A review of full-depth reclamation of pavements with Portland cement: Brazil and abroad

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Highlights

- FDR-PC review promoting its application and serving as a guide for future research.
- Mix design methods are well-established, while structural design methods are limited.
- Strength and stiffness data are presented and analysed based on previous research.
- The effects of some factors on the behaviour of FDR-PC materials are presented.

Abstract:

This paper presents a literature review of full-depth reclamation of pavements with Portland cement (FDR-PC). The paper consists of the following topics: history, construction steps, advantages and disadvantages, mix design, structural design, and behaviour in the laboratory and the field. All sections provide comparisons between international and Brazilian experience. The paper highlights that FDR-PC is used worldwide with significant benefits. While mix design methods are well-established internationally, structural design methods still need to be adapted in most countries. The paper presents ranges of strength and stiffness values based on previous research. Analysis of previous research also identified a suitable test for field modulus prediction and general effects of some characteristics on the behaviour of FDR-PC materials. Furthermore, it identified knowledge gaps for future research, which could promote FDR-PC application with confidence.

Keywords: pavement cold recycling; full-depth reclamation with cement; reclaimed asphalt pavement; mix design; structural design; mechanical behaviour

1 Introduction

The industrial and agricultural development of a country requires increased expansion/enhancement of road transportation systems, which includes rehabilitating existing deteriorated pavements. In the recent past, alternative pavement rehabilitation technologies started gaining importance internationally because of their environmental-friendly aspects. Among others, cold recycling is an example of such a technology [1].

Full-depth reclamation/recycling with Portland cement (FDR-PC) is a cold technique that can treat most distresses of old asphalt pavements. FDR-PC consists of in situ pulverisation of the existing asphalt layer and blending it with a predetermined amount of underlying base material while stabilising these materials with cement to, after compaction, produce a new base layer [2, 3]. The constituent materials of such a layer are reclaimed asphalt pavement (RAP), recycled base material, cement (2-6% by weight of total aggregates) and water (optimum content for compaction). The amount of RAP in the mixture depends on the asphalt layer thickness, being typically lower than 50% of total aggregates. The base material is usually a granular material, but it can also be a stabilised material or even soil. Sometimes, there is a need for adding virgin aggregates for grading correction.

Due to the presence of RAP, materials produced using FDR-PC (i.e. cold recycled cement-treated mixtures) may have a behaviour different from that of conventional cement stabilised materials. Therefore, standards and methods (e.g. mix and structural design) need to be adapted or even developed to cover such materials. In this regard, many researchers have studied the complex behaviour of FDR-PC materials, using laboratory and field testing. However, despite FDR-PC technical, environmental and economic benefits, the road industry still considers it a non-traditional rehabilitation technique and further efforts are necessary to make it a standard choice.

Xiao et al. [1] reported a comprehensive literature review on cold recycling technology of asphalt pavements. However, the authors mainly focused on recycling using asphalt stabilisers. To date, there is no literature review specifically on FDR-PC that could promote the application of the technique and serve as a guide for future research.

Taking this into account, this paper aimed at consolidating findings and data from previous research and identifying gaps for further research. Note that FDR-PC is used for deteriorated asphalt pavements with substantial asphalt layers. The paper consists of six sections. Firstly, it focuses on the history of FDR-PC, briefly describes its construction steps and shows its advantages and disadvantages. Then, the paper presents mix and structural design methods for FDR-PC. All these sections present comparisons between international and Brazilian experience. Finally, the paper shows a comprehensive review of the laboratory and field behaviour of materials produced using FDR-PC. The last section analyses and compares over 1800 testing data collected from 55 studies.

2 History

Jasienski & Rens [4] reported that the use of pavement recycling with cement addition started in the 1950s with the USA and France as the pioneers. In Malaysia, the first project using FDR-PC occurred in 1985 through the recycling of 15 km of pavement in Pahang state. Since then, FDR-PC has become widely accepted in that country, being one of the main solutions for pavement rehabilitation [5].

In 1989, Belgium introduced the technique by recycling a pavement area of 6000 square meters in the city of Vaux-sur-Sûre. Between 1989 and 2001, a further 300,000 square meters of pavements were recovered in the country using the technique [4]. FDR-PC was introduced in South Africa in 1991 when 23 km of a national highway was recycled. Currently, there are several recycling machines in that country, and thousands of km of pavements were recycled, especially using cement as stabilising binder [6].

According to Vorobieff & Wilmot [7], the first recycling machines arrived in Australia in 1992. Portland cement is the commonly used binder for recycling works in that country, due to its ability to stabilise most pavement materials, and its price and availability. The technique became widespread in Spain after the country's first experience in 1992. Studies estimate that more than 2.5 million square meters of pavements are recycled annually [8].

Table 1 presents a compilation of locations where FDR-PC was employed internationally following a chronological order. It also provides brief information on the publications. The table only considers cases that provided information on construction year and technique used, and it does not include test sections.

Brazil has been using FDR-PC for about three decades. According to Paiva & Oliveira [9], the technique has already recovered millions of square meters of pavements. For instance, the state of São Paulo frequently uses the technique, which has resulted in the rehabilitation of thousands of kilometres of pavements in that state. Authors mention several highways in which the technique was successfully used (SP-294, SP-272, SP-300, SP-304, SP-264, SP-141, SP-079, and SP-563) [10-12]. Furthermore, there are reports of FDR-PC usage in other Brazilian regions, especially in the state of Minas Gerais (highways BR-040, BR-459 and BR-135) [9, 10, 13].

Table 1. Summarised compilation of the international experience using FDR-PC.

Year	Location	Characteristics	Source
1985	Pahang, Malaysia	15-km-long section	Sufian et al. [5]
1989	Pahang, Malaysia	55-km-long section	Sufian et al. [5]
1990	Belgium	Area of 10,000 m^2	Jasienski & Rens [4]
1991	National Route N2, South Africa	23-km-long section	Collings [6]
1992	Znojmo, Czech Republic	300-mm-thick layer	Stehlik et al. [14]
1993	Belgium	Area of 50,000 m^2	Jasienski & Rens [4]
1994	Valladolid, Spain	-	Minguela [15]
1995	Acedera, Spain	220-mm-thick layer	Minguela [15]
1995	Amarillo, Texas, USA	260-mm-thick layer	Federal Highway Administration, FHWA [2]
1995	Ruta de la Plata, Spain	36-km-long section	Segarra [16]
1996	Mariembourg, Belgium	Area of 16,300 m^2	Jasienski & Rens [4]
1997	Ávila, Spain	4.5- km-long section	Minguela [15]
1998	Saint-Ghislain, Belgium	Area of 33,600 m^2	Jasienski & Rens [4]
1999	Spain	Area of 1,220,000 m^2	Minguela [15]
2000	Spain	Area of 1,547,000 m^2	Minguela [15]
2000	KwaZulu-Natal, South Africa	60-km-long section	Paige-Green & Ware [17]
2001	Belgium	Area of 7000 m^2	Jasienski & Rens [4]
2002–04	Malaysia	90-km-long section	Sufian et al. [5]
2004	Long County, Georgia, USA	1.8-km-long section	Lewis et al. [18]
2007	Laramie County, Wyoming, USA	First use in the region	Portland Cement Association, PCA [19]
2008	Powhatan and Goochland, Virginia, USA	-	Amarh et al. [20]
2009	Richland County, Montana, USA	-	Portland Cement Association, PCA [19]
2009	Wyoming, USA	230-mm-thick layer	Wilson & Guthrie [21]
2012	Hennepin, Minnesota, USA	-	Minnesota Department of Transportation, MnDOT [22]

Table 2 provides a brief description of some FDR-PC applications in Brazil in a chronological order. The table only presents cases that provided information on construction year and technique used, not including test sections.

Table 2. Summarised compilation of the Brazilian experience using FDR-PC

Year	Location	Characteristics	Source
1998	Highway BR-381, São Paulo–Belo Horizonte	Volume of 30,000 m^3	Silva & Miranda Jr [23]
2000	Highway SP-352, São Paulo	-	Paiva et al. [12]
2004	Highway SP-351, Bebedouro–Palmares Paulista, São Paulo	22-km-long section	Oliveira et al. [24]
2007	Highway SC-150 (BR-282), Santa Catarina	30-km-long section	Trichês & Santos [25]
2011	Highway BR-381, São Paulo–Belo Horizonte	-	Aranha [26]; Bessa et al. [27]
2012	Highway GO-222, Anápolis–Nerópolis, Goiás	8-km-long section	Santos et al. [28]
2013	Highway SC-463, Santa Catarina	23-km-long section	Luvizão [29]
2016	Highway SC-453, Tangará–Luzerna, Santa Catarina	35-km-long section	Fedrigo et al. [30]

3 Construction

The four main steps in the construction of FDR-PC are cement spreading, pulverisation (addition of water and mixing), compaction, and application of a surfacing layer [2]. Since most documents on FDR-PC are construction specifications, presenting a detailed description of the process is not one of the main objectives of this paper. However, this section briefly describes each of the mentioned steps based mainly on the USA experience which is used all over the world.

Figure 1. FDR-PC construction: (a) cement spreading; (b) pulverisation/mixing; (c) compaction; and (d) curing membrane application

Cement is spread in a controlled manner by spreader trucks specifically designed for this process (Figure 1a) [3]. It is also possible to perform this operation manually, even though it is seldomly used, especially in large projects where recycling machines are used. If it is necessary to correct the grain size distribution, it is also possible to spread additional aggregates before spreading the cement [2]. Pulverisation usually occurs to a depth of 100 mm to 300 mm, but modern recycling machines can pulverise to depths of 450 mm. The recycling machine mixes the existing materials with cement/virgin aggregates while injecting the proper amount of water from the water truck into the mixing chamber (Figure 1b) [2, 3].

Compaction generally takes place with heavy smooth-wheeled vibrating rollers and padfoot vibrating rollers operating in high-amplitude vibration mode (Figure 1c) [1]. Pneumatic tired rollers kneading action can help to eliminate excess water, but should be done with care to avoid removing cement. After compaction, using a proper curing method is necessary to achieve the required strength and inhibit shrinkage cracks. A membrane of residual bitumen from a slow setting emulsion is preferred (Figure 1d). Repeated wetting, and subsequent drying, is not advised as this promotes carbonation and a resultant loss in strength.

If it is not possible to prevent vehicle movements over the constructed section, a surface treatment (e.g. chip seal) can help to protect the recycled layer. Once the recycled layer has gained strength, it is possible to apply a bituminous surfacing layer, completing the process and providing a new pavement structure [3]. Table 3 provides details on the layer strength threshold and curing period before traffic release, based on Brazilian standards.

The current Brazilian standards for FDR-PC are also construction specifications developed by the National Department of Transport Infrastructure (DNIT), by the Santa Catarina State Department of Infrastructure (DEINFRA-SC), and by the Highway State Departments of Paraná (DER-PR) and São Paulo (DER-SP). These specifications are as follow:

- DER-PR ES-P 33/05 – Pavements: In situ pavement recycling with cement addition [31];
- DER-SP ET-DE-P00/035 – In situ asphalt pavement recycling with cement and crushed stone [32];
- DNIT 167/2013-ES – Pavements: Full-depth reclamation with Portland cement – Construction specification [33];
- DEINFRA-SC ES-P 09/16 – Pavements: Full-depth reclamation [34].

As mentioned, these standards only present best-practices for FDR-PC construction; they do not provide any information on the mix or structural design. Table 3 presents a comparison between these standards. The table shows that the standards suggest the same curing method and mainly use the strength and the degree of compaction to assure quality control; those developed by DER-PR and DER-SP also suggest ranges for field moisture content control. Furthermore, Table 3 shows how different the approach can be in a large country, which becomes evident when comparing the most recently published standards (DNIT and DEINFRA-SC) with those published a decade earlier (DER-PR and DER-SP). The main difference concerns the required grain size distribution. Figure 2 shows that there is no agreement between the standards, except for those developed by DER-PR and DER-SP. The comparison made in Table 4 also shows such differences.

Table 3. Comparison between Brazilian standards

Characteristic	Brazilian standard			
	DER-PR [31]	**DER-SP [32]**	**DNIT [33]**	**DEINFRA-SC [34]**
Recycling machine minimum milling depth (mm)	-	120	300	300
Maximum cement content (%)	-	-	-	3
Maximum RAP content (%)	-	-	50	50
Compaction effort	Brazilian intermediate*	Brazilian intermediate	AASHTO modified	AASHTO modified
Minimum degree of compaction (%)	100	100	98	100 (top) and 98 (bottom)
Field moisture content (%)	OMC [-1; +1]	OMC [-2; +1]	-	-
7-day UCS (MPa)	3.5–8.0	-	2.1–2.5	> 2.1
7-day ITS (MPa)	-	-	0.25–0.35	> 0.25
Curing method	Asphalt prime-coat	Asphalt prime-coat	Asphalt prime-coat	Asphalt prime-coat
Traffic release	After 7 days of curing	After surface treatment and adequate strength	After surface treatment; 3–7 days to verify possible deficiencies	After surface treatment

RAP: Reclaimed Asphalt Pavement; AASHTO: American Association of State Highway and Transportation Officials; OMC: Optimum Moisture Content; UCS: Unconfined Compressive Strength; ITS: Indirect Tensile Strength; *Approximately half the effort of AASHTO modified

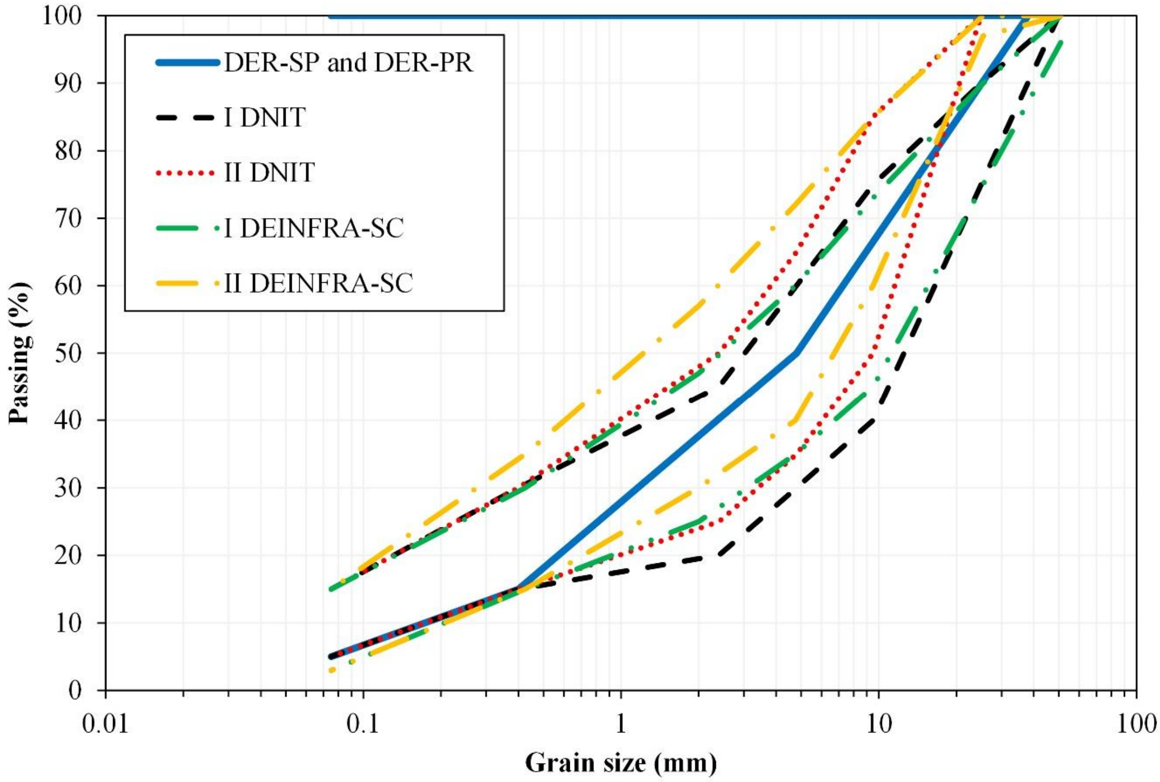

Figure 2. Grain size distribution envelopes suggested by Brazilian standards

Table 4. Characteristics of the envelopes suggested by Brazilian standards

Parameter	**Envelope**				
	DER-SP [32] and DER-PR [31]	**I DNIT [33]**	**II DNIT [33]**	**I DEINFRA-SC [34]**	**II DEINFRA-SC [34]**
Maximum grain size (mm)	25	37.5	19	50	19
Passing No. 10 sieve (%)	38–100	20–45	25–50	25–47	30–57
Passing No. 200 sieve (%)	5–100	5–15	5–15	3–15	3–15
Coefficient of curvature*	1	8.3	5.8	2.9	1.8
Coefficient of uniformity*	35	75	50	55	35

*Only for lower limit since upper limit does not allow effective size (D_{10}) determination

4 Advantages and disadvantages

This section presents a summary of advantages and disadvantages of FDR-PC based on the literature [3, 8, 15, 35, 36]. FDR-PC has unique technical advantages which are not available with other rehabilitation techniques. These are:

- Allows rehabilitating a distressed pavement or upgrading a weak pavement structure, due to the generation of a stabilised layer which will be homogeneous, stable and thicker, providing better mechanical characteristics.
- Reduces the vertical compressive stress at the subgrade and the horizontal tensile stress at the bottom of the asphalt wearing course, due to the inclusion of a stabilised layer.
- Provides a moisture- and frost-resistant stabilised layer.
- Recycles and improves existing materials which generally do not possess adequate technical characteristics.
- Allows rehabilitation under traffic since traffic is usually allowed on one lane of the road while construction occurs on the other.
- Maintains road elevation, avoiding problems with curb/gutter and overhead clearances. Taking into consideration the thickness of the new surfacing, milling a certain thickness of the upper pavement layer would be necessary.
- Generates minimal disturbance by construction traffic because of the fast construction cycle and small quantity of material volume transported in or out.
- Allows performing improvements in road geometry simultaneously with pavement rehabilitation.
- Portland cement acceptance and availability. The material is well-known and well-specified by the construction industry.

Besides technical advantages, the technique can also offer economic benefits. The main economic advantages of using Portland cement as the stabilizing agent in FDR are:

- Reduces costs of new material, as well as with its production and transportation since it reuses existing pavement materials.
- Allows a quick return of local traffic and avoids detours, which reduces user costs.
- It is one of the lowest cost alternatives for rehabilitating a distressed pavement, especially in comparison to thick structural overlay or removal and replacement. It is usually 25–50% cheaper than the latter.
- Portland cement is usually cheaper than asphalt cement.

All the previously mentioned advantages are important, but one of the main reasons for FDR-PC relevance is its environmental-friendly aspects. Some of the environmental benefits of the technique are:

- Conserves natural resources by recycling existing materials and avoids the disposal of materials in landfills, especially in comparison with the removal and replacement of the base layer (Table 5).
- Reduces energy consumption since it is a cold recycling technique (performed at ambient temperature), especially in comparison with the removal and replacement of the base layer (Table 5).
- Decreases the carbon dioxide emission and the impact in the adjacent area (erosion, dust, etc) due to the reduced transport needed. Since the cement industry is a significant source of carbon emission, using alternative cementitious binders (e.g. fly ash geopolymers) could further assist [37, 38].
- Causes minimal environmental impacts since it is an in situ technique, avoiding plant installation problems (vegetation removal, drainage change, etc).

Complementing the advantages reported above, Table 6 presents a comparison between FDR-PC and other rehabilitation techniques (structural overlay and removal and replacement).

Table 5. Benefits in material and energy use of FDR-PC compared with removal and replacement [35]

Characteristic	**FDR-PC base**	**Base removal and replacement**
New materials (t)	300	4500
Material landfilled (m^3)	0	2100
Fuel consumed (L)	1900	11,400

Based on 1.6 km of 7.3-m-wide 2-lane road, 150-mm base

Table 6. Benefits of FDR-PC in comparison to other rehabilitation techniques [19]

Benefit	**Rehabilitation technique**		
	FDR-PC	**Structural overlay**	**Removal and replacement**
New structure	X	X	X
Fast construction	X	X	
Minimal traffic disruption	X		
Minimal haulage	X		
Conserve resources	X		
Possible to maintain existing elevation	X		X
Low cost	X		

As previously seen, FDR-PC offers several advantages considering different aspects. However, it is necessary to consider FDR-PC disadvantages before choosing it as the rehabilitation option. Some of its disadvantages and limitations are as follows:

- The recycling of a non-uniform structure, regarding both materials and thicknesses, may result in a heterogeneous recycled mixture [15].

- FDR-PC is a single lane strategy, requiring adequate precautions to avoid longitudinal cracks [15].
- Cement stabilised materials inherently shrink and, as a consequence, some shrinkage cracks may reflect through the asphalt wearing course. Adequate curing methods and crack minimisation strategies can help to inhibit such problems [3, 36].
- FDR-PC may generate a brittle material, which may result in early fatigue fracture of the layer, resulting in reflection cracks on the pavement surface. Thicker layers with less strength (cement contents as low as 2%) are preferred to avoid such brittleness [3, 36].
- Although FDR-PC construction cost is generally cheaper than that of other rehabilitation techniques, recent life-cycle cost analysis studies considering agency and user costs show that FDR-PC might become more expensive [39]. Environmental benefits are usually not considered in the life-cycle analysis.

5 Mix design

Table 7 summarises the main characteristics of some internationally known mix design methods. The table presents an Australian (Austroads), an American (PCA) and three European methods (Instituto Español del Cemento y sus Aplicaciones – IECA, a German method and the French method). Austroads method is a guide for in situ stabilisation in general (not specifically FDR-PC) including virgin and recycled materials.

Table 7. International FDR-PC mix design methods

Characteristic	PCA [3]	IECA [8]	German method [36]	Austroads [40]	French method [41, 42]
Country	USA	Spain	Germany	Australia and New Zealand	France
Existing material characterisation*	Sieve analysis	Sieve analysis and Atterberg limits	Sieve analysis and Atterberg limits	Sieve analysis and Atterberg limits	Sieve analysis and MBV
Grain size distribution envelope	Figure 3	-	Figure 3	Figure 3	European Standard EN 13285
Maximum RAP content (%)	50	-	-	-	Usually between 5 and 20
Compaction effort	Standard Proctor	AASHTO modified	AASHTO modified	Standard Proctor or AASHTO modified	AASHTO modified
Main design parameter	UCS	UCS	UCS	UCS	Direct tensile strength and stiffness (or estimated from ITS)
Specimen dimensions (mm)	101.6 (diameter) × 116.4 (height)	-	150 (diameter) × 127 (height)	-	-
Typical cement content (%)	-	≥ 4	2–4	1–5.5	4–6
Minimum number of cement contents	3	-	3	-	-
Minimal number of specimens	2	3	2	-	-
Curing type	Moisture room	Moisture room	Moisture room (or accelerated in oven)	Moisture room (or accelerated in oven)	Moisture room
Curing time (days)	7	7	7	28	360 (or estimated from 28-day results)
Strength (MPa)	2.1–2.8	> 2.5 MPa (depending on traffic and subgrade)	< 4: Lightly cemented; 4–10: Cemented	< 1: Modified; 1–4: Lightly bound; > 4: Heavily bound	≥ 0.5
Additional tests	Moisture sensitivity (tube suction test)	Density sensibility and workability	ITS	Capillary rise, swell, drying shrinkage and erodibility	Fatigue (two-point bending test)

RAP: reclaimed asphalt pavement; PCA: Portland Cement Association; IECA: Instituto Español del Cemento y sus Aplicaciones; CIMBÉTON: Centre d'information sur le ciment et ses applications; MBV: methylene blue value; AASHTO: American Association of State Highway and Transportation Officials; UCS: unconfined compressive strength; ITS: indirect tensile strength; *Dry material collected using a recycling machine

Since the test is simple and cheap, 7-day unconfined compressive strength is the main design parameter in most of the methods (excepting the French one, which suggests 28- or 360-day direct tensile strength). There is no consensus in the level of strength to be achieved, but there is an agreement that the compaction should follow AASHTO (American Association of State

Highway and Transportation Officials) modified effort (only PCA does not suggest this effort). It is important to note that a few researchers have also used the shear gyratory compactor [43, 44, 45]. They reported satisfactory results, but such equipment is rather expensive and not common in many laboratories. Furthermore, in addition to strength tests, all methods suggest tests to characterise other important properties (e.g. durability).

The typical cement content is variable, depending especially on the type of material desired (lightly or heavily stabilised) [36, 40]. Due to the variability of the existing materials, some methods suggest high quantities of cement as the minimum content [8]. It is worth noting that, although not presented by any of the mentioned methods, the initial consumption of stabiliser (ICS) test, which is common in many countries (e.g. South Africa), is critical to ensure a minimum quantity of binder for cement stabilised materials. Sometimes, FDR-PC also incorporates asphalt emulsion or foamed asphalt. Xiao et al [1] presented a comprehensive review of how to determine the optimum content of such stabiliser agents. They reported that the most common design methods are Hveem, Marshall and Superpave, with some modifications.

Figure 3 presents the grain size distribution envelopes suggested by some of these methods. Additionally, Table 8 also compares some characteristics regarding the envelopes. The figure shows that the envelopes suggested by the German method and Austroads are similar, although the first is wider than the latter. PCA uses only three sieves for grain size distribution control, but it limits the RAP content to 50% unless approved by the engineer and included in an adequate mixture design. In general, PCA and the German method seem the most detailed, since both cover all considered characteristics except one (typical cement content and maximum RAP content, respectively). On the other hand, the French method is the one that most diverges from the others, especially because of the suggested tests (e.g. methylene blue value and direct tensile strength). Designing a mix using the latter also depends on traffic and characteristics of recycling equipment and recycled mixture.

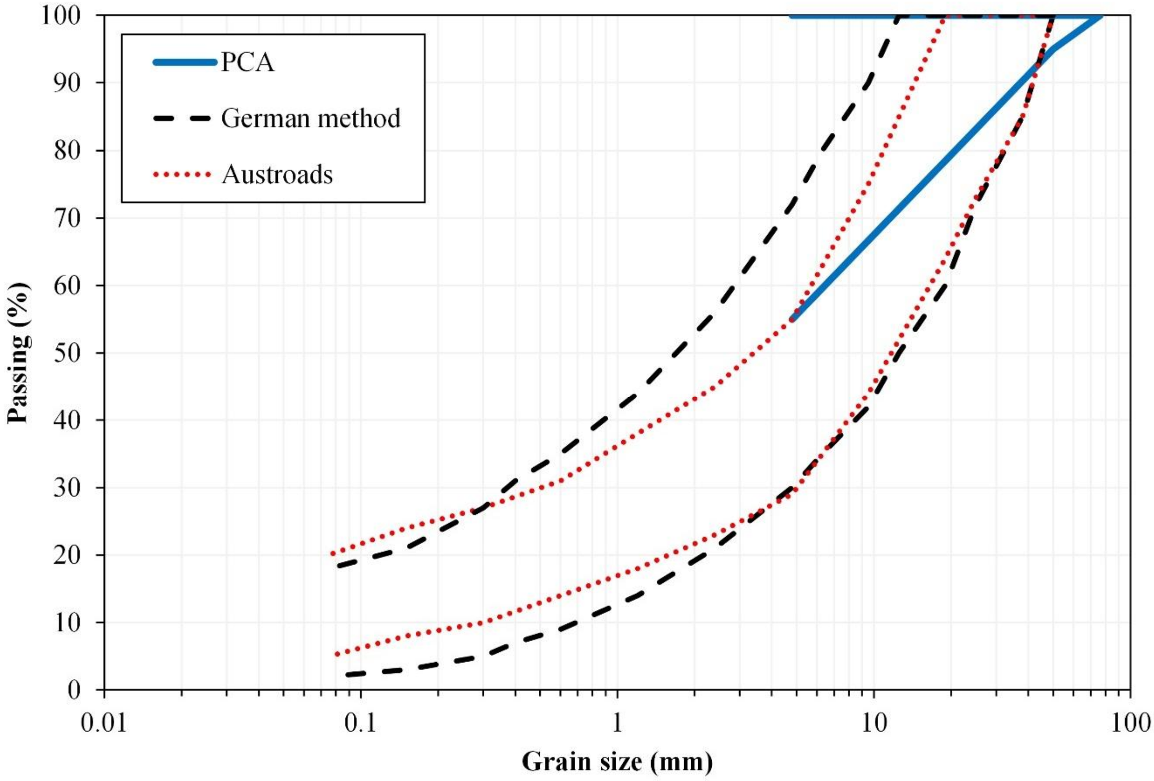

Figure 3. Grain size distribution envelopes suggested by mix design methods

Table 8. Characteristics of the envelopes suggested by mix design methods

Parameter	Envelope		
	PCA [3]	**German method [36]**	**Austroads [40]**
Maximum grain size (mm)	50	37.5	37.5
Passing No. 10 sieve (%)	-	21–56	23–45
Passing No. 200 sieve (%)	-	2–18	5–20
Coefficient of curvature*	-	1.8	5.6
Coefficient of uniformity*	-	30	50

*Only for lower limit since upper limit does not allow effective size (D_{10}) determination

In Brazil, there is no consensus on a mix design method for FDR-PC. Although the standards mentioned in Section 3 present technical characteristics that the recycled layer should follow (Table 3), there is no information on the mix design. Some of them [31, 33] only mention the importance of an adequate mix design, covering possible material and thickness variations along the length of the road. In the absence of such a method, it is common to use standards developed for soil-cement mix design in FDR-PC works [10]. As a consequence, some authors started focusing on this topic [13, 46].

Fedrigo et al. [46] adapted the Austroads method to Brazilian recycled pavement materials. The studied mixtures included different cement and RAP contents and four base materials of existing pavements (graded crushed stone, soil-cement, cement-treated crushed stone and lateritic soil), resulting in an unofficial draft standard. For each kind of mixture, the method presents contour plots relating 7-day strength (UCS and ITS) to cement and RAP contents to help decide the initial cement content. Figure 4 presents an example of such contour plots for mixtures containing graded crushed stone base material. Maximum density and optimum moisture content for the cement content are determined using compaction tests (AASHTO modified effort). Due to the inherent variability of the existing materials, it is still necessary to perform strength tests using three different cement contents (initial content ± 1%). The method also presents details on specimen preparation and testing, as well as acceptance criteria for the results. Furthermore, depending on environmental conditions, the method suggests additional testing to reduce the likelihood of moisture sensitivity, unacceptable shrinkage cracking and erosion.

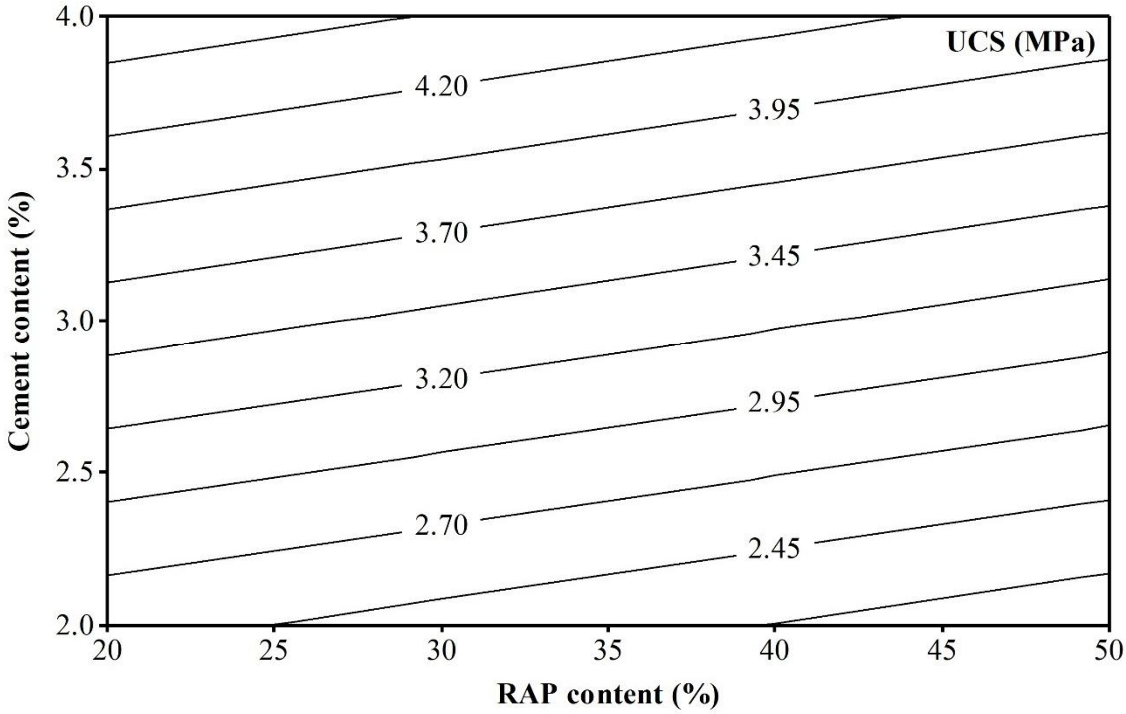

Figure 4. Example of contour plot relating UCS to cement and RAP contents for mix design purposes [46]

6 Structural design

There are limited studies on the structural design of FDR-PC layers in the literature, with the common practice being empirical methods. In this regard, some researchers determined layer structural coefficients of such materials based on the AASHTO guide for design of pavement structures of 1993, obtaining similar values to those of conventional cement stabilised materials [43, 47, 48]. Several papers reported studies on rational design parameters (e.g. resilient modulus) or even on the fatigue behaviour of FDR-PC materials [15, 29]. However, research aiming at developing/adapting mechanistic-empirical structural design methods for FDR-PC started being reported only in the last few years [20, 49-52].

It is important to note that FDR-PC is a single thick layer process, whereas conventional cement stabilised layers are generally constructed in two layers with a maximum thickness of 150 mm each. From an understanding of the performance of such a pavement, the lower cemented layer is usually the one that starts breaking down first (especially when there is a minimal bond between layers). The modular ratio between subsequent layers should not be larger than about 10, to avoid the glass plate on a feather mattress effect. Inadequate support by the lower layers will also limit the degree of field compaction.

Table 9 summarises the main characteristics of some internationally known structural design methods. The table presents methods from the USA (AASHTO Mechanistic-Empirical Pavement Design Guide, MEPDG), South Africa (South African Mechanistic Design Method, SAMDM), Australia and New Zealand (Austroads Pavement Design Guide), and France (French design method). Besides, Table 9 also presents a recently reported Brazilian mechanistic-empirical method.

Note that most of the methods do not include recycled materials, only conventional cement stabilised materials. The French method is the exception, considering mixtures with up to 20% RAP. The characteristics shown in Table 9 are those that apply to cement stabilised layers, but the documents cited in the table provide the complete pavement design procedures (i.e. materials, traffic, climate, etc). The methods follow similar theoretical bases and are usually available in manuals and software.

Table 9 shows that fatigue is the main structural design criterion, but some methods use strain-based fatigue models while others use stress-based models. Besides, considering that each model has its particular characteristics (e.g. material constants, calibration coefficients, shift factors), it is expected that results will not be the same. The methods from South Africa and the USA also evaluate a second failure mode related to the compressive stress at the top of the layer to control crushing/erosion. All methods use flexural tests to characterise the material properties for design; once again, the only exception is the French method. However, there is no universal flexural test method, and this may affect the results [53]. Testing the materials is always preferred, but using estimated/typical property values is also possible.

Table 9. International and Brazilian structural design methods

Characteristic	French method [41, 42, 54]	SAMDM [55, 56]	Austroads Pavement Design Guide [57]	MEPDG [58, 59]	MeDiNa [60, 61]
Country	France	South Africa	Australia and New Zealand	USA	Brazil
Material	Cement stabilised or recycled	Conventional cement stabilised	Conventional cement stabilised	Conventional cement stabilised	Conventional cement stabilised
Main failure mode	Fatigue	Fatigue (additional: crushing)	Fatigue	Fatigue (additional: erosion)	Fatigue
Tests used to develop models	Two-point bending test	Flexural test and APT	Flexural test and APT	Flexural test, cyclic impact erosion test and field data (FWD and traffic)	Flexural test and indirect tensile test
Fatigue models	$\sigma = \sigma_6 \left(\frac{N_f}{10^6}\right)^b$	$N_f = SF10^{c\left(1-\frac{\varepsilon}{dFT\varepsilon_b}\right)}$	$N_f = RF\left(\frac{SFk}{\varepsilon}\right)^{12}$	$N_f = 10^{\left[\frac{k_{c1}\beta_{c1}\left(\frac{\sigma}{FTS}\right)}{k_{c2}\beta_{c2}}\right]}$	$N_f = 10^{\left(a+\frac{\sigma}{FTS}\right)}$
Main tests required	360-day direct tensile strength	7-day UCS and FTS ($FT\varepsilon_b$)	28-day UCS and 90-day FTS	28-day UCS and 28-day FTS	FTS and ITS
Typical UCS (MPa)	-	1.125–2.250	-	1.8–5.5	-
Typical tensile strength (MPa)	0.35–0.70 (at 10^6 cycles)*	-	1.0–1.5 (flexural)	0.25–0.75 (flexural)	0.78–2.27 (flexural/indirect)
Typical modulus (MPa)	13,000–2,0000 (direct tensile)*	1500–2000 (APT)	3000–5000 (flexural)	750–1100 (flexural)	6000–16,000 (flexural/indirect)
Typical $FT\varepsilon_b$	-	125–145	-	-	-
Observations	Properties can be estimated using 28-day results and ITS tests; Frost-thaw evaluation	Two-phase analysis: effective fatigue and equivalent granular	FTS can be estimated using UCS; Post-cracked phase may be considered	Three input levels (testing; estimating; typical values); Durability and shrinkage models; Damage and distress transfer functions not calibrated	Modulus decrease follows a sigmoid function; Laboratory models only

SAMDM: South African Mechanistic Design Method; SANRAL: South African National Roads Agency SOC Limited; MEPDG: Mechanistic-Empirical Pavement Design Guide; AASHTO: American Association of State Highway and Transportation Officials; NCHRP: National Cooperative Highway Research Program; CIMBÉTON: Centre d'information sur le ciment et ses applications; APT: accelerated pavement testing; FWD: falling weight deflectometer; FTS: flexural tensile strength; $FT\varepsilon_b$: flexural tensile strain at break; σ/ε: tensile stress/strain at the bottom of the layer; σ_6: stress level at 10^6 cycles; N_f: fatigue life; RF: reliability factor; SF: shift factors; a, b, c, d, and k: constants; k_{c1}, k_{c2}, β_{c1}, and β_{c1}: calibration coefficients; UCS: unconfined compressive strength; ITS: indirect tensile strength; *Depends on qualities of recycling equipment and recycled mixture

Although theoretically similar, each method has its own approach. South African and Australian methods incorporate the evaluation of the stabilised layer in a post-cracked condition, considering properties and failure modes of a granular layer. On the other hand, the methods from the USA and France present models for predicting the durability of the layer. Moreover, the French method presents structural design catalogues containing recycled layers, developed using its mechanistic-empirical approach [41]. Spain also uses the same practice [8, 15].

Brazilian researchers have been working on a mechanistic-empirical method for decades, releasing its first version in 2007 [60]. The current version, known as MeDiNa (National Design Method), comes with manuals and software [61]. Table 9 shows that the Brazilian method also considers fatigue as the main failure mode for conventional cement stabilised materials. As with most international methods, it also does not take into account recycled materials. Although it states that testing is preferable, the method presents typical properties of Brazilian cement stabilised materials [62, 63] and roller-compacted concrete [64]. However, the method has deficiencies even for conventional cement stabilised materials. For instance, it uses fatigue models based only on laboratory results without field calibration, thus showing the importance of advancing the knowledge of such materials, including FDR-PC.

7 Laboratory and field behaviour of FDR-PC materials

This section presents characteristics of the laboratory and field behaviour of FDR-PC mixtures.

7.1 Laboratory behaviour

Based on previous studies, Tables 10 and 11 present ranges of strength of FDR-PC materials. Similarly, Tables 12 and 13 present ranges of elastic modulus and cyclic modulus, respectively. These tables consider only mixtures containing RAP and specific software (Engauge digitizer) allowed obtaining values presented in graphs by some researchers.

Table 10. Ranges of strength reported for FDR-PC materials (part 1)

Source	Country	Existing base material	Cement content (%)	RAP content (%)	Compact. method	Curing time (days)	Test temp. (°C)	UCS (MPa)	ITS (MPa)	FTS (MPa)	DTS (MPa)
Paiva & Oliveira [9]	Brazil	LG	4	34	BI	3-28	-	1.60–4.99	-	-	-
Oliveira [10]	Brazil	Soil-cement	3–5	30	SP	7	-	0.97–2.82	-	-	-
Oliveira [10]	Brazil	LG	3–5	85	SP	7	-	1.33–2.17	-	-	-
Paiva & Oliveira [11]	Brazil	Soil-cement	3	77	AM	7	-	0.72–2.28	0.10–0.45	-	-
Gusmão [13]	Brazil	GCS	3–5	40–60	BI	1–28	-	0.49–3.00	0.04–0.42	-	-
Minguela [15]	Spain	Granular	2.5–4.5	33	AM	7–548	-	1.31–5.17	0.19–0.50	0.45–0.69	-
Wilson & Guthrie [21]	USA	Silty sand	4	50–70	AM	7–90	-	1.52–6.96	-	-	-
Grilli et al. [45]	Italy	Granular	3	50–80	GC	7	25	4.20–6.20	0.21–0.31	-	-
Taha et al. [47]	Oman	Granular	3–7	70–100	AM	3–28	-	0.80–3.60	-	-	-
Castañeda López [49]; Castañeda López et al. [50]	Brazil	GCS	2–6	20–70	AM	28	24 ± 3	-	-	0.21–1.53	-
Adresi et al. [65]	Iran	Granular	3–7	40–80	AM	7	25–50	1.20-5.80	0.20-0.95	-	-
Chakravarthi et al. [66]	India	Granular	2–6	25–100	AM	7	-	0.40–3.40	0.06–0.74	-	-
Dalla Rosa & Muller [67]	Brazil	Granular	1–7	60–100	AM	7	-	-	-	0.06–1.66	-
Dalla Rosa et al. [68]	Brazil	Granular	3.4	35	AM	28	-	-	0.45	-	-
D'avila [69]; D'avila et al. [70]	Brazil	CTCS	2–6	20–70	AM	28	24 ± 3	-	-	0.44–1.34	-
Dellabianca [71]	Brazil	LG	2	25	BI	3–28	-	0.70–1.30	-	-	-
El Euch Khay et al. [72]	Tunisia	Granular	6	25–100	AM	7–28	-	5.85–14.7	1.04–1.55	1.08–2.38	-
Ely [73]	Brazil	GCS	4	70	BI	3–14	-	1.29–2.08	0.19–0.28	-	-
Ely [73]	Brazil	GCS	4	70	AM	3–14	-	2.03–2.72	0.21–0.45	-	-
Fedrigo [74]; Fedrigo et al. [75]	Brazil	GCS	2–4	20–50	AM	3–14	-	1.61–6.08	0.34–1.0	-	-
Fedrigo [74]; Fedrigo et al. [75]	Brazil	GCS	4–6	20–50	BI	3–14	-	1.61–5.78	0.29–1.11	-	-
Ghanizadeh et al. [76]	Iran	Clayey gravel	3–6	20–60	AM	7–28	-	1.60–4.10	-	-	-
Ghanizadeh et al. [76]	Iran	Clayey sand	3–6	20–60	AM	7–28	-	1.30–4.80	-	-	-

RAP: reclaimed asphalt pavement; GCS: graded crushed stone; CTCS: cement-treated crushed stone; LG: lateritic gravel; AM: AASHTO modified; SP: standard Proctor; BI: Brazilian intermediate; VC: vibratory compactor; GC: gyratory compactor; UCS: unconfined compressive strength; ITS: indirect tensile strength; FTS: flexural tensile strength; DTS: direct tensile strength

Table 11. Ranges of strength reported for FDR-PC materials (part 2)

Source	Country	Existing base material	Cement content (%)	RAP content (%)	Compact. method	Curing time (days)	Test temp. (°C)	UCS (MPa)	ITS (MPa)	FTS (MPa)	DTS (MPa)
Ji et al. [77]*	China	CTCS	3–4	30–100	VC	7–90	-	2.50–7.70	0.25–0.77	-	-
Jiang et al. [78]*	China	CTCS	3–4	30–100	VC	90	-	-	0.27–0.78	-	-
Gonzalo-Orden et al. [79]	Spain	Granular	3	35	AM	90	-	3.73	0.40	0.60	-
Guthrie et al. [80]	USA	Granular	0.5–2	25–100	AM	7	-	0.76–4.55	-	-	-
Isola et al. [81]	Italy	Granular	3.5–4	30–70	AM	7	-	3	1.20–1.40	-	-
Katsakou & Kolias [82]; Kolias et al. [83]	Greece	Granular	3–5	25–100	VC	1–60	0–35	1.0–15.5	0.15–1.50	0.10–3.45	0.1–1.7
Kleinert [84]	Brazil	CTCS	1–7	7–92	AM	3–14	-	1.00–5.57	0.17–1.18	-	-
Kleinert [84]; Kleinert et al. [85]	Brazil	Soil-cement	1–7	7–92	AM	3–14	-	1.89–6.49	0.21–1.22	-	-
Kolias [86]; Kolias [87]	Greece	Granular	5	25–100	VC	7–360	20	5.03–11.7	0.43–1.43	1.67–2.16	-
Ma et al. [88]	China	-	1–3	100	VC	7	-	-	0.16–0.50	-	-
Melese et al. [89]	Canada	Granular	2–6	20–60	SP	7–56	-	1.50–4.20	0.43–0.48	-	-
Mohammadinia et al. [90]	Australia	-	2–4	100	AM	1–28	-	2.80–5.40	-	-	-
Oliveira & Paiva [91]	Brazil	LG	3	35	AM	3–28	-	2.14–3.48	0.29–0.55	-	-
Schreinert [92]	Brazil	Lateritic soil	1–7	7–92	AM	3–28	24 ± 3	-	0.10–0.98	0.28–1.43	-
Suddeepong et al. [93]	Thailand	GCS	3–7	20–80	AM	7–28	-	1.80–14.5	-	-	-
Suebsuk et al. [94]	Thailand	LG	1–5	30–100	AM	7–28	-	0.10–4.90	-	-	-
Sufian et al. [95]	Malaysia	GCS	3	25–100	AM	1–28	-	0.40–6.03	0.14–0.55	-	-
Trichês et al. [96]	Brazil	Granular	3–4.5	35	AM	3–28	25	0.97–4.84	0.21–0.71	0.24–0.82	-
Trichês et al. [96]	Brazil	GCS	2–4	30	BI	3–28	25	0.54–2.65	0.22–0.84	-	-
Trichês et al. [96]	Brazil	Granular	2–4	25	AM	7–28	25	1.24–2.86	0.27–0.70	-	-
Yuan et al. [97]	USA	Granular	2–6	50–100	SP	7	-	0.70–7.00	0.12–0.72	-	-

RAP: reclaimed asphalt pavement; GCS: graded crushed stone; CTCS: cement-treated crushed stone; LG: lateritic gravel; AM: AASHTO modified; SP: standard Proctor; BI: Brazilian intermediate; VC: vibratory compactor; GC: gyratory compactor; UCS: unconfined compressive strength; ITS: indirect tensile strength; FTS: flexural tensile strength; DTS: direct tensile strength; *Only mixtures without virgin aggregates

Table 12. Ranges of elastic modulus reported for FDR-PC materials

Source	Country	Existing base material	Cement content (%)	RAP content (%)	Compact. method	Curing time (days)	Test temp. (°C)	CEM (MPa)	FEM (MPa)	DTEM (MPa)	NDEM (MPa)
Minguela [15]	Spain	Granular	2.5–4.5	33	AM	7–481	-	690–3502	-	-	-
Grilli et al. [45]	Italy	Granular	3	50–80	GC	28	20	-	-	-	8100–10,000
Castañeda López [49]; Castañeda López et al. [50]	Brazil	GCS	2–6	20–70	AM	28	24 ± 3	-	1422–13,255	-	-
Chakravarthi et al. [66]	India	Granular	2–6	25–100	AM	7	-	20–380	-	-	-
D'avila [69]; D'avila et al. [70]	Brazil	CTCS	2–6	20–70	AM	28	24 ± 3	-	1800–7600	-	-
El Euch Khay et al. [72]	Tunisia	Granular	6	25–100	AM	28	-	-	-	-	4687–15,430
Ghanizadeh et al. [76]	Iran	Clayey gravel	3–6	20–60	AM	28	-	9.3–38.5	-	-	-
Ghanizadeh et al. [76]	Iran	Clayey sand	3–6	20–60	AM	28	-	18.4–38	-	-	-
Ji et al. [77]*	China	CTCS	3–4	30–100	VC	7–90	-	476–1521	-	-	-
Katsakou & Kolias [82]; Kolias et al. [83]	Greece	Granular	3–5	25–100	VC	1–60	20	1200–18,500	3500–20,000	500–20,000	-
Kolias [86]; Kolias [87]	Greece	Granular	5	25–100	VC	28–720	0.5–30	5000–24,100	-	-	15,100–31,200
Melese et al. [89]	Canada	Granular	2–6	20–60	SP	28	-	2400–11,500	-	-	-
Yuan et al. [97]	USA	Granular	2–6	50–100	SP	7	-	-	-	-	5200–14,000
Fedrigo et al. [98]	Brazil	Lateritic soil	2–4	20–70	AM	28	24 ± 3	-	983–2908	-	-

RAP: reclaimed asphalt pavement; GCS: graded crushed stone; CTCS: cement-treated crushed stone; AM: AASHTO modified; SP: standard Proctor; GC: gyratory compactor; VC: vibratory compactor; CEM: compressive elastic modulus; FEM: flexural elastic modulus; DTEM: direct tensile elastic modulus; NDEM: elastic modulus (non-destructive methods); *Only mixtures without virgin aggregates

Table 13. Ranges of cyclic modulus reported for FDR-PC materials

Source	Country	Existing base material	Cement content (%)	RAP content (%)	Compact. method	Curing time (days)	Test temp. (°C)	Load freq. (Hz)	TRM (MPa)	ITRM (MPa)	FRM (MPa)	CDM (MPa)
Mallick et al. [43]; Mallick et al. [44]	USA	Granular	5	67	GC	90	-	-	-	10,469	-	-
Grilli et al. [45]	Italy	Granular	3	50–80	GC	28	10–30	0.1–20	-	-	-	3300–9600
Puppala et al. [48]	USA	-	2–4	100	SP	7	-	1	200–515	-	-	-
Castañeda López [49]; Castañeda López et al. [50]	Brazil	GCS	2–6	20–70	AM	28	24 ± 3	5	-	-	2913–7725	-
Dalla Rosa et al. [68]	Brazil	Granular	3.4	35	AM	28	-	1	-	16,000	-	-
Dellabianca [71]	Brazil	LG	2	25	BI	7	-	-	450–800	-	-	-
Ely [73]	Brazil	GCS	4	70	BI	3–14	24 ± 3	1	-	3663–7892	-	-
Ely [73]	Brazil	GCS	4	70	AM	3–14	24 ± 3	1	-	4865–8420	-	-
Fedrigo [74]; Fedrigo et al. [75]	Brazil	GCS	2–4	20–50	AM	3–14	24 ± 3	1	-	10,873–25,719	-	-
Fedrigo [74]; Fedrigo et al. [75]	Brazil	GCS	4–6	20–50	BI	3–14	24 ± 3	1	-	10,390–24,842	-	-
Fedrigo et al. [75]	Brazil	GCS	2	50	AM	3–14	24 ± 3	1	88–1412	-	-	-
Kleinert [84]	Brazil	CTCS	1–7	7–92	AM	3–14	24 ± 3	1	-	484–20,031	-	-
Kleinert [84]; Kleinert et al. [85]	Brazil	Soil-cement	1–7	7–92	AM	3–14	24 ± 3	1	-	2199–19,357	-	-
Kolias [87]	Greece	Granular	5	25–100	VC	720	4–30	1–16	-	-	-	7100–23,600
Mohammadinia et al. [90]	Australia	-	2–4	100	AM	1–7	-	1	200–3200	-	-	-
Oliveira & Paiva [91]	Brazil	LG	3	35	AM	28	25	1	-	8076	-	-
Schreinert [92]	Brazil	Lateritic soil	1–7	7–92	AM	3–28	24 ± 3	1	-	860–16,927	-	-
Sufian et al. [95]	Malaysia	GCS	3	25–100	AM	1–28	25	-	-	1267–15,500	-	-
Trichês et al. [96]	Brazil	GCS	2–4	30	BI	28	25	1	602–2615	-	-	-
Trichês et al. [96]	Brazil	Granular	2–4	25	AM	7–28	25	1	2669–5518	-	-	-
Fedrigo et al. [98]	Brazil	Lateritic soil	2–4	20–70	AM	28	24 ± 3	5	-	-	1226–4163	-
Godenzoni et al. [99]	Italy	Granular	3	33	Not specified	2520	0–50	0.1–20	-	-	-	3752–9390
Graziani et al. [100]	Italy	Granular	3	33	Not specified	2520	0–50	0.1–20	-	-	-	3300–7500
Louw et al. [101]	USA	Granular	5	50	AM	1440	-	1	12,000–17,500	-	-	-
Romeo et al. [102]	Italy	Granular	3	Not specified	AM	90	-	1	650–750	-	-	-

RAP: reclaimed asphalt pavement; GCS: graded crushed stone; CTCS: cement-treated crushed stone; LG: lateritic gravel; AM: AASHTO modified; BI: Brazilian intermediate; SP: standard Proctor; GC: gyratory compactor; VC: vibratory compactor; TRM: triaxial resilient modulus; ITRM: indirect tensile resilient modulus; FRM: flexural resilient modulus; CDM: compressive dynamic/complex modulus

Figure 5 shows box and whisker plots for all values of strength found in the literature (Tables 10 and 11). Approximately 1200 values from 43 studies were used to compile Figure 5. The whiskers represent the minimum and maximum values. The boxes represent the first quartile (25% of data are below this value), the median and the third quartile (25% of data are above this value).

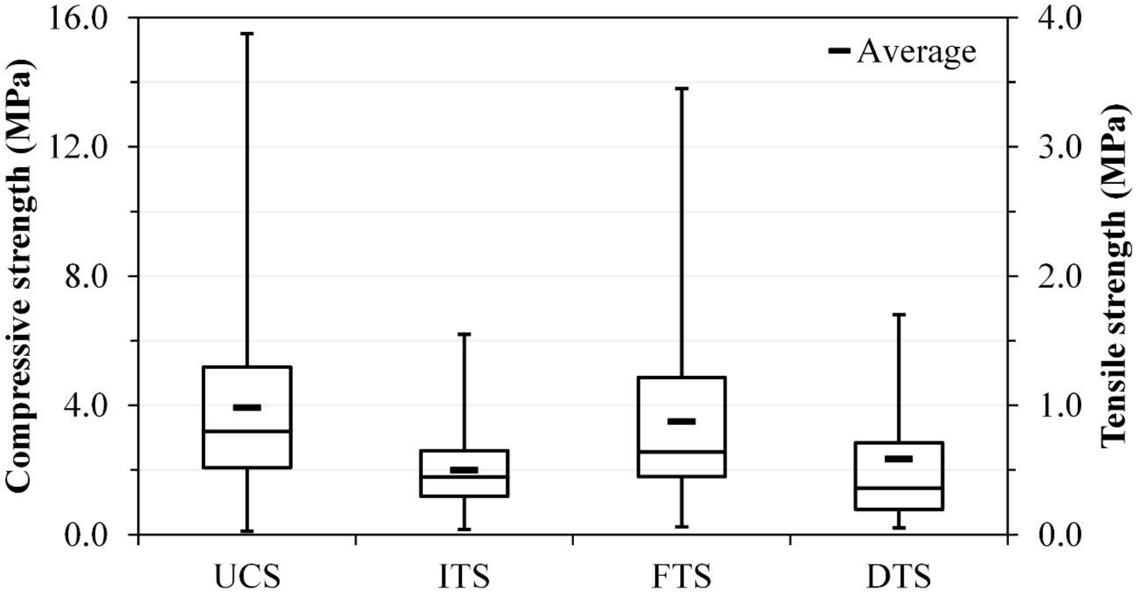

Figure 5. Box and whisker plots for the strength values reported in previous research

The average values of unconfined compressive strength (UCS), indirect tensile strength (ITS), flexural tensile strength (FTS) and direct tensile strength (DTS) are 4.0 MPa, 0.5 MPa, 0.9 MPa and 0.6 MPa, respectively. The values of ITS and DTS are similar, and the ratio of tensile to compressive strength varies from 10% to 25%. About 75% of the individual values of UCS, ITS, FTS and DTS are lower than 5.2 MPa, 0.65 MPa, 1.2 MPa and 0.7 MPa, respectively. Furthermore, the 90th percentiles (90% of data are below this value) are equal to 7.5 MPa for

UCS, 0.85 MPa for ITS, 1.67 MPa for FTS and 1.53 MPa for DTS. Although only a few studies focused on the flexural tensile strain at break of FDR-PC materials, this property seems to be preferable for the structural design of cement stabilised materials [53]. Flexural tensile strain at break of FDR-PC materials varies from 100 $\mu\varepsilon$ to 1200 $\mu\varepsilon$ for FDR-PC [50, 70, 98].

Figure 6 shows box and whisker plots for the values of elastic modulus (Figure 6a) and cyclic modulus (Figure 6b) found in the literature (Tables 12 and 13). The figures also present field modulus values (discussed in Section 7.2). Figure 6 included approximately 700 values from 42 studies. The average values of elastic modulus under compressive (CEM), flexural (FEM) and direct tensile (DTEM) conditions are similar (5500–5900 MPa). However, the average elastic modulus obtained using non-destructive methods (e.g. ultrasonic pulse velocity test), NDEM, is higher (16,500 MPa) because of the lower strain values during the test. Besides, more than 75% of the individual values of CEM, FEM, DTEM and NDEM are lower than 9600 MPa, 7200 MPa, 5900 MPa and 20,600 MPa, respectively. Furthermore, the 90th percentiles are equal to 17,340 MPa for CEM, 13,330 MPa for FEM, 12,250 MPa for DTEM and 28,590 MPa for NDEM.

Figure 6b shows similarities between the average resilient modulus under triaxial (TRM) and flexural (FRM) conditions (3600 MPa and 3400 MPa, respectively), which agrees with statements by Fedrigo et al. [75]. Moreover, compressive dynamic/complex modulus (CDM) average value (5900 MPa) is similar to the average elastic modulus measured using static loading conditions (Figure 6a). However, the indirect tensile resilient modulus (ITRM) average value (9900 MPa) is higher than all modulus values measured using static or cyclic loading conditions. The third quartile for TRM, ITRM, FRM and CDM are 1900 MPa, 13,900 MPa, 4400 MPa and 7200 MPa, respectively. Additionally, 90% of data are below 14,300 MPa for TRM, 18,700 MPa for ITRM, 4860 MPa for FRM and 13,330 MPa for CDM.

The graphs in Figures 5 and 6 disregard all specific testing characteristics (e.g. cement and RAP contents, curing time, testing temperature, and so on). However, based on the analysed laboratory studies, Table 14 shows the effect of some of these characteristics on the mechanical and durability properties of mixtures produced using FDR-PC. The following sections discuss some of these effects in detail.

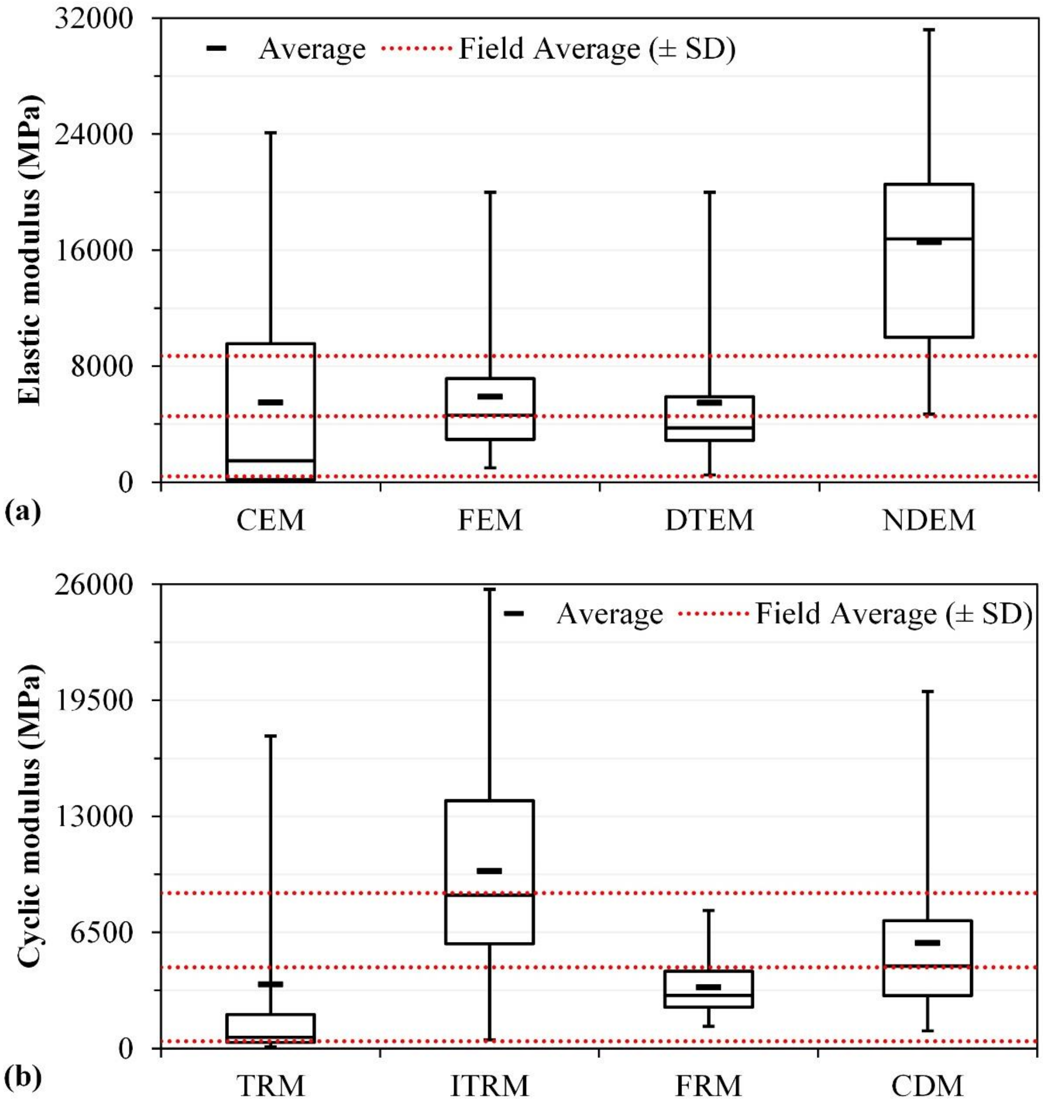

Figure 6. Box and whisker plots for the modulus values reported in previous research: (a) elastic; and (b) cyclic

Table 14. Effects of some characteristics on the properties of FDR-PC materials

Behaviour	Property	Effect on the property caused by increase of						Source
		Cement content	**RAP content**	**Compaction effort**	**Curing time**	**Temperature**	**Load frequency[3]**	
Mechanical	Unconfined compressive strength	↑	↓	↑	↑	↓	–	Tables 10 and 11[4]
	Indirect tensile strength	↑	↓[1]	↑	↑	↓	–	Tables 10 and 11[4]
	Direct tensile strength	↑	↓	–	↑	–	–	Tables 10 and 11[4]
	Flexural tensile strength	↑	↓[1]	–	↑	–	–	Tables 10 and 11[4]
	Flexural tensile strain at break	↑[1]	↑	–	–	–	–	[50, 70, 98]
	Compressive elastic modulus	↑	↓	–	↑	↓	–	Table 12[4]
	Direct tensile elastic modulus	↑	↓	–	↑	–	–	Table 12[4]
	Flexural elastic modulus	↑	↓[1]	–	↑	↓	–	Table 12[4]
	Elastic modulus (non-destructive tests)	↑	↓	–	↑	↓	–	Table 12[4]
	Triaxial resilient modulus	↑	↓	–	↑	–	–	Table 13[4]
	Indirect tensile resilient modulus	↑	↓[1]	↑	↑	–	–	Table 13[4]
	Flexural resilient modulus	↑	↓[1]	–	–	–	–	Table 13[4]
	Compressive dynamic/complex modulus	–	↓	–	–	↓	↑	Table 13[4]
	Phase angle	–	↑	–	–	↑	↓	[45, 87, 100]
	Fatigue life	↑[2]	↓[2]	–	–	–	–	[78, 83, 103]
Durability	Moisture sensitivity (tube suction test)	↓	↓	–	–	–	–	[80, 97]
	Shrinkage	↑	=	=	↑	–	–	[72, 104]
	Capillary rise	↓	↓	↓	–	–	–	[84, 91, 104]
	Absorption	↓	↓	↓	–	–	–	[84, 91, 104]
	Erodibility	↓	↓	↓	–	–	–	[84, 104]
	Swell	=	=	=	=	–	–	[84, 91, 104]
	Mass loss (wet-dry cycles test)	↓	↑	–	–	–	–	[93]

↑: increase; ↓: decrease; =: no effect; –: unknown/not studied; RAP: reclaimed asphalt pavement; [1]Authors reported the opposite trend for mixtures with fine lateritic soils [92, 98]; [2]Authors stated that cement and RAP effects on the fatigue are more complex [50, 98]; [3]Only applied to cyclic loading tests; [4]Effects based on the studies cited in Tables 10, 11, 12 and 13

7.1.1 Reclaimed asphalt pavement effect

In general, increasing RAP contents reduce strength and stiffness of FDR-PC mixtures [45, 47, 51, 67, 70-72, 75-77, 80, 85-87, 94, 95, 97, 104]. However, some studies on FDR-PC mixtures containing lateritic soils report the opposite trend [92, 98, 105, 106]. Note that the lateritic soils were fine grained. Based on the literature, some reasons causing this reduction trend are: 1) RAP has agglomerations formed by fines and asphalt binder, which present air voids and are weaker than natural aggregates, resulting in higher deformations under loading; 2) residual asphalt binder in RAP reduces the surface area that could be coated by cement, inhibiting the generation of bonding points between aggregates and cement paste; and 3) this residual asphalt binder also affects the shape of the aggregate, which becomes rounded, reducing interlocking. Studies using scanning electron microscopy (SEM) confirm some of these facts [77].

RAP addition also makes the cement stabilised mixture time- and temperature-dependent. However, this viscoelastic behaviour is not as strong as for asphalt mixtures or even cold recycled mixtures with asphalt binders [20, 45, 52, 65, 87, 99, 100]. A possible explanation is that cement, which is not temperature sensitive, governs the behaviour of FDR-PC mixtures, inhibiting the thermal sensitivity of the residual asphalt binder in RAP [81].

RAP is generally a heterogeneous material, presenting, for instance, different residual asphalt binder contents. Yuan et al. [97] stated that RAP asphalt binder content does not have a strong effect on the strength of FDR-PC mixtures, even for asphalt binder contents as high as 8%. However, Fedrigo et al. [107] confirmed that the type, content and ageing of the asphalt binder present in RAP affect the mechanical behaviour of FDR-PC mixtures.

Some authors state that high RAP contents reduce the fatigue life of FDR-PC mixtures [78, 103] and that their behaviour is intermediate between those of conventional cement stabilised mixtures and asphalt mixtures [83]. However, studies also report that RAP content effect on the fatigue behaviour of such mixtures is more complex, depending on the cement content and on the thickness of the layers [50, 98]. Because of this and the previously mentioned effects, some authors argue that it is necessary to add virgin aggregates to FDR-PC mixtures. It increases the aggregate surface area to be coated by cement and the interlocking, resulting in higher strength and stiffness [77, 78, 88].

7.1.2 Portland cement effect

Increasing cement contents increase the strength and stiffness of FDR-PC mixtures; the higher the cement content, the higher the hydration reactions, generating bonding points between aggregates [12, 46-48, 50, 67, 70, 75-77, 85, 96, 97, 105, 106]. Cement increase also reduces porosity, which results in less moisture sensitivity and higher durability [80, 84, 97, 104]. Although high cement contents increase mechanical and durability properties, its usage is often limited to a minimum, due to shrinkage problems [104]. Although not common, some FDR-PC works use the cement in the form of a slurry, which leads to slightly weaker mixtures. In this case, it is necessary to increase the cement content to achieve the desired strength [108].

The type of Portland cement also affects the strength of FDR-PC mixtures [9]. Paiva & Oliveira [9] recommend using cement types with less clinker and gypsum, which reduces the heat of hydration and setting time, and, consequently, shrinkage effects. In this regard, Portland composite cement types are the preferred [9, 109]. In such types of cement, other compounds (e.g. ground-granulated blast-furnace slag or pozzolanic materials) substitute a certain amount of clinker (6-34%).

7.1.3 Compaction effect

The compaction effort causes similar effects as the cement content; that is, when increased, it reduces the mixture porosity and increases its strength and stiffness [30, 73, 104]. Aranha [26] states that this effect is stronger on compressive behaviour than on tensile behaviour. Besides, Fedrigo et al. [53] observed the same trend for conventional cement stabilised materials. Therefore, using a higher compaction effort and achieving an adequate degree of compaction may counterbalance using lower cement contents, reducing shrinkage effects and costs [11, 104]. It is also necessary to avoid compaction delays since it can reduce the strength of the FDR-PC layer [10].

7.1.4 Curing effect

Like any cementitious material, FDR-PC mixtures become stronger and stiffer while curing [13, 21, 47, 75-77, 87, 96, 105]. Besides, their moisture resistance also increases with age [84, 104]. In the field, traffic opening usually happens a few hours after recycling (with adequate surface protection applied). However, some recommend longer curing times before traffic is permitted. Laboratory studies show that shrinkage effects are stronger in the early stages [72, 85, 104], which can result in cracks, compromising the quality of the layer. Thus, proper curing is necessary to avoid such problems; this can be achieved by applying a sealing compound or membrane [3].

7.1.5 Existing base material effect

Since FDR-PC often incorporates the existing base layer, the base material affects the behaviour of the recycled layer. Generally, an FDR-PC mixture containing a coarser base material (e.g. graded crushed stone or gravel) will present higher strength and stiffness [50, 75, 82, 84, 85, 104-106]. However, some authors verified similar behaviour between FDR-PC mixtures with gravel or sand base materials [76], while others reported that higher fines content led to higher strength [97]. FDR-PC mixtures with higher fines content also tend to be highly sensitive to water and shrinkage effects, then presenting less durability [84, 85, 104]. This behaviour was observed for conventional cement stabilised materials as well [110-112].

7.2 Field behaviour

Compared with laboratory studies, field studies are still limited, but they show that FDR-PC not only rehabilitates a distressed pavement but also enhances its performance; the deflection values reduce and become more homogeneous along the length of the road [18, 23, 24, 113]. Furthermore, FDR-PC pavements generally show lower deflections than pavements recycled with other cold technologies [51, 52]. After recycling, deflections continue to reduce since the FDR-PC layer stiffness continues to increase due to curing [20, 21, 26, 52, 81, 99, 114]. However, under traffic loading, deflections tend to increase, which is a result of FRD-PC layer stiffness decreasing due to fatigue microcracking and the breakdown of cement bonds. Once microcracks evolve to macrocracks, the layer deteriorates due to fatigue and becomes smaller blocks [51, 52].

FDR-PC layers achieve higher initial (post-construction) and residual (under traffic) moduli than layers recycled without any or with asphalt stabilisers (e.g. asphalt emulsion or foamed asphalt) [51, 52]. Asphalt stabilisers also show a higher rate of modulus decrease, which is more pronounced in the wheelpaths [21, 51, 52]. However, FDR-PC pavements can outperform pavements recycled with asphalt stabilisers, providing a longer life [20].

Water-related and shrinkage effects may accelerate the deterioration of FDR-PC layers. Adequate mix design can reduce the first, while techniques such as induced micro-cracking, construction joints or even using geosynthetics have been very successful in minimising shrinkage cracks [3, 8, 21, 41, 113, 115]. It is important to ensure that the layers supporting the FDR-PC are not moisture sensitive, as rapid degradation will occur when moisture enters the pavement through unsealed cracks.

The level of other defects (e.g. irregularity and permanent deformation) in FDR-PC pavements are generally low provided cracks are sealed, especially in comparison with pavements recycled without or with different stabilisers [18, 51, 52]. Laboratory studies also confirm that FDR-PC mixtures are resistant against permanent deformation [44, 102]. However, cement stabilised materials may still undergo permanent deformation due to crushing/erosion at the top of the layer, especially when overlaid by thin surface layers [59, 116-118]. Proper structural design can avoid such a problem.

As in the laboratory, field studies show that FDR-PC layers have little sensitivity to temperature, especially in comparison with asphalt mixtures. This fact corroborates the hypothesis that the addition of cement not only improves the strength but also reduces the temperature sensitivity of the residual asphalt binder in RAP [20, 52, 99]. However, high cement content FDR-PC may result in slabs forming as a result of transverse shrinkage cracks, and under a thin surfacing a temperature gradient with depth may result in the slabs warping, which give a poor riding quality.

Table 15 shows the ranges of back-calculated modulus of FDR-PC layers, obtained by some authors using field data (falling weight deflectometer, FWD, or light weight deflectometer, LWD). Table 15 data comes from test sections of in service pavements or laboratory test tracks subjected to accelerated pavement testing (APT). Specific software (Engauge digitizer) allowed obtaining values presented in graphs by some researchers. Figure 6 (Section 7.1) shows the average value and the standard deviation (SD) of all back-calculated moduli obtained by the authors while comparing them with the moduli obtained using laboratory tests.

Figure 6 shows that indirect tensile cyclic tests and non-destructive methods overestimate the modulus of FDR-PC layers. Furthermore, 75% of the modulus obtained using other laboratory tests fall within the range of average field modulus plus or minus one SD; the average field and laboratory values are also close. However, while most tests still overestimate field modulus (sometimes by more than a factor of 2), the flexural test with cyclic loading is the only one that leads to a similar range of modulus as the back-calculation. The latter supports statements by Fedrigo et al. [75] and the preference for flexural tests by most structural design methods.

Table 15. Ranges of field modulus reported for FDR-PC layers

Source	Country	Existing base material	Cement content (%)	RAP content (%)	Curing time (days)	M_{FWD} (MPa)	M_{LWD} (MPa)
Amarh et al. [20]	USA	Not specified	5	Not specified	21–780	2600–7200	-
Wilson & Guthrie [21]	USA	Silty sand	4	50–70	3–90	-	621–12,765
Jones et al. [51]; Wu et al. [52]	USA	Granular	5	50	28–550	3000–22,000	-
Isola et al. [81]*	Italy	Granular	4	70	1	-	360–400
Godenzoni et al. [99]	Italy	Granular	3	33	40–2520	1072–5650	-
Trichês & Santos [113]	Brazil	Granular	3	40	35	732	-

RAP: reclaimed asphalt pavement; M_{FWD}: modulus back-calculated using falling weight deflectometer data; M_{LWD}: modulus back-calculated using light weight deflectometer data; *M_{FWD} values are not presented since the authors combined surface and recycled base layers into a single layer

8 Conclusions and recommendations

The paper aimed at consolidating findings and data from previous FDR-PC research, and the following are the main conclusions:

- Internationally, there are various mix design methods for FDR-PC materials. The analysed methods are similar, being based on strength tests and suggesting some additional tests to characterise other important properties, especially durability. Brazilian standards do not provide a mix design method.
- While most countries use structural design methods developed for conventional cement stabilised materials, the French method also considers FDR-PC (up to 20% RAP). All analysed methods consider fatigue as the primary failure mode of FDR-PC and suggest using flexural tests (excepting the French one). The Brazilian method is based only on laboratory testing.

- The majority of reported research on FDR-PC are laboratory studies on the mechanical behaviour of such materials; only a few are field studies or focus on durability properties. The paper presents ranges of strength and stiffness based on several studies. According to these data, cyclic load flexural tests lead to a better prediction of field modulus, while indirect tensile tests (one of the most used worldwide) overestimate field modulus values. Furthermore, the paper tabulates the effects of some characteristics on the behaviour of FDR-PC materials, emphasising that there are doubts regarding some effects while others are still unknown.
- There are reports of FDR-PC usage all over the world. However, despite the generally accepted advantages of the technique, the lack of standards or even the divergences between them might be limiting further application of FDR-PC in some countries (e.g. Brazil).

The following are recommendations for further research on an international scale:

- To evaluate economic and environmental issues of FDR-PC using life-cycle cost analysis and life cycle assessment, respectively. Such studies (only one study reported in the literature) could show the advantages of FDR-PC, helping to make the technique a standard choice.
- To further study the field behaviour of FDR-PC to help in the development/calibration of mechanistic-empirical structural design methods. Even though it is harder than in the laboratory, varying cement and RAP contents in test sections could help to understand their effect on the behaviour of FDR-PC materials. Accelerated pavement testing (APT) could be useful to this matter (only one study reported in the literature).
- To further study the fatigue behaviour of FDR-PC materials, since there are still doubts, especially regarding RAP effect.

- To further evaluate the viscoelastic behaviour of FDR-PC materials. Although such materials have little sensitivity to temperature and frequency, this might change for different ranges of cement and RAP.
- To further investigate the durability of FDR-PC, since there are only a few studies on this matter and several effects remain unknown (e.g. RAP content and existing base material).
- To determine the flexural behaviour of different FDR-PC materials, since such test properly predicts field modulus and provides an adequate structural design property (strain at break). Although several studies focused on the mechanical behaviour of FDR-PC, only a few used flexural tests.
- To further study the effect of the asphalt binder present in RAP on the behaviour of FDR-PC materials, since much remains unknown.

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