IN SITU PAVEMENT RECYCLING WITH CEMENT DESIGN

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ABSTRACT

Road maintenance and restoration are expected to comply with modern society's demands for sustainable development. Recycling pavement in situ with cement enhances the sustainability of road maintenance.

Pavement recycling is a modern road restoration technique in which degraded pavement is transformed into a new base course reusing the existing materials. Depending on the temperature of the mix, the process is known as cold or hot recycling, and may involve operations conducted in place or at a mixed plant.

Cold in place recycling of pavements with cement increases the bearing capacity and improves the durability (reducing water susceptibility and increasing strength to reduce the erosion) with the following associated environmental advantages: reduction in waste and extraction of aggregates from quarries or pits.

In recent studies, the authors characterised the performance of a recycled material derived from the upper 30 cm of a road pavement consisting of 10 cm of bituminous mix and 20 cm of granular material.

The present paper proposes a catalogue of cement-bound recycled pavement designs for all traffic categories and to different subgrade qualities. The calculations performed are based on Spanish traffic regulations (axle load of 13 tonne).

The Brown and Pell equation is used to define fatigue-induced subgrade failure. Fatigue in the bituminous mix is determined as laid down in Spanish legislation. The main innovation is the use of a fatigue equation for the recycled layer recently developed by the authors in studies conducted to characterise this material.

The designs proposed are both structurally valid and cost-effective, inasmuch as they constitute a solution for restoring the bearing capacity of any worn road more efficiently and economically than other approaches.

1 INTRODUCTION

Today's society expects road maintenance and rehabilitation to meet its demands for sustainable development. In situ pavement recycling with cement is a modern road rehabilitation technique closely linked to the concept of sustainability. It converts a degraded pavement into a new course with significant structural strength, in an operation in which the existing road is used as a "quarry" or source of aggregates. With this technique, the materials in the road are reused after breaking them down and adding cement, water and sometimes a small percentage of aggregate or even admixtures in the proportions established through preliminary testing. This mixture is then appropriately compacted and cured to form the highest strength layer in the new pavement.

In-place cement-bound recycling has a number of technical, economic and environmental advantages. It improves the durability, reduces the water susceptibility and increases strength to reduce the erosion that decreased the stress on the subgrade induced by traffic loads. This high performance technique requires no mixing plant or material haulage. It is also environmentally friendly: since the materials are reused in situ, extraction of aggregates from quarries or pits are not necessary. The elimination of the need for haulage reduces both CO_2 emissions and the impact of road construction on adjacent roads and local flora.

This technique is widely used in Spain, where a total of close to 24 million m^2 of pavement has been recycled since 1991. In recent years, around 2.5 million square metres of pavement are recycled annually. This is a proven method that has shown exceptional results to date and, based on its many advantages, it will have a promising future.

The subgrade bearing capacity is critical to design, as are the characteristics of the material before and after recycling. These include the thickness and nature of the layers to be recycled, the percentage of remaining bitumen, the binder content and the type, but the scale of deterioration is not as a rule factored in by the design engineer when calculating thickness.

The main factors involved in pavement design are: the heavy vehicle traffic intensity, the subgrade bearing capacity, the characteristics of the recycled product and the design service life (a life span of 20 years is considered in this study).

Other construction-related conditioning factors such as equipment availability, project size and climate may affect the recycling feasibility, but they are of little significance in recycled pavement design.

In Spain, in the absence of a specific fatigue equation for cement-bound recycled pavements, their design has been based on fatigue expressions determined for soilcement or cement-bound granular material. However this approach is not entirely accurate because recycled pavement contains bituminous elements that reduce its rigidity.

Prior studies by the authors (Díaz 2011, Diaz et al. 2008) established short-and-long term strength relationships as well as fatigue equations for cement-bound recycled pavements, contributing to an understanding of the behaviour of this material.

The present article proposes an original catalogue to design recycled sections supported by two types of subgrades, based on the fatigue equation developed for recycled cement materials.

2 PRELIMINARY STUDIES

The findings discussed here were obtained in trials conducted over a 3-year period for a PhD. thesis entitled "El estudio del comportamiento de los firmes reciclados in situ con cement" (Behaviour of in-place recycled pavement with cement) (Díaz 2011). The laboratory study was performed on material derived from the upper 30 cm of cement-free road pavement consisting of 10 cm of bituminous mix and 20 cm of granular material.

The material grading, described in table 1 and figure 1, was within the range defined for SC 40 soilcement in Spanish legislation (Dirección General de Carreteras, 2004). The recycled material exhibited no plasticity and was free of organic matter and other substances that might prevent the cement setting.

Table 1: Particle size distribution of recycled material

Sieve (mm)	100	50	40	25	20	12.5	8	4	2	0.5	0.063
% passing	100	100	100	85	80	68	61	51	44	24	6

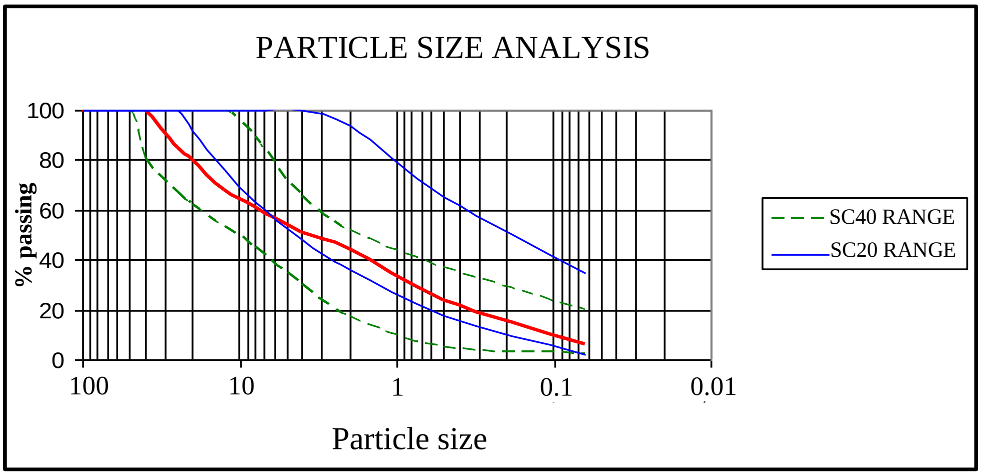

Figure 1: Grading of recycled material and Spanish soilcement legislation grading curves

The preliminary study showed that a cement content of 3.5 % was enough to achieve 2.5 MPa, that is the minimum 7-day compressive strength stipulated in Spain (Dirección General de Carreteras, 2001), in 15-cm diameter and 18-cm long specimen. These specimens were compacted to the required density of 2.10 g/m^3 with an optimal moisture content of 7.61 % determined by the modified Proctor test. The cement used was ESP VI-1 32.5 N, a lower strength cement that contents a large amount of fly ashes.

Recycled pavement design requires an understanding of material fatigue as well as its bending strength. Compressive strength tests at 7days intervals are readily conducted in the work site and it is the usual control parameter. Earlier studies have established correlations between the short-term (7 day) and long-term (90 day) compressive, tensile and bending strength values. These last defined the material behaviour together at the fatigue equation for the recycled layer that has been developed by the authors.

A total of 350 trials were conducted on 15 cm square and 60 cm long prismatic specimens and 15 cm diameter and 18 cm long cylindrical specimens, as follows.

- A total of 37 bending strength trials (AENOR 2009) were run on prismatic specimens. Compressive (CEDEX 1990) and splitting tensile (AENOR 2005) strength tests were performed to failure, each on one of the halves into which the specimens were divided (for a total of 74), to find the bending-compressive strength and bending-tensile strength ratios.
- A total of 35 trials were run (18 on prismatic specimens and 17 on cylindrical specimens) to determine the variations in compressive strength over time.
- A total of 55 dynamic tests were run to determine fatigue in prismatic specimens. Each half of the divided specimen was tested to failure to find the compressive (CEDEX 1990) or tensile (AENOR 2005) strength.

- A total of 18 trials were run on cylindrical specimens to determine the modulus of deformation (ASTM 2004).

Figure 2: Bending strength trials, compressive and splitting tensile strength tests

Figure 3: Dynamic and modulus of deformation test

3 TRAFFIC

Spanish legislation (CEDEX 2003, JCYL 2004) classifies heavy vehicle traffic into six categories (from T00 to T4) depending on the average daily truck traffic per way for the design lane in the first year (ADDT) as follows:

Table 2: Heavy traffic categories

Traffic category	T00	T0	T1	T2		T3		T4	
Subcategory	-	-	-	T21	T22	T31	T32	T41	T42
ADTT(*)	> 4000	2000	800	400	200	100	50	25	0

(*) Average daily truck traffic per sense in the first year.

The ADDT boundary values determine the equivalent design traffic (EDT) requirement (or number of 13-tonne single axle loads to be borne by the design lane) for each heavy traffic category throughout the service life span. This parameter is found from equation 1 (Junta Andalucía, 2007):

$$EDT = MDI_d \cdot EC \cdot 365 \cdot F \cdot \gamma_t \qquad (1)$$

where “EC” is the mean equivalence coefficient for trucks. The value adopted here, 0.6, is used by the CEDEX (Ministry of Development) for semi-rigid pavements and certain other studies (Kraemer C. & Albelda R, 2004), “F” is the heavy vehicle traffic growth factor, for which a constant 3 % growth rate over a 20-year service life was assumed and “γt” is the load safety factor, ranging from 1.2 for categories T00 to T1, to 1.1 for categories T2 and T3 and 1.00 for category T4 (Junta Andalucía, 2007).

Equation 1 was used to find the equivalent design traffic (EDT) values for each subcategory of heavy traffic listed in table 3

Table 3: Equivalent design traffic (cumulative number of axle loads to be borne without failing)

Heavy traffic category	Subcategory	ADTT	Trucks	EDT requirement (number of axle loads)
T00	T00	7 000	82 384 568	49 430 741
T0	T0	4 000	47 076 896	28 246 138
T1	T1	2 000	25 538 448	14 123 069
T2	T21	800	8 630 764	5 178 459
	T22	400	4 315 382	2 589 229
T3	T31	200	2 157 691	1 294 615
	T32	100	1 078 846	647 307
T4	T41	50	490 384	294 231
	T42	25	245 192	147 115

4 THE SUBGRADE

Since the subgrade characteristics cannot be modified when pavement is recycled in situ (unless the entire pavement is raised and replaced), two situations are considered:

1. high quality subgrade, well compacted, with a California Bearing Ratio (CBR) of at least 20, characterised by a modulus of elasticity of 200 MPa and a Poisson's coefficient of 0.35.
2. low quality subgrade (layer contaminated with clay,...) with a CBR of at least 5, characterised by a modulus of elasticity of 50 MPa and a Poisson's coefficient of 0.35.

In both cases, the Brown and Pell (Brown S.F. & Pell P.S, 1967) fatigue equation 2 was used:

$$\varepsilon_z = 2.16 \cdot 10^{-2} \cdot N^{-0.28} \qquad (2)$$

where ε_z is the vertical strain under compressive stress and N the number of typical loadings.

5 IN SITU RECYCLED LAYERS WITH CEMENT

The fatigue expression determined in earlier trials for cement-bound recycled material derived from the upper 30 cm of a road pavement, consisting of 1/3 severely worn bituminous mix and 2/3 granular material, was as follows:

$$\frac{\sigma}{R_f} = 1 - 0.058 \cdot logN \qquad (3)$$

where σ is the ultimate bending stress after N typical loadings and R_f is the bending strength of the material.

The combined effect of the lesser slope of this expression than the obtained for soilcement and the greater flexibility of this material due to the asphalt mortar is translated into greater recycled material performance.

A modulus of deformation of 5,000 MPa was obtained in the tests conducted.

6 ASPHALT LAYERS OVER THE RECYCLED LAYER

The modulus of deformation for bituminous mix varies with mix characteristics, as well as with the season of the year, given the thermo-sensitive behaviour of bitumen. A modulus of deformation of 6,000 MPa and Poisson's coefficient of 0.33 were adopted, as these are the values generally accepted in Spain for a standard trial temperature of 20 ºC and a loading frequency of 10 Hz in AC type mixes.

For the heaviest traffic categories (T1 and heavier), a discontinuous road surface (such as BBTM 11B BM-3c) was assumed, to ensure both certain comfort standards and safety in rainy weather. In this case, the modulus used was 4,000 MPa and the Poisson's coefficient was 0.35.

The fatigue equation used in Spanish design [4] is laid down in 6.1-IC standard (Ministry of Development, 2003). The critical parameter is the horizontal tensile strain (ε_r) induced at the bottom of the asphalt layer in contact with the recycled layer.

$$\varepsilon_r = 6.925 \cdot 10^{-3} \cdot N^{-0.27243} \tag{4}$$

where ε_r is the horizontal tensile strain and N the number of typical loadings.

7 RESPONSE MODEL

The most common of all the possible response models was the one chosen: the multi-layer elastic model developed by Burmister (Burmister D.M., 1943).

Analytical calculus software was used, defining the load type, the pavement layers and their thicknesses as well as the characteristic parameters for each material. The model output included the critical parameters defined by the radial and vertical stress and strain in each layer.

Fatigue equations provide the number of typical loadings that can be withstood by each layer. The smallest value found is the number of loadings that the pavement as a whole can bear. If that value is higher than the equivalent design traffic requirement for this heavy traffic category, with a certain margin of safety, the design is regarded as valid. Otherwise, the thickness of the bituminous mix or the recycled layer must be increased until an acceptable solution is reached.

8 DESIGN FOR RECYCLED PAVEMENTS LAID ON GOOD QUALITY SUBGRADE

A large number of pavements with the characteristics defined for each layer were checked and the selected ones are able to bear the requisite 13 t equivalent axle loads with a comfortable margin. The pavement thicknesses calculated for each category of heavy traffic are shown in figure 4. The bituminous mix layer distribution and thicknesses are given in table 4.

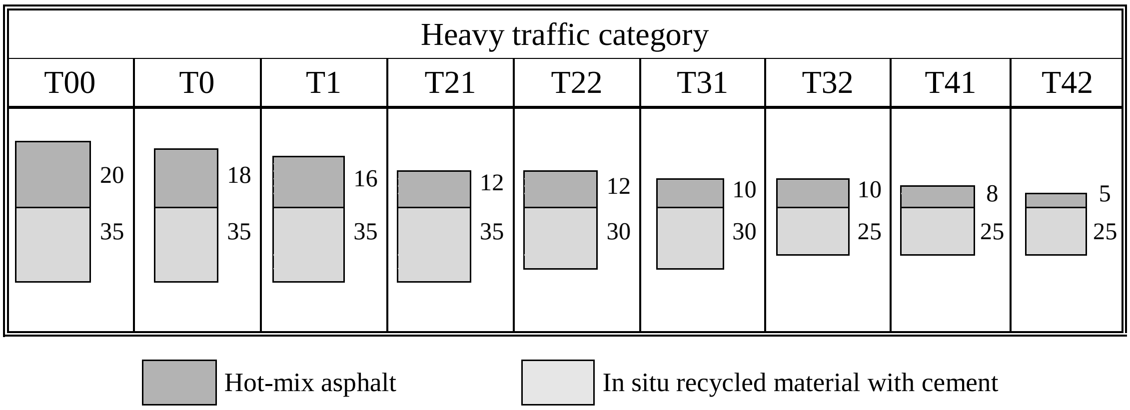

Figure 4: In situ recycled pavement with cement sections laid on subgrade of proven quality

Table 4: Bituminous mix types and thicknesses used in the calculations

Heavy vehicle traffic category	AM thickness	Surface	Intermediate	Base
T00	20	3 cm BBTM	8 cm AC 22 bin S	9 cm AC 32 base S
T0	18	3 cm BBTM	6 cm AC 22 bin S	9 cm AC 32 base S
T1	16	3 cm BBTM	5 cm AC 22 bin S	8 cm AC 32 base S
T21 / T22	12	6 cm AC 22 surf S	6 cm AC 22 bin S	--
T31 / T32	10	5 cm AC 16 surf S	5 cm AC 22 bin S	--
T41	8	4 cm AC 16 surf S	4 cm AC 16 bin S	--
T42	5	5 cm AC 16 surf S	--	--

The critical parameters obtained and the numbers of equivalent axle loads that can be borne by each pavement are given in table 5.

Table 5: Model output: critical stress and strain and EDT requirement for each pavement type

Heavy traffic category	Bituminous mix ε_r (10^{-6})	Recycled layer σ_r (kp/cm^2)	Subgrade ε_z (10^{-6})	Layer most liable to fail	EDT requirement (num. of axle loads)	Minimum number of axle loads calculated
T00	-16.60	-2.087	80.60	Subgrade	49 430 741	469 734 581
T0	-18.40	-2.224	85.90	Subgrade	28 246 138	374 173 931
T1	-20.50	-2.373	91.80	Subgrade	14 123 069	295 147 790
T21	-21.00	-2.415	104.20	Subgrade	5 178 459	187 724 754
T22	-20.70	-2.879	124.10	Subgrade	2 589 229	100 562 395
T31	-20.30	-3.104	133.90	Subgrade	1 294 615	76 656 158
T32	-19.80	-3.773	162.60	Subgrade	647 307	38 311 830
T41	-15.70	-4.100	177.10	Recycled	294 231	10 986 310
T42	-32.20	-4.680	203.90	Recycled	147 115	396 142

In roads with light traffic, structural failure is assumed to be due more to overloads than to cumulative loading, given the low intensity of road use. Further to usual practice, design for pavement subcategories T41 and T42 (in particular the latter) was based on experience or the performance of other roads in the area.

Certain factors of vital importance to ensure the service life of recycled pavements with cement were also taken into account in the design, such as total bonding between the layers and the use of at least the recommended thickness and strength for recycled layers. Other factors may also have an adverse, albeit less decisive, effect on pavement service life, such as the type of bituminous mix used, its bitumen content or the aggressive climates. In addition, the bearing capacity of the subgrade on which the recycled layer rests may decline. To address situations where no corrective action on the subgrade is possible, pavement sensitivity to such declines in quality was analysed. In these circumstances, pavements were designed to be structurally acceptable when a lower modulus of subgrade deformation is adopted (i.e., a value of 120 instead of 200 MPa). An economic balance was also sought in all sections.

9 DESIGN OF RECYCLED PAVEMENTS LAID ON LOW QUALITY SUBGRADE

For subgrades with a low bearing capacity and no guarantee of quality, the pavement designs proposed are as shown in figure 5.

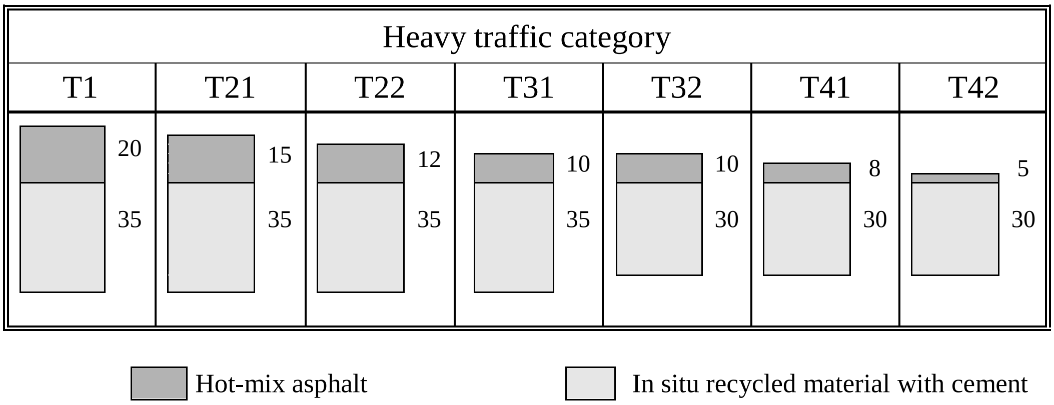

Figure 5: In situ recycled pavement with cement sections laid on low quality subgrade

Pavement design for heavy traffic categories T0 and T00 on low quality subgrade has not been studied, for such situations are essentially non-existent. If they did exist, the most suitable action would be to strengthen the subgrade (after removing the pavement) or use the road itself as the subgrade for the new pavement. Even for traffic category T1, the design requires an exceptionally thick bituminous mix layer in light of the technical difficulty involved in suitably compacting a recycled layer over 35 cm thick.

Another alternative, not addressed in this proposal, would be to maintain layer thickness while increasing the 7-day compressive strength required of the recycled material, to 3.5 MPa for instance. With that higher modulus and greater structural capacity, such a material could afford the traffic loads envisaged.

The critical parameters calculated, as well as the number of equivalent axle loads that can be borne by each pavement, are given in table 6.

Table 6: Model output: critical stress and strain and EDT requirement for each pavement type

Heavy traffic category	Bituminous mix ε_r (10^{-6})	Recycled layer σ_r (kp/cm^2)	Subgrade ε_z (10^{-6})	Layer most liable to fail	EDT requirement (num. of axle loads)	Minimum number of axle loads calculated
T1	-17.70	-2.889	124.00	Subgrade	14 123 069	100 852 333
T21	-17.30	-3.034	146.90	Subgrade	5 178 459	55 059 012
T22	-18.60	-3.375	164.00	Subgrade	2 589 229	37 156 549
T31	-17.80	-3.634	177.00	Subgrade	1 294 615	28 295 412
T32	-16.90	-4.404	215.40	Recycled	647 307	1 925 396
T41	-12.40	-4.790	235.20	Recycled	294 231	-
T42	41.20	-5.481	271.30	Recycled	147 115	-

10. PROPOSED CATALOGUE OF RECYCLED PAVEMENT WITH CEMENT STRUCTURAL SECTIONS

Design calculations were performed for the in situ recycled pavements with cement proposed using the fatigue equation (3) obtained in the laboratory for the recycled material:

$$\frac{\sigma}{R_f} = 1 - 0.058 \cdot logN \qquad (3)$$

where σ is the ultimate bending stress after N typical loadings and Rf is the bending strength of the material.

On those grounds, the pavements designed are regarded as suitable, for they have proved to be both structurally valid and cost-effective, while constituting a solution for restoring the bearing capacity of any worn road more reasonably and economically than other approaches. The in situ recycled pavement with cement designs proposed for the subgrades and heavy vehicle traffic categories studied are shown in figure 6.

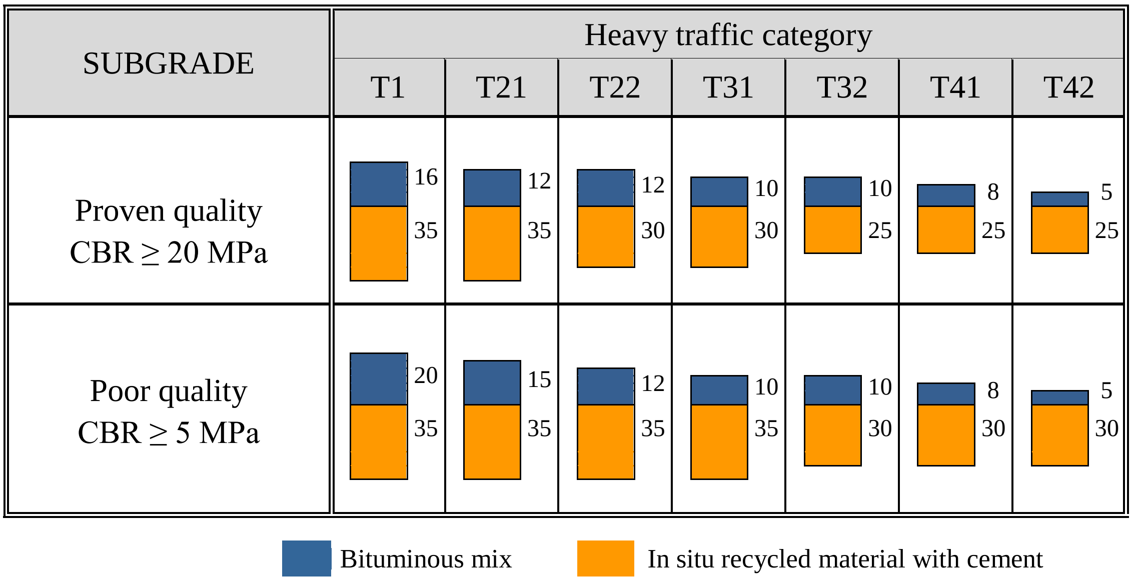

Figure 6: Catalogue of in situ recycled pavement with cement structural sections

REFERENCES

Asociación Española de Normalización y Certificación AENOR (2005). Norma UNE-EN 12390-6:2001/AC: 2005. Ensayos de hormigón endurecido. Parte 6: Resistencia a tracción indirecta de probetas, Madrid, España.

Asociación Española de Normalización y Certificación AENOR (2009). Norma UNE-EN 12390-5. Ensayos de hormigón endurecido. Parte 5: Resistencia a flexión de probetas, Madrid, España.

ASTM Standards worldwide. American Society for Testing and Materials (2004). C469-94. Standard test method of static modulus of elasticity and Poisson’s ratio of concrete in compression. EEUU.

Brown, S.F. and Pell, P.S. (1967). An experimental investigation of the stresses, strains and deflections in a layered pavement structure subjected to dynamic loads. *Proceedings of the 2nd International Conference on the Structural Design of Asphalt pavements*. Preprint Volume, Michigan, USA. pp 384 – 403.

Burmister D.M. (1943) The general theory of stresses and displacements in layered systems and applications of the design of airport run ways. *Proceedings of the Highway Research Board*, 23, 126-148.

CEDEX. Dirección General de Carreteras, Ministerio de Fomento (1990). Normas NLT de ensayo de carreteras: Norma NLT-305/90 Resistencia a compresión simple de materiales tratados con conglomerantes hidráulicos, Madrid, España.

Dirección General de Carreteras, Ministerio de Fomento (2003). Norma 6.1-IC, Secciones de Firme y Capas Estructurales de Firmes, Orden FOM/3460/2003 de 28 de noviembre. Madrid, España.

Díaz, J., Murga, P., Gonzalo-Orden, H., González, D. (2008). Estudio del comportamiento de firmes reciclados in situ con cemento, *Proceedings of the VIII Congreso Nacional de Firmes,* Asociación Española de la Carretera (AEC), Valladolid, España, pp. 519-527.

Díaz, J. (2011). El estudio del comportamiento de los firmes reciclados in situ con cemento. Tesis Doctoral. Universidad de Burgos. Burgos, España.

Dirección General de Carreteras. Ministerio de Fomento (2001). Pliego de Prescripciones Técnicas Generales PG-4, Capitulo 21: Reciclado in situ con cemento de capas de firmes. O.C. 8/2001, de 28 de diciembre. Madrid, España.

Dirección General de Carreteras, Ministerio de Fomento (2004). Pliego de Prescripciones Técnicas Generales PG-3, capitulo 513, materiales tratados con cemento (suelocemento y gravacemento). Orden FOM/891/04. Madrid, España.

JCYL Dirección General de Carreteras e Infraestructuras, Consejería de Fomento (2004). Recomendaciones de proyecto y construcción de firmes y pavimentos, Valladolid, España.

Junta de Andalucía .Consejería de Obras Públicas y Transporte (2007). Instrucción para el diseño de Firmes de la red de carreteras de Andalucía. Sevilla, España.

Kraemer, C. Albelda R. (2004). Evaluación técnico – económica de las secciones de firme de la Norma 6.1-IC. *Proceedings of the IV Congreso Nacional de Firmes, Normalización e Innovación*. Junta de Castilla y León y AEC. León, España.