Soils and Rocks

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743
ISSN-e 2675-5475

Durability and mechanical long-term performance of reclaimed asphalt pavement stabilized by alkali-activation

Alessandro Graeff Goldoni[1], Deise Trevizan Pelissaro[1], Eriky Silveira[1], Pedro Domingos Marques Prietto[1], Francisco Dalla Rosa[1#]

Article

Keywords
Reclaimed asphalt pavement
Fly ash
Alkali activated binder
Durability
Long-term performance

Abstract

The application of alkali-activated industrial by-products for the stabilization of reclaimed asphalt pavement (RAP), can become a sustainable solution to reduce the carbon footprint of road construction and maintenance activities. Furthermore, this approach can also reduce the increasing depletion of natural resources. Thus, the durability and long-term mechanical performance of RAP stabilized with alkali-activated fly ash were assessed in this study. The alkaline activator was a solution composed of sodium hydroxide and sodium silicate. To this extent, unconfined compressive strength (UCS) and durability tests were conducted in this research. The proposed alkali-activated binder significantly increased the UCS of RAP mixtures, with long-term (365 days) results reaching values up to 32 MPa; fulfilling the strength requirements for cement-stabilized soil mixtures and even stable inorganic binder materials for road base and sub-base layers of pavements. These results indicate that when stabilized with an alkali-activated fly ash binder, RAP presents several applications for road engineering; even when subjected to seasonal variations in humidity and temperature, as shown by the durability tests.

1. Introduction

The increase in traffic load has been a constant concern on the performance of existing roadways. In Brazil, maintenance operations are mainly focused on resurfacing the older asphalt layer; however, to preserve a satisfactory Level of Service (LOS), the other structural layers of the pavement should also be considered for maintenance. Among the different solutions available to improve the structural response, reclaimed asphalt pavement (RAP) materials are becoming a viable option to increase the mechanical performance of pavements.

The increase in the extraction of raw materials for roadway applications has been the focus of different studies, especially regarding its impact on mechanical consequences and environmental and economic aspects. Traditional techniques, such as granular materials stabilized with Portland cement (PC), increase the bearing capacity of pavements. Furthermore, alternative types of cement have shown comparable mechanical and economical performances to OPC, while resulting in better environmental behavior. It is estimated that 7% to 8% of total the global CO_2 generation results from PC production (Celik et al., 2015; Luukkonen et al., 2018). The growing PC demand on infrastructure construction or maintenance operations has represented a critical issue for Global Warming Potential (GWP) since these operations usually consume reasonable volumes of raw materials.

Different sustainable techniques have been proposed to improve the bearing capacity of granular materials with PC, such as biopolymers (Rezende et al., 2021; Porter et al., 2018), lime-ash blends (Haas & Ritter, 2019; Shen et al., 2007) and geosynthetic reinforcements (Consoli et al., 2009; Gowthaman et al., 2018; Wu et al., 2015). On the other hand, alkali-activated binders have represented an alternative to the chemical stabilization of granular materials. Alkali-activated mixtures are normally composed of two components: precursors (e.g. slags, amorphous silica, or silicates) and activators (e.g. solid sodium or potassium hydroxide). It is important to highlight that different industrial waste can be applied as precursor materials. In this sense, an important industrial waste is coal fly ash (FA) derived from the burning of coal in thermoelectric plants. More than 750 Mt of this waste are generated annually worldwide, but the average reuse in this global perspective is only about 25% (Blissett & Rowson, 2012).

Several studies have demonstrated the benefits of alkali-activated materials in RAP mixtures (Adhikari et al., 2020; Avirneni et al., 2016; Horpibulsuk et al., 2017; Hoy et al., 2018, 2016a, c; Singh & Middendorf, 2020). Most research has been focused on the strength behavior of the mixtures

#Corresponding author. E-mail address: dallarosa@upf.br
[1]Universidade de Passo Fundo, Programa de Pós-graduação em Engenharia Civil e Ambiental, Passo Fundo, RS, Brasil.

Submitted on July 2, 2022; Final Acceptance on October 21, 2022; Discussion open until May 31, 2023.
https://doi.org/10.28927/SR.2023.007422

while trying to set a relationship between field and laboratory performance. These alkali-activated mixtures are known for obtaining quick hardening when compared to PC, which in turn may be suitable for roadway structure reconstruction. In addition, alkali-activation could be seen as a competitive alternative to PC, considering that this technique is less energy intensive and, consequently, represents a more sustainable roadway life cycle.

On the other hand, the durability performance of alkali-activated mixtures is an important issue, considering that maintenance operations in granular layers are not usually a technical solution to improve roadway performance. Previous studies (Solanki & Zaman, 2014) have utilized the wetting/drying durability tests to evaluate the long-term performance of cemented layers. In general, the wetting-drying cycles increased the unconfined compressive strength (UCS), not representing the proper deterioration mechanism of the cemented layer; this increase in UCS is related to the water availability and temperature increase during testing, which accelerates the cementitious reactions. An alternative to this problem would be the frost/defrost durability test, however, this test is more appropriate for cold-weather places (e.g. Europe and North America). Tropical countries, such as Brazil, normally experience hot and wet weather conditions, resulting in more complex analysis of the weathering effects on long-term performance.

With that in mind, this research analyzed RAP mixtures stabilized with alkali-activated FA in different proportions, aiming to test their efficiency as a base material for flexible pavements. To this extent, wetting-drying durability tests were carried out on the stabilized RAP mixtures, with a new method for evaluating the weathering effects. In addition, cement fixation and strength of the mixtures were also evaluated in long-term periods (up to 365 days). This study aims to help in the promotion of innovative and sustainable materials such as RAP stabilized with alkali-activated FA in pavement construction without premature failures.

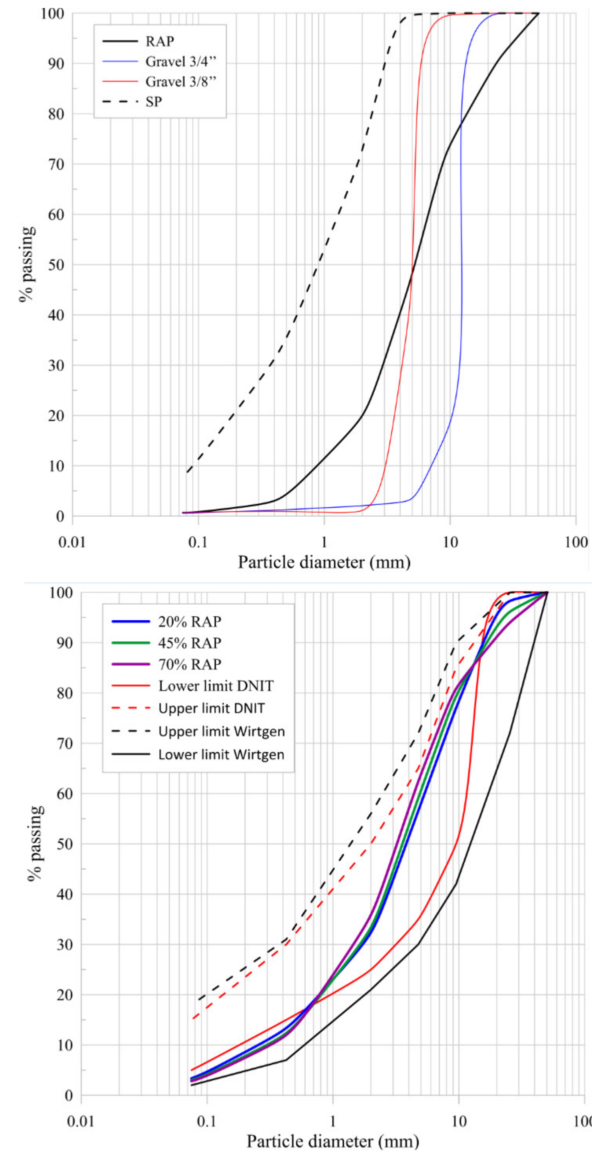

Figure 1. Grain size distribution of (a) granular materials and (b) mixtures.

2. Materials and methods

RAP was collected in a Brazilian roadway (BR-285, kilometers 275-276) in southern Brazil. The virgin aggregates were acquired from a deposit in the city of Passo Fundo, also southern Brazil; these aggregates are normally composed of basaltic rocks. In addition, tropical weather is observed in this region, with an annual average temperature of 16 °C (INPE, 2021). The RAP utilized in this research is the result of a milling operation, that was later transported and conditioned into specific piles. Considering that the milling process usually results in large pieces of RAP, all the mixtures were sieved down to 25 mm. Other three virgin aggregates: gravel 3/8" (20mm grain size), gravel 3/8" (12.5mm grain size), and stone powder (4.0mm grain size) were used in the mixture composition. The grain size distribution of the materials is shown in Figure 1a. The bitumen content of the RAP was determined in accordance with ASTM D2172 (ASTM, 2011), resulting in a value of 5.5%, while the specific gravity was 2.7 g/cm^3.

Two types of cement were explored in this research: high early-strength Portland cement (control group) (ASTM, 2012a) and alkali-activated cement. The first cement was chosen based on its capacity of developing most of its strength on the first days of curing.

As for the second cement, its composition was based on an alkali-activated solution obtained from the precursor and activator mixture. Two precursors were applied in this research, commercial metakaolin and FA, with FA being a byproduct of a thermoelectric power plant located in Charqueadas, southern Brazil (260 km from the local of this study). Two main minerals (diffraction intensity) of quartz and mullite were detected by XRD pattern in the region of 15 °- 50 ° 2θ for FA, as shown in Figure 2. Alkali-activate materials produced from sodium hydroxide regularly exhibit lower mechanical strength compared to mixtures produced with silicate-based activators (Provis et al., 2005). With that in mind, two compounds were used as activators to establish proper conditions for the precursor activation. The activation process was carried out using a solution combination of sodium hydroxide (NaOH) and sodium silicate. Due to its lower cost and reasonable efficiency, NaOH has also been used in different research. The 99% purity NaOH was dissolved into water and then added the precursors until a 10M concentration was reached.

2.1 Dosage parameters, molding, and curing procedures

RAP percentage in Full Depth Recycling (FDR) is considered an important issue in structural conception of pavements, considering that it establishes the necessary binder amount to reach a satisfactory mechanical performance. To obtain a proper grain size distribution, virgin aggregates were added to complement the fine grain size portion (Figure 1). This procedure was needed, once RAP was collected directly from the milling process, which results in larger particles, not representing the grain size of material after the reclamation process. Figure 1b shows the maximum and minimum limits of grain size distribution. These limits are compatible with the "C" granular distribution interval as specified in the Brazilian standard (DNIT, 2010). Table 1 shows the percentages of each material used to compose the grain size distribution curves that fit the DNIT curve "C" and Figure 1b shows the grain size distribution curves resulting from these compositions. The adopted mixture intervals have been considered satisfactory to the ones suggested by the Wirtgen company (Wirtgen GmbH, 2012).

As for the mixtures composition, the objective was always to utilize the highest amount of RAP possible. Thus, mixtures with 20, 45, and 70% of RAP stabilized with contents of 2%, 4%, and 6% cement were studied. The 45% RAP content was considered satisfactory and this value was later set for the stabilization analysis. The alkali-activated binder was utilized in amounts of 10%, 20%, and 30% (S/L ratio of 0.5). In addition, $NaOH:Na_2SiO_3$ ratios of 70:30, 80:20, and 90:10 were also studied for the alkali-activated cement. These mixtures were submitted to UCS testing to verify the requirements/guidelines for base layers of flexible pavements (DNIT, 2013). The weathering of the specimens was studied by the wetting-drying cycles of the durability test. It is important to highlight that the performance of the mixtures can also decline over time due to specimen deterioration. Thus, UCS tests were carried out in the durability specimens, to estimate the strength loss after the weathering cycles. A detailed flowchart of the experimental program is shown in Figure 3.

As for the molding procedures, specimens of 100mm in diameter and 200mmin height were utilized. A tolerance of 0.1 g/cm^3 and 1% were adopted for specific mass and moisture content, respectively. After molding, OPC specimens were immediately placed in a temperature and moisture content controlled chamber. On the other hand, alkali-activated specimens required a different treatment; specimens were oven-cured at 50°C for 24 hours after the molding process. After this process, specimens were also placed in a temperature and moisture content controlled chamber.

As previously mentioned, the curing process of all samples was carried out in a temperature and moisture content controlled chamber ($\omega = 90 \pm 2\%$ and $T = 23 \pm 2$ °C). The curing period for UCS testing was set as seven days for all specimens.

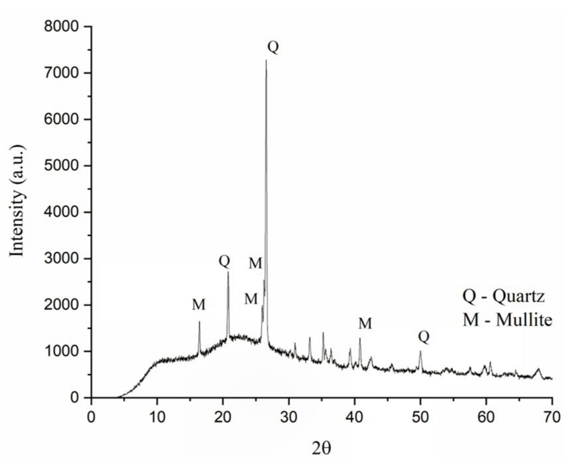

Figure 2. Mineralogical composition of FA.

2.2 Compaction test

The Proctor compaction test (modified energy) was performed to define the optimal moisture content ($w_{optimal}$) and the maximum dry unit weight (γ_d) of all mixtures. A typical behavior for granular compacted materials was obtained from the compaction tests; however, a clear maximum γ_d was not identified for all mixtures. For the molding procedures, a dry unit weight of 19.5 kN/m^3 and a moisture content of 7.5% were utilized for all combinations, representing the minimum water content to obtain the highest γ_d. It is noted that for the alkali-activated mixtures, the compaction test was conducted

Table 1. Proportions of granular materials.

Reclaimed asphalt pavement content (%)	Stone powder content (%)	Gravel 3/4 " content (%)	Gravel 3/8 " content (%)
20	38	21	21
45	33	10	12
70	30	0	0

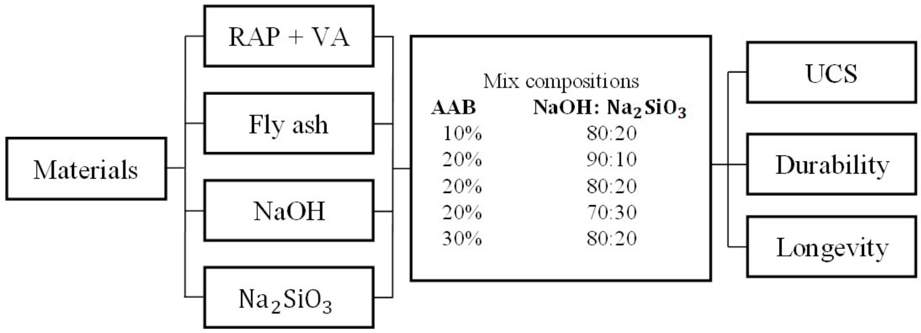

Figure 3. Flowchart of the experimental program.

without adding the activating solution, considering that the cementitious process occurs quickly; also, an adjustment in water content was necessary to obtain the optimum moisture for compaction, which resulted in an equal discounting of the water volume of the activator solution. Therefore, the solution was prepared 24 hours before the final mixture with the raw materials.

2.3 Unconfined compressive strength (UCS)

UCS tests were carried out following the procedures of ASTM D2166 (ASTM, 2016). The cylindrical mold mass was checked before and after molding to obtain the mass of the wet specimen. After that, specimens were placed in hermetic bags for 24 hours; then, specimens were demolded and placed in a temperature and moisture content ($\omega = 90 \pm 2\%$ and $T = 23 \pm 2$ °C) controlled chamber for curing during 7 days. A hydraulic loading press with a 0.45 MPa/s shear speed was utilized. Neoprene disks were used at the ends of the specimens to improve the contact area during testing.

2.4 Durability testing and long-term performance

The durability and long-term performance test followed the guidelines of ASTM D 559 (ASTM, 2012b). The specimens were immersed in water for 5 h at room temperature. Then, specimens were oven-dried at 70 °C for 42 h. This exposure for 47 h to both wet and dry scenarios constitute a single cycle. After wetting and drying, specimens were weighed after two firm strokes all around the surface with a wire brush. Contrary to the standard procedure, the number of cycles of this research was increased to 16, providing an evaluation of the specimens' deterioration at long-term.

The long-term performance of stabilized RAP as base course material in pavements is questionable, since several reactions between the stabilizer and the amorphous asphalt content are not clearly understood. Concerning the potential effects of the different binder combinations over long curing periods, a long-term behavior investigation was also conducted. To this extent, specimens cured for 365 days were submitted to 2, 4, 8, and 16 wet/dry cycles and then tested regarding their UCS.

3. Results

3.1 Unconfined compression strength of PC-stabilized RAP

The influence of RAP and cement content on the unconfined compressive strength is shown in Figure 4. Results indicate that the increase in PC content increases the mechanical strength, especially for the lowest RAP content. This behavior was also observed in other studies (Consoli et al., 2007; Diambra et al., 2017; Festugato et al., 2018; Mohammadinia et al., 2016; Suebsuk & Suksan, 2014; Taha et al., 2002).

RAP content presents no significant influence on the mechanical behavior of the mixtures. This preliminary result attests to the possibility of using high levels of RAP for cemented bases. However, a great variability was evidenced for 6% cement content specimens. This behavior can be attributed to the greater amount of water needed for higher cement content specimens, impairing the molding process. In addition, despite being statistically equal, the average values of UCS for the 70% RAP specimens presented a worse mechanical behavior; which can be attributed to the grain size composition of the mixture. For 70% RAP specimens, only stone powder was added to the mixture, with no other granular materials; thus, less packing of the particles was evidenced, resulting in a reduction of strength. With that in mind, the other mechanical parameters of this study were evaluated only for the 45% RAP content specimens.

3.2 Unconfined compression strength of alkali-activated stabilized RAP mixtures

Figure 5 presents the UCS results for the alkali-activated binder (AAB) stabilized RAP blends. The increase in AAB content led to an increase in UCS for all mixtures; increasing AAB content reduces porosity, enhancing strength development.

The porosity reduction induces a larger contact area between particles, intensifying the interlocking and mobilizing the friction between particles. Furthermore, the increase in AAB content is linked to the increase in cementitious reactions, also contributing to the development of strength (Pereira dos Santos et al., 2022). Similar results were found for RAP stabilized with alkali-activated ligands (Hoy et al., 2016b, d; Mohammadinia et al., 2016).

In addition, only mixtures with 30% AAB and $NaOH:Na_2SiO_3$ ratio of 70:30 and 80:20 showed a minimum strength of 2.1 MPa at 7 days (minimum requirement of the National Department of Infrastructure and Transport in Brazil (ABNT, 2012a) for utilization as road construction material).

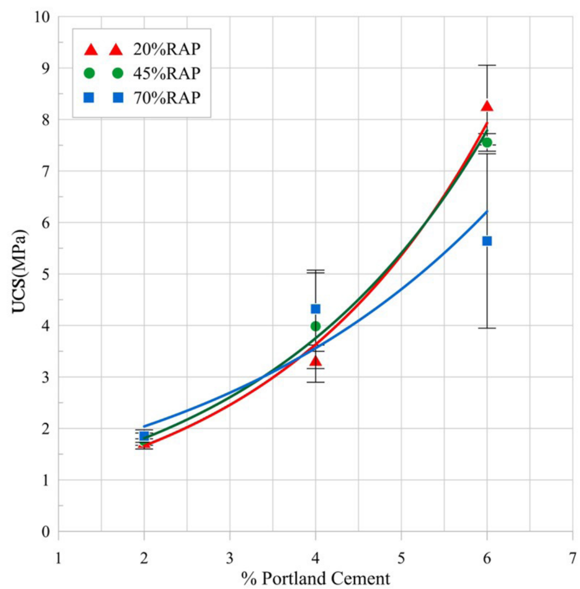

Figure 4. Unconfined compressive strength of PC-stabilized RAP.

3.3 Durability and long-term performance

Figure 6 presents the accumulated loss of mass (ALM) results of the alkali-activated mixtures. In general, it is noted that the ALM is more significant in the first cycle, considering that more unbounded grains can be found on the surface of the specimen. Furthermore, most of the ALM occurred at the interface between the RAP and the binder, where the RAP particles are coated by bitumen. This can be attributed to the poor cementation/bonding between the asphalt coating and the binder (fly ash) (Avirneni et al., 2016). The sample with the lowest AAB content (10%AAB – $NaOH:Na_2SiO_3$ ratio = 80:20) presented a contradictory behavior, resulting in a significant loss of mass in the last 6 cycles, possibly due to the low amount of binder that was not able to involve most of the aggregates.

The increase in silicate content reduced the ALM for the studied mixtures; this behavior can be associated with the greater amount of material that reacted with the NaOH solution and fly ash. Thus, the increase in silicate content resulted in more durable specimens, corroborating the behavior found in the other mechanical tests and indicating that durability is directly linked to strength. Such behavior may also be associated with a greater mobilization of friction due to the reduction of porosity associated with the increase of cementitious reactions (Pereira dos Santos et al., 2022). Similar behavior was also found for soils stabilized with Portland cement (Consoli & Tomasi, 2018); stabilized dispersive

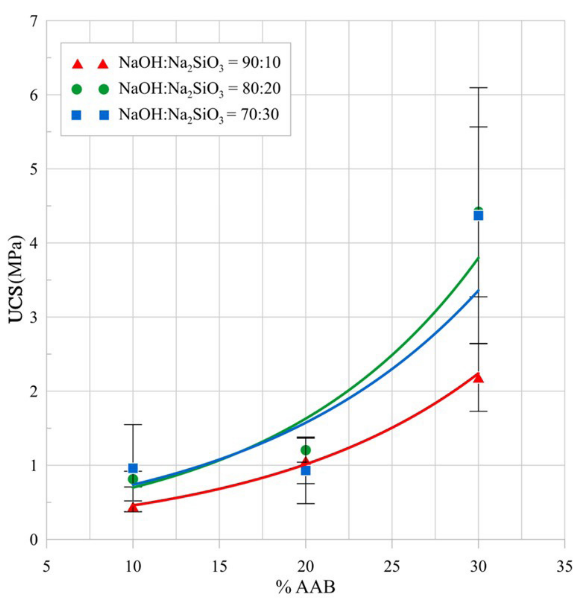

Figure 5. Unconfined Compression Strength of alkali-activated FA binder stabilized RAP.

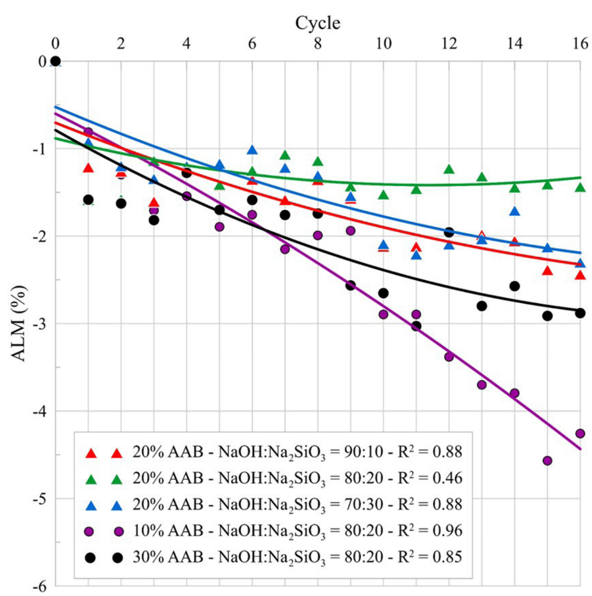

Figure 6. Accumulated loss of mass after wet-dry cycles for alkali-activated FA binder stabilized RAP.

soils (Consoli et al., 2016); soils stabilized with ash and lime (Consoli et al., 2020, 2018b); stabilized reclaimed asphalt pavement (Consoli et al., 2021, 2018a) and gold tailings stabilized with Portland cement (Consoli et al., 2018c), in which lower porosities showed greater durability.

Regarding the AAB content, the highest ALM values were observed for 10% and 30% AAB specimens, indicating the existence of an optimal content that provides a matrix with greater durability, when subjected to weathering conditions.

According to the Portland Cement Association (PCA, 1956), the maximum ALM after 12 wet-dry cycles for granular soils cured at room temperature for 7 days is 14%. In this study, all mixtures met this requirement, indicating the feasibility of the proposed treatments to improve durability. However, specimens with higher levels of sodium silicate had better performance. Thus, mixtures with 20% AAB and 20% sodium silicate (20% AAB – NaOH:Na_2SiO_3 ratio = 80:20) are potentially better in terms of performance under field conditions. However, the other mixtures are also considered feasible, as the mass loss is within the limits of PCA.

The long-term strength (365 days) of the mixtures after the wetting-drying cycles was also evaluated and the results are shown in Figure 7. Although there are no standard specifications for the compressive strength after the wetting/drying cycles, this long term assessment is important especially when alternative/waste materials are used in high amounts.

The mixture with the highest ALM resulted in a reduction of strength over the cycles, while the other maintained or even increased strength over time. Even after the weathering cycles, all specimens still met the minimum regulatory strength requirements of 2.1 MPa (ABNT, 2012b). For specimens that increased in strength over time, the wetting-drying cycles played the role of thermal curing and not of material degradation mechanisms as observed in previous studies (Miraki et al., 2022; Nazari et al., 2011).

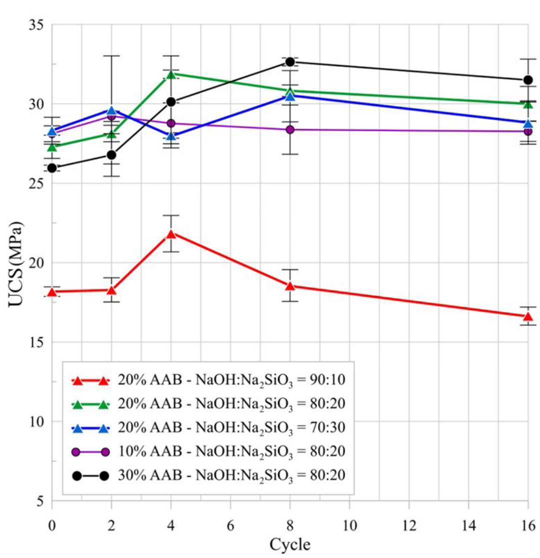

Figure 7. Long-term UCS after wet and dry cycling for alkali-activated FA binder stabilized RAP.

Despite the slow reaction process, characteristic of activated alkali materials, an average increase of about 3 times was observed when compared with the strength obtained at 7 days (Figure 5). The tendency of increasing strength for long-term periods was also observed in similar works using secondary materials (e.g., RAP and fly ash); however, authors concluded that from the 56-days mark, the rate of improvement in strength was negligible (Avirneni et al., 2016).

Furthermore, it can be concluded that the AAB content influenced the results, and the 30% content showed the best strength performance after the wetting-drying cycles. In addition, based on the performance of the mixtures submitted to the 16 cycles of wetting/drying, more than 16 years of project life in the field can be estimated, since each cycle can be considered a year of seasonal variation in humidity and temperature (Avirneni et al., 2016).

4. Conclusions

This study investigated the durability and long-term mechanical performance of RAP stabilized by an alkali-activated fly ash-based binder, activated by a combination of sodium hydroxide and sodium silicate. A group 84 samples were utilized to investigate the strength and durability performance of cemented materials.

Fly ash was successfully activated for the 30% AAB mixtures at activator ratios (NaOH:Na_2SiO_3) of 70:30 and 80:20, increasing strength and fulfilling design requirements for granular materials. This indicates a great potential of alkali-activated materials for ground improvement applications. In addition, the durability investigation indicated that all blends satisfactorily attended the Portland Cement Association ALM specifications.

Even though the specimens were submitted to weathering cycles, all mixtures demonstrated UCS higher than the standard requirements for paving applications. Nevertheless, the durability test methodology was not useful to evaluate the degradation of the mixtures, since strength increased over the cycles. This evidence suggests that the weathering cycles played a role in curing due to the process of drying into the thermal chamber.

The long-term study has shown no significant reduction in strength over time, which indicates that the binder remained in the RAP mixtures. Thus, alkali-activated materials may be an alternative for traditional Portland cement. However, futures studies considering experimental segments are required for the road structural performance.

Acknowledgements

The authors are grateful to the University of Passo Fundo for supporting the scholarships provided to the Ph.D. students.

Declaration of interest

The authors whose names are listed in this manuscript certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Authors' contributions

Alessandro Graeff Goldoni: conceptualization, data curation, investigation, methodology, visualization, writing – original draft, funding acquisition. Deise Trevizan Pelissaro: conceptualization, data curation, methodology, supervision, validation, writing – original draft. Eriky Silveira: data curation, investigation, methodology. Pedro Domingos Marques Prietto: writing – reviewing; Francisco Dalla Rosa: formal analysis, funding acquisition, investigation, methodology, project administration, resources, software.

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

List of symbols

AAB	Alkali-Activated Binder
ALM	Accumulated Loss of Mass
FA	Fly Ash
FDR	Full Depth Recycling
LOS	Level of Service
PC	Portland Cement
RAP	Reclaimed Asphalt Pavement
UCS	Unconfined Compression Strength
VA	Virgin Aggregate
$w_{optimal}$	Optimal Moisture Content
XRD	X-ray Diffraction
γ_d	Dry unit weight

References

ABNT NBR 12253. (2012a). *Solo-cimento - Dosagem para Emprego como Camada de Pavimento*. ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ.

ABNT NBR 12253. (2012b). *Solo-cimento - Dosagem para Emprego como Camada de Pavimento*. ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ.

Adhikari, S., Khattak, M.J., & Adhikari, B. (2020). Mechanical characteristics of Soil-RAP-Geopolymer mixtures for road base and subbase layers. *The International Journal of Pavement Engineering*, 21, 483-496. http://dx.doi.org/10.1080/10298436.2018.1492131.

ASTM D2172/D2172M-11. (2011). *Standard Test Methods for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures. American Society for Testing and Materials*. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D2172-11.2.

ASTM C150/C150M–12. (2012a). *Standard Specification for Portland Cement*. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0150-07.

ASTM D559-03. (2012b). *Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures*. ASTM International, West Conshohocken, PA.

ASTM D2166/D2166M. (2016). *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D2166.

Avirneni, D., Peddinti, P.R.T., & Saride, S. (2016). Durability and long term performance of geopolymer stabilized reclaimed asphalt pavement base courses. *Construction & Building Materials*, 121, 198-209. http://dx.doi.org/10.1016/j.conbuildmat.2016.05.162.

Blissett, R.S., & Rowson, N.A. (2012). A review of the multi-component utilisation of coal fly ash. *Fuel*, 97, 1-23. http://dx.doi.org/10.1016/j.fuel.2012.03.024.

Celik, K., Meral, C., Petek Gursel, A., Mehta, P.K., Horvath, A., & Monteiro, P.J.M. (2015). Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder. *Cement and Concrete Composites*, 56, 59-72. http://dx.doi.org/10.1016/j.cemconcomp.2014.11.003.

Consoli, N.C., Foppa, D., Festugato, L., & Heineck, K.S. (2007). Key parameters for strength control of artificially cemented soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 133, 197-205. http://dx.doi.org/10.1061/(ASCE)1090-0241(2007)133:2(197).

Consoli, N.C., Vendruscolo, M.A., Fonini, A., & Rosa, F.D. (2009). Fiber reinforcement effects on sand considering a wide cementation range. *Geotextiles and Geomembranes*, 27, 196-203. http://dx.doi.org/10.1016/j.geotexmem.2008.11.005.

Consoli, N.C., Samaniego, R.A.Q., & Villalba, N.M.K. (2016). Durability, strength, and stiffness of dispersive clay–lime blends. *Journal of Materials in Civil Engineering*, 28(11), 04016124. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001632.

Consoli, N.C., & Tomasi, L.F. (2018). The impact of dry unit weight and cement content on the durability of sand-cement blends. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, 171, 96-102. http://dx.doi.org/10.1680/jgrim.17.00034.

Consoli, N.C., Giese, D.N., Leon, H.B., Mocelin, D.M., Wetzel, R., & Marques, S.F.V. (2018a). Sodium chloride as a catalyser for crushed reclaimed asphalt pavement – Fly ash – Carbide lime blends. *Transportation Geotechnics*, 15, 13-19. http://dx.doi.org/10.1016/j.trgeo.2018.02.001.

Consoli, N.C., Samaniego, R.A.Q., González, L.E., & Bittar, E.J. (2018b). Impact of severe climate conditions on loss of mass, strength, and stiffness of compacted fine-grained soils–portland cement blends. *Journal of Materials in Civil Engineering*, 30(8), 04018174. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0002392.

Consoli, N.C., da Silva, A.P., Nierwinski, H.P., & Sosnoski, J. (2018c). Durability, strength, and stiffness of compacted gold tailings – cement mixes. *Canadian Geotechnical Journal*, 55, 486-494. http://dx.doi.org/10.1139/cgj-2016-0391.

Consoli, N.C., Festugato, L., Scheuermann Filho, H.C., Miguel, G.D., Tebechrani Neto, A., & Andreghetto, D. (2020). Durability assessment of soil-pozzolan-lime blends through ultrasonic-pulse velocity test. *Journal of Materials in Civil Engineering*, 32(8), 04020223. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0003298.

Consoli, N.C., Tebechrani Neto, A., Correa, B.R.S., Quiñónez Samaniego, R.A., & Cristelo, N. (2021). Durability evaluation of reclaimed asphalt pavement, ground glass and carbide lime blends based on unconfined compression tests. *Transportation Geotechnics*, 27, 100461. http://dx.doi.org/10.1016/j.trgeo.2020.100461.

Diambra, A., Ibraim, E., Peccin da Silva, A., Consoli, N.C., & Festugato, L. (2017). Theoretical derivation of artificially cemented granular soil strength. *Journal of Geotechnical and Geoenvironmental Engineering*, 143(5), 1-25. http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0001646.

DNIT. (2010). *Pavimentação – Base estabilizada granulometricamente – ES DNIT 141/2010*. DNIT - Departamento Nacional de Infraestrutura de Transportes, Rio de Janeiro, RJ.

DNIT. (2013). *Pavimentação – Reciclagem profunda de pavimentos "in situ" com adição de cimento Portland – Especificação de Serviço - ES-167*. DNIT - Departamento Nacional de Infraestrutura de Transportes, Rio de Janeiro, RJ.

Festugato, L., Peccin da Silva, A., Diambra, A., Consoli, N.C., & Ibraim, E. (2018). Modelling tensile/compressive strength ratio of fibre reinforced cemented soils. *Geotextiles and Geomembranes*, 46, 155-165. http://dx.doi.org/10.1016/j.geotexmem.2017.11.003.

Gowthaman, S., Nakashima, K., & Kawasaki, S. (2018). A state-of-the-art review on soil reinforcement technology using natural plant fiber materials: past findings, present trends and future directions. *Materials (Basel)*, 11(4), 553. http://dx.doi.org/10.3390/ma11040553.

Haas, S., & Ritter, H.-J. (2019). Soil improvement with quicklime – long-time behaviour and carbonation. *Road Materials and Pavement Design*, 20, 1941-1951. http://dx.doi.org/10.1080/14680629.2018.1474793.

Horpibulsuk, S., Hoy, M., Witchayaphong, P., Rachan, R., & Arulrajah, A. (2017). Recycled asphalt pavement fly ash geopolymer as a sustainable stabilized pavement material. *IOP Conference Series. Materials Science and Engineering*, 273, 012005. http://dx.doi.org/10.1088/1757-899x/273/1/012005.

Hoy, M., Horpibulsuk, S., & Arulrajah, A. (2016a). Strength development of Recycled Asphalt Pavement - Fly ash geopolymer as a road construction material. *Construction & Building Materials*, 117, 209-219. http://dx.doi.org/10.1016/j.conbuildmat.2016.04.136.

Hoy, M., Horpibulsuk, S., & Arulrajah, A. (2016b). Strength development of Recycled Asphalt Pavement - Fly ash geopolymer as a road construction material. *Construction & Building Materials*, 117, 209-219. http://dx.doi.org/10.1016/j.conbuildmat.2016.04.136.

Hoy, M., Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., & Arulrajah, A. (2016c). Recycled asphalt pavement – fly ash geopolymers as a sustainable pavement base material: strength and toxic leaching investigations. *The Science of the Total Environment*, 573, 19-26. http://dx.doi.org/10.1016/j.scitotenv.2016.08.078.

Hoy, M., Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., & Arulrajah, A. (2016d). Recycled asphalt pavement – fly ash geopolymers as a sustainable pavement base material: strength and toxic leaching investigations. *The Science of the Total Environment*, 573, 19-26. http://dx.doi.org/10.1016/j.scitotenv.2016.08.078.

Hoy, M., Horpibulsuk, S., Arulrajah, A., & Mohajerani, A. (2018). Strength and microstructural study of recycled asphalt pavement: slag geopolymer as a pavement base material. *Journal of Materials in Civil Engineering*, 30, 1-11. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0002393.

Instituto Nacional de Pesquisas Espaciais – INPE. (2021). Retrieved in July 2, 2022, from http://www.inpe.br/

Luukkonen, T., Abdollahnejad, Z., Yliniemi, J., Kinnunen, P., & Illikainen, M. (2018). One-part alkali-activated materials: a review. *Cement and Concrete Research*, 103, 21-34. http://dx.doi.org/10.1016/j.cemconres.2017.10.001.

Miraki, H., Shariatmadari, N., Ghadir, P., Jahandari, S., Tao, Z., & Siddique, R. (2022). Clayey soil stabilization using alkali-activated volcanic ash and slag. *Journal of Rock Mechanics and Geotechnical Engineering*, 14(2), 576-591. http://dx.doi.org/10.1016/j.jrmge.2021.08.012.

Mohammadinia, A., Arulrajah, A., Sanjayan, J., Disfani, M.M., Bo, M.W., & Darmawan, S. (2016). Strength development and microfabric structure of construction and demolition aggregates stabilized with fly ash–based geopolymers. *Journal of Materials in Civil Engineering*, 28, 04016141. http://dx.doi.org/10.1061/(asce)mt.1943-5533.0001652.

Nazari, A., Bagheri, A., & Riahi, S. (2011). Properties of geopolymer with seeded fly ash and rice husk bark ash.

Materials Science and Engineering A, 528, 7395-7401. http://dx.doi.org/10.1016/j.msea.2011.06.027.

Pereira dos Santos, C., Bruschi, G.J., Mattos, J.R.G., & Consoli, N.C. (2022). Stabilization of gold mining tailings with alkali-activated carbide lime and sugarcane bagasse ash. *Transportation Geotechnics*, 32, 100704. http://dx.doi.org/10.1016/j.trgeo.2021.100704.

Porter, H., Dhami, N.K., & Mukherjee, A. (2018). Sustainable road bases with microbial precipitation. *Proceedings of Institution of Civil Engineers: Construction Materials*, 171, 95-108. http://dx.doi.org/10.1680/jcoma.16.00075.

Portland Cement Association – PCA. (1956). *Soil-cement laboratory handbook*. Portland Cement Association.

Provis, J.L., Duxson, P., van Deventer, J.S.J., & Lukey, G.C. (2005). The role of mathematical modelling and gel chemistry in advancing geopolymer technology. *Chemical Engineering Research & Design*, 83, 853-860. http://dx.doi.org/10.1205/cherd.04329.

Rezende, I.M., Prietto, P.D.M., Thomé, A., & Dalla Rosa, F. (2021). Mechanical behavior of microbially induced calcite precipitation cemented sand. *Geotechnical and Geological Engineering*, 4, 1997-2008. http://dx.doi.org/10.1007/s10706-021-02006-4.

Shen, W., Zhou, M., & Zhao, Q. (2007). Study on lime-fly ash-phosphogypsum binder. *Construction & Building Materials*, 21, 1480-1485. http://dx.doi.org/10.1016/j.conbuildmat.2006.07.010.

Singh, N.B., & Middendorf, B. (2020). Geopolymers as an alternative to Portland cement: an overview. *Construction & Building Materials*, 237, 117455. http://dx.doi.org/10.1016/j.conbuildmat.2019.117455.

Solanki, P., & Zaman, M. (2014). Effect of wet-dry cycling on the mechanical properties of stabilized subgrade soils. In *Geo-Congress 2014 Technical Papers : Geo-Characterization and Modeling for Sustainability* (pp. 3625-3634). ASCE. http://dx.doi.org/10.1061/9780784413272.351.

Suebsuk, J., & Suksan, A. (2014). Strength assessment of cement treated soil-reclaimed asphalt pavement (RAP) mixture. *International Journal of GEOMATE*, 6, 878-884. Retrieved in July 2, 2022, from https://geomatejournal.com/geomate/article/view/2931

Taha, R., Al-Harthy, A., Al-Shamsi, K., & Al-Zubeidi, M. (2002). Cement stabilization of reclaimed asphalt pavement aggregate for road bases and subbases. *Journal of Materials in Civil Engineering*, 14, 239-245. http://dx.doi.org/10.1061/(asce)0899-1561(2002)14:3(239).

Wirtgen GmbH. (2012). *Wirtgen cold recycling technology*. Wirtgen GmbH.

Wu, H., Huang, B., Shu, X., & Zhao, S. (2015). Evaluation of geogrid reinforcement effects on unbound granular pavement base courses using loaded wheel tester. *Geotextiles and Geomembranes*, 43, 462-469. http://dx.doi.org/10.1016/j.geotexmem.2015.04.014.