Concrete Pavements for Climate Resilient Low-Volume Roads in Pacific Island Countries

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Contents

Acknowledgements

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1. Introduction

1. Roads in Pacific Island Countries (PICs)[1] are suffering from the effects of climate change. The conventional choice of paved road in PICs has been some form of a bituminous pavement (most commonly a thin bituminous chip seal[2] on an aggregate base – also referred to as a flexible surface dressing or surface treatment), which due to extreme weather events are often having shorter than expected service lives. While regular routine and periodic maintenance needs are increasing, dependable maintenance budgets , as discussed in the Pacific Region Infrastructure Facility (PRIF) report 'Challenging the Build-Neglect-Repair Paradigm' (PRIF 2013), seldom materialize. The dispersed nature of a small road system across many islands further increases the difficulty and cost of providing the necessary maintenance.
2. Applications of concrete paving technology around the world have shown that concrete pavements for low-volume roads, whilst incurring high initial construction cost, can have lower whole-life cost (Embacher & Snyder 2001; Ministry of Transport Vietnam 2009; Muzira & Diaz 2014; Adow & Allotey 2015, Whalley 2016; Babashami et al. 2016; Anochie-Boateng et al. 2017). They require minimal maintenance and are suitable for labor-based construction.[3] These attributes mean that concrete pavements may have potential for application in PICs—particularly in the context of reducing the negative impact from climate change and poor maintenance regimes. While some concrete pavements have been constructed in some PICs (e.g. Papua New Guinea, Fiji, Samoa, Solomon Islands, Tonga and Vanuatu), they are the exception rather than the norm. Vanuatu appears to have the most varied experience with low-volume roads and has tested eight types of concrete pavement, but experimentation has largely occurred only since 2017.[4]
3. This report explores four concrete pavement types which offer potential for improving the climate resiliency of roads: (i) jointed plain concrete pavement, (ii) concrete block pavement, (iii) geocell concrete pavement, and (iv) roller compacted concrete pavement. ***A principal aim of this report is to stimulate discussion in the PIC road engineering community on the use of concrete pavements, and how to design, construct and maintain them.*** The audience for this report includes managers, engineers and technicians of road entities, road sector consultants and contractors in the PICs, as well as development partners. It is anticipated that some of the pavement options covered here will be considered for construction in World Bank financed road projects in PICs.

[1] For the purposes of this report, PICs include all developing countries that are in the North and South Pacific regions. The PIC population and road networks are spread across hundreds of islands scattered over an area of ocean equivalent to 15% of the globe's surface. Countries are isolated from major markets by vast distances of ocean. Especially relevant to this guidance report, PICs are some of the most vulnerable in the world to the effects of climate change and natural disasters. The 2016 World Risk Report ranked five Pacific countries in the top 20 worldwide for average annual disaster losses scaled by gross domestic product.
[2] Hot mix asphalt plants are typically only available for major externally (donor) financed projects.
[3] Roller compacted concrete is an exception to this, but the pavement type has still been included in this report as it is a good option if machinery is available (e.g. nearby urban centres).
[4] Details of pavement trials available at: https://www.dropbox.com/s/xh290lw5wiigny6/180510_Pavement%20trials_PWD.pptx?dl=0

4. Given the nature of the PIC road networks, the focus is on low-volume roads (although the findings apply equally to higher volume road infrastructure). For the purposes of this report low-volume traffic is defined as less than 400 vehicles per day.[5] The vast majority of PIC roads fall into this category and thus the content of this report has wide applicability.[6] In PICs, due to small, dispersed populations and relatively low levels of vehicle ownership, low-volume roads extend across the full spectrum of functional road classes (from arterial to local access roads, urban and rural areas). This study applies to roads to be upgraded as well as greenfield low-volume roads.

5. Low-volume roads provide many development benefits to communities and society that are self-evident, and there is also a large body of evidence to support this proposition (Faiz 2012, Stein et al. 2018). The last leg of the supply chain is often the least efficient, comprising up to 28% of the total cost to move goods. Inadequate or unreliable rural road infrastructure contributes significantly to the 'last mile' problem in logistics management. This is also relevant to the delivery of goods to areas in need of humanitarian relief. Aid supplies may arrive expeditiously at a central transportation hub in an affected area but cannot be distributed due to lack of road infrastructure or damage caused by a climate-related disaster. Some of the key benefits of investing in low-volume roads include:

   - Access to healthcare, education, employment, markets and leisure (preferably all-weather access);
   - Transport cost reduction (cost and time savings for freight and passengers);
   - Addressing the 'last mile' problem in supply chain management and disaster/humanitarian relief delivery;
   - Reduction in delivered cost of imported goods and improved quality of exported goods ; and
   - Opportunities for tourism.

6. The report begins with a short discussion on when is the right time to upgrade an unpaved low-volume road to a paved road, as this is often the best opportunity to select a concrete pavement (if otherwise appropriate). From there, the focus narrows down to considering the suitability of four concrete pavement types for possible application in the PICs, comparing the pavements against each other so that the reader can comprehensively understand the characteristics of the pavements and assess their suitability for their local country context. There is not one concrete pavement type that is optimal for all situations – each pavement type has advantages and limitations which lend them to some contexts but not others. Subsequent chapters cover *Material Requirements* and *Design, Construction* and *Maintenance* comparisons as these are important considerations in choosing among pavement alternatives.

[5] For discussions on defining low-volume roads, see Faiz 2012; Douglas 2017; Stein, Weisbrod & Sieber, 2018.

[6] It is noted that "low-volume" roads can be segmented into finer categories based on general vehicle traffic volume (to define pavement width) and heavy vehicle traffic volume (to define pavement thickness) and that the preferred concrete pavement type and design should be tailored to these traffic characteristics. For example, one -lane (4m wide) and narrow two- lane (6m) wide rural access roads may be constructed using a single concrete slab with transverse joints, as provided in China's technical standards. However, restrictions may need to be placed on use of heavy commercial vehicles on such roads as a single passage of a fully laden wide truck could cause severe damage to the pavement.

2. Pavement considerations in a time of climate change

7. The 2017 World Bank report *Climate and Disaster Resilient Transport in Small Island Developing States: A Call to Action* outlined that the two most cost-effective policies to building climate resilience in the road sector were:
    - raising design standards; and,
    - improving road maintenance.
8. This is particularly true in the PICs where, as noted earlier, there is a tradition of 'Build, Neglect, Repair' (PRIF, 2013). The PIC road networks include extensive lengths of unsealed roads—which are particularly vulnerable to the changing weather patterns resulting from climate change, as well as thin bituminous surfaces which, if not maintained properly, will not reach their design service lives. Most of the design standards adopted in PIC countries favor bituminous surfaces—in most instances to the exclusion of concrete pavements.[7]
9. In other parts of the developing world, concrete pavements for low-volume roads are common, with many thousands of kilometers constructed in China, Philippines, South Korea, Chile and South Africa. Durability and longevity are the hallmarks of a properly designed and well- constructed concrete pavement. The first concrete pavement in the world was built in Inverness, Scotland, in 1865. Some of the concrete pavement laid in Edinburgh, Scotland, in 1872 is still in use today.[8] With adequate routine maintenance, bituminous surfaced pavements may hold steady up to 10-12 years and then begin accelerated deterioration. Regular periodic maintenance interventions (e.g. structural pavement repairs, resealing, overlays) are required to maintain service levels. On the other hand, concrete pavements can hold steady service levels for decades (3-4 decades on average) with only routine maintenance. In concrete pavements, functional obsolescence commonly precedes structural inadequacy.
10. Both bituminous and concrete pavement lives are governed by construction quality. If poorly constructed (with inadequate attention to material and/or construction quality and workmanship), concrete pavements may suffer from catastrophic failure within a short period after initial construction. Concrete pavements may occasionally fail on account of loss of subgrade/subbase and/or edge support over time. Most cases of premature failure are on account of mistakes in construction, such as concrete of inadequate strength, misaligned dowel bars, badly sawed joints (frozen joints), and poorly compacted aggregate subbases. In case of block/geocell pavements, inadequate attention to edge support and compaction of bedding materials is often the cause of premature distress and defects.
11. The Cement and Concrete Institute of South Africa (1998) offers the following advantages and benefits of jointed concrete pavement roads, but the benefits are the same for the other concrete pavement types considered for PICs:
    - Durable;
    - Lower whole-life cost for comparable flexible surfacing pavement design;
    - Very low maintenance costs;
    - Skills acquired are not limited to road construction but are transferable to the wider building construction industry;
    - Ideal for upgrading deteriorated roads (paved and unpaved) by overlaying with a concrete surface; and
    - Drainage may be integrated in road structure, reducing need for separate drainage infrastructure.

[7] For example, the 2016 PRIF report on pavement options for PICs (https://www.theprif.org/documents/regional/transport-land/road-pavement-design-pacific-region) only has a passing mention of concrete pavements.
[8] https://www.asce.org/project/first-concrete-pavement/

12. The tropical environment in most PICs offers pronounced technical advantages for the use of concrete pavements. There is relatively small variation in diurnal and annual temperatures so that the provision for thermal strains in the concrete slabs is not of paramount importance and joints may be more widely spaced. The availability of sandy or coralline aggregate subgrades, especially in the atoll islands (Babinard et al. 2014, PRIF 2016), offer a stable (and often a strong foundation) for the concrete slabs and blocks; the granular interlock across the joint between the two concrete faces can provide adequate wheel load transfer without the need for steel dowels (i.e. load transfer devices spaced across the joint). Also, in case of poorly consolidated or poorly-drained soils (weak subgrades) commonly encountered on volcanic islands, concrete pavement (with an adequate subbase) provides a clear advantage over flexible pavement alternatives. While freeze/thaw durability is not an issue in PICs, concrete pavements can be damaged by deleterious alkalis and salts, either in the aggregate or entering the concrete in solution from an external source (marine environment). Corrosion resistant steel reinforcement (e.g. for tie bars and dowels in jointed concrete pavements) and appropriate hydraulic cements and additives can help to mitigate such deleterious impacts.

13. With aggregates comprising between 70% to 85% by mass of the concrete mixture, concrete pavement recycling offers both economic and environmental benefits. Typically, recycled concrete aggregate is used as granular fill, base and sub-base material, or as aggregate in new concrete pavement. Crushing and reusing old concrete minimizes the amount of virgin aggregate required for a new pavement structure; thus, cost savings would be substantial in the PIC context, given the scarcity of good aggregate material. Recycling has significant environmental benefits, including reduced truck traffic, fuel savings, and improved air quality by limiting exhaust fumes. Recycled concrete pavement on exposure to the atmosphere (e.g. in embankment fills, gravel roads, railroad ballast etc.) can sequester carbon by reacting with carbon dioxide in the air (PCA 2010).

14. The critical design consideration for low-volume roads in PICs is not traffic, but the climatic and terrain conditions. Frequent, intense rainfall and poor drainage pose the biggest challenge to road durability. In a time of climate change, these impacts are likely to become even more significant. Concrete pavements thus have technical advantages over bituminous surface dressings for climate change adaptation in both areas, as identified in the 2017 World Bank report:

    - Resilience to flooding, inundation, erosion (on steep gradients) and heavy surface runoff; and,
    - Reduced maintenance needs compared to bituminous surface dressings.

15. Maintenance of surface dressing roads is typically not done well in PICs with the dispersed and often remote location of the road networks. Many islands do not have access to bitumen or expertise for surface dressing repairs, whereas access to concrete is less of an issue.

16. The decision to construct a concrete pavement is often taken at the time of upgrading from unsealed to a paved road surface. The following are all contextual factors that contribute to a decision to upgrade a road from unpaved to paved (Muzira & Diaz 2014):

    - Gravel quality is poor;
    - Compacted density and thickness cannot be ensured during the life cycle of the road;
    - Motorized traffic volumes are relatively high;[9]
    - Haul distances are long (there is a trade-off between gravel quality and initial cost);
    - Rainfall is high;
    - There are dry season dust problems (binding fines removed by traffic or wind, inappropriate wearing course);
    - There are steep longitudinal gradients;

[9] Based on engineering-economy studies, a commonly accepted AADT threshold for paving a gravel road is 150, with a range of 100 to 300. However, such AADT thresholds are heavily influenced by site-specific conditions, such as availability of good quality gravel, the traffic mix (inclusive of pedestrian and non-motorized vehicles), road geometry (e.g. steep longitudinal grades), and rainfall/drainage conditions among others.

- Adequate maintenance cannot be ensured;
- Subgrade is weak or soaked because of poor drainage;
- Gravel deposits limited/environmentally sensitive.

17. Cook et al. (2013) and Henning et al. (2016) provide guidance on a range of proven road surfacing and paving techniques that offer relatively low cost and sustainable solutions for low-volume roads. This guidance includes analytical methodologies and decision frameworks for comparing and assessing surfacing alternatives ranging from engineered earth roads through gravel to various unbound, natural stone, bituminous, cement- based, and clay brick surfacing and pavement layers. The decision frameworks can be used for making an informed choice between concrete and bituminous options for paving projects.
18. The assessment of the concrete pavements in Chapter 3 shows that they have better climate resilience than bituminous surfacing alternatives. From a climate adaptation standpoint, all the four concrete pavement types can handle flooding, steep road gradients, and surface runoff when designed and constructed correctly. Concrete pavements also are more resistant to uplift vapor and air pressure under the pavement caused by sea level rise due to high tides (also called ‘sunny day flooding’) and storm surges. The construction of concrete pavements (other than roller compacted concrete) tends to be less energy intensive than bituminous pavements. Due to its higher albedo, concrete pavement absorbs less solar radiation and contributes less to the urban heat island effect. While concrete pavements have significantly higher GHG emissions compared to the bituminous alternatives, mostly as a function of the amount of clinker in the Portland cement used to produce the concrete, this is being mitigated by substituting clinker with fly ash, bottom ash, slag and other additives. In the broader climate change context, however, pavements in PICs would be a miniscule contributor to GHG emissions, where benefits of pavement installation justifiably outweigh costs.

3. Concrete pavement options for Pacific Island Countries

19. This chapter provides a brief introduction to the four concrete pavement options evaluated in this study and then compares them relative to engineering (functional and structural) attributes, climate proofing, expected lifespan, initial construction cost and equipment requirements, and traffic type and volumes. The four concrete pavement technologies are:

    - Jointed concrete pavement (with or without steel/polymer fibers)
    - Concrete block paving
    - Geocell concrete
    - Roller compacted concrete

3.1. Jointed concrete pavement

20. Jointed concrete pavement (JCP) is by far the most common type of Portland cement concrete pavement. Most of the world's concrete pavements, ranging from footpaths and parking lots to motorways and airfields, have been constructed with this technology. JCP for low-volume roads is cast in slabs with a typical longitudinal length of 4 to 5m[10,11] between joints and a width of 3 to 4m.[12] The slabs are sized to dimensions such that uncontrolled cracking from thermal, traffic and moisture stresses should not occur. Thermal loads arise in the concrete slab when its natural tendency to expand or contract is constrained by the deadweight of the concrete which prevents the slab to curl. Warping or curling stresses are directly dependent on the temperature gradients that develop within the slab as a function of diurnal and seasonal variations in temperature. As noted before, the relatively small range of diurnal and seasonal variations in temperature in PICs make JCP a technically attractive alternative in terms of both slab thickness requirements and longer-term serviceability.

21. Joint spacing is also related to slab thickness. In general, the thinner a concrete, the higher the curling stresses and thus, the shorter the joint spacing. As a general rule-of-thumb, joint spacing should be less than 24 x slab thickness. Thus, a 230 mm slab should have joints spaced no more than about 5.5 m apart. Also, as a general guide, concrete slabs (panels) should be as square as possible, with the ratio of panel length (longer slab side) to panel width (shorter slab side) kept less than about 1.25 (Pavement Interactive, 2019). Perrie (1998) recommends a maximum transverse joint spacing of 4.5 m and a maximum longitudinal joint spacing of 3.8 m for South African conditions.

[10] In climates with small changes in diurnal and annual temperatures and where there is no excessive overloading, the joint spacing may be increased to 7 meters or so provided that lean dry mixtures required in pavement concrete is used. Such concrete mixes also minimize initial shrinkage of concrete (Millard 1993; p. 243).

[11] The choice of joint spacing is a simple function of linear thermal cracking (ignoring warping). However, once a joint opening exceeds around 1 mm, the granular interlock across the joint between the two concrete faces becomes minimal; thus, it is the extent of joint opening that really controls spacing. For most climates, joint spacings between 3.5 to 6 m represent the range of a reasonable balance between the cost and nuisance of joint construction and maintenance and the need to maintain effective wheel load transfer (Thom 2008; pp 248-249).

[12] The 3-4 m wide slabs (cast separately) are separated by a pre-formed longitudinal joint with the adjacent slabs tied with steel tie-bars at about 1-meter interval. The lack of tie bars could result in slab faulting and cracking. In lane-at-a-time construction (using labor-based methods) keyed joints are generally used, with or without tie bars. (Yoder & Witczak 1975; pp.94-97). To cater to heavy truck loads, a wider slab width (incorporating 0.3 to 0.5 m of shoulders) can provide extra edge support with some reduction in slab thickness.

22. In labor-based construction, alternate slabs are cast, and the missing slabs are filled in later. Aggregate interlock between adjacent slabs typically provides adequate load transfer. But on low-volume roads with heavy-loaded truck traffic steel dowels may be required for effective load transfer. Where the slabs serve as adjacent traffic lanes, the adjacent slabs are tied by deformed steel tie bars (about 0.75 m long), with one meter spacing across the longitudinal joint.[13] In mechanized construction, the longitudinal or transverse joint (a weakened plane) may be formed by creating a notch into the top of the finished concrete. When tension develops, a crack occurs at this specific point rather than at any random location. This can be accomplished by creating a weakened plane by inserting plastic, fiber or metal strips in the fresh concrete. Most current specifications, however, require or permit the use of special saws to cut joints into the concrete after the initial set, resulting in a clean and trim joint. With steel reinforced JCP, transverse joints can be spaced in larger intervals but such reinforcement to control temperature stresses is not likely to be required in PICs.

23. A base course (usually called subbase) is used under a concrete pavement for prevention of pumping[14], for drainage, prevention of volume change of the subgrade, increased structural capacity (especially with stabilized materials), and to provide a construction platform for the concrete slab. A subbase should always be used in case of weak subgrades with poor drainage characteristic or on roads with heavily loaded truck traffic. The primary function of the subbase is to prevent pumping and hence it must be either well-draining or highly resistant to the erosive action of water. To control pumping, a subbase must prevent the subgrade soil from pumping through the subbase and, secondly, it must not pump itself (Yoder & Witczak 1975; pp. 372-374).

24. A variant of the JCP is fiber reinforced JCP where a consistent proportion of polymer (or other) fibers are blended into the concrete mix. The addition of fibers greatly increases the failure strain (with no change in failure stress) with fibers reinforcing the granular interlock between aggregate particles and thus retarding both crack progression and crack widening. Reinforcement with fibers will help to control crack progression and widening but will not stop cracking from occurring.

25. Concrete for JCPs can be mixed on site, poured, compacted and cured using local labor and inexpensive, simple equipment. There is also the possibility to employ precast concrete panels. A precast concrete pavement (PCP) system is a set of specific panel details, materials and associated installation methods used in concert to rapidly create a fully functioning concrete pavement. High-quality materials are used in a carefully controlled manufacturing process to produce durable precast panels. Effective and rapid methods of placing, bedding and connecting those panels in the roadway complete the system, creating a concrete pavement (Smith & Snyder 2018).

[13] Longitudinal joints are designed as hinges to provide edge support while permitting rotation between the slabs. In this way flexural stresses are relieved which might otherwise cause irregular and unsightly cracks along the pavement length.

[14] 'Mud pumping' describes the action where fine soil and water are forced up through the cracks and joints in the concrete to the surface or on the edge on to the shoulder. Pumping is defined as movement of material underneath the slab or ejection of material from underneath the slab as a result of water pressure. Water accumulated underneath a PCC slab will pressurize when the slab deflects under load. This pressurized water can do one of the following: (i) move about under the slab, (ii) move from underneath one slab to underneath an adjacent slab-this type of movement leads to faulting, and (iii) move out from underneath the slab to the pavement surface – this results in a slow removal of base, subbase and/or subgrade material from underneath the slab resulting in decreased structural support, which can lead to linear cracking, corner breaks and faulting.

Notable Application for Low-Volume Roads in PICs

26. Examples of JCPs (both plain and reinforced) are found in some PICs (Papua New Guinea, Fiji, Samoa, Solomon Islands, Vanuatu, Tonga) as well as in the US and French administered territories but their use is mostly confined to urban roads and streets. Vanuatu provides the first applications for low-volume roads (see Box 1).

Box 1: Vanuatu experimental concrete pavements

With support from the government of Australia's Department of Foreign Affairs and Trade (DFAT), the government of Vanuatu Public Works Department (PWD) is considered to have had the most experience with testing concrete pavements for low-volume roads in PICs. PWD has tested seven types of 150-200 mm concrete pavement including plain JCP, as well as variations such as polymer-fiber and steel reinforcing, embedded stone, and strip road pavements. However, pavement trials have largely occurred only since 2017. From the testing, construction costs ranged from US$44-105/$m^2$ (2018), which includes labor, equipment, local and non-local materials and indirect costs. Stone wearing course mortar was the lowest cost at US$44/$m^2$ whilst 150 mm steel reinforced concrete was the highest at US$105/$m^2$. More information on the trials including detailed cost breakdown, technical assessment and recommended practice is available in *Government of Vanuatu Public Works Department and Australian Aid* (2018) in section 8 *References* of this report. These pavement trials point to the critical importance of materials testing and construction quality control in obtaining a durable JCP. From a design standpoint, a granular subbase must be provided in road sections with weak subgrades and/or poor drainage conditions.

JCP slab under construction (note the poor Personal Protective Equipment). Espiritu Santo, Vanuatu. (Johnson 2018a).

Recently constructed JCP low-volume road. Espiritu Santo, Vanuatu. (Johnson 2018b).

3.2. Concrete block paving

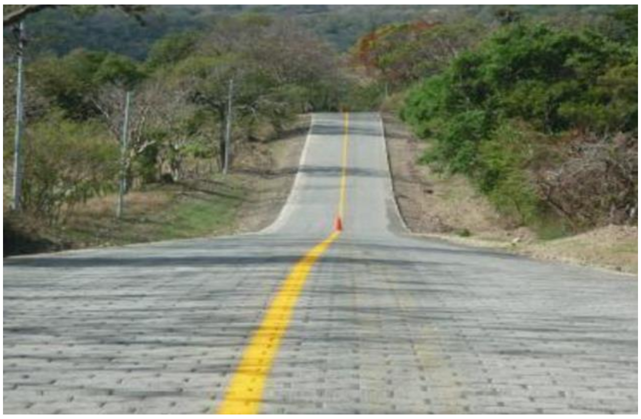
27. Concrete block paving is a system of individual blocks arranged to form a continuous hard-wearing surface pavement. The block can be made in different shapes and sizes, with grooved interlocking pavers as in *Figure 1* being the most durable shape for vehicular traffic. The blocks are typically laid in a herringbone pattern and are confined by edge constraints that are placed before or after the blocks are laid. Concrete block pavers are precast in an offsite factory, or alternatively made on site labor-intensively using individual molds. The challenge with the latter approach is risk of quality variability without good quality control processes. The blocks typically require a minimum 28-day cube strength of 20-25 MPa (Cook et al. 2013) although splitting tensile strength is favored as it is independent of the block aspect ratio. Critically, block paving relies on manual labor rather than on heavy or sophisticated mechanical equipment. The pavement layers are constructed by conventional equipment, and the bedding layer of sand and paving blocks are then placed labor intensively. Under traffic action, concrete block pavements tend to develop interlock, which increases the load-spreading ability of the blocks and reduces the rate of deformation. The blocks must be of sufficiently good quality especially in a marine environment to resist erosion from wave action and damage from exposure to sea mists.

28. This type of pavement requires regular maintenance (initially from 3-12 months until the blocks have interlocked, and later at longer intervals) to ensure that the jointing sand lost through vehicle action and erosion is replaced. If this does not happen, the blocks become loose and damaged, and the riding quality is impaired. It is not a recommended solution for very steep gradients or where sheet flow of water passes over the road, nor where drainage is poor.

<u>Notable Applications for low-volume roads in PICs</u>

29. Although use of paving blocks is not uncommon on private roads, streets and parking lots in PICs (e.g. in tourist resorts and gated residential communities in Fiji), no known applications were found for low-volume roads in the literature review for this report.

Interlocking herringbone block paving. (Pixabay 2014).

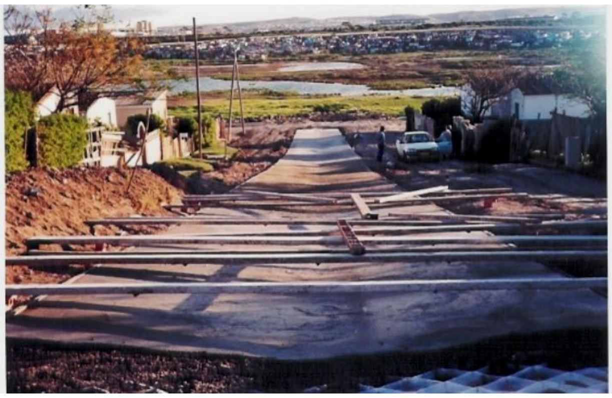


Rural road with labor-based construction using 'adoquine' blocks in Nicaragua. (Muzira & Diaz, 2014).

Figure 1. Block paving

3.3. Geocell concrete

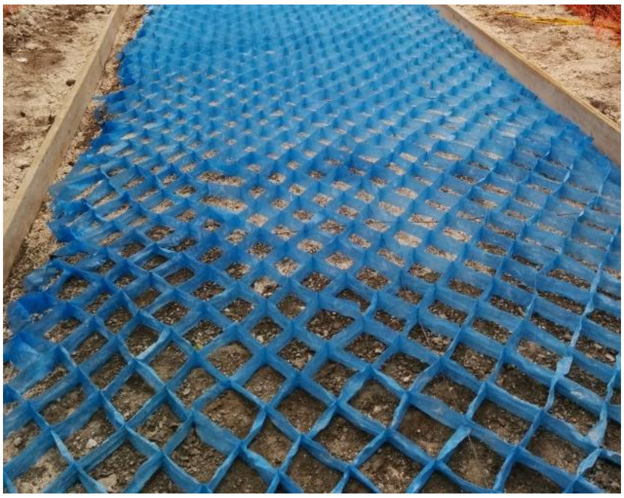
30. Geocell concrete pavement is constructed by filling a honeycombed plastic geocell formwork with concrete. Geocell concrete pavement has been successfully used under poor drainage conditions in South Africa, India, Kiribati, Tuvalu, as well as other countries in southern Africa and in Australia. Construction can be done by hand labor, no special equipment is required besides a roller to compact the formed earthworks and a concrete mixer. These equipment requirements are within the capacity of small-scale contractors operating on remote islands.[15] Geocell concrete can incorporate drainage into the pavement by using a V cross-section with the drain in the middle of the road. Hydrostatic pressure can release from below whilst at the same time (unlike with concrete block pavements) the pavement is impermeable to surface flow as the gap between the cell blocks is very small.



Road and drain incorporated. Drain can also be to side of road. (Hall & Hall 2007).

Dimpled formwork creates interlock between cells poured in situ (thin geocell formwork). (Hall & Hall 2007).

Strips of thick (>20 mm) geocell formwork (National Rural Roads Development Agency n.d., pg. 4).



Geocell formwork expanded and tensioned and ready for placement of concrete (Whalley, O 2016).

Figure 2. Geocell concrete

[15] They can be built with even less equipment using a grouted-concrete approach. This entails placing the single sized (19 or 26 mm) concrete aggregate in the cells first, and then filling the voids with a sand/cement slurry which is vibrated into the layer with a plate vibrator. By first placing the coarse aggregate only 40 percent of the volume of the slab needs to be mixed and handled. The slurry is mixed using a 90-litre plastic drum with a cap on the one end and a pulling handle, known as a 'Hippo Roller'. This is used by villagers in South Africa to fetch water. By rolling the Hippo with water, cement and sand in the correct proportions a thorough mix is achieved, which is then poured onto the layer.

31. The geocell is a high-density polyethylene (HDPE) sacrificial formwork and results in cast in- situ concrete blocks 75 – 200 mm thick. There are thin (approximately 0.2 mm thickness) and thick (20 – 35 mm thickness) geocell plastic formworks on the market which behave similarly but have important differences in the way that they impact on concrete slump requirements, block interlock, and construction speed and cost. Both thin and thick geocell formworks will be covered in this report. As the geocell blocks are typically on 150 – 300 mm square there are minimal bending moments, unlike JCP slabs, which crack under heavy truck loads. The typical concrete strength that is required for geocells is a minimum of 20 MPa.

Feature	Thin (0.2 mm) HDPE geocells	Thick (> 20 mm) HDPE geocells
	FACTORS IMPACTING SPEED AND COST OF CONSTRUCTION	
Concrete mix	High-slump or grout-filled concrete.	Can be normal slump, high slump or grout-filled concrete. High slump concrete is preferred if conditions allow as this will achieve fastest construction rate.
Layer works	If subgrade CBR > 5, then laying directly onto subgrade is acceptable.	Regardless of subgrade CBR, guidelines recommend minimum subbase of 100 mm, and the additional equipment and labour requirements to achieve this is a constraint.
Ease and speed of rigging large areas	Standard module is 200 m^2 and weighs 40 kg. Rigging speed is much faster than for thick geocells.	Standard module 15 m^2 and weighs approx. 30 kg. Rigging is much slower than for thin geocells due to the time it takes to connect adjoining geocell modules. Plastic sheets need to be welded and stitched at approx. 300 mm intervals.
	FACTORS IMPACTING PAVEMENT PERFORMANCE	
Shear interlock	Cells that are dimpled on all four sides such that each block keys into adjacent blocks, create mechanical interlock which is better able to transfer loads (see *Figure 2*).	Since there is no “keying” into adjacent blocks, there is no mechanical interlock and load transfer. The limiting factor for load bearing is the shear strength of the geocell plastic and if this is exceeded then the blocks can “punch through”.
Edge protection	Cells are flexible and can be draped to follow a radius of 100 mm to 200 mm (depending on cell depth). This allows a "tuck-in" termination edge beam to combat potential undercutting edge damage.	Inflexible so edge tuck in is not possible. Requires construction of separate edge beam.

Notable Applications for low-volume roads in PICs

32. **Kiribati, 2015** – 7.3 km of feeder roads in peri-urban areas on the main island of South Tarawa, Kiribati. As a remote coral atoll, material supply was an issue for the project with some pavement materials needing to be imported by barge from Fiji, some 2000 km of open ocean away. In this context, 5-meter-wide geocell pavements cost approximately US $43/m^2—about one-third less than bituminous pavements (Whalley 2016).

33. **Tuvalu, 2018** – 400 m of low-volume roads have been constructed as a pilot to test this technology for the atoll country; the first paved road that the public works department has built without international contractor support.

3.4. Roller compacted concrete

34. Roller-compacted concrete (RCC) is a pre-mix produced at a central batching plant that is laid using a purpose built mixing and paving machine and compacted by heavy vibratory steel drum and rubber-tired rollers. No dowels, reinforcing or formwork are required. The RCC mix is stiff and has very low water content, and this aggregate skeleton means that the pavement at first behaves like a granular untreated base. Consequently, short-term concrete strength is not needed, and the pavement can be opened to traffic immediately after construction.

Notable Applications for low-volume roads in PICs

35. No known applications in PICs were found in the literature review for this report.

Transferring RCC from mixing plant to truck. (Harrington et al. 2010; p. 69).

RCC loaded into paver. (Roller compacted concrete n.d).

Comparison of steel drum and rubber-tired roller. (Harrington et al. 2010; p. 73).

RCC consistency. (FHWA 2016).

Figure 3. Roller compacted concrete

4. Comparing concrete pavement options

36. The following section is designed for the reader to obtain a rapid but succinct understanding of the strengths, weaknesses and implementation implications of each pavement type. Specific materials, design and construction guidance will be covered later in the report. This section covers:

- Key strengths
- Key weaknesses
- Overall climate resilience
- Suitable traffic volumes
- Area types where pavement likely suitable
- Area types where pavement likely NOT suitable
- Expected lifespan
- Construction costs
- Equipment required for construction
- Time for the road be opened to traffic
- Suitability of labor-based construction

JCP	BLOCK PAVING	GEOCELL	RCC
Key Strengths (all)			
• Well suited to unskilled labor • Knowledge of plain concrete or block paving construction-- useful skill outside of road construction • Low surfacing maintenance needs • Good recycling potential with recycled concrete aggregate used as granular fill, base and sub-base material, or as aggregate in new concrete pavement			
• Well understood, well tested method • Does not require expensive equipment	• Very simple to construct and repair relative to other concrete pavements[16] • Can generate social and economic benefits for communities through local block manufacture • Does not require expensive equipment • In urban areas provides easy access to underground utilities • At end of life pavers can be repurposed for other building applications • Localized repairs and reconstruction easy	• No joints, virtually no maintenance • Does not require expensive equipment • At end of life blocks can be repurposed for other purposes • Localized repairs and reconstruction easier than JCP *Applies to thin (0.2 mm) geocell plastic only* • Surface is waterproof (hairline cracks between blocks only fraction of a millimeter)[17] • Can cast the drainage and road in one go[18]	• Can be driven on immediately after construction • Can be more rapidly built than other pavements if sophisticated equipment available • Surface quality can be enhanced (comparable to JCP) with use of concrete additives and finishing equipment

[16] Concrete slabs require concrete cutting machines. For block paving, the base simply needs to be relevelled and compacted and blocks laid again by hand. The ease of rearranging the blocks makes block paving a promising option in urban areas where utilities beneath the pavement may need to be accessed over time.

[17] The waterproofness of geocell concrete produced with thin geocell plastic is such that it has been used to construct irrigation canals and water reservoirs with a depth of water of 10 m.

[18] JCP and block paving can also be used as drains, but geocell has additional advantage due to having no joints so no chance of seepage. Gap between geocell is too small to allow surface water in, but large enough to relieve pore pressure from pavement below. Drainage can be embedded as v-drain in the road, or one/two side drains.

JCP	BLOCK PAVING	GEOCELL	RCC
Key Weaknesses (all)			
• Require imported cement			
• Joints can let water in if not maintained; pumping of fines • Shoulders must be well maintained against erosion • Poor workmanship can lead to roughness • If slab cracks badly may require mechanical equipment to rehabilitate • Reconstruction requires rubblization[19] of pavement	• Correct gradation of joint sand may not be available • Joints can let water in if not maintained, pumping of fines • Riding surface may not be as even as JCP or RCC • When blocks come loose, they need to be fixed promptly else additional adjacent blocks will come loose	• Plastic geocells need to be imported • Riding surface may not be as even as JCP or RCC • Requires good site quality control	• Requires heavy roller and paver /motor grader • Must be mixed at a central facility and then transported • Finish is rough compared to JCP but can be improved with use of additives. • Reconstruction requires rubblization of pavement

Overall climate resilience

All pavement types have improved climate resilience relative to bituminous surfacing alternatives. From a climate adaptation standpoint, all can handle flooding, steep road gradients, and surface runoff when designed and constructed correctly. All need to have sufficient edge support to protect against erosion and scour from surface flow. JCP and block paving need to have their joints maintained on a routine basis to ensure that the supporting layer works are not compromised by surface flow. Concrete pavements also are more resistant to uplift vapor and air pressure under the pavement caused by sea level rise due to high tides (also called 'sunny day flooding') and storm surges. Concrete pavements have significantly higher GHG emissions compared to the bituminous alternatives, mostly as a function of the amount of clinker in the Portland cement used to produce the concrete. This is being mitigated by substituting clinker with fly ash, bottom ash, slag and other additives. On the positive side, the construction of concrete pavements (other than RCC) tends to be less energy intensive than bituminous pavements. Due to its higher albedo, concrete pavement absorbs less solar radiation and contributes far less to the urban heat island effect. In the global climate change context, however, pavements in PICs are a miniscule contributor to GHG emissions.

Suitable traffic volumes (all)

All pavements are technically suitable for low-volume roads (< 400 AADT). The greater the number of heavy vehicle movements expected, the thicker the pavement required. All pavement types are capable of being constructed with thicker pavements.

JCP	BLOCK PAVING	GEOCELL	RCC
Area types where pavement likely viable			
• Flat terrain • Steep terrain • Urban areas (with integrated curb and gutter drainage and sidewalks)	• Flat terrain • Urban areas[20]	• Flat terrain • Steep terrain • Technical advantage over other pavements for high rainfall areas	• Flat terrain • Steep terrain
Area types where pavement likely NOT viable (all)			
• When there is no suitable aggregate available			
	• Steep sections • Areas of high rainfall and poor drainage		• When no paver, roller machinery or large batching infrastructure available

[19] Rubblization is a construction and engineering technique that involves saving time and transportation costs by reducing concrete into rubble at its current location rather than hauling it to another location.
[20] Concrete block paving particularly well suited to urban areas due to the ease of removing blocks when utilities under the roadway need to be accessed.

<table>
<tr><th>JCP</th><th>BLOCK PAVING</th><th>GEOCELL</th><th>RCC</th></tr>
<tr><td colspan="4"><u>Expected lifespan[21]</u></td></tr>
<tr><td>• 30 years +</td><td>• 20 years +</td><td>• 30 years +</td><td>• 30 years +</td></tr>
<tr><td colspan="4"><u>Construction Costs</u>
Cost depends on raw materials, road condition, subgrade strength, design width of road, volume of fill, speed of installation, and use of labor based/machinery-based approach. These costs need to be calibrated to local conditions. Whilst there are construction costs available for non-PIC projects, it is difficult to use these as an estimate of what the cost will be for a project in a PIC. It can be expected that majority of the cost of the concrete pavement will come from the cost of (i) imported cement and (ii) extracting, preparing and transporting aggregate material. If the aggregate material must be imported from another island or internationally, this will have a major effect on unit cost and should be considered early on by the engineer. For roads through steep terrain or being built on low strength subgrade, site preparatory earthworks, drainage provision and layer works will be a significant proportion of the cost per kilometer.</td></tr>
<tr><td colspan="4"><u>Equipment required for construction[22]</u>
In addition to the equipment specified below, all concrete pavement types will require a hauling truck/s (minimum 3 tons), vibratory roller (1-4 tons), plate compactor, water tanker, site clearing and earthworks tools[23], motor grader[24] for clearing and shaping and importantly safety equipment.[25]</td></tr>
<tr><td>• Concrete mixer
• Poker vibrator
• Concrete saw cutter
• Crack sealing squeegees
• Sealant pouring jars</td><td>• Block cutter</td><td>• Concrete mixer / Hippo roller</td><td>• Paving machine
• Concrete batching plant
• Heavy roller (smooth drum vibratory / rubber-tired)</td></tr>
<tr><td colspan="4"><u>When can the road be opened to traffic?</u></td></tr>
<tr><td>• JCP does not have enough load carrying capacity to support vehicular traffic until the sawing window is reached or passed</td><td>• Immediately after the jointing sand has been placed. Opening to traffic before the paving is complete is not advised as the blocks become misaligned</td><td>• Opened to light traffic within 2 days and to heavy traffic within 7-14 days when the concrete has achieved a strength of 15 MPa (depends on the cement proportion in mix and whether any admixtures added)</td><td>• Can be opened to all traffic within 2 days[26]</td></tr>
<tr><td colspan="4"><u>Suitability for community-based construction</u>
There is a difference between community-based construction and labor-based construction. In the latter, the focus is on using labor instead of equipment, but this may be carried out under close technical supervision. In the former, it is about the community being able to organize the whole work, possibly hiring some skilled labor to assist them. Although community-based construction tends to be labor-based, but labor-based construction is generally not community-based (usually labor-based contractors or government staff from outside the community). Some of the concrete pavements can viably be built with community-based construction. This is aligned with the desire of PIC governments to provide employment opportunities for communities through road projects, especially in remote areas.</td></tr>
<tr><td>• Viable, but likely more difficult than block paving given the more complicated site planning and need for quality control</td><td>• Viable. Has been done extensively in Nicaragua and other places. See Muzira & Diaz (2014) for details on Nicaragua</td><td>• Viable, but likely more difficult than block paving as more complex construction requirements and need for quality control</td><td>• Not viable</td></tr>
</table>

[21] Defined as the expected lifespan before the concrete pavement has deteriorated such that a new pavement must be constructed and assumes that the pavement was originally built to specification quality. These expected lifespan figures should be treated as a minimum bound. Literature review found concrete pavements that have lasted 40 – 60 years in reasonable condition.

[22] The list of machinery required assumes that the road is a flat road and subgrade has CBR > 5. If the road has poor subgrade and/or is situated in steep terrain, then additional equipment will be required for earthworks and layer works. For JCP, the indicated equipment is for labor-based construction; machine-based construction will require a paver, concrete batching plant/ concrete mixer trucks.

[23] General site establishment equipment includes brooms, shovels, hoes, pickaxe, rakes, machetes, watering cans, buckets and wheelbarrows.

[24] Can be achieved without a motor grader with local labour (may be the only option on remote islands) but will take significantly longer.

[25] Safety equipment includes safety cones, vests, helmets, boots, gloves and first aid kits.

[26] The road can be traffic immediately after construction however in this case some accelerated surface wear has to be expected.

5. Concrete pavement material requirements

37. A concrete mix[27] is a proportional combination of aggregates (coarse and fine), cementitious material (including Portland cement, fly-ash, bottom ash, slag, pozzolans) and water[28, 29] (See Box 2). It may also include admixtures (e.g. to retard or accelerate hydration; for curing etc.) and in some cases fibers to enhance strength and durability.[30] The specified proportions of these ingredients are different depending on the concrete pavement type, and the site circumstances. Across the PICs, the engineering properties (based on international standards and specifications) of all ingredients except the aggregate material are reasonably consistent[31]; however, aggregate properties vary depending on the locally available materials. Where suitable local aggregate is not available, aggregate is sourced from distant locations by barge involving seaborne transport over hundreds to thousands of kilometers. Aggregate quality and sourcing are likely to be the binding constraint in mainstreaming the use of concrete pavements in PICs.

[27] CCAA (2010) provides a basic introduction to concrete fundamentals. Concrete mix design and test methods, however, fall outside the scope of this study. The *Design and Control of Concrete Mixtures, 16th Edition,* published by the Portland Cement Association (PCA) is a concise, current reference on the fundamentals of concrete technology and construction, including concrete mix design (Kosmatka and Wilson 2016). American Concrete Institute, Committee 325 (2017) is a standard engineering guide (US practice) on the design and proportioning of concrete mixes for pavements.

[28] A general expression for the proportions of cement, sand and coarse aggregate in a concrete mix is 1 : n : 2n by volume, such as 1:2:4; 1:3:6 and so on (the volume of aggregate is twice that of sand). In UK practice, grades of concrete (M5 to M70) are defined by the strength and composition of the concrete; e.g. a M15 grade concrete represents a mix (M) with a 28- day compressive strength of 15 MPa (2175 psi) and corresponds to a cement- sand - aggregate ratio of 1:2:4.

[29] The water–cement ratio is the ratio of the weight of water to the weight of cement in a concrete mix. A lower ratio implies higher strength and durability but may result in workability problems. The water-cement ratio in a concrete mix typically ranges from 0.4 to 0.6 by weight. For higher-strength concrete, lower ratios are used, along with a plasticizer to increase flowability. Excess water will cause sand and aggregate to segregate from the cement paste.

[30] A concise review of typical concrete admixtures is provided by Rodriguez (2019); the fracture characteristics and flexural capacity of high performance fiber-reinforced concrete are discussed in Denneman et al. (2011, 2012).

[31] For a basic understanding of the properties and uses of cement, see https://www.understanding-cement.com/cembytes-resources-page1832.html

Box 2: Can seawater be used in concrete mixes?

Water is an essential ingredient in any concrete mix. The preference should always be to first and foremost utilize fresh water in concrete mixes if it is easily available – but in many cases in PICs such fresh water is in short supply. For these situations, it is possible to use seawater – with or without additives. Many public works departments in PICs have firsthand experience with seawater use in concrete out of necessity (for example, nearly all concrete seawall protection structures in Kiribati have been built using seawater). Wegian (2010) found that concrete made with the seawater may have a higher early strength than normal concrete and the reduction in strength with age can be compensated by reducing the water–cement ratio. In their review of the use of sea-sand and seawater in concrete, Xiao et al. (2017) found that both seawater and sea-sand can affect the workability of concrete, but this effect is influenced by the seashell content in the sea-sand. Also, the initial and final setting times of seawater concrete were shorter than those of ordinary concrete. They further observed that both sea-sand and seawater are likely to accelerate the strength development of concrete during early stages due to the rich chloride content in seawater and sea-sand. Concrete made with sea-sand and/or seawater has a significantly higher 7-day compressive strength, a comparable 28-day compressive strength and a similar long-term compressive strength to ordinary concrete. Younis et al. (2018) noted that using seawater in concrete mixtures had almost no effect on the density, yield, and air content of the fresh concrete. However, a reduction in workability was observed due to a significantly reduced slump. They also confirmed the earlier findings regarding the effect of seawater on workability and the change in the strength of hardened concrete over time but noted that the workability and strength loss may be mitigated by the use of chemical admixtures (retarders and superplasticizers). In the foregoing studies, different concrete mixes were prepared with fresh water and seawater, testing for a variety of combinations of cement content, type of cement, aggregate type (including sea-sand) and chemical additives. Road authorities in PICs should undertake comparable experiments using local laboratories to determine the effect of seawater on concrete properties under local conditions to determine appropriate specifications for the use of seawater in concrete pavements.

It goes without saying that the use of seawater in concrete mix immediately rules out the option of steel-fiber reinforcement, and also means that additional consideration needs to be made to ensure that equipment used in construction are appropriate for exposure to seawater and will not rapidly deteriorate. However, geocell, concrete block and RCC pavements in particular can likely be reliably constructed with seawater.

5.1. Coarse aggregate requirements

38. Generally, the requirements for coarse aggregates include (i) durability, (ii) cleanliness, (iii) good abrasion and skid resistance and (iv) workable shape and texture. Generally, uncrushed coarse aggregate makes a concrete with a lower strength than one with crushed angular aggregate. Crushed aggregates can be tested for appropriateness using particle size distribution. Angular particles are generally better for strength, whilst rounded particles are better for workability- a trade-off that the engineer needs to be cognizant of. Engineers should investigate appropriateness of locally available igneous and coronus[32] rock, alluvial gravel and sand, and submerged coral for concrete construction. To the extent possible (especially for World Bank financed projects) use of beach coral and sand should be avoided due to sustainability issues and impact on coastal erosion.

5.2. Fine aggregate requirements

39. Generally, the requirements for fine aggregates are that they are free from deleterious contaminants, particularly organic material, silt and clay, and that the grading is consistent with the grading of the fine aggregate used for the design mix. Concrete can be made from fine aggregates with a wide range of particle size distributions, but a large percentage of fines is detrimental. Sand with rounded particles is essential to facilitate workability; crusher sand is harsh and does not place easily. Some ocean sands in PICs have been known to have chemical issues that limit their suitability for road construction.
40. Alkali-aggregate reaction could lead to significant premature damage to concrete so sand and aggregates for Portland cement concretes should be selected to preempt such durability problems.[33]

5.3. Materials available

41. There are six main material types that can be used for concrete aggregates in PICs:
    - Igneous (volcanic) rock
    - Coronus
    - Beach coral[34]
    - Submerged coral[35]
    - Beach sand
    - Alluvial sand/gravel
42. In addition, recycled plastic pellets could provide a sustainable source of concrete aggregate in the future (see Box 3).
43. Atoll countries (Kiribati, RMI[36], Tuvalu) only have the option of using beach sand, beach coral and submerged coral for construction, whilst all other PICs typically have a wider range of material types present on their islands. This section briefly overviews the properties of the materials and considerations for use in concrete. Given the variability in material properties from site to site, it is recommended that the engineer do laboratory testing for all extraction sites used.

[32] Uplifted, decomposed or weathered coral found on land away from the beach. Also spelt as coronous.
[33] *Alkali–aggregate reaction* refers to a chemical reaction which occurs over time in concrete between the highly alkaline cement paste and non-crystalline silicon dioxide, which is found in many common aggregates. It causes expansion of the altered aggregate, leading to spalling and loss of strength of the concrete. The alkali–silica reaction (ASR) is the most common form of alkali–aggregate reaction. Proactive avoidance of ASR is reviewed at: https://www.engr.psu.edu/ce/courses/ce584/concrete/library/chemical/asrproact.html
[34] Lagoon sediments, incomplete material from associated reef. Also referred to as cascajo.
[35] Live or dead material from either fringing, barrier or atoll reef formation. Only used in exceptional circumstances.
[36] Republic of the Marshall Islands.

Igneous (volcanic) rock

44. On some islands igneous rocks are available, occasionally within a matrix of volcanic tuff and residual soils. In a moisture surplus region basic igneous rocks are prone to weathering, even in a pavement. Weathered basalt or andesite must not be used as untreated pavement layers in sealed roads, as clay may be formed which would result in early distress. Weathered basalt may contain smectite as a clay, and this expansive clay is known to cause early distress in Portland cement concrete.

Strengths[37]

- Can be found almost everywhere within 10 km of the construction site on volcanic islands
- Can be sieved manually or with equipment (sieve, crusher, etc.)
- Often a better environmental option (compared to beach/alluvial sand and gravel)

Weaknesses

- Angular particles will reduce workability and may require more paste (cement)
- May weather and produce smectite which is an expansive clay and affects the concrete durability

Coronus

45. Coronus covers a wide range of diverse materials, including moderately hard limestone, weathered and decomposed limestone with highly plastic fines, and aggregations of loose coral debris uplifted and only partly weathered. Coronus can usually be easily excavated without the use of explosives. A detailed review of locally available coronus materials is provided in *Road Pavement Design for the Pacific Region* (PRIF 2016). Although coral-derived materials have been successfully used for pavement construction in the past, traditional engineering tests have generally indicated that it is a substandard product, and material from most pits does not pass typical “traditional” specification tests for gravel as well as chip sealed bituminous roads. Hard angular coronus material is required for use in concrete, and during the mix design process the strength of concrete with these aggregates must be confirmed. Low strength in the field would result in durability problems, and the concrete layer may break up.

Strengths

- Except in low-lying atoll islands, can be found almost everywhere within 10 km of the construction site
- Can be sieved manually or with equipment (sieve or crusher)
- Often a better environmental option (compared to beach/alluvial sand and river run gravel)
- Angular particles, if hard, contribute to interlocking strength

Weaknesses

- Fairly weak particles which without crushing may remain as irregular shaped aggregates and weaken the concrete
- Must be well washed to remove the fines adhering to the gravel (not with seawater if used in steel reinforced concrete)
- Angular particles will reduce workability and may require more cement

Beach coral / sand

46. In PICs beach coral is sometimes used as an aggregate. Beach coral can vary from coarse sand to weak coral debris to larger pieces of hard coral that can be crushed to provide limestone aggregates. In atoll countries, beach coral is the predominant source of aggregate. Beach mining is regarded as environmentally damaging,

[37] Strengths and weaknesses for igneous rock are adapted from government of Vanuatu Public Works Department (2014).

so the World Bank does not support its use. Studies in South Tarawa (Kiribati) and elsewhere have highlighted the causal link between the coastal mining of aggregate and the increased threat of erosion and flooding in coastal communities (Webb 2005; Webb 2006; Worliczek 2010). Beach coral should be used as an aggregate only when no other aggregate sources away from the beach are available; this should be done in collaboration with the relevant environmental protection agency to ensure appropriate sites are selected.

Strengths

- Easily accessible and prepared

Weaknesses

- Contributes to coastal erosion

Submerged coral

47. In some specific cases submerged coral is used as a least-harm aggregate option. For example, on South Tarawa, Kiribati, with no coronus or igneous options, widespread beach mining was contributing to serious coastal erosion. To combat this, a project[38] was established with financial support from a development partner to permit offshore extraction of aggregate materials from the lagoon for 50 years.

Strengths

- Can be a least-harm alternative to beach coral mining

Weaknesses

- Environmental impacts

Alluvial sand/gravel

48. This material is loose, normally clean and often rounded.

Strengths

- Easily accessible and prepared

Weaknesses

- Can contribute to erosion
- Alluvial gravel has a rounded shape which may need crushing and /or higher cement content to achieve the desired concrete strength

Box 3: Plastic pellets – a potential sustainable concrete aggregate of the future?

Recent innovative research globally has found that non-recyclable plastics, when processed into plastic pellets, can be an effective substitute for traditional concrete aggregates (Cembureau 2018). The vast amounts of plastic drifting in some regions of the Pacific, plus the plastic produced domestically, could potentially be sources of material for concrete aggregate that would otherwise continue to cause damage to the environment and cost to government. The use of plastic pellets for aggregate would of course require the development of a financially sustainable supply chain and processing industry, which is currently not in place. However, this does not detract from the potential opportunity, and the business case for plastic pellet aggregate in PICs is worthy of further detailed investigation.

[38] Environmentally Safe Aggregates Tarawa (ESAT) project, supported by the European Union. Reports containing lessons learned available online; http://gsd.spc.int/geologymineralshydrocarbons/esatproject

6. Design, construction and maintenance considerations

49. This chapter describes the practical considerations with implementing the four pavement technologies. Section 6.1 contains links to specific design guides and detailed resources that the reader can consult in parallel with reading the chapter, or bookmark for future reference. Section 6.2 is a snapshot comparison of design, construction and maintenance considerations for the concrete pavements. This is then followed by a more substantive walkthrough of each pavement type individually (sections 6.3-6.6). The following steps are covered:

DESIGN

Step 1) Determine drainage approach
Step 2) Understand subgrade properties
Step 3) Design thickness of concrete layer and layer works (if required)
Step 4) Determine mix material proportions
Step 5) Choose joint spacing (if applicable)
Step 6) Design edge supports
Step 7) Adjust design for steep terrain

CONSTRUCTION

Step 8) Site preparation
Step 9) Transporting materials
Step 10) Batching
Step 11) Mixing
Step 12) Laying and compacting
Step 13) Levelling
Step 14) Surface texturing
Step 15) Curing

MAINTENANCE

Step 16) Routine maintenance requirements
Step 17) Periodic maintenance requirements

6.1. Recommended resources for review

50. It is recommended that whilst reading this chapter the reader should review the following resources, for detailed, well tested guidance. Most of the resources are freely available via the hyperlinks or internet search.

	Recommended Resources
Jointed concrete pavement	• Austroads 2017, *Guide to Pavement Technology Part 2: Pavement Structural Design*. Accessible at: https://www.onlinepublications.austroads.com.au/items/AGPT02-17 • American Concrete Institute Committee 325 2002, *Guide for Design of Jointed Concrete Pavements for Streets and Local Roads*, ACI Report 325.12R-02, American Concrete Institute, Farmington Hills, MI. Accessible at: http://civilwares.free.fr/ACI/MCP04/32512r_02.PDF • Indian Roads Congress 2014, *Guidelines for design and construction of cement concrete pavements for low-volume roads,* IRC:SP:62-2014, New Delhi. (Includes an excel file tailored for low-volume road structural design). Accessible at : https://archive.org/details/govlawircy2014sp62 • FHWA 2001—2010, *Pavement Preservation Checklist Series (#6,7,8,9,10)*. Accessible at: https://www.fhwa.dot.gov/pavement/preservation/ppcl00.cfm • FHWA 2012, *Field Reference Manual for Quality Concrete Pavements* . Publication No. FHWA-HIF-13-059 September 2012. Accessible at https://www.fhwa.dot.gov/pavement/concrete/pubs/hif13059.pdf • FHWA 2014, *Distress Identification Manual for the Long-Term Pavement Performance Program (Fifth Revised Edition;* Chapter 2. Accessible at: https://highways.dot.gov/sites/fhwa.dot.gov/files/docs/research/long-term-pavement-performance/products/1401/distress-identification-manual-13092.pdf • FHWA 2017, Tech Brief: Bases and subbases for concrete pavements, FHWA-HIF-16-005 Aug 2017. Accessible at: • https://www.fhwa.dot.gov/pavement/concrete/pubs/hif16005.pdf • Missouri Department of Transportation 2017, *Concrete Repair Best Practices: A Series of Case Studies* . Accessible at: https://library.modot.mo.gov/RDT/reports/TR201618/cmr17-013.pdf • NCHRP 1975*, PCC Pavements for Low Volume Roads and City Streets*, Synthesis 27, Transportation Research Board, Washington D.C . Accessible at: http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_syn_27.pdf • Pavement Interactive, *Free on-line knowledge for the paving industry*. Accessible at https://www.pavementinteractive.org/reference-desk/ (Note: this is a comprehensive resource for all aspects of concrete pavements from design to asset management) • Perrie, B 1998, *Low-volume concrete roads*, Cement and Concrete Institute, Midrand, South Africa . • Smith ,K & Harrington, D 2014, *Concrete Pavement Preservation Guide*. Accessible at: https://www.fhwa.dot.gov/pavement/concrete/pubs/hif14004.pdf • US Department of Defense 2014, *Standard Practice for Concrete Pavements,* United Facilities Criteria, Report UFC 3-250-04. Accessible at: https://www.wbdg.org/FFC/DOD/UFC/ufc_3_250_04_2004_c2.pdf • Wehbe, N., Reid, R., Mahgoub, H., Stripling, J., Postma Edgar, B& Underberg, M 2018, *Jointed Plain Concrete Pavement Design and Construction Review*, Report MPC 18-364 , Mountains Plains Consortium, Brooking, South Dakota., USA. Accessible at: https://www.ugpti.org/resources/reports/downloads/mpc18-364.pdf

Block paving

- British Standards Institution 2001, *Pavements constructed with clay, natural stone or concrete pavers: Guide for the structural design of heavy duty pavements constructed of clay pavers or precast concrete paving blocks*, BS7533-1:2001. Accessible at: https://shop.bsigroup.com/ProductDetail/?pid=000000000019997088
- Concrete Manufacturers Association 2008a, *Concrete block paving: Book 1 – Introduction* , Midrand. Accessible at: http://www.cma.org.za/Portals/0/Docs/paving/cma_concrete_block_paving_book_1_content.pdf?ver=2014-04-21-170831-513
- Concrete Manufacturers Association 2008b, *Concrete block paving: Book 2 – Design Aspects*, Midrand. Accessible at: http://www.cma.org.za/Portals/0/Docs/paving/book21.pdf?ver=2014-04-21-170924-193
- Concrete Manufacturers Association 2008c, *Concrete block paving: Book 3 – Specifications and installations*, Midrand. Accessible at: http://www.cma.org.za/Portals/0/Docs/paving/cma_book_3.pdf?ver=2014-04-21-170851-793
- Concrete Manufacturers Association 2008d, *Concrete block paving: Book 4 – Site management and laying*, Midrand. Accessible at: http://www.cma.org.za/Portals/0/Docs/paving/cma_book_4.pdf?ver=2014-04-21-170840-577
- Concrete Manufacturers Association 2008e, *Concrete block paving: Book 5 – Training manual,* Midrand. Accessible at: http://www.cma.org.za/Portals/0/Docs/paving/book_5_compressed.pdf?ver=2014-04-21-170918-390
- Concrete Masonry Association of Australia 2014, *PA02 Concrete Segmental Pavements – Design Guide for Residential Accessways and Roads*. Accessible at https://cmaa.blob.core.windows.net/media/1021/pa02-concrete-segmental-pavements-design-guide-for-residential-accessways-and-roads.pdf
- Indian Roads Congress 2018, Guidelines for the use of interlocking concrete block pavement, IRC:SP:63-2018, New Delhi.
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Geocell concrete

Thin (0.2mm) geocell plastic formwork

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- Visser, A. T & Hall, S 2003, Innovative and cost effective solutions for roads in rural areas and difficult terrain, Transportation Research Record No. 1819, vol. 1, pp. 169-173, Washington D.C. Accessible at: https://www.researchgate.net/publication/245560620_Innovative_and_Cost-Effective_Solutions_for_Roads_in_Rural_Areas_and_Difficult_Terrain
- Whalley, O 2016, Geocells for Affordable Low-volume Pavements, Technical and Scientific Papers ,2nd IRF Asia Regional Congress & Exhibition, Kuala Lumpur, Malaysia, 16 – 20 October, pp. 289-295. Accessible at: https://www.road.or.jp/international/pdf/20170215_ronbun.pdf

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6.2. All pavements

51. This section is a snapshot comparison of design, construction and maintenance considerations for the concrete pavements

<table>
<tr><th>JCP</th><th>BLOCK PAVING</th><th>GEOCELL</th><th>RCC</th></tr>
<tr><td colspan="4">DESIGN</td></tr>
<tr><td colspan="4"><u>Step 1. Determine drainage approach</u></td></tr>
<tr><td colspan="4">All pavement types can be built with side drains or v-drain (as needed); however, thin plastic geocell formwork concrete is likely to perform best due to being waterproof, with no joints through which water can pass.</td></tr>
<tr><td colspan="4"><u>Step 2. Understand subgrade properties</u></td></tr>
<tr><td colspan="4">If CBR > 5, uniform support and soil not prone to pumping, and if traffic pavement lifetime traffic volume is < 1 million ESAs[39], then typically all concrete pavements can be constructed directly on subgrade. If subgrade has CBR < 5, then stabilization (cement, lime, emulsion, other) and/or replacement of subgrade will be required. For JCP a well-draining/non-erodible subbase layer is required above a weak or poorly draining subgrade.</td></tr>
<tr><td colspan="4"><u>Step 3. Design thickness of concrete and layer works (if required)</u></td></tr>
<tr><td>• Many international design manuals available, see section 6.1 resources
• Can be with/without dowels[40]
• Can be with/without reinforcing[41]
• Subbase normally required[42]</td><td>• Design method must consider block shape, thickness and pattern placement, see section 6.1 resources</td><td><u>Thin (0.2 mm) geocell plastic formwork</u>
• Refer to guidance manual Whalley, O (2016) in section 6.1 for methodology of one leading supplier

<u>Thick (>20 mm) geocell plastic formwork</u>
• Refer to guidance manual National Rural Roads Development Agency n.d in section 6.1 for methodology used in India</td><td>• Many international design manuals available, see section 6.1 resources</td></tr>
<tr><td colspan="4"><u>Step 4. Determine mix material proportions</u></td></tr>
<tr><td>• Many international design manuals available, see section 6.1 resources</td><td>• Contact brick/block manufacturers in region to learn required mix for block pavers
• See Section 6.1 resources</td><td>• See section 6.1 resources for thin and thick geocell plastics respectively. Both thickness types can use high slump and grouted concrete mixes, whilst only thick geocell concrete can utilize typical concrete mix consistency</td><td>• Many international design manuals available, see section 6.1 resources
• Mix has very low water content</td></tr>
<tr><td colspan="4"><u>Step 5. Choose joint spacing</u></td></tr>
<tr><td>• Critical. Refer to design manuals noted above</td><td>• Joints are between block pavers</td><td>• No joints</td><td>• Cracks naturally occurring, no joints</td></tr>
</table>

[39] Equivalent Standard Axles, which is based on a Single Axle Dual Tire exhibiting a force of 80kN. Also known as Equivalent Single Axle Load (ESAL).
[40] Normally recommend no dowels. Details covered in section 6.3.
[41] Normally recommend no reinforcing. Details covered in section 6.3.
[42] Especially with heavy truck loads and weak subgrade soils to avoid pavement slab pumping.

JCP	BLOCK PAVING	GEOCELL	RCC
Step 6. Design edge supports			
• Slab widening or concrete curbs may be required to prevent damage from excessive edge/corner loadings	• Edge constraints are critical	*Thin (0.2 mm) geocell plastic formwork* • Can be tucked in at edges to protect from edge loading[43] *Thick (>20 mm) geocell plastic formwork* • Edge constraints are required. Plastic is too thick and cannot be bent to tuck in	• No edge constraints required
Step 7. Adjust design for steep terrain			
• Direction of paving should be up the hill • Low slump concrete to prevent downhill creep of plastic concrete • Panel anchors and blocks may be needed (especially at bottom of the grade) for vertical gradients exceeding 6%	• Transverse beams required	• Slab to be anchored	• No anchoring required

CONSTRUCTION

JCP / BLOCK PAVING	GEOCELL	RCC
Step 8. Site preparation		
• Compact and level subgrade appropriately. Strengthen any soft spots to acceptable CBR	• Compact and level subgrade appropriately. Strengthen any soft spots to acceptable CBR • Geocell formwork needs to be set precisely. Thick geocell formwork takes much longer to set out than thin since formwork packs are much smaller (approx. 15 m^2) than thin geocell formwork packs (200 m^2) due to the need to join adjacent packs with heat welding and stitching approx. every 300mm	• Compact and level subgrade appropriately. Strengthen any soft spots to acceptable CBR

[43] Further details on methodology in section 6.5 of this report.

JCP	BLOCK PAVING	GEOCELL	RCC
Step 9. Transporting materials			
• Raw materials transported, concrete mixed on site for labor-based construction; for machine-based construction fresh concrete delivered to site by truck or cement mixer	• Pavers to be transported from place of manufacture, which may be on construction site	• Raw materials transported, concrete mixed on site for labor-based construction; for machine-based construction fresh concrete delivered to site by truck or cement mixer	• Fresh concrete transported to site via truck or concrete truck
Step 10. Batching[44]			
• Volume batching on site for labor-based construction; plant batching for machine-based construction	• N/A for block paving	• Volume batching on site for labor-based construction; plant batching for machine-based construction	• Plant batching at specialized RCC batching plant
Step 11. Mixing			
• Using site concrete mixer for labor-based construction; mixed off-site at batching plant for machine-based construction	• N/A for block paving	• Using site concrete mixer / Hippo Roller; mixed off-site at batching plant for machine-based construction	• Mixed offsite at specialized RCC batching plant
Step 12. Laying and compacting			
• Laying with cement trucks or wheelbarrows; compacting with vibrating pokers/rods • For machine-based, laid with paving machine and compacted with vibrator tamper bar screed	• Bedding sand applied first, pavers laid, jointing sand added, pavement compacted	• Laying with cement trucks or wheelbarrows; compaction by plate compactor (grout concrete) or self-compacting (high slump) • For machine-based, laid with paving machine and compacted with vibrator tamper bar screed	• Laying with asphalt-type paver • Compaction by vibrator tamper bar screed, then heavy vibratory roller
Step 13. Levelling			
• Straightedge is used	• Done in compacting step	• Straightedge is used, very important concrete must not overtop plastic formwork[45]	• Done in compacting step
Step 14. Surface texturing			
• Manual or mechanical broom	• N/A for block paving	• Manual or mechanical broom	• Texture will remain rough

[44] More remote areas will require mixing concrete onsite. Roads to be constructed in or nearby sizable towns may have established ready-mix plants supporting the building industry that can be used to reduce the unit cost of concrete, as well as ensure quality control. For significant road projects the establishment of a concrete batching plant close to the construction site may be justified.

[45] Discussed in detail in section 6.5.

JCP	BLOCK PAVING	GEOCELL	RCC
Step 15. Curing			
• Curing compounds and application of wet hessian for 7 days minimum	• N/A for block paving	• Curing compounds and application of wet hessian for minimum 3 days[46]	• Curing compounds and application of wet hessian

MAINTENANCE

In additional to appropriate routine and periodic maintenance methodology, all pavements require the following to be in place for sustainable maintenance: (i) as built records of pavement and surfacing, (ii) suitably financed and resourced asset management program, (iii) asset monitoring procedures and (iv) a database of deterioration and maintenance undertaken. Refer to section 8 of Cook et.al., 2013 for detailed guidance.

Step 16. Routine maintenance requirements

All pavement types will benefit from vegetation clearing from sides of road.

JCP	BLOCK PAVING	GEOCELL	RCC
• Regular joint and crack re-sealing	• Re-sanding of joints	• None	• None

Step 17. Periodic maintenance requirements

Very limited periodic maintenance is expected to be required for all options if pavements are constructed per design and specification. However, given below are some typical pavement distress issues[47] that can arise, requiring non-scheduled periodic interventions.

JCP	BLOCK PAVING	GEOCELL	RCC
• Restoring edge support • Mud- jacking or undersealing of a slab that has been subjected to pumping action for an extended period • Patching of areas with extensive D (durability) - cracking, map cracking and scaling, corner breaks • Regrinding of spalled joints • Slab or slab section replacement on account of blow-ups, severe slab faulting, or corrosion	• Re-establishing damaged/misaligned pavers • Restoring edge support	• Remove damaged geocell/s, new cells poured • Restoring edge support	• None

[46] Or once the minimum strength of 15 MPa is reached. There may be minor wear when opened to traffic.

[47] For a catalog of distress and damage in JCP, see FHWA 2014; and for block paving see ICPI 2007.

6.3. Jointed concrete pavement

52. This five-page section is a summary of the minimum factors that the engineer should be considering at each step of the process. The aim is to provide enough information to pilot a concrete paving program utilizing jointed concrete pavement. Refer to section 6.1 **Recommended Resources** for further detail.

DESIGN

STEP 1. ***Determine drainage approach***	• **Drainage is the dominant factor affecting the performance of low-volume roads in the Pacific Islands.** Roads typically fail due to inadequate drainage, resulting in undercutting and ingress of water into the pavement structure which weakens the road and makes it much more sensitive to heavy traffic loading. Drainage should be the first and foremost consideration when designing a concrete pavement for a specific site, not an afterthought. • For JCPs, conventional side drain/s or an integrated curb and gutter are commonly used to manage water runoff and provide lateral support to the pavement.
STEP 2. ***Understand subgrade properties***	• **Uniform support is more important than high subgrade strength.** Concrete can distribute loads more evenly across areas of the subgrade due to its rigidity, which means that a concrete pavement does not require as strong a subgrade as an equivalent bituminous pavement. The important consideration with subgrade is that support is uniform under the concrete. Distress in the concrete pavement may occur if there is an abrupt change in moisture conditions and subgrade support. To be avoided are subgrades that are known to be highly sensitive to moisture change (expansive) or tend to mud-pump. Dynamic Cone Penetration (DCP) tests should be conducted at multiple points along the route to determine subgrade support at ruling moisture content. The frequency of DCP tests will depend on the engineer's knowledge of variation in the soil and geological conditions along the route.
STEP 3. ***Design thickness of concrete and layer works (if required)***	• **Layer works required?** Layer works should be defined based on an understanding of the current and future traffic volume for the road section, as well the subgrade strength and soil permeability. Passenger cars typically cause little or no distress to concrete pavements. Pavement stress comes in the form of truck usage, temperature gradients, moisture changes and shrinkage. Illegal overloading due to ineffective axle weight enforcement is a common occurrence in PIC and this should be considered by the engineer. Similarly, the engineer should consider whether there is a chance that logging and/or mining vehicles may legally or illegally use the road in the future. Since concrete roads are chosen specifically for their longer design life, it is important that the engineer considers future loading to minimize risk of early failure. • **Subbase required?** If the structural design process finds that subbase layer is required, the sub-base should prevent mud-pumping, allow for drainage and provide uniform support. A minimum thickness of 100 mm is recommended in American Concrete Institute Committee 325 (2013). ERA (2013) recommends a minimum thickness of 150 mm. The subbase, however, does not contribute significantly to load-bearing capacity. Indian Roads Congress (2014) section 3 is a good reference which compares the subbase options for different traffic volumes ranging from less than 50 to up to 450 commercial vehicles per day. Refer to the *Recommended Resources* in section 6.1. • **Reinforcing steel/polymer fibers?** For low-volume roads the addition of polymer fibers or steel reinforcement <u>is not regarded as necessary</u>. Steel reinforcing cannot address cracking caused by nonuniform subgrade support; it is provided to control thermal cracking in longer slabs. Polymer fibers will control cracking but not stop it. Material properties including strength vary with the source and type of polymer fiber and this should be considered by the engineer. • **Concrete thickness.** For low-volume roads, thickness of 150mm is normally appropriate. Possible design methods include Indian Roads Congress (2014), AASHTO (1998, 2015), Canadian Portland Cement Association (1984) and Austroads (2017). See section 6.1 *Recommended Resources.*

STEP 4. ***Determine mix material proportions***	• **The *Recommended Resources* list provide detailed direction on mix material requirements.** Well – graded coarse and fine aggregates typically account for 60 to 75% of the concrete mixture by volume. A typical water-to-cement ratio is 0.40 to 0.45, which makes a cement paste wet enough to thoroughly coat the aggregate particles and fill spaces between the particles (Harrington et. al. 2010). The strength of the concrete must be an absolute minimum of 20 MPa. Mix properties should be confirmed by laboratory trial mixtures. Review the *Recommended Resources* list for detailed guidance on mix proportioning.
STEP 5. ***Choose joint spacing***	• **Joints are provided to control cracking and are essential for JCP durability.** Joints for JCP can be of four types including (i) contraction joints, (ii) construction joints, (iii) expansion joints and (iv) longitudinal joints. Periodic maintenance of joint sealing is essential. The role of joint sealant is to minimize surface water penetration into the subbase/subgrade. With almost all regions within PICs experiencing heavy and/or regular rainfall, joint sealing is an essential activity. Joints should be sealed with polymer modified bitumen, silicone sealants or similar. Section 4.7 of American Concrete Institute Committee (2002) has a useful table of possible sealants and links to specifications. Useful for reference are section 13 of Perrie (1998) and NCHRP (1975) which provide many diagrams illustrating different joint layouts. • **Contraction joints.** Contraction joints have spacing varying from 3.5 – 7 m depending on the manual referred to and pavement thickness. The purpose of a contraction joint is to control cracking cause by shrinkage tensile stress that exceeds the early tensile strength of the concrete (American Concrete Institute Committee 2002). To be formed by concrete saw cutting within 24 hours of casting, or by wet forming (Indian Roads Congress 2014; Perrie 1998). • **Construction joints.** Construction joints divide the pavement into suitable lengths and widths for construction purposes. Joints should be 2 – 5 mm wide. Construction joints are provided whenever work is suspended for more than 90 minutes or when day's work is completed (Indian Roads Congress 2014). • **Expansion joints**. Expansion joints are required when abutting bridges and culverts. • **Longitudinal joints.** Longitudinal joints are required for two-lane low-volume roads to control longitudinal cracking. A spacing of 4 – 5 m is appropriate (American Concrete Institute Committee 2002). Joints are usually keyed in and tie bars will need to be used where the road is not edge constrained. • **Are dowels required?** Dowels can be used for load transfer, or alternatively if no dowels are used then load transfer occurs through aggregate interlock. Generally low-volume pavement designs do not require dowels (American Concrete Institute Committee 325. 2002; Cook et. al. 2013; Thom 2008). • **Impact of reinforcing on joint spacing**. Steel reinforcing will increase the distance between contraction joints. Polymer fibers will have no effect on joint spacing.
STEP 6. ***Design edge supports***	• **Design supports for expected heavy vehicles on slab edge.** For low-volume roads, the aim of the engineer is typically to design the minimum width road that can safely provide for the traffic volume at the lowest cost possible. The edges of the pavement need to be appropriately designed such that if heavy vehicles drive on the edge (when vehicles are passing for example) it does not cause failure. Deflections due to wheel loads are larger at the corner causing displacement of weaker subgrade resulting in loss of support under repeated loading and consequent corner breaking. Pavement edges also need to be designed to give appropriate protection from stormwater which could otherwise erode subgrade support to the concrete pavement. One approach is to increase the slab width by 0.3- 0.5 m so that heavy wheel loads are not applied at or close to the slab edge and /or corner. The extended slab width may result in a slight decrease in slab thickness. Another approach is to provide a thickened slab edge at critical sections (such as steep slopes).
STEP 7. ***Adjust design for steep terrain***	• **Concrete slabs should be anchored to avoid movement.** Perrie (1998) recommends provision of blocks (thickened lateral edges) if grade > 3% and anchors for steeper grades but the engineer should refer to preferred manual from the *Recommended Resources*. In general, such blocks and anchors may only be needed at grades exceeding 6% if a structurally adequate subbase is used and mostly at the bottom end of the slope.

CONSTRUCTION (LABOR-BASED)[48]

STEP 8. ***Site preparation***	• Compact and level subgrade appropriately. Strengthen any soft spots to acceptable CBR.
STEP 9. ***Transporting materials***	• **Transporting raw materials to site can be highly challenging**. Be aware of all appropriate nearby locations to extract and prepare (e.g. crush, wash, etc.) coarse and fine aggregates. • Transporting and placing fresh concrete can lead to segregation of the constituents, which negates efforts made to produce a consistent mix. The most common causes of segregation are (i) the mix being too workable, (ii) vibration or jolting during transport, (iii) 'sieving' through congested reinforcement, and (iv) falling from a height. Since concrete is almost always mixed directly on site in PICs, transportation is unlikely to be an important consideration. Contemporary JCP designs utilize plain slabs with no steel reinforcement.
STEP 10. ***Batching***	• Batching by volume is the typical method for low-volume roads in PICs and is achieved using a wooden or metal measuring box. <u>Measuring with shovel counts is not acceptable</u>. Weight batching is the most reliable method for achieving consistency. • **Water/cement ratio**. One of the most important quality parameters (as discussed in step 4) is the strength of the concrete. This is proportional to the water/cement ratio, so the weight or volume of water added to each mix must be controlled carefully. Moisture content of the fine aggregate must be monitored, especially during wet periods. • **Workability.** Another quality parameter is workability (or 'slump' from the slump test for measuring workability). Concrete must be workable to ease placing and compaction. Concrete that is too stiff will be difficult to compact and concrete that is too workable is more prone to segregation and will almost certainly lack strength when hardened and cured. Workability is proportional to water content thus mixes can be made more workable by adding water. This is bad practice however, as adding water increases the water cement ratio and reduces the strength of the hardened concrete.
STEP 11. ***Mixing***	• **All concrete mix constituents must be thoroughly mixed to give a uniform material when placed.** Ready mix plants are generally not sufficiently close to sites where low-volume concrete roads are being constructed so cannot be considered as a mixing option. The most common and reliable method is to mix by machine on site with a diesel power mixer. Depending on the production target, determine the minimum size mixer, or vice versa. Mixing by hand using shovels and wheelbarrows occurs in outer islands of PICs where labor is cheap, and machinery is expensive. However, this method is much less reliable for producing a uniform mix.
STEP 12. ***Laying and compacting***	• **Formwork.** Formwork should be oiled or wetted so it is damp when concrete is poured. Formwork should not be removed for 24 hours. The formwork should provide a key (tongue and groove) along the longitudinal joint between slabs, and at lateral joints on steep slopes. • **Lay quickly and consistently**. The chemical reactions that create the process of concrete setting start as soon as the cement and water are mixed together. The rate at which concrete sets is dependent on the water/cement ratio and temperature and, to a lesser extent, other constituents in the concrete. The stronger the mix (which means the lower the water/cement ratio) and the higher the temperature, the faster the concrete sets. Thus, concrete should be placed and compacted as quickly as possible after mixing. Placing and spreading is done with wheelbarrows and shovels. If laying on a permeable base or direct subgrade, the base/subgrade should be sprinkled with water so that water in the concrete mix is not drained out of the concrete. When placed, concrete contains air and if allowed to solidify may honeycomb with the concrete suffering from loss of strength, lack of durability and porosity. Concrete already placed should not be allowed to take an initial set before more concrete is added. Concrete that has already set creates a 'cold joint' where two adjacent mixes are not properly bonded together. Cold joints are sources of weakness, porosity and future cracking in the concrete.

[48] For machine-based construction, refer to Perrie 1998; and NCHRP 1975 in *Section 6.1 Recommended Resources* for further detail.

STEP 12. ***Laying and compacting*** *(continued)*	• **Alternating slabs method.** In PICs an alternating slab method is appropriate. This is when a slab of concrete is laid, compacted and finished, the next slab is missed, then the next is laid, between stop-ends. A single panel must be poured and finished within 90 minutes maximum. After 4 – 7 days the intermediate slabs are filled in. • **Compaction is achieved using two possible methods:** (i) vibrating pokers and (ii) steel rods/wooden dowels. With (i) *vibrating pokers*, these are immersed in the plastic concrete until the air no longer bubbles up to the surface. Further guidance is given in this footnote ([49]). In *(ii)*, steel rods or wooden dowels are vigorously inserted into and removed from the fresh concrete with tamping.[50]
STEP 13. ***Levelling***	• Using a straightedge beam is a suitable approach for levelling JCP.
STEP 14. ***Surface texturing***	• Manual or mechanical broom finish.
STEP 15. ***Curing***	• **Curing is the process of maintaining appropriate water/cement content.** Concrete strength and durability are dependent on the chemical reaction between cement and water. To develop full strength, the water mixed into the concrete must be retained in the mix. Water is lost from the surface of the concrete by evaporation and in hot and/or dry and/or windy weather evaporation reduces the amount of water available for the chemical reaction, leading to loss of strength (paradoxically) and surface cracking. This can be particularly serious for thin slabs with a high ratio of surface area to volume. The simplest way to cure concrete is to keep it damp. Water is applied once the concrete has hardened sufficiently for it not to be damaged by the water. Water can be sprayed on or applied to wet fabric laid on the concrete (hessian or sacking is a popular fabric for this) or applied to wet sand laid on top of the concrete after hardening. Alternatively, or in addition, curing compounds can be applied to the pavement surface. • Formwork should not be removed until at least 12 hours have passed since the concrete pour (Indian Roads Congress 2014).

MAINTENANCE

STEP 16. ***Routine maintenance requirements***	• **Typical routine maintenance.** Regular joint sealing is required to prevent water entry into the layers below the slab. • **Typical equipment requirements.** Including but not limited to: (i) 3-ton truck, (ii) crack sealing squeegees, (iii) sealant pouring jars and (iv) concrete cutter.
STEP 17. ***Periodic maintenance requirements***	• Periodic maintenance is not expected to be required if pavement constructed per design and specification. As noted in section 6.2, **typical failure modes include**: cracking (corner breaks, longitudinal cracking, transverse cracking, D-cracking), joint deficiencies (seal damage, mud pumping), surface defects (scaling, polished aggregates) and shoulder erosion (FHWA 2014). • **Further resources.** Refer to Smith et.al. 2014 for the comprehensive United States Department of Transport Federal Highway Administration *Concrete Pavement Preservation Guide* which contains detailed advice on responding to multiple defect types.

[49] The area of influence of vibrating pokers is limited, so they must be immersed to the bottom of the section and through into any previously placed concrete below or to the side. They must be withdrawn and replaced in different parts of the mix frequently. This ensures that as much of the air as possible is removed.
[50] This is only effective for thin slabs (<200 mm thickness).

6.4. Concrete block paving

53. This three-page section is a summary of the minimum factors that the engineer should be considering at each step of the process. Its aim is to provide enough information to pilot a paving program using concrete block pavers. Refer to section 6.1 **Recommended Resources** for further detail.

DESIGN

STEP 1. ***Determine drainage approach***	• Designing the road as a v-drain is not appropriate for block paving in PICs as it is likely that appropriate maintenance to jointing sand will not occur. For steep sections, block paving should be supplemented with lined drains.
STEP 2. ***Understand subgrade properties***	• If the CBR < 5 then, depending on the road profile and drainage, there may be need for a granular or cement bound bedding layer (subbase) to max thickness of 200mm, as a function of type and volume of traffic (Muzira & Diaz 2014; Sharma et. al 2009).
STEP 3. ***Design thickness of concrete and layer works (if required)***	• **There are multiple structural design methods for concrete block pavin**g including (i) Equivalent thickness concept, (ii) Catalogue design method, (iii) Research-based design methods, and (iv) Mechanistic design method such as Lockpave. These design methods include guidance on sub-layer requirements. Concrete Manufacturers Association 2008b has an excellent summary of these methods, beginning pg. 5. • **Block shapes and thicknesses.** There are many different shapes and thicknesses of blocks, and patterns of laying them. Blocks for low-volume roads typically range from 80-100 mm thick. Blocks should be interlocking on all side faces, and herringbone is likely to preferred pattern in most circumstances. Blocks should have a minimum compressive strength of 20 MPa, and preferably 25 MPa (Concrete Manufacturers Association 2008b) although splitting tensile strength is now used, as it is independent of the aspect ratio. If pavers are being manufactured on site, then quality control will be an important challenge.
STEP 4. ***Determine mix material proportions***	• **Contact brick/block manufacturers in the region to find the appropriate material mix for block pavers.** The raw materials of concrete blocks are typically cement, fine aggregates, coarse aggregates, filler, and water.
STEP 5. ***Choose joint spacing (if applicable)***	• **Joints between blocks are a key weakness of concrete block pavers.** The joint width should be between 2 – 5 mm. It is important that the blocks are not in direct contact as room needs to be left for the jointing sand to bond the blocks. Routine maintenance by adding new jointing sand is essential.
STEP 6. ***Design edge supports***	• **Concrete curb or edge beam is needed on both sides to lock block pavers in and ensure that sand bed materials do not wash away.** This is very important. Failure to provide an appropriate edge constraint will create excessive maintenance and reduce the life of the pavement.
STEP 7. ***Adjust design for steep terrain***	• **Transverse cordons/beams essential to stop pavers from sliding downhill.** Transverse cordons/beams should be installed every 30m to lock the pavers in. In situ concrete curbs 100 mm wide can be used effectively as anchor beams approximately every 30 m to lock pavers in (although this will depend on the gradient of the road , typically >4%). 25 mm holes must be provided at the level of the bedding sand to permit water to flow through, in cases where no provision has been made for water to exit as it permeates into the bedding sand layer. • **Binding/jointing sand losses.** On steep slopes the binding sand is washed out by water flowing over the road. This can be addressed by stronger camber, using interlocking blocks, adding a polymer stabilizer to the sand (not cement) and laying the blocks in a pattern that guides the water to the sides/drain and breaks the flow of water at the joints (e.g. herringbone).

CONSTRUCTION

STEP 8. ***Site preparation***	• **Compact and level subgrade appropriately**. Strengthen any soft spots to acceptable CBR. The bedding sand layer should not be used to make up for irregularities in the subgrade as water that enters through the joints will permeate into the bedding sand. • Sand and blocks should be stockpiled conveniently.
STEP 9. ***Transporting materials***	• Bedding sand should be transported to site, stockpiled, then screeded. Care must be taken that the screed sand is not compacted locally by walking or pushing wheelbarrows over it. • **Block pavers will need to be transported from place of manufacture.** Paving units should be placed as close as possible to work site. When transporting using a wheelbarrow, stack the blocks so they are easier to unload.
STEP 10. ***Batching***	• Not applicable for block paving.
STEP 11. ***Mixing***	• Not applicable for block paving.
STEP 12. ***Laying and compacting***	• **Establish bedding sand layer.** A layer of bedding sand 25 mm +/- 10 mm is placed and levelled in accordance with the design camber. The South African Concrete Manufacturers Association (2008d) recommends that the grading of the sand should follow *Table 1* to the right. Note that it is a coarse sand to allow for drainage. Check lines and levels are correct. • **Sand screeding.** The sand can be screed using screeding rails or 25 mm water pipes. Workers should not be allowed to walk on the screeded sand. If this occurs, then remove compacted material and fill the depressions with sand and re-screed. • **Laying methodology.** Block paving should be done working uphill. Two rows of blocks in the centerline are placed first to act as a guidance for the placement of the rest of the blocks. Blocks are placed from the centerline to the side following the camber. Depending on the pattern to be used, a specific sequence is followed in adding additional blocks, working from the center outwards while sitting on already placed blocks. On slopes the blocks are laid from bottom to top. New blocks are hand tamped against laid blocks using rubber hammers. The blocks should stand proud of the edge constraints by 5 – 10 mm to allow for settlement that will occur. Spacing between blocks should be 2 – 5 mm. • **Laying blocks against edge constraints.** Blocks will need to be cut to fit the spaces up against the edge constraints. The use of in situ concrete for fillings gaps is strictly not recommended. Trimmed blocks should not be less than one-third of a block as small pieces are easily dislodged, and double cuts may be necessary. • **Adding jointing sand and compacting.** After laying all the blocks, a plate vibrator is used to further tamp them in place. Jointing sand is added on the brick, swept into the joints using a broom and then plate compacted two or three times. Do not use a bedding sand as jointing sand as this is often too coarse (Concrete Manufacturers Association 2008). For road sections where regular significant sheet flow is expected, the engineer may consider reducing the permeability of the joints through the addition of a special polymer stabilizer, lime or clay. Do not use cement as the shrinkage opens the joint and prevents interlock. • **Multi-day paving.** When paving over multiple days, ensure that pavers are compacted up to the hold point, and use a plastic sheet to cover exposed bedding sand to shield for overnight downpour. Sand and pavers should be kept as dry as possible. Pedestrian and vehicle movements should be restricted until the paving is completed.

Sieve size, mm	% passing
9.25	100
4.75	95 - 100
2.36	80 - 100
1.18	50 - 85
0.500	25 - 60
0.300	10 - 30
0.150	5 - 15
0.075	0 - 10

Table 1 Recommended grading of bedding sand (Concrete Manufacturers Association 2008d).

STEP 12. ***Laying and compacting*** *(continued)*	• **Review *Recommended Resources*.** Concrete Manufacturers Association 2008c has an excellent table of recommended checks and permissible degrees of accuracy on pg. 10, as well as extensive range of template CAD drawings for different circumstances starting from pg. 12. • **Future of block laying – paving machines?** A developing innovation in the block paving space are the block paving machines which are reported to "print" roads at rates greater than 300 m^2 per day. The paving machines are loaded with the block pavers in the required interlocking patterns and these pavers are lowered down onto the ground by the machine as it rolls forward. The machines can lay roads up to 6 m wide and cost US$100,000 and upwards to purchase. Videos of such paving machines in action can be found on YouTube.
STEP 13. ***Levelling***	• To be done as part of compacting.
STEP 14. ***Surface texturing***	• Not applicable for block paving.
STEP 15. ***Curing***	• Not applicable for block paving.

MAINTENANCE

STEP 16. ***Routine maintenance requirements***	• **Re-sanding of the joints when there is evidence of sand loss.** Activity would also include the removal of any vegetation or organic material from the joints. The contractor should re-sand during the maintenance period as it takes time for the interlock to establish and jointing sand is still loose. Some studies have reported that joint re-sanding should be done every 2 years (Ministry of Transport Vietnam 2009). • **Other periodic maintenance** can include the removal of any vegetation or organic material from the joints. • **Typical equipment requirements.** Including but not limited to: (i) 3-ton truck[51], (ii) wheelbarrow, (iii) herbicide spray equipment and block cutter.
STEP 17. ***Periodic maintenance requirements***	• **Re-establishing damaged/misaligned pavers.** Block pavers are simply removed, the affected area is re-stabilized and re-compacted, and a new sand bed is placed with the block pavers following on top. Activity can also involve (i) repairs to the shoulders where necessary and (ii) repairs to edge beams where necessary. In their 2017 Ghana study, Anochie-Boateng et al. found that interlocking concrete paving blocks could be maintained (removal and replacement of damaged blocks) at 10 years and thereafter every five years at about 5% of initial construction cost (about USD $5.7/m²).

[51] Only if new pavers need to be laid.

6.5. Geocell concrete

54. This five-page section is a summary of the minimum factors that the engineer should be considering at each step of the process. The aim is to provide enough information to pilot the use of geocell concrete pavement (using either thin or thick geocell plastic formwork). Refer to section 6.1 **Recommended Resources** for further detail.

DESIGN

STEP 1.
Determine drainage approach

- Since the thin geocell formwork is only 0.2 mm thick, the hairline cracks between blocks are only a fraction of a millimeter. Consequently, this means that roads made using thin geocell formwork can confidently be used as a drain if required (option top left in *Figure 4*). Roads built using thick geocell formwork can also be used as a drain but will likely not be as durable and will have additional maintenance needs since the larger gaps between cells will allow for some water ingress.

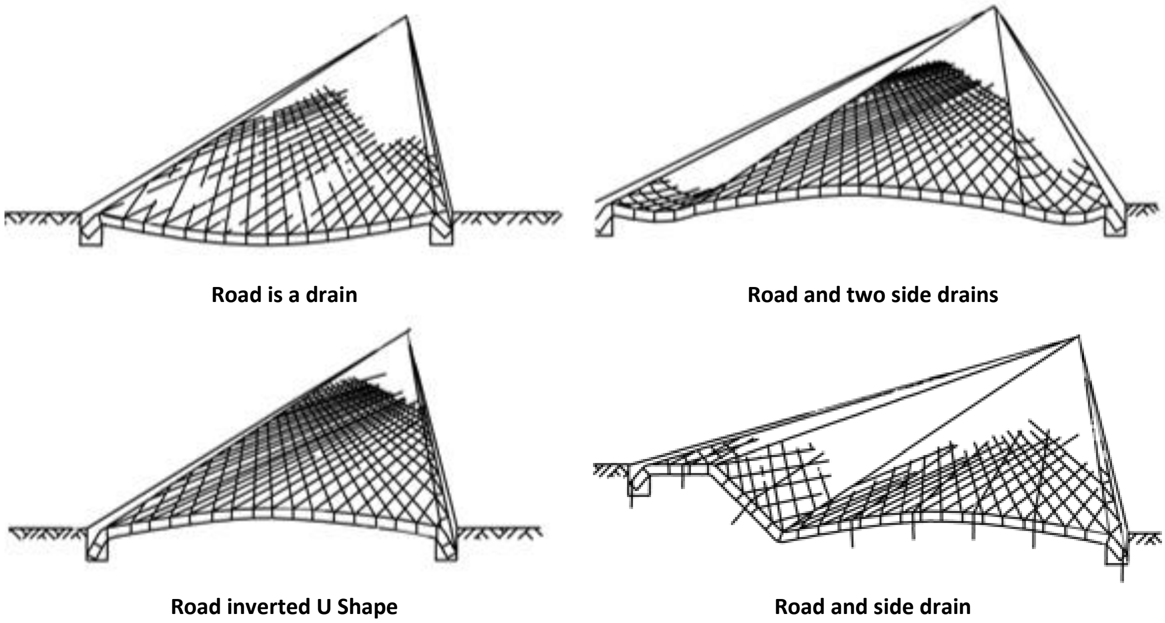

Figure 4 Various configurations of geocell concrete to manage drainage (Hall, n.d.).

STEP 2.
Understand subgrade properties

- For low-volume roads with CBR >5, the geocell concrete can be placed directly on the subgrade for low-volume roads. If CBR <5, then base course and possibly subbase need to be added. Refer to most applicable national pavement design manual.

STEP 3.
Design thickness of concrete and layer works (if required)

- **Typically, a geocell concrete thickness of 75 – 100 mm is appropriate.** Geocell concrete typically does not need to be as thick as JCP slabs due to efficient load transfer between blocks and no bending moments.
- **Design methodology.** A summary of the methodologies to design concrete pavements utilizing both thin and thick geocell formwork is given below.

Thin (0.2 mm) geocell plastic formwork

- Refer to Whalley (2016) for detailed step by step guidance. The design methodology is very simple as it only requires two points of data that are easy to acquire even in very low-resource environments. In essence, the method estimates the design thickness of the geocell pavement based on the (i) expected traffic in Equivalent Standard Axles (ESA) over the design life of the pavement (yearly traffic from traffic counts plus expected growth) and (ii) the stiffness of the subgrade (estimated from in-situ CBR recorded on site using a DCP. Importantly, if the subgrade CBR is > 5, then this method recommends that the concrete pavement can be built directly on subgrade with no subbase required.

STEP 3.
Design thickness of concrete and layer works (if required) *(continued)*

Thick (>20 mm) geocell plastic formwork

- Refer to National Rural Roads Development Agency (n.d) for detailed step by step guidance. In this method, a 75 mm or 100 mm concrete thickness is assumed and then the subbase thickness is determined based on the known ESA and CBR of the subgrade. Importantly, this method recommends that a minimum of 100 mm of subbase should always be added regardless of the CBR of the subgrade, which will lead to additional cost compared with the thin geocell plastic formwork approach.

STEP 4.
Determine mix material proportions

Thin (0.2 mm) geocell plastic formwork

- There are three possible mixes that can be used with thin geocell plastic formwork: (i) high slump ready-mix concrete (often with additives such as plasticizers), (ii) on-site high slump concrete and (iii) grouted sand/cement slurry. "Typical" JCP concrete mix with a slump of 50 mm cannot be used as it cannot be placed into the cells. A high slump (120 to 150 mm) is required and this is achieved by using a plasticizer, not more water which will reduce strength. A minimum strength of 20MPa is required.

Thick (>20 mm) geocell plastic formwork

- Thick geocell plastic formwork can use concrete mixes (i-iii) as for thin geocell plastic formwork, however it is also possible for typical JCP concrete mix with a slump of 30-50 mm to be used because the thicker cells are stiff enough to deform when being filled unlike thin geocell plastic formwork. Indian national guidelines for cement concrete mix design are recommended, with a target concrete strength of 30 MPa.

STEP 5.
Choose joint spacing (if applicable)

- **Not applicable as geocells do not have joints.** For both thin and thick geocell plastic formwork, geocell concrete blocks transfer load like interlocking block pavement through physical shear transfer, but the gap between cells is < 0.2 mm which is too small to attract the issues that typical block paving joint widths of 3 to 5 mm attract.

STEP 6.
Design edge supports

- Thin geocell formwork is flexible and can allow for a "tuck-in" termination edge beam to accommodate potential undercutting edge damage. The geocell plastic can be manipulated to "tuck in" into a trench that is typically about 100 mm below the depth of the geocell concrete slab.[52] See *Figure 5* for an example of tucking the edges in. Thick geocell formwork is rigid and does not allow for edge tuck in, and instead the geocell must be confined by stone/concrete (precast or in-situ) blocks or edge beams.

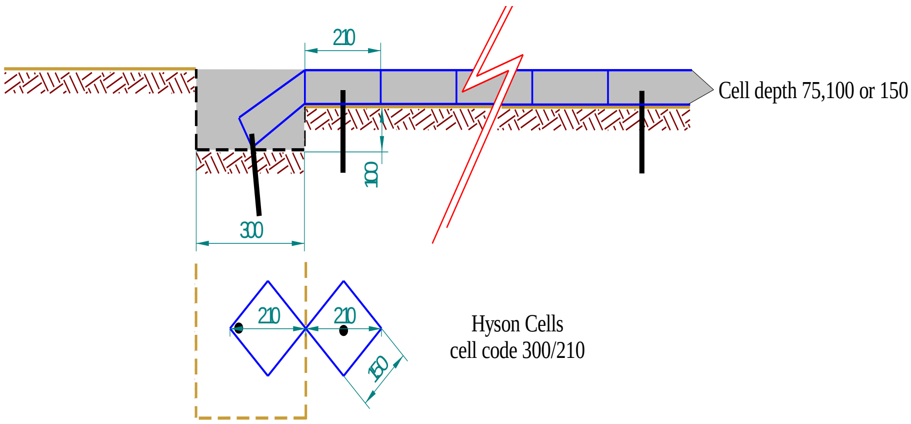

Figure 5 Example of tucking the edges in (Hall, n.d.).

STEP 7.
Adjust design for steep terrain

On steep slopes it is recommended that 200 mm by 200 mm deep keys slot be cut into the underlying subgrade (or layer works, if present) across the width of the road and cast with the geocell concrete slab at regular intervals. The purpose of these keys is to prevent slippage of the slab and the potential formation of drainage paths underneath the slabs. The spacing of the keys would depend on local circumstances, but in general 50 m is the maximum spacing.

[52] The "tuck-in" may need to be much deeper if significant running water is expected.

CONSTRUCTION

STEP 8. ***Site preparation***	*Thin (0.2 mm) geocell plastic formwork* • Compact and level subgrade appropriately. Strengthen any soft spots to acceptable CBR by replacing. The setout of the geocell plastic formwork is critical to the whole construction and must be done with finer quality control than typical JCP construction. The sacrificial geocell formwork is durable and can be stood on and will spring back to position, although this is not recommended. Once the plastic cells are stretched, they must be pulled very taut with supplied rigging. If rigging is not used the cells will collapse and this is a situation that cannot be rectified. The section will need to be cleared and started again from scratch. If the cells are not securely fixed to the underlying material, then the geocell plastic will tend to "float" on the poured concrete. A continuous slab of concrete will pool beneath the cell formwork. The cell matrix now ceases to perform its function of dividing the slab into discrete interlocking blocks. Curing shrinkage no longer results in controlled cracks of only a few microns. Instead, the slab formed from the pool concrete will result in uncontrolled cracking at its weakest point. These cracks may be millimeters wide. They will also probably propagate through the slab to the surface. Fines may now be allowed to pump from the underlying material and surface water will penetrate to destroy the underlying layer work. • **Joining two plastic geocell formworks**. Geocell plastic formwork is easily cut with a knife or scissors and joined on site. Joining two geocell formworks is a simple pinning exercise using the galvanized pins supplied and tying the rigging. It is important that the cell formworks are joined to each other and not simply positioned next to each other without joining. If the mats are not joined, then uncontrolled cracking will take place at some place on the concrete beam formed between the two geocell formworks. The final surface will mirror the underlying earthworks which must be carefully controlled. *Thick (>20 mm) geocell plastic formwork* • Thick geocell formwork takes much longer to set out than thin since formwork packs are much smaller (approx. 15 m^2) than thin geocell formwork packs (200 m^2) due to the need to join adjacent packs with heat welding and stitching approx. every 300 mm.
STEP 9. ***Transporting materials***	• **Transporting raw materials to site can be highly challenging**. Be aware of all appropriate nearby locations to extract and prepare (e.g. crush, wash, etc.) coarse and fine aggregates. For site-mixed high slump concrete and grout filled concrete**,** the concrete is mixed on site with labor so no fresh concrete to be transported. • **For the ready-mix plant approach** (only applicable in urban areas, if at all), normal precautions with transporting ready-mix concrete should be taken.
STEP 10. ***Batching***	• For site-mixed normal / high slump concrete and grout-filled concrete, volume measuring using measuring box is adequate. • For ready-mix normal / high slump concrete, this is batched at the ready-mix plant.
STEP 11. ***Mixing***	• **Site-mixed normal / high slump concrete** is mixed using concrete mixer (size of mixer will determine daily production, or vice versa). • **In grout-filled concrete mix**, the 19 or 26 mm single sized aggregate is first placed inside the plastic geocells, so it is only the sand-cement slurry that needs to be mixed. This can be achieved with wheelbarrows, or by mixing with a 90-litre plastic drum with a cap on the one end and a pulling handle.[53]
STEP 12. ***Laying and compacting***	*Reminder: normal slump concrete cannot be used with thin geocell plastic formwork as the formwork will deform irreparably.* • **On-site labor-mixed normal / high slump concrete** is poured onto formwork using wheelbarrows. High slump mix is self-compacting due to plasticizer and requires minimal compaction whilst normal slump will require more compaction. The geocell plastic serves as sacrificial formwork and the plastic cell barrier means that it is not possible for cold joints to develop between adjacent concrete pours.

[53] This is sold as a commercial product called a Hippo. The Hippo is used in some villages in South Africa to fetch water. By rolling the Hippo with water, cement and sand in the correct proportions a thorough mix is achieved, which is then poured onto the aggregate layer.

STEP 12. ***Laying and compacting*** *(continued)*	• **Grout-filled concrete** is poured from wheelbarrow or *Hippo* roller and should be compacted and vibrated into the voids with a plate vibrator. • **In ready-mix normal / high slump approach**, concrete is poured into geocell formwork directly from ready-mix truck. • **For all concrete mixes, special care needs to be taken for steep slopes to avoid step formation.** This could involve placing a stiffer mix by hand on the surface during the finishing operation or delaying the finishing operation until the initial set has taken place.
STEP 13. ***Levelling***	• **For grout-filled concrete,** the finish of the concrete is highly dependent on the evenness of the compacted coarse aggregate in the process where the grout is added after the stone is placed. It is strongly recommended that a straight edge be used to ensure evenness, as the grout is ineffective in taking out depressions, or to smooth over stones that are standing proud. • **For all concrete mixes,** care must be taken to ensure that the concrete does not overtop the geocell formwork, as this can lead to cracking, spalling and chipping of this thin top layer. High slump concrete mixes may form steps on steep gradients, but this is rectified by floating the surface after the initial set.
STEP 14. ***Surface texturing***	• Brooming is preferred for all mix designs, and can be manual or mechanical.
STEP 15. ***Curing***	• Should be cured following same methodology as JCP pavements are cured (see section 6.3).

MAINTENANCE

STEP 16. ***Routine maintenance requirements***	• No routine maintenance required except for vegetation clearing from sides of road.
STEP 17. ***Periodic maintenance requirements***	• In the event of damage to the geocell concrete and the likelihood of potholes, the damaged section is removed by pick or jack hammer up to the sound area bounded by the geocells. If needed the underlying layers are repaired. New geocells are stitched onto the existing cells and refilled with fresh high slump concrete or grouted concrete prepared by hand. • **Typical equipment requirements.** Including but not limited to: (i) 3-ton truck and raw materials[54], (ii) pick / jackhammer, (iii) wheelbarrow and (iv) plate compactor.

[54] For pouring replacement geocells.

6.6. Roller compacted concrete

55. This three-page section is a summary of the minimum factors that the engineer should be considering at each step of the process. The aim is to provide enough information to pilot the use of roller compacted concrete pavement. Refer to section 6.1 **Recommended Resources** for further detail.

DESIGN

STEP 1. ***Determining drainage approach***	• RCC can be formed such that the water drains down the center of the road. However, typically storm runoff is cambered to lined drains that are constructed on one or both sides of the pavements.
STEP 2. ***Understand subgrade properties***	• RCC pavements are usually placed directly on the subgrade of low-volume roads, only a top layer of organic soil is eliminated when necessary.
STEP 3. ***Design thickness of concrete and layer works (if required)***	• For detailed advice on multiple competing structural design approaches including worked examples, see section 5 of Harrington et. al. 2010 in the *Recommended Resources* section.
STEP 4. ***Determine mix material proportions***	• **Typical mix proportions**. RCC contains the same ingredients as JCP concrete, but they are used in different proportions. Dense – and well-graded coarse and fine aggregates typically comprise 75 to 85 % of RCC mixtures by volume. RCC mixtures are drier than conventional concrete due to their higher fines content and lower cement and water contents. The water content would typically be at the optimum moisture content using laboratory compaction tests. Water/cement ratio is typically in the range of 0.48 to 0.55 (Harrington et. al. 2010). Admixtures can be used to improve workability and increase transport and placement time. • **For detailed advice on mixture proportioning,** including aggregate gradation bands and examples from numerous projects, see section 4 of Harrington et. al. 2010. In summary, the mixture proportioning process includes the following steps: (i) select well-graded aggregates, (ii) select cement (iii) determine max dry density, (iv) determine optimum moisture content, (v) test specimens and select required cement content and finally (vi) calculate mixture proportions.
STEP 5. ***Choose joint spacing (if applicable)***	• **Joints are not usually sawed in RCC.** When sawing is not specified, random transverse cracks appear 4.6 m to 6.1 m apart and are normally tight, enabling load transfer through aggregate interlock. If sawed joints are specified and they are greater than 6.4 mm width, they will need to be sealed (Harrington et. al. 2010).
STEP 6. ***Design edge supports***	• **No edge supports in standard design.** This lack of lateral constraint results in some reduction in the degree of compaction obtained alongside the pavement. Edge slumping and poor consolidation at the pavement edge can be an issue.

STEP 7. ***Adjust design for steep terrain***	• Direction of paving should be uphill. RCC is a stiff pavement and has rough non-erodible interface with the subgrade/subbase, so not likely to move or slip. • Panel anchors and blocks may be needed at bottom of the grade for vertical gradients exceeding 9%.

CONSTRUCTION

Section 8 of Harrington et. al. 2010 has a construction troubleshooting table which lists over 15 possible problems and root causes. This is essential reading.

STEP 8. ***Site preparation***	• Compact and level subgrade appropriately. Strengthen any soft spots to obtain acceptable CBR strength.
STEP 9. ***Transporting material***	• **Concrete transport.** Concrete needs to be transported in trucks, which means that distance from plant to site cannot be long. The low water content of RCC increases the potential for segregation to occur. Trucks need to be covered by tarps or similar covering to avoid moisture loss. They need to be cleaned after each delivery to ensure older RCC does not end up mixed in with new RCC. • **Maximum transport time**. Harrington et. al. (2010) recommends that transportation time should be kept to a maximum of 45 minutes when ambient temperatures are 27 degrees Celsius. In PICs the time period would be even shorter as ambient temperatures tend to be higher than this for much of the workday. With the use of additives, the hauling and placement times can be significantly increased.
STEP 10. ***Batching***	• **Weight batching preferred.** Although in the literature RCC has historically been produced onsite in easily transportable twin-shaft pugmill mixers that can be set up in one day by two to three workers and generate 300 to 800 tons per hour, recent literature strongly emphasizes a weight batching approach that happens at offsite plant to ensure effective quality control. This also permits the use of admixtures to produce a pavement comparable to JCP in surface finish and serviceability. RCC mixtures can be efficiently produced off-site in a continuous or batch fashion by using horizontal twin-shaft mixers that are inserted directly below batch plants. The batching plant must have the required power rating to mix the stiff mix and capacity to fill a truck within 10 minutes to avoid problems with placing and compaction. • **Zero slump.** RCC mixtures have zero slump, any slump in the mixture is too much.
STEP 11. ***Mixing***	• **Mixing occurs at the batching plant**. The mixture has the consistency of damp, dense-graded aggregates. RCC's relatively dry and stiff (zero slump) mixture is not fluid enough to be manipulated by traditional concrete paving machines.
STEP 12. ***Laying and compacting***	• **RCC can be placed with purposed built mixing and paving plant.** When laid with a paver, compaction is achieved with vibratory tamper bar screeds (preferably two), with the addition of static or vibratory rollers. Pavers produce concrete of 90-96% target density, and productivity is estimated at 2 – 3 meters/minute (FHWA 2016). • **Roller compaction.** Rolling typically consists of initial compaction with a 10 – 12-ton vibratory roller compaction (4 – 6 passes) and then finished rolling with a 3 – 6-ton roller which can be dual steel or rubber tired (FHWA 2016). Final compaction is typically achieved within one hour of mixing. Diagrams of roller patterns are available in section 7 of Harrington et. al. 2010. • **Cement/water content ratio is critical and sensitive.** Due to low-water content, RCC paving has low margin for error regarding water loss to evaporation. Similarly, the subgrade and any layering must be uniformly moist at the time of placement to prevent moisture being taken away from the RCC.
STEP 13. ***Levelling***	• This is achieved in the *compaction* activity.
STEP 14. ***Surface texturing***	• **RCC pavement typically has a texture similar to asphalt.** Admixtures can be added that allow for a broom finish. Diamond grinding is also used in United States, but this is almost certainly not possible for low-volume roads in PICs.

STEP 15. ***Curing***	• **Curing must occur as soon as possible after final compaction.** A concrete curing compound is recommended over water moisture curing as the latter requires many applications for at least seven days. Water can be sprayed on or applied to wet fabric laid on the concrete (hessian or sacking is a popular fabric for this) or applied to wet sand laid on top of the concrete after hardening.

MAINTENANCE

STEP 16. ***Routine maintenance requirements***	• No routine maintenance required except for vegetation clearing from sides of road.
STEP 17. ***Periodic maintenance requirements***	• **None**. If catastrophic failure of the pavement occurs due to overloading, then this section must be upgraded – it is not a periodic maintenance task. As traffic volumes increase, a bituminous surfacing (asphalt concrete, seal coat or micro-surfacing) could be applied to seal the cracks and obtain a smoother surface.

7. Conclusions

56. The critical pavement design consideration for low-volume roads in PICs is not traffic, but the climatic and terrain conditions. Frequent, intense rainfall and poor drainage pose the biggest challenge to road durability**. Concrete pavements have improved climate resilience relative to bituminous surfacing alternatives in the following ways:**

    - From a climate adaptation standpoint, all four concrete pavement types can handle flooding, steep road gradients, and surface runoff when designed and constructed correctly.
    - Concrete pavements also are more resistant to uplift vapor and air pressure under the pavement caused by sea level rise due to high tides (also called 'sunny day flooding') and storm surges.
    - The construction of concrete pavements (other than RCC) tends to be less energy intensive than bituminous pavements.
    - Due to its higher albedo, concrete pavement absorbs less solar radiation and contributes far less to the urban heat island effect.
    - While concrete pavements have significantly higher GHG emissions compared to the bituminous alternatives, mostly as a function of the amount of clinker in the Portland cement used to produce the concrete, this is being mitigated by substituting clinker with fly ash, bottom ash, slag, pozzolans and other additives. In the broader climate change context, however, concrete pavements in PICs would be a miniscule contributor to GHG emissions.

57. Concrete pavements have other technical advantages:

    - Concrete pavements offer a more robust alternative to bituminous surface dressings in terms of durability (more than double the service life), maintainability and managing truck overloading; their life-cycle costs are competitive with or cheaper than bituminous surfaced pavements.
    - Concrete pavements require much less maintenance than surface dressings, a significant advantage given that maintenance is typically not done well in PICs.
    - Concrete pavements can be constructed using labor-based technologies and small/community-based contractors; three of the four concrete pavement technologies assessed in this study are labor intensive and have the potential to create substantial rural off- farm employment, both skilled and unskilled.
    - Unlike bituminous pavements, under high ambient temperatures, they do not soften, rut or become brittle.

58. The tropical environment in most PICs offers pronounced technical advantages for the use of concrete pavements over other countries. There is relatively small variation in diurnal and annual temperatures so that the provision for thermal strains in the concrete slabs is not of paramount importance and joints may be more widely spaced. The availability of sandy or coralline aggregate subgrades, especially in the atoll islands offer a stable (and often a strong foundation) for concrete pavements.

59. Learning from pilot applications in Kiribati*,* Vanuatu*,* and Tuvalu (its Public Works Department recently built 400m+ of geocell roads with own account labor despite limited prior experience in road construction), it is evident that concrete pavements can be built in PICs with basic equipment and semi-skilled staff. The study concludes that there is substantial scope for the use of concrete pavements in PICs. Four concrete pavement types, namely (i) plain jointed concrete pavement, (ii) concrete block pavement, (iii) geocell concrete pavement, and (iv) roller compacted concrete pavement were assessed including their strengths, weaknesses and operations and maintenance (O&M) requirements. This technology assessment, presented in the form of a concise technical guide, constitutes the core of the study. It represents a synthesis of international practice, drawing primarily on the technical guidelines, standards and pavement engineering practice in Australia, China, India, Nicaragua, and South Africa.

60. The concrete pavement types assessed in this study show good promise for application in the PICs and are deserving of further testing and field trials. Such experimentation should include a range of concrete pavement types (e.g. JCP, block paving, etc.) and area types (flood-prone terrain, steep terrain, urban area, etc.). PIC governments should seek to conduct these trials using their road agencies, while development partners in the region including World Bank and others should make financial and technical support available to governments to support the trials. Lessons learned on design, construction and maintenance, as well as pavement performance and cost should be shared openly with the engineering profession across the Pacific Islands to rapidly build a knowledge base for these promising pavement types.

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