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Performance of Recycled Materials in Pavement Subbase After 4 Years in a Hot Desert Climate

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Abstract: The paper presents a field investigation on the use of alternative subbase materials from excavation and demolition waste in subbase applications in a desert area. A road trial was constructed with three subbase sections, comprising excavation waste (EW) and crushed concrete aggregate (RCA) plus a control section of EW with 20% dune sand (control). Visual inspection after 4 years in service revealed excellent performance with no surface defects or obvious differences between the different sections. The subbase surface was exposed and field-testing using lightweight deflectometer indicated very similar values for the unbound subbases of EW and the control section. The RCA subbase exhibited excellent performance due to self-hardening, providing much higher stiffness than the unbound subbases. The extracted unbound subbase materials satisfied the physical and mechanical requirements of the Qatar Construction Specifications with the exception of liquid limit, plastic limit, and sand equivalent, which are of less significance where the material is placed above the water table. The paper demonstrates that recycled aggregate can perform as well as conventional subbase materials and promotes their wider use to support sustainable development.

Key words: alternative aggregates, construction & demolition waste, excavation waste, field investigation, natural resources

1. Introduction

The State of Qatar occupies a small peninsula on the south shore of the Arabian Gulf. In common with other states in the region, the construction boom witnessed in Qatar over the past two decades is associated with increased consumption of materials and intensive use of energy. With sustainability being the main factor in the government's 2030 national vision, there is a challenge to balance between development needs and protecting the environment. Qatar lacks quality aggregate, and the construction industry relies mainly on imported aggregate for use in asphalt and concrete. The use of local and recycled materials contributes to sustainable development, with reduced energy consumption in transporting materials from neighbouring countries as well as minimizing the disposal of construction waste to landfills.

Geologically, Qatar lies on rock that is mostly weak and friable limestone and dolomite, limiting its wider use as aggregate in construction. The strength of local limestone can vary widely with strong bands interbedded with weaker materials [1], and small amounts of the clay mineral attapulgite (palygorsite) in separated bands or disseminated throughout the matrix [2]. A cross section of the excavated limestone in a quarry up to 15 m depth with clay contamination is shown in Fig. 1. Current practice in Qatar is to blend local limestone with 10-20% dune sand to improve its properties and enable compliance with the Qatar Construction Specifications [3]. This material has been successfully used for unbound subbase in road pavement for many years. However, dune sand is not

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available in large quantities and the government has recently restricted its use in construction [4].

Construction waste is mainly composed of excavation waste (EW) and construction & demolition waste (CDW) and potentially provides a source of sustainable aggregate supply. In 2010, Qatar generated 12 Mt (million tonnes) of solid waste, including 80% construction waste. In addition, there is approximately 80 Mt of construction waste accumulated in various landfill sites, with the majority in Rawdat Rashid landfill site [5]. A recent survey by the Planning and Statistics Authority [6] showed a positive reduction in the generation of solid waste to 8.2 Mt in 2017, with 50% construction waste. A recycling target of 20% of the total materials used in construction projects was set in the Qatar Second National Development Strategy by 2022 [7].

Fig. 1 Limestone quarry with disseminated clay contamination (brown colour) across the excavated face

The use of recycled materials is relatively new in Qatar and hence there is a need to provide evidence-based research on their performance in service. There is very little information available on the field performance of construction materials in Qatar. Field trials are important because they consider the exposure environment in Qatar and the region generally of excessive heat and humidity, aggressive ground conditions, and heavy traffic loading as well as the engineering properties of the materials. This paper presents a field study on the use of recycled materials in road subbase applications by comparing construction data with performance after 4 years in service. It aims to support the government strategy of sustainable development by providing confidence for the wider implementation of recycled materials in construction.

2. Construction and Testing of Subbase Road Trials

The access road to Rawdat Rashid, the largest landfill site for construction waste in Qatar was selected for trials. It covers a length of approximately 500 m with heavy traffic loading, in the range of 500-1000 lorries/day, with the existing road suffering from extensive deformation and potholes. The trial was constructed in October 2014 as replacement of the existing access road. Details of the construction data were reported previously [8, 9] and are summarised below. The subbase construction consisted of 3 sections, Fig. 2, each of 120 m length and comprising:

- Section 1: excavation waste (EW) subbase
- Section 2: recycled concrete aggregate (RCA) subbase

- Section 3: a control section made of EW + 20% dune sand

The control section represents the current practice of adding dune sand to local limestone to produce a subbase material to the requirements of the QCS 2014. After removing the existing road and exposing the natural subgrade of limestone, the construction was made in different layers as illustrated in Fig. 3. The new pavement construction consisted of 2 subbase layers, 150 mm each, with an asphalt overlay of 80 mm. The subbase materials were produced by Lafarge-Qatar, who were managing the Rawdat Rashid landfill site in 2014, by crushing and screening EW and RCA into different sizes. The dune sand was obtained from a nearby deposit in Karaana, managed by the Qatar Primary Materials Company. The subbase materials were mixed and stockpiled near the construction site.

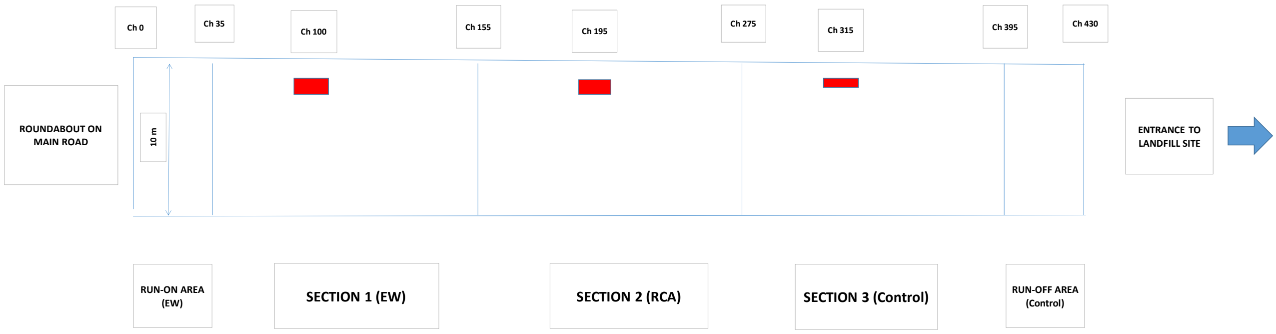

Fig. 2 Layout of the subbase road trials with locations of exposed subbase (not to scale); test sections after 4 years shown in red.

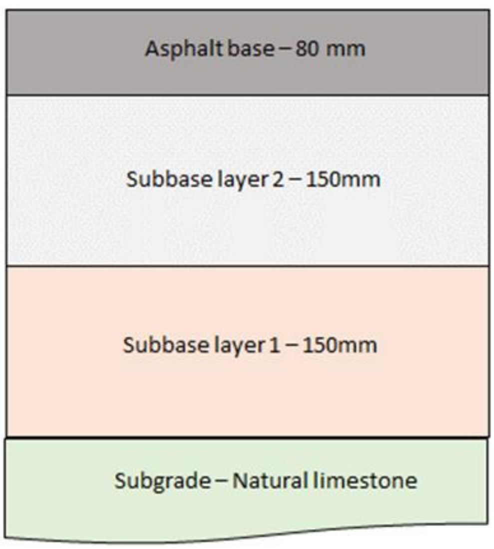

Fig. 3 Cross section of the pavement layers (not to scale).

During construction, the moisture content was adjusted by adding drinking water from a tanker to the stockpile and mixing mechanically with an excavator. The subbase materials were laid using a paver to minimize segregation. Compaction was initially made with 6 passes of a 9-tonne steel wheeled roller followed by 16 passes of a 28-tonne pneumatic tired roller. Further compaction was provided by 6 passes of a 15-tonne steel vibrating roller. Site testing was conducted on the top of compacted subbase layers, with loose samples collected for laboratory testing.

Field-testing of in-situ density, surface modulus and a trafficking trial were carried out on the top of subbase layer 2. The in-situ density was determined using the sand replacement test to BS EN 1997-2 [10] and the trafficking trial according to the procedure described in the UK Specification for Highway Works — Series 800 [11]. Table 1 presents the results of in-situ density and rut depth after trafficking.

The QCS 2014 specified a maximum dry density (MDD) of minimum 2.05 g/cm^3 for unbound subbases, with in place moisture content ±2% of the optimum water content (OWC) and a relative compaction of 100% of the MDD. The results in Table 1 show the three subbase materials satisfied the laboratory MDD, but the field dry density was lower than 100% of the laboratory values. The dry density is dependent on the moisture content, and the hot environment in Qatar caused rapid drying of the materials after compaction as reflected in the field moisture content being on the lower side of the OWC. However, the laid subbase materials visually appeared well compacted. The trafficking trial provided a further assessment of the subbase materials after being subjected to 1000 equivalent standard axles. The average and maximum rut depths are shown in Table 1. The average rut depth was less than 10 mm for each subbase section, well below the maximum specified limit of 30 mm in the UK Specification for Highway Works.

Table 1 In-situ density and rut depths after trafficking.

Subbase	Laboratory		In-situ density (layer 2)			Rut depth (mm)	
	MDD (g/cm^3)	OWC (%)	Dry density (g/cm^3)	MC (%)	Relative compaction (%)	Average	Maximum
EW	2.18	7.1	2.07	5.8	95	7.5	11.0
RCA	2.09	9.2	1.87	8.2	89	7.4	11.0
Control	2.32	5.0	2.12	4.9	91	0.4	6.0
QCS 2014	2.05	± 2%	-	-	100%	-	-

MDD: Maximum Dry Density as per ASTM D1557 [12]
OWC: Optimum Water Content as per ASTM D1557 [12]

To assess the performance of the subbase materials after 4 years in service, small areas of the asphalt overlay were removed to expose the subbase surface. For each road section, an area of 900×1600 mm was exposed from the subbase, highlighted in red in Fig. 2. The asphalt overlay was initially cut into small slabs using a diamond saw, loosened at the edges using a vibrating hammer, and lifted to provide an undisturbed subbase surface. A thin layer of dune sand was sprayed on top of the exposed subbase to provide an even surface for the surface modulus field testing, after which the dune sand was removed and the exposed subbase was loosened using a pick axe and a spade and the loose materials collected in sealed bags for laboratory testing (Fig. 4). The RCA subbase (Section 2) was found to have hardened after 4 years in service and was therefore treated as a bound subbase and cores were extracted for testing as shown in Fig. 5.

3. Testing Programme and Results

Testing of the subbase materials was carried out during construction and after 4 years in service. The programme included field and laboratory testing to assess the changes in subbase properties after trafficking in service. The RCA subbase cores after 4 years were tested for compressive strength, moisture content and density. Details of the testing programme and results are discussed in the following sections.

Fig. 4 Exposed subbase and sampling of the control unbound materials.

Fig. 5 Self-hardened RCA subbase exposed after 4 years in service during coring.

3.1 Visual Inspection

Visual assessment of the road trials was made immediately after construction in November 2014 and periodically every year to October 2018. The access road was heavily trafficked with loaded trucks bringing construction waste into the landfill site and most of the trucks leaving the site loaded with processed recycled materials. The visual inspection showed excellent performance of the road trials in service. No surface defects in the form of cracks, deformation or bleeding were observed on the asphalt overlay, with identical performance between the different sections.

3.2 Grading

The QCS 2014 was issued in December 2014, shortly after construction of the trial, and therefore the grading at construction was made to the requirements of the QCS 2010 specification. Three samples were tested for each subbase material and the average grading curves are shown in Fig. 6. All the samples complied with the QCS 2010 grading envelope except the EW subbase, which was slightly coarser between 2 and 5 mm. The effect of adding dune sand on the grading of the control subbase significantly increased the percentage passing at 0.6 mm, but the material remained within the grading limits.

Fig. 7 shows the difference in grading between dune sand and RCA fines (0-5 mm). Whilst the RCA fine aggregate was not used in the field trial to improve the properties of local limestone for subbase applications, it could be used as an alternative to dune sand to achieve compliance with the QCS 2014. The dune sand is almost a single size material with its grading within the narrow range of 0.15 and 0.6mm, hence could not affect the full grading of the subbase material when blended in large quantities. The crushed RCA fines provide a more continuous grading across the different sizes of 0-5 mm, with a relatively high fines content (passing 0.075 mm).

After 4 years in service, the extracted unbound subbase materials (EW and Control) were tested as per

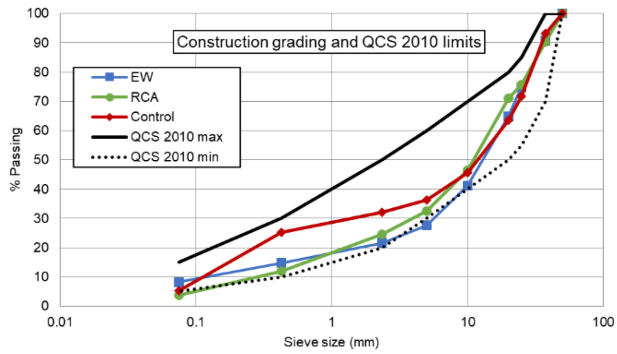

Fig. 6 Grading of the subbase materials at construction (2014) and QCS 2010 limits.

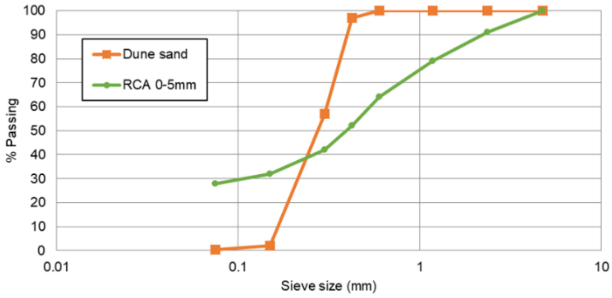

Fig. 7 Grading of dune sand and RCA fines.

ASTM D6913 [13], following the grading requirements of the QCS 2014 as shown in Fig. 8. The QCS 2014 provides a narrower grading envelope than the QCS 2010 subbase, mainly at the minimum specified limit whereas the maximum limit is almost the same for both specifications. The grading curve for each subbase material represents the average of 3 tested samples. The EW and control showed significantly finer grading than at construction at all sieve sizes. The EW subbase, with its initial coarser grading at construction, remained within the QCS grading envelope with the fine particles of 0.6-0.075 mm towards the higher specified limits. However, the control subbase exceeded the maximum limit between 2 and 0.25 mm, associated with the dune sand addition. The different grading of the unbound materials after 4 years could be attributed to the effect of trafficking but could also be due to the method of extracting the unbound materials causing breakdown of the weak limestone particles, and to the variability of recycled materials.

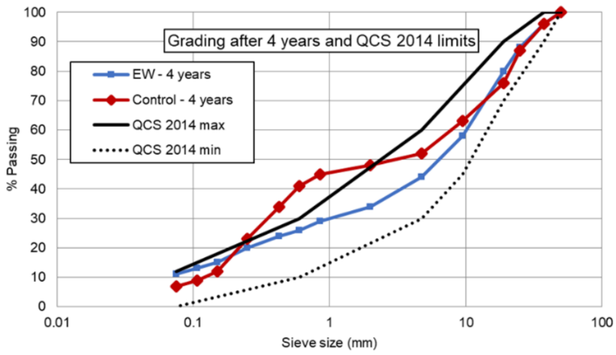

Fig. 8 Grading of the subbase materials after 4 years trafficking and QCS 2014 limits.

3.3 Liquid Limit, Plasticity Index and Sand Equivalent

Liquid limit, plastic limit and plasticity index were tested in accordance with ASTM D4318 [14] and sand equivalent to ASTM D2419 [15]. Table 2 shows the test results of the subbase materials together with the QCS 2014 specified limits. The results show that none of the subbase materials satisfied all the three criteria at construction. The EW subbase failed the QCS 2014 requirements of liquid limit, plasticity index and sand equivalent. The RCA subbase failed the liquid limit but satisfied the plasticity index and sand equivalent requirements. The control subbase passed the liquid limit and plasticity index but failed the sand equivalent.

Table 2 Index tests on the subbase materials at construction and after 4 years in service.

Test/Subbase	At construction			After 4 years			QCS 2014 limits
	EW	RCA	Control	EW	RCA	Control	
Liquid limit (%)	47	47	25	47	-	NP	25 max
Plastic limit (%)	26	NP	NP	27	-	NP	-
Plasticity index (%)	21	NP	NP	20	-	NP	6 max
Sand equivalent	13	34	17	36	-	21	25 min

NP: Non-plastic

After 4 years in service, the EW subbase showed slight changes in the liquid and plastic limits but a significant increase in the sand equivalent to exceed the minimum limit specified in the QCS 2014. A slight increase in the sand equivalent was also observed for the control subbase.

3.4 Physical and Mechanical Properties

The results of Los Angeles Abrasion to ASTM C131 [16], soundness to ASTM C 88 [17] after 5 cycles in magnesium sulfate solution, soaked California Bearing Ratio (CBR) to ASTM D1883 [18], and swell to ASTM D1883 [18] are given in Table 3. All the subbase materials comfortably satisfied the requirements of the QCS 2014.

Table 3 Physical and mechanical properties of subbase materials.

Test / Subbase	At construction			After 4 years			QCS 2014 limits
	EW	RCA	Control	EW	RCA	Control	
LA abrasion (%)	30	30	28	27	-	27	40 max
Soundness (%)	16.6	2.3	10.6	7.0	-	5.4	20 max-
Soaked CBR (%)	190	145	260	265	-	164	70 min
Swell (%)	0.16	0.17	0.13	0.20	-	0.80	1 max

The surface modulus of the subbase materials was measured using a light weight deflectometer (LWD) in accordance with ASTM E2583 [19]. Six tests were carried out in each subbase section on the top of subbase layer 2 at construction and after 4 years in service. At construction, the measurements were conducted after compaction, before laying the asphalt overlay, at approximately 20 m intervals. After 4 years, the measurements were conducted on the exposed subbase surface (900×1600 mm). The average and minimum modulus values are given in Table 4, together with the Foundation Classes of the UK pavement design as given in the Interim Advice Note (IAN) 73/06 (20), which was the standard in force at the time the work was carried out.

The LWD values at construction show no significant difference between the three subbase sections with average values ranging between 105 to 109 MN/mm^2. All the three materials would be a Class 2 Foundation, suitable for traffic loading up to 80 million standard axles. The exposed subbase after 4 years gave slightly lower values for the unbound materials of 101 and 81 MN/mm^2, for the EW and control respectively. The RCA subbase would be a Class 3 bound subbase with an average surface modulus exceeding 200 MN/mm^2. However, it only just exceeds the minimum value for this Class.

Table 4 LWD values for subbase materials at construction and after 4 years in service.

Age	Subbase	Average dynamic deflection modulus Evd (MN/mm^2)	Minimum dynamic deflection modulus Evd (MN/mm^2)
At construction	EW	107	70
	RCA	109	87
	Control	105	90
After 4 years in service	EW	101	58
	RCA	205	151
	Control	81	63
Foundation Class 1 (UK guidance)		40	25
Foundation Class 2 (UK guidance)		80	50
Foundation Class 3 (UK guidance)		200	150

3.5 RCA Subbase After 4 Years in Service

Cores (150 mm diameter and 150mm height) were extracted from the hardened RCA subbase, Section 2. The cores were sealed in plastic bags and tested in the laboratory for compressive strength as per BS EN 12390-3 [21], density and moisture content. The irregularities at the core ends were minimised by sawing to produce flat perpendicular surfaces. Unbounded metal caps were used for the compressive strength testing as per ASTM C1231 [22], Fig. 9. Three cores were tested for compressive strength in “as-received” conditions, and the crushed cores were dried in an oven at 105±5°C for the moisture content determination. Another set of three cores were used for the density measurement, weight in air and water, and soaked in water for 7 days at 24±5°C. The saturated-surface dry cores were tested for compressive strength for the determination of retained strength as per the QCS 2014.

The results of compressive strength, density and moisture content of the cores are given in Table 5,

Fig. 9 Compressive strength testing of sled-hardened RCA subbase cores.

together with the standard deviation and coefficient of variation. The average “as-received” strength of the RCA subbase was 2.3 MPa, and the variation of results was 9%. For the soaked strength, one core was excluded as it became short after sawing. The average soaked strength of the remaining two cores was 2.2 MPa, with a relatively high variation of 16%. The retained compressive strength, measured as the ratio of soaked to as-received strength, was 96% and exceeded the minimum specified value of 80% in the QCS 2014. The high retained strength indicates high durability for the ingress of water into the pavement. The average density and moisture content results were 2,124 kg/m^3 and 2.1%, respectively. The hardening of the RCA material, placed and compacted as an unbound subbase like the other sections, is due to the hydration of unhydrated cement particles over time due to moisture added to the fill to bring it to the OWC prior to compaction.

Table 5 Core results of strength, density and moisture content.

	Compressive Strength (MPa)		Retained strength (%)	Density (kg/m^3)	Moisture content (%)
	As received	After soaking			
Core 1	2.1	2.0		2131	1.97
Core 2	2.4	2.5		2149	2.01
Core 3	2.5	-		2092	2.31
Average	2.3	2.2	96%	2124	2.1
SD	0.2	0.4		28.8	0.2
CV %	8.9	15.7		1.4	8.9

4. Discussion of Results

The paper presents a field investigation on the performance of recycled materials in unbound subbase applications after trafficking for 4 years. The assessment was made by comparing the in-service performance with construction data and the QCS 2014, and was based on the recycled materials achieving at least similar performance to the adjacent conventional subbase made with 20% dune sand. Visual inspection revealed excellent performance with no surface defects or cracking of the asphalt overlay, and no obvious differences between the different subbase sections.

The field trial showed that recycled materials satisfied the maximum dry density of the QCS 2014 but failed to achieve the field density of 100% of the maximum dry density achieved in the laboratory. This is attributed to the hot environment in Qatar and its effect on the rapid drying of materials in-situ, making it hard to achieve laboratory values of MDD. Despite the failure in achieving the specified level of density, the subbase materials exhibited excellent performance in the trafficking trial with only minor development of rutting after loading of 1000 ESALs. The average surface modulus results exceeded 80 MN/mm^2, with no significant difference between the three subbase sections at construction and after 4 years in service. The surface modulus is a function of the foundation stiffness and thickness of the subbase and the results indicate satisfactory performance under high traffic loading as per the UK Specification for Highway Works. Recycled materials also met comfortably with the QCS 2014 requirements of Los Angeles abrasion, soundness, soaked CBR and swell.

The grading curves of the three subbase materials at construction fell within the grading envelope of the QCS 2010 Class B, except the EW subbase. After 4 years of trafficking, the unbound subbase materials EW and control showed finer grading at all sieve sizes. The control subbase exceeded the maximum specified limits of the QCS 2014 between 0.25-0.2 mm, due to the single-size dune sand grading. The results may indicate the breakdown of the unbound particles under the effect of traffic loadings but could also be attributed to the extraction method of the unbound subbase material and the variability of materials. It is also important to consider the limitation of the small exposed subbase surface after 4 years compared to the full size of the trials at construction.

The main parameters that failed the QCS 2014 requirements were the index properties of liquid limit, plasticity index and sand equivalent. None of the unbound subbase materials satisfied all the three requirements at construction or after 4 years in service. The addition of 20% dune sand to the control subbase brought the liquid limit and plasticity index into compliance but failed the sand equivalent. The EW subbase failed the liquid limit and plasticity index, but unexpectedly met the sand equivalent requirement. The RCA failed only the liquid limit at construction and hardened with time to become a bound subbase.

There is no doubt the use of dune sand improves the index properties of subbase materials, but the current restriction on its use in construction could widely affect the use of local and recycled limestone materials. The restriction could impose a new threat of the need to import more primary aggregate materials with negative impacts on cost and fuel consumption. RCA fines (0-5 mm) could provide an alternative to dune sand with its more continuous grading and improvement in the plasticity index and sand equivalent properties. They could also lead to self-hardening with enhanced subbase properties. This is an area where further research is required.

As can be seen from Fig. 1, clay is widely disseminated throughout the limestone and it is not possible to separate the clay from the limestone entirely. The clays are highly plastic, so even small amounts of contamination will lead to material failing the current limits for liquid limit, plasticity index and sand equivalent. These index properties are less significant to the pavement performance where the unbound materials are not subjected to water. In a hot and arid environment, such as in Qatar, the unbound materials are generally placed in dry conditions and covered by impermeable asphalt overlay. TRL Overseas Road Note 31 [23] recommends plasticity characteristics for granular subbases in arid and semi-arid climates; the liquid limit should be less than 55% and the plasticity index less than 20%. The materials used in the trial satisfied these requirements. There could be a potential to revise the QCS requirements to the values proposed by TRL where the unbound materials are placed in a dry environment above the ground water level.

The RCA subbase offered a superior performance with strength gain over time. The RCA material was placed as unbound material and met with all the QCS 2014 requirements with the exception of liquid limit and field density lower than 100% of the maximum dry density. However, the material hardened with time to become a bound subbase and achieved average values of surface modulus just exceeding 200 MN/mm^2 and compressive strength of 2.3 MPa. The hardening of the RCA materials is due to hydration of unreacted cement particles in the RCA in the presence of water [24], as evident from the available moisture content, to become a cement bound material. The weak strength developed by the RCA subbase provides an excellent support to the overlaying pavement and reduces the risk of reflection cracking compared to high strength cement bound materials. To minimize the risk of reflection cracks, Highways England specifies induced cracks for hydraulically bound materials that are expected to reach a compressive strength of $\geq$ 10 MPa at 7 days [25].

While the RCA material could be used at all sizes to produce an alternative subbase material, the fine fraction (0-5 mm) could be blended with local limestone and excavation waste to modify the plasticity criteria instead of dune sand. If RCA fine particles are used to replace dune sand, it is expected to be in the range of 20-30%, leading to a more consistent grading of the subbase material, with potential self-hardening across the subbase layer and enhanced sustainable construction. Further work is required to confirm the practicality of blending RCA fines with limestone aggregate and to optimise the mix design and performance in service.

The road trials clearly demonstrate that recycled materials can perform as well as conventional subbase materials in pavement construction in the arid conditions of Qatar and other areas with similar climate. The results presented in the paper provide practical evidence on the excellent performance of recycled and local materials in service and encourage their wider implementation in practice to support the government strategy of sustainable development.

5. Conclusions

The performance of recycled materials in pavement subbase was determined by excavating the asphalt overlay after 4 years in service and comparing field and laboratory results with construction data and the Qatar Construction Specifications (QCS 2014). The road trial proved to be successful, with the subbase materials made of recycled materials of EW and RCA performing at least similar or better than the control subbase made with conventional materials. Visual inspection showed no signs of surface defects or cracking of the asphalt overlay with no difference in appearance between the 3 subbase sections.

A finer grading was found for the unbound subbase after trafficking for 4 years, with the control section made with dune sand falling out of the QCS 2014 specified grading envelope. The subbase materials comfortably met with the key subbase parameters of Los Angeles abrasion, soundness, soaked CBR and swell, with initial satisfactory resistance to rutting and surface modulus under very high traffic loading. However, the unbound subbases did not meet with all the index properties of liquid limit, plasticity index, and sand equivalent, which could be of less significance in the arid climate of Qatar where the material is not subjected to water.

An excellent performance was achieved from the RCA subbase, with the material initially laid as unbound material and hardening with time to provide support to the pavement structure. A further set of construction trials is proposed to investigate the potential use of RCA fines to replace dune sand to enable the wider utilization of recycled and local materials in construction towards more sustainability in Qatar.

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