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A Review of Current Design and Construction Practice for Road Kerbs and a Sustainability Analysis

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Abstract: Kerb is an integral part of road infrastructure and performs several important functions, including providing stability to the edges of the road and providing effective drainage. Their performance can significantly influence the behaviour and service life of a road. The design conditions, construction materials and their sustainability can be important to assess from an asset management and sustainable construction point of view even though this area has been paid limited research attention in the past. This paper reviews the available literature on the design and construction considerations for kerbs and critically analyses them with a special focus on sustainable construction practice. The different materials commonly used around the world for the construction of kerb in terms of their properties, failure and available design guidelines have been discussed along with their management practice. Special situations, such as expansive soil movement and tree root-related problems, have also been considered, and the current guidelines for designing in such situations have also been discussed. A carbon footprint and sustainability analysis has been conducted on the current practice of using natural aggregate concrete and compared against several potential alternatives. The review of the design process indicated that the current practice relies on over-simplified design procedures and identified scopes for improvement, especially with the incorporation of mechanical behaviour of the material being used in construction. The carbon footprint and sustainability analysis indicated that the use of alternative materials could result in significant savings in the kerb construction industry's carbon footprint.

Keywords: kerb; design; material; soil–kerb relation; kerb failure

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1. Introduction

The kerb (British English) or curb (American English) is the raised edge of the road where the footpath or median is separated from the street or roadway. The use of kerbs was first discovered in the city of Pompeii, Italy, which was buried under volcanic ash and pumice in the eruption of Mount Vesuvius in AD 79 [1,2]. The main functions of kerb are to provide structural support to the edges of the roads [3] and channel rainwater away [4–13]. By providing effective drainage, it can reduce cracking and other surface and structural defects and effectively increase the service life of a pavement. The failure of kerbs often leads to excessive moisture ingress into the pavement structure, leading to the softening of the pavement materials, which can significantly affect the structural performance of the road and increase the repair and maintenance cost.

Kerbs also help to reduce the risk of soil erosion, discourage drivers from parking and driving on the footpath and have a re-directive capacity for slow-moving vehicles [14]. Kerbs improve the aesthetic aspects of a road and can be used as road markings. Sometimes a kerb is extended to obtain extra space for bench and planting [15] or a refuge island for pedestrians at the median of the road [16].

Kerbs can be divided into different categories based on their shapes (straight, square, round, concave, convex), functions (mountable, semi-mountable, barrier, high profile barrier [17], hollow kerb for drainage [18]), materials [19–21] (stone, masonry block, precast concrete, cast on pavement, rubber, plastic) and heights (bus boarding, with ramp, trief kerb). Figure 1 shows a cross-section of a typical barrier kerb.

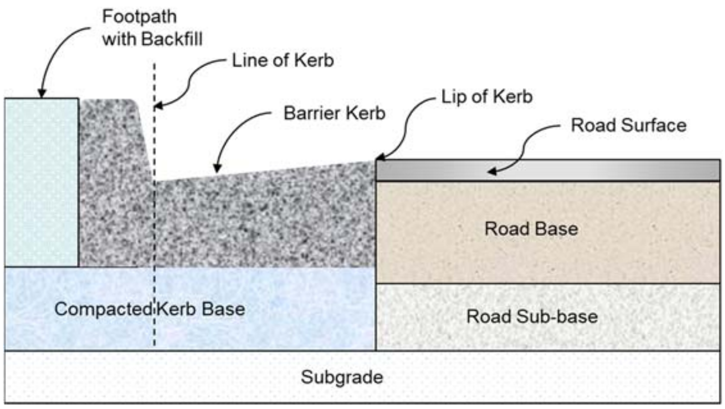

Figure 1. Barrier kerb and Road cross-sections.

Generally, kerbs are constructed on urban and suburban roads [18] and often constructed/managed by different local governments and roads authorities. There are no unified and well-developed design codes/standards available for its design. The current practice is limited to prescribed compressive strength and cross-sectional details for different scenarios. These guidelines are not necessarily developed based on a rigorous mechanical assessment of its behaviour (often based on experience), and significant differences can be found in guidelines from different authorities [22–25]. Part of this could be due to a lack of research effort in this area [26].

Throughout their design life, kerbs have to withstand lateral load from vehicles, lateral load from the pavement structure [18] and loads exerted by tree root migration as well as expansive soil movement when constructed on such soils. There was no work found in the literature that scrutinizes the current design practice and compares guidance from different authorities. Based on a literature search and limited consultation with the relevant authorities, this paper discusses the importance of incorporating different site conditions, properties of kerb material, failure types and management practices into the design of kerbs. To the author's best knowledge, such a review on current road kerb design and construction practice is non-existent in the literature.

2. Road Kerb Design Consideration

The useful life of a kerb is considered to be 40 to 100 years [27,28]. However, there is no unified/standard structural design procedure of kerbs available in Australia. The situation is much the same in other parts of the world. The design is mostly carried out following some specific material properties requirements imposed by different local governments and road authorities. Generally, the shape and height are decided based on the design speed limit and their functions, and the structural design is limited to specifying a minimum strength for the material to be used in construction.

The relevant design documentation was not easily accessible as many of the local government and road authorities do not publish them online. During the preparation of this manuscript, a total of 23 council/administrative body documents were collected and critically reviewed. Based on a review of these documents, a summary of the current design practices, including the criteria for kerb height and material, is presented in the following sub-sections.

2.1. Size and Shape of the Kerb

The height of the road kerb should be such that it can absorb the torsional load from the vehicles and restrict the tilting of the road kerb. The height of the kerb that is visible over the road surface is termed as kerb-reveal. According to the Federal Highway Administration (FHWA) guideline, the height of the kerb can vary between 100 mm to 225 mm in urban and rural roads [26]. In general, the kerb reveal is designed according to the design stormwater flow, and it was found to vary from 100 to 200 mm as analysed from the drawings of different councils and AASHTO policy [17,29]. A kerb-reveal greater than 150 mm can obstruct the full opening of the car door [30]. Higher kerbs (150–180 mm) are often used in bus stoppage for easy access for the passengers, and they are known as Kassel kerb [31]. The University of British Columbia [26] produced guidelines for deducing the height of a kerb from loads from the vehicles, and the European Standard [32] presents a guideline for the height of a stone kerb to be dependent on the breaking load and flexural strength of the material used. Except for these two sources, no other guidelines/methodology could be found in the literature that takes mechanical aspects, such as load, into account while deciding the height of the kerb.

The choice of height in footpath or pedestrian areas can be dictated by other considerations, such as health hazards [33]. One study found the right-angled kerb to be liable for the outdoor fall of 6% of elderly people while approaching the kerb during walking [33]. They could also be a possible risk for cyclists. Two-thirds of single bicycle crashes happened due to hitting the kerb [33]. Thomas [34] suggested a minimum height of 60 mm for kerb for blind and partially sighted people and also proposed the use of dropped kerb crossings. Kerb cut is introduced for the mobility of disabled people and small vehicles that have small wheels, such as a tricycle, wheelchair, prams and strollers. A longer kerb cut is also used in driveways to cross the footpath or sidewalks [35,36]. There are several acts and rules for access and mobility over road kerbs for disabled people in every country, such as AS 1428.1 and AS1428.2 for Australia and the AASHTO policy [29,37,38].

A study by Plaxico [39] recommended not constructing kerb in the rural roads with a speed limit over 80 km/h because the errant high-speed vehicles can jump or rollover. The study also suggested that the kerb height should not exceed 100 mm, and the kerb face should be 1:3 or flatter in the roads designed for greater than 60 km/h operating speed. A kerb of the height of 150 mm and less performs poorly in redirecting the vehicles over the 72 km/h speed, so it is not recommended where the primary requirement is to redirect the vehicles [40]. A kerb with a height of 325 mm or higher is recommended for such a scenario. No kerb is recommended where the design speed is 96 km/h or higher [40]. Kerb height guidelines presented by Plaxico, Ray, Weir, Orengo, Tiso, McGee, Council and Eccles [22] are shown in Table 1.

Table 1. Maximum kerb height guidelines presented by Plaxico, Ray, Weir, Orengo, Tiso, McGee, Council and Eccles [22].

Design Speed, km/h	Maximum Kerb Height, mm
60–70	150 (sloping face)
71–85	100–150 (sloping face)
$\geq$85	$\leq$100 (sloping face)

In an intersection, curves and U-turns of a road section, the kerb has to face large loading from long, heavy vehicles (Class 3 to 12 according to Austroads [41]) due to excessive off-tracking and, thus, often fails prematurely [42]. The modification of road geometry is recommended for such a situation, but it is often not possible due to space restrictions. To reduce the chance of kerb failure in such circumstances, Suh, Ha and Won [26] suggested extending the kerb width to 600 mm. There is no guideline found for the selection of the kerb width; however, by analysing different drawings of the road cross-section, it was found that it is the design engineer's responsibility to select a width which is based on experience.

The width of the kerb can be extended to 450 mm in the heavy rainfall areas with cross fall between 4–6% [17]. On the high side of a pavement, a kerb is constructed without the channel, which is used on the lower side of the road.

2.2. Material Properties

Based on the review of the available documents (e.g., standards and different local and road authorities guidelines), this section discusses the required minimum material strength and other properties.

2.2.1. Concrete

Concrete is the most commonly used material for kerb construction. For example, 86% of the length of kerbs are made from concrete in Macedon Ranges Shire Council, Australia [43]. Table 2 summarizes the requirements for kerbs from different authorities from Australia and around the world.

Table 2. Concrete property requirements set by different authorities.

Country	Authority/State	Minimum Compressive Strength (MPa) *	Air content (%)	Depth (mm)	Cross Slope (%)	Reference
Australia	City of Salisbury	25	-	-	-	[28]
	City of Sydney	25	-	-	-	[44]
	City of Perth	25–32	-	130–150	-	[45]
	Mount Barker	25	-	-	-	[46]
	Murray Bridge	20–32	-	150	-	[47]
	City of Whittlesea	25	-	-	-	[48]
	City of Port Adelaide Enfield	25	-	-	-	[49]
	Western Australia	20	-	-	-	[50]
	DPTI, SA	20–28	-	125–250	0.5–10%	[23]
USA	Texas	20	-	100–225	1.5–6.0	[26]
	Alabama	20	-	100–225	1.5–6.0	
	North Carolina	17	-	100–225	1.5–6.0	
	Virginia	20–27	-	100–225	1.5–6.0	
	Delaware	20	-	100–225	1.5–6.0	
	Kentucky	25	-	100–225	1.5–6.0	
	AASHTO	-	-	100–200	-	[22]
Canada	City of Toronto	32	6.5 ± 1.5	100–170	-	[51]
	City of Burlington	32	5–8	-	-	[52]
	City of Brantford	30	-	150	0.5–0.8%	[53]
	Township of Springwater	32	-	-	2%	[54]
	Province of Manitoba	32	5–8	-	-	[55]
United Nations	ESCAP	-	-	75–150	-	[24]
Europe	European Standard	1. 2.8–6.0 MPa Bending strength 2. ≤6% Water Absorption 3. ≤1.0 kg/m^2 Mass loss after freeze-thaw 4. ≤23 mm loss in Wide wheel abrasion test or ≤20,000 mm^3/5000 mm^2 loss in Böhme test [56]				[25]

* 28-days compressive strength.

From the table, it can be seen that concrete compressive strength has been the most important property set by different authorities across the world. The required compressive strength for kerb concrete varied between 17 and 40 MPa [57]. It is also noticeable that the compressive strength is defined by the local government, but it is not a part of a country's standards. There are also special requirements in the Australian standard on the minimum amount of cement in the concrete for local access and cul-de-sac roads, collector and distributor roads and main roads, highways and freeways, which are 240 kg/m^3, 280 kg/m^3 and 320 kg/m^3, respectively [58]. Some other requirements found in these documents are related to workability (e.g., slump), surface smoothness, shrinkage or expansion joints and construction joints [55,59,60]. Fresh concrete properties, such as air content, are also considered important by some of the authorities. The European Standards (EN 1340) added other properties, such as bending strength, water absorption, abrasion resistance and freeze-thaw durability, for the concrete kerb [61]. The concrete durability properties, such as water absorption and the freeze-thaw resistance, were added considering the weathering effect because the kerb needs to withstand the stress from the freeze-thaw cycle in particular areas. Again, the flexural strength is included because the kerb is acting as a beam over the sub-base and abrasion is included to confirm the longevity of the kerb.

2.2.2. Reinforcement in Concrete Kerbs

Adding reinforcement to concrete kerbs has both positive and negative effects. The positive side is the reinforced kerb will perform better sustaining a heavy tyre load, differential load from expansive soil movement and tree root migration. On the negative side, reinforcement in kerb concrete can be prone to chemical attacks and rusting due to insufficient protection, which often leads to cracking and other damages, as shown in Figure 2 below.

(**a**) (**b**)

Figure 2. Failure of a kerb due to insufficient clear cover for reinforcement (**a**) Longitudinal crack after initiation, and (**b**) after failure.

In the majority of cases, reinforcements are not used in the concrete kerb. There was no guideline to reinforce the kerb, but sometimes, the implementing authority can ask for kerb reinforcement in their working drawings [55]. Sometimes, dowel bars are used in concrete kerbs to allow better load transmission in rigid pavements. When provided, the amount of reinforcement should be dependent on the wheel load's magnitude or the force exerted by the soil or other factors. The kerbs constructed in road intersections, curves and entry portions are subjected to heavy loads. Therefore, reinforcement can be provided in the road kerb to prevent structural failure based on the loading type and value. Fibres can also be used to increase the crack resistance of concrete [62].

2.2.3. Other Required Properties

The European Standard (EN 1340) described tests for bending strength, abrasion resistance and freeze-thaw durability for the concrete kerb [25]. However, the tests defined by the European standards might not always be enough to cover for all possible failure mechanisms, for example, a failure due to concrete cancer (rusting in the reinforcement) or traffic accidents or other impact loads from traffic [63–65]. There is no appropriate test for measuring the impact load from road traffic accidents. Mason, Korostynska, Cordova-Lopez, Al-Shamma'a and Ledsham [3] developed a kerb test method against the impact load coming from road traffic collisions. It is a point load dropping test of a steel cylinder of 150 mm of diameter and 65 mm of height free falling from a height of 1100 mm to the kerb face. The falling of the steel cylinder is repeated over the kerb until failing. The number of drops is counted for initial damage, and the damage on the kerbs is observed after 50 repetitions of free falling. The sorptivity of concrete is also important for the reinforced kerb. It measures the capillary rise of water into the concrete. The depth of capillary rise of water will help to determine the clear cover in the kerb.

2.3. Other Materials Used in Kerb Construction and Related Design Practice

2.3.1. Recycled Concrete

On average, four tons of new concrete per capita is used around the world, and it is the second most used material after water for human activities [66,67]. At the same time, nearly three billion tons of construction and demolition waste are produced every year worldwide [68]. Currently, a significant proportion of the construction and demolition wastes are recovered as recycled aggregate for concrete. For example, in Australia, 12.3 million tons (72% of total) are recovered, and 4.8 million tons (28%) are disposed of in landfills [69,70]. Recycled concrete often produces inferior performance compared to natural aggregate concrete [71,72]. As the structural performance requirement for kerb is lower compared to many other structures, it can be a suitable application area for such materials. Past research has shown that up to 30% of natural aggregate in concrete can be replaced by recycled aggregate without significantly affecting its properties [73,74]. López Gayarre et al. [75] found that for kerb application, the addition of an increased proportion of recycled aggregate in concrete did not highly affect its physical and mechanical behaviour, even though the surface finish was inferior as the recycled aggregates were more angular. They indicated that kerbs can be constructed with up to a 70% replacement of natural aggregate with recycled ones; however, for above 50% replacement, good surface finishing may not be achievable. The properties of recycled aggregates can be highly variable depending on the source and processing involved. Özalp et al. [76], López Gayarre et al. [77] and Lan et al. [78] emphasized the proper separation and classification of recycled aggregate for consistent performance of concrete. The Australian standards also allow the use of up to 100% uniform recycled concrete aggregate for up to 25 MPa concrete for non-structural use [57].

Over the last couple of decades, tyre-derived aggregates (TDA) have been looked at as a potential replacement for natural aggregates [79]. The use of TDA can lead to a reduction in compressive and tensile strength; however, at the same time, it has been shown to improve certain properties of concrete, including ductility, toughness, ability to deform, deflection capacity, energy dissipation and impact resistance [80–85], which can be desirable in certain applications. For example, the use of rubberized concrete can lead to an increased length between construction joints or can even be used in the jointless pavement because of its high strain capacity [86]. Many of the studies agreed that rubber could be used up to 25% by volume for concrete in different applications [80–82,87,88]. From most of the studies, it is clear that TDA can be used up to 25% by volume to achieve a compressive strength of 40 MPa [80–82,87,88]. Since the flexural properties of concrete are important for kerbs, especially when constructed on reactive soils, rubberized concrete can be a potential solution in such scenarios. Some researchers already used TDA in kerb application and found it desirable, e.g., Komaki et al. [89], Munikanan et al. [90] and Johari et al. [91].

2.3.2. Stone

Stone kerbs are preferable where de-icing chemicals are used on pavements for snow and ice removal [29]. Specifications for the construction and placement of stone kerb have been developed in many countries, including Australia. The flexural strength, density, water absorption, freeze-thaw tests of stone kerb are described in the European standards EN 1343 [32]. This standard describes the test method and minimum flexural breaking loads for different site scenarios. For example, the minimum flexural breaking loads for pedestrian areas, light vehicles, marketplaces, delivery vehicles, heavy lorries and petrol stations are 3.5, 6.0, 9.0, 14.0 and 25.0 kN, respectively. The standards from other countries could not be obtained through the internet search, but some guidelines from different local government authorities were obtained. The required property range of Granite and Sandstone kerb are compared from two different councils of Australia with the related testing standards are shown in Table 3. The comparison shows that there is significant variability in the stone property as well as the requirement.

Table 3. Comparison of Granite and Sandstone properties with the requirements of the City of Sydney and the City of Perth.

Property	Test Standard	Granite				Sandstone	
		Range [92]	Sydney [44]		Perth [45]	Range [92]	Sydney [44]
			Granite (Austral Black)	Granite (Austral Verde)			
Bulk density (kg/m^3)	ASTM C97	2600–2650	>2900	>2560	2700	2000–2350	>2000
Compressive Strength (MPa)	ASTM C170	175–350	>185	>140	140	25–100	>50
Flexural Strength (MPa)	ASTM C880	10–30	>14	>12	12–15	3–10	N/A
Abrasion Resistance (Ha)	ASTM C1353	-	>113	>54	-	-	>2
Water absorption, %	ASTM C97	0.10–0.40	<0.1	<0.1	0.12	3.0–20.0	<8%

2.3.3. Polymer

Apart from concrete and stone, some research indicated alternative materials, such as polymer (recycled rubber and recycled plastic), could be used for kerb construction. These kerbs can weigh significantly lower compared to the concrete kerb, and the plastic kerbs have been experimentally constructed in the Isle of Man, UK. The main view was to reduce workforce injury [3]. The plastic kerbs have better flexural strength, higher deflection and better impact resistance than the precast concrete kerb. The finding of using plastic kerbs was that it is suitable for straight roads, but it is not suitable in bends or tight corners. It is also an opportunity to reduce the carbon footprint because they made kerbs from 100% recycled plastics and concluded that they can be recycled again after these kerbs' end of life [3]. The rubber kerbs are usually used in parking areas. Unfortunately, there is no standard found for this type of alternative materials.

The comparative performance of all the kerb materials is presented in Table 4 below, which is based on the literature described in the previous paragraphs. It is to be noted that for different kerb materials (concrete, stone and polymer), even for the same property, the testing procedure applicable may be different; for example, a testing method applicable for concrete may not be particularly applicable to polymer or stone, and caution should be exercised while interpreting values and comparison presented in Table 4.

Table 4. Comparison of Mechanical and Durability Performance of Kerb Materials.

Material	Compressive Strength (MPa)	Bending/Flexural Strength (MPa) and Deflection Tolerance	Impact Resistance	Abrasion Resistance	Freeze-Thaw Resistance after 28 Cycle as per EN 1340 [25]	Water Absorption	Density (kg/m^3)
Natural Concrete, (NC)	17–40 [57]	2.8–6.0 [25]	Lower than plastic [3]	Less than 23 mm loss [1] [25]	≤1.0 kg/m^2 loss [25]	≤6% [25]	2100–2800 [93]
Recycled Concrete	Slightly lower than NC [75]	Flexural strength slightly lower than NC [75]	Slightly less than NC [94]	Lower than NC [95]	Less than NC [96]	Slightly higher than NC [75]	Slightly lower than NC [75]
Rubberized Concrete	Lower than NC [97]	Higher deflection tolerance than NC [85]	Higher than NC [81]	Higher than NC [89]	Improved than NC [89]	Lower than NC [89]	Slightly lower than NC [97]
Sandstone	25–100 [92]	3–10 [92] [2]	-	>2 Ha [44] [3]	-	3.0–20.0% [32,92]	2000–2350 [32,92]
Granite Stone	140–350 [44,92]	10–30 [92] [2]	-	>54–113 Ha [44] [3]	-	0.10–0.40% [32,92]	2560–2900 [32,44]
Recycled Rubber [4]	-	Higher deflection tolerance than NC [85]	-	-	-	Lower than NC [97]	950–1150 [97]
Recycled Plastic	-	Higher deflection tolerance than NC [3]	Higher than NC [3]	-	-	-	<1000 [3]

[1] According to European standards EN 1340 the required limit of abrasion resistance for kerb is ≤ 23 mm loss in the Wide wheel abrasion test or ≤20,000 mm^3/5000 mm^2 loss in the Böhme test [25]. [2] European standards EN 1343 defined the breaking load of stone kerb at a range of 3.5–25 kN [32]. [3] Ha is the Abrasive hardness index. [4] The recycled rubber kerbs are only used in parking areas. "-" The properties are not found in literature or were not relevant to kerb application.

3. Kerb Construction

Concrete kerbs can be prepared by precast and cast in situ methods. The precast concrete kerbs can be manufactured by conventional (using a vibrator), dry-pressed and wet-pressed methods [98] and can be installed in almost all weather conditions. Possible rainfall, temperatures and sunlight hours are considered in casting in situ kerbs, and they are more labour-intensive compared to the precast variations. However, cast in situ kerb can better handle sudden changes of direction [3]. There is no study found comparing different aspects of in situ casting and precast kerb. Both types of concrete kerb are suggested for construction by all authorities, such as the Austroads and AASHTO [29,41].

The precast kerbs require manual placement and have been a major source of workplace injury in the United Kingdom [3]. Past studies have suggested that the use of special lifting equipment (such as vacuum lifters, lifting clamps or stone magnets), reduction in kerb section length, reduction in kerb foundation depth, use of a lightweight or hollow concrete section or other lightweight materials, such as polymer, can reduce the likelihood of such workplace injuries and may also lead to quicker construction as well as better construction quality [3,18].

3.1. Base Preparation

Kerbs can be constructed into a trench, over granular base/sub-base course or over the surface course. The main requirement is that the subgrade/sub-base shall be compacted to 95–98% of modified maximum dry density, and where these layers are used, the bedding material shall be adequately compacted with a minimum thickness of 75 mm and extended to 150–300 mm beyond the back of the kerb [28,58]. The mortar of concrete is suggested to be used as bedding material up to a thickness of 12–40 mm in British Standard BS 7533-6 [99]. Haunching at the back of the kerb is conducted with the concrete bedding material to give support against tilting. Dowels are provided and bonded by the mortar for the case of placing the kerb over the surface course [55,99]. The Australian Standard imposes additional requirements on the properties of the kerb base, e.g., the subbase material needs to have less than a 35% liquid limit, 12% plasticity index and 6% linear shrinkage [58]. The base of the pavement can be damaged due to water ingress through the kerb joint, interface with fill materials at the back of the kerb (shrinkage, low backfilling), rotation of the kerb due to heavy loading from vehicles and poorly compacted concrete. Sub-surface drains beneath or behind the kerb also affect the stability of the kerb. The drainage trench backfill under the kerb should be properly compacted to prevent the rotation or deflection of the kerb [41].

3.2. Additional Considerations for Construction on Expansive Subgrade

Expansive soils are common in different parts of the world. These soils increase in volume with an increase in moisture content and shrink when dried. This shrink-swell cycle continues with seasonal variations in soil moisture content. Differential movements due to shrink-swell cycles put additional stresses on structures founded or constructed within a shallow depth (up to 4 m) [100–104]. Various other parameters, such as the presence of vegetation, root depth, canopy area and drainage condition of a nearby area, can also influence the ground movement potential. A low permeable material sub-base with a minimum thickness of 150 mm is suggested to be used and extended to a minimum of 500 mm past the kerb over expansive soil in the Austroads guideline [41]. The guideline for rigid pavement in Austroads is to make the kerb over the concrete shoulder with structural-grade concrete effectively tied with the pavement [41]. Figure 3 below shows uplift movement at a kerb joint due to movement in expansive soil, which is a place of water intrusion into the pavement.

(a) (b)

Figure 3. Upward displacement of a kerb due to expansive soil movement (**a**) view along the length, and (**b**) side view.

To the author's best knowledge, there has been no rigorous study investigating the behaviour of concrete kerbs on expansive soils. The soil under the sealed pavements usually has stable moisture distribution throughout the year, but it is exposed to moisture movement near the edges. Gordon and Waters [105] suggested that these failures can be reduced by using impermeable paving layers, such as kerb or polythene, under the shoulder.

The kerb effectively acts as a beam laid over the soil. Thus, deflection tolerance and flexural behaviour are important concrete properties, especially when it comes to kerbs constructed on expansive soil [105]. Other options considered in the past when dealing with such situations are replacing the expansive soil using a stabilization procedure, preventing moisture movement, compaction, and surcharge loading to reduce these expansive soil problems [106].

3.3. Consideration for Mitigation of Tree Root Migration Effect

Roadside shrubs and trees near the edge of the road are common, and they can extract water from a significant depth and increase soil's movement potential [107–111]. The presence of tree roots under the kerb causes substantial damage, such as cracking, breaking, upheaving, displacement, spalling, fracture and surface deterioration [112–119]. Most of the trees start to cause damage to the kerb when the diameter of the tree at its breast height becomes 11–20 cm [120]. The differential movement of kerbs on expansive soil can be 30 to 40 mm [121]. Pile [122] first investigated the effect of tree root migration on road pavement and kerb performance. Some observations from Pile [122] and subsequent work by Wagar and Barker [123], Francis et al. [124], McManus and Brown [125], Randrup, McPherson and Costello [120], O'Malley and Cameron [121], Lucke and Beecham [126], Johnson et al. [127] and Hilbert et al. [128] are summarized here:

- Tree-related variables, such as species, height, trunk diameter, growth rate, extraction capacity, tree roots properties (radius, depth, lateral spread, trajectory), mature age, wilting point, watering frequency, transpiration rate and distance from the kerb, should be considered;
- Soil-related variables, such as particle size, moisture content, reactivity, compaction, compacted depth and groundwater level, should be considered;
- Weather-related variables, such as climate, temperature and rainfall, should be considered;
- Drainage condition is influencing factors for kerb and pavement damage.

Figure 4 below shows kerb damage due to bending and upliftment caused by tree roots.

(a) (b)

Figure 4. Damage to kerb caused by tree roots (**a**) single point breakage, and (**b**) multiple point breakage.

To minimize/mitigate the effect of tree root migration, the following measures have been suggested:

- Significant pruning of the trees can reduce the root growth, thus helping reduce the damage to kerbs [120,122,126].
- The distance of the kerb from trees should be greater than 3m or their mature height to avoid the effect of trees on ground movement [100,102,126].
- Compacted soil is more resistant to tree root growth compared to uncompacted natural soil [126].
- Root barriers can also be used. Three types of root barriers are commonly used, i.e., deflectors, inhibitors and traps [120]. Some of the new and environmentally friendly technology, such as bio-cementation [129–131], can also be useful in such scenarios.
- Permeable pavements with 100 to 300 mm depth of granular material base can lead the tree roots to go deeper into the subgrade soil and reduce the harmful effect [126]. However, this may not be very effective in a humid climate due to the presence of a shallow groundwater table [127].

4. Road Kerb Failures and Management

On average, around 4% of kerbs are replaced due to different types of failures in the United Kingdom [18]. In Australia, some councils reported the repair or replacement of 5–6% kerbs every year [27,28]. Rens [132] investigated different failure/distress modes for kerb and stated that kerb distresses, e.g., cracks, spalls, heaving, rotation, misalignment, settlement, drainage problems and base failure can be caused by heavy tyre load, weak concrete, poor subgrade, impact load from accidents, tree root migration, expansive soil movement, faulty drainage and weakness in base. An investigation by Wawrzenczyk et al. [133] evaluated the causes of the early failure of concrete kerb and found that the water absorption of the concrete is the main reason for early kerb surface scaling. The asset management practice in Australia, Canada, England and New Zealand are similar [134]. In the asset management document, the kerbs are ranked on a qualitative scale (From very poor to very good). During this study, only North Sydney Council was found to be accounting for cracking and failure properties. It is possible that other councils also evaluated kerbs based on failure properties, but those documents are not publicly available.

Expansive soil movement can cause the kerbs to crack, rotate or become misaligned. This may not lead to the ultimate failure of the kerb but may lead to ponding as uplift prevents proper drainage (as shown in Figure 5), subsequently leading to water ingress into the pavement structure.

Different road authorities may use different condition assessment guidelines while monitoring kerb failure [27,135,136]. An example of condition assessment guidelines from North Sydney Council is [27] presented in Table 5 below.

Figure 5. Faulty drainage due to differential movements of a kerb at entry.

Table 5. An example kerb condition assessment guideline [27].

No.	Grade *	Description					Repair
		Public Safety	Cracking	Misalignment due to Uplift, Settlement, Rotation	Chipping, Spalling	Ponding	
1.	Very Good	Low risk	No	Nil	Nil	Nil	No Repair
2.	Good	Low to medium risk	Fine	<5 mm	Minor	Minor	Minor work
3.	Fair	Medium to high	3–5 mm up to 20% length	5–15 mm up to 30% length	<30 mm diameter, 5 m apart	10 mm deep, 30% affected	Some work
4.	Poor	High to very high	>5 mm, 20–50% affected	15–50 mm, over 50% length, water infiltration	water infiltration, <50% length	30 mm deep, <30% length	Repair within 1 year
5.	Very Poor	High to very high	water infiltration, >50% length	>50 mm, 50% length, water infiltration	water infiltration, >50% length	>30 mm deep, >30% length	Urgent replacement

* Most of the councils categorize the quality of kerb as in the grade column.

The Dunedin City council in New Zealand is using a computer-based street asset and management system (SAM) for making decisions related to the management of road components, such as kerbs, since 1982 [137] and has demonstrated the effectiveness of the tool in reducing maintenance backlog. Rens [132] demonstrated the effectiveness of a GIS-based asset management system and also showed a linear relationship between the construction age and the simplified condition index of the kerb. Most of the local government authority uses an asset management system, but it needs to confirm that the kerb should be a separate item on the system with all the data, such as type, material, lifecycle and failure type. The reason behind it is the function, property, material, maintenance and life cycle of the kerb are significantly different from the pavement.

5. Carbon Footprint and Sustainability Analysis of the Kerb

Along with the suitability of different kerb materials from a mechanical behaviour point of view, it is also important to assess the sustainability of using those materials. Over the past few decades, there have been significant research efforts on recycling waste products in construction [138]. Construction and demolition wastes and TDA have been shown to have promising potential. This section presents a comparative economic and environmental cost-benefit (sustainability) study involving eight different construction materials, as detailed later in this section. The environmental cost-benefit aspect in the analyses has been captured through carbon footprint.

Four concrete mix designs have been chosen. The concrete mix designs were prepared and tested in the laboratory at the University of South Australia for similar workability and compressive strengths of 25 MPa. The mixes are named CC-25 (prepared with 100% natural aggregate), R100C-25 (prepared with 100% recycled concrete aggregate), CTr-c20-25 (prepared with natural aggregate with 20% replacement of 5–10 mm TDA) and RTr-c20-25 (prepared with recycled concrete aggregate with 20% replacement of 5–10 mm TDA). A target compressive strength of 25 MPa was chosen since many of the local government or other road authorities have similar requirements. The durability properties of these concrete products are expected to be different but not considered in this assessment. The four mix designs of concrete and their material requirements are presented in Table 6. Four other kerb construction materials, i.e., sandstone, granite, recycled rubber and recycled plastic, were also included in the comparison.

Table 6. Material requirements (kg/m^3) in different concrete mix designs with a target strength of 25 MPa.

Mix Type	Mix No.	Water	Cement	Fly Ash	TCM	Coarse Aggregate			FA	Superplasticizer
						NA	RCA	TDA		
Control Concrete with natural coarse aggregate (NA)	CC-25	173	225	75	300	850	-	-	900	0.45%
20% Natural coarse aggregates replaced by TDA (NA–TDA)	CTr-c20-25	180	345	115	460	680	-	79	900	0.45%
Recycled Concrete (RA)	R100C-25	160	236.25	78.75	315	-	784	-	900	0.45%
20% Recycled coarse aggregates replaced by TDA (RA–TDA)	RTr-c20-25	179	375	125	500	-	627.2	79	900	0.45%

Notes: TCM = Total Cementitious Material, NA = Natural Aggregate, RCA = Recycled Concrete Aggregate, TDA = Tyre Derived Aggregate, Tr = Tyre Rubber, c = Coarse Aggregate, FA = Fine Aggregate.

The carbon footprint for each material is estimated based on the CO_2 generation of different materials during their full production cycle, cumulating the total carbon footprint. Materials or energy recovered from recycling reduced the carbon footprint and were accommodated accordingly.

While estimating the embedded CO_2 emissions in the kerb materials, the life cycle of the materials was considered, and emissions from key processes in the life cycle were accounted for. The unit emissions (or emission factors) were taken from published works, which sometimes varied widely among different publications due to the variations in processing and manufacturing activity. The analysis was therefore conducted based on some assumptions, and the relevant emission factors were considered.

The embedded CO_2 emission from cement includes the mining of raw materials, production and transportation-related emissions. The fly ash emissions are comprised of emissions due to its collection from the power station, grinding, milling, and transportation. Quarrying and crushing-related CO_2 emissions were considered for natural coarse and fine aggregates. The emissions from the use of explosive use during mining were considered to be insignificant and were not included in calculations [139]. In the case of the recycled concrete aggregate (RCA), emissions from cleaning, milling and crushing at the production plant along with the emissions from demolition, crushing, screening and stockpiling at the demolition site were included. For tyre-derived aggregate, the shredding process was considered for the embedded CO_2 emissions calculation. Concrete batching, transport, placing and lying were considered for CO_2 emissions in the concrete preparation and placing stage. The emission factors considered in this research for the carbon footprint analysis were obtained from different literature, which might have different underlying conditions. However, the approach was adopted due to the lack of relevant data for specific materials and processes. Therefore, the estimation might deviate from the exact extent; however, the tentative estimation is still capable of demonstrating the carbon footprint accounts for different scenarios. The CO_2 emission factors that were considered for the analysis are summarised in Figure 6, along with how the total embedded emissions were estimated for each kerb material.

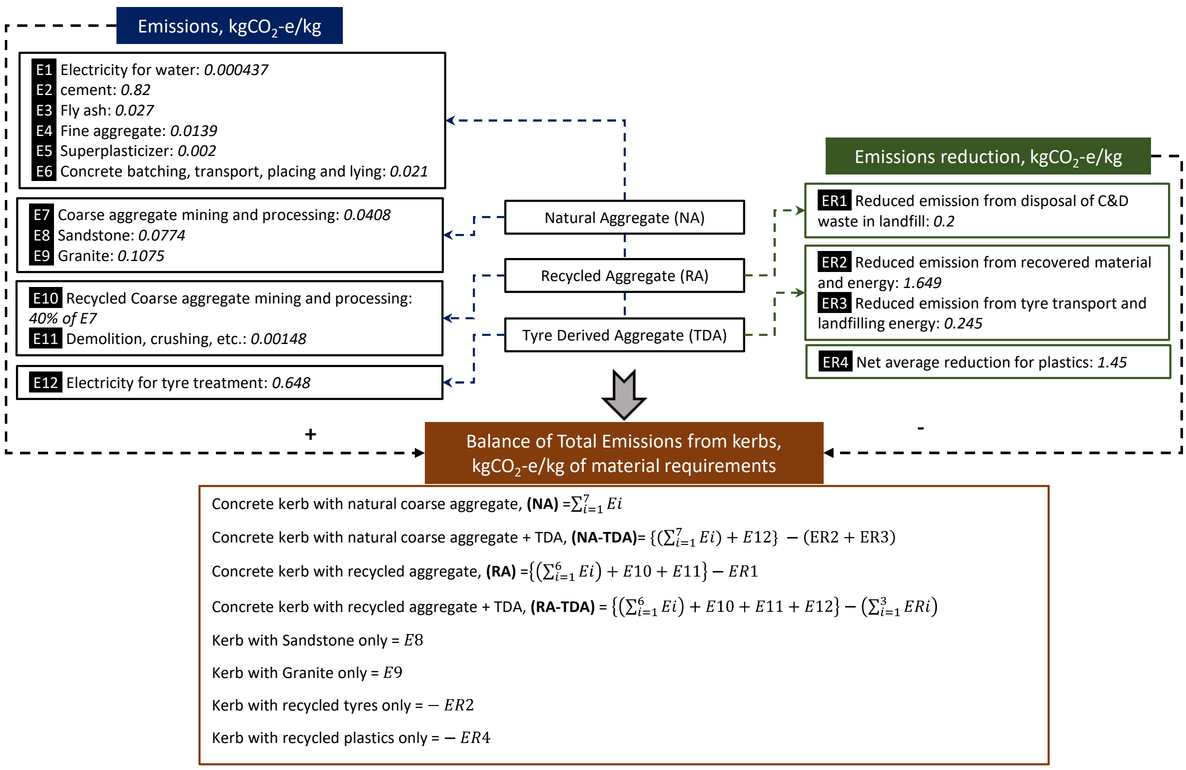

Figure 6. CO_2 emission factors considered for different materials and processes in estimating the carbon footprint of different kerb designs. Note: [E1] estimated based on energy intensity for water supply (0.54 kWh/m^3) [140], and CO_2 emission for energy consumption (0.81 kgCO_2-e/kWh) [141], [E2, E3, E4, E6, E7] [142], [E5] [143], [E8, E9] [139], [E10] [144], [E11] [145], [E12] estimated based on energy intensity for tyre treatment (0.8 kWh/kg) [146] and CO_2 emission for the energy consumption [141], [ER1] [140], [ER2] [146], [ER3] [147], [ER4] [148].

The use of RCA in the concrete mix would reduce the CO_2 emissions due to the eliminated emissions from disposal of RCA to landfills. Assuming the end-of-life tyres are disposed to landfills, recovering the materials instead of disposing of them would save energy and materials, and so the emissions would reduce. Similarly, the net emission reduction for using recycled plastics was considered for the assessment. The net emissions for any material are thus the combined total of emissions generated and the potential emission reductions.

A typical barrier kerb with a half-battered front profile and a dimension of $1000 \times 350 \times 150$ mm^3 (length × height × width) [58] is considered for the analysis of the net carbon footprint. The density of concrete, which was obtained from the laboratory test, is used to obtain the weight of the kerb. The density of tyre-derived aggregate from the laboratory test is considered as the density of the recycled rubber kerb. The weight of the recycled plastic kerb is considered 10 kg following Mason, Korostynska, Cordova-Lopez, Al-Shamma'a and Ledsham [3]. The resulting carbon footprint per unit length of a barrier kerb is presented in Figure 7.

Kerb Type	Unit Weight, kg/m³	Weight, kg/m	Carbon Footprint, $kgCO_2$-e/m
CC-25	2283	113	11.57
R100C-25	2238	111	3.25
CTr-c20-25	2206	109	11.28
RTr-c20-25	2168	107	5.49
Sandstone	2000	99	7.66
Granite	2600	129	13.84
Recycled Rubber	1129	56	-92.13
Recycled Plastic	-	10	-14.14

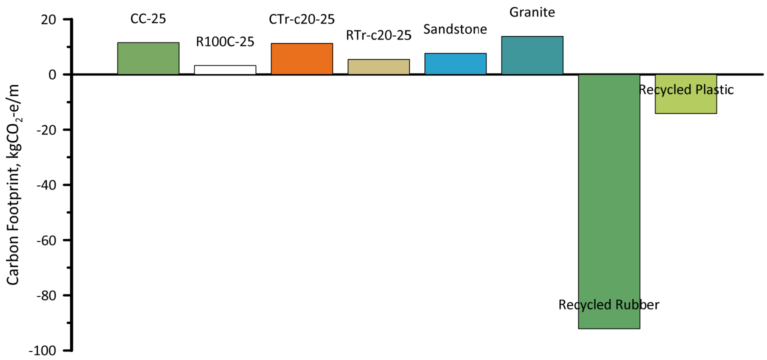

Figure 7. Carbon footprint of a typical 1 m (0.05 m^3) barrier kerb with different materials. Note: carbon footprint ($kgCO_2$-e/m) [concrete mixes] = emissions from kerb materials (kg CO_2-e/kg) (Figure 6) × material requirements (kg/m^3) (Table 6) × kerb volume (m^3/m kerb length) [0.05 m^3]; OR, carbon footprint ($kgCO_2$-e/m) (stone, rubber, plastic) = emissions from kerb materials (kg CO_2-e/kg) (Figure 6) × material requirements (kg/m) (Figure 7).

The concrete mix with natural aggregates (CC-25) and natural aggregates replaced by 20% TDA (CTr-C20-25) was found to have similar carbon footprints. The kerb made from 100% recycled aggregates (R100C-25) was found to have the lowest carbon footprint among the concrete products compared. This is due to the benefits of energy recovery as the materials did not go to landfills. This was closely followed by the kerb made from recycled aggregates with 20% TDA (RTr-C20-25) and sandstone. The granite was found to have a slightly higher carbon footprint compared to the control concrete (CC-25). It is to be noted that in concrete products, an increased proportion of recycled aggregates and TDA lead to an increase in required cementitious materials to achieve the same compressive strength. However, as observed here, the carbon footprint due to the increased proportion of cementitious materials was offset by the benefits achieved from the energy recovery as the materials did not go to the landfill. The recycled rubber and plastics, as per Figure 7, had a -ve carbon footprint, meaning the net effect of using the material in kerb construction was the removal of CO_2 from the environment. Once again, this is due to the energy and material recovered from the wastes, which would otherwise go to the landfill site.

Apart from the environmental benefits, the economic feasibility of different concrete mix designs was also analysed in this research, considering the use-value (market value) and option-value (potential hidden benefits from an alternative approach) of resources. An Australian perspective of the aggregate market price (61 AUD/m^3 and 51 AUD/m^3, respectively, for NA and RCA) and cement price (0.5 AUD/kg) was used for calculating the use-value of the concrete mix designs [129,144]. The option value included calculations for the cost savings from landfilling. The landfill cost of construction and demolition and tyre wastes in Australia was estimated to be 161 AUD/m^3 for landfilling [144]. The density of whole tyre (270 kg/m^3) waste was estimated by considering a typical small vehicle tyre dimension and weight. The option value of cement replacement with bio-cementation [129] or any other strategies was not considered for analysis, which might enhance the benefit further if considered.

The benefit-cost ratio (BCR) is a representation of the net achievable benefits compared to the cost involved in the process. For instance, the net benefit from using recycled aggregate instead of the conventional approach of using natural aggregate would be $[\{use\ value\ (NA) - use\ value\ (RCA)\} + option\ value\ (RCA)]$. Thus, the BCR for using the recycled aggregate would be $[Net\ benefits\ (RCA)/cost\ (RCA)]$. The economic (use-value + option-value) and environmental (carbon footprint) BCR of different concrete mix designs is analysed. In the analysis, the BCR is null for the mix with natural aggregate, as there is no change in costs/benefits for using NA.

Figure 8 shows the economic BCRs for different concrete mix designs suitable for kerb construction (mix with NA, RCA, RCA–TDA and NA–TDA). As the concrete mix is the most common kerb material, the analysis focused on assessing the economically feasible mix for the kerb. The use of TDA is associated with the increased demand for cement (higher cost), which reduces the economic BCR. Thus, the use of TDA with natural aggregates is economically less feasible than the conventional design with natural aggregates only (see inset of Figure 8). However, the option value of using RCA has led to increased economic benefits in concrete mixes with RCA.

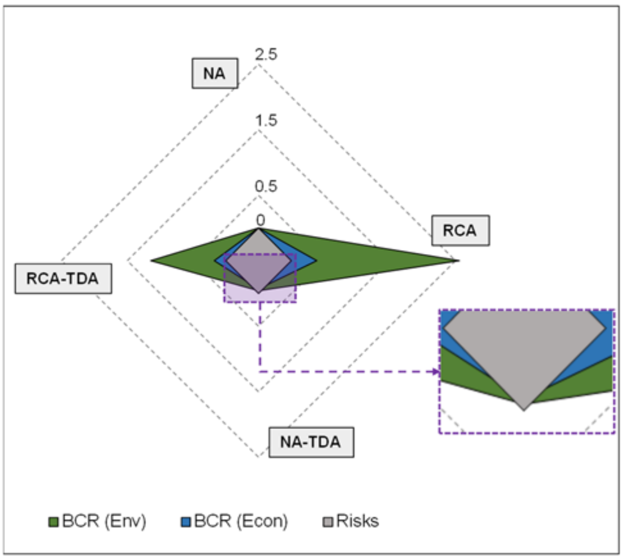

Figure 8. BCR scenarios of different concrete mix designs for the kerb.

The environmental BCR was also found to be higher in concrete mixes with RCA. The higher requirement of cement uses in the concrete mixes with TDA reduced the environmental benefit as more cement was required. Consequently, the BCR of the NA–TDA mix was found to be slightly negative (Figure 8 inset). It is to be noted that the analyses presented here considered the life cycle of the materials used for the preparation of the mix but did not consider the life cycle of the constructed concrete kerb and how that would behave during its service life.

6. Discussion and Conclusions

Some observations and conclusions from this investigation are summarised below.

- The kerb is an integral part of road infrastructure. The structural design of kerb can be a significant part of roadway design. In current practice, the mechanical behaviour of the kerb materials and the structural interaction of kerb with the surrounding environment are largely ignored in their design.
- A relatively large proportion of kerbs require replacement before the end of their expected design life, possibly due to inadequate design and a lack of understanding of the material behaviour.
- The current practice is mostly limited to assigning a minimum compressive strength for the material to be used in construction.
- All types of failures should be considered, and the design of the kerb should be site-specific and should be integrated into the planning stage of roadway pavement. Unfortunately, this is not a widespread practice in Australia or the rest of the world.
- The size and shape of the kerb are often decided on an ad hoc basis, and traffic or other loading are often ignored even though some guidelines exist in the literature for taking them into account, e.g., the University of British Columbia guidelines for deducing the height of kerb from vehicle loads or the European Standard for the height of stone kerb based on breaking load and flexural strength.

- The flexural strength and deflection capacity, along with their fatigue characteristics, are ignored in current practice but can be important considerations in designing kerb over expansive soil or where ground movement due to tree root migration or expansive soil may be a problem.
- Long-term behaviour of recycled concrete and their field performance, especially over expansive soil, is still not well understood. Similarly, no design guideline based on mechanistic analysis of the interaction between the kerb and expansive soil movements exists.
- Kerb materials need to be able to withstand rubbing, skidding, and scraping from vehicular movements, and abrasion resistance can be an important consideration in such situations.
- Impact load should be considered for the kerb at the curve, median, intersection and the place where it is subjected to frequent traffic impact loads.
- Water absorption for a kerb can be important where water flow over a kerb is a common phenomenon.
- Adding reinforcement to the kerb has both positive and negative effects on its behaviour. Reinforcement can be provided in the kerb considering appropriate clear cover can be maintained.
- The kerb construction process (precast, cast-in-situ) and placing process (manual and in situ slip form) should be selected considering weather, lifting equipment and workplace health safety.
- Base preparation for kerb can be dependent on several parameters, including soil reactivity, drainage condition, compaction, presence of trees and so forth.
- There are some control measures followed by the councils to prevent tree root growth, but it is often not enough to prevent kerb damage.
- Some of the tree-related design considerations that can be imposed for better kerb performance are maintaining adequate distance from the kerb, introduction of a permeable layer, using root barrier and significant tree pruning.
- Inventory and management systems using GIS technology can be a strong tool for better kerb asset management.
- The concrete kerb is constructed mostly with the flexible road, but the interaction between these two different materials is not considered, which can be an important consideration for kerb design.
- A design guideline could be developed and used to select appropriate design mix for different areas with different ground conditions (e.g., soil reactivity, drainage condition, presence of trees, etc.).
- In the cost-benefit analysis, the use of recycled aggregate in concrete showed significant environmental benefits in terms of savings in CO_2 footprint.
- The addition of TDA in concrete required a larger amount of cement to be used, and its environmental benefit was reduced. The concrete prepared with TDA, however, still had a lower CO_2 footprint compared to concrete prepared with natural aggregates.
- A kerb made entirely of recycled plastic or recycled rubber could lead to a negative CO_2 footprint even though very limited research was available in this area.

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