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THE UNIVERSITY OF QUEENSLAND
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Performance Requirements for Footpath with Recycled Materials

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Executive Summary

This guideline outlines the performance requirements for incorporating recycled materials in footpath construction. As part of the SmartCrete CRC-funded project "Recycled Waste in Concrete for Municipal Applications," it emphasises sustainable practices in footpath infrastructure, utilising recycled polyethylene terephthalate (PET), crumb rubber (CR), and ground granulated blast-furnace slag (GGBFS).

This guideline presents an overview of footpaths, focusing on pedestrian and shared paths, discussions on using PET as fine aggregate, CR from end-of-life tyres, and GGBFS as supplementary cementitious materials (SCMs). The properties, benefits, and challenges of each material were evaluated. In addition, practical recommendations are provided for placing concrete on site with recycled materials, highlighting potential issues such as segregation and reduced compressive strength.

This document aims to serve as a practical reference for municipal projects seeking to adopt recycled waste-based materials in concrete, promoting more sustainable and environmentally responsible construction practices.

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1. Introduction

Concrete is the cornerstone of modern urban development and remains the most extensively utilised manufactured material in construction worldwide [1]. Despite its widespread use in civil and infrastructure engineering, the production of concrete exacts a significant environmental toll. The concrete manufacturing process significantly contributes to greenhouse gas (GHG) emissions, primarily due to cement production. Concrete production is estimated to account for 9% of total GHG emissions, with 7–8% originating from cement plants [2]. Moreover, as a synthetic material composed of cement, sand, gravel and water [1], concrete production heavily relies on non-renewable resources, notably sand and gravel. Annually, 48-50 billion tons of natural aggregates are consumed for concrete [3]. In Australia alone, approximately 130 million tonnes of aggregates are extracted each year, a figure expected to rise in the near future [4].

In response to these environmental challenges, exploring alternative materials has gained momentum. A significant focus has been on using supplementary cementitious materials (SCMs). According to the Australasian (iron & steel) Slag Association (ASA) [5], 3.177 million tonnes (Mt) of iron and steel slag were generated or imported within Australasia for national consumption in 2021. Of this amount, 2.489 Mt, or 78%, was effectively utilised in various construction projects throughout Australasia. Replacing cement with SCMs can assist in reducing GHG emissions, which are quantified CO_2 equivalent (CO_2-eq) [6]. A report [7] evaluating the environmental impact of concrete produced in Australia indicated that substituting 30% of cement with SCMs, i.e., ground granulated blast-furnace slag (GGBFS) and fly ash (FA), can reduce GHG emissions by 19.10% to 26.57% compared to the Ordinary Portland Cement (OPC) concrete, depending on the target compressive strength, as illustrated in Figure 1.

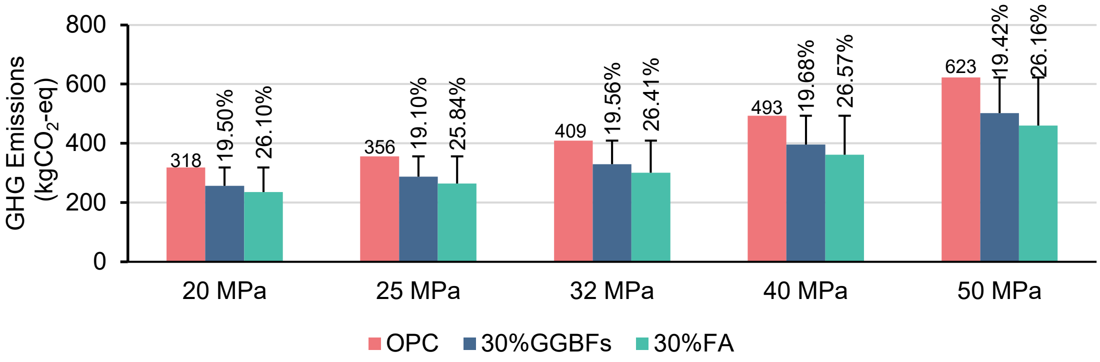


Figure 1 GHG emissions of different types of concrete per m^3. The error bar represents the percentage of reduction compared to OPC (adapted from [7]).

Besides, incorporating recycled municipal solid waste (MSW) and commercial and industrial (C&I) waste, e.g., plastic, end-of-life tyres and industrial products, shows potential to replace natural aggregates for low-strength or non-structural concrete when appropriately shredded [8, 9]. By substituting natural aggregates with recycled alternatives, the depletion of natural resources is mitigated, while the carbon footprint of concrete production is substantially reduced. For instance, a well-designed concrete mix that integrates waste can reduce CO_2 emissions by up to 50% compared to OPC concrete of similar strength [10]. This reduction is critical in curbing overall GHG emissions caused by the construction industry, which is essential for meeting global climate targets. Additionally, integrating recycled MSW and C&I waste in concrete can help alleviate the growing problem of landfill space scarcity [11], thus addressing two environmental challenges simultaneously—resource conservation and waste management.

A notable application of waste-based concrete in urban areas can be pedestrian paths, i.e., footpaths, which are integral components of municipal infrastructure. These paths facilitate walking trips or other modes of transport, e.g., in some jurisdictions, these paths may also accommodate cyclists [12]. Given the relatively low strength requirement for footpath concrete, as specified by AS 3727.1 [13] with a minimum concrete grade of N20, there is significant potential to incorporate recycled materials, e.g., polyethylene terephthalate (PET) fines, crumb rubber (CR), and GGBFS, as sustainable alternatives to concrete components. However, the varying quality, characteristics, and bonding properties of recycled materials compared to natural aggregates necessitate comprehensive evaluation to ensure long-term performance.

This guideline aims to provide strategies for developing sustainable footpath solutions that reduce GHG emissions, conserve natural resources, and address waste management challenges. The objectives include outlining current Australian footpath design requirements, assessing the feasibility of incorporating PET fines, crumb rubber and GGBFS into footpath concrete, and offering recommendations for construction practices. This guideline is prepared based on the research findings from the SmartCrete CRC-funded project 387 21.FT.0011-P, titled “Recycled Waste in Concrete for Municipal Applications.” This document does not purport to address all potential safety concerns and should not be seen as a substitute for consulting with professional experts on specific projects.

2. Footpath in Streetscape

2.1 Path Types

Streets are fundamental components of urban infrastructure, influencing how individuals move through and engage with a city [14]. Rather than being a single entity, a street comprises various surfaces and structures that facilitate movement, access, and diverse activities. Figure 2 presents an example of a typical street, highlighting its main elements. Interchangeable elements such as parklets, trees, transit stops and parking spaces can be designed flexibly, allowing streets to be adapted based on their surroundings and usage demands. In contrast, elements such as bicycle lanes, footpaths and travel lanes must remain continuous and connected to ensure effective functionality [14]. In this context, footpaths are crucial in ensuring safe and continuous pedestrian flow.

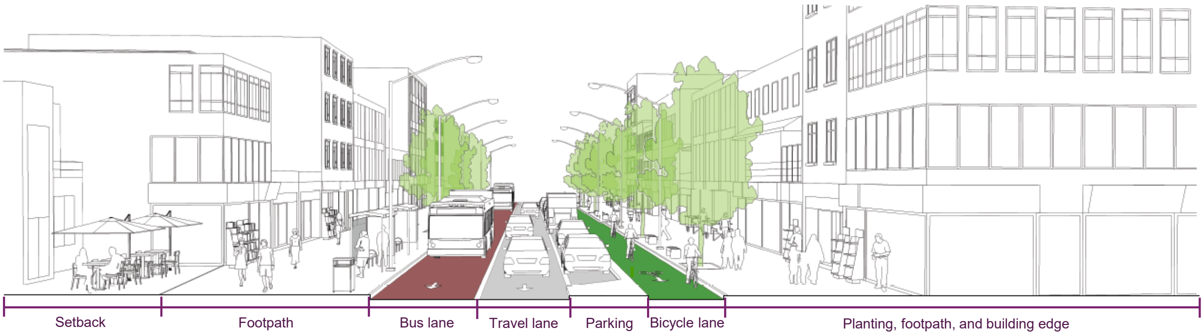


Figure 2 An example of streets with main elements (adapted from [14])

2.2 Footpath Function

2.2.1 Pedestrian Path

Footpaths, i.e., pedestrian paths, designed for individuals on foot as well as those using mobility scooters, wheelchairs and personal mobility devices such as walking frames, serve a critical function in the transportation network [12]. The area between the road edge and the frontage of adjacent properties comprises several distinct zones. The zones associated with pedestrian paths are shown in Figure 3. As shown in Figure 3, the street furniture zone is intended for placing various features. It can include lighting columns, signal poles, seats, sandwich boards, hatch covers and parking meters [14]. Additionally, this zone can incorporate soft landscaping or vegetation, which adds aesthetic appeal and environmental benefits. Functionally, it serves critical functional purposes by creating a psychological buffer between motorised vehicles and pedestrians, diminishing the risk of splashback from passing vehicles and providing necessary space for accommodating driveway gradients [14].

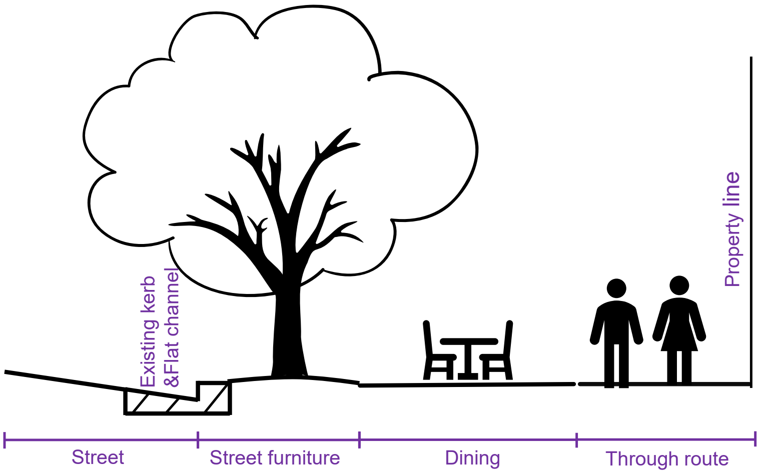


Figure 3 An example of a pedestrian path zone

The other two zones associated with pedestrian paths are the dining zone and the through route. The dining area is intended for outdoor dining and social interaction, providing a designated space for these activities. Conversely, the through route (the clear width) is the pathway pedestrians commonly navigate. It must always remain unobstructed to facilitate safe and efficient movement. In retail areas, individuals with visual impairments may rely on the building line as a navigational aid along the path. It is crucial to distinguish between the total width of this zone and the specific section that pedestrians are likely to occupy while passing through [15].

2.2.2 Shared Path

In certain jurisdictions, a shared path may be suitable where there is a demand for both pedestrian and bicycle pathways, but the volume of users, whether pedestrians or cyclists, is relatively low. This arrangement is referred to as a shared path [12]. Figure 4 illustrates an example of a shared path.

Shared paths serve a variety of functions, including local access, recreational use and connections to high-capacity paths. When designing these links, it is essential to incorporate measures that help moderate cyclist speeds to ensure pedestrian safety. The effectiveness of shared paths is particularly notable when they incorporate existing pedestrian routes, as they can provide a convenient and secure option for inexperienced, recreational, and younger cyclists.

However, due to the narrow widths of pedestrian paths and the frequent presence of driveway crossings or side streets, these paths are only suitable for low-speed cycling. Shared paths may offer a safer alternative for cyclists in certain situations, such as narrow, heavily trafficked sections of roads, bridges, roundabouts, underpasses, or railway-level crossings. In such cases, it is crucial that connections between the pedestrian path and the roadway are appropriately designed to allow cyclists are well-designed to enable cyclists to re-enter the traffic flow safely and conveniently. This may involve special ramps with gentler gradients and smooth transitions to facilitate bicycle access.

One significant challenge of shared paths is accommodating diverse users, each with unique characteristics that can lead to conflicts and discomfort. These differences include variations in speed, spatial needs, user age and expectations. For instance, some users may anticipate exclusive or priority access and predictability of movements, such as pedestrians, cyclists, inline skaters, skateboard riders and dog walkers.

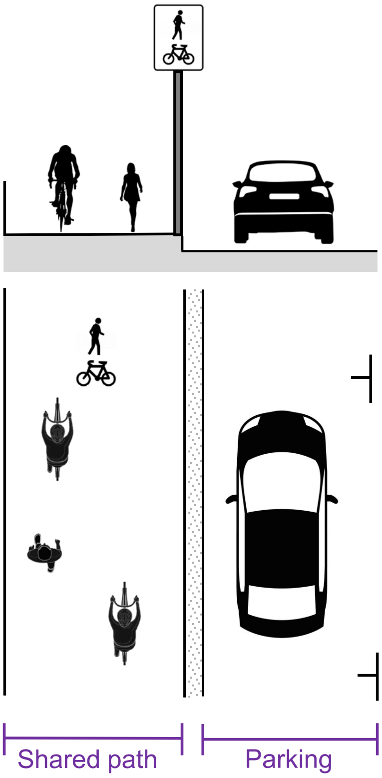


Figure 4 An example of a shared path

2.3 Design Considerations

To develop appropriate and practical design solutions, it is essential to provide users with a convenient, safe, and pleasant journey. These networks should include direct routes that minimise both travel distance and time. Figure 5 highlights the key characteristics of a path network that addresses the needs of footpath users. The paths should be safe, connected, legible, comfortable, convenient, universal, pleasant, and sustainable. The first 7 features are recommended by the NZ Transport Agency [15], while sustainability is the momentum of the development of this guideline.

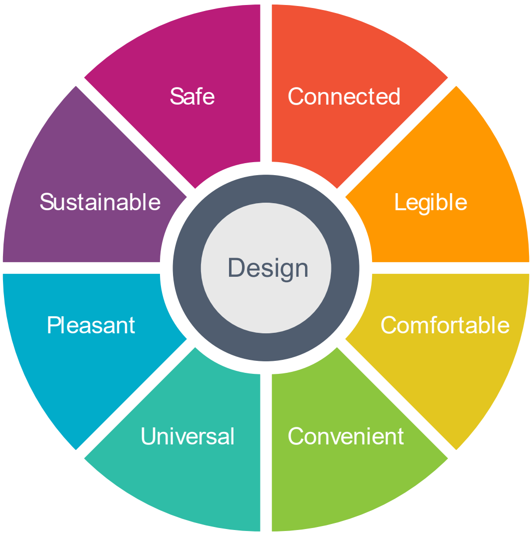


Figure 5 Design considerations for path users

For concrete footpaths, the elements recommended by the Cement and Concrete Association of Australia (CCAA) [16], as shown in Figure 6, are essential for determining the design thickness of the concrete base and detailing the pavement to ensure long-term functionality throughout its design life. Each element will be discussed in the following sections. Note that this guideline primarily focuses on concrete, emphasising the use of recycled materials as aggregate and cement replacements.

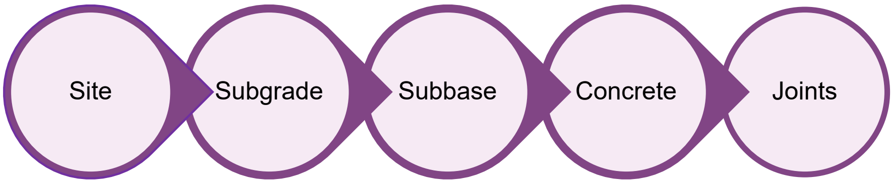


Figure 6 Design elements for concrete pavement

3. Site, Subgrade and Subbase

3.1 Concrete Pavement Layer

The basic elements or layers of concrete pavement are shown in Figure 7. From bottom to top, it includes the subgrade, which is in situ granular or stabilised granular; the subbase, composed of cement-stabilised crushed rock, dense graded asphalt, or lean-mix concrete; and the concrete base, which may be surfaced with an asphalt-wearing course [17, 18].

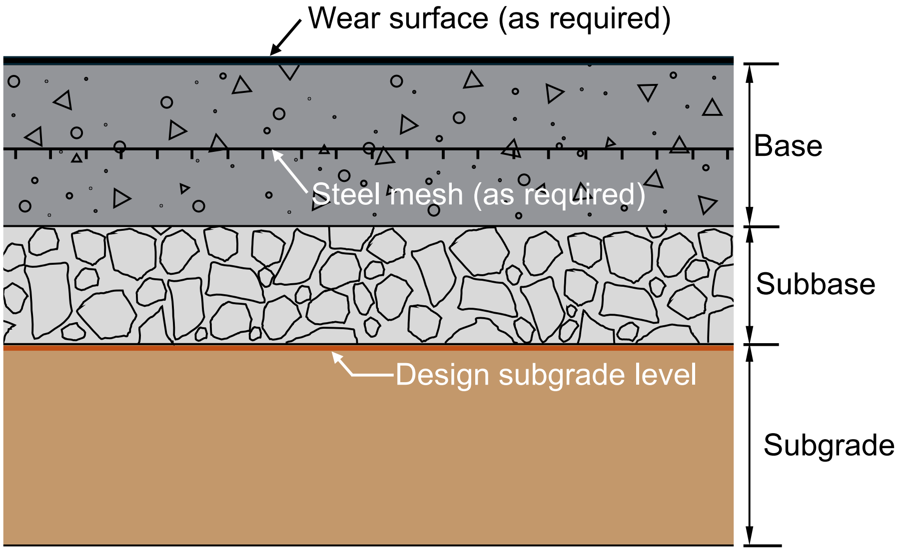


Figure 7 Elements or layers of a concrete pavement

3.2 Site Investigation

The site investigation is the first and necessary step for pavement design. It encompasses soil investigation, traffic estimation, and site survey. Soil properties influence the preparation of the subgrade and the requirements and specifications for a subbase. However, the design thickness of the concrete base may not be significantly affected by the strength of the subgrade [16].

The performance of a footpath is significantly influenced by the type and the traffic demand it encounters during its design lifespan. For lightly trafficked residential streets, pavement thickness is primarily determined by pedestrian activity and the presence of service or delivery vehicles.

Additionally, the geometric design of the pavement is affected by drainage considerations, site topography, surface, and existing or proposed public utilities. Therefore, it is essential to allocate sufficient planning lead time and site survey for the installation or relocation of public utilities in both construction and reconstruction projects. A notable advantage of concrete pavement is the ability to mark the locations of utility conduits on the surface, facilitating future maintenance and reducing the likelihood of damage during excavation activities.

For paths near trees with canopies extending to the edge of the path, it is essential to consider installing vertical root barriers, as illustrated in Figure 8. These barriers help prevent large roots from growing directly beneath the pavement, which can lead to longitudinal roughness over time.

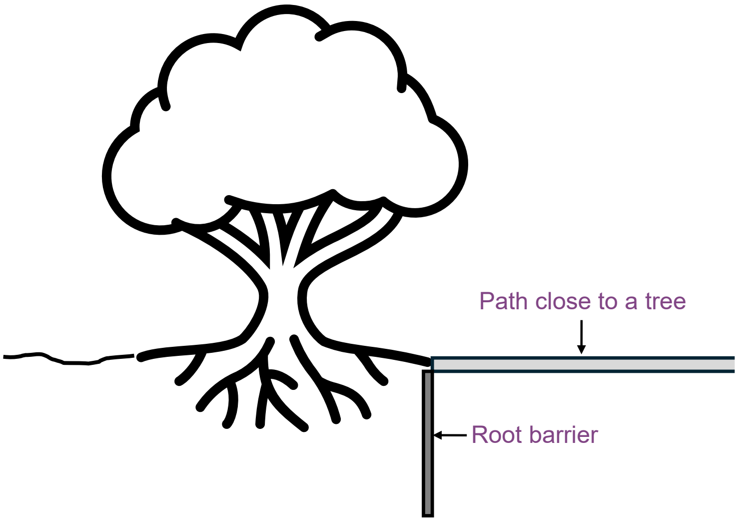


Figure 8 An example of a root barrier

3.3 Subgrade

The support provided by the subgrade is essential for the durability of a concrete base. The level of support, characterised by subgrade strength or modulus, depends on factors such as soil type, density, and moisture conditions during both construction and service [19]. Subgrade strength for pavements is assessed by the California Bearing Ratio (CBR) of the underlying subgrade material, which measures the resistance of the underlying subgrade material to the penetration of a piston at a speed of 1.27 mm/min [20]. This resistance is compared to that of a standard crushed rock sample at the same penetration depth [20]. The typical values of CBR range from 2% for weak soils to 15% for stronger soils [16]. The detailed categories are CBR = 2% (poor), CBR = 5% (moderate), CBR = 10% (high), and CBR = 15% (very high). It should be noted that predicting changes in soil strength over a period of 20 years or more is challenging due to factors such as environmental changes, pavement drainage effectiveness and the limited availability of test data on soil strength [16].

3.4 Subbase

The subbase performs several important functions, such as minimising deflection at joints to ensure effective load transfer, offering uniform support to the concrete base, and managing volume changes in moderately to highly expansive soils [16]. Additionally, it prevents erosion and subgrade pumping, particularly at joints, which can be a failure mode in heavily trafficked pavements. Lastly, the subbase provides a stable working platform for the construction of the pavement base [16].

Footpaths are generally not subjected to erosion from heavily loaded vehicles, which may eliminate the need for a subbase. However, specific projects may still require the additional functions that a subbase provides, such as enhancing load distribution and minimising volume changes. The thickness of the subbase is typically determined empirically, and minimum recommended thicknesses can be found in Table 1.

Table 1 The minimum recommended thickness of subbase

Concrete base thickness (mm)	**Subbase thickness (mm)**		
	Soaked subgrade CBR ≤ 5%	Soaked subgrade CBR 5-10%	Soaked subgrade CBR > 10%
Up to 125	100	-	-
125 - 150	125	100	100
Above 150	150	125	125

When selecting materials for the subbase, granular options can include crushed rock, crushed slag, sand gravel, crushed recycled concrete or a combination of these materials. For bound subbases, it is essential to use a cemented material rather than merely a modified one. The recommended range of cement content is generally 4–6% by weight of the untreated granular subbase materials [16]. This selection and specification of materials contribute to the overall performance and durability of concrete pavement.

4. Concrete

4.1 General Requirements

The concrete base provides the majority of the structural capacity in concrete pavements, and the main compositions of the concrete mix are shown in Figure 9. The supply of concrete without recycled materials shall be in accordance with AS 1379 [21].

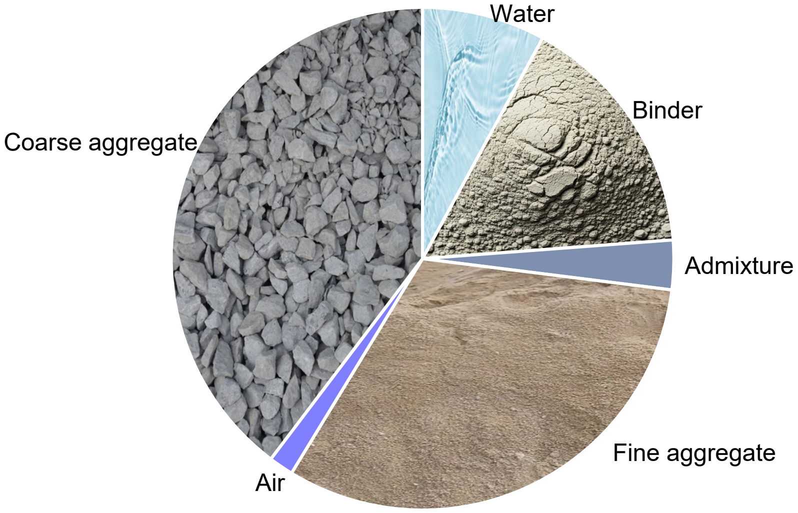


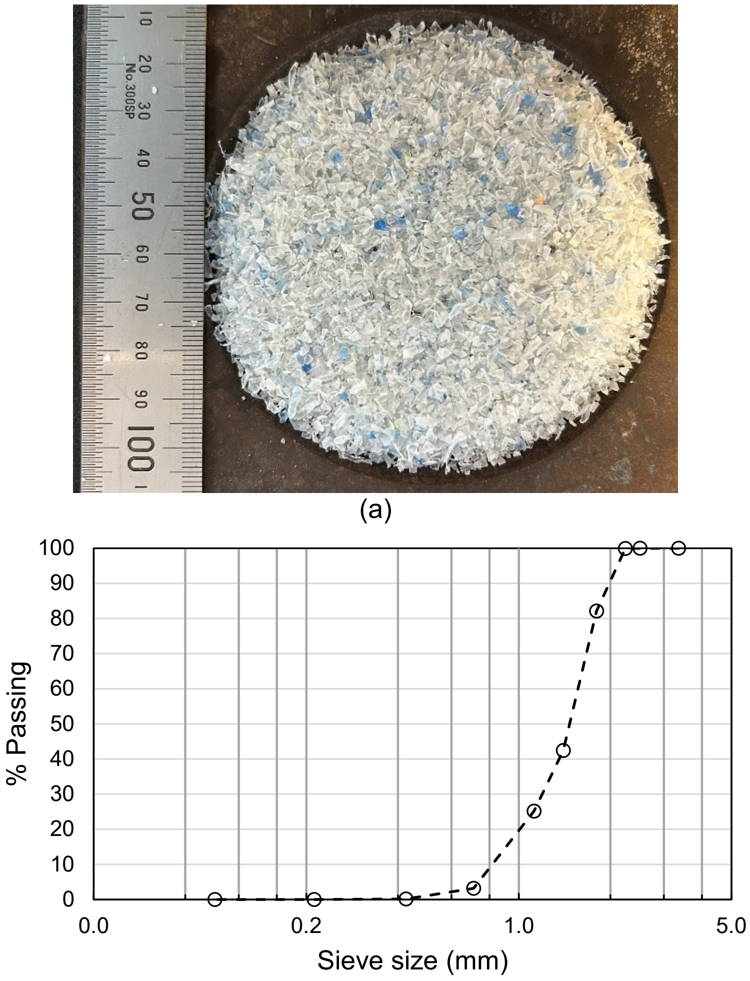
Figure 9 Typical composition of a concrete mix

According to AS 3727.1 [13], the concrete shall be handled, placed, and compacted to ensure the formation of a dense, fully compacted pavement layer. This process should minimise segregation or material loss, prevent premature stiffening, fully fill the formwork to the intended level, expel trapped air, closely encapsulate all reinforcement, dowels, and other embedment, and provide the specified textured surface finish where necessary. The surface on which concrete is placed should be damp at the time of placement, with no ponding of water. An 80-mm slump is recommended for hand-placing [16]. The concrete should be continuously cured for at least 3 days and protected from traffic until it has gained sufficient strength to withstand the traffic loadings, but for no less than 7 days.

For lightly trafficked footpaths, the minimum concrete grade is N20 with a base thickness of 75 mm for pedestrian use and N25 with a base thickness of 100 mm for pedestrian and light vehicle use, as outlined in AS 3727.1 [13]. In VicRoads 703 [22], the Portland cement-based concrete should meet the standard strength grades of N20, N25, N32, or VR330/32 for the shared-use path that is specified in VicRoads 610 [23]. The geopolymer concrete for paving should meet the minimum 28-day compressive strength ranging from 20 MPa to 32 MPa, or the equivalent of grade VR330/32 for shared-use paths. The concrete grade refers to the 28-day characteristic strength, which should be exceeded by 95% of the tested samples [21].

4.2 PET as Concrete Fine Aggregate

PET is a thermoplastic polymer with a melting point of approximately 260℃ [24]. Recycled PET should be obtained from post-consumer or commercial and industrial (C&I) plastic waste, ensuring that it is thoroughly cleaned and free from contaminants such as oils, labels, food residues, and liquids. The material must be properly crushed into fine particles with a nominal size of less than 5 mm for use as fine aggregate. Due to PET's hydrophobic nature and smooth surface, spherical, flaky, or elongated particles are generally unsuitable, as they can excessively enhance concrete workability while weakening the bond strength between the binder and the PET. Figure 10 illustrates the PET fines and the particle size distribution (PSD) that can be utilised as a replacement for fine aggregate.



(a)

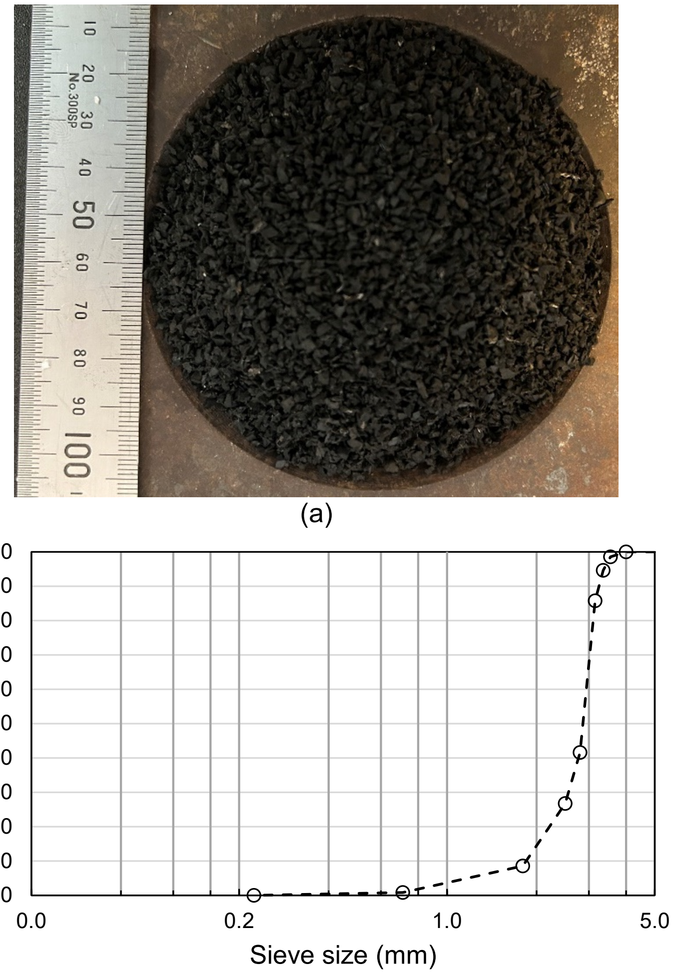
(b)

Figure 10 An example of PET fine: (a) sample, (b) proposed PSD

Since PET fines generally exhibit lower specific gravity and bulk density compared to natural sand, the unit weight of concrete incorporating PET is less than that of conventional concrete. The mechanical properties of PET concrete are often diminished due to the weak bond between the binder paste and the PET. Nonetheless, the strength must still meet the requirements specified in section 4.1. The hydrophobic nature of PET can impede proper blending and effective hydration on its surface, resulting in increased concrete porosity. Consequently, this affects the durability of PET concrete. Although PET is non-biodegradable, it is susceptible to degradation by Ca^{2+}, Na^{+}, K^{+}, and OH^{-} ions in the highly alkaline environment of concrete [25], which possibly further compromises the long-term performance of the concrete with PET.

4.3 CR as Concrete Fine Aggregate

CR is predominantly sourced from end-of-life tyres and can be processed either using cracker mills at ambient temperatures or via a cryogenic method with liquid nitrogen at temperatures below -80°C, producing particles ranging in size from 4.75 mm to less than 0.075 mm [26]. The CR should be thoroughly cleaned and free of contaminants and odour. An example of CR and the PSD are shown in Figure 11. The specific gravity of CR is lower than that of natural sand, resulting in a reduced fresh density compared to conventional concrete [27]. Additionally, the hydrophobic nature of CR can cause it to float during mixing, leading to segregation [27]. Similar to PET aggregates, CR used as fine aggregate exhibits a weak bond with the binder paste. Consequently, the mechanical properties of CR concrete are generally inferior to those of conventional concrete, with increased water permeability due to microcracks around the CR creating interconnected voids [28, 29]. In contrast, CR concrete enhances fatigue resistance [30].



(a)

(b)

Figure 11 An example of CR: (a) sample, (b) proposed PSD

For pavement applications, it is crucial to understand the reaction of rubber to oxidation, as both hardening and softening can present unique environmental and health risks. Polybutadiene and polyisoprene, which are commonly found in tyre rubber, exhibit different behaviours when oxidised; polybutadiene tends to harden, become brittle, and break down into fine particles, while polyisoprene softens [24]. Other challenges associated with the use of CR include variability in supply quality, unpleasant odours, and the emission of carcinogenic polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) [24] [31]. Although the incorporation of CR does not appear to exacerbate negative health effects in humans, appropriate personal protective equipment (PPE) is recommended [24].

4.4 GGBFS as SCMs

GGBFS is a by-product of the steel and iron manufacturing industry, resulting from the rapid quenching of molten iron blast-furnace slag. GGBFS often appears off-white in colour, as shown in Figure 12. The GGBFS typically has a specific gravity ranging between 2.85 and 2.95 [32], which is lower than cement but exhibits greater fineness in comparison [33]. The shape of the GGBFS particle is usually angular, with rough surfaces combined with smaller flakes, as shown in Figure 13. The requirement for GGBFS as SCMs and chemical composition should comply with AS 3582.2 [34].

Due to the angular shape of GGBFS particles, the workability of fresh concrete can be generally lower compared to conventional concrete. Additionally, the early strength of GGBFS-concrete is lower because GGBFS hydrates less than cement. However, studies indicate that the flexural strength of GGBFS concrete is comparable to or even exceeds that of conventional concrete, which is attributed to the compactness of the binder paste [35]. Furthermore, GGBFS used as a SCM promotes the development of dense microstructures that reduce permeability, thereby enhancing the durability of the concrete [35].

The quantity of GGBFS that can be applied as SCMs for pavement needs to meet the requirement of the minimum quantity of cement, which is expressed as follows [36]:

$$Cement_{min} \geq 100 - 0.55 \times (FA + 0.5 \times GGBFS) \tag{1}$$

where $Cement_{min}$ represents the minimum cement used in the binder (% by mass), and FA represents the fly ash. In addition, the SCMs limits in the binder are dependent on the alkali-aggregate reactivity (AAR) as follows [36]:

$$10 - 2 \times FA\% < GGBFS\% < 65 - 2 \times FA\% \quad \text{for non-reactive AAR} \tag{2}$$

$$40 - 2 \times FA\% < GGBFS\% < 65 - 2 \times FA\% \quad \text{for reactive AAR} \tag{3}$$

where $GGBFS\%$ represents the percentage of GGBFS by mass in the total binder and $FA\%$ represents the percentage of FA by mass in the total binder.

Figure 12 An example of GGBFS

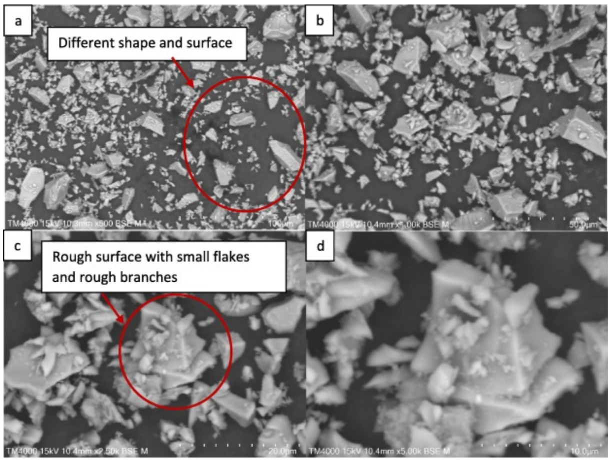


Figure 13 GGBFS particles: (a) 500×, (b) 1000×, (c) 2500×, and (d) 5000× [37]

4.5 Green Star Rating

4.5.1 Green Star Credit

The incorporation of recycled waste and industrial by-products can help reduce the environmental impact, which can be rated by the Green Star system [38]. Green Star points are awarded based on three key criteria: Portland cement reduction, water reduction, and aggregate reduction.

Specifically, up to 2 points can be obtained by reducing the Portland cement content in all concrete used within the project through the replacement with SCMs. A reduction of 30% in Portland cement content, measured by mass across all concrete in the project compared to the reference case, qualifies for 1 point, while a 40% reduction qualifies for 2 points. The reference Portland cement contents are suggested in Table 2.

Table 2 Reference Portland cement contents [38]

Concrete Grade*	**Reference Portland cement content (kg/m^3)**
20	280
25	310
32	360
40	440
50	550
65	550
80	610
100	660

* As defined by AS 1379 [21]

For water reduction, 0.5 points are awarded if at least 50% of the mix water in all concrete used within the project consists of captured or reclaimed water, measured across all concrete mixes in the project.

Regarding aggregate reduction, 0.5 points can be earned if either:

- A minimum of 40% of the coarse aggregate in the concrete is replaced with crushed slag aggregate or another alternative material (measured by mass across all concrete mixes), provided that this does not result in an increase of more than 5 kg/m^3 in Portland cement usage.
- A minimum of 25% of the fine aggregate (sand) in the concrete is replaced with manufactured sand or other alternative materials (measured by mass across all concrete mixes), provided that this does not result in an increase of more than 5 kg/m^3 in Portland cement usage.

4.5.2 Example

To illustrate the procedure for claiming concrete Green Star credit points, two footpaths constructed for this project are used as examples. The concrete mixes are described in Table 3.

Table 3 Specification for concrete for the example

Description		**Mix 1 (Control)**	**Mix 2 (PET-CR)**
Materials	GP cement (kg/m^3)	186	186
	SCMs (kg/m^3)	174	174
	Portable water (kg/m^3)	198	198
	Captured/Reclaimed water (kg/m^3)	0	0
	Natural coarse aggregate (kg/m^3)	600	600
	Alternative coarse aggregate (kg/m^3)	0	0
	Natural fine aggregate (kg/m^3)	830	610
	Alternative fine aggregate (kg/m^3)	347	375
Properties	Mean compressive strength (@28 day) (site)	46 MPa	24 MPa
	Mean flexural strength (@28 day) (site)	6.1 MPa	5.8 MPa
	Dry shrinkage (@ 56 days) $\mu\varepsilon$ (site)	840	980
	Slump (site)	130 mm	190 mm

Others	Volume	2 m^3	2 m^3
	Used for	Footpath	Footpath
	Max. aggregate size	14 mm	14 mm

The assessment of these two concrete mixes in Table 3 based on the criteria in section 4.5.1 is presented in Table 4. The summary of reduction and Green Star points for one project (two footpaths) is presented in Table 5.

Table 4 Mix design assessment

	Reference concrete (N20)	**Mix 1 (Control)**	**Mix 2 (PET-CR)**
Portland cement	280 kg/m^3	186 kg/m^3	186 kg/m^3
Reduction in Portland cement	N/A	$\frac{(280-186)}{280} = 33.6\%$	$\frac{(280-186)}{280} = 33.6\%$
Replacement of natural coarse aggregate	N/A	0	0
Replacement of natural fine aggregate	N/A	$\frac{347}{(347+830)} = 29.5\%$	$\frac{375}{(375+610)} = 38.1\%$
Proportion of Captured/Reclaimed water	N/A	0	0

Table 5 Green Star Points

Portland cement reduction					
Concrete Mix	Volume in project (m^3)	Reference case		Actual	
		kg/m^3	Portland cement content (kg)	kg/m^3	Portland cement content (kg)
Mix 1 (Control)	2	280	560	186	372
Mix 2 (PET-CR)	2	280	560	186	372
Total	4		**1120**		**744**
Reduction in cement	$\frac{\mathbf{1120-744}}{\mathbf{1120}} = \mathbf{33.6\%}$				
Cement Credit Points eligibility	More than 30% but less than 40% of the cement was replaced; therefore, the cement credit point is **1**.				
Water reduction					

Mix 1 (Control)	0
Mix 2 (PET-CR)	0
Water Credit Points eligibility	**0**
Aggregate reduction	

Concrete Mix	Volume in project (m^3)	Total fine aggregate (kg)	Total alternative fine aggregate (kg)	Total coarse aggregate (kg)	Total alternative coarse aggregate (kg)
Mix 1 (Control)	2	$(830 + 347) \times 2 = 2354$	$347 \times 2 = 694$	$600 \times 2 = 1200$	0
Mix 2 (PET-CR)	2	$(610 + 375) \times 2 = 1970$	$375 \times 2 = 750$	$600 \times 2 = 1200$	0
Total	4	**4324**	**1444**	**2400**	**0**
Total fine aggregate replacement	$\frac{\mathbf{1444}}{\mathbf{4324}} = \mathbf{33.4\%}$				
Total coarse aggregate replacement	$\frac{\mathbf{0}}{\mathbf{2400}} = \mathbf{0\%}$				
Aggregate Credit Points eligibility	More than 25% of the fine aggregate (sand) in the concrete was replaced; therefore, the aggregate credit point is **0.5**.				

According to Table 5, the project of constructing two footpaths can be awarded 1.5 Green Star points.

4.6 Construction Practices

In a concrete batch plant, GGBFS should be stored in silos or sealed steel bins to protect it from excessive moisture and heat, preventing premature hardening. Handling should comply with the Hazardous Manual Tasks Code of Practice to ensure safety and efficiency. For PET particles, storage conditions should minimise exposure to direct sunlight or artificial UV light sources to prevent degradation. Additionally, high humidity at high temperatures exceeding 73°C should be avoided to prevent hydrolysis. Regular inspections of the storage area are essential to maintain cleanliness since certain fungi (e.g., Rhizopus delemar) and bacteria (e.g., Ideonella sakaiensis) can contribute to PET degradation [39]. CR particles should be stored per ISO 2230 [40]. As ozone is particularly detrimental to rubber, the storage area must not contain any equipment that generates ozone.

Due to the low specific density of PET and CR particles, they are susceptible to being displaced by air movement on conveyor belts. Furthermore, a standard batch plant conveyor system may not be designed to transport these materials directly from their storage to the mixer. Therefore, it is recommended that PET and CR be pre-weighed and manually dosed into the mixer via the designated chute (Figure 14) to ensure accurate dosing and minimise material loss.

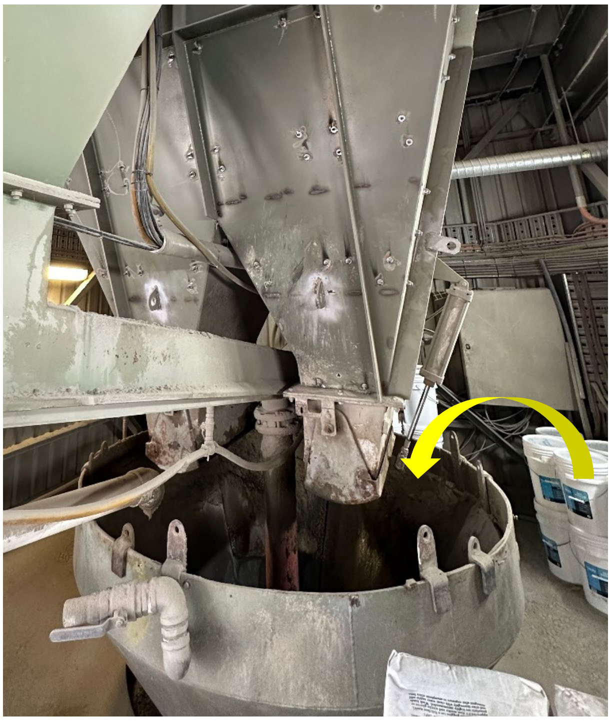


Figure 14 Chute for adding PET or CR

When pouring the concrete, the workability of fresh concrete needs to align with the chosen construction method. The workability is assessed by the slump test in accordance with AS 1012.3.1 [41]. The recommended slump range for fixed-form (manual) paving is 50-70 mm [36]. For slip-form construction with side forms, the slump range should be 30-50 mm [16]. The hydrophobic properties of PET and CR likely contribute to mitigating workability loss during delivery caused by water absorption of the aggregates. To further minimise workability loss, it is advisable to reduce delivery time, as the degree of cement hydration within the first 30–40 minutes is minimal [36], and it can help limit water evaporation [42]. It is also important to note that a high initial slump at the batching plant may lead to greater workability loss on site. To manage this, the use of water reducers and retarders is recommended, along with proper control of concrete temperature and avoiding high ambient temperatures during transport. The admixtures should be used within the dosage limits recommended by the supplier and should be sufficiently prediluted in water to prevent adverse reactions.

In addition, the concrete should be thoroughly compacted. Careful attention should be given to the corner, reinforcement, and form edge. Due to the low specific gravity of CR and PET, floating can occur during mixing and pouring, leading to non-uniform particle distribution in the concrete mix. Excessive floating of CR on the surface should be avoided, as the bond between CR and the binder paste is low, making finishing difficult and reducing the abrasion resistance of the concrete. Experimental observations from this research project show that the flaky shape of PET can reduce slump and tends to float more easily, complicating the spreading, levelling, and finishing. The PET and CR shown in Figures 10 and 11 may be suitable for pavement applications. Additionally, compaction or vibration time may need to be reduced when incorporating CR, as this can increase floating and reduce the compressive strength of the concrete [43].

In hot or windy weather, the fresh cement paste can undergo a volumetric contraction due to the evaporation of water. The contraction induces tensile stress on the concrete surface, leading to cracks. Plastic shrinkage is highly dependent on the evaporation rate which is related to the concrete temperature, wind velocity and relative humanity. The evaporation rate can be estimated by the chart below (Figure 15), and the recommended evaporation rate is less than 0.5 kg/h/m^2 to avoid plastic shrinkage [44].

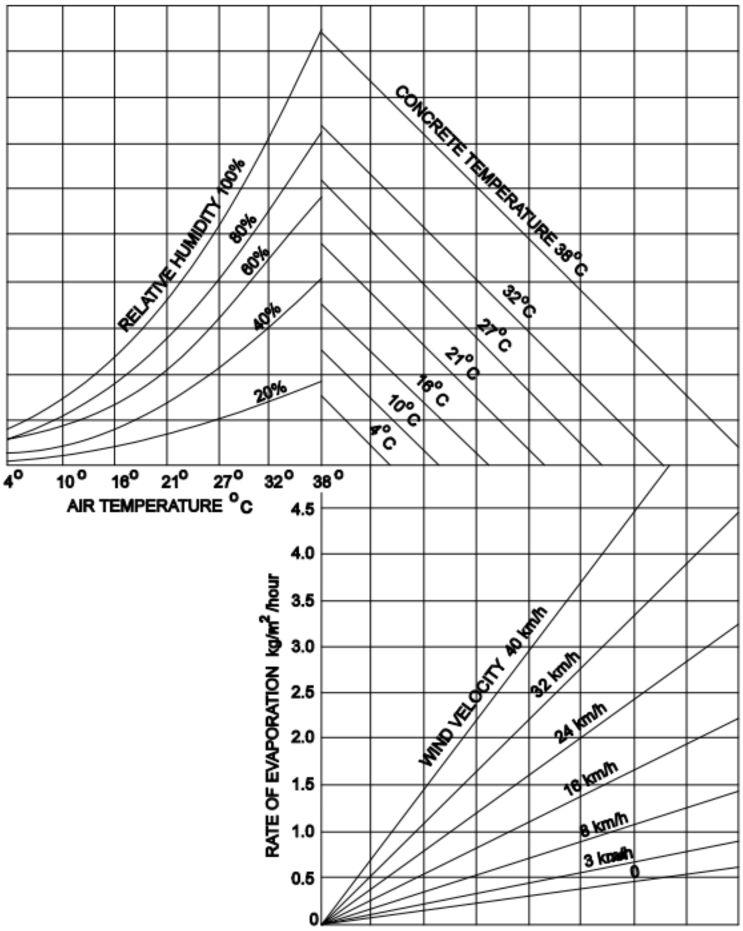


Figure 15 Evaporation rate estimation for fresh concrete on-site [36]

An appropriate surface texture is essential for providing sufficient friction to reduce the risk of skidding, particularly in wet conditions. To improve skid resistance on footpaths, the use of a steel float during screeding should be avoided. Instead, a wood float is recommended, as it provides a slightly textured surface that is less likely to become slippery when wet. Additionally, a broom finish should be applied transversely to the surface, as shown in Figure 16. If crushed aggregate is used, an exposed aggregate finish can be applied, while a coarse stencil can be considered if it ensures a uniform, positive texture. However, caution is required when applying rough cobblestone finishes, as they may cause difficulties for wheelchair users and cyclists [16].


(a) (b)

Figure 16 Broom finishing: (a) finishing, (b) texture

In addition to skid resistance, the concrete surface plays a key role in reflecting light under both wet and dry conditions. Luminance is influenced by the surface texture and colour. A durable surface that retains its texture and resists abrasion is preferred, as it ensures long-term luminance in wet weather. Lighter colours are also recommended, as dark-coloured surfaces absorb more light, reducing overall brightness compared to lighter surfaces [16].

5. Joints

The function of joints is to control transverse and longitudinal cracking while providing sufficient load transfer [16]. For footpaths, transverse contraction joints and expansion joints are applicable by wet forming. The schematics of the transverse contraction joint and expansion joint are shown in Figures 17 and 18, respectively. Joints should be spaced less than 20 times the base thickness and should be formed to a $1/4$ depth of base thickness. The layout of joints recommended by CCAA [16] for the footpath is shown in Figure 19.

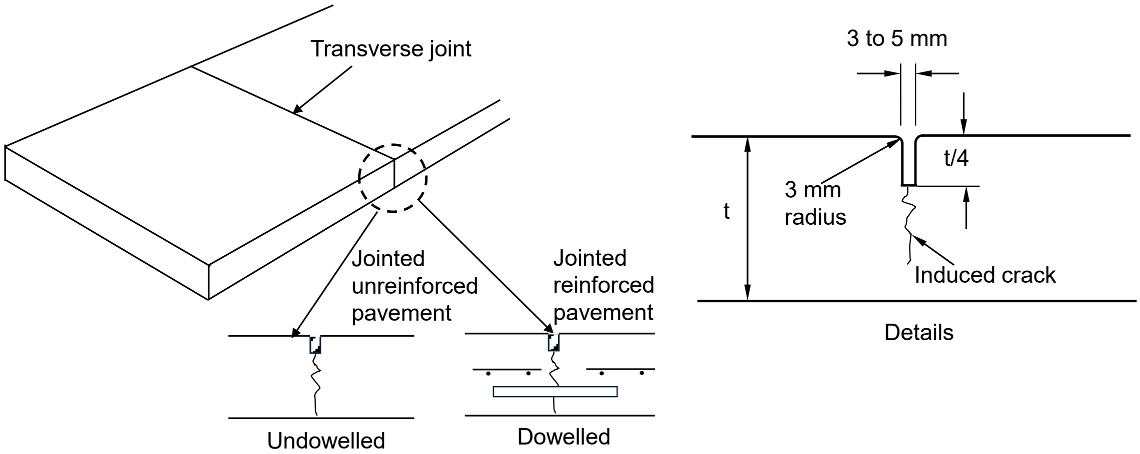


Figure 17 Schematic illustration of transverse contraction joints

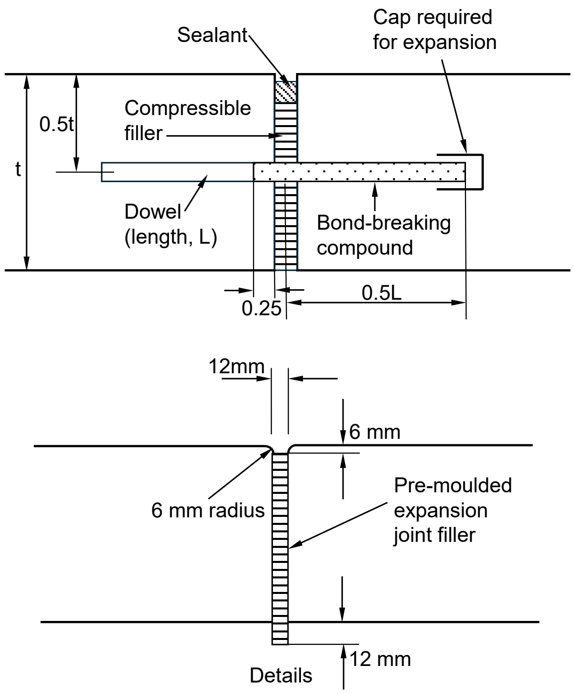


Figure 18 Schematic illustration of expansion joints

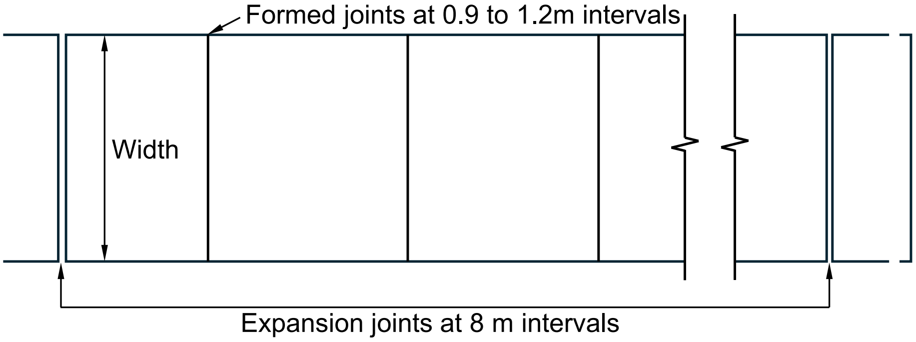


Figure 19 Footpath joints layout

When joint specifications cannot be met, SL62 mesh [45] should be placed in the upper half of the slab, starting and ending about 35 mm from the formed joint, and the reinforced base must be at least 100 mm thick [16].

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