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# Advances in the Study of the Behavior of Full-Depth Reclamation (FDR) with Cement

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**Abstract:** Road maintenance and rehabilitation are expected to meet modern society's demands for sustainable development. Full-depth reclamation with cement as a binder is closely linked to the concept of sustainability. In addition to the environmental benefits of reusing the existing pavement as aggregate, this practice entails significant technical and economic advantages. In Spain, in the absence of tests specifically designed to determine the behavior of recycled pavements stabilized with cement, these materials are treated as soil-cement or cement-bound granular material. This assumption is not entirely accurate, because this recycled pavement contains some bituminous elements that reduce its stiffness. This study aimed to obtain the relationships between flexural strength (FS) and the parameters that describe the pavement behavior (long-term unconfined compressive strength (UCS) and indirect tensile strength (ITS)) and compare the findings with the relationships between these parameters in soil-cement and cement-bound granular materials. The results showed that the similar behavior hypothesis is not entirely accurate for recycled pavements stabilized with cement, because they have lower strength values—although, this is not necessarily an indication of poorer performance.

**Keywords:** full-depth reclamation; recycling; pavement rehabilitation; cement-treated materials; base materials; unconfined compressive strength; flexural strength; splitting tensile strength; indirect tensile strength

## 1. Introduction

Pavement recycling is a road-rehabilitation technique in which a deteriorated pavement is transformed into a new course. Depending on the recycling processes and mixing temperature, pavement recycling technique can be classified as hot recycling (HR) and cold recycling (CR). HR methodology involves two techniques: Hot in-place recycling and hot central-plant recycling. On the other hand, there are three techniques for CR according to the processing place, the construction technology, and the reclamation depth: Cold in-place recycling, cold central-plant recycling, and full-depth reclamation [1,2].

Full depth reclamation (FDR) is a recycling technique in which all the asphalt pavement section and a previously quantified amount of underlying base material are treated. This mixture is pulverized, either mixed with a stabilizing agent or not, and compacted to produce a stabilized base course [3]. The usual depth that is reclaimed varies from 100 to 300 mm [4–6]. Sometimes, due to the structural capabilities of the mixture, it is not necessary to add any stabilizing additive, and therefore, the compacted material can be the base for a new surface layer. Nevertheless, if the obtained material does not provide enough structural strength, possible stabilizers are classified as

chemical additives (Portland cement, hydrated lime, calcium chloride, and fly ash) and bitumen additives (bitumen emulsions). The most employed stabilizers worldwide are bituminous emulsions and Portland cement [3,6–9].

In this case, full depth reclamation with Portland cement (FDR-PC) yields a base course with significant structural capacity, for which the existing road is used as a “quarry” or source of aggregate. With this technique, the materials in the road are reused by pulverizing them, and adding cement, water, and sometimes a small percentage of aggregate or even an additive, in the proportions established through preliminary testing. This mixture is compacted and cured to form the course with the greatest structural strength in the new pavement [6,10–14].

This procedure is, without a doubt, more effective for ensuring user comfort and safety than reinforcing or rebuilding heavily cracked or deteriorated pavements.

FDR with cement has a number of technical, economic, and environmental advantages [15]. It results in a longer-lasting, less erosive, and water-resistant pavements, able to withstand the stress from traffic loads that reach the subgrade more efficiently. This high-performance technique requires no manufacturing plant or transportation of materials. It is also environmentally friendly; since the materials are reused in their present location, new aggregate deposits need not be found, nor existing quarries over-mined. The elimination of transport reduces CO<sub>2</sub> emissions and the associated impact on the road and the traffic [3,16]. Furthermore, the reclaimed pavement can be regarded as solid waste generated from deteriorated roadways [5]. Finally, a life cycle cost analysis of construction and maintenance practices indicates that the maintenance and rehabilitation strategy based on pavement in situ recycling is the least costly, providing savings to the overall economic performance of the road pavement over the life cycle [17].

In recent years, around one million square metres of pavement were recycled in Spain annually, covering a total surface area of nearly 30 million square metres between 1998 and 2018 [18]. This is a proven method that has been widely used and has shown exceptional results to date. Based on the many advantages described, it has a promising future.

Pavement recycling as a rehabilitation method is a technique that was first used in the United Kingdom in the 1940s to repair secondary roads damaged during World War II [19]. However, FDR did not make a comeback until the mid 1980s, when a better understanding of the characteristics of semi-rigid pavements and the development of advanced machinery led to the inclusion of cement in the mix [1,20].

In Spain, cold-recycling techniques first came into use in 1991 after several unsuccessful hot-recycling experiments in the early 1990s [19,21]. The first cold-recycling trial was in Huelva, where the Ministry of Public Works recycled a 12 km stretch of road, N-431, to a depth of 30 cm [22]. Other regions subsequently undertook experiments of their own, and in some cases, such as in the region of Castilla y León, standardized the technique through widespread use. The number of recycled roads quickly grew, ultimately reaching the aforementioned 30 million square metres.

Although FDR with cement is, in principle, more widely used on roads with traffic of low intensity [3,16,23], good results have also been obtained in some of the trials conducted on roads with high-intensity flows of heavy vehicles [8,19].

However, it must be taken into account that these pavements are being designed based on the assumption that FDR with cement and soil-cement exhibit similar behavior, but it differs due to the inclusion of reclaimed asphalt pavement aggregates in their blend, which reduces the stiffness and strength of the mixture [8,14,24]. Therefore, to verify this hypothesis, the long-term characteristics of the recycled material must be determined, as they have only been estimated to date [4].

In 2001, Koliás et al. [25] reported the results of an analysis of the mechanical properties of recycled pavements with different granular and bituminous mix percentages and 3% and 5% cement. The aim was to determine the effect of the bituminous mix percentage and temperature on the strength of the recycled pavement with cement. Compressive, tensile, flexural, and fatigue strength values were found for a small number of one and 60 day specimens. The authors determined that both compressive

strength and the modulus of elasticity declined with rising bituminous content. At the same time, they concluded that flexural and tensile strength did not fall at low proportions of bituminous mix, but did so very quickly at higher contents.

In 2008, Díaz et al. [26] published a preview of the unconfined compressive strength (UCS), indirect tensile strength (ITS), and flexural strength (FS) results that form part of the first phase of this study. Since then, the number of trials conducted has grown significantly.

In FDR, the most used test to verify that material was manufactured correctly is the unconfined compressive strength (UCS) test at short-term [10,27–30]. But, in order for a better long-term characterization, it is necessary to perform flexural strength tests, and, more specifically, the four-point flexural beam test [8,31–38].

This FS test is carried out using prismatic specimens and manufacturing them requires a high level of qualification and experience within the testing team [10,39]. This is the main reason for usually estimating their behavior from standardized tests, such as the unconfined compressive strength and the indirect tensile strength (ITS) tests [31,40–42]. For this reason, the method used in this research is the one proposed by the University of Burgos [33].

This research aimed to fill the void in the understanding of the relationships among flexural strength, unconfined compressive strength, and indirect tensile strength based on the results of the tests conducted. To this end, the methods used for other materials mixed with hydraulic binders [33,34,40,43] and the tests described by Koliass et al. [25] were taken as a starting point. Here, however, the applicable European (EN) or Spanish (UNE or NLT, as appropriate) standards were used to characterize the behavior of an FDR with cement. The accuracy of the initial hypothesis of similarity with soil-cement and cement-bound granular material was also evaluated.

## 2. Materials and Methods

### 2.1. Material

While the number of possible granular material/bituminous material combinations is virtually countless, the proportion consisting of one-third mix asphalt and two-thirds granular material is the one most commonly used in roads [16], and was consequently chosen for this study (10 cm of mix asphalt and 20 cm of granular material), as can be seen in Figure 1. The bituminous layer has approximately 4.5% of bitumen.

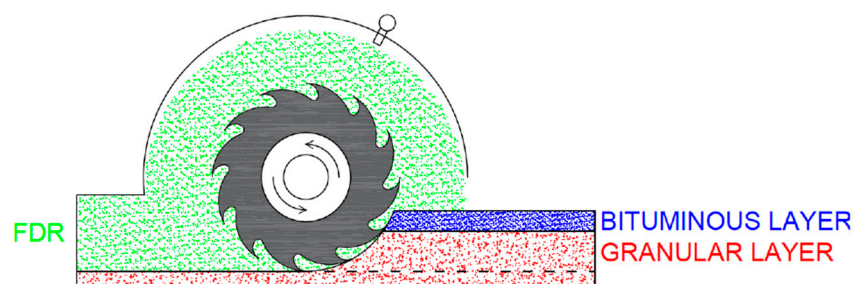


Figure 1. Full-depth reclamation section.

The granular material used in the laboratory trials was recycled pavement taken from road SA-801 (Peñaranda de Bracamonte to Campo de Peñaranda) from the west of Spain, with a maximum aggregate size of 40 mm. Figure 2 shows the granulometry of the material, which is inside the range of the SC40 (soil-cement with a maximum aggregate size of 40 mm) according to the Spanish standards [28]. It not was necessary to add any aggregate to improve the grading. The recycled material exhibited no plasticity and was free of organic matter and other substances that might prevent the cement setting.

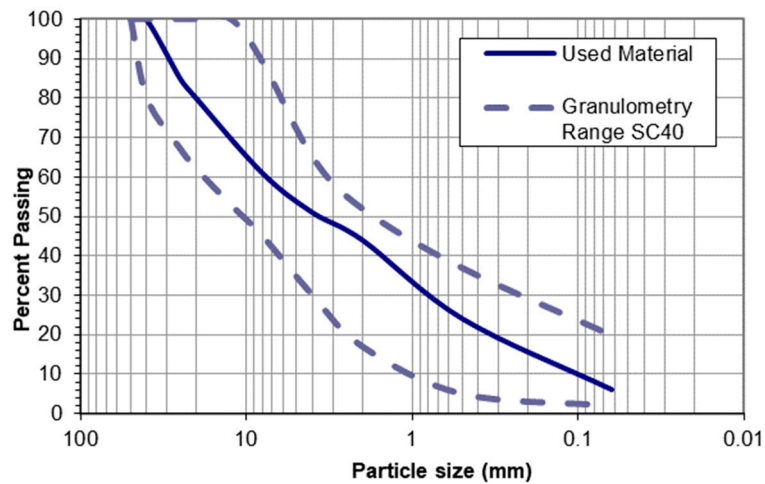


Figure 2. Used material granulometry and granulometry range for SC40.

The cement used was ESP VI-1 32.5 N [44]. This is a widely used cement type for recycled pavements stabilized with cement in roads, because of its low thermal shrinkage and long period workability due to the low quantity of clinker (<50%), high quantity of additives, and moderate strength, mainly short-term [45].

The characteristics of this type of cement are showed in Table 1.

Table 1. Cement ESP VI-1 32.5 N properties [44].

Main Standardized Component	Value	Cement Standardized Specifications	Value
Clinker (K)	25–55%	Sulfate	≤3.5%
Silica fumes (D) <sup>1</sup>		Initial setting time	≥60 min
Natural pozzolans (P) <sup>1</sup>		Final setting time	≤720 min
Calcined natural pozzolans (Q) <sup>1</sup>	45–75%	Expansion	≤10 mm
Siliceous fly ash (V) <sup>1</sup>		UCS at 28 days	22.5 ≤ R ≤ 42.5 MPa
Calcareous fly ash (W) <sup>1</sup>		UCS at 90 days <sup>2</sup>	≥32.5 MPa
Minority components	0–5%	Puzzolanicity	8 to 15 days
Chlorides	≤0.10%	-	-

<sup>1</sup> The natural pozzolans (P) content for Cements ESP VI-1 must be lower than 40%. <sup>2</sup> The code for special cements it is given by its UCS at 90 days.

### 2.2. Mix Design

The determination of maximum dry density and optimum moisture content was conducted following the UNE 103-501-94 [46] for cylindrical samples, whose prescriptions are analogous to the ASTM D1557-12 [47]. The density to be achieved in the test specimens was 2.10 g/cm<sup>3</sup> with an optimum modified Proctor moisture content of 7.61% [46] (Figure 3).

Further to the results of the proportioning study, 3.5% ESP VI-1 32.5 N cement [44] was used to ensure a 7-day compressive strength [48,49] of at least 2.5 MPa, the minimum value required by the Spanish Ministry of Public Works [29] and the Council of Castilla y León [50] (Table 2).

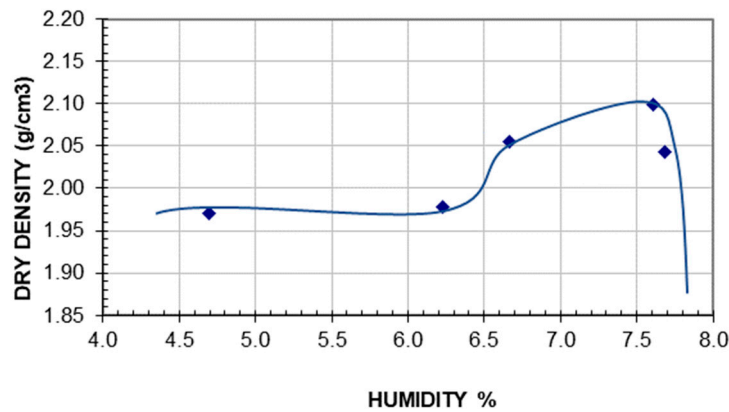


Figure 3. Modified Proctor density of the material.

Table 2. Unconfined compressive strength (UCS) at seven days for different cement content.

Sample	% Cement	Dry Density (g/cm <sup>3</sup> )	UCS at 7 Days (MPa)	Average UCS (MPa)
P1.1	3.0	2.151	1.757	2.071
P1.2	3.0	2.108	1.465	
P1.3	3.0	2.122	2.991	
P2.1	3.5	2.070	2.259	2.637
P2.2	3.5	2.143	2.560	
P2.3	3.5	2.151	3.092	

### 2.3. Testing Program

Twenty-four prismatic specimens were prepared for flexural strength testing to characterize the recycled pavement in accordance with standard UNE-EN 12390-5, “Testing hardened concrete. Flexural strength of test specimens” [51], which is analogous to the ASTM D1635/D1635M-12 [52]. The mould dimensions were 15 cm × 15 cm × 60 cm. Samples were stored in a curing room at 20 ± 2 °C and 95% relative humidity [53]. At a curing age of at least 90 days, the four-point flexural beam test was conducted. This method ensures that the specimens break at the weakest section (uniformity of the bending moment between the two points where the load is applied).

The rollers over the specimen were placed at a distance of 15 cm (the height of the specimen), and the rollers below the specimen at a distance of 45 cm (three times the height of the specimen).

The applied load was transmitted by means of a plate between the specimen and the rollers over it. An increasing tension of 0.04 MPa was selected in the slowest way of the standard range of 0.04–0.06 MPa/s [51].

After each specimen of 15 × 15 × 60 cm was tested for flexural strength, specimens are broken approximately in the middle. The two resulting halves were also tested without being trimmed, one for the unconfined compressive strength (UCS) test and the other for the indirect tensile strength (ITS) test, to find the relationship between these values and the FS of the initial test specimen.

For simulating the behavior of a cubic sample in the UCS test, an auxiliary metal sheet (15 cm × 15 cm) was introduced between the lower plate and the lower side of the sample (a half from the prismatic sample), and between the top plate and the top side of the sample. This way, a uniform tensile distribution in a 15 cm cube is obtained (Figure 4a). In the case of the ITS test, the load was applied perpendicularly to the axle of the specimen with a modified metal sheet. Hence, the load was applied with a width of 15 cm (Figure 4b).



Figure 4. (a) UCS test; (b) indirect tensile strength (ITS) test.

UCS tests were conducted following the standard UNE-EN 13286-41 [49], with a load speed in the range interval of  $0.1 \pm 0.1$  MPa/s [54]. ITS strength tests were performed in accordance with UNE-EN 12390-6, “Testing hardened concrete. Tensile splitting strength of test specimens” [55].

### 3. Results and Discussion

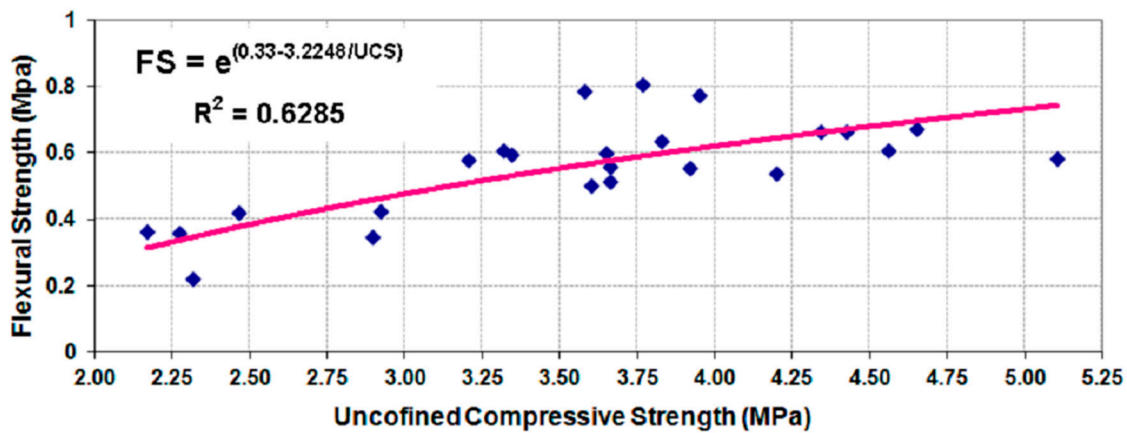
Obtained results from the 72 tests conducted on the 24 prismatic specimens are shown in Table 3.

**Table 3.** Long-term results obtained for flexural strength, unconfined compression strength, and indirect tensile strength tests.

Sample	FS (MPa)	UCS (MPa)	ITS (MPa)
S1	0.806	3.766	0.520
S2	0.598	3.344	0.313
S3	0.580	3.203	0.402
S4	0.775	3.947	0.447
S5	0.787	3.580	0.423
S6	0.610	3.317	0.398
S7	0.361	2.273	0.198
S8	0.350	2.896	0.273
S9	0.599	3.649	0.393
S10	0.366	2.169	0.209
S11	0.538	4.199	0.488
S12	0.667	4.340	0.483
S13	0.556	3.918	0.457
S14	0.221	2.313	0.155
S15	0.638	3.827	0.394
S16	0.427	2.919	0.174
S17	0.420	2.465	0.128
S18	0.585	5.103	0.314
S19	0.673	4.651	0.345
S20	0.609	4.559	0.427
S21	0.561	3.663	0.380
S22	0.516	3.660	0.379
S23	0.667	4.423	0.386
S24	0.501	3.600	0.310

#### 3.1. Relationship Between Flexural and Unconfined Compressive Strength

The correlation between the values of the UCS at long-term and FS at long-term is shown in Figure 5.



**Figure 5.** Relationship between unconfined compressive strength at long-term ( $UCS_{LT}$ ) and flexural strength at long-term ( $FS_{LT}$ ).

After examining various possible functions for correlating these two variables, the best correlation was obtained with an S shape function, with natural logarithm of the FS as dependent variable and  $1/UCS$  as the independent variable. The developed relationship is shown in Equation (1).

$$\ln(FS_{LT-UCS}) = 0.33 - 0.3225/UCS_{LT} \tag{1}$$

where  $FS_{LT-UCS}$  is the estimated value of the flexural strength at long-term by means of  $UCS_{LT}$ , and  $UCS_{LT}$  is the unconfined compressive strength at long-term, both expressed in MPa.

The coefficient of determination ( $R^2$ ) has a value of 0.629, which indicates that the model can explain more than the 62% of the variability of the model.

The average values obtained in the tests for these two parameters for the recycled material were compared to the usual values for soil-cement and cement-bound granular material [26,42,45,56–58] in Table 4.

**Table 4.** Comparison between average UCS values at long-term and flexural strength (FS) values at long-term for soil-cement, cement-bound granular material, and obtained values for the full-depth reclamation (FDR) with cement of the study.

Materials	$UCS_{LT}$ (MPa)	$FS_{LT}$ (MPa)	$UCS_{LT}/FS_{LT}$
Soil-cement	4	0.9	4–5
Cement-bound granular material and compacted concrete	8	1.6	5–6
FDR with cement	3.73 (2.9 to 4.9)	0.60 (0.53 to 0.69)	6.21

As seen in Table 4, while the values obtained in the analysis were lower than soil-cement strength due to the bituminous matrix, the relationship between the two parameters was closer to the cement-bound granular material.

### 3.2. Relationship Between Flexural Strength at Long-Term and Indirect Tensile Strength at Long-Term

The correlation between FS and ITS values at long-term is shown in Figure 6, indicating a linear relationship between these parameters.

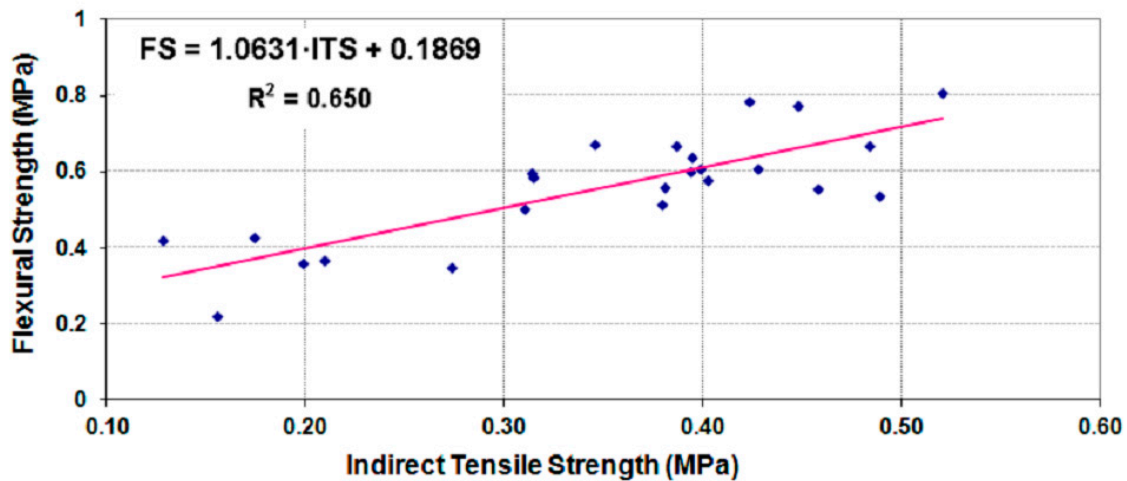


Figure 6. Relationship between indirect tensile strength and flexural strength.

A statistical analysis was performed and it was observed that the best relationship was obtained by means of a simple linear regression, expressed in Equation (2).

$$FS_{LT-ITS} = 0.187 + 1.063 ITS_{LT} \tag{2}$$

where  $FS_{LT-ITS}$  is the estimated value of the flexural strength at long-term obtained by means of  $ITS_{LT}$ , and  $ITS_{LT}$  is the indirect tensile strength at long-term, both in MPa.

The regression has a  $R^2$  value of 0.65 and the  $F$  of Fisher-Snedecor test indicated that the relationship was true with a significance level over 99%. The Student’s  $t$ -tests for the coefficients indicated that they were true, different from 0 with a significance level over 99%.

Once again, the average values obtained in the tests for these two parameters for the recycled material were compared to the usual values for soil-cement and cement-bound granular material [45] in Table 5. Although a direct relationship between ITS and FS is not established for cement-bound granular materials, it is indicated that the UCS value is approximately 10 times the ITS value [26,42,45,56–58]. This assumption is adopted for the analysis in Table 5.

Table 5. Comparison between averages of ITS values at long-term and FS values at long-term for soil-cement, cement-bound granular material, and obtained values for the FDR with cement of the study.

Materials	$ITS_{LT}$ (MPa)	$FS_{LT}$ (MPa)	$ITS_{LT}/FS_{LT}$
Soil-cement	0.4	0.9	0.4–0.5
Cement-bound granular material and compacted concrete	0.8	1.6	0.5–0.6
FDR with cement	0.40 (0.33 to 0.48)	0.60 (0.53 to 0.69)	0.67

It is observed that the ITS of the recycled material was similar to the value specified for soil-cement, while the relationship between ITS and FS was closer to a cement-bound granular material.

### 3.3. Relationship Between Indirect Tensile Strength and Unconfined Compressive Strength at Long-Term

The values of these two parameters (UCS and ITS) are compared in Figure 7.



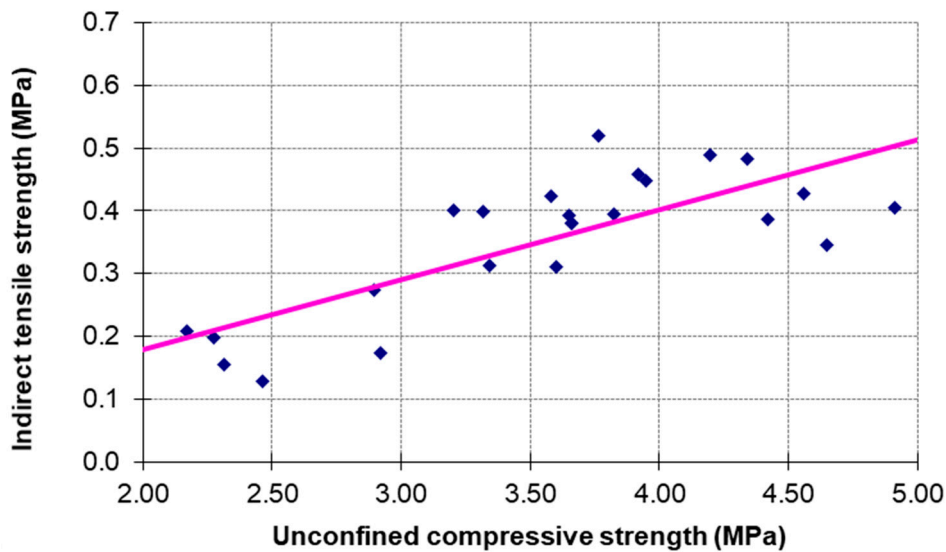


Figure 7. Relationship between ITS and UCS at long-term.

The correlation between both parameters was statistically analyzed and a linear correlation was proposed, as shown in Equation (3).

$$ITS_{LT} = 0.098 UCS_{LT} \tag{3}$$

where  $ITS_{LT}$  and  $UCS_{LT}$  are as defined in Equations (1) and (2), respectively, both in MPa.

Equation (3) omitted the intercept because the  $p$ -value of the Student’s  $t$ -test was over 0.99, indicating that it was not significant. The relationship has an  $R^2$  value of 0.49. The  $F$  test indicated that the relationship was true with a significance level over 99%.

The relationship between these two parameters at long-term obtained for the recycled material and the usual values for cement-treated base courses [45] were found to be similar (Table 6).

**Table 6.** Comparison of the relationship between unconfined compressive strength and indirect tensile strength at long-term for soil-cement, cement-bound granular material, and obtained values for the FDR with cement of the study.

Materials	$UCS_{LT}/ITS_{LT}$
Soil-cement, cement-bound granular material, compacted concrete	8–10
FDR pavement with cement	10.20

### 3.4. Estimation of Flexural Strength at Long-Term Using the UCS and ITS Values

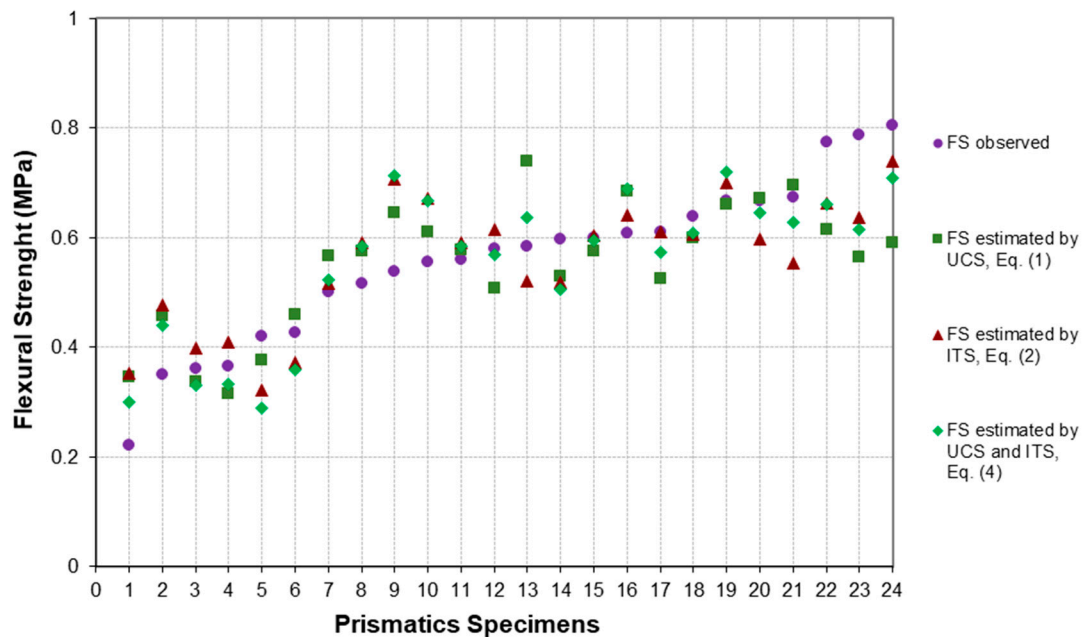
An additional equation for estimating the flexural strength at long-term of the FDR with cement was developed as a function of the unconfined compressive strength and the indirect tensile strength by means of a multiple linear regression, as shown in Equation (4).

$$FS_{LT-2} = 0.074 UCS_{LT} + 0.826 ITS_{LT} \tag{4}$$

where  $FS_{LT-2}$  is the flexural strength at long-term by means of  $UCS_{LT}$  and  $ITS_{LT}$  simultaneously, and  $UCS_{LT}$  and  $ITS_{LT}$  are as defined in Equations (1) and (2), respectively.

Equation (4) has a coefficient of determination ( $R^2$ ) of 0.684. Including an intercept in Equation (4) made the coefficients of the intercept and UCS not significant. Without the intercept, both coefficients are different from 0, with a significance level over 99% ( $p$ -value of the Student’s  $t$ -test  $> 0.99$ ).

Figure 8 shows the obtained values of FS and the values estimated by Equations (1), (2), and (4).



**Figure 8.** Relationship between observed flexural strength and predicted values by means of the proposed equations.

As seen in Figure 8, Equation (4) is suitable for calculating FS at long-term, especially with regard to the average values of the material, despite the disperse values obtained for some specimens of the recycled material. For the extreme values, the proposed model does not fit so accurately. For specimens with the lowest values in FS, higher values are predicted with all the developed equations. On the other hand, for the highest values of FS, lower values are predicted. This fact can be attributed to the heterogeneity of the material or flawed specimen preparation or testing.

From the point of view of sustainability, the advantages of FDR when compared with soil-cement and cement-bound granular mixture are considerable. When manufacturing FDR, it is avoided to transport -remove material to landfills; there is no need to use quarries and the quantity of material that must be transported is lower and, hence, CO<sub>2</sub> emissions are reduced. Moreover, the roads that are used for transporting the material are not so damaged.

With regard to the (expected) behavior, it can be said that the average UCS and ITS value at long-term are similar to soil-cement. In the case of the FS at long-term, the value is lower than usual for soil-cement. The fact that the FS values are lower could be regarded as a disadvantage, and perhaps the expected life of the pavement structure would not be as long as with soil-cement. However, if we compare the expected life of the new higher quality base that we are designing with the previous pavement structure, which was composed of unbound aggregates, an improvement is observed. The quality is not as high as with soil-cement, but it must be taken into account that there is a big increase in the quality of the new base compared to the previous one. With this technique, a material that is near to a standardized material is designed, which is cheaper and more sustainable. Consequently, the advantages overcome the disadvantages.

#### 4. Conclusions

The study aimed to establish the long-term relationships among flexural, unconfined compressive, and indirect tensile strength in FDR with cement, and compared them to the strength relationships between soil-cement and cement-bound granular materials to verify the hypothesis that their behavior was similar.

The statistical analysis proved the existence of fairly close relationships among these three strength tests in the FDR, but with different behaviors to what it was expected. Flexural strength exhibited

lower values in the recycled pavements than in soil-cements, whereas the indirect tensile strength and unconfined compressive strength values were similar. The relationships between unconfined compressive strength and flexural strength, and between indirect tensile strength and flexural strength, were even closer than in cement-bound granular material. In the analyzed recycled material, only the relationship between unconfined compressive strength and indirect tensile strength was similar to the relationship in cement-bound granular material and soil-cement.

With the research, in the case that only the unconfined compressive strength value is available, Equation (1) is recommended to calculate the flexural strength at long-term of the FDR. If only the indirect tensile strength is known, Equation (2) is then recommended to calculate the flexural strength of the FDR. If we have both the unconfined compressive strength and indirect tensile strength at long-term, Equation (4) is proposed to estimate the flexural strength of the FDR.

It is important to know the flexural strength, because the fatigue strength of the FDR material is calculated using this value. The hypothesis that the FDR with cement, soil-cement, and cement-bound granular material exhibit similar behaviors is not accurate and, therefore, there is a need to undertake a fatigue behavior study on this type of recycled base course to ensure the optimum design of this type of pavements.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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