Title

Alkali-activated Materials: Environmental Preliminary Assessment for U.S. Roadway Applications

Permalink

https://escholarship.org/uc/item/76z7m878

Authors

Kurtis, Kimberly E.
Lolli, Francesca

Publication Date

2020-09-01

DOI

10.7922/G2HD7SZT

Data Availability

The data associated with this publication are within the manuscript.

Alkali-activated Materials: Environmental Preliminary Assessment for U.S. Roadway Applications

September 2020

A Research Report from the National Center for Sustainable Transportation

Kimberly E. Kurtis, Georgia Institute of Technology

Francesca Lolli, Georgia Institute of Technology

National Center for Sustainable Transportation

Georgia Tech School of Civil and Environmental Engineering
College of Engineering

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. NCST-GT-RR-20-24	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A

4. Title and Subtitle Alkali-activated Materials: Environmental Preliminary Assessment for U.S. Roadway Applications	**5. Report Date** September 2020
	6. Performing Organization Code N/A
7. Author(s) Kimberly E. Kurtis, PhD, https://orcid.org/0000-0002-1252-7323 Francesca Lolli, PhD, https://orcid.org/0000-0003-4610-3171	**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Georgia Institute of Technology School of Civil and Environmental Engineering 790 Atlantic Dr, Atlanta, GA 30332	**10. Work Unit No.** N/A
	11. Contract or Grant No. USDOT Grant 69A3551747114
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE, Washington, DC 20590	**13. Type of Report and Period Covered** Final Report (September 2018 – April 2020)
	14. Sponsoring Agency Code USDOT OST-R

15. Supplementary Notes

DOI: https://doi.org/10.7922/G2HD7SZT

16. Abstract

The capital investment in the U.S. for construction and maintenance of the infrastructure road network is on the order of $100 billion/year. On average, investments in Organization for Economic Cooperation and Development (OECD) countries are likely to stabilize, while China will face an exponential growth of investments for new infrastructures driven by the development of metropolitan cities. Continued "business-as-usual" practice for portland and asphalt cement concrete pavement construction ignores the increasing warning calls for the identification of more sustainable and less energy intensive paving materials. It is therefore important to explore alternative pavement materials, which may have benefits in terms of environmental impact and durability performance over the current technology. Alkali activated materials concrete (AAM) exhibit these beneficial characteristics. AAM compositions have been studied with growing interest during the last three decades, and showing promising results in terms of mechanical performance, while also having a global warming potential impact 30-80% less than that of portland cement concrete. The global warming potential of these material is closely dependent on: 1) the alkali activating solution used to activate the raw material 2) the origin of the raw material. Specifically, the impact of the transport for both of these components has an impact quantifiable around 10% of its global warming potential. Hence, to increase the adoption of AAM for civil applications such as pavements, it is fundamental to analyze the existing literature to clarify the link between environmental and mechanical performance, identifying opportunities for applications that are tailored to the local availability of raw material, reducing transport environmental costs.

17. Key Words Alkali activated materials, life cycle assessment, pavements, CO_2 intensity	**18. Distribution Statement** No restrictions.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 22	**22. Price** N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

About the National Center for Sustainable Transportation

The National Center for Sustainable Transportation is a consortium of leading universities committed to advancing an environmentally sustainable transportation system through cutting-edge research, direct policy engagement, and education of our future leaders. Consortium members include: University of California, Davis; University of California, Riverside; University of Southern California; California State University, Long Beach; Georgia Institute of Technology; and University of Vermont. More information can be found at: ncst.ucdavis.edu.

Disclaimer

Acknowledgments

This study was funded, partially or entirely, by a grant from the National Center for Sustainable Transportation (NCST), supported by the U.S. Department of Transportation (USDOT) through the University Transportation Centers program. The authors would like to thank the NCST and the USDOT for their support of university-based research in transportation, and especially for the funding provided in support of this project. The authors acknowledge the contribution of Hana Herndon.

Alkali-activated Materials: Environmental Preliminary Assessment for U.S. Roadway Applications

A National Center for Sustainable Transportation Research Report

September 2020

Kimberly E. Kurtis, Department of Civil and Environmental Engineering, Georgia Institute of Technology

Francesca Lolli, Department of Civil and Environmental Engineering, Georgia Institute of Technology

[page intentionally left blank]

TABLE OF CONTENTS

List of Figures

Alkali-activated Materials: Environmental Preliminary Assessment for U.S. Roadway Applications

EXECUTIVE SUMMARY

The capital investment in the U.S. for construction and maintenance of the infrastructure road network is on the order of $100 billion/year. On average, investments in OECD countries are likely to stabilize, while China will face an exponential growth of investments for new infrastructures driven by the development of metropolitan cities. It is important to explore alternative pavement materials such as Alkali activate material concrete (AAM), which may have benefits in terms of environmental impact and durability performance over the current technology.

AAM compositions show promising results in terms of mechanical performance, while also having a global warming potential impact 30-80% less than that of portland cement concrete. The global warming potential of these material is closely dependent on: 1) the alkali activating solution used to activate the raw material 2) the origin of the raw material. Specifically, the impact of the transport for both of these components has an impact quantifiable around 10% of its global warming potential. Hence, to increase the adoption of AAM for civil applications such as pavements, it is fundamental to analyze the existing literature to clarify the link between environmental and mechanical performance, identifying opportunities for applications that are tailored to the local availability of raw material, reducing transport environmental cost.

The market for AAM should benefit from the relative abundance of raw materials globally and the stated interest in reducing CO_2 emissions, of which cement production contributes significantly. Due to the transition to renewable and alternative sources of electricity, as well as the relative reduction in steel production, it is likely that AAM production in the future will utilize metakaolin or other sources of that are locally available (e.g., reclaimed fly ash) in particular in the U.S. and European market, where the coal industry is being phased out in many states. The increasing demands for construction materials and energy in the growing Asian markets will result in AAM production likely based on fly ash and ground granulated blast furnace slags in those areas. From the Life Cycle Assessment studies that have been analyzed, AAM have a lower CO_2 intensity when compared to portland cement and portland cement + supplementary cementitious material binders, while providing the required compressive strength for pavement applications.

Introduction

Investments on paved infrastructures in the United States and abroad

Since 2010 the U.S Federal Highway Administration allocated an annual capital investment for construction and maintenance of more than $100 billion /year [1] for more than 2.7 million miles of paved public roads [2]. Future projections for transport-mode scenarios have been hypothesized for the Organization for Economic Cooperation and Development (OECD) countries [3], on one hand predicting that utilization and construction of roads may decrease in the future with more ridesharing and public transit options, while on the other hand stating that private vehicles will remain the preferred mode of personal travel worldwide. It is then likely that on average, in the near future, the amount of investments for road construction and maintenance will tend to increase in alignment with the past trends for OECD countries (as shown in Figure 1) [3].

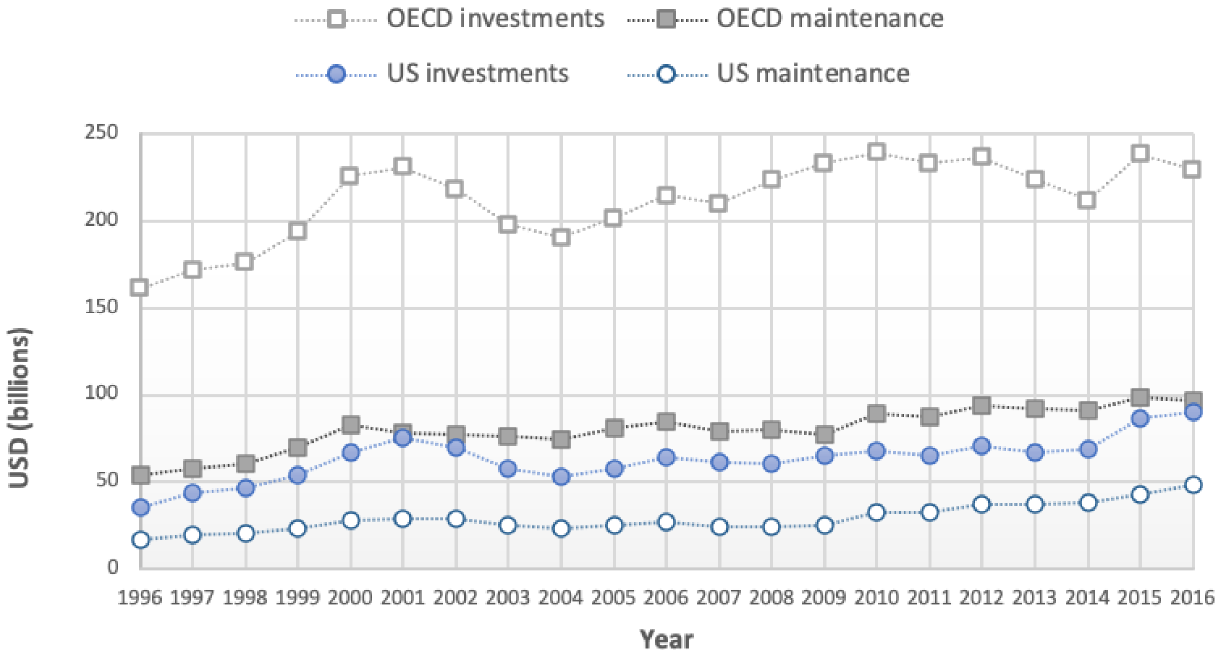

Figure 1. Investments and maintenance for road construction, data for OECD countries and United States [3].

Non-OECD countries, such as China, have instead experienced a dramatic increase in investments on road construction in the last ten years, reaching over $560 billion in 2017 [3]. These planned substantial investments in infrastructure prompt an examination of the current technology, researching alternatives that are able to overcome the intrinsic issues associated with asphalt and portland cement concrete. Specifically, the following issues should be addressed:

- Environmental impact of the current technology
- Frequency of maintenance and repair
- Material costs

Environmental impact of the current technology

Both asphalt and portland cement concrete production are associated with an intensive consumption of natural resources while also producing CO_2 emissions, and water pollution. The extraction from petroleum, often needed for asphalt, and the cement production for concrete causes significant greenhouse gas emissions. In 2017, in the U.S., asphalt has been responsible for 6% of the consumption of fossil fuel for non-energy use [4], and it should be noted that the production of cement alone accounts for around 8% of the global anthropogenic CO_2 emissions [5].

Frequency of maintenance and repair

Asphalt pavement requires frequent maintenance, resulting in huge investments at the local level [6]. For example, the Georgia Department of Transportation invests ~US$300 per capita/year (see Figure 2) to preserve, reconstruct and maintain road and bridges, corresponding to $2-$3 billion/year [6]. The state of Georgia has more than 95% of the State's roads made with asphalt [7]. However, despite this funding in 2014, only a third of the planned pavement resurfacing was completed, largely due to insufficient funding for resurfacing, which has caused a dilation of the maintenance cycle from 15 years to 50 years [8]. To try to reduce the maintenance cycle, in 2015 the State Government allocated an additional by $5.4 billion of investments via the Transportation Funding Act [8].

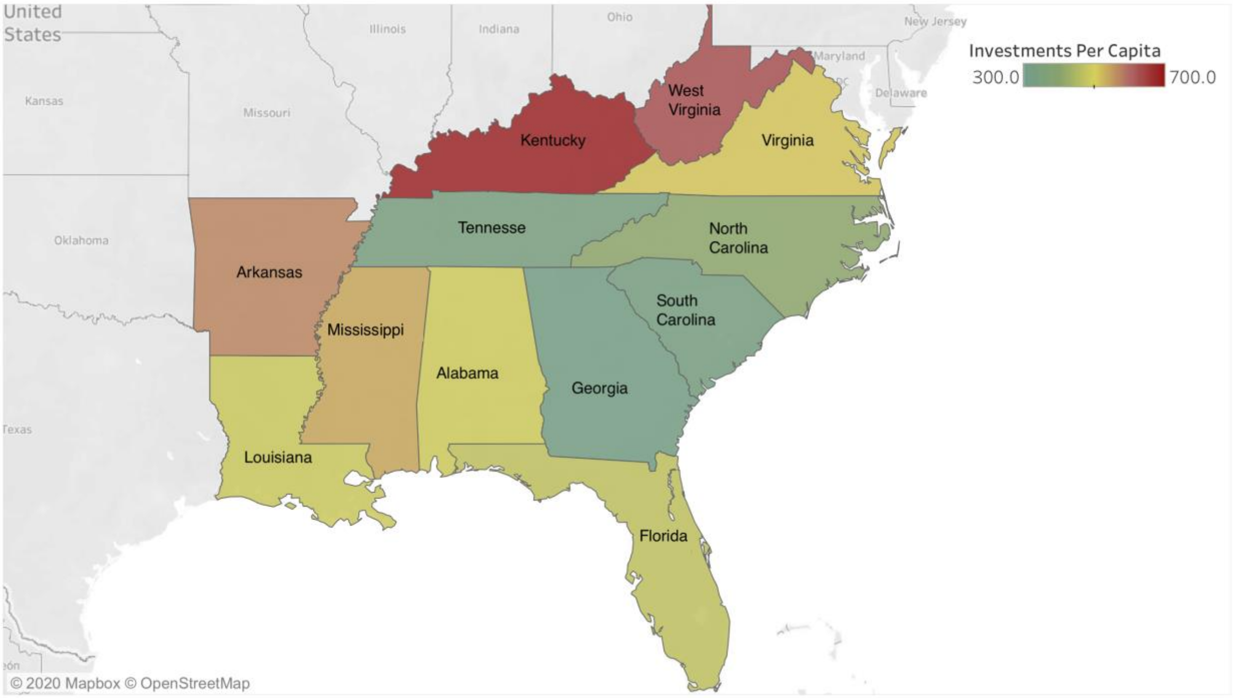

Figure 2. Investments for roads maintenance per capita in the South East of the U.S. for the year 2015, visualization created with Tableau [6].

Furthermore, it should be noted that the existing infrastructure network might not be sufficient to accommodate future increased urbanization. In the next 30 years, the city of Atlanta alone is expected to reach a population of 8.6 million [9] (6 million in 2019 [10]), straining the lifecycle of the paved network. Even if the strain on the existing and future network will be less than anticipated, due to preference of shared mode of transport over private ones, it will be imperative to improve the ride quality and decrease the rate of repair to assure robustness of the road surface. It is clear that increasing research in materials with enhanced wear resistance is necessary to provide a longer-term solution. Alternative materials with comparable mechanical properties to asphalt and concrete pavements, but with a more rapid strength development can facilitate rapid construction and large-scale repair and maintenance operations, minimizing road closures and the related environmental and economic costs.

Material costs

The cost of pavement material has risen substantially, even when considering the ~19% inflation rate, with asphalt costs rising from US$150/ton of 2000 to US$470/ton of January 2020 [11] as shown in Figure 3. It is theorized that alkali activated materials may be produced at lower costs than conventional asphalt or concrete if they are made from by-products of other industrial processes and if locally available materials/wastes are preferred. Furthermore, if combined with a longer service life, additional savings can be added over the lifetime of the infrastructure.

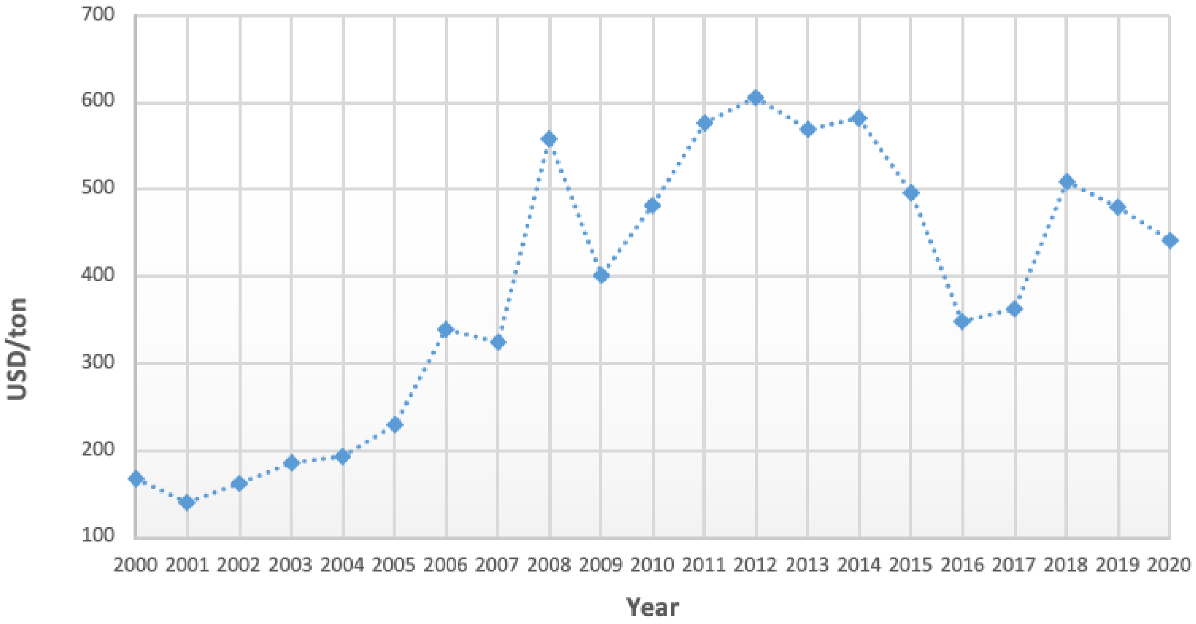

Figure 3. Evolution of asphalt price over the last 20 years. Average yearly data from [11].

To address some of these issues more sustainable alternatives to asphalt and concrete should be studied for pavements. The following paragraph describes alkali activated materials as a viable alternative to current technology, in particular focusing on considerations on their environmental impact.

Alkali activated cement and concrete

AAM refers to inorganic binders resulting from the activation of an alumino-silicate source (e.g., metakaolin or fly ash) with an alkaline solution, typically sodium hydroxide, sodium silicate and/or potassium silicate, with ongoing research on less carbon intensive activators [12]. The final product is a material with comparable mechanical properties to cement based binders, but with lower global warming potential (GWP) than cement. The lower GWP is attributable to the alumino-silicate source used as raw materials, which are mainly by-products of other industrial processes. Typical examples are coal fuel ashes, by-product of the coal industry, industrial slags, by-products of steel production, or calcined clays.

To evaluate the environmental impact of AAM as compared to asphalt or concrete production, a Life Cycle Assessment (LCA) approach is recommended [13]. For cement-based materials, LCA follows the “cradle to gate” approach, considering all the components of the production process (cradle) through bringing the product to market (gate), excluding the impacts from transportation, placement, maintenance and disposal of the product throughout its full life cycle. This is a common approach because cement-based materials are used in various end-products, which affects their environmental impacts in a non-informative manner. LCA discretizes the impact of the material production into several impact categories, but for the construction sector, the global warming potential (GWP) category is the most important impact, since cement production is a leading contributor to global CO2 production. When comparing GWP among construction materials, the most conservative practice is to assume equal volume among the replacements.

Methodology

Research shows promising results when fly ash and slags are used on concrete pavements (both raw materials that can be alkali activated). By substituting 50% by mass of cement with a mix of fly ash and slag, the GWP can be reduced up to 14.9 kg CO_2eq/m^2 [14]. To the authors' knowledge, only a few applications of AAM for pavements have been experimented, with the first airport pavement built in Australia [15]. Brisbane West Wellcamp Airport, operative since 2014, was built with 40,000 m^3 of AAM concrete, which was preferred over Portland concrete because of its low shrinkage, high durability, and flexural strength. In Georgia, a commercially produced chemically activated aluminosilicate-based paving material was placed on a small test section of I-16 in Dublin in 2008 and served well until 2013 when it was removed for inspection [16].

However, only a small number of peer-reviewed papers have been published on the CO_2 emissions associated with the production of AAM, even if since 2010 over 2000 articles have been published comparing AAM and portland cement binders [12]. Of the papers considering CO_2 emissions, nine provided information on mechanical performance and environmental impact for both AAM and reference cement binders [14-22], and were thus examined in this study. The consensus among the nine papers is that from LCA studies, AAM have a lower GWP than portland cement, and it appears that the main source of CO_2 impact for AAM is the production of the sodium silicate solution. There are, however, aspects of these LCA studies that warrant further consideration. First, predicting the impacts of the sodium silicate solutions is hindered by outdated data on the production process [23], based on the environmental performance of 1995 Solvay technology. It should be noted that sodium carbonate, the raw material used to obtain sodium silicate, can either be produced through the Solvay process or directly sourced by mining carbonate salt deposits. Direct mining technology involves up 10 times less production of CO_2 than the Solvay process [24].

Second, LCA studies may neglect to consider the local availability and composition of the AAM's raw materials. Due to the abundance of raw materials, and thorough diffusion of cement production technologies, cement production is now an established market with a wide availability of production sites around the world. On the contrary, AAM are not produced extensively, due to the relative concentration of their raw materials, which may result in a large CO_2 impact from transporting the materials to market [25].

Hence, the focus of this work is to analyze a selection of published LCA literature [14-22] relating availability of raw materials with conducted research on AAM. The data collected are specifically referred to:

- Performance parameter expressed as CO_2 intensity.
- Location of the conducted research
- Raw materials employed

Results

Worldwide availability of raw materials for AAM production

From the literature analyzed [17-25] three alumino-silicate materials have been identified as the most common precursors for alkali activation: fly ashes (FA), ground granulated blast furnace slags (GGBS), and metakaolin (MK) (calcined kaolin clay). Figure 4 shows the availability of these raw materials on a global scale.

FA are a by-product of the coal industry, hence in Figure 4 the availability of FA is considered to be proportional to the produced power in MW from coal plants (data from 2018). In Figure 4 only power plants with a capacity of more than 30 MW are tracked, for location specific data see [29]. The availability of GGBS, a by-product of iron production, is considered to be proportional to their exported value in 2017, with each block representing the economic value associated with the trade of GGBS. For GGBS the references used combine trade data of main exporters and importers of GGBS [30], and steel plants locations [31]. MK is the product of the calcination of kaolinite, hence its availability has been represented by considering the worldwide availability of topsoil kaolinite, with data from Ito et al. [32].

Figure 4 presents an overview of the abundance of key raw materials for AAM worldwide. From Figure 4 the most disperse raw material appears to be kaolinite. Kaolinite is one of the most abundant natural clays worldwide. It is found predominantly in humid areas such as North and South America, Eastern Europe and Russia, Central Africa and Eastern Asia, both in the top and subsoil (easier for extraction the closer to the surface). Metakaolin, the form needed to produce the AAM, is traditionally produced by calcining kaolinite at around 750°C. The current uses of kaolin are mainly in the ceramic and paper industry, and MK as supplementary material for cement-based binders.

From Figure 4, it appears that FA is more geographically dependent, due to its reliance on coal combustion, which is reducing in the European and U.S. market as renewable and gas fuel electricity production is promoted [29, 33]. In the past, FA have been stored in onsite retention ponds, and reclaiming those deposits as requalified land is attracting significant interest. The main challenge is to find uses for this waste material, which is characterized by a wide variability in chemical composition. AAM might be a suitable application for reclaimed FA. The Chinese and Indian market exhibit a reversed trend to Europe and U.S., with new planned coal power plants to be ultimate in the next years as a result to their economic growth [29].

GGBS production, which is reliant on iron production, is following a similar trend to that of FA, with the Chinese and Indian market increasing their production/export, while the U.S. and European market are decreasing it. Japan and South Africa remained instead primary exporters in the last 10 years. The overall findings are that MK based AAM could be produced worldwide, whereas FA and GGBS based AAM rely on more geographically dependent resources. Therefore, to reduce the transportation emissions, FA and GGBS based AAM should be produced more readily in Asia and South Africa.

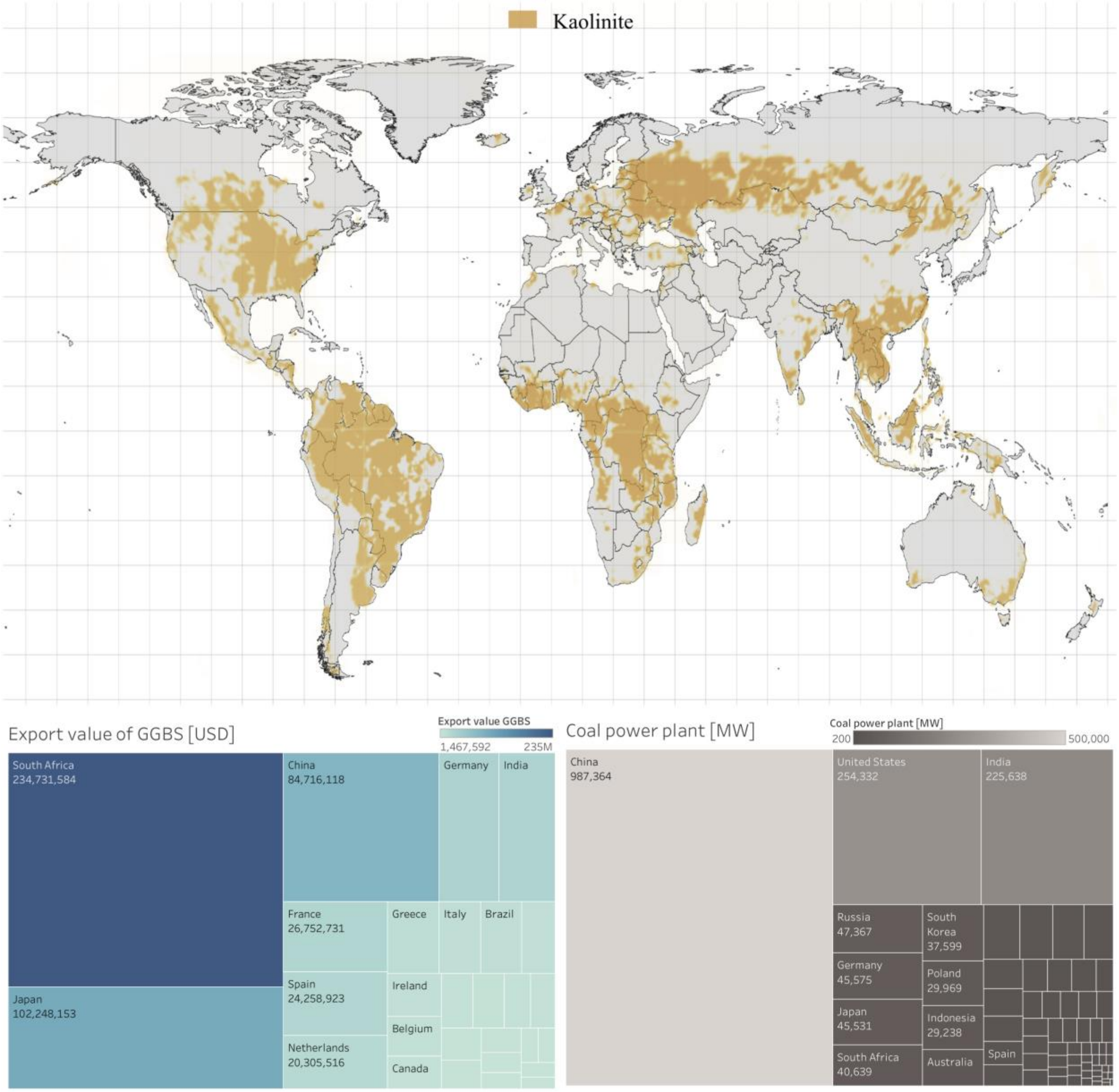

Figure 4. Map and graph displaying the worldwide availability of the raw materials used for AAM production. GGBS and Coal power plant visualization created with Tableau [6] and data sourced from [30-32]. Kaolinite visualization created with data sourced from [29]

Comparing the availability of raw material to the published LCA articles

While acknowledging the limited size of the dataset analyzed, it may still prove worthwhile to compare the geographic distribution of available raw materials in Figure 4 to the published LCA articles in those areas. Intuitively, AAM production and scientific interest should be correlated to the local availability of precursor materials. This hypothesis is generally observed when examining the 9 LCA studies in Table 1 [17-25].

Table 1. Comparison of published LCA articles

Reference	Location	Raw materials
[17]	Central America	Zeolite
[18]	Central Europe	MK; GGBS; FA
[19]	South Korea	MK; GGBS; FA
[20]	Australia	FA; GGBS
[21]	Western Europe	MK; GGBS; FA
[22]	United States	GGBS
[23]	Australia	GGBS; FA
[24]	Southern Europe	FA
[25]	Central America	Red Clay Brick Waste

As previously anticipated, the most frequently used materials for alkali activation are MK, FA and GGBS with the exception of two recent studies [17, 25] which adopted natural zeolite and red clay brick waste, both materials locally available. A clear exception to the hypothesis is the U.S. study for which GGBS is used as the raw material, even if the current supply is decreasing. Considering the relative abundance of MK in the U.S., one area of future work might focus more on MK-based AAM, particularly impure MK due to financial considerations. As mentioned prior, another field of research that is likely to receive significant interest is the development of AAM from local reclaimed FA, which may present economic benefits over MK. Countries like Australia, however, have low relative availability of kaolinite, and thus are unlikely to shift to a MK based AAM, even if the amount of FA decreases in the future from reduced coal utilization for power. Instead, new local materials should be preferred, such as in [17, 25].

CO_2 intensity

To clarify the link between environmental impact and mechanical performance, data from the analyzed LCA literature [17-25] has been represented as a function of CO_2 intensity in Figure 5. Ideally, data based on the same geographic location (hence considering like to like materials and energy source) should be preferred. However, enough data at this level of detail are not available yet, therefore all the available data are presented as aggregated. CO_2 intensity defines the amount of embodied CO_2 in a cubic meter of material with a specific compressive strength (as a reference, a typical pavement application requires a compressive strength on the order of 30 MPa).

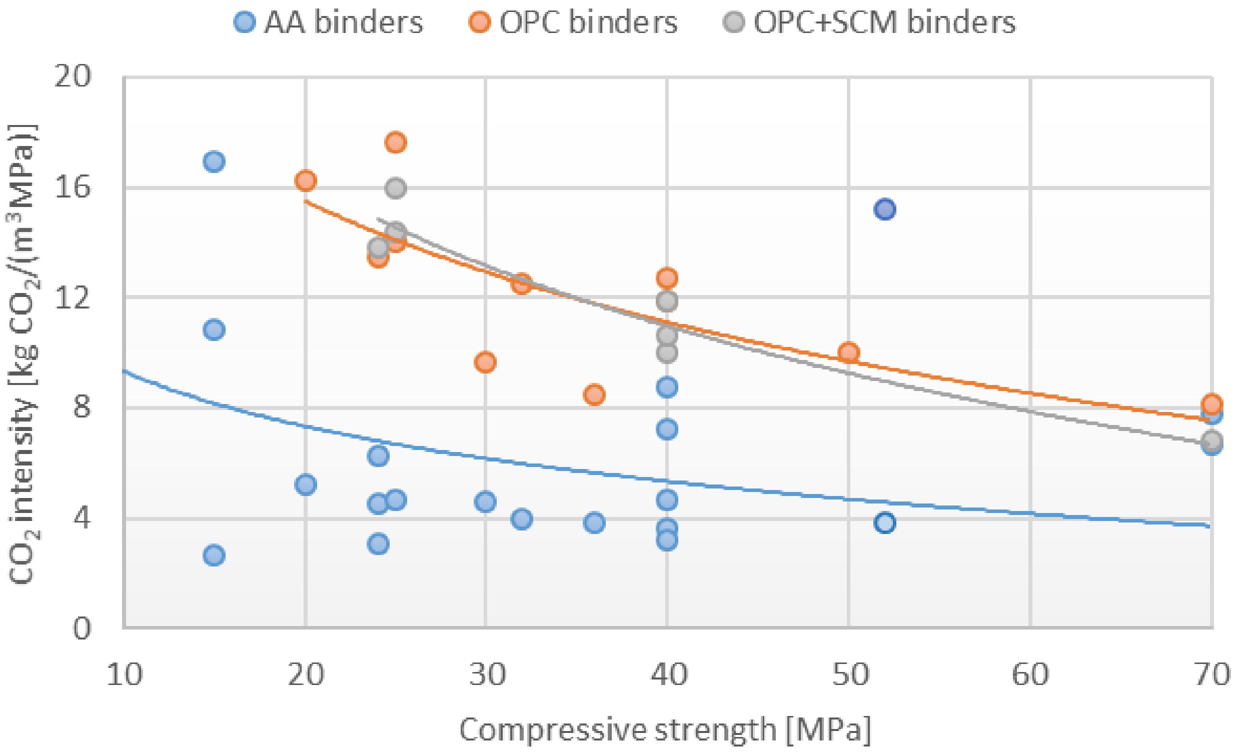

Figure 5. CO$_2$ intensity as a function of compressive strength. Data from published LCA literature [17-25].

Figure 5 distinguish between three categories of materials: alkali activated binders (both mortars and concrete binders are considered), portland cement binders (both mortars and concrete) and cementitious binders with both portland cement and supplementary cementitious materials. Based on the trend lines for all the classified materials an increase in compressive strength corresponds to a decrease in embodied CO$_2$. This result is also reported in the literature [34], likely due to more efficient use of clinker at higher strengths. From the analysis of these studies traditional portland cement binder and PC and SCM binders display a similar behavior, with only a clear environmental advantage of PC+SCM binders for concretes with compressive strength over 40 MPa. Alkali Activated binders display reduced CO$_2$ emissions with low correlation to the compressive strength when exceeding ~20 MPa. When considering pavement applications, Figure 5 suggests that AA binders may provide the required strength with considerably less CO$_2$ emissions than traditional technology, though future work should be performed to ensure that durability indicators (e.g., permeability and wear resistance), are also considered.

Conclusions

The capital investment in the U.S. for construction and maintenance of the infrastructure road network is likely increasing in the near future, similarly to OECD countries. Some countries like China are expected to exponentially increase their investments in new infrastructures as a result of the rapid growth of metropolitan cities.

Sustainable alternatives to portland cement and asphalt pavement should be considered to lower the GWP embedded in the infrastructure network. AAM might represent a possible alternative to more traditional technology, as summarized in this report. The results show that, from the LCA studies that have been analyzed, AAM display a lower CO_2 intensity when compared to PC and PC+SCM binders, while providing the required compressive strength for pavement applications.

Furthermore, an analysis of available raw material for alkali activation is presented, showing a relative global abundance of precursors, even if local specificity should be addressed. Due to reduction in steel production and the transition to renewable and alternative sources of electricity, with the coal industry being phased out in many states [28, 32], the availability of GGBS and FA will be limited in the U.S. and European market. Therefore, in those markets, AAM production will utilize MK or other sources that are locally available, such as reclaimed FA. In Asia, the increasing demand for construction materials and energy will continue to drive the coal and steel industry, and therefore AAM production will likely be based on FA and GGBS.

References

1. Federal Highway Administration: Total disbursement for highways 1956-2016, https://www.fhwa.dot.gov/policyinformation/statistics/2016/disbc.cfm, last accessed 05/12/2019.
2. Bureau of Transportation Statistics: Public Road and Street Mileage in the United States by Type of Surface, https://www.bts.gov/content/public-road-and-street-mileage-united-states-type-surfacea, last accessed 09/01/2020.
3. Organization for Economic Co-operation and Development: Infrastructure investment (indicator), https://data.oecd.org/transport/infrastructure-investment.htm#indicator-chart, last accessed 01/13/2020.
4. United States Environmental Protection Agency: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017. 2019.
5. Global Cement and Concrete Association: GNR Project Reporting CO2, https://gccassociation.org/gnr/, last accessed 06/12/2019.
6. Tripnet: Modernizing Georgia's Transportation System, https://tripnet.org/wp-content/uploads/2018/08/GA_Progress_and_Challenges_TRIP_Report_May_2018.pdf, last accessed 08/12/2019.
7. Tsai, J., Z. Wang, and R.C. Purcell: Improving GDOT's Highway Pavement Preservation. (2010).
8. Georgia Department of Transportation: Transportation Funding, http://www.dot.ga.gov/IS/TFA, last accessed 05/12/2019.
9. Atlanta Regional Commission: Improving Mobility in the Atlanta Region, https://atlantaregional.org/transportation-mobility/transportation-planning/transportation-overview/, last accessed 02/01/2020.
10. Metro Atlanta Chamber: Population, https://www.metroatlantachamber.com/resources/reports-and-information/executive-profile#:~:text=Home%20to%206%20million%20people,people%20from%202010%20to%202019., last accessed 09/01/2020.
11. Maryland Asphalt Association: Asphalt Index, https://mdasphalt.org/asphalt-index/, last accessed 05/01/2020.
12. Shi, C., B. Qu, and J.L. Provis: Recent progress in low-carbon binders. Cement and Concrete Research 122 227-250 (2019).
13. International Organization for Standardization: ISO 14040:2006 Environmental management Life cycle assessment Principles and Framework. International Organization for Standardization, Geneva (2006).

14. H. E. Gilberta, P. J. Rosadoa, G. Ban-Weiss, J. T. Harvey, H. Li, B. H. Mandel, D. Millstein, A. Mohegh, A. Saboori and R. M. Levinson, “Energy and environmental consequences of a cool pavement campaign,” Energy and buildings, vol. 157, pp. 53-77 (2017).
15. Wagners: Efc Geopolymer Pavements In Wellcamp Airport, https://www.wagner.com.au/main/our-projects/efc-geopolymer-pavements-in-wellcamp-airport/, last accessed 09/01/2020.
16. L. Burris, K. Kurtis and T. Morton, “Novel Alternative Cementitious Materials for Development of the Next Generation of Sustainable Transportation Infrastructure,” FHWA-HRT-16-017 (2015).
17. Salas, D.A., et al.: Life cycle assessment of geopolymer concrete. Construction and Building Materials 190 170-177 (2018).
18. Weil, M., K. Dombrowski, and A. Buchwald, Life-cycle analysis of geopolymers, in Geopolymers. 2009, Elsevier. p. 194-210.
19. Yang, K.-H., J.-K. Song, and K.-I. Song: Assessment of CO2 reduction of alkali-activated concrete. Journal of Cleaner Production 39 265-272 (2013).
20. Rouwette, R.: LCA of geopolymer concrete (e-crete). Start2See Pty Ltd, Australia. 2012.
21. Habert, G., J.D.E. De Lacaillerie, and N. Roussel: An environmental evaluation of geopolymer based concrete production: reviewing current research trends. Journal of cleaner production 19(11), 1229-1238 (2011).
22. Matheu, P., K. Ellis, and B. Varela: Comparing the environmental impacts of alkali activated mortar and traditional portland cement mortar using life cycle assessment. In IOP Conference Series: Materials Science and Engineering, pp. Page. IOP Publishing, (2015).
23. Teh, S.H., et al.: Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. Journal of cleaner production 152 312-320 (2017).
24. Dal Pozzo, A., et al.: Life cycle assessment of a geopolymer mixture for fireproofing applications. The International Journal of Life Cycle Assessment 1-15 (2019).
25. Robayo-Salazar, R.A., J.M. Mejía-Arcila, and R.M. de Gutiérrez: Eco-efficient alkali-activated cement based on red clay brick wastes suitable for the manufacturing of building materials. Journal of cleaner production 166 242-252 (2017).
26. Ouellet-Plamondon, C. and G. Habert, Life cycle assessment (LCA) of alkali-activated cements and concretes, in Handbook of alkali-activated cements, mortars and concretes. 2015, Elsevier. p. 663-686.
27. Provis, J.: Green concrete or red herring?–future of alkali-activated materials. Advances in Applied Ceramics 113(8), 472-477 (2014).
28. McLellan, B.C., et al.: Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. Journal of cleaner production 19(9-10), 1080-1090 (2011).

29. Carbon Brief: Mapped: The world's coal power plants, https://www.carbonbrief.org/mapped-worlds-coal-power-plants, last accessed 05/12/2019.
30. Observatory of Economic Complexity: Granulated slag from iron, steel industry, https://oec.world/en/profile/hs92/261800/, last accessed 05/12/2020.
31. American Iron and Steel Institute: AISI Member Map, https://www.steel.org/public-policy/resources/aisi-member-map, last accessed 10/12/2019.
32. Ito, A. and R. Wagai: Global distribution of clay-size minerals on land surface for biogeochemical and climatological studies. Scientific data 4 170103 (2017).
33. Climate Analytics: Coal phase out in the European Union, https://climateanalytics.org/briefings/eu-coal-phase-out/, last accessed 05/01/2020.
34. Schneider, M.: The cement industry on the way to a low-carbon future. Cement and Concrete Research 124 105792 (2019).

Data Management

Products of Research

This project involved a literature review on the topics of: investments and maintenance for road constructions, both in the U.S. and for all OECD countries; alkali activated materials and cementitious systems and their mechanical performance compared to greenhouse gas emission footprint. The main product of this study is the correlation between these different fields, as demonstrated in the manuscript.

Data Format and Content

The data used in this study so far consists of literature on the topics noted above; this is summarized in the narrative text of this report.

Data Access and Sharing

The data, as summarized in this report, will be available to the general public via this document.

Reuse and Redistribution

There are no restrictions to sharing or distributing this research report.