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GEOTECHNICAL REQUIREMENTS FOR CAPTURING CO_2 THROUGH HIGHWAYS LAND

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ABSTRACT: Roadside verges in Britain support 238,000 hectares of vegetated land and approximately 10 hectares of vegetated central reserves. These areas have the potential to be engineered in such a way that they deliver a range of ecosystem services including flood regulation and biodiversity conservation in addition to their primary functions such as comfort of sidewalk users (mostly un-vegetated), protection of spray from passing vehicles, a space for benches, bus shelters, street lights and other public amenities, and visual improvement of the roads and designated green belts. Previous research has shown that in soils, calcium-rich materials such as recycled crushed concrete or natural crushed dolerite undergo carbonation. This effectively captures CO_2 from the atmosphere and stores it in the form of $CaCO_3$ precipitated between soil particles. Engineering this process can potentially assist the UK in achieving its ambitious target to reduce CO_2 emissions by 80% of 1990 levels by 2050. Rates of carbonation measured at urban brownfield sites in the UK suggest that treating 12,000 hectares of land containing suitable amendments could remove 1 million tonne CO_2 annually. However, brownfield sites are often subjected to re-construction activities which would reduce the rate of CO_2 absorption from the atmosphere by sealing. To optimize the rate of carbonation, engineered soils need to be constructed at locations subjected to least post-construction activities and roadside verges and central reserves represent a key opportunity in this regard. This paper calculates limits to $CaCO_3$ formation within the first 1 m of pore spaces of soils at roadside verges and central reserves in Britain considering a soil porosity of 20%.

Keywords: Britain roads, engineered soil, CO_2 capture, roadside verges and central reserves

1. INTRODUCTION

Roadside verges and central reserves are an integral part of road construction. Pieces of land between the road-surface and the boundary line, for example adjacent hedgerows, fences or hard development, are called roadside verges [1]. Central reserves are the areas that separate the carriageways of a dual carriageway exclusive of any hard strips [2].

There are estimated to be 238,000 hectares of roadside verges in Britain [3]. In 2014, the United Kingdom's Department of Transport estimated the length of roads (Motorways and type A, B, C and U roads) in Britain to be 245,800 miles. Considering the length of roads and associated central reserves, there are nearly 31,200 miles of central reserves along the roads in Britain.

Roadside verges and central reserves are areas of great potential to capture carbon in addition to their primary functions, if managed and designed appropriately. The ambitious UK target of reducing CO_2 emissions by 80% by 2050, compared to a 1990 baseline, can only be achieved by engaging diverse sectors of society. It is likely that major CO_2 emission reduction will be achieved through improved efficiency in the energy system (for example [4]). However, capturing and storing atmospheric carbon in a form of carbonate in urban soil also appears to be an economically and environmentally effective method [5 - 7]. Measurements at an urban brownfield site in the UK suggest that in one year, each 12,000 hectares of engineered land could remove 1 million tonnes of CO_2 annually [7]. The formation of pedogenic carbonates, which are predominately composed of the mineral calcite ($CaCO_3$), depends on two main factors: (i) the availability of calcium; and (ii) carbonate in solution.

Calcium is naturally derived from the weathering of silicate minerals (plagioclase feldspars, pyroxenes etc.) that commonly occur in basic igneous rocks (for example basalts and dolerites), or from artificial calcium silicate and hydroxide minerals within concrete and cement [8], [9]. Carbonate carbon is mainly derived ultimately from photosynthesis, based on stable isotope studies [10]. During the process, silicate minerals, in particular calcium silicates, react with dissolved CO_2 to form carbonates (Equation 1).

$$CaSiO_3 + CO_2 + 2H_2O \longrightarrow CaCO_3 + H_4SiO_4 \quad (1)$$

This leads to the removal of atmospheric carbon and its subsequent storage in a stable, inorganic state [6 - 8], [11 - 15]. Once formed, this is a stable store for CO_2 since it will only be naturally removed by dissolution, when carbon would normally stay stable as carbonate in solution, entering surface and groundwater systems.

In this paper, we investigate possible constraints to realising the potential for CO_2 sequestration (through $CaCO_3$) in roadside verges and central reserves of Britain. The result of this investigation will assist in designing more sustainable roads, globally, which would provide their primary functions while also sequestering CO_2 emissions discharged into the atmosphere partly from vehicles using internal combustion engines. We also highlight the implications of engineering roadside verges and central reserves to capture carbon on their ability to also deliver a range of additional ecosystem services, such as flood regulation and biodiversity.

2. THEORETICAL BACKGROUND

$CaCO_3$ formation occurs within soil pore spaces. The porosity of soils ranges between 20–60%, depending on soil type and degree of compaction [16]. Pore spaces within coarser soils provide higher potential for carbon sequestration because larger pore spaces having lower surface areas result in decreased friction and provide higher permeability. Higher permeability results in faster weathering of silicate minerals and provides access to sufficient water for the chemical reaction (Equation 1) to take place.

For roadside verges and central reserves to maintain their primary functions, they should reach a certain degree of compaction that leads to significant reduction of porosity. However, optimum compaction of soil with small grains fitting within the larger grain pores would give a porosity of around 20% [16]. This means that even at the highest degree of compaction, 20% of the total soil volume is comprised of voids which can provide a potential location for $CaCO_3$ formation.

Based on previous measurements at the Science Central development site in Newcastle, UK [6], the majority of carbonation occurs in the top 1 m of the soil profile, depending on soil type and precipitation. Based on that result, the calculations presented here consider the first 1 m soil depth for roadside verges and central reserves. The porosity of the soil at roadside verges and central reserves is assumed to be 20%.

In addition to the carbon capture function, there is also an argument that enhanced levels of CO_2 may increase the carbon capture rate, therefore a roadside pot experiment is currently being conducted (2016-2017) to determine how elevated levels of CO_2 produced by emissions from vehicles, mainly N_2O and CO_2, affect the local soil and plant processes. The roots of plants and their development are to be studied as they act as the main exchanger of C from the atmosphere to the soil. For example, it is already known that vegetation with a C_3 photosynthesis mechanism (very common in Europe) responds to elevated CO_2 enrichment through substantial growth in root structures and C absorption [17].

3. RESULTS

Cross-sections and dimensions for rural and urban roads in Britain are shown in Fig. 1. Based on the dimensions provided, the total volume of the soil associated with the first 1 m of road central reserves is calculated and presented in Table 1.

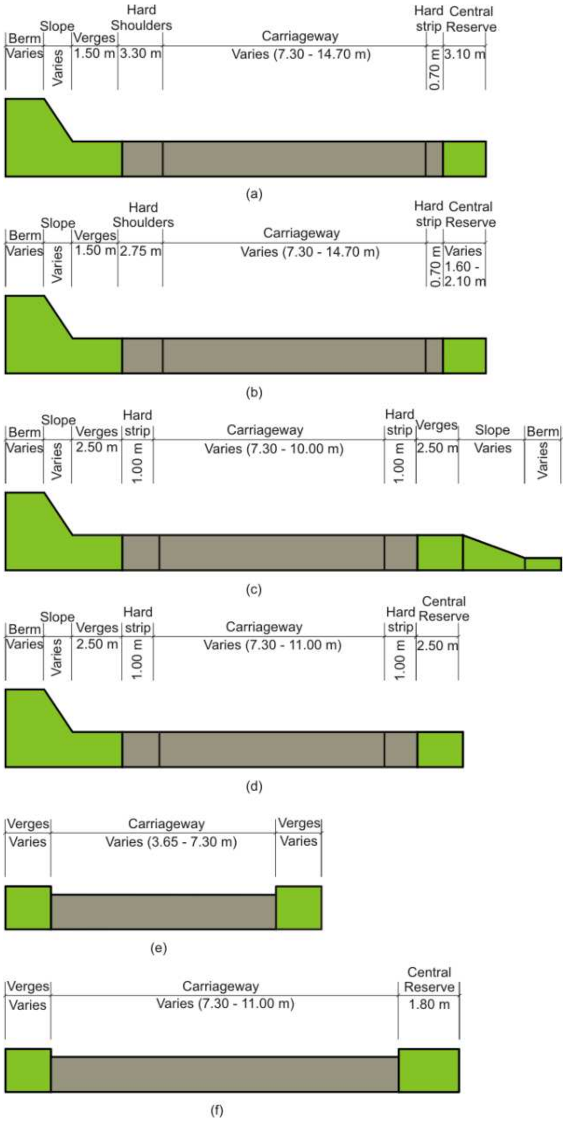

FIG. 1 Dimensions of cross-section components for (a) rural motorway, (b) urban motorway, (c) rural single carriage all-purpose, (d) rural dual carriage all-purpose, (e) urban single carriage all-purpose and (f) urban dual carriage all-purpose roads mainline [2].

Based on an estimated density of pure $CaCO_3$ as 2715 kg/m^3 [18] for soil at roadside verges and central reserves, maximum ranges of $CaCO_3$ deposition within pore spaces are calculated and presented in Table 2. For the calculations, the porosity of 20% is considered and it is assumed that 100% of the pore spaces are filled with $CaCO_3$. Therefore, potentially 543 kg of $CaCO_3$ for each cubic metre of soil could be stored within soil pore spaces in roadside verges and central reserves.

Table 1 Total volume of soil present within the first 1 m of soils along road central reserves in Britain

Type of roads	Total length of central reserve (mile) [19]	Volume of soil present in the upper 1 m of central reserves (m^3)
Rural/urban motorway	2,212	8,815
Rural dual carriageway	22,122	88,710
Urban dual carriageway	6,882	19,870

Table 2 Total potential $CaCO_3$ storage capacity within the top 1 m of soil depth along roadside verges and central reserves in Britain. For the calculations of this table, porosity of 20% is considered

Type	Volume of soil present in the top 1 m (m^3)	Potential $CaCO_3$ storage (million tonne)
Roadside verges	2,380,000,000	1292
Road central reserves	117,395	0.06
		$\sum = 1292$

4. DISCUSSION

Results from Table 2 show that roadside verges have considerable potential for $CaCO_3$ deposition compared with road central reserves.

Table 2 indicates the limit to the formation of $CaCO_3$ within the first 1 m of sediments at roadside verges and central reserves, which is defined by porosity and hence particle size and degree of compaction. Considering the porosity of 20% and assuming all of the void spaces within the top 1 m of soil within roadside verges and central reserves are filled with $CaCO_3$, they have the capacity to deposit an estimated maximum of 1,292 million tonne $CaCO_3$ (Table 2), equivalent to 150 million tonne C. However, in reality, other factors such as solution pH, the presence of organic complexes and fluid flow rate also play an important role in the formation of $CaCO_3$ [11].

Clearly, engineering all roadside verges and central reserves for carbon sequestration in Britain is not feasible since they are mostly operational and reconstruction to implement carbon capture design into the roadside verges and central reserves requires significant funding and time. However, the Department for Transport (DfT) statistics in 2014 show that total road length in Britain increased 2% over ten years, compared with the 2004 baseline [19]. Considering a similar rate for the next ten years, if roadside verges and central reserves of new roads are engineered for carbon capture purposes during construction they have the potential to deposit nearly 25 million tonnes of $CaCO_3$ which equates to 11 million tonne of CO_2. This figure is separate from roads which will be upgraded and resurfaced in future providing further opportunity to implement carbon capture design during re-construction. The calcium source required for new engineered soils could be partly acquired through recycling of concrete from the demolition of bridges and other concrete structures associated with roads as they reach the end of their life. Remaining calcium sources could be acquired from nearby demolition sites or dolerite quarries.

Vegetated roadside verges and central reservations represent an important component of ‘green infrastructure’ (GI). GI is defined as ‘a network of multifunctional green space, urban and rural, which is capable of delivering a wide range of environmental and quality of life benefits for local communities’ [20], [21]. In addition to carbon capture, roadside planting should be designed to provide an array of functions or ‘ecosystem services’ including aesthetic appeal for pedestrians, localized urban cooling and removal of particulate matter from vehicle emissions [22]. The choice of planting and management of vegetation on roadside verges and central reserves could also influence calcite formation. Carbon stored in carbonates is plant derived, implying that encouraging plant growth on engineered urban soils may facilitate carbon capture [8], as well as providing other ecosystem services associated with vegetated land. Although roads generally have a negative impact on biodiversity (for example [23], [24]), sympathetically managed or restored roadside verges make an important contribution to the conservation of grassland species (for example [25]) and pollinating insects [26]. For instance, Highways England is committed to the implementation of the National Pollinator Strategy for England [27] and will undertake a programme of works to achieve a significant area of species rich grasslands, estimated at 3,500 hectares by 2021.

If fully carbonated, the permeability of soil approaches zero in which case roadside verges would have a reduced capacity to drain water, possibly (depending on specific design) leading to flooding during periods of heavy rainfall. For roads in general and motorways in particular, if it occurs, such flooding might lead to damaging events. Accordingly, a proper drainage system such as SUDS [28], [29] should be considered for roadside verges and central reserves if engineered to capture carbon in addition to their primary functions. A further benefit of SUDS is that the created wetland can provide habitat for supporting biodiversity [30], [31].

The use of aggregates for carbon sequestration purposes, no matter how much carbon is stored, is ultimately controlled by economic and practical viability and there are many factors influencing the price of carbon emission mitigation techniques. For the purposes of this study, the European Emissions Trading Systems (EU ETS) found from the European Energy Exchange (EEX) can be used as an obtainable price for CO_2; which on the 8th August 2015 stood at €7.94 (£5.63) per tonne of CO_2. The UK government has capped in Carbon Floor Price (CFP) at £18 per tonne recently in order to compensate for this low EU value of carbon dioxide, however, for simplification here, we assume a market price based on the EEX.

Accordingly, considering the calculated capacity of roadside verges and central reserves of new roads built within the next 10 years to sequester 11 million tonne of CO_2, the land can obtain a price of £61,930,000 for CO_2 sequestration, which is in line with increasing demand for climate mitigation.

In terms of the cost of enhanced weathering as a technology, extraction, comminution and transportation should be taken into account. The operational costs of enhanced weathering using basic rocks such as dolerite or basalt is £44-361 tonne of CO_2 [32]; this wide price range is indicative of the variability in economic modelling. Operational costs are however highly influenced by extraction and comminution costs. When considered for this study, this cost may be reduced because the targeted aggregates could be sourced from aggregate industry by-products with otherwise limited markets. Therefore, the dominant costs to consider are transportation and mixing. Transportation within the UK can be done by sea for dolerite sources close to the sea, which is feasible due to the distinct distribution of basic rocks in the UK. In the case of dolerite from the Whin Sill, transportation would be more appropriate by land. By using transportation cost of £0.0496 per tonne per km [32], to engineer one hectare of roadside verges and central reserves of new roads for carbon sequestration using 800 tonne of crushed dolerite, transportation would have to be limited to approximately 50 km (£1984) in order for the site to return any profit (based on carbon prices used above). This may limit the use of dolerite for carbonation purposes to local developments.

Alongside transportation costs, there are also application and mixing costs to consider. Renforth [32] discusses energy requirements for spreading crushed rocks at a rate of 0.40 tonne per hectare annually. Although this study recommends mixing silicate minerals with the substrate rather than spreading, an approximate cost of £8.13-15.50 per tonne of CO_2 stored is estimated for the cost of silicate minerals application [32].

Predicting the saturation point for the $CaCO_3$ formation between soil particles is an essential factor which largely controls the geotechnical properties of the substrate such as permeability and this can be done using multiple regression modelling [33].

5. CONCLUSIONS

Limits to $CaCO_3$ formation within pore spaces of sediments at roadside verges and central reserves have been calculated and we show that roadside verges have the greatest potential deposition rate. Considering a porosity of 20%, the top 1 m of soil at roadside verges and central reserves along rural and urban roads in Britain has a theoretical capacity of 1,292 million tonne $CaCO_3$, equivalent to 150 million tonne C, of which almost all is in verges. Road length in Britain is expected to increase by 2% over the next ten years. This will lead to increased vehicle movements and CO_2 emissions. If managed and engineered appropriately, roadside verges and central reserves associated with new roads have the theoretical capacity to store 25 million tonne $CaCO_3$ (from 11 million tonne CO_2; 3 million tonne C). This equates to economic benefit of £61,930,000 in terms of mitigation of CO_2 emission. Recycling of concrete from demolition of bridges and other concrete structures associated with roads as they reach the end of their life could be an appropriate calcium source for new engineered soil.

This study indicates that road components such as roadside verges and central reserves have potential to provide the function of passive CO_2 removal. However, considering the possibility that deposition of $CaCO_3$ within soil pore spaces may reduce permeability, design to maintain proper drainage in the soil profile may be required to avoid flooding. Engineering a carbon capture function into roadside verges needs to be sympathetic to the provision of other ecosystem services, such as biodiversity conservation.

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7. REFERENCES

[1] Thomas C, “ROADSIDE VERGES”, Warwickshire, Coventry and Solihull Local Biodiversity Action Plan, 2005, pp.8.

[2] Department for Transport, “Design Manual for Roads and Bridges - Cross-Sections and Headrooms”, Volume 6, Section 1, Part 2, 2005.

[3] Department for Transport, “Road lengths in Great Britain”, 2013, available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/208692/road-lengths-in-great-britain-2012.pdf.

[4] Pacala S, Socolow R, “Stabilization wedges: Solving the climate problem for the next 50 years with current technologies”, Science 305, 2004, pp. 968– 972.

[5] Manning DAC, “Biological enhancement of soil carbonate precipitation: passive removal of atmospheric CO_2”, Mineralogical Magazine 72, 2008, pp. 639-649.

[6] Washbourne CL, Renforth P, Manning DAC, “Investigating carbonate formation in urban soils as a method for capture and storage of atmospheric carbon”, Science of the Total Environment 431, 2012, pp. 166-175.

[7] Washbourne CL, Lopez-Capel E, Renforth P, Ascough PL, Manning DAC, “Rapid removal of atmospheric CO_2 by urban soils”, Environmental Science and Technology 49, 2015, pp. 5434-5440.

[8] Manning DAC, Renforth P, “Passive sequestration of atmospheric CO_2 through coupled plant-mineral reactions in urban soils”, Environmental Science and Technology 47(1), 2013, pp. 135-141.

[9] Jorat ME, Goddard MA, Kolosz BW, Sohi S, Manning DAC, “Sustainable Urban Carbon Capture: Engineering Soils for Climate Change (SUCCESS)”, In: 16th European Conference on Soil Mechanics and Geotechnical Engineering (XVI ECSMGE 2015). 2015, Edinburgh, pp. 2559 – 2564.

[10] Cerling TE, “The stable isotope composition of modern soil carbonate and its relationship to climate”, Earth and Planetary Science Letter 71,1984, pp. 229-240.

[11] Renforth P, Manning DAC, Lopez-Capel E, “Carbonate precipitation in artificial soils as a sink for atmospheric carbon dioxide”, Applied Geochemistry 24, 2009, pp. 1757-1764.

[12] Renforth P, Edmondson J.; Leake, J. R.; Gaston, K. J.; Manning, D. A. C. Designing a carbon capture function into urban soils. Proc. Inst. Civ. Eng.: Urban Design Plann. 2011, 164 (2), pp. 121−128.

[13] Kolosz BW, Goddard MA, Jorat ME, Aumonier J, Sohi SP, Manning DAC, “A Sustainability Framework for Engineering Carbon Capture Soil In Transport Infrastructure”, International Journal of Transport Development and integration 2017, 1, pp. 74-83 (In-press).

[14] Kolosz BW, Manning P, Goddard MA, Jorat ME, Sohi SP, Manning DAC, “A Multifunctional Soil Inorganic Carbon Prediction Model”, In: 8th International Congress on Environmental Modelling and Software. 2016, Toulouse France (In-press).

[15] Kolosz BW, Goddard MA, Jorat ME, Sohi S, Manning DAC, “Developing Lifecycle Inventory Indices for Estimating the Carbon Sequestration of Artificially Engineered Soils and Plants”, In: 5th Asian conference on Sustainability, Energy, and the Environment, 2015, pp. 93-112.

[16] Jorat ME, Kolosz BW, Sohi S, Lopez-Capel E., Manning DAC, “Changes in geotechnical properties of urban soils during carbonation”, In: 15th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, 2015, Buenos Ares, Argentina, pp. 912 – 918.

[17] Smith P, Powlson DS, Smith JU, Falloon P, Coleman K, “Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture”, Global Change Biology 6, 2000, pp. 525-539.

[18] Deer WA, Howie RA, Zussman J, “An introduction to the rock forming minerals”, Longman Scientific & Technical, Essex, 2013, 3rd Edition.

[19] Department for Transport, “Road lengths in Great Britain”, 2014, available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/428857/road-lengths-in-great-britain-2014.pdf.

[20] Department for Communities and Local Government [DCLG], “Planning Practice Guidance. Green Infrastructure”, 2016, available at: http://planningguidance.communities.gov.uk/blog/guidance/natural-environment/green-infrastructure/.

[21] European Environment Agency, “Soil resource efficiency in urbanised areas - analytical framework and implications for governance”, edited by Geertrui Louwagie, Publications Office of the European Union, 2016, pp. 92.

[22] Cameron RWF, Blanusa T, “Green infrastructure and ecosystem services - is the devil in the detail?”, Annals of Botany, 118, 2016, pp. 377-391.

[23] Muñoz P, Torres F, Megías A, “Effects of roads on insects: a review”, Biodiversity and Conservation, 24, 2015, pp. 659-682.

[24] Benítez-López A, Alkemade R, Verweij PA, “The impacts of roads and other infrastructure on mammal and bird populations: A meta-analysis”, Biological Conservation, 143, 2010, pp. 1307-1316.

[25] Auestad I, Rydgren K, Austad I, "Road verges: Potential refuges for declining grassland species despite remnant vegetation dynamics", Annales Botanici Fennici, 48, 2011, pp. 289-303.

[26] Hopwood JL, "The contribution of roadside grassland restorations to native bee conservation", Biological Conservation, 141, 2008, pp. 2632-2640.

[27] DEFRA, "The National Pollinator Strategy: for bees and other pollinators in England", 2014.

[28] Poleto C, Tassi R, "Sustainable Urban Drainage Systems", Drainage Systems, Prof. Muhammad Salik Javaid (Ed.), ISBN: 978-953-51-0243-4, InTech, 2012, available from: http://www.intechopen.com/books/drainage-systems/sustainable-drainage-systems.

[29] Zhou Q, "A Review of Sustainable Urban Drainage Systems Considering the Climate Change and Urbanization Impacts", Water, 6, 2014, pp. 976-992.

[30] De Martis G, Mulas B, Malavasi V, Marignani M, "Can Artificial Ecosystems Enhance Local Biodiversity? The Case of a Constructed Wetland in a Mediterranean Urban Context", Environmental Management, 57, 2016, pp. 1088-1097.

[31] Hassall C, Anderson S, "Stormwater ponds can contain comparable biodiversity to unmanaged wetlands in urban areas", Hydrobiologia, 745, 2015, pp. 137-149.

[32] Renforth, P., "The potential of enhanced weathering in the UK", International Journal of Greenhouse Gas Control, 10, 2012, pp. 229-243.

[33] Fox J, "Applied Regression Analysis, Linear Models, and Related Methods", Published by Sage Publications, Inc., ISBN: 0-8039-4540-X, the United Stated of America, 1997, Chapter 2, pp.15.