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On Site Improvement of Fines-Rich Unbound Granular Materials with Hydrophobic Polymer and Lime

Cameron Hopkins, Donald Cameron * and Md Mizanur Rahman

UniSA STEM, Scarce Resources and Circular Economy (ScaRCE), University of South Australia, Adelaide, SA 5000, Australia; chopkins@stabilis.com.au (C.H.); mizanur.rahman@unisa.edu.au (M.M.R.)
* Correspondence: donald.cameron@unisa.edu.au

Abstract: Many roads that were initially designed for relatively low traffic volumes need re-surfacing or partial replacement of the unbound granular material to satisfy current traffic demand. Significant research efforts based on laboratory studies have been seen in the literature to characterize the suitability of virgin materials, which is relatively expensive and unsustainable. Therefore, the object of this study is the in situ recycling of existing materials in two road sections by improving their properties with a suitable additive. A hydrophobic synthetic polymer was chosen for two trials due to the high plasticity of fines of the in situ materials and a high chance of water intrusion in the low-lying plains in Adelaide. The extensive laboratory characterization shows that hydrophobicity is imparted in capillary rise tests, improved drainage in permeability tests, and greater matric suction at the same moisture content. Furthermore, the unconfined compressive strength was increased. The repeated loading triaxial testing showed higher stiffness and lowered permanent strain to withstand higher traffic volume. In general, in situ recycling is adaptable and considered to be cheaper and sustainable. The estimated current costs and carbon footprints are presented for re-construction and in situ recycling with dry powder polymer, or solely with lime, to help construction planning.

Keywords: hydrophobic dry powder polymer; unbound granular pavement; capillary rise; permeability; matric suction; repeated load triaxial testing; carbon footprint

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1. Introduction

Australia has a large network of local roads, which has been built at relatively low cost, using materials which do not meet current specifications for major road pavements [1]. Furthermore, these roads were initially designed for relatively low traffic volumes and so many of these roads have a low structural capacity for the increased traffic volumes over time. The annual budget for maintaining roads is usually quite limited [2]. Re-surfacing or partial replacement of the unbound granular material (UGM, also referred to simply as "aggregates") with asphalt is a common but relatively expensive solution. Therefore, innovative solutions are needed to ensure a sustainable and cost-effective road network.

One attractive solution is to re-use the existing pavement material after milling the road base/subbase to the required depth (usually 200 to 250 mm). The existing aggregates are recycled in situ, and the costs of quarrying and transporting replacement aggregates are avoided. The wearing course can either be removed and stockpiled or, in the case of sprayed seals, be incorporated into the aggregates to be re-worked. An additive or stabilizer is spread evenly over the re-worked pavement surface, and then it is intimately mixed using the milling equipment and compacted to provide a reconditioned pavement layer (Figure 1).

Figure 1. Mixer mixing the Polyroad dry powder polymer (DPP) on the lane on the left, and to the right, Polyroad DPP spread on the other lane ready for mixing.

There are a number of additives that can be used, depending upon the quality and composition of the existing aggregates, as well as the road environment, in particular the propensity for the flooding of the road [3]. Additives for UGM include foamed bitumen, bitumen emulsion, cement, lime, and polymers. Polymers can be either hydrophilic or hydrophobic. Hydrophilic polymers absorb water and form a gel, which hardens as water evaporates. Good compaction control and curing are required to achieve the required engineering behaviour for a pavement [4]. Hydrophilic polymers have often been used to protect unsealed roads. Hydrophobic polymers coat aggregated clusters of fine soil particles in the pavement material and repel water, making these additives ideal for the protection of water-susceptible unbound pavement materials, such as clayey gravels [5,6].

In Australia, there are two proprietary forms of each type of polymer, namely, Polycom (hydrophilic) and Polyroad (hydrophobic). Polyroad dry powder polymer (DPP) is an insoluble synthetic polymer produced by Polymix Industries. In its current form, the polymer is mixed with finely ground limestone and forms a fine cationic emulsion after mixing in with the unbound pavement material. The first documented field trial using Polyroad was in 1988 [7]. DPP is spread on the roadbed and mixed into the pavement material. The material is then compacted. Finer soil particles (silt and clay) in the UGM are encapsulated by the polymer [8]. Polycom is a polyacrylimide (abbreviated to PAM) developed by Biocentral Laboratories Ltd. in South Australia fairly recently in 2003 [8]. It is a synthetic soluble copolymer, which when added to water during the compaction process forms an anionic copolymer emulsion [6]. Again, fine soil particles within the pavement material are encapsulated, and as the water evaporates, some bonding is achieved.

The literature on the engineering benefits of Polyroad DPP has been sparse. In contrast, there has been a recent concerted research effort on Polycom from researchers at Swinburne University [4,9–13]. Generally, basic engineering tests have been reported on Polyroad-treated pavement aggregates such as the California Bearing Ratio (CBR), along with experience of subsequent serviceability of treated pavements [6,7]. It should also be noted that these investigations concerned an earlier form of Polyroad DPP, which included fly ash, a product that is no longer available.

The protection from water ingress has been hailed as the major attribute of the two additives. Both proprietary additives have been reported to reduce capillary rise [5,9]. Indeed, a capillary rise test is recommended by suppliers of the additives and consultants to assess the suitability of materials for treatment [7]. The vertical permeability measured in falling head tests was reduced after treatment with Polycom PAM [13]. The possibility of some weak interparticle bonding has been conceded in the past [5,8]. Bonding improves the strength and resilience of pavement materials. However, recorded increases in strength and stiffness appear for Polyroad DPP to be in excess of that expected from weak bonding and the keeping of a relatively dry state. The four-day-soaked CBR testing of untreated and Polyroad treated aggregates [7] indicated that the CBR was at least doubled for all but one sample of the eight tests that were reported. An example was provided in this same paper of the improvement of resilient modulus from testing at the University of Tampere in Finland [7]. A 300% increase in the modulus was observed for specimens at a bulk stress of 200 kPa. Poli [14] reported on the improvement of the resilient behaviour of essentially a stream gravel treated with Polyroad DPP. It was found that permanent strain was reduced, and the resilient modulus of the treated material became insensitive to the initial moisture content of the sample. Similar findings were reported by the authors of this paper in 2016 [15].

Treatment with Polycom has been shown to also provide some engineering improvements. In detailing these improvements in this paper, it needs to be noted that Modified Proctor compaction [16] was deemed to be inadequate as, apparently, the densities did not match “the compaction effort in the field” [13]. So, subsequent laboratory preparation of specimens recommended much higher compaction energy throughout the research conducted into Polycom at Swinburne University, typically 80% more energy for a subbase material. Furthermore, observations made in this paper of the research into Polycom relate to subbase material A, as this material most closely aligns with the UGMs of the current study. The other tested materials B and C could best be described as fill or subgrade, that is, soils that are outside the scope of this paper.

The CBR for four-day-soaked tests on PAM treated and untreated samples were essentially no different at almost 170% [13]. However, an improvement of some 22% was observed when the CBR test was conducted without soaking and after being left for 14 days to air dry. This difference in behaviour has been put down to the need for at least one drying cycle to enable the polymer to activate. Unconfined compressive strength did show a significant increase with PAM treatment (27%) when conducted on specimens that were dried back to 50% of the optimum moisture content (OMC) [9]. Specimens were compacted to maximum dry density (MDD) at OMC then dried back to 50% of OMC and allowed time to equilibrate in accordance with pavement construction practice in Australia [11].

The resilient performance of Polycom PAM treated subbase was investigated with repeated loading triaxial tests [10,11]. The dry-back procedure was used to prepare all specimens after compaction at three different levels above Modified Proctor compaction effort. Generally, permanent strains were lowered with the greatest reduction of permanent strain evident at the higher levels of specimen compaction [11]. The resilient modulus increased by a minimum of 31% [10]. The resilient modulus improvements were more significant at stresses further from potential failure stresses.

In summary, the earlier available literature on the use of a proprietary hydrophobic DPP concentrated mainly on basic engineering properties. The original DPP formulation included fly ash and this formulation is no longer available. Therefore, a knowledge gap exists with respect to the current hydrophobic DPP and its application to improving the engineering properties of UGM bases and subbases. In contrast, the hydrophilic polymer or PAM produced by Polycom has been investigated relatively extensively. Consequently, the objective of this paper is to report an investigation, which began in 2013 to quantify the benefits of pavement treated with the hydrophobic DPP from Polyroad. This paper reports laboratory studies into two Polyroad DPP products, arising from separate field trials on local government roads in the northern suburbs of Adelaide, the capital city of South Australia. Comparisons are made with pavement material A of the Swinburne research effort and the reported benefits of treatment with Polycom, although it is noted that the comparisons are fortuitous and too indirect to make any solid conclusions between the advantages and disadvantages of hydrophilic and hydrophobic polymers.

2. Existing Site Conditions and Implemented Treatments

2.1. Existing Site Conditions

Both roads were constructed in a low-lying coastal area in Adelaide, the capital city of South Australia, and so water ingress and poor drainage was a contributing factor for the choice of road improvement. Water can enter the pavement either by direct infiltration or capillary rise from the adjacent or lower layers. Polyroad DPP treatment of aggregates can potentially protect the pavement from saturation and decrease the capillary rise in the treated material without any decrease in strength.

Diment Rd (site 1) is a two-lane road with kerb and channel to promote drainage. The road consisted of 125–175 mm of granular material, overlain by sprayed seal. The pavement cross-section was quite variable, with respect to the depth and quality of the granular material.

McEvoy Rd (site 2) is a two-lane road with deep swales along its length for drainage of surface water. This road services market gardens and is subsequently in a low-lying irrigated environment. The road had been built up over time to cater for increased traffic loads. The road cross-section consisted of a sprayed seal wearing course over 270 mm (+/−20 mm) of variable granular material. There were distinct layers in the pavement with the first 100 mm thick layer of 20 mm nominal aggregate, contaminated with fines, overlying a 90 mm thick layer of weak aggregate with large misshapen stones (maximum dimension 60 mm). The deepest layer (cca 80 mm thick) consisted of badly degraded 20 mm nominal aggregate. McEvoy Rd had been maintained with patch and fill over recent years, i.e., partial replacement of base with asphalt over badly damaged sections.

2.2. Pavement Treatments

All treatments were recommended by Polyroad Stabilising after a quick evaluation of the pavement materials that were to be treated. Grading limits allow fines contents between a minimum of 10% and a maximum of 30%. The plasticity of the fines dictates the proportion of polymer to lime in the DPP. If the Plastic Index (PI) of the fines is less than 12%, PR.21L (two parts polymer to one part lime) is recommended, otherwise, PR.11L (equal parts polymer and lime) for PI up to 20%. These products are applied at 1.5% to 2% by the dry mass of aggregates. Then, a capillary rise test, similar to that suggested by AS 1289.5.2.1 [17], is conducted to evaluate the suitability of the treatment. A maximum capillary rise of 25% over a 24 h period is deemed acceptable, without any swelling.

Owing to site restraints with service piping at this site, pavement thickness was limited. The design of the road consisted of 200 mm base/subbase material, overlain by 40 mm of hot mix asphalt to provide a design life of 20 years. The subgrade was stabilized to a depth of 200 mm with lime (1.5%), partly to compensate for the limited thickness of the pavement, the low soaked CBR value of the subgrade of just 1% and the anticipated increase of traffic, including heavy truck movements. The trial was conducted over a road length of 0.2 km, with half of this length being treated and the other half constructed without any additive. The treated section had 2% PR11L by dry mass added to the road aggregate. Construction took place in June 2015.

The McEvoy Rd trial was constructed in June 2016. A road length of 0.3 km incorporated DPP treatment with aggregate milled to a depth of 225 mm. The fines content after the milling of the aggregates was 19.5%. For this material, PR21L (2:1 polymer to lime) was applied at the rate of 1.5% by the dry mass of the road aggregate. The wearing course consisted of a sprayed seal.

3. Materials

The hydrophobic DPP was provided by Polyroad Stabilising in Australia. Desirable grading limits as set by Polyroad are indicated on the particle size distribution plots provided in Figure 2 for the existing materials after milling and before treatment. The grading curve for Diment Rd aggregates was slightly below that set by the DPP supplier for particles less than or equal to 2 mm. The McEvoy Rd material sat comfortably between the upper and lower grading boundaries set by Polyroad.

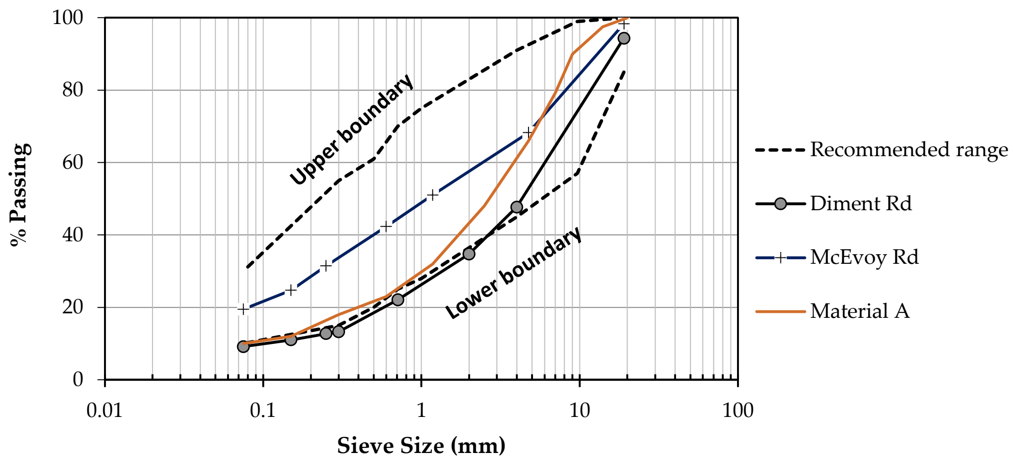

Figure 2. Particle size distributions.

A higher percentage of fines was evident for the material from McEvoy Rd having 20% compared with just 9% for Diment Rd. Moreover, the plasticity of fines was higher (plastic index of 22% and linear shrinkage of 17%, compared with 15% and 12%). Material A from the Swinburne research [13] falls between the grading limits, has a fines content similar to that of the Diment Rd material, but is poorly graded. Moreover, the fines were silt-sized [13] and non-plastic, as seen in the comparison of data in Table 1.

Table 1. Material data.

Soil Property	Diment Rd	McEvoy Rd	Material A
% Fines materials	9	20	10.1
% Clay (<0.002 mm)	–		1.0
Liquid limit (%)	44	55	22.2
Plastic limit (%)	29	33	None
Plasticity Index (%)	15	22	None

The modified Proctor test method [16] was used to determine the optimum moisture content (OMC) and maximum dry density (MDD) for each material before and after treatment. As seen in Table 2, OMC increased and MDD decreased slightly with the addition of Polyroad DPP. However, the hydrophilic polymer caused slight increases in both OMC and MDD when applied to Material A.

Table 2. Modified Proctor compaction values. Note: Material A treated with Polycom and compacted with energy 80% higher than Modified Proctor [13].

Site	Treatment	Max. Dry Density (t/m^3)	Opt. Moisture Content (%)
Diment Rd	untreated	2.15	6.5
	treated	2.135	7.25
McEvoy Rd	untreated	2.09	7.0
	treated	2.08	7.5
Material A	Untreated	2.36	5.4
	Treated	2.38	5.7

4. Methods

Testing included particle size distributions, permeability testing, and Repeated Load Triaxial Testing (RLTT), which is required for the mechanistic design of pavements. Soil Water Characteristic Curves (SWCC) were established for the treated and untreated materials since it has been found that the response of unbound materials and subgrades to repeated loading is dependent upon the moisture state as well as the stress state (e.g., [10,11,15]). The SWCC enables the estimation of matric suction from water content. In the following sections of the paper, moisture related tests, strength tests, and repeated loading stiffness tests have been separated.

4.1. Moisture Related Tests

4.1.1. Capillary Rise

Capillary rise tests were conducted on untreated and treated material from both site locations, post-construction, to check if Polyroad's specifications had been met. The tests were conducted in accordance with AS 5101.5 [17]. Specimens were compacted to maximum dry density using Modified compaction in a 115 mm high and 100 mm diameter mould at 2% dry of OMC.

4.1.2. Falling Head Permeability

The function of the base layer in flexible pavement relates chiefly to strength, but it may need to serve as a drainage layer to discharge unwanted water [18]. To determine the permeability of the aggregates, falling head permeability tests were conducted according to AS 1289.6.7.2 [19]. Specimens were prepared at a constant density of 98% of MDD and at moisture contents equivalent to 80% and 100% of OMC. Pavement materials were compacted in a cylindrical mould of 150 mm diameter and 200 mm in height. Permeability was recorded after the passing of water through the sample equivalent to a minimum of one void volume.

4.1.3. Soil Water Characteristic Curve (SWCC)

The last test relating to water involved the establishment of SWCCs for both treated and untreated pavement aggregates. The SWCC was determined using the filter paper method for measuring matric suction [20] of specimens prepared at OMC to 55% of OMC at a target density ratio of 98% MDD. The filter paper method is applicable for suctions less than 1500 kPa [21].

Each UGM specimen was statically compacted in two stages using a close-fitting plunger. The final height of the specimen was 200 mm by 100 mm in diameter. After extrusion of the specimen, the two halves of the sample were pulled apart and a stack of three air dry filter papers was placed in between the sample halves. A Whatman #42 (90 mm diameter) filter paper was sandwiched between two 100 mm diameter filter papers to make the stack. The determination of matric suction relied on the equilibrated mass of the central filter paper. Thereafter, the specimen was enclosed in a water-tight membrane and then placed in a close-fitting poly-vinyl chloride (PVC) container with PVC caps taped to the ends. The container was stored in a constant temperature room (22 °C) for 10 days before measuring the mass of the Whatman #42 filter paper in the same room. The calibration equation for these filter papers as given in [21] was applied for the estimation of the matric suction. Best fits to the data were applied to achieve the fitting parameters. It was assumed that no swelling occurred, i.e., that dry density stayed constant.

4.2. Strength Tests

4.2.1. California Bearing Ratio (CBR)

CBR tests were conducted on the different aggregates according to AS 1289.6.1.1 [22], which is equivalent to modified Proctor compaction. The specimens were pre-soaked in water for four days before testing to simulate the worst case. Specimens were mixed to a moisture content of 80% of OMC and then compacted to 98% of Maximum Dry Density (MDD). Two CBR tests were conducted on each sample from the two test sites, and the two results were averaged.

4.2.2. Unconfined Compression Strength (UCS)

All specimens were compacted at optimum moisture content by a falling weight hammer to 98% of their respective maximum dry density. Cylindrical test specimens of 105 mm diameter and 115 mm high, were stored in the curing room at a temperature between 21° and 25 °C, and then tested after two days of curing. A deformation rate of 1.2 mm/min was applied in accordance with AS 5101.4 [23].

4.2.3. Consolidated Isotropically and Drained (CID) Triaxial Compression

CID triaxial tests were conducted on the UGMs from Diment Road and McEvoy Road. Drained triaxial testing is required to appraise the field stress state relative to the failure stress state, which is an important component of RLTT modelling for unbound granular materials [24]. CID tests were performed according to AS 1289.6.4.1 [25] to determine the shear strength properties (apparent cohesion, c′, and angle of friction, ϕ′) of the blends. Specimens were tested after saturation and isotropic consolidation. Three specimens of each blend were compacted to 98% of MDD at different levels of moisture content (80% and 100% OMC). For this study, two specimens were tested for each test preparation. Samples of 100 mm in diameter and 200 mm high were compacted by dynamic compaction using a falling weight hammer. Five days of curing occurred before testing. The specimens were subject to three confining pressures of 10, 25, and 50 kPa. Owing to the high shear strength of these granular materials, greater confining pressures could not be considered with the available equipment.

4.3. Repeated Loading Triaxial Test (RLTT)

In order to evaluate the dynamic stiffness, strength, and permanent strain characteristics of the blends, RLTTs were performed on the pavement materials, according to the test method AG:PT/T053 [26]. Specimens were compacted by a falling weight hammer to dimensions of 100 mm in diameter and 200 mm high. In Australia, subbase and base unbound granular pavement material are usually constructed at 80% OMC and 98% modified MDD. Actual dry density ratios of test specimens varied between 98 and 100% at relative moisture contents of 100 and 80% of OMC. Additionally, some specimens were dried back from 100% to 80% OMC, which is a common practice in pavement construction. Specimens were also tested after being treated with the specified lime component from Polyroad, but without the polymer, to provide some guidance on the influence of the lime. The target moisture content for these samples was 80% OMC.

All materials were tested with replicates. After compaction, specimens which were not dried back were sealed and cured for five days before conducting RLTT. However, when drying back, each specimen was sealed on all sides except the top surface to allow dry back to a pre-determined mass. Once the target mass was reached, the specimen was completely sealed to redistribute moisture to a uniform state over five days.

Axial strain was measured using two pairs of inductance coils (Emu coils) attached across the middle third of the specimen. Further details of the Emu coils can be found in Gabr et al. [27]. Generally, resilient moduli cannot be measured sufficiently accurately above 1000 MPa due to the small displacements involved.

Permanent deformation testing was performed in accordance with Austroads [26] at a confining pressure of 50 kPa. Three different deviator stresses (350 kPa, 450 kPa, and finally 550 kPa) were applied over 10,000 cycles in each stage of testing. Austroads permits resilient modulus testing on the same specimen after the permanent strain test, provided that the total permanent strain is less than 80% of the static failure strain (or 1% strain). In addition, the difference between the final and initial resilient strain for each stage must be less than 10%. In subsequent resilient modulus testing, specimens were subjected to 66 different combinations of stresses (or stress stages), with 250 loading repetitions within each stage. The resilient modulus was averaged over the last six load cycles of each stage.

5. Results

5.1. Water Related Tests

5.1.1. Capillary Rise

Results of capillary rise testing are presented in Figure 3. The Diment Rd material showed greater resistance to capillary rise with DPP treatment, particularly over the first 8 h of exposure to water. The untreated McEvoy Rd specimen swelled significantly (6% of the original height) and had reached full capillary rise by 24 h, while the treated material had not reached full capillary rise and did not swell. No other specimen experienced significant swelling. However, erosion was observed for all untreated specimens but was absent in all the treated specimens.

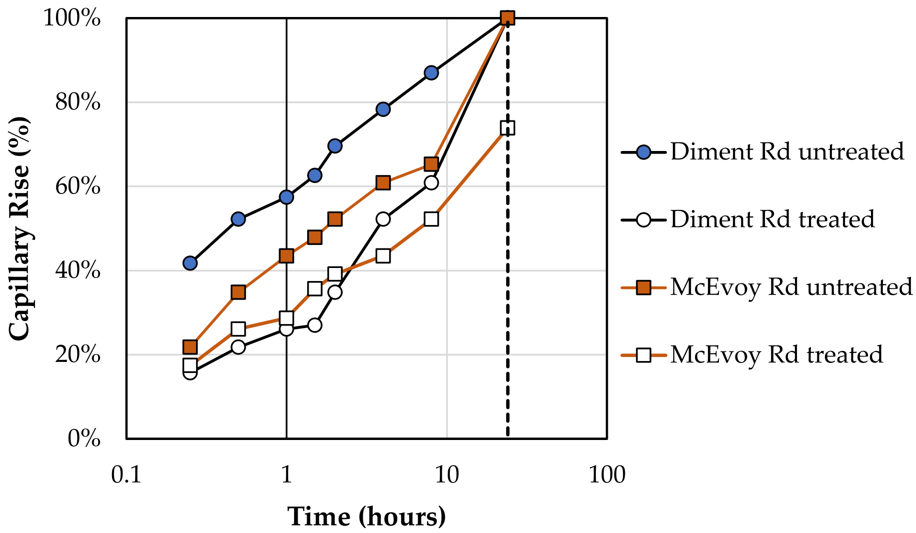

Figure 3. Capillary rise against time (log scale).

5.1.2. Permeability

The results are summarized in Table 3. The USDA ratings of permeability [28] are presented in this same Table. The permeability increased with Polyroad DPP treatment, presumably as a consequence of the imparting of hydrophobicity to coated clusters of fine particles within the UGM and the reduction of porosity due to these clusters. Therefore, it may be stated that materials with plastic fines and treated with Polyroad DPP will drain more readily. In contrast, the permeability of Material A was reduced by about 23% after treatment with PAM [9], although the material was far less permeable ($<10^{-8}$ m/s and rated as very slow either treated or untreated) than either Diment Rd or McEvoy Rd aggregates (cca 10^{-6} m/s and 10^{-5} m/s, respectively).

5.1.3. Soil Water Characteristic Curves

For each of the four geomaterials, an SWCC has been plotted in Figure 4. The SWCC of the untreated McEvoy material was dictated by its relatively high weighted plastic index (wPI) of 4.4, compared with 1.1 for the untreated Diment Rd aggregate, which was controlled more by its grading. Perera et al [28] proposed empirically based equations for predicting SWCC and the curve based on wPI for McEvoy Rd is shown as a dashed line in Figure 4. However, the Diment Rd material data could not be well represented by equations based on either grading or wPI.

Table 3. Measured values of permeability.

Site	Preparation	Treatment	Permeability (m/s)	USDA Rating [29]
Diment Rd	100% OMC	untreated	9.7×10^{-7}	Very slow
	100% OMC	treated	2.7×10^{-6}	Moderately slow
	80% OMC	untreated	6.4×10^{-6}	Moderate
	80% OMC	treated	2.9×10^{-5}	Moderately rapid
McEvoy Rd	100% OMC	untreated	1.7×10^{-5}	Moderately rapid
	100% OMC	treated	8.8×10^{-4}	Very rapid
	80% OMC	untreated	3.8×10^{-6}	Moderately slow
	80% OMC	treated	2.1×10^{-5}	Moderately rapid
Material A	100% OMC	untreated	8.1×10^{-9}	Very slow
	100% OMC	treated	6.2×10^{-9}	Very slow

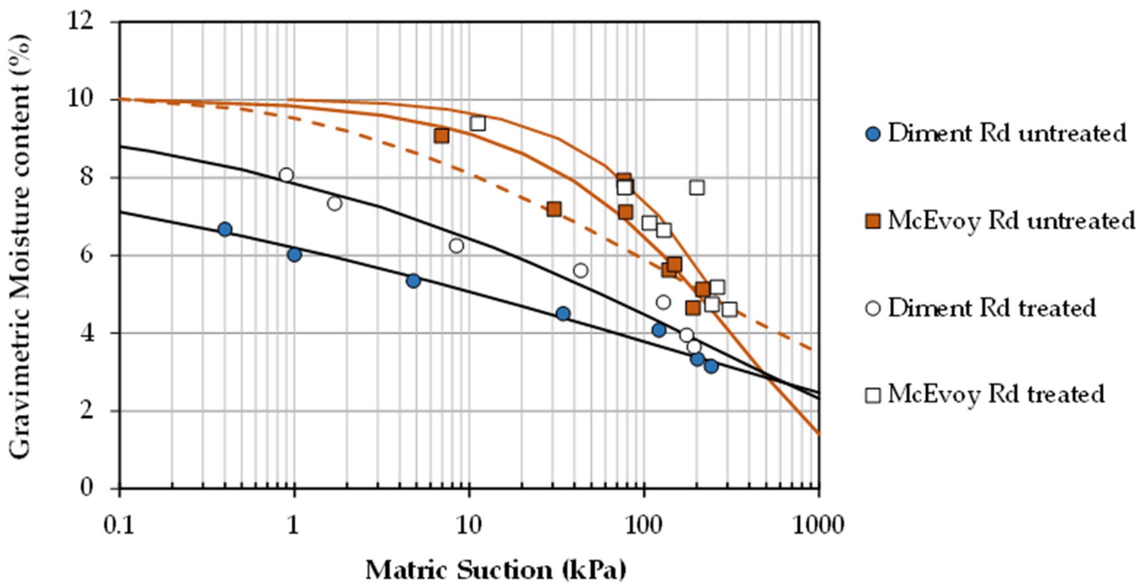

Figure 4. Soil water characteristic curves.

Treatment with Polyoad DPP saw a rise in the position of the SWCC relative to that of the untreated material. In other words, more moisture was retained at a given suction value, or conversely, higher suctions were realized at a given moisture content. The air entry values (AEVs) were low for Diment Rd, 4 kPa maximum, while they were high for the McEvoy Rd aggregate at 70 kPa for untreated material and 105 kPa for the treated material. The higher AEVs are indicative of higher plasticity of the fines in the UGM. The values of OMC in Table 2 would correspond to matric suctions of about 0.5 and 25 kPa for the Diment Rd UGM for untreated and treated specimens, respectively. The corresponding suctions for the McEvoy Rd UGM are 70 and 90 kPa, approximately.

5.2. Strength Tests

5.2.1. California Bearing Ratio

The four-day-soaked CBR tests of the subgrade samples resulted in the low values of 1% and 3% for Diment Rd and McEvoy Rd, respectively. As noted previously, the Diment Rd subgrade was lime stabilized, and the design CBR value was assumed to have increased to 6% to achieve a 20-year design life for the projected traffic.

The CBR values for the UGMs are provided in Table 4. The CBR values increased from a CBR of 60% for both materials to over 150% after the addition of Polyroad DPP. According to both VicRoads [30] and QTMR [31], the treated materials are considered to be lightly bound materials. The CBR for PAM treated and untreated samples for four-day-soaked tests were essentially the same at almost 170% [13] as shown in Table 4. However, an improvement of some 22% was observed when the CBR test was conducted without soaking and after leaving the specimens for 14 days to air dry.

Table 4. Soaked CBR of values of the granular pavement materials.

Site	Treatment	CBR (%)
Diment Rd	untreated	60
	treated	240
McEvoy Rd	untreated	60
	treated	173
Material A	untreated	169
	treated	167

5.2.2. Unconfined Compression Strength

The treated blends were significantly stronger than the untreated blends in unconfined compression as seen in Table 5. As expected, the Diment Road material had higher values for both treated and untreated aggregates. AustStab [32] uses 1.2 MPa as the boundary between bound (>1.2) and unbound or lightly bound material (<1.2). In contrast, QTMR Pavement Rehabilitation Manual [33] suggest a range of 1.0 to 2.0 MPa is applicable for lightly bound aggregates. Despite a 100% increase of UCS observed between untreated and treated blends, the treated aggregates would remain classified as “lightly bound”.

Table 5. UCS values.

Site	Treatment	UCS (MPa)
Diment Rd	untreated	0.65
	treated	1.1
McEvoy Rd	untreated	0.5
	treated	1.0
Material A	untreated	4.5
	treated	5.1

For Material A, prepared at OMC and MDD for the previously described higher compaction effort, and after curing for 14 days, UCS values were quite high with and without Polycom, at approximately 5.1 and 4.5 MPa, respectively [13]. The classification of these UGMs would be “modified [33]”. Modified UGMs may be susceptible to tensile cracking in flexure.

5.2.3. Drained Shear Strength Parameters

Examples of the stress–strain responses in triaxial shear are provided in Figure 5 for the Diment Rd material prepared at 98% MDD and 80% OMC and under confining stresses of 10 and 50 kPa. Significant increases in the peak deviator stress are evident after treatment with Polyroad DPP. A summary is provided in Table 6 of the derived drained strength parameters, angle of friction, ϕ', and apparent cohesion, c'. Some difficulties were encountered in constructing reliable failure envelopes given the small range of applied confining stresses, so no result is reported in Table 6 for the treated specimens prepared at 100% OMC from Diment Rd. Quite high deviator stresses at failure (q_f) were observed, but values varied little with confining pressure; q_f ranged from just 2.05 to 2.1 MPa.

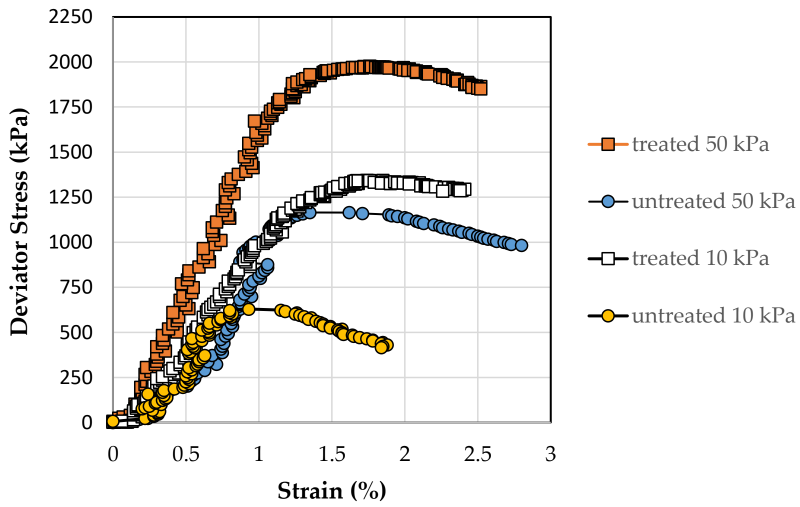

Figure 5. Triaxial stress–strain responses for Diment Rd prepared at 80% OMC. Effective confining pressures of 10 and 50 kPa are indicated in the legend.

Table 6. Drained strength parameters from CID triaxial tests.

	Preparation	Treatment	φ′ (deg.)	c′ (kPa)
Diment Rd	100% OMC	untreated	68	0
	100% OMC	treated	–	–
	80% OMC	untreated	60	70
	80% OMC	treated	67	105
McEvoy Rd	100% OMC	untreated	61	0
	100% OMC	treated	70	0
	80% OMC	untreated	67	65
	80% OMC	treated	59	183

It is evident from the Table that friction angles were substantial, varying between 59° and 70°, as one would expect with pavement aggregates, while the apparent cohesion ranged between 0 and 185 kPa. The treatment generally improved the shear strength of the aggregates.

5.3. Repeated Loading Triaxial Testing (RLTT)

5.3.1. Permanent Strain

The average permanent strain of the pairs of specimens for each site over the three stages of applied stress are presented in Figure 5 for all specimens. It must be noted that the McEvoy Rd material without treatment was difficult to test and only a single test result was obtained for all three moisture preparations. Untreated samples of Diment Rd UGM generally suffered greater permanent strain than the untreated McEvoy Rd UGM did, particularly when prepared at OMC (Figure 6a); by the end of permanent strain testing, the Diment Rd UGM had experienced 134% more strain than the McEvoy Rd UGM.

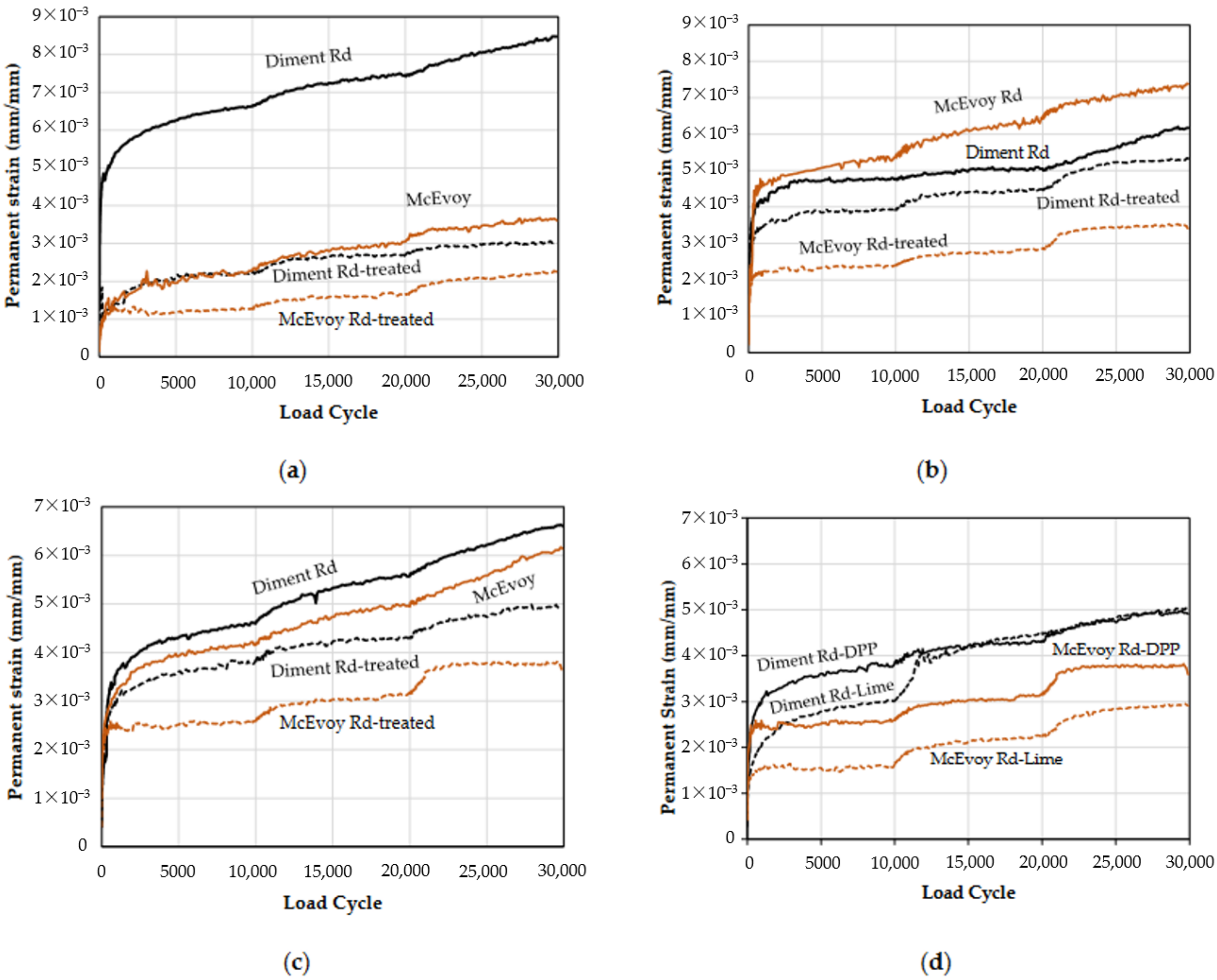

Figure 6. Permanent strain development with load cycles: (**a**) OMC—effect of DPP treatment; (**b**) OMC dried back to 80%—effect of DPP treatment; (**c**) 80% OMC—effect of DPP treatment; (**d**) 80% OMC—comparison of DPP and lime treatments.

As expected, untreated specimens experienced higher permanent strains than the treated samples, however, the reduction in strains for McEvoy Rd appeared to be most significant for specimens dried back to 80% OMC (Figure 6b) or prepared at 80% OMC (Figure 6c). By the end of testing, the comparable values of average reduction in permanent strain were 38%, 54%, and 41% for specimens prepared at OMC, specimens dried back to 80% OMC, and specimens prepared at 80% OMC, respectively. This finding is probably a result of the higher fines content and the higher plasticity of the fines for the McEvoy Rd UGM compared to that for the Diment Rd UGM.

Figure 6d provides a direct comparison between DPP and lime only treatments. For Diment Rd, the comparison of permanent strains was close, but for McEvoy Rd, the lime treatment outperformed the DPP, which infers that the lime was inhibited from having full effect by the presence of the polymer.

RLTT results for Polycom treated Material A could be used to compare with the Polyroad DPP results, however it must be noted that the UGM was treated as a subbase, and consequently, the applied deviator stresses were substantially reduced. Furthermore, specimens of Material A were dried back from OMC to just 50% of OMC. Accordingly, permanent strains were much lower, being between 1.0×10^{-3} to 1.5×10^{-3}, generally [11]. Even at these low levels of strain, a reduction of about 13% was reported at the end of the three stages owing to treatment with Polycom.

The data for average permanent strains (PS) of the UGMs in the current study were examined by comparing the strain after 10,000 cycles (stage 1), PS_{10K}, and the change in strain over the last 2000 cycles of testing (ΔPS) in stage 3. The latter measure has been promoted as a potential guide to material stability using shakedown theory [34], and its application is shown in Figure 7 for specimens compacted at OMC and at 80% OMC.

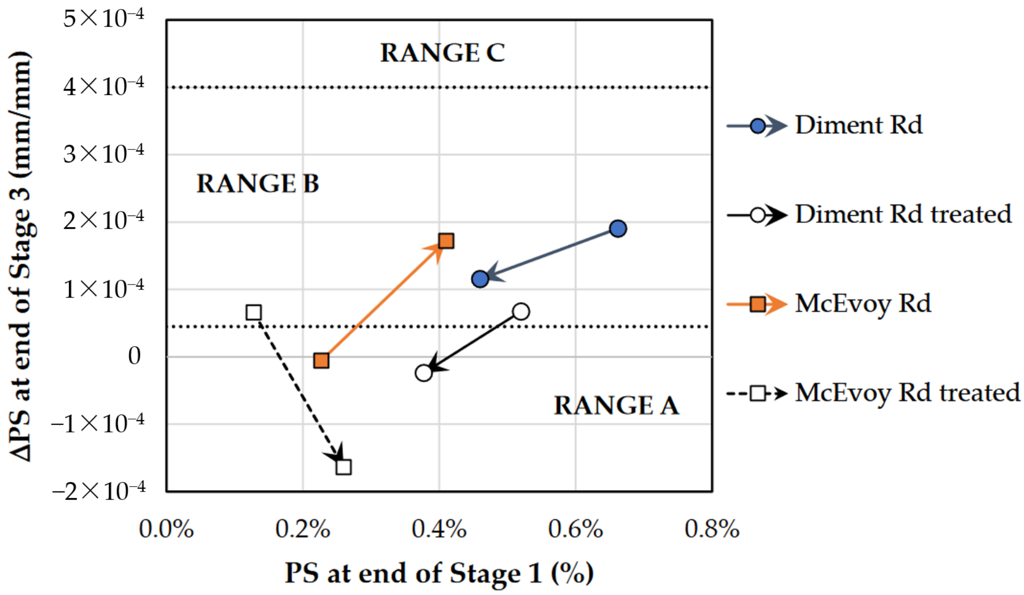

Figure 7. Change in permanent strain over the last 2000 cycles in stage 3 against permanent strain at the end of 10,000 cycles (arrows start at OMC and finish at 80% OMC).

However, it must be cautioned that the criteria were developed for a different form of permanent strain testing, conducted over 100,000 cycles, not 30,000 cycles. The boundaries of the ranges of the shakedown behavior are shown as horizontal lines in this plot of ΔPS against PS_{10K}. Range A is most desirable as it approximates an elastic response (plastic shakedown), while range B is plastic creep and C represents incremental collapse.

Figure 7 indicates that an increase in PS by the end of stage 1 resulted generally in an increase in ΔPS. Usually, a higher moisture content preparation led to better performance, but this was not the case for the McEvoy Rd untreated aggregate, with specimens prepared at OMC performing better than when at the lower moisture content or when dried back (not shown in Figure 7). At 80% OMC, the McEvoy Rd material had a much lower value of PS_{10K}, but a better value of ΔPS.

In terms of shakedown ranges, all untreated Diment Rd preparations fell in range B. The only specimens in range A, based on the average PS data, were:

Diment Rd: 80% OMC specimens treated with either DPP or lime;

McEvoy Rd: OMC untreated, 80% OMC and dried back specimens treated with DPP, and lime treated specimens (80% OMC).

Three test results fell just above the borderline between ranges A and B: DPP treated Diment Rd material, at OMC and when dried back to 80% OMC, and DPP treated McEvoy Rd aggregate at OMC. In summary, resistance to permanent strain, and hence, rutting was improved by both DPP and lime treatment.

Finally, the outcome for untreated pavement base from Diment Rd at OMC is somewhat anomalous as only one specimen out of the three prepared did not fail during PS testing. One failed test specimen passed through stage 2 before failing and by the end of stage 1 had experienced a permanent strain of 8.8×10^{-3}, which is more than four times higher than the successful test shown in Figure 6a. In addition, the resilient modulus realized from the one successful test was relatively modest, as can be seen in the following section.

5.3.2. Resilient Modulus

The resilient modulus (M_r) obtained from RLTT expresses the recoverable axial strain under repeated deviator stress for a given confining stress. M_r was compared with the three different preparations of the treated and untreated aggregates, and the average values over the 66 stages for each set of replicates are presented in Figure 8. In this Figure, "to 80%" indicates that specimens were dried back from OMC to 80% of OMC. The error bars show one standard deviation on either side of the average value. The differences due to preparation moisture content were small for the untreated specimens, except in the case of McEvoy Rd, where clearly 80% OMC outperformed the other preparations. Diment Rd was the stiffer of the two untreated materials with an average M_r of about 430 MPa, while McEvoy Rd was around 250 MPa for the preparation of test specimens at OMC or dry-back to 80% OMC.

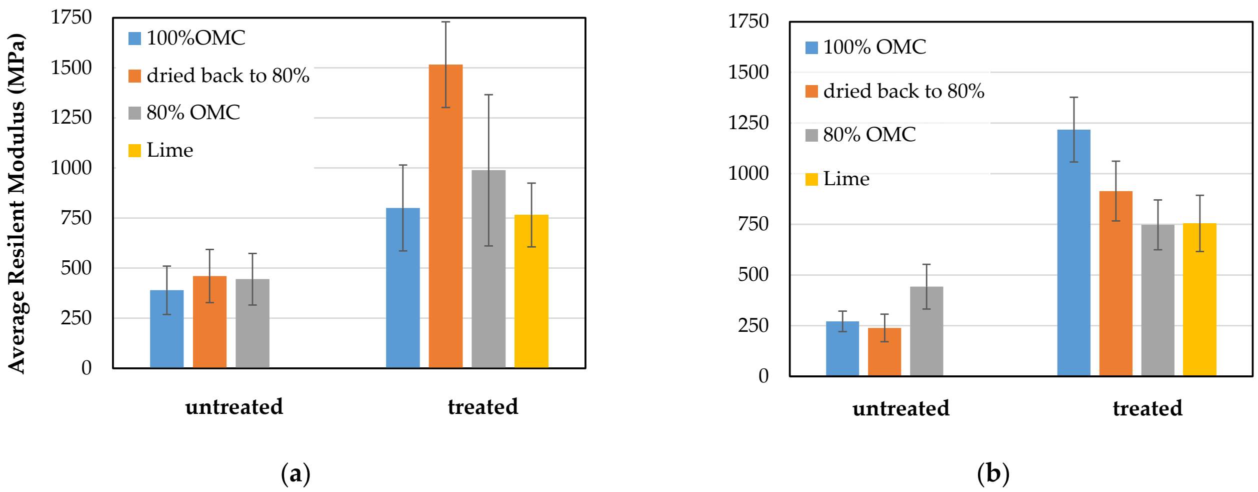

Figure 8. Average values of resilient modulus over 66 test cycles. Note: error bars indicate a standard deviation above and below the average value. (**a**) Diment Rd; (**b**) McEvoy Rd.

Treatment with DPP increased M_r values significantly with values at least twice as high and sometimes three to four times higher than the M_r values realized for the untreated aggregate. A minimum average M_r of 750 MPa could be adopted for all treated materials, and that would include treatment with lime only, based on the aggregates being prepared at 80% OMC. Allowing for a standard deviation less than the average value would still permit a value of 600 MPa to be used as a possible pavement design value. Considering that the typical maximum design value of resilient modulus for a normal grade crushed rock base under a thin bituminous cover is 500 MPa [35], these observed values are excellent.

Interestingly, lime treatment proved to be as good as DPP treatment at 80% OMC for the McEvoy Rd material but was less than the values realized for the Diment Rd material by 30%. This difference between the two UGMs is probably due to the higher fines content of the base from McEvoy Rd and higher plasticity of those fines, resulting in more effective treatment with lime.

Another interesting observation is that specimens of the McEvoy Rd material prepared at 80% of OMC did not realize as much improvement in resilient modulus after treatment, as did the other two preparations. This may have been caused by the reduced availability of water for the lime to react with immediately after compaction.

The minimum and maximum M_r values reported for Material A (605 and 310 MPa) [10] were similar to that for Diment Rd when dried back to 80% of OMC (770 and 230 MPa. After treatment with Polycom, the maximum and minimum M_r values for Material A rose to 750 and 460 MPa, respectively. In contrast, the maximum and minimum M_r values for the Diment Rd UGM rose sharply with Polyroad DPP treatment to 1740 and 1280 MPa, respectively.

6. Economic and Environmental Considerations

Options for the improvement of both roads are described, and the estimated costs of each and their calculated carbon footprints are presented in this section. For both roads, four options were investigated, as detailed in Table 7: full depth asphalt, full granular reconstruction, and in situ recycling of the existing crushed rock with either lime or DPP. The level of lime stabilisation was chosen at 3% by the dry mass of pavement material, while DPP levels were as originally specified at 2 and 1.5% for Diment Rd and McEvoy Rd, respectively. The industry standard in Australia is for a minimum of 3% lime [36], far more than was applied in resilient modulus tests reported here. However, it should be noted that the lime in the DPP treatment was finer and had a higher available lime index than that normally used in road stabilization.

Table 7. Options for bases.

Option	Thickness [1] (mm)	Base Course Material
1. Full depth asphalt	140/180	Size 20 type SI asphalt (2 layers)
2. Lime stabilisation	200/250	Lime stabilisation of existing crushed rock at 3%
3. Full granular reconstruction	200/250	Class 2 crushed rock (20 mm)
4. DPP stabilisation	200/250	Polyroad DPP stabilisation of existing crushed rock at 2% for Diment Rd and 1.5% for McEvoy Rd

[1] Thickness for Diment Rd is stated first, followed by values for McEvoy Rd.

An in-house industry program named Environmental Calculator was developed by the firm Stabilized Pavements. The Australian arm of this firm is the current employer of the first named author. Consequently, this program was used to deduce for each road treatment the carbon footprint, the mass of recycled materials, and truck movements. Carbon equivalents (CO2-e) were taken largely from [37] or from industry estimates.

For simplicity, the polymer was assumed to have the same carbon footprint as lime. Deep lift asphalt consisted of 5% bitumen, 80% aggregate, 10% Recycled Asphalt Pavement (RAP) and 5% filler. Truck movements included the transport of materials and the milling and compaction operations. Distances to suppliers and waste disposal sites were considered, with the largest distances being 45 and 36 km for the Diment Rd and McEvoy sites, respectively. These maximum distances, however, do not include the haulage distance of 900 km required to obtain DPP from interstate.

6.1. Diment Rd

The surface area requiring treatment for Diment Rd is 1000 m^2. The in-situ recycling options considered either lime at 3%, or DPP at 2% (PR11L) as applied in the road treatment. Common to all options, a 40 mm thick Hot Mix Asphalt (HMA) layer was required, size 14. The design subgrade CBR was 6%.

6.2. McEvoy Rd

The surface area requiring treatment for McEvoy Rd is 2500 m^2. The in-situ recycling options consider either commercial lime at 3% or DPP at 1.5% (PR11L), again, as physically applied in the road trial. Common to all options, the wearing course consisted of a sprayed seal. This part of the construction was not considered in estimating the carbon footprint. The design subgrade CBR was 3%.

6.3. Potential Carbon Emissions

The plots of the CO2-e against treatment for the two roads are given in Figure 9a for 1000 square metres of road. The plots are similar for both roads, as are the plots of mass of recycled materials, as shown in Figure 9b. The trends are as expected, with deep lift asphalt responsible for approximately twice or more the potential carbon emissions for in situ recycling with DPP and lime for McEvoy Rd, and a little less so for Diment Rd, where an HMA wearing course was assumed. Full granular replacement was predicted to have similar CO2-e values as lime treatment but higher than DPP and with minimal recycling. It should be noted here once more that the DPP's carbon footprint was assumed to be equal to that of lime, and the percentage by mass of DPP was less than assumed for lime stabilization.

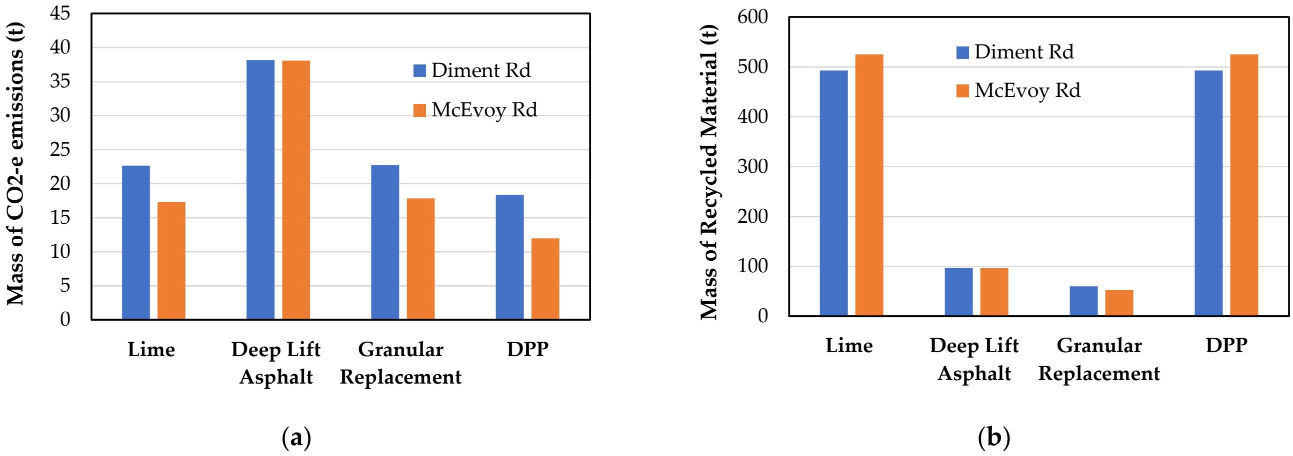

Figure 9. Environmental outputs. (**a**) Comparison of CO2-e emissions per 1000 m^2 of road; (**b**) Mass of recycled material per 1000 m^2 of road.

The Environmental Calculator provides the number of truck movements for each option. Granular replacement required 108 and 162 movements per 1000 m^2 for granular replacement at Diment Rd and McEvoy Rd, respectively, which reduced to just 48 and 5 for both of the recycling options.

6.4. Cost Evaluations

There are several factors that go into the cost associated with having roads open to the public. These include the costs associated with construction, maintenance, rehabilitation, traffic disruption/road user delay costs, and the salvage value. Additional factors include maintenance requirements, road safety considerations, the scale of the project, and noise and spray effects [38].

Current costs in Australian dollars (AUD) for the treatment options, which include profiling out material, are provided in Table 8. It should be noted that Polyroad DPP costs three times more per tonne than cement and is twice the price of commercial lime, although application rates tend to be low. Of all the options, deep lift asphalt is potentially the most expensive option and requires about a week to complete. Granular replacement is the next most expensive option and is equally time consuming. The in situ stabilization processes are much more time efficient and less costly, with lime stabilization being a little less expensive overall than DPP treatment. The costs of base construction have been included in Table 8 for a more direct cost comparison. The McEvoy Rd operations do not require an HMA seal as is the case with Diment Rd, and so the total cost for the pavement treatments tend to be cheaper than the comparable in situ treatments for Diment Rd.

The costs for the bases in Table 8 were used in the model proposed by Rahman et al. [38] to estimate an economic Benefit Cost Ratio (BCR) between the full granular replacement of the base and in situ stabilisation. The recycled material is not imported as it would be with recycled concrete aggregate as in the referenced paper and so the BCR may be underestimated. The model from [38] relies simply on volumes of recycled and virgin material, material cost estimates, and cited costs of landfill and mining operations. The economic BCR for Polyroad DPP stabilisation of the Diment Rd base was estimated to be 3.4. The BCR was slightly less for McEvoy Rd (3.3). Lime stabilisation increased BCR values to 4.3 and 4.0 for Diment and McEvoy Rds, respectively.

Table 8. Direct construction costs and required durations of operations.

Option	Site	Total Cost (AUD/m^2)	Cost of Base (AUD/m^2)	Duration (Days)
Lime stabilisation	Diment Rd	48	15	4
	McEvoy Rd	32	18	4
Deep lift asphalt	Diment Rd	118	80	6
	McEvoy Rd	122	90	7
Granular replacement	Diment Rd	69	28	7
	McEvoy Rd	70	36	9
DPP stabilisation	Diment Rd	58	19	4
	McEvoy Rd	36	22	4

7. Discussion

The lime in Polyroad DPP flocculates clay particles in the fines, which are subsequently coated with the hydrophobic polymer. The calcium in the lime will react over time with water and the silica and alumina in the clay to form cementitious products and stronger particle bonding. This process is responsible for significant increases in the strength and stiffness of a UGM with plastic fines. So, it was not unexpected to observe increases in CBR, UCS, and resilient modulus, as well as a reduction in permanent strain under repeated loading, although the extent of the changes was unexpected. However, it has been shown in this paper that the refined lime component of Polyroad DPP appears to be responsible for much of the improvements of dynamic stiffness of the materials in this study, at least as tested with specimens prepared at 80% OMC and 98% MDD.

The stabilizing action of the DPP on UGMs with plastic fines may explain why permeability is increased as the agglomerated clay particles effectively result in greater porosity and the polymer coating deflects water flow through the aggregated fines.

It has been stated in the past that Polyroad DPP decreases permeability [5,6,8]. The authors believe that statement has arisen from confusion with the reduction in capillary rise and is not based on soil permeability testing.

The capillary rise of the UGMs was reduced after treatment with Polyroad DPP, despite the increased initial matric suction of each UGM specimen at OMC at Proctor compaction, the moisture content selected for testing, as determined by the appropriate SWCC (Figure 4). In non-hydrophobic soils, capillary rise is dictated by the initial suction; the higher the suction, the greater the rise. Therefore, it may be concluded that the polymer restricted the capillary rise.

Although there were two different pavement materials in this study and each was prescribed a different treatment by Polyroad Stabilising, the treatments worked well for both UGMs with respect to water ingress, strength, and repeated loading. The UGMs drained more effectively, capillary rise was inhibited, swelling and erosion were negated, and the UGMs were stronger and stiffer under repeated loading. The UGMs were less susceptible to rutting (reduced permanent strain in repeated load triaxial testing). Both UGMs after treatment were classified as “lightly bound”.

Although the information regarding Material A before and after treatment with Polycom might indicate to the casual reader that Polyroad DPP provides potentially greater benefits, to the authors, it serves to remind readers that each UGM needs to be considered separately. Material A, a poorly graded subbase, had fines that were non-plastic and were shown to be silt-sized, with just 1% by mass of the UGM being clay [10]. Polyroad DPP may not have been suitable for this UGM.

The costs of four pavement repair options were considered in this paper, and their carbon footprints were evaluated. In situ stabilization is generally an economical form of road rehabilitation, particularly for the deeper granular pavement layers at McEvoy Rd.

At this site, granular replacement was approximately twice as expensive as lime or DPP stabilisation (2.2 and 1.9 times, respectively). Granular replacement was reported [39] in 1991 as being 2.5 times the cost of cement or lime stabilisation, a figure which is supported by this study, allowing for the difference in time between reporting costs. The economic Benefit Cost Ratio, which compared all the direct and indirect costs of the basecourse replacement with virgin aggregate to in situ recycling, was estimated to be at least 3.3 and 4.0 for DPP and lime stabilization, respectively. Lime stabilisation was assumed to be at a rate of 3% by the dry mass of aggregates and employed commercially available lime.

The estimated carbon footprints of the pavement repair options were highest for full depth asphalt replacement and lowest for DPP treatment. Some caution is needed with this finding, however, as assumptions were made about the carbon footprint of producing DPP. Granular replacement had a carbon footprint close to that for lime stabilisation. In situ stabilization with either lime or DPP is far quicker than granular replacement and involves far fewer truck movements. Less than half the truck movements were required at Diment Rd with most of these being associated with the construction of the HMA wearing course. Just five movements per 1000 m^2 were required at McEvoy Rd, as it had a sprayed seal wearing course. Therefore, it may be concluded that the social impact of road work is reduced with in situ stabilization.

8. Conclusions

In situ recycling with Polyroad DPP is cost effective, and like all in situ treatments, has a low carbon footprint and reduces the inconvenience which may arise from other rehabilitation options. The drainage of pavement materials is improved with this DPP treatment, and the stability, strength, and stiffness of granular material with plastic fines were observed to increase significantly. DPP-treated aggregates in this study were shown to become lightly bound after treatment, rather than "modified". As with other additives, DPP treatment will not be effective if applied to unsuitable aggregates. Particle size distributions and plasticity of fines are a good starting point to ascertain suitability of materials. Where material falls outside the recommended limits, other additives or construction methods may be better suited to improve engineering properties.

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