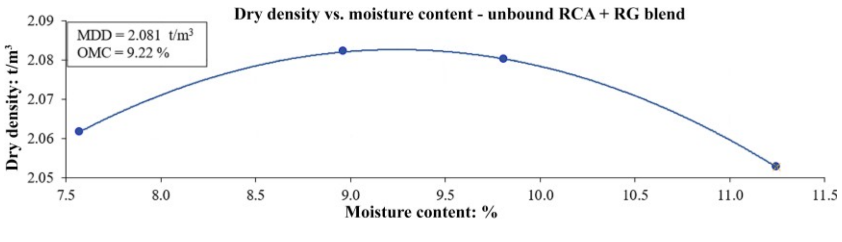


Figure 6. Dry density plotted against moisture content for the unbound RCA + RG blend

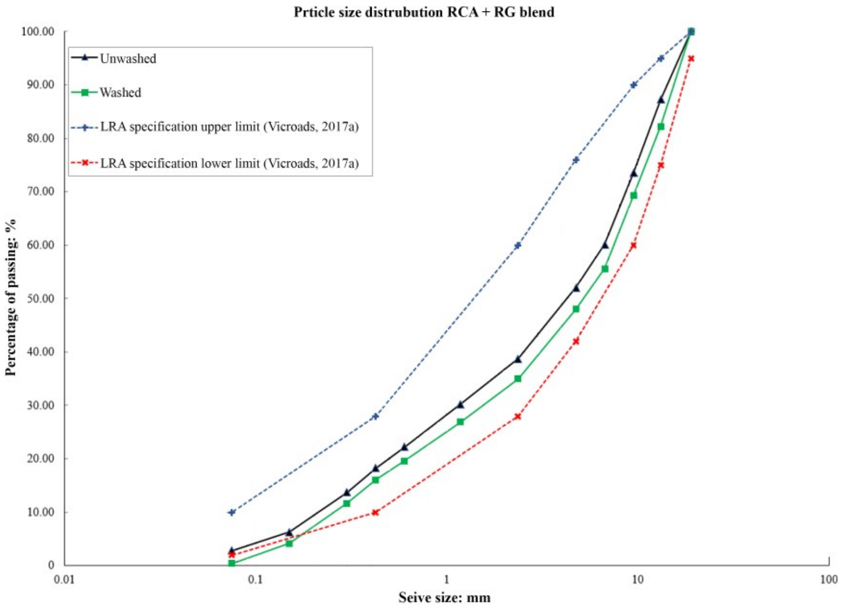


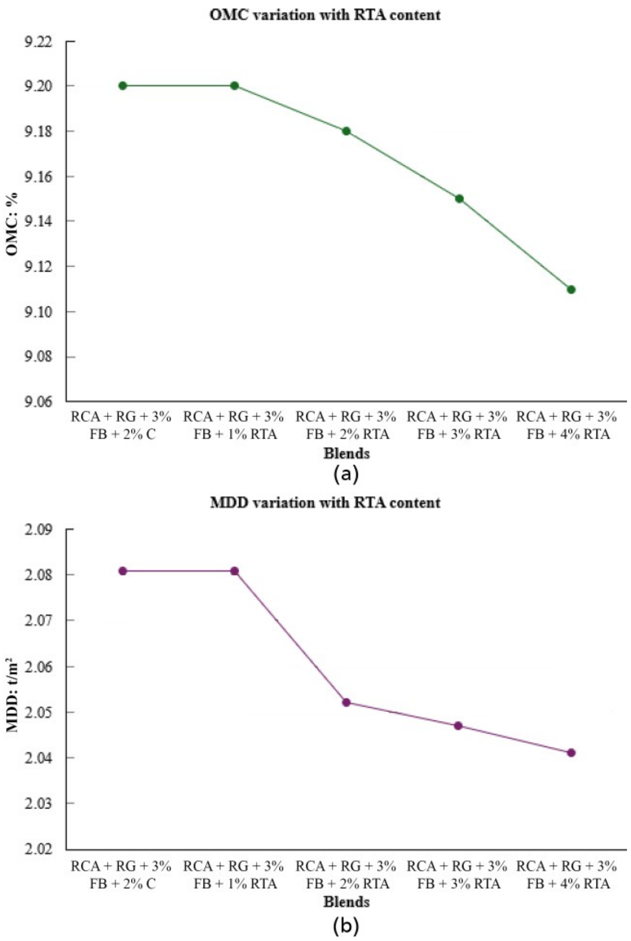
Figure 7. Particle size distribution of unbound RCA and RG blend

Table 3. OMC, MDD, CBR, UCS, and ITM_r results of FB-stabilised blends with cement or RTA

Blends	OMC: %	MDD: t/m^2	CBR: %	UCS 3-day 20°C: MPa	UCS 3-day 40°C: MPa	ITM_r initial 3 h: MPa	ITM_r 3-day (dried): MPa	ITM_r 3-day (soaked): MPa	Retained resilient modulus
RCA + RG + 3% FB + 2% C	9.20	2.081	430	1.510	2.063	1157	1514	797	0.53
RCA + RG + 3% FB + 1% RTA	9.20	2.081	81	0.156	0.484	Failed	1316	740	0.56
RCA + RG + 3% FB + 2% RTA	9.18	2.052	81	0.101	0.613	Failed	1210	955	0.79
RCA + RG + 3% FB + 3% RTA	9.15	2.047	72	0.107	0.641	Failed	1140	712	0.63
RCA + RG + 3% FB + 4% RTA	9.11	2.041	59	0.097	0.573	Failed	495	101	0.20

specifications, FB-stabilised materials should meet the following modulus requirements: an initial modulus greater than 700 MPa, a 3-day cured modulus between 2500 and 4000 MPa, and a soaked modulus between 1500 and 2000 MPa, and a retained modulus ratio greater than 0.5 (Vicroads, 2017b). The ITM_r value for the FB-stabilised control blend satisfied the LRA's requirement for the initial resilient modulus after 3 h. However, the control blend did not meet the required resilient modulus for both dried and soaked conditions after 3 days. All FB-stabilised blends containing RTA failed the ITM_r tests after 3 h drying, and the results for all blends containing RTA for both dried and soaked conditions did not conform to the LRA's requirements. Insufficient adhesion and compatibility issues with FB can result in weak bonding, potentially lowering the material blends' ITM_r (Vicroads, 2016). The results are presented in Table 3 and Figure 10.

A series of laboratory tests was conducted to assess the strength and stiffness properties of FB-geopolymer-stabilised blends containing RCA and RG. These blends included 10%, 20%, and 30% of geopolymers made from FA, S, FA + S, used as secondary binders to enhance FBS. All test results are shown in Table 4. In all blends, increasing the proportion of each geopolymer secondary content led to a decrease in both OMC and MDD values, as anticipated and shown in Figure 11. FA, S geopolymers typically have lower specific gravities compared to RCA or RG. As greater amounts of these lighter materials are incorporated into the blend, the overall bulk density of the mixture decreases, leading to a lower MDD. Furthermore, the increased presence of fine geopolymer particles enhances particle packing by filling voids, which contributes to a reduced OMC (Lin *et al*., 2023). In many instances, stabilisation leads to a reduction in OMC compared to



(a)

(b)

Figure 8. Variation of (a) OMC and (b) MDD with RTA content

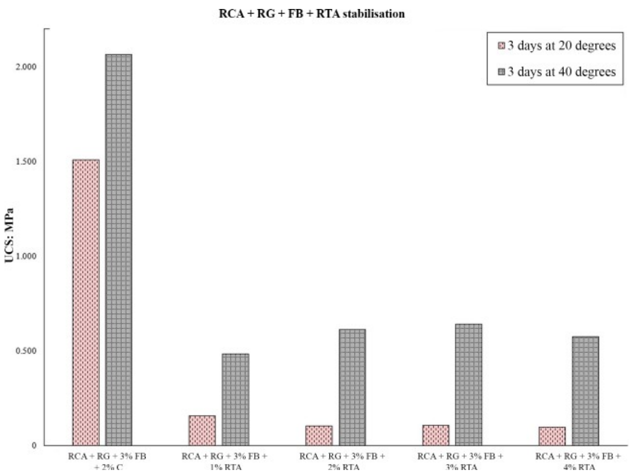


Figure 9. UCS values of FB-stabilised blends with various RTA contents

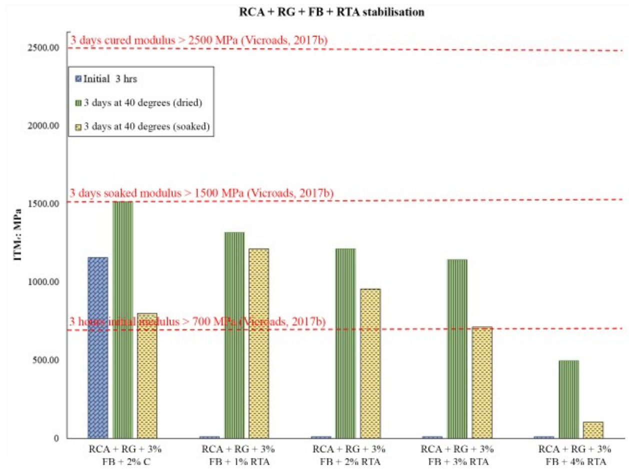


Figure 10. ITM$_r$ values of FB-stabilised blends with varying RTA contents after 3 h of drying, 3 days of drying, and 3 days of drying followed by soaking conditions

unbound material mixes (Lin *et al*., 2023). This reduction is commonly attributed to binder-induced changes, such as improved particle packing, which reduce the material's water absorption capacity. As OMC is influenced by various factors such binder composition, there is no standard OMC value for stabilised mixes. However, previous studies on similar unbound material blends have reported OMC values exceeding 10% (Maghool *et al*., 2021). In contrast, the stabilised mixes assessed in this study showed lower OMC values, ranging from 8.5% to 9.75%. With the exception of the S category, all geopolymer types demonstrated an increasing trend in CBR values as the proportion of the secondary binder increased, as illustrated in Figure 12. In contrast, increasing the S content from 20% to 30% negatively affected the workability of the mixture, likely due to the irregular shape of the S particles, which impeded uniform mixing and promoted agglomeration. Overall, all blends, except for RCA + RG + 3% FB + 10% FA, met the LRA's CBR requirement of 80%. Figure 13 illustrates the UCS test results for all blends containing geopolymers, as well as the control blend. In UCS tests, blends containing FA as a secondary binder demonstrated an increase in UCS values with higher FA content. The 3-day UCS values at 40°C were consistently higher than those at 20°C. Heating accelerates the pozzolanic reaction, enhancing cementation and increasing the strength of the stabilised material. The maximum UCS recorded was 2.713 MPa, achieved with the RCA + RG + 3% FB + 30% FA blend at 40°C. For blends using S as a secondary binder, UCS values decreased as the S content increased. Elevated temperatures did not enhance UCS for these blends; instead, UCS values decreased. Higher temperatures can speed up chemical reactions within the S, which might lead to a less stable interface with the bitumen and weaken the bonding strength. The maximum 3-day UCS recorded for S containing blends was 6.603 MPa, achieved with the RCA + RG + 3% FB + 10% S blend at 20°C. An increase in S and FA + S

Table 4. OMC, MDD, CBR, UCS, and ITM$_r$ results of FB-stabilised blends with geopolymers

Blends	OMC: %	MDD: t/m^2	CBR: %	UCS 3-day 20°C: MPa	UCS 3-day 40°C: MPa	ITM$_r$ initial 3-h: MPa	ITM$_r$ 3-day (dried): MPa	ITM$_r$ 3-day (soaked): MPa	Retained resilient modulus: %
RCA + RG + 3% FB + 10% FA	8.98	2.079	36	0.272	0.879	Failed	2590	2525	0.97
RCA + RG + 3% FB + 20% FA	8.69	2.057	144	1.150	2.668	767	2797	1215	0.43
RCA + RG + 3% FB + 30% FA	8.56	2.005	291	2.022	2.713	1119	1920	688	0.39
RCA + RG + 3% FB + 10% S	9.72	2.124	686	6.603	5.420	Failed	2706	2106	0.78
RCA + RG + 3% FB + 20% S	9.36	2.098	739	6.174	4.081	1001	5232	1529	0.29
RCA + RG + 3% FB + 30% S	9.17	2.093	595	1.098	1.418	548	1880	915	0.49
RCA + RG + 3% FB + 10%(FA + S)	9.13	2.116	364	4.782	4.185	Failed	5672	4390	0.77
RCA + RG + 3% FB + 20%(FA + S)	8.79	2.091	534	4.979	3.059	1000	3521	2601	0.74
RCA + RG + 3% FB + 30%(FA + S)	8.67	2.057	864	0.476	0.720	759	1988	929	0.47

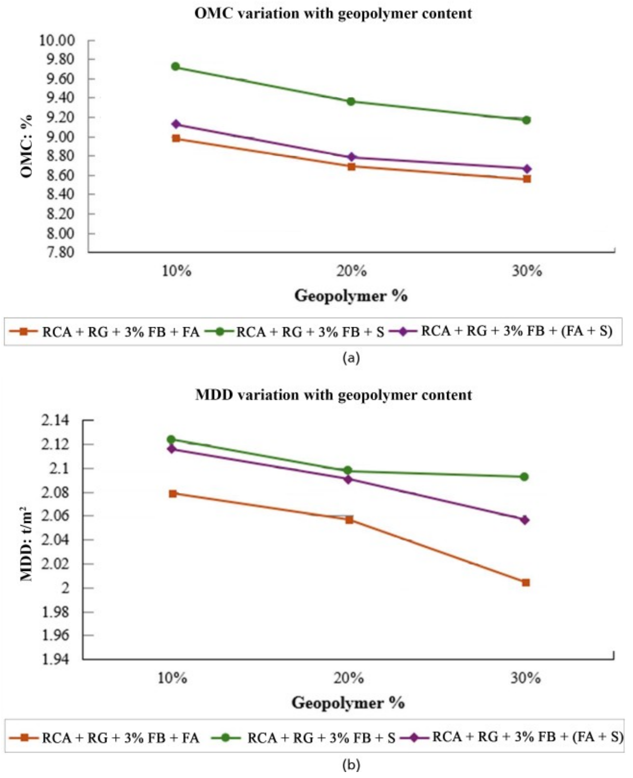


Figure 11. Variation of (a) OMC and (b) MDD with geopolymer content

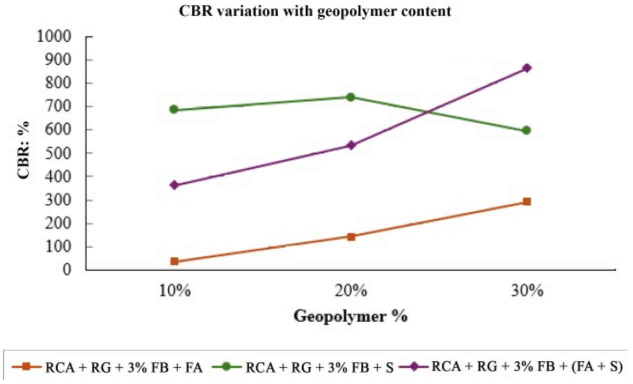


Figure 12. CBR variation with geopolymer content

contents resulted in reduced workability, primarily due to the angular and irregular shape of the slag particles, which caused the material to agglomerate into a paste-like mass and hindered uniform mixing. Additionally, the rough surface texture of the slag particles diminished the effectiveness of FB coating, further compromising the integrity of the mix. These combined factors contributed to the observed reduction in UCS with increasing proportions of S and FA + S. In contrast, FA used alone, owing to its spherical particle morphology, facilitated more uniform mixing and improved coating efficiency, thereby enhancing the compressive strength of the stabilised material. The highest UCS value, 4.979 MPa, was obtained from the RCA + RG + 3% FB + 20%(FA + S) blend cured at 20°C. Blends incorporating 10% S, 20% S, 10% (FA + S), and 20% (FA + S) demonstrated significantly higher UCS values than the control blend at both 20°C and 40°C, where the control blend achieved 1.510 MPa and 2.063 MPa, respectively. Among the geopolymer types, S was the most effective secondary binder in enhancing the strength of the stabilised blends. FA is mainly composed of silica, alumina, and iron oxide, whereas S consisted predominantly of glassy phase materials along

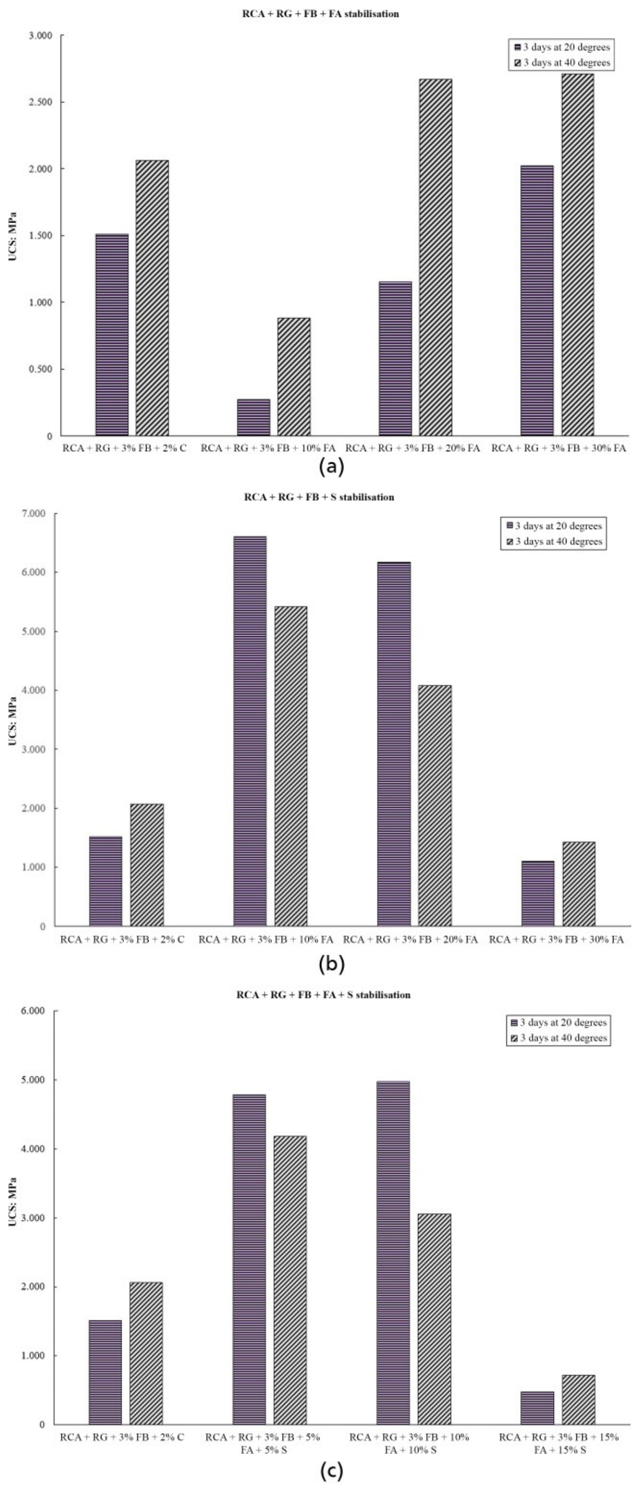


Figure 13. UCS values for the control blend and FB-stabilised blends with secondary binders: (a) FA, (b) S, (c) FA + S

with crystalline calcite (Sun *et al*., 2024). The high calcium content in S increases its reactivity with moisture, leading to the formation of a stronger stabilised material.

ITM_r tests were performed on the FB-stabilised blends incorporated with FA, S, and FA + S, and the test results are presented in Figure 14. The 3-day dried samples exhibited the highest ITM_r values compared to those dried for 3 h or dried for 3 days followed by soaking, regardless of their composition. FB-stabilised blends containing FA (10%, 20%, and 30%) did not conform with LRA specifications. The blend of RCA + RG + 3% FB + 20% S achieved resilient modulus values of 1,001 MPa after 3 h of drying, 5,232 MPa after 3 days of drying, and 1,529 MPa after 3 days of drying followed by soaking. These values met the LRA requirements but did not satisfy the retained resilient modulus criteria. The blend of RCA + RG + 3% FB + 20%(FA + S) achieved resilient modulus values of 1,000 MPa, 3,521 MPa, and 2,601 MPa under 3-hour drying, 3-day drying, and 3-day drying followed by soaking, respectively. The blend exhibited a retained resilient modulus of 0.74, and therefore, it satisfies all the requirements set forth by the LRA specifications. Compared to dried samples, wet conditioning can cause water ingress into the partially formed binder matrix, weakening interparticle bonds. This leads to reduced cohesion and elasticity of the blend, thereby directly decreasing the tensile modulus. FB forms a stabilising film around the aggregates; however, in the presence of excess moisture, adhesion between the bitumen and aggregates deteriorates, resulting in a loss of stiffness and resilient modulus (Vinet-Cantot *et al*., 2019). FBS involves reducing stiffness and enhancing the flexibility of the bound layer, which improves its fatigue resistance (Ramanujam and Jones, 2007). The ITM_r offers an indirect measure of fatigue resistance by assessing stiffness under tensile stress. Therefore, 20%(FA + S) is recommended as secondary binders for FBS in pavement applications.

Conclusions

This laboratory-based experimental study was conducted to investigate the strength and stiffness properties of FB-stabilised blends containing 50% RCA and 50% RG, supplemented individually with various secondary binders, including RTA and the geopolymers FA, S, and FA + S.

CBR testing showed that the blends only marginally meet the LRA specification requirements, even when 1%–2% RTA is used as a secondary binder. UCS values are significantly lower compared to the control blend, even at increased 40°C temperature curing. The results for all blends containing RTA, under both dried and soaked conditions, failed to meet the LRA's requirements. RTA, which is typically composed of carbon and soft plastic, does not provide the same bonding properties as traditional binders like cement or hydrated lime. This weaker bonding reduces the overall strength of the stabilised material, leading to lower CBR and UCS values. The components in RTA contribute to reduced elasticity, lowering stiffness and, consequently, the ITM_r values. The chemical composition of RTA can also vary significantly between different brands and types, making it difficult to ensure consistent quality. While the FB-stabilised RCA and RG blends with RTA do

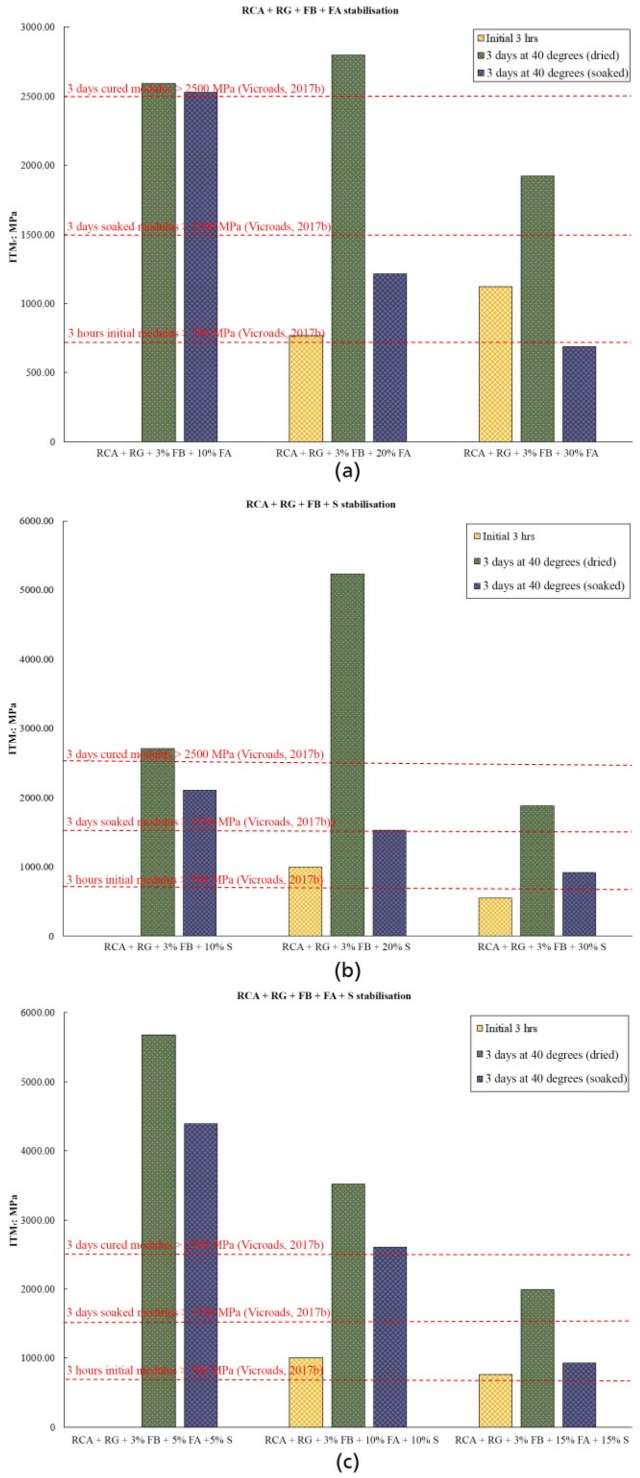


Figure 14. ITM$_r$ values of FB-stabilised blends with varying contents of (a) FA, (b) S, and (c) FA + S, measured after 3 h of drying, 3 days of drying, and 3 days of drying followed by soaking conditions

not fully meet the base LRA specifications for even roads with Equivalent Standard Axles less than 100, these blends are still overqualified for use in applications such as fills.

When performing FBS with FA, S, and FA + S as secondary binder geopolymers, each material behaves differently. With FA, increasing its content generally enhances both the CBR and UCS due to FA's pozzolanic characteristics, and UCS values improve with higher temperatures. In contrast, increasing the S content tends to reduce both CBR and UCS, as S forms coarser crystalline structures that do not integrate as effectively with FB. Higher S levels can result in a more brittle, less flexible pavement structure, and unlike FA, UCS values with S do not improve at higher temperatures. In ITM$_r$ tests, the blend RCA + RG + 3% FB + 20%(FA + S) met LRA specification requirements, demonstrating suitability for pavement stabilisation as an alternative to conventional high carbon-emitting methods.

Field trials may verify the effectiveness of the secondary binders mentioned above. However, several past laboratory and field comparisons of FBS have indicated that the field resilient modulus closely matches the soaked resilient modulus observed in the laboratory (Ramanujam and Jones, 2007). Based on the findings, it is recommended to use 20%(FA + S) as a secondary binder for the FBS of pavements containing RCA and RG.

CRediT authorship contribution statement

Muditha Senanayake: conceptualisation, investigation, methodology, software, writing – original draft. Youli Lin: conceptualisation, investigation, writing – review and editing. Arul Arulrajah: conceptualisation, resources, supervision, funding acquisition, writing – review and editing. Farshid Maghool: conceptualisation, resources, supervision, funding acquisition, writing – review and editing. Suksun Horpibulsuk: conceptualisation, writing – review and editing.

Data availability

Data will be made available on request.

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