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The SCORE project Final reckoning

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ABSTRACT

In spite of the important measures proposed by the European Commission, which will raise spending on R&D programmes to 3% of the GDP by the year 2010 in order to encourage R&D development in Europe, the current situation does not compare favourably with the USA or Japan. The Commission's Framework Programme currently amounts to 3.7% of the total budget for the European Commission. Although the document handled by the Commission does not yet give specific figures, the experts have set their sights on an investment of 9 billion euros per year for the VII Framework Programme.

R&D is the keystone to economic growth and improved European competitiveness. Doubling the annual R&D investment compared to the VI Framework Programme, as proposed by Research Commissioner Janez Potocnik, would increase exports by as much as 0.64% in 2030 and would cut imports by some 0.3%.

The European outlook in terms of R&D investment is not particularly encouraging. When the spotlight is centred on the construction sector and more specifically on the road building and maintenance sectors the situation is substantially worse.

Very few references prevail among European companies in the road sector with available funds and a proven track record in research, development and innovation (R&D&i). In order to correct this situation, all European countries are, to a greater or lesser extent, attempting to boost these initiatives by several solutions.

This article gives the final reckoning on a project developed during the V Framework Programme and financed by the European Commission – the SCORE Project.

The purpose of the SCORE Project (www.score-project.org) was to make an in-depth study of the state-of-the-art of cold-recycled asphalts and make attempts to optimise the technique. This would then provide attractive options for those responsible for the maintenance of the European road networks. The optimisation process covers conventional recycling techniques incorporating emulsions and the development of innovative processes using foam bitumen and micronised emulsions (or nanoemulsions).

The Project lays out a systematic approach covering all stages from the characterisation of the component materials to the laying of the final asphalt mix and the cost benefit/analysis from technical, economic and environmental points of view.

Keywords: *Recycling, Emulsion, Nanoemulsion, Cold-recycling, Foam bitumen, Bituminous binder, SCORE.*

Background

Specific aspects of the SCORE Project have been considered throughout the seven preceding articles appearing in this publication(I-VIII). A description of the tasks distributed among the organizations taking part in the project has already been given and is recapitulated and examined in this article.

The SCORE Project formed part of the 5th Framework Program of Research and Development of the European Community for Research and Development (Contract No. G1RD-CT-2002-00742), promoting Environmentally Friendly Construction Technologies (EFCT). The complete title of the research programme and that giving rise to the SCORE acronym was: "Superior COld REcycling based on benefits of bituminous microemulsions and foamed bitumen. An EFCT system for the rehabilitation and the maintenance of roads".

The fundamental aim of the Project was to improve the design, characterisation of materials and the execution and behaviour of cold recycling of asphalt mixes as a technique to maintain and renew asphalt pavements.

The in-situ recycling technique aims to take advantage of the deteriorated materials of the road without transferring these to a manufacturing centre, by the milling or crumbling of the material in question, followed by the mixing of this material with a bituminous binder, water and aggregate and additives where it be the case; and the laying and compacting of the resulting material. All these operations are conducted on site.


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Probisa y la Dirección General de Carreteras de la Junta de Andalucía han celebrado en Huelva una jornada técnica en la que técnicos de las administraciones de la zona y constructores estudiaron las Aplicaciones prácticas del Proyecto SCORE en la rehabilitación del firme de la A 494 entre Moguer y Palos de la Frontera mediante la técnica de reciclado en frío "in situ" con emulsión, respetuosa con el medio ambiente. La carretera A 494 es una vía de dos carriles de circulación que soporta una intensidad media de tráfico de 258 vehículos pesados/día por carril y que da servicio a las poblaciones de San Juan del Puerto, Moguer, Palos de la Frontera, Mazagón y Torre de la Higuera.

Jornada técnica sobre la rehabilitación con reciclaje en frío con emulsión

Permitió estudiar las aplicaciones prácticas del Proyecto SCORE en la rehabilitación de la A–494

■ El Proyecto SCORE pretende profundizar en los conocimientos de los materiales bituminosos reciclados en frío y conseguir optimizar la técnica.

Photo 1. *One of the acts reporting on results and appraising the SCORE project, as appearing in the local press in Andalucia.*

In 2003, shortly after the start of the SCORE project, the World Road Association (PIARC) Technical Committee 7/8 on Road Pavements, headed by Jean-François Corté, issued a document on "Cold in-situ recycling with emulsion or foamed bitumen" («Retraitement en place à froid à l'émulsion ou à la mousse de bitume»)(IX).

This document was developed on the basis of the work conducted by a committee of 8 members and collaborators from various countries (Estonia, Canada, Norway, United States and Japan). I had the privilege to participate within the working group responsible for drafting the document together with seven colleagues from different countries.

Among the findings of this report was the very low degree of development of this technique at an international level and the need to promote strategies to minimise the waste produced by road construction and maintenance activities.

The document on "Cold in-situ recycling with emulsion or foamed bitumen" listed a series of practical drawbacks regarding the technique, which may be summarised in seven main points:

- 1. Quality of materials to be recycled,
- 2. Quality of pavement,
- 3. Presence of materials that rule out milling,
- 4. Presence of difficulties that rule out milling,
- 5. Adverse weather conditions
- 6. Mechanical limitations, and
- 7. Limitations due to protection.

The SCORE project has attempted to address each and every one of these drawbacks. In the seven preceding articles we have shown some of the specific aspects developed within the project[I-VIII].

Country	Available material (tons)	Percentage used in hot recycling	Percentage used in cold recycling	Percentage production of new mixes containing recycled
Austria	550,000	10	10	
Bélgica	1,500,000	40		36
República Checa	425,000			
Dinamarca	218,000	83		48
Francia	6,500,000	13	<2	<10
Alemania	14,000,000	82	18	60
Hungría		15	0	0,6
Irlanda	36,000	36	0	1.5
Italia	14,000,000	18		7
Holanda	3,000,000	75		63
Noruega	406,000	23	20	10
Polonia	1,080,000	4	55	0.1
Eslovaquia	123,000			
Eslovenia	22,000	50		15
España	2,250,000	8	4	3.5
Suecia	750,000	40	60	35
Suiza	600,000	50	50	
Reino Unido	4,500,000			
Japón				71.4
Ontario - Canadá	3,000,000	60	0	
Venezuela		0		0

Table 1. *Recycling of road materials in Europe and worldwide (Source: EAPA, Asphalt in Figures 2005).*

Participation and distribution of the knowledge gained

Projects such as SCORE, with over 300 man months of dedication and work, require a great deal of focus and effort. The success of these projects with so many partners depends on the competence, complementarity, confidence and degree of implication in the development of this technique by all the partners involved.

The creation of a Steering Committee, formed by expert international members unrelated to the participating members, has enabled the combination of R+D with sectorial strategies and the distribution of the results (see Photo 1).

True collaboration with the correct partners always exceeds even the most optimistic expectations.

The development of a R+D+i project should not depend on the potential awarding of grants or tax incentives. Any project developed purely on this premise is almost certainly doomed to failure. R+D should, instead, be based on the certainty that any investment in research and development can only be reflected by improved competitiveness and enhanced economic growth and social well-being.

Each and every one of the industrial partners participating in the SCORE project have appraised the possibilities of improvement in both technical and financial terms. In this regard, the funding obtained from the European Commission, covering 50% of costs, has undoubtedly contributed to a more favourable economic balance.

The SCORE project will subsequently contribute to the greater and far rapid development in Europe of the technique of recycling asphalt pavements with bitumen binders. As a result of a research project involving organizations from various European countries, the experiences in this technique will surely spread more rapidly. The construction of test sections in three European countries: Spain, France and the Czech Republic[V,VII], will further promote the technique in Europe.

The final objective of the SCORE project (www.score-project.org) was to gain improved knowledge of cold recycled asphalt materials and to optimise the technique so that this could be seen as an attractive alternative for road network maintenance managers in Europe.

Unfortunately, the current situation in Europe is very far removed from this objective. According to statistics published by the European Asphalt Pavement Association (EAPA) on the basis of results for 2005 (see Table 1), the volumes available for recycling in different European countries exceeded 40 million tons. In ten of the 18 countries offering details, the employment of cold recycling was non-existent. According to the information contained in the publication, cold recycling is only conducted in Austria, France, Germany, Norway, Poland, Spain, Sweden and Switzerland.

Photo 2. *Example of milled material in Spain, obtained in one of the tests of the SCORE project*

The main advantages of cold recycling from an environmental point of view are:

- Transport savings, on account of the limited contribution of new materials,
- Energy savings, as this is a cold technique that does not require the heating of component materials,
- Savings in natural resources, due to the use of existing road materials. The reduction in the amount of mineral aggregates required is of particular relevance as these are produced in quarries and/or gravel banks which have a considerable environmental impact. The method also reduces the amount of bitumen necessary when compared with the preparation of non-recycled asphalt mix.
- Waste reduction, and
- Reduction in construction risks and polluting emissions

All these advantages, however attractive, are not reflected by the current situation and the level of employment of cold recycling techniques for road renewal continues to be very limited in Europe.

The drawbacks concerning the technique indicated in the PIARC publication[IX] and the arguments expressed by the Steering Committee of the SCORE project have all been taken into account in order to orientate the tasks considered in the project to the work programmes.

SCORE appraisal of technical drawbacks

The SCORE project has attempted to address each and every one of the technical drawbacks described in the PIARC document.

1. Quality of the pavement and materials to be recycled

In order to correctly define the quality requirements of the recycled materials and that of the pavement, it is necessary to make an in-depth study of the influence of the particle size of the milled material obtained during the recycling process. In the first project task, Effect of particle size, an assessment has been made of the basic parameters (forward speed of the machine, milling depth, speed of rotation, number of teeth, etc.). This work has been covered in the first and fourth publications of this series of articles (Photo 2)[V].

One of the objectives of the milling process should be to reduce the amount of particle sizes of over 25 mm to a minimum. In the preliminary analysis of pavement condition it is essential to establish the level of bond between the pavement layers in order to establish the potential milling levels that may be obtained. The LCPC (Laboratoire Central des Ponts et Chaussées) has come to this very interesting conclusion in Task Number 1[V].

In those cases where there is a partial de-bonding of the pavement courses to be recycled and particularly when the upper layer is subject to extensive cracking,

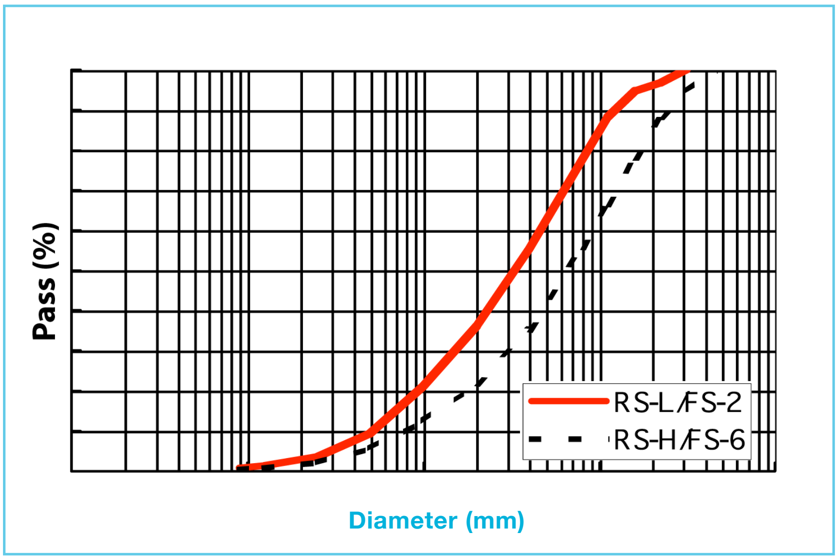


Figure 1. *Effect of forward speed of scarifying equipment (FES = 2 to 6m/min) and the rotating speed of the drum (RS = 130 to 200 rpm) in the particle size of the milled asphalt pavement, obtained from a thickness of 10 centimetres at a site in Žďár (Czech Republic).*

with perhaps the most extreme characteristics.

- In Spain, with asphalt mixes with a 4 to 5% binder content and a high degree of ageing, penetration at 25ºC below 10 1/10mm and a ring and ball temperature of 70 to 80ºC (Photo 4), and
- In the Czech Republic, with milling from asphalt mixes with a 5.8 to 8% binder content and a low degree of ageing, penetration at 25ºC of 25 1/10 and ring and ball temperature of 50 to 55ºC[VII].

This range of characteristics covers the milling materials that may be obtained in the majority of European countries.

it is necessary to conduct one or more of the following measures according to the case in hand:

- preliminary milling of both layers by a milling drum equipped with sufficient teeth,
- reduce forward speed and/or increase speed of rotation of the drum (figure 1), and
- recycle a pavement thickness of at least 8 centimetres

One important aspect of the research conducted by the Score project on the different materials incorporated within the milling process was that of their different chemical reactivity[X]. When speaking of recycling, there is a general tendency to refer to the importance of the degree of ageing of the binder in the recycled mix and this aspect shall be dealt with further on. However, the project noted the different reactivity presented by the millings and this aspect has been considered in the fourth communication.

A method has been developed to evaluate the reactivity (see Photo 3) and then obtain technical criteria to establish the formulation of the most suitable emulsion[X].

It has been seen that recycling with foamed bitumens is less sensitive to the nature of the millings and the parameters of the mix formulation than those recycled with conventional emulsion or nanoemulsion[IV].

An analysis has been conducted and test sections prepared in two European countries that reveal millings

It has been observed, both at laboratory level and on test sections, that the degree of ageing of the milling did not have a direct influence on the mechanical properties of the mix[VI,VII].

2. Regeneration of aged binder

Another aspect of the SCORE project was the scientific analysis of possible interaction between the old binder

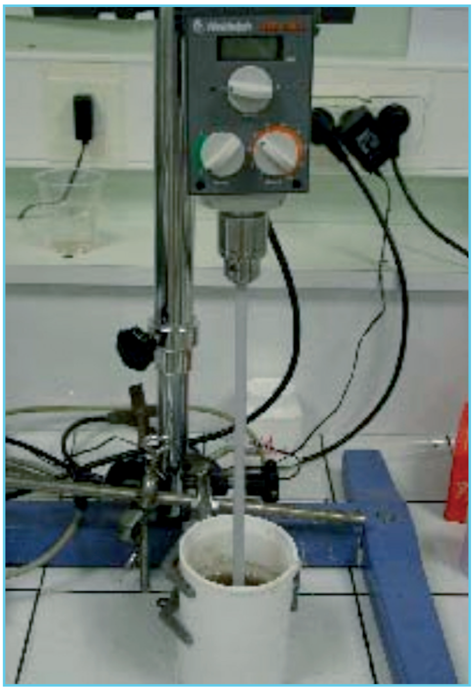


Photo 3. *Test equipment to evaluate reactivity employed in the SCORE project.*

Photo 4. *Test section prepared under the SCORE project at Moguer (Huelva).*

and the new bitumen(I). To what extent may an aged binder be reconditioned by a regenerating additive? How much time does this take? The potential results of this particular project task will establish certain guidelines regarding the selection of the new binder. This aspect has been dealt with in the first publication of this series of articles(I).

The work, conducted on the basis of rheological measurements, has analysed the kinetics of diffusion between the old and new binder. A layer of old binder and a further layer of new binder are installed on each plate of a plate-plate type rheometer. The modulus of the system is then measured over time and the results can then be interpreted in terms of diffusion parameters. Diffusion kinetics have also been directly measured on mixes to establish the degree by which the theoretical results meet up with those found in practice.

The variable to be analysed is the increase in the apparent modulus measured by DSR of a two-layer material, resulting from the diffusion of one 0.1mm layer of bitumen with a penetration value of 400 1/10 mm and a second 0.2 mm layer of artificially aged bitumen with a penetration of 15 1/10 mm. The diffusion becomes evident very slowly, taking over 30 hours at 80°C(I). Two tests have been conducted and the method of analysis has been reproduced fairly well. However, diffusion is seen to be very slow at this temperature.

These and other experiments have shown that at ambient temperature, the speed of diffusion of a soft bitumen into an aged bitumen is extraordinarily slow and so much so that one is forced to think that under these conditions the time necessary to make the diffusion for the regeneration of the aged binder, exceeds the service period of the recycled mix!

One very interesting contribution to the project has been the possibility of adding regenerating oils to the milled materials prior to using the same(I). An ideal period of one week is required for this to take full effect and while this rules out its application for in-situ recycling, it makes it perfectly viable for recycling in a central plant.

The addition of a small amount of regenerating oil, of around 0.1 pph of the dry milled materials, seven days prior to the use of the same and the employment of a harder binder in the formulation of the emulsion together with the addition of lime of cement, in quantities of less than 1 pph, have all made it possible to obtain mixes with better mechanical properties.

3. Adverse weather conditions

One of the current drawbacks of cold recycling is the sensitivity to water and the lack of cohesion immediately after laying. This situation becomes even worse under adverse weather conditions with high

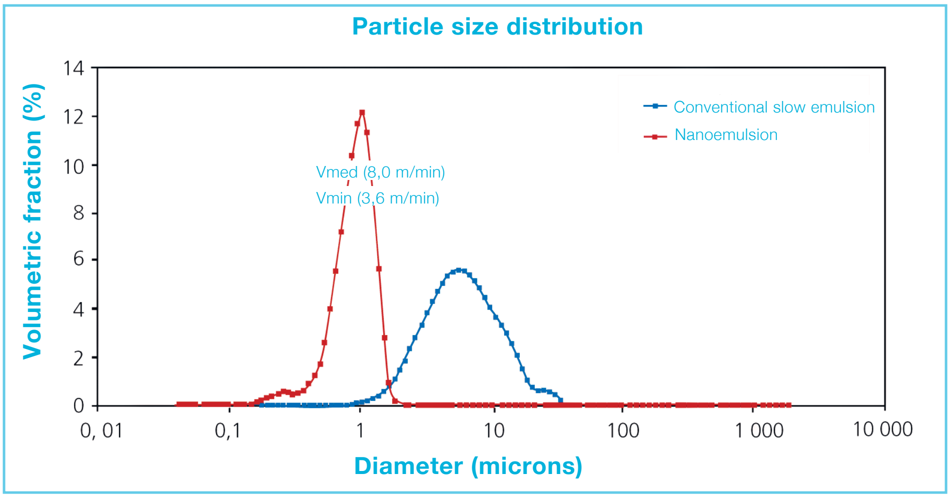


Figure 2. *Comparison of particle sizes of a conventional slow emulsion with a nanoemulsion*

humidity and low temperatures.

In the Score project a bitumen nanoemulsion was employed for the first time[III to VIII]. A bitumen nanoemulsion is a bituminous emulsion with a far lower spread of particle sizes than a conventional bitumen emulsion (see Figure 2) and with an average diameter similar or smaller than one micron. This reduction in particle size then gives the nanoemulsion a greater specific surface area which, in turn, provides greater coating capacity.

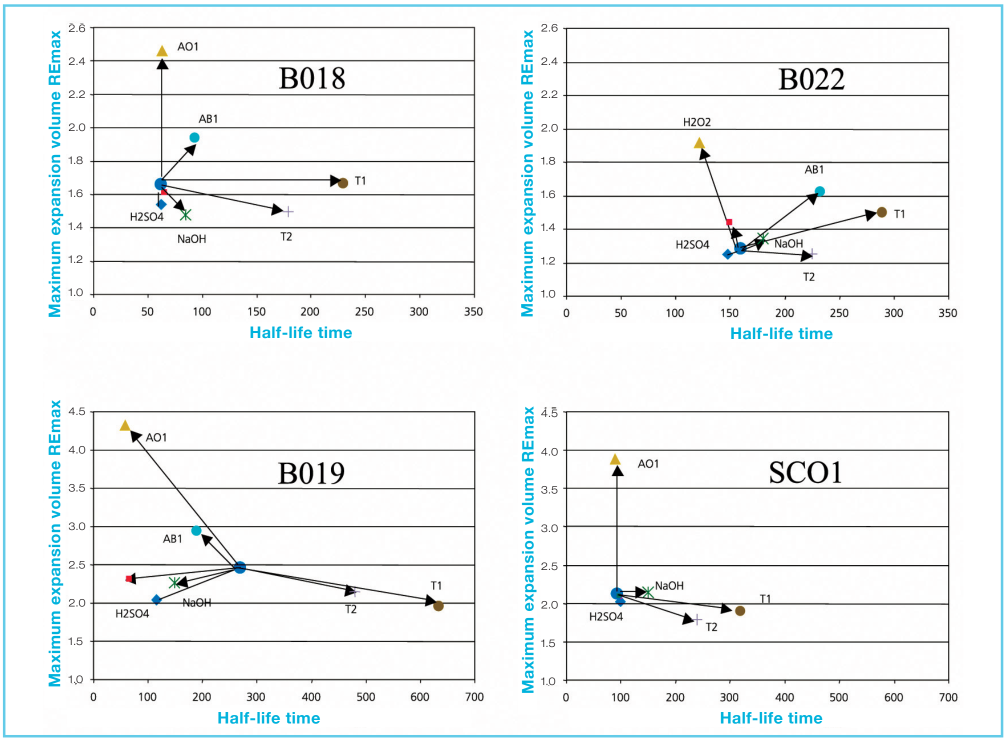


Figure 3. *Effect of different parameters on the formulation of foamed bitumen conducted with 4 different bitumens, in terms of maximum expansion volume (Remax) and life time.*

This then means that with the same content of residual binder, the sensitivity to water is lower and this has been verified with low and very low contents of residual binder[III].

In order to ensure that recycling is less dependent on the weather conditions, it is necessary to recover the initial cohesion of the mix. According to the conventional line of thought a soft binder or a regenerating agent would be the best solution. However, the information indicated in the preceding paragraphs raises doubts regarding their necessity in terms of the recovery of the aged binder. Furthermore, and from the perspective of initial and final cohesion, a hard binder offers better cohesion than a soft binder.

Furthermore, the addition of an active filler, 0.5-1 pph of cement, very noticeably improves both the initial cohesion and the conserved strength and modulus without losing flexibility. This development has made it possible to extract site specimens just three weeks after the recycling of the pavement!

Method of compaction	Initial density (g/cm³)
1	2.01
2	1.85
3	1.87
4	2.02

Table 2. *Initial densities according to method of compaction[VII].*

The objective behind the addition of 0.5-1 pph of cement is similar to the effect of cement in bituminous slurries and, namely, to

- Accelerate the breaking up process by a sharp change in pH which then provides increased initial cohesion,
- Reduce the water content in the mix. This leads to an increase in the density of the mix and improved mechanical properties.
- Increase the conserved strength. From 10 to 15 points for the same binder content, and
- Increase the modulus of elasticity. Up to 30% for the same moisture content.

Initial cohesion is a critical aspect for the speed of opening to traffic and the possibility that the recycling process be less weather dependent.

One drawback of the technique was the impossibility to take site specimens until several moths had passed.

As a result of the developments described above, this situation has rapidly developed and in the case of the A-494 road from San Juan del Puerto-Matalascañas (Photo 4)[VII], it was possible to obtain specimens just 4 weeks after the work had been carried out. This confirms the improvement in the initial cohesion and also allows the possibility of mechanically characterising the mix, the development of mechanical properties and the bonding between layers.

4. Mechanical performance of the mix

Fundamental aspects of the technique were tackled in project tasks 6 and 7: Mix design and Mechanical characterisation. It is necessary to design and characterise the final mix in a suitable manner as current design tests are inadequate.

The load applied in the Spanish immersion-compression test and in the French Duriez test is far higher than the load applied on site. This is so high that it is possible to design recycled mixes without binder in the laboratory that exceed the minimum required specifications!

In tests carried out on recycled materials with foamed bitumen it has been shown that the standard characterisation measurements such as volume of expansion and time (Figure 3) could not be correlated with the mechanical properties of the recycled material[II,IV].

Modifications in the manufacturing conditions of the foam have not had a significant effect on the final mechanical properties.

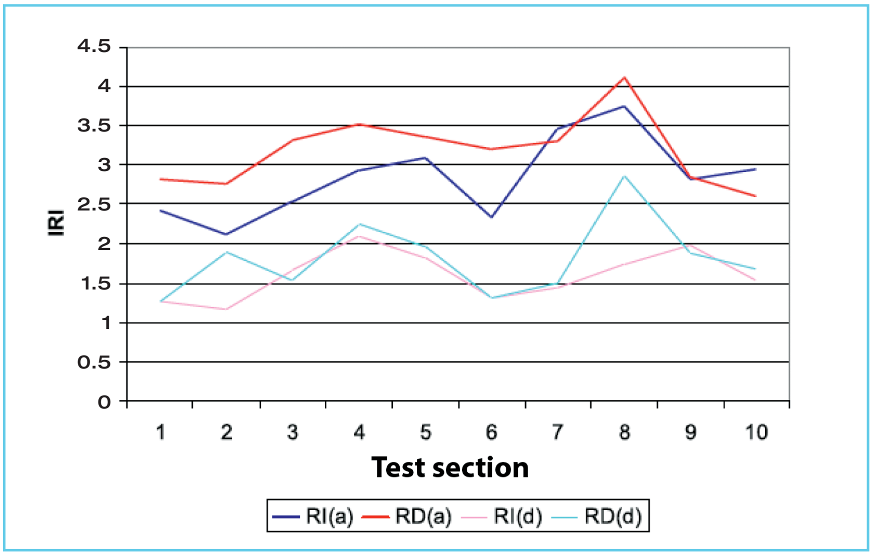
In the test sections made in Spain, on the A-494 road, four different compaction systems were carried out, as described in the final article of this series[VII], which made it possible to establish certain differences in the initial density (Table 2).

In-situ recycling carried out with current equipment shows very significant improvement with regard to the smoothness of the pavement. Table 3 and Figure 4 show the reduction in the IRI obtained on ten test sections. Reductions of over one point and close to two points have been obtained in the international roughness index, as from values close to 3.

A further key aspect is the degree of adherence obtained after in-situ recycling performed by equipment that simultaneously conducts the milling operation and

BEFORE RECYCLING		
Section	IRI left lane	IRI right lane
1	2.416	2.826
2	2.126	2.758
3	2.534	3.318
4	2.940	3.517
5	3.087	3.367
6	2.329	3.203
7	3.458	3.303
8	3.744	4.109
9	2.813	2.841
10	2.947	2.613
AFTER RECYCLING		
Section	IRI left lane	IRI right lane
1	1.264	1.264
2	1.174	1.892
3	1.665	1.544
4	2.094	2.252
5	1.823	1.962
6	1.310	1.310
7	1.444	1.500
8	1.743	2.857
9	1.981	1.873
10	1.517	1.674

Table 3. *IRI results before and after in-situ recycling performed on the A494 road (same data as Figure 4).*



RI: Left lane: RD: Right lane, (a) before, (b) after in-situ recycling
Figure 4. *IRI results before and after in-situ recycling performed on the A494 road (same data as Table 3).*

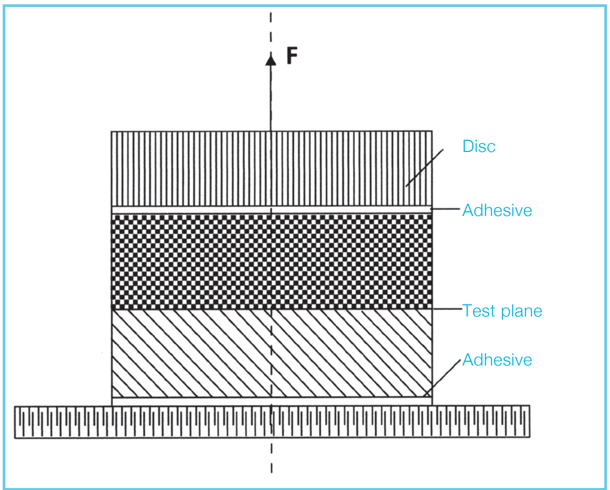


Figure 5. *Schematic diagram of German test to evaluate bond between two layers*

Test number	Specimen number	Max. load (kN)	Max. strain (mm)
1	11	8.91	3.83
4	6	19.25	0.99
4	6-1	15.65	1.51
4	7	14.85	0.91
4	8	14.69	1.88
6	6	11.67	2.21
6	7	7.10	1.12
6	8	19.74	1.66
7	12	21.65	2.28
7	13	9.74	1.99
7	14	6.11	2.03
9	11	11.62	2.35
9	12	8.43	1.90
9	13	12.44	2.41
average		12.32	1.98

Table 4. *Maximum load and strain recorded in German test (figure 5) on 16 specimens taken from 5 of the 10 test sections on the A494 road.*

the laying of the recycled material and which do not, subsequently, apply a tack or bond coat.

The bond between layers of 16 specimens from 5 test sections have been measured in accordance with the German method of measuring the adherence between mixes, as shown in schematic form in Figure 5.

Table 4 shows the maximum stress and strain values obtained at the bond between the recycled mix and the old asphalt mix 2 months after laying. This data has been

Test number	Specimen number	Max. load (kN)	Max. strain (mm)
4	7w	15.98	1.18
4	8w	8.01	1.76
6	7w	22.5	1.79
average		15.50	1.58

Table 5. *Maximum load and strain recorded in German test (figure 5) on 3 specimens*

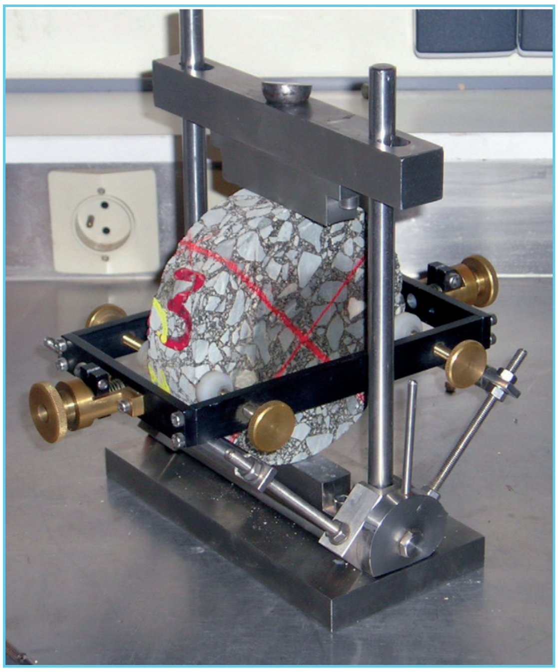


Photo 5. *Modulus test specimen.*

compared with three specimens obtained on site but when measuring the bond between two layers of aged bituminous mix. The results are indicated in Table 5.

These figures show that the bond between recycled mix layers and base layers are similar to that of conventional asphalt mixes.

A further essential aspect is the modulus of the mix. This aspect was considered in project task 7 and reported on in the sixth publication[VI]. In general terms the stiffness modulus essentially appears to depend on the nature of the milled material.

The following method was employed to establish the module after one or two years: storage of the specimen after compaction in a gyratory compactor over 14 days at 35ºC and 20% humidity. The manufacture of the specimens in the gyratory compactor (Photo 5) makes it possible to establish compaction levels that reproduce a mix density and water content similar to that obtained on site.

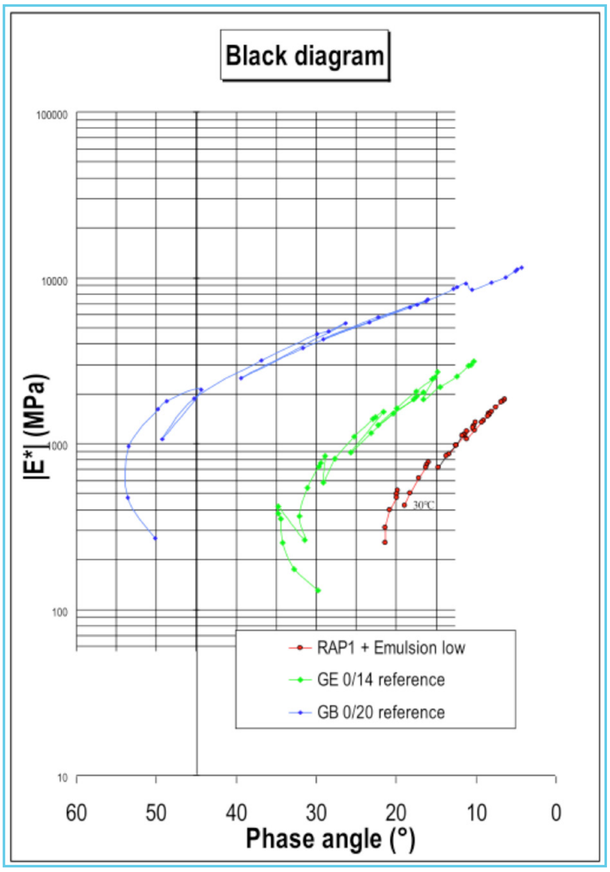


Figure 6. *Results obtained in modulus testing of the specimen*

The values of the modulus under these conditions was 3000 MPa +/- 1000 MPA[VI]. This value may increase by 15-30% according to the characteristics of the milled material and may increase by some 10 to 20% if the void content of the mix is reduced by 5%.

The use of different binders: bitumen emulsion, bitumen nanoemulsion or foamed bitumen has had less importance.

A comparison has also been made of the rheological behaviour of the recycled mix with that of an aggregate-emulsion mix. In Figure 6 it may be seen that the recycled mix has a lower thermal susceptibility and stress rate effect. This is justified by the degree of ageing of the binder and the employment of a small amount of cement, of less than 1 pph, in the recycled mix.

The addition of cement or lime in amounts of less than 1 pph in recycled mixes with foamed bitumen appears to be the safest way of improving the mechanical properties of the mix and water resistance[IV].

Section	Indirect deformation modulus (Mpa)	Confidence interval		Hypothesis testing
1	2,737	1,813	3,660	0.001189
2	3,901	3,480	4,322	2.46e06
3	3,552	2,646	4,458	0.000404
4	3,582	1,694	5,470	0.006223
5	3,695	2,372	5,019	0.000303
6	3,122	1,283	4,962	0.009226
7	2,847	1,093	4,061	0.01077

Table 6. *Indirect deformation modulus and confidence intervals obtained on recycled materials on the A494 road[VI].*

The possibility of manufacturing harder binder bitumen nanoemulsions paves the way for the improved mechanical properties of the mix. In this project, and in the third publication of the series[III], it has been noted that higher moduli have been obtained, one month after compaction, when employing nanoemulsions rather than conventional emulsions. These values are within the range of moduli obtained in the different test sections made on the A.494 road (see Table 6 and Figure 7).

The variations in modulus, among other factors, are related to the density values obtained in each of the test section (see Table 7 and Figure 8). These values have been described in detail in the seventh publication[VII].

Testing has been conducted in Cooper test equipment to establish fatigue under stress and strain criterion for each test section and the results obtained for test section 1 are shown in Figures 9 and 10.

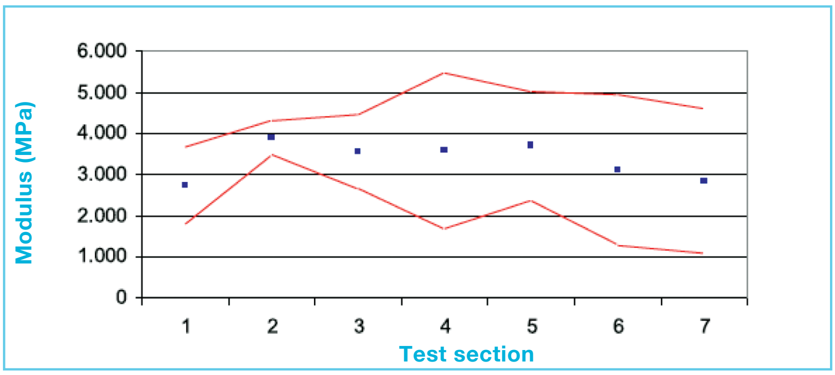


Figure 7. *Results of indirect deformation modulus and confidence intervals obtained on recycled materials on 7 of the 10 test sections on the A494 road (and included in Table 6).*

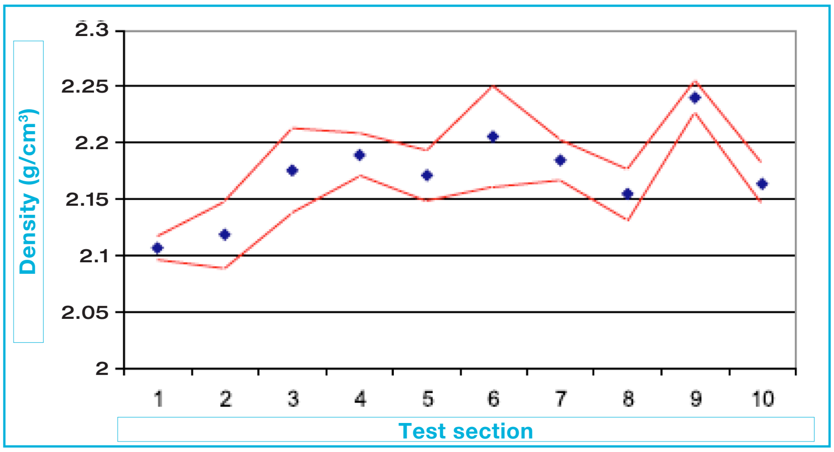


Figure 8. *Results of density and confidence intervals obtained on recycled materials on the 10 test sections on the A494 road (and included in Table 7).*

Section	Density (g/cm^3)	Confidence interval		Hypothesis testing
1	2.107	2.096	2.118	2.20e-16
2	2.119	2.088	2.149	7.56e-14
3	2.175	2.137	2.213	3.00e-13
4	2.190	2.171	2.208	2.04e-15
5	2.171	2.149	2.193	7.92e-15
6	2.206	2.161	2.251	9.05e-13
7	2.184	2.166	2.202	2.20e-16
8	2.154	2.131	2.177	2.20e-16
9	2.240	2.226	2.255	2.20e-16
10	2.164	2.146	2.182	1.71e-15

Table 7 *Density and confidence intervals obtained on recycled materials on the A494 road[VII].*

A more statistical analysis of each test section has enabled the correlation of the modulus values obtained for each section with the main variables (Figure 11).

5. Protection of the recycled mix

One of the common drawbacks of cold recycling is the need to protect the laid mix. In many documents regarding the cold recycling of pavements, indications are given to allow several days to pass between the execution of the recycling and the application of a sealing layer so as not to impede the rate of water evaporation of the mix.

From the experience gained by Probisa in cold in-situ recycling, as described in various recent documents[X,XI], it has been established that the most suitable moment for the application of the sealing layer is that of the same day of laying as the application of some 500-700 grams of emulsion per square metre will not prevent water evaporation from the mix.

The density and evolution of modulus seen in test sections made on the A-494[VII] road have demonstrated that this practice is correct and noticeably reduces the period prior to opening to traffic.

In accordance with weather conditions and type of traffic, the road may be opened within a few hours.

Using this system it has been possible to obtain specimens of in-situ cold recycling within just three weeks of laying.

Conclusions

Finally, on the conclusion of the Score project and as a result of the intense effort and quality of the works presented, as acknowledged by the representative for the European Commission during the closing meeting of the project, the basic objective of the same and, namely, the promotion of cold recycling, now has a far greater scientific and technical basis for employment in road renewal projects. This series of publications aims to justify the same and provides the most relevant results contributing to this objective.

In the words of the Secretary General of PIARC, in his foreword to the first publication[I], the SCORE project was a very ambitious yet highly complex project in view of the

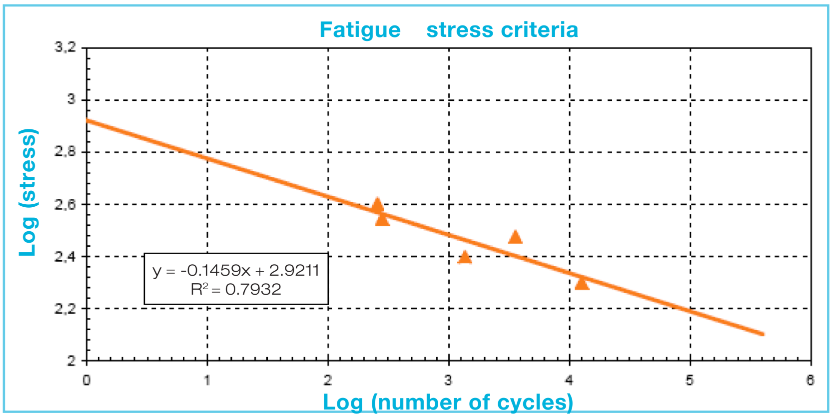


Figure 9. *Fatigue under stress criteria of samples obtained from test section 1 of the A494*

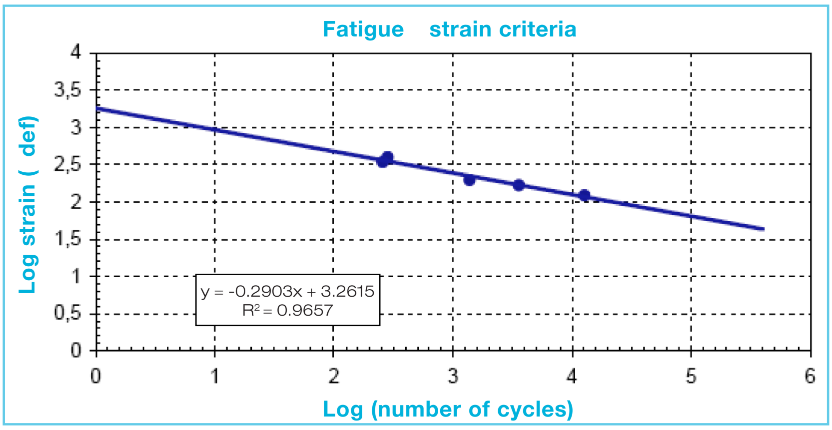


Figure 10. *Fatigue under strain criteria of samples obtained from test section 1 of the A494*

diversity of factors influencing the final result, that is to say the mechanical behaviour of the recycled mix.

Throughout these eight publications an independent description has been given of the partial results of each of the tasks within the Score project. In this publication, the last of the series, we have attempted to provide a final reckoning and to give a very brief summary of the main contributions of the project.

It has once again been a great privilege to coordinate a European project. Following on from the experience of the OPTEL project(XIII), the SCORE project has demonstrated yet again that European cooperative research serves as the best means of tackling tasks of this scale.

The technical and personal capacity of the thirty plus people directly involved in the SCORE project has once more helped to create a working atmosphere in which technical and scientific collaboration has ensured the improved quality and depth of the tasks that were initially set out.

In Europe today, with its 27 member states, and in view of the opportunities opened by the 7th Framework Programme, it is necessary to make a collective effort to promote cooperative research at a European level within our sector. Large European groups in the sector have on certain occasions rejected this model out of self-sufficiency and this has been reflected by the very few examples of European research projects funded by the European commission within our sector.

However, the scale and length of a European project makes it possible to develop objectives with a European dimension, as observed in other sectors.

In our sector in Spain, consideration is now being given to the possibility of acknowledging and promoting those companies that invest in R+D+i in procurement procedures for public works. This would undoubtedly be very well received and could well serve as a turning point in the development of R+D+i in road construction and maintenance.

As a result of this project it has been possible to prepare various test sections, two in the Czech Republic and one in Spain. The Spanish section on the A-494 road was, in turn, divided into ten sub-sections and was all made possible through the intervention of the Andalucia Regional Council (Photo 6). I hereby wish to express both

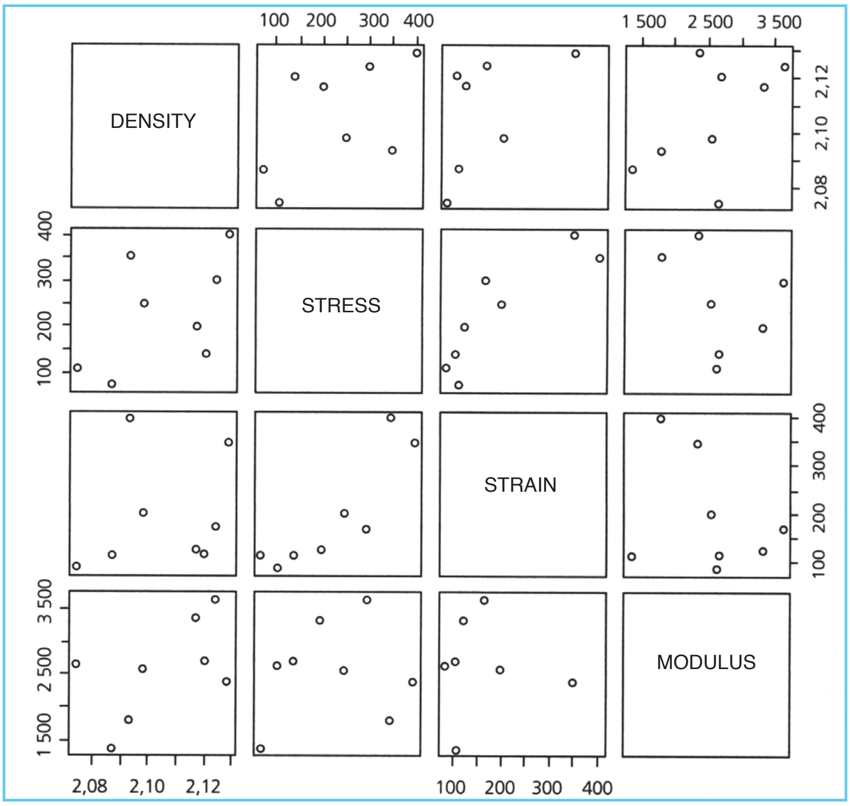


Figure 11. *Correlation between different parameters recorded on test sections on A494 road.*

Photo 6. *View of the test section on the A-494 conducted with the backing of the Andalucia Regional Council*

my gratitude to the Council and confidence regarding the monitoring of these sections.

The monitoring of these sections may well provide very important information for the establishment of new national or European standards.

Acknowledgements

In the name of the SCORE Consortium, I wish to publicly acknowledge the European Commission for their important financial contribution through the 5th Framework Programme within the specific programme for "Promoting competitive and Sustainable Growth".

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Finally, I wish to express my gratitude to all the members of the Steering Committee, the Management Committee and all those technicians who have collaborated on this project.

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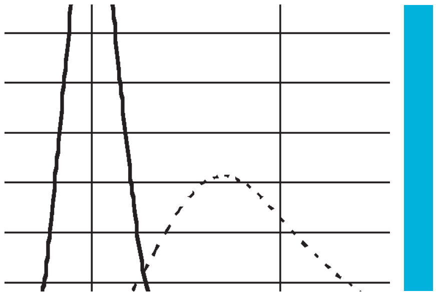
Bitumen nanoemulsions and their application in the cold recycling of asphalt mixes



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ABSTRACT

In-situ cold recycling is specifically prepared to achieve rapid cohesion immediately after laying, thereby giving the pavement sufficient mechanical properties to support traffic after only a short lapse of time. This result can currently be achieved using purpose made formulas, employing breakdown additives such as cement. The method could be improved by the use of submicronic bituminous emulsions as these provide total control over the morphology of the emulsion.

This article presents the work carried out within the SCORE Project on the production of submicronic bituminous emulsions. These are bitumen emulsions with an average diameter of less than a micron, referred to as "micronised bitumen emulsions" or "nanoemulsions" (a binder formally known as "microemulsion", though this term has since been abandoned as it is also used in other technological fields for different formulations).

The article first describes the process used to produce these nanoemulsions. This technology allows bituminous emulsions to be tailor made with a totally controlled particle size. It goes on to describe the application of nanoemulsions in cold recycling. The results show an improvement in conserved strength, in line with initial expectations. The short-term elastic modulus also increases, demonstrating an improvement in the initial cohesion.

This confirms the potential application of this innovative technology, particularly where cold recycling is concerned.

Keywords: *Emulsion, Micronised emulsion, Submicronic emulsion, Nanoemulsion, Grain diameter, Cold recycling, SCORE Project.*

Cold recycling is a fairly commonly employed technique for the in-situ recycling of asphalt pavements. This consists of scarifying or milling the existing road surface and mixing the reclaimed asphalt pavement or RAP with a new binder which may come, for example, in the form of a bitumen emulsion. This process is performed by plant and machinery specially designed for this purpose[I]. In this type of treatment, the mix based on the reclaimed material is prepared in such a way as to ensure rapid cohesion immediately after laying, thereby giving the road surface sufficient mechanical properties to withstand traffic in just a short period of time.

Cold recycling can currently be achieved using purpose-made formulas, employing, by way of example, a breakdown additive such as cement or lime[II]. One possible means of improvement could be the use of submicronic bituminous emulsions as these permit total control over the morphology of the emulsion[III]. These bitumen emulsions have an average diameter of less than a micron and are subsequently referred to throughout this article as micronised emulsions or nanoemulsions (a binder formally known as microemulsion, though this term has since been abandoned as it is also used in other technological fields for different formulations).

This article presents the work carried out within the SCORE project on the manufacture of these bitumen nanoemulsions and their application in cold recycling. A description is given of the process employed to manufacture these nanoemulsions, indicating the technology employed and then comparing the main characteristics of the same with those of conventional emulsification systems.

The article concludes by referring to the potential application of these nanoemulsions in cold recycling, when compared with conventional emulsions.

The manufacture of bitumen nanoemulsions

Bitumen emulsions are primarily formed in colloid mills at present. The hot liquid bitumen, normally at temperatures of 140°C, and the water phase carrying the emulsifier are mixed for a very short time and pass through a rotor-stator system with a very small opening (less than 1 mm) and high shear (around 3,000 rotations per minute, rpm). If the ingredients are correctly selected, both in terms of quality and quantity, an aqueous bitumen emulsion will come out of the mill, characterised by a large granulometric curve.

While mechanical factors such as speed of rotation, opening (not always controllable) or flow rate, together with mix factors such as the type and content of the emulsifier, all affect the fineness of the emulsion, it is fairly complicated to obtain a distribution of particle or drop sizes different from those obtained with the most commonly employed parameters. The cationic bitumen emulsions subsequently tend to have a typical average diameter of 3 to 6 microns.

However, theoretical and practical knowledge regarding the emulsification of viscous products has improved considerably and it is now possible to employ different methods from the traditional colloid mill. Emulsification technologies with high internal phase ratio (HIPR) may be applied to bitumen and allow the precise control of the morphology of the emulsion. This method can then be employed to manufacture submicronic bitumen emulsions.

The patented HIPR process is based on the following:

The emulsion is manufactured in concentrate form, that is to say with a dispersed phase content of between 75 and 95% (by weight), and

The dispersed phase is viscous, with a viscosity of over 1 Pa.s.

Under these two conditions, together with a suitable formula for the aqueous stage, it is then possible to obtain fine emulsions with little polydispersity.

The first aspect mentioned is very easy to obtain as this is a matter of the composition off the emulsion. The second aspect is similarly easy to achieve as this value corresponds to the viscosity of bitumen at temperatures below 90°C.

This process has the advantage of reducing manufacturing temperatures and avoiding the boiling of water. The concentrated emulsion formed in this manner is a viscous product that is difficult to handle. In order to overcome this problem, the emulsion is normally diluted to 60% bitumen in order to give it a viscosity similar to that of conventional emulsions.

In our case, all the emulsions prepared by HIPR were made in accordance with the following procedure:

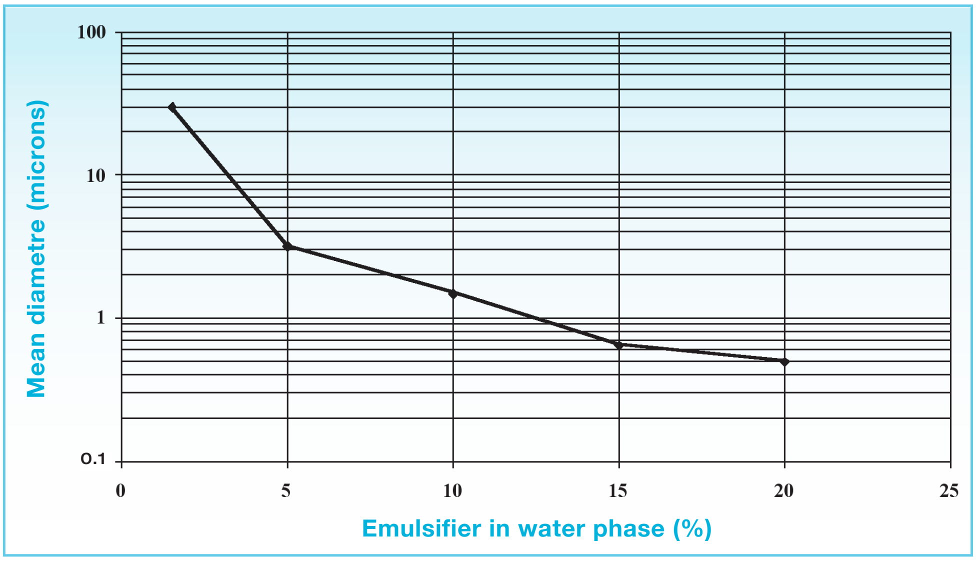

Figure 1. *Evolution of the mean diameter of the emulsion according to emulsified content in the water phase, when employing a convention cationic emulsion.*

The bitumen is placed in the reactor until reaching a uniform temperature of 90°C.

At the same time, the aqueous phase is prepared with the surface active agent (surfactant) at the selected concentration and the pH set at 2.5 by the use of hydrochloric acid.

- Once the bitumen has reached the required temperature, the aqueous phase is introduced at low agitation.
- The agitation is increased to 680 rpm and is maintained at this level until obtained the desired size, and
- The emulsion is diluted to 60% through the addition of water with a pH acid

Comparison with conventional techniques

In order to illustrate the application of HIPR technology to achieve calibrated emulsions, various emulsions were prepared with a bitumen 70/100 and a widely available commercial emulsifier. The content in the aqueous phase was kept in all cases at 9% in the concentrated emulsion and the content of the surfactant was increased to up to 20%.

As shown in Figure 1, the emulsifier content in the aqueous phase controls the size of the bitumen drops. This process makes it possible to obtain average diameters of 0.5 microns with 20% in water phase of the concentrated emulsion. Once the emulsion has been diluted to 60% bitumen, the concentration of emulsifier is 1.2% of the emulsion.

In order to illustrate the differences between a conventional emulsion and a submicronic emulsion, Figure 2 compares the granulometric curve obtained by HIPR technology and that obtained in a colloid mill with the same ingredients (bitumen and surfactant). The HIPR prepared emulsions have a very narrow distribution of particle sizes, with a totally controlled diameter. This clearly demonstrates the application of HIPR technology to manufacture tailor made bitumen emulsions.

Potential application in cold recycling: coating quality

In order to illustrate the application of nanoemulsions in cold recycling, mixes were made from milled and reclaimed material from a Spanish site, with 4.6% reclaimed asphalt pavement (RAP) millings and 2 or 3% emulsion by weight of the RAP. Emulsions were obtained both in laboratory colloid mill (conventional emulsion) and using HIPR technology (nanoemulsion) using the same Nynas bitumen 70/100 and the same emulsifier in both cases. 0.5% cement by weight of dry RAP was also systematically added.

In order to evaluate the coating quality, immersion-compression tests were carried out in accordance with standard testing procedure (NLT-162), but with a modified method of compaction to obtain more realistic densities, that is to say with a void content of 15%, as is usually observed on site. For this reason the compaction pressure was set at 5 MPa instead of the 20.6 indicated in the code. As a result, the compressive strength values were more or less half those obtained under normal compaction. In another article in this special edition,

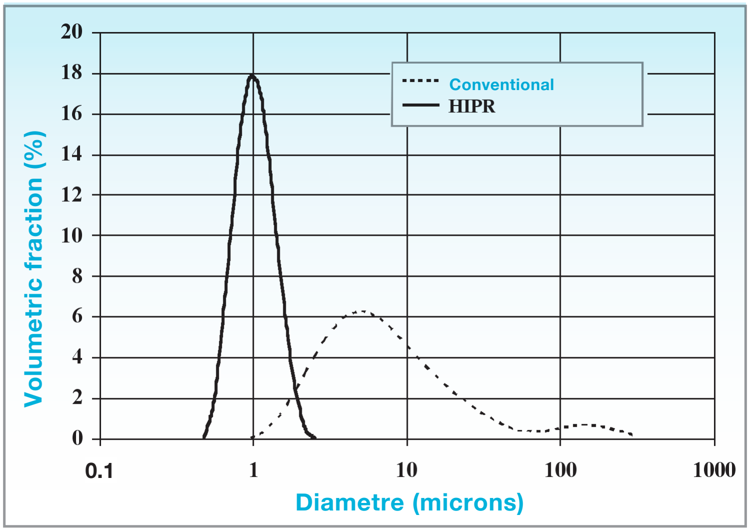

Figure 2. *Comparison between the particle size of a conventional emulsion (made in colloid mill) and that of a nanoemulsion made by HIPR with the same ingredients.*

more precise details are given of the method employed to prepare the mixes. The results obtained for mixes with 2 and 3% conventional emulsion are indicated in Figure 3.

It is noted that with 2% of emulsion by weight, the nanoemulsion did not only achieve better dry (R) and wet (r) compressive strengths, but also showed increased conserved strength r/R. When using identical types and penetration of bitumen (Nynas 70/100) and emulsifiers, this difference is most probably due to the greater specific surface provided by the nanoemulsion, and its ensuing improvement in coating quality.

With 3% of emulsion by weight, the nanoemulsion formula had lower dry R and wet r strengths than the conventional reference and maintained the same level of conserved strength r/R. This appears to be a result of an excess of binder in the nanoemulsion and where the optimum binder content appears to differ around 1% by weight from that of a conventional emulsion.

To summarise, with just 2% emulsion the nanoemulsion provides comparable results to those obtained using 3% conventional emulsion. Furthermore, the conserved strength values r/R remain at a very high level from 2% and demonstrate the high coating quality obtained by the nanoemulsion.

Potential application for cold recycling: initial cohesion

During a second stage, mixes were made with another RAP, this time from a site in England, with 5.5% residual bitumen and 2.5% emulsion by weight (1.5% by weight of the residual bitumen). Emulsions were obtained in the same manner as in the preceding case, that is to say in both laboratory colloid mill (conventional emulsion) and using HIPR technology (nanoemulsion). Nynas 70/100 or 160/220 bitumen was employed in both cases.

The specimens were compacted in a gyratory press to 15% air voids. The stiffness modulus of the specimens was processed with time in a NAT (Nottingham Asphalt Tester) press. The results obtained are shown in Figure 4.

It may be seen that formulas based on conventional emulsion have a higher initial stiffness than those made with nanoemulsions, and continue as such over approximately 20 days from curing. After this time, the specimens recycled with nanoemulsion have a somewhat higher modulus, of around 20% over and

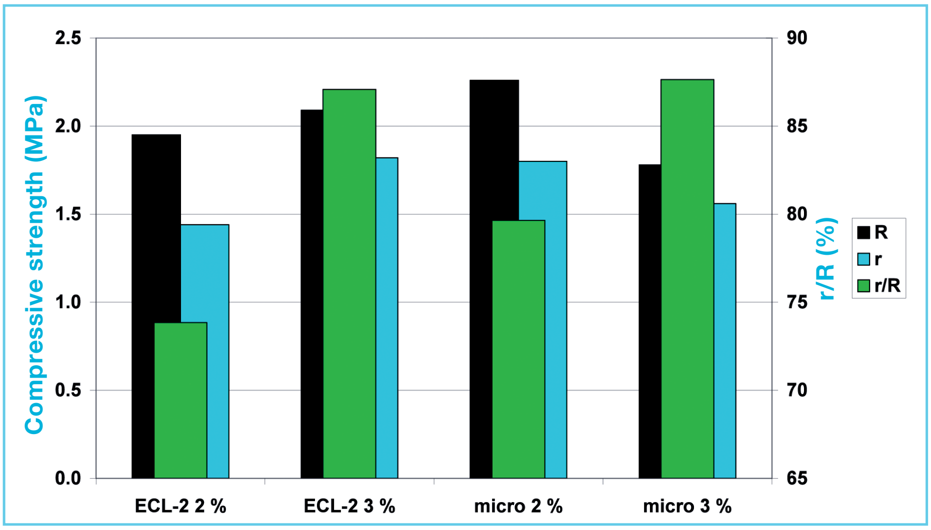

Figure 3. *Dry compressive strength (R), wet compressive strength (r) and conserved strength r/R for recycled specimens with conventional emulsion and nanoemulsion, compacted to 15% air voids (static pressure of 5 MPa)*

above that of specimens using conventional emulsions.

Mixes containing nanoemulsions may then be seen to have a higher final modulus, with values of over 2,000 MPa at 20ºC after 1 month of curing.

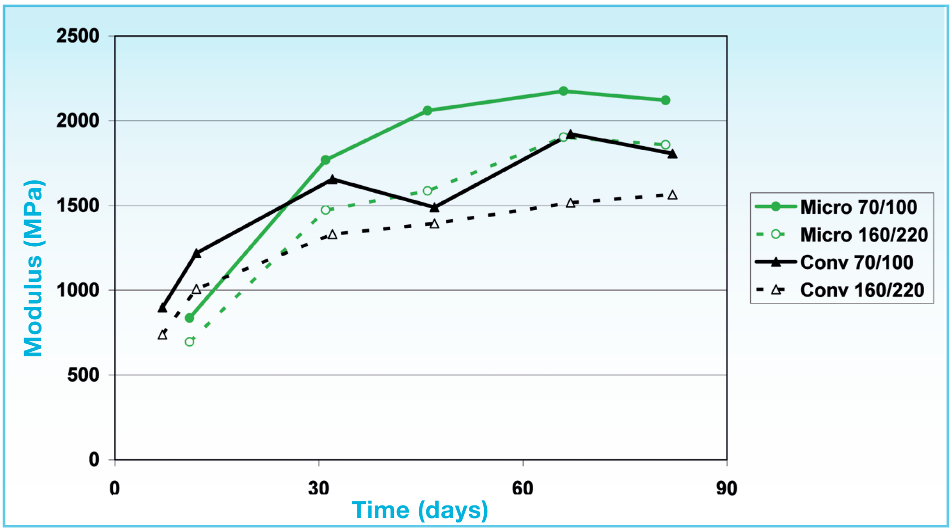

Figure 4. *NAT Modulus at 20ºC for various recycled specimens with conventional emulsions and nanoemulsions, made with Nynas bitumen 70/100 or 160/220*

Conclusions

This article has presented a new system (using HIPR technology) for manufacturing bitumen emulsions that allows the formation of purpose-made, calibrated and submicronic emulsions.

The article has presented and described the application of these nanoemulsions in cold recycling. It was initially thought that this method would provide a better coating quality and this has since been confirmed by compression-immersion tests.

Mixes employing nanoemulsions were also seen to have a higher stiffness modulus in the mid-term (at one month and over) than those employing conventional emulsions.

By way of conclusion, this innovative technology appears to be very promising and more detailed tests have since been conducted, including in-situ test sections during the SCORE project, as is described in other articles within this special edition of the journal.

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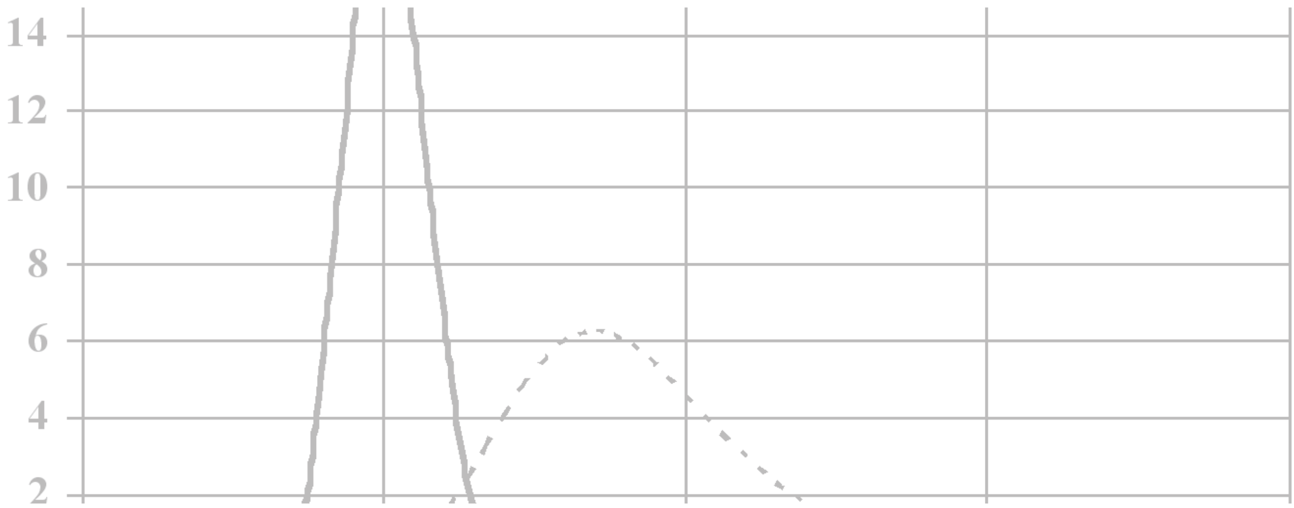

Using lime for soil stabilization: preliminary action

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ABSTRACT

There are numerous parameters and conditions involved in a road construction project and the soil conditions and materials take on particular importance. When clayey soils appear, as is very often the case in many parts of Spain, it is necessary to stabilize these soils. Lime is a good alternative for soil stabilization, both in technical and economical terms, and may readily and swiftly be applied to stabilize the soil.

The article examines the four main elements of system: the lime, the soil, the lime-soil mixture and the conditions required of the Preliminary Study on the preparation and proportion of the lime in order to obtain the best possible results on site and optimise the quantity of lime employed.

Keywords: *Lime, Soil, Non-hydraulic lime, Quicklime, Hydrated lime, Soil stabilization, Soil characteristics.*

One of the most interesting applications of lime is its use in the stabilization of soils for roads and other infrastructure supported on unstable soils.

Lime has been used to stabilize clay in construction work for over 5,000 years. However, when referring to more recent times, the treatment of clay soils by lime began in the 1960s in the United States, where soil mechanics were applied to lime and soil mixes and rapidly gained in popularity and where thousands of kilometres of roads were subsequently built on stabilized clay soils as well as numerous airports such as Dallas-Fort Worth Airport.

In France, the technique of soil stabilization was applied throughout the sixties and seventies, mainly for the reuse of water sensitive soils in embankments.

When planning the construction of a road or motorway, it is obviously essential that the design cater for the scale and characteristics of the traffic using the same. However, it is equally important, as far as construction is concerned, to give particular consideration to the environment, the geomorphologic and topographic characteristics of the area in question and the potential reuse of materials throughout the route.

The stabilization of heavy clay soils with lime has become a very advantageous alternative to the traditional methods of constructing roads and other infrastructure, from both a technical and economical point of view, and may be rapidly executed with all the advantages that this entails for these types of works with regard to scheduling and contract performance.

The stabilization of clay soils with lime takes on particular interest in the following types of work:

- Motorways, main and secondary roads,
- Runways and taxiways at airports,
- Car parks and factory yards,
- Slope stabilization,
- Local roads, forest tracks and by-roads,
- Railway tracks,
- Reclaim of abandoned docklands,
- Reclaim of contaminated soils,
- Structural infill.

Three essential factors intervene in the stabilization of soil with lime:

- The soils,
- The lime, and
- The lime-soil mix

On considering the three elements of the system and in order to establish the correct preparation and proportion of lime in the stabilization work, it is necessary to make a Preliminary Study which will largely depend on the knowledge of the soil and prior experience concerning soil treatment (see Photo 1).

These points shall be expanded upon in the following sections, with reference to the Estabilización de Suelos con Cal (Lime Soil Stabilization Manual) published by the Spanish Association of Lime and Derivatives (ANCADE 1977), the Technical Guidelines on Treatment of Soil by Lime and Hydraulic Binders (LCC 2005) and diverse studies and experiments.

The soils

Soils are taken to be natural materials formed by particles or grains which may be easily separated by simple crushing or subsequently by the action of a stream of water. These particles or grains have been generated by mechanical or physicochemical changes of all types of native rock. Their characteristics may vary widely according to the nature of the native rock and, particularly,

Photo 1: *Preliminary study of soil for lime stabilization, at Arcos de la Frontera*

Photo 2. *Soil characterization (in the photo, Arcos de la Frontera) is conducted in accordance with parameters concerning the nature and state of the soil*

by the form and degree of alteration (which is then seen by the extent of the active clay fraction).

Prior to starting any soil treatment, it is essential to gain the most precise information possible regarding:

- The characteristics of the component materials
- The problems that these materials might cause, and
- The solutions that may be adopted (such as lime stabilization treatment).

As a general rule it may be indicated that soil stabilization with lime is only effective if the soils are plastic and, in this regard, it is considered that any soil with a Plasticity Index (PI) of 10 or over will suitably react to lime stabilization, as this is the key for the chemical reactions that will provide an immediate and continuous improvement in the soil properties.

Soil characterization is conducted in accordance with two types of parameters, referred to as nature and state parameters (Photo 2).

Parameters concerning the nature of the soil will not vary with time nor through any manipulation of the soil during the work. The key parameters in this regard are:

- Grain size or fineness, calculated according to maximum diameter and the percentages of particles passing through a No. 80 (80 µm) sieve.
- Plasticity, evaluated by the Plasticity Index (PI) and the Methylene Blue Value (MBV).
- Swelling.

The soil state parameters do not depend on the characteristics of the soil itself but on the ambient conditions in the area. In the case of sensitive soils, the parameter determining all the conditions of fills, embankments and subgrades is that of the Hydric State which is measured by two properties or values:

- Compaction by Proctor Test (Standard Proctor in embankments and Modified Proctor in base courses), and
- The California Bearing Ratio (CBR)

Once the soil has been examined it is very useful to make a classification according to groups of materials with known properties, in order to establish the conditions concerning their use with treatment. This classification shall distinguish the rocky materials of the soils and consider the behaviour of these materials when defining the most adequate employment, use or treatment of the same both in fills and embankments or subgrades.

There are several different soil classification systems, though the most widely used are those indicated below. Within these classification systems, those soils considered appropriate for lime treatment and stabilization are as indicated in Table 1.

- PRA (US Public Road Administration)
- CASAGRANDE (prepared by Arthur Casagrande: the most well known system and one adopted by various organizations)
- L.C.P.C.-SETRA (prepared by the French organizations L.C.P.C.-SETRA in the 70s and contained in the French Standards NFP 11300).
- Article 330 of PG3 (Technical Specifications for works on Roads and Bridges prepared by the Spanish Ministry of Development)

P.R.A.	CASAGRANDE	L.C.P.C.- SETRA	PG3 (ART. 330)
A4	OL	A2	Unsuitable
A5	OH	A3	Close to tolerable
A6	CL	A4	
A7	MH	B6	Tolerable

Table 1. *Soils suitable for lime stabilization, according to various classifications*

In road construction (see Photo 3), the use of natural soils throughout the route may present certain problems such as:

• High water content.

• The presence of clay

• The combination of water and clay

The importance of the water content is well known by all as if this is too high it poses difficulties, not to say impossibilities, for the circulation of heavy machinery, and if this is too low it will be very difficult to compact.

Materials containing clay are renowned for their poor geotechnical properties which also vary according to the weather conditions.

LIME

Limes used in soil stabilization are high-calcium or non-hydraulic limes that harden with the CO_2 present in the air. These are mainly composed of calcium and magnesium hydroxide and oxide.

Lime is a chemical substance that is obtained from limestone, mainly formed by calcium carbonate ($CaCO_3$). The limestone is calcined at temperatures of between 950-1000ºC in a lime kiln to decompose the calcium carbonate, by means of the following chemical reaction:

$CaCO_3$ + Heat (50 Kcal) → $CaO + CO_2$

The calcium oxide or quicklime CaO may then be combined with water in a hydration process that then gives rise to calcium hydroxide ($Ca(OH)_2$) known as hydrated lime:

$CaO + H_2O \rightarrow Ca(OH)_2$ + Heat (15.5 Kcal)

The limes employed in soil stabilization are non-hydraulic limes characterised by:

• Slow hardening by air through the action of the CO_2 in the atmosphere.

• The lack of hydraulic properties, by which it does not harden with water.

In soil stabilization, and in accordance with the Spanish Code 80502, the following types of non-hydraulic limes should be employed:

• *Quicklimes (Q)* mainly formed by calcium oxide and magnesium oxide. Types CL-90-Q or CL 80-Q should be employed. If the percentage of magnesium oxide is greater than 5%, these limes are defined as dolomitic lime or calcinated dolomite.

• *Hydrated or slaked limes (S)* mainly composed of calcium hydroxide and created when quicklime chemically reacts with water. Types CL 90-S or CL 80-S should be employed.

• *Lime slurry,* a suspension of hydrated lime in water which can also be obtained by mixing quicklime with water to give hydrated lime and then adding further water to form the lime slurry suspension. Lime slurry may be made in a factory or on site and may be directly applied to the soil.

The advantages of each of these forms of lime are indicated below:

• Advantages of quicklime:

  ▪Greater effective content of lime per unit mass than hydrated lime. According to the Spanish Code UNE 80502/97, in calcium rich limes used in soil stabilization, 3% quicklime is equivalent to 4% hydrated lime.

  ▪Reduces the moisture content of wet soils,

  ▪Higher density than hydrated lime,

  ▪Reduced storage and transport costs on account of the preceding factors,

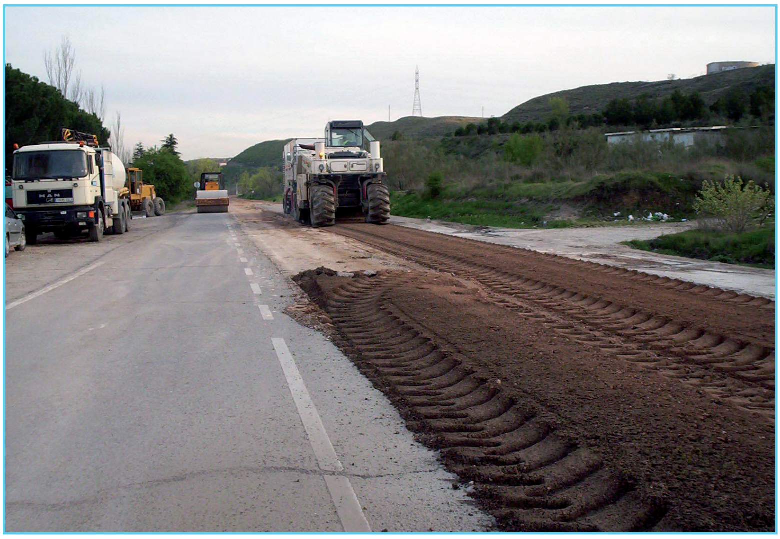

Photo 3. *Preparation of soil for lime stabilization during road widening.*

• Disadvantage of quicklime

- Requires greater safety precautions during transport and handling.

• Advantages of hydrated lime

- Much smaller average grain size than pulverized quicklime and rapidly disperses into the soil during mixing.

- With dry soil conditions, it may be advantageous under certain conditions to add hydrated lime or lime slurry.

- Requires fewer safety precautions than quicklime.

• Advantages of lime slurry:

- Elimination of dust produced during the spreading of lime.

- Humidification of dry soil

Lime that may have been stored under unsatisfactory conditions should not be employed on account of the potential alterations of the lime under humid conditions. In the case of doubt regarding the condition of the lime, it is necessary to check:

• In the case of quicklimes: the reactivity in water (its value will drop in the event of hydration and recarbonation) and CO_2 content.

• For hydrated limes: the CO_2 content (an increase in value will indicate that it has undergone recarbonation) and moisture content at 110ºC.

• For lime slurries: its characteristics (essentially concentration) are determined in accordance with the real demands of the materials at the time of application. As such, it is only necessary to check the concentration of the same in terms of dry extract (DE).

In addition to the non-hydraulic limes indicated above, there are other lime-based stabilizers in the form of materials with a high proportion of lime which are suitably manufactured to respond to specific requirements of road construction and which have to comply with technical standards or specification prior to use on site. These lime-based applications include mixes formed by:

• Ground blast furnace slag + lime + aggregate

• Silica-alumina fly ash + lime + aggregate

• Sulphur-calcium fly ash + aggregate

• Pulverized pozzolans + lime + aggregate

The limes to be employed in soil stabilization are defined by the Spanish Code UNE-EN 4591 Building Lime. Part 1: Definitions, specifications and conformance criteria.

This is a harmonised standard for limes employed in construction, which then implies that all lime products employed in soil stabilization have to have CE marking according to that established by Spanish legislation for the transposition of European Construction Products Directive.

This code is supplemented by two additional codes: the UNE-EN 459-2 Building Lime. Part 2. Test Methods: and UNE-EN 459-3 Building Lime. Part 3: Conformity evaluation.

In order to ascertain the quality of the lime employed in the treatment, it is necessary to analyse the following:

• Calcium and magnesium content.

• The calcium/magnesium oxide content of a calcined sample should be over 90 percent in mass (CL-90).

• Carbon dioxide content (CO_2) (< 5% in mass)

• Fineness of pulverized lime by sieve testing, whereby all particles must be smaller than 6.3 mm and 90% smaller than 0.2 mm.

• Reactivity of the lime.

The reactivity allows the measurement of the chemical kinetics or rate of reaction of the lime with water, recording the time taken to reach a temperature of 60ºC on agitating the specimen and where this should be under 25 minutes. Those limes reaching this temperature in shorter times are subsequently more reactive, and the higher the reactivity the faster the soil stabilization action.

Lime reactivity depends on:

• The porosity of the lime

• The degree of calcination

• The raw material (limestone) employed, and

CARACTERISTICS	PARTICLE SIZE	MICRONIZED
Calcium and magnesium oxide content in calcined specimes[(a)]	>90 % in mass	
Carbon dioxide content on manufacture	<5 % in mass	
Fineness. Cumulative retained percentage in: • Sieve UNE 6.3 mm • Sieve UNE 0.2 mm	0% --	0'1" <1 en;)
Reactivity. minimum temperature: • Quicklime with MgO < 5% • Dolomitic lime with MgO > 5% Maximum time to reach minimum temperature in both	>60°C >50°C 25 minutes	

(a) Conducted on specimens previously calcined in electric furnace at 975°C ± 25°C

Table 2. *Lime Class I, according to the PG3 of the Ministry of Development*

• The fineness of the lime at the time of testing.

Reactivity is an essential parameter as this:

• Determines the quality of the lime in terms of its capacity to react (indicating that the reactions will occur rapidly), and

• Allows an estimation of the effectiveness of the lime to dry out wet soils.

When considering limes that may be employed for soil stabilization, it is also necessary to take into account that established in articles 200 High calcium limes, 204 Limes for soil stabilization, and 510 In situ soil stabilization by lime contained in the Technical Specifications for works on Roads and Bridges prepared by the Spanish Ministry of Development (PG-3) together with current standards for the application of lime in soil stabilization work. Tables 2 and 3 contain a summary of these standards.

The lime-soil combination

Lime presents an interesting and economical solution to soil stabilization problems, as:

• The addition of quicklime dries out waterlogged soils.

• When employed in all its different forms (quicklime, hydrated lime or lime slurry), it improves and stabilizes the characteristics of clay soils in both the short and long term.

• This allows the use of existing soils on the roadbed and prevents the environmental impact caused by their removal to landfill sites or replacement by other soils.

Lime mixed with clay soils has two main effects:

• Rapid reaction (minutes/hours) with immediate and beneficial modification of the soil, affecting soil humidity and its geotechnical properties, improving both workability and reaction to water (see Photo 4).

• Long-term reaction (weeks/months) providing stabilization through a cementing effect.

1. Improvements by immediate modification

The modification of the water content depends on the type and quantity of lime applied. If quicklime is employed, this will cause an immediate drop in the water content of the soil of approximately 3-4% for every 1% of mixed quicklime, due to the combined effect of the following three processes:

• Hydration of the quicklime

• Evaporation of a certain quantity of water

• Provision of dry material (lime dust, dry spreading) which reduces the water/solid weight ratio, defining the calculation of the water content of the resultant material.

In extremely waterlogged soils, this dewatering process by drying out during the mixing stage is particularly necessary. However, in soils with a moisture content close to the optimum before compaction, or even lower, this drying out process should be offset by additional

CARACTERISTICS	
Calcium and magnesium oxide content in calcined specimens[(a)]	>90 % in mass
Carbon dioxide content on manufacture	<5 % in mass
Fineness. Cumulative retained percentage in: Sieve UNE 0.2 mm	< 10 %

(a)Conducted on specimens previously calcined in electric furnace at 975°C ± 25°C

Table 3. *Lime Class II, according to the PG3 of the Ministry of Development*

wetting by adding around 30 percent water of the weight of lime.

With regard to the modification of the characteristics of the clay fraction of the soil, lime produces ionic changes which brings about the flocculation of the clay particles as this acts on the electric charges of the same and modifies their electric fields.

Once the lime has been incorporated in the soil, the fine particles of clay become friable and granular in a process known as flocculation and explained by the formation of $Ca(OH)_2$ nodules between the fine laminas of the clay, causing an ionic exchange of Na+ ions of the soils by Ca++ ions of the lime.

This can be verified in the laboratory by:

- A drop in the natural moisture content of the soil (with quicklime)
- A fall in the Plasticity Index (PI) or Methylene Blue Value (MBV).
- Increase in plastic limit (PL)
- Fall in maximum Proctor density
- Increase in CBR
- Levelling out of the Proctor curve

The following geotechnical actions occur in the soil:

Photo 4: *On mixing lime with clay soils, the water content and geotechnical properties of the soil are modified, with an ensuing improvement in its workability and water resistance.*

- A considerable rise in the plastic limit (PL) of the soil without this significantly varying its liquid limit (LL), which then implies a large drop in the plasticity index (PI). This means to say that the clay soil immediately changes from a plastic and, subsequently, deformable and tacky state to a solid state, becoming granular and friable and, thereby, improving their site condition.

On site, the wet soil is seen to lose its sticky nature and become more granular, making it easier to handle and considerably improving both its bearing capacity and spreadability. In general terms a proportion of around 1% quicklime is sufficient to obtain these modifications.

- Clay soils generally tend to expand and swell in the presence of water, though when this disappears they shrink back until regaining their initial state. This expansion is reduced or eliminated as a result of their ensuing lower plasticity which subsequently improves the volumetric stability of the soil.
- This reduction in plasticity and expansion is accompanied by an increase in the shear strength of the soil which is reflected by an immediate improvement in its bearing capacity (test on material to obtain its bearing capacity; IPI immediate bearing index).

2. Stabilization or long-term improvement

The stabilization itself consists of a long-term improvement (months/years) through hardening, in accordance with the ambient temperature and the nature of the clay:

- Increase in the bearing capacity of the soil (allowing employment in more demanding layers).
- Improvement in structural properties over time
- Eliminating soil sensitivity to water and freeze-thaw cycles.

This is brought about by a pozzolanic type reaction: whereby the lime raises the pH of the stabilized soil up to values of over 12, releasing silica and alumina from the clay which react with the calcium ions from the lime to form hydrated calcium silicates and aluminates which increase mechanical strength in the manner of cement.

The length of this pozzolanic type reaction in the soil depends on the ambient temperature and the nature of the clay.

Photo 5. *Lime stabilization treatment*

- Ambient temperature. It has been shown that the strengths obtained by a soil-lime mix over one year at holding temperatures of 20 °C may normally be obtained, in less than 30 days if the holding temperature is kept around 40 °C and the hardening process detains when the temperature falls below 5 °C.

- The quantity and nature of the clay fraction in the soil. The higher the proportion, the faster the silica and alumina dissolve and the greater the crystallization (in accordance with the necessary amounts of lime and free water).

This normally lasting between several months and two years.

This progressive pozzolanic effect increases:

- The impermeability,
- Mechanical strength, and
- Freeze resistance of the treated soil.

Laboratory testing confirms:

- An additional increase in CBR,
- Increased shear strength, tensile strength and unconfined compressive strength,
- Improved stability with reduced expansion and contraction, and
- Improved freeze resistance.

The stabilization mechanism is far more complex than that of modification, as in addition to the two variables affecting the development of the same and, namely, time and lime-clay reaction, a number of other factors intervene in the kinetics of the hardening process of soil-lime mixes, such as:

Some soils, while being defined as clay soils in geotechnical terms, do not produce pozzolanic reactions. This being the case of sericite clay with high mica content resulting from shale alteration and which also occurs when certain substances such as carbonate organic matter alter the chemical conditions.

In all these cases it is necessary to conduct the pertinent geotechnical study to ensure whether the lime will improve the soil or not.

- The moisture content of the soil. It is essential that there is a sufficient amount of free water in the soil:
  - To ensure the high pH ionization of the medium necessary for solubilization, and
  - For the hydration of the compounds cementing the granular particles.

As such, the stabilization process has to consider two basic conditions:

- The predicted long-term mechanical characteristics of the soil-lime mixes vary widely from one soil to another. For this reason it is necessary to conduct preliminary studies, even though long-term stabilization is not a precise technique on account of its complexity, and

- There is a maximum proportion of lime that can be added, in accordance with the maximum consumable quantity of the clay in the soil, and over which the mechanical characteristics cannot increase any further and even run the risk of deteriorating.

Study of the preparation and proportion of lime

In view of the numerous variables affecting soil stabilization, all such projects require a preliminary study. The arrangement and scope of this preliminary study will depend on the available knowledge of the soil in question and prior experience of soil treatment.

The object of the study consists of establishing the type of lime to be employed and the proportions to be added in accordance with:

- The soil characteristics, and
- The end-purpose of the treated materials (fill, subgrade, base course/subbase, wearing course)

A precise geotechnical study and awareness of the soil characteristics will, in the majority of cases, be of vital importance for the design and construction of the work, and will essentially serve to conduct the study into the preparation and mix proportion of the most suitable lime in accordance with the characteristics of the work in question.

The study carried out, through exploratory bores and laboratory tests, should provide a description of the soils (Photo 6), in order to allow:

- Their grouping under uniform and representative soil families in accordance with the corresponding classification, marking the boundaries of each different soil zone and the volumes present in the same.
- Establishing geotechnical characteristics and potential water content at the time of conducting the work. The study should also indicate the presence of any elements that might influence soil treatment, such as:

Photo 6. *Aerial view of lime stabilized area*

- Organic matter,
- Sulphides and sulphates,
- Nitrates (fertilizers), in the case of combined lime + cement treatment, and
- Chlorides (rock salt) etc., once again in the case of combined lime + cement.

Special mention should go to sulphides and sulphates, as when total sulphur compounds, expressed as sulphates, exceed 1% in mass of the original soil, this may cause a secondary reaction in the presence of water, causing the swelling and cracking of the stabilized mix. In this case it is necessary to conduct the pertinent tests under conditions that are as close as possible to those affecting the stabilized soils on site.

The potential presence and penetration of groundwater (which may carry sulphates) within the lime stabilized soil takes on particular importance. In order to prevent this, it is essential that the stabilized soil is compacted with a void ratio of no more than 5% and, as such, particular attention should be paid to the moisture content of the soil at the time of compaction.

The study is essential from a design perspective as the potential results may well determine:

• Materials that may be stabilized and treated with lime, and

• The most suitable type of lime and the mix proportions required.

The study of the preparation consists of an analysis of the development in mechanical performance of the soil-lime mix in accordance with:

• The type of lime (class and proportion),

• The characteristics of the mix (density and moisture content),

• Curing period, and

• Form of curing (ambient, immersion, freeze, that, etc.).

The mix preparation study should conclude with the selection of the most suitable lime and the proportions to be employed in accordance with each type of application (embankments, subgrades, subbases, base courses, wearing courses) and the performance required for each type of application.

The proportion of the product is given as a percentage that represents the mass of the treating product in relation to the sum of the masses of the dry products present in the mix, as described by the following equation:

d% = Q*100/(Mds + Q + mpsc)

Where:

• Q is the mass of the treatment product (lime),

• Mds is the dry mass of soil or pre-treated mass (e.g. with lime), and

• Mpsc is the mass with particle size correction factor

The procedure to establish the optimum lime proportion is based on strength criteria and where the most commonly employed index is the CBR.

A comparison is made of the CBR of the unstabilized soil and that of the soil stabilized by a proportion of lime that provides the required CBR for the treated soil.

This comparison makes it possible to ascertain the soil improvement obtained by the treatment.

The procedure may entail different operations depending on whether this concerns embankment or subgrade materials.

A quick method to establish the percentage of lime with a certain degree of accuracy is that given by the ASTM C-977 standard.

1. Embankments

In the case of embankments, it is necessary to seek a lime proportion capable of providing immediate and sufficient bearing capacity to the treated soil which enable it to support site traffic and obtain the designed compaction. This is an area where quicklime is of particular application.

It is possible to employ the development of the Immediate Bearing Index (unloaded CBR), according to the French standard NFP 94078, in accordance with the lime proportions for different and representative water contents.

This may also be made on the basis of the proportion of lime necessary for the treated soil compacted under Standard Proctor Test, to reach a CBR value (obtained by penetration of the plunger immediately after the preparation of the specimen) and sufficient to allow placing in good conditions. The generally admissible CBR value is set between 5 and 15 according to the site characteristics.

The standard recommended proportions of quicklime, expressed as a percentage of dry soil, vary between 1 and 3% according to the water content of the soil, or between 2 and 4% for hydrated lime.

2. Subgrades

In the case of subgrades, and where the clays in the soil react particularly well with lime (as is the case of certain marly or lime marl soils), treatment provides suitable mechanical results to allow the use of lime. In these cases it is recommended that;

• If the soil is too waterlogged, to use quicklime to provide immediate bearing capacity, essential for the correct movement of site traffic, and

• If the soil is dry, to resort to hydrated or slaked lime or lime slurry.

In both cases the development of the CBR shall be examined, after the immersion of the specimens in water over four days, and in accordance with the lime proportions for different water contents. In temperate zones, subject to mild frosts, experience shows that a CBR > 20, obtained after immersion in water, is sufficient for the use of these materials.

In all events it shall be necessary to obtain a mix proportion that gives the treated soil:

• Sufficient immediate bearing capacity to allow site traffic, in the case of soils with high water content.

• The final mechanical strength required of the base course material.

However, it is too idealistic to attempt to find a single type of stabilization that responds to both of these requirements, as the natural water content of soils is rarely constant and uniform.

Experience in this field has shown that the pre-treatment with lime of wet or dry clay soils noticeably aids treatment by other hydraulic binders (combined treatment) and greatly improves the final level of performance.

In this case, the study is divided into two successive stages:

• The establishment of the immediate bearing capacity (the study is conducted in the same manner as that of lime for embankments), and

• The establishment of the required mechanical strength. Here a study is made of the development of the mechanical strength of the treated soil after 7. 28 or even 90 days with regard to the speed of reaction according to the proportion of cement and other factors. The generally considered measurement parameter in this regard is the compressive strength (CS) of cylindrical specimens, and where admissible strengths are CS> 1 to 2 Mpa (approximately corresponding to a Tensile Strength TS > 0.1 to 0.2 Mpa).

3. Base and Subbase courses

The procedure for base and subbase courses is the same as that indicated for the subgrades, but with generally stricter requirements. The studies are more involved, as greater attention is paid to the tensile strength of the material associated with the modulus of deformation, together with additional parameters used in the dimensioning of roads and, where necessary, a study of fatigue behaviour.

Impact on territory, occupation and fragmentation

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ABSTRACT

Biodiversity is a globalizing concept with all the advantages and disadvantages that this entails in the study of the same. The guaranteed conservation of biodiversity is fundamental in a long-term preventative focus, which should start from the earliest planning stages and establish a system of protected areas, supplemented by wildlife corridors to ensure connectivity.

Transport, largely as a result of the major infrastructure required, can cause serious negative effects on biodiversity as a result of land occupancy; changes in profile, hydrology and the atmosphere; air, soil and water pollution; overexploitation of non-renewable resources; destruction of the ozone layer; hazards involved with the transport of dangerous goods and emissions causing global warming and climate change.

The main effects on biological diversity are the loss of numbers and the fragmentation of communities, the lowering of genetic diversity and ecosystems. This article focuses on habitat fragmentation and occupancy and the measures required to reduce this impact, as well as considering the work carried out by the Working Group on Habitat Fragmentation caused by transport infrastructure..

Keywords: *Biodiversity, Transport infrastructure, Fragmentation, The environment, Road planning, Environmental impact, Environmental assessment, Ecology.*

Biodiversity or biological diversity describes the total variety and variability of all living things and the ecosystems they form part of. Biodiversity is the most widely employed concept in the area of conservation on account of its globalizing character, which allows nature to be considered as a whole and enables the study of the effects caused by our ever-changing world. Two fairly antagonistic objectives are raised with regard to biodiversity: its conservation and its use, and attempts are made to appease these objectives through the oft-quoted concept of sustainable use or sustainability which generally tends to end with the conquest of so-called development over conservation. This while ignoring the fact that our biological resources are essential not only because they provide food and medicine, but also as a result of the social, cultural and environmental benefits they provide and which make the conservation of biodiversity not just an ethical obligation, but also a need for survival.

The institutional response ratifying the concept of biodiversity, in which nature is no longer seen as a combination of isolated parts and, instead, as a global unity of interrelated ecosystems, was established in the Convention of Biological Diversity, adopted at the UN Conference on Environment and Development, held in Rio de Janeiro in 1992. Spain ratified this Convention in 1993 and established the present *Ministry of the Environment and Rural and Marine Affairs* and issued a *Strategy for the Conservation and Sustainable Use of Biological Diversity*. This strategy established the general framework for national conservation policy and the sustainable use of biological diversity, indicating the state of biodiversity and identifying the processes and sectors responsible for the deterioration of the same and indicating the guidelines and measures to be adhered to by ensuing sectorial plans and specific programmes of the State, Autonomous or Regional Communities, Local Corporation and the public in general.

In terms of that concerning the subject of this article, the guiding principles are primarily those of prevention and planning:

- Prevention demands long-term goals based on a dynamic diagnosis of the state of conservation of the environment and on a forecast of the potential effects on the same caused by projected activities.

- Territorial planning and environmental evaluation, of both plans or programmes as well as projects, are the key instruments for the incorporation of sustainability objectives at the initial stage of the decision making process.

In order to guarantee the conservation of biological diversity it is essential that the establishment of a system of protected areas be supplemented by the introduction of wildlife corridors or passages to ensure the interconnection of wildlife populations. Transport, on account of the large infrastructures involved, may well cause serious effects on biodiversity as a result of:

- The occupation of land;
- Changes in land profile, hydrology and the atmosphere;
- Noise pollution and soil and water pollution;
- Over-exploitation of non-renewable resources;
- Destruction of the ozone layer;
- Risks of transport of hazardous goods, and
- Emissions leading to global warming and climate change.

Photo 1. *Wildlife crossing for roe deer*

The main effects of these changes with regard to biological diversity are the loss of specimens and the fragmentation of populations, a decrease in genetic diversity and the fragmentation, modification and destruction of habitats and ecosystems.

Habitat fragmentation and occupation

Transport networks occupy and divide natural habitats, giving rise to more isolated fragmentation by creating barriers between the same and producing two main effects on species:

- A reduction in the size and form of the fragments leading to the potential destruction of more sensitive species, and

- A disruption in the continuity between fragments that may handicap or entirely prevent the movement of wildlife between the same.

In both cases, certain species face the risk of extinction with ensuing overall negative effects on biological diversity.

Transport infrastructures, mainly roads and railways, have primary and secondary ecological repercussions that may have a negative effect on biodiversity. Among the primary repercussions we may refer to the loss of habitat, the barrier effect, the mortality caused by collisions with vehicles, disturbance and pollution and the ecological function of adjacent areas. Among the secondary effects, reference can be made to the changes in land use, the increase in human and industrial settlements and increased human presence. Furthermore, these effects are generally interrelated and their combined effect causes even greater repercussions.

The area of land occupied by an infrastructure is the most evident direct cause of loss of habitat. However, the physically occupied space is not the only cause of problems, as noise disturbance and pollution amplify the repercussions of these infrastructures over large adjacent areas.

In Spain, roads and their areas of influence occupy almost 1.5% of the total surface of the country. In absolute terms this figure may appear comparatively low, but in local terms this may take on considerable importance.

Many different studies have been made on the width of the area of influence alongside road infrastructures, and these have given rise to very different results varying from tens to hundreds of metres, and even up to kilometres in accordance with the impact and the physical and climate conditions of the surrounding areas, the affected habitats and the road layout and traffic.

The barrier effect is often considered as one of the most serious negative impacts of land transport infrastructures, as the capacity of dispersion of wildlife is one of the most important factors for the survival of the species. The capacity to move around a territory in search of food, refuge or for breeding is negatively affected by the barriers which are sometimes imposed by infrastructures.

Roads and railways may impose physical or behavioural barriers for certain animals under certain design conditions and use. A conventional road with a traffic flow of under 4,000 vehicles a day and which only imposes a barrier to the more sensitive species is not the same as a motorway with over 10,000 vehicles a day which is all but impenetrable to the majority of species if the layout is not planned and designed with care and if not fitted with design correction measures, boundaries and wildlife corridors. Furthermore, many species avoid the areas adjacent to roads on account of the disturbance caused by human activity and this only increases the physical barrier effect of the infrastructure.

Modifications to the ecological characteristics of habitats adjacent to roadways lead to changes in the way in which these are employed by flora and fauna. Hydrological changes caused by earthworks may dry out aquifers, cause flooding or soil erosion with a very direct effect on associated fauna and vegetation. Chemical pollutants (heavy metals, sodium chloride salt flux, carbon monoxide and dioxide, nitrogen oxide and hydrocarbons from exhaust fumes) also have important repercussions on soils, vegetation and fauna.

Traffic noise tends to affect humans most of all, but also has an effect on numerous species, keeping them away from the road. Road lighting may also affect the mortality of insects such as moths and butterflies (there is a well known case in Spain of nocturnal butterflies associated with the Kermes oak woodlands around Aranjuez that have been affected by the by-passes around the town).

The number of animals killed on the roads only makes up a small percentage (under 4%) of the mortality of the most common species (rabbits, rodents, sparrows, etc.) but may pose an important and significant factor for the survival of the local or global population of certain sensitive or endangered species, such as the Iberian lynx in this country. The number of collisions with birds may also be high, particularly on those roads crossing or running alongside wetlands or intercepting flight paths such as those between woods and pastures.

The most sensitive species to road barriers tend to be the less common species with small local populations and covering large territorial areas (bears, lynx, etc.) and those that make daily or seasonal passages between different local habitats (in Spain, mainly birds, deer and boars). In other European countries these barriers may have an important effect on other species such as elk or reindeer that have to make large annual migrations.

Photo 2. *Planting of shrubs to conceal fencing.*

It is also necessary to underline the value of the verges of these lineal infrastructures, as these may serve to create a new habitat for certain species, with both positive and negative effects on the area. If roadsides and embankments are managed correctly, they can serve as refuge for certain species, increasing the areas of natural vegetation in densely populated areas with little plant cover, though they can also lead animals to areas with higher risk of mortality, and they can even serve as corridors for the propagation of invasive species, as has occurred with Senecio species such as ragwort in El Cabo in Spain.

Finally, among the secondary ecological effects reference may be made to the changes of land use caused by infrastructures and particularly by roads as a result of increased accessibility and which may heighten the negative effects created by the infrastructure network on the conservation of biodiversity. The urbanization of a territory and tourism with its associated increased human presence, brought about by the easier access to a territory created by roads, and particularly large-capacity roads, both cause great concern with regard to the conservation of biodiversity.

The combination of these effects leads to the fragmentation and occupation of habitats and the global repercussions on the countryside should be considered from a broader focus on account of the loss and isolation of habitats and the changes in land use close to roads and railways. The study of the effects of roads on the countryside, when considered as a "phenosystem" or the perceptible components of ecosystems and the large scale ecological effects, comes under the field of landscape ecology which is still in a fledgling state in this country. However, serious studies are now being made, such as those by Díaz Pineda and others[V] on the cultural landscape and socio-economic structure and its application to an area in Almeria, in which the authors have quantified the impact and potential of tourist activities..

Measures to reduce the impact of habitat occuation and fragmentation

The measures that should be promoted to reduce the negative effects of habitat occupation and fragmentation are based on three basis principles: prevention, correction and mitigation[3]. Monitoring is also necessary to ascertain the efficiency of adopted measures and to ensure that the proposed objectives are met.

The essential tool at the prevention stage is that of different scale planning: plans, programmes, studies and projects, including both new infrastructure and improvements to existing infrastructure. *The Environmental Assessment of Plans and Programmes and the Environmental Impact Assessment* of studies and projects are the technical-administrative tools employed to guarantee that environmental aspects, such as habitat fragmentation and occupation, are considered in the decision making process regarding the route and form of the infrastructure.

On deciding upon the action to be taken and the environmentally viable routes of the same in terms of occupation, it is then necessary to design the corrective and mitigating measures, as applicable, to offset the negative impact of the fragmentation and to ensure suitable transverse permeability.

Two types of measures are employed to reduce habitat fragmentation:

- Those that directly reduce fragmentation: adapted culverts or livestock crossings and specific wildlife crossings (Photograph 1), and

- Those that improve road safety and prevent wildlife-vehicle collisions (roadkill) (fences, roadside management, exit systems, etc. (Photo 3).

1. Fragmentation in Plans and Programmes

In the technical studies conducted to prepare a *Sectorial Road Plan* developed by the *Spanish Strategic Infrastructure and Transport Strategy (PEIT) 2005-2020* and within the *Environmental Sustainability Report*, an assessment has been made of the affects on biodiversity by means of indicators that consider parameters such as the occupation, density of spaces in the vicinity and the affect of the same, fragmentation of territory and affect on fauna.

In terms of occupation, a 50 m strip or fracture zone has been taken into account, though in terms of impact, this has been extended to strips of 100 m, 200 m and 1000 m. The baseline scenario has considered Natura 2000 sites (Sites of Community Interest (SCIs) and Special Protection Areas (SPAs)), Ransar Wetlands, Biosphere Reserves, IBAs, Priority Habitats, Regional Protected Areas and National Parks. The total current occupation is relatively low in absolute terms as this does not exceed in any case 0.4% of the total surface area of the different categories.

The land occupation considered in all the action planned in the PEIT will in no case affect Natural Parks, but will affect numerous Natura 2000 areas (68 SPAs and 38 SCIs) as well as 24 priority habitats and 26 Regional Protected Areas. The effect on these and other neighbouring spaces will depend on the routes and the strips or fracture zones taken into account.

As the Spanish Sectorial Road Plan (PSC) has not yet been passed and some of the actions considered in the PEIT have been or may well be discarded following Environmental Impact Assessment (as is the case of the Toledo-Ciudad Real-Cordoba Toll Motorway), it is not

Category I:	Coastal habitats and rootless vegetation
Category II:	Maritime and continental dunes
Category III:	Freshwater habitats
Category IV	Temperate zone heathland and scrub
Category V:	Sclerophyllous woodland and scrub
Category VI:	Natural and semi-natural grasslands
Category VII:	High and low moorland
Category VIII:	Rocky habitats and caves
Category IX:	Forests

Table 1: *Broad categories of habitat according to Directive 92/43*

possible to quantify the potential effect on biodiversity that would be caused by the introduction of the plan.

Habitat fragmentation is defined as the process of dividing habitats that were once continuous into separate fragments which become more isolated from each other as they get smaller and which, in their entirety, only occupy a fraction of the original surface area. In order to establish this fragmentation, reference has been made to the National Inventory of Habitats and classifying these, in accordance with Directive 92/43, into the nine basic categories indicated in Table 1.

The fragmentation indicators have considered the number of specimens affected, their average area and the ratio between perimeter and area. If there is a high percentage variation in the indicators, this then indicates that the habitat area is very small or that much of its surface area is affected and that the planned action has to be avoided in both cases.

Fragmentation has an unequal effect on different types of habitats, and where the most affected appear to be Holm oak pastures, Sweet Chestnut forests and alpine rivers with ligneous vegetation on its banks such as false tamarisk (*Myricaria germanica*) and Rosemary Willow (*Salix elaeagnos*) (Annex I of *Directive 92/43*). In the majority of affected habitats, there is an increase in the number of specimens of below 5% which is not very high in absolute terms.

The affected surface area is an indicator that provides valuable information when analysing potential fragmentation. The results in this regard have shown that the practical total loss of the same is less than 1% of the surface area. The most affected habitats are once again the alpine rivers bordered by wood or shrub vegetation which may be seriously affected, particularly when considering their restricted surface area throughout the Spanish peninsular.

With regards to the perimeter-area ratio, the indicator that aims to quantify the influence of the form of specimens and which may be of importance in certain ecological processes, the majority of habitats were not seen to be modified in a particularly significant manner (in no case exceeding a 2% variation).

By way of conclusion and on considering the three indicators referred to above, it may be stated that the fragmentation caused by prospective road construction activities considered in the PEIT would not be of great importance in absolute terms for the majority of habitats, but could have repercussions in isolated cases and particularly in habitats of Sweet Chestnut forests and alpine rivers with ligneous vegetation on its banks such as false tamarisk (*Myricaria germanica*) and Rosemary Willow (*Salix elaeagnos*), which appear to be the most affected in the three indicators.

In order to appraise the effects on fauna of the potential Sectorial Road Plan developed by the PEIT, consideration has been given both to species of Community interest (Annexes of the *Habitats Directive* and Annexe II of the *Birds Directive*) as well as to protected species in accordance with the Natura 2000 specifications and coming under the categories of endangered or vulnerable species in the *National List of Threatened Species*.

In addition to which, a detailed study has been conducted on the effects on the five species of vertebrates listed in the special recovery plan at national level: the Iberian lynx, brown bear, osprey, capercaillie and imperial eagle. The high-capacity roads that could have the greatest potential repercussions on these species are the Toledo-Ciudad Real-Cordoba toll motorway and the Linares-Albacete highway which would affect the Iberian lynx and the imperial eagle. The first of these routes has been declared environmentally unviable by the Environmental Impact Statement (EIS) of 29 May 2007, which deemed that the project was incompatible with the conservation of habitats and species of priority interest and threatened the integrity of the Natura 2000 network.

The Linares-Albecete highway received a positive EIS on 21 November 2006 following a supplementary study on the effect to the Iberian lynx and which subsequently forced changes in route and the introduction of numerous wildlife crossings and mitigating measures to revegetate streams and river beds where crossings were to be placed for specific fauna. The route was changed from its initial hillside location to one set on a northern plain, as the experts considered that the lynx roamed the hillside, where it was difficult to predict their movement, and only used the plain as a passage to other areas, and where its movements would be more predictable and where suitable measures could be installed to prevent vehicle collision.

Finally, it is worth mentioning that in the drafting of plans and programmes, attention should not solely be restricted to assessing the potential effects on the biodiversity caused by the creation of new infrastructures, but also to including programmes or sub-programmes for the environmental integration of existing infrastructures. As such, in the studies for a Sectorial Road Pan developed under the PEIT, it has been proposed that an environmental quality sub-programme be included within the Conservation and Management Programme in order to improve the territorial, landscape and environmental integration of existing roads, incorporating specific wildlife crossings, improving transversal permeability, planting roadside vegetation and environmentally integrating stream channels affected by drainage works..

2. Corrective and mitigating measures

Prior to establishing corrective and mitigating measures, it is first necessary to study a potential route that makes these unnecessary, as the real policy for protecting biodiversity is through prevention.

As such, during the informative study of roads and railways the territory has to be examined to identify sensitive habitats and areas which should preferably be avoided by the infrastructure and to establish the horizontal and vertical alignment that least affects the landscape.

Once this exercise has been carried out it is then possible to consider potential corrective and mitigating measures. As we have already indicated at the start of the section Measures to reduce the impact of habitat occupation and fragmentation the actions to protect fauna from the impact of lineal transport infrastructures and to reduce habitat fragmentation may be divided into two types:

those that directly reduce fragmentation: adapted culverts or livestock crossings and specific wildlife crossings (Photograph 1), and

those that improve road safety and prevent wildlife-vehicle collisions (roadkill) (fences, roadside management, exit systems, etc. (Photograph 3).

Certain measures may, in fact, belong to both groups and may even have contradictory effects. This is the case of fencing which reduces roadkill, but increases fragmentation, particularly if there are insufficient wildlife crossings.

While the introduction of specific fauna crossings is becoming increasing widespread, consideration may similarly be given to the adjustment of overpasses, underpasses, culverts or drainage works which may similarly perform this function in an effective manner and where their adaptation for this purpose is far less costly (Photograph 3).

One aspect that has not been given sufficient consideration, at least in the planning stage, is the location of these wildlife crossings as it necessary to conduct a field study of wildlife crossings to establish the true effectiveness of the same. From the very few studies carried out to date on the use of specific wildlife crossings once roads are in operation, in many cases these crossings are seen to be ineffective on account of poor location or design.

In order to select the most suitable crossing for each case, it is necessary to consider the landscape, the affected habitats and the species using these crossings. A crossing necessary to maintain the permeability of a regional corridor for large mammals, and requiring a large “ecoduct”, is not the same as one maintaining a migration corridor for a local amphibian population, which would only require the adaptation of a small culvert (see Photo 3).

A further aspect to be taken into account in the arrangement of corrective measures is the necessary density or frequency of wildlife crossings. Any decision on the number and type of measures will depend on the existing species and the distribution of habitats in the area in question. In some cases it will be enough to have a small number of large crossings, while in others it will be necessary to have a larger number of small crossings.

Another important factor, that is sometimes ignored, is the maintenance of these crossings, particularly in the case of culverts or drainage works. It would not go amiss if contracts for the integral conservation or maintenance of state roads gave increasing importance to these tasks, including specific reports in the efficiency of the corrective measures adopted.

With regard to the application of mitigating measures, it is first necessary to underline their exceptional nature and by which we mean to say that these should only be employed when the preventative and corrective measures have failed. The application of these measures covers both cases of loss of habitat as well as those where the degradation of the habitat affects its normal function.

Photo 3. *Extended vaulted culvert with pavement for passage of reptiles and amphibians.*

There is no legislation in Spain regarding mitigating measures and, in this regard, reference may only be made to the European *Bird Directive (1979*) and *Habitat Directive (1992).* Though the application of mitigating measures is a relatively recent practice in Spain, reference may be made to some of the measures that have been conducted recently.

Frequent agreements have been made with the Autonomous or Regional Communities of Spain for the transfer of funds to permit land purchase to ensure this retains its current function (the case of the Trujillo-Caceres Highway), or those recovered to create habitats with greater ecological wealth (the case of the Mediterranean Highway between Motril and the border of the province of Almeria where the aim was to prevent or restrict the introduction of commercial nurseries).

Other common measures include the introduction of artificial nests for kestrels, the building of ponds, repopulation of rabbits and alfalfa plantations serving as food for birds of prey or lynx, the installation of electrocution prevention systems on existing electrical lines, the replacement of barbed wire fences by livestock fencing, etc.

Finally, in compliance with the Environmental Impact Statements and the obligation contained in the same to perform monitoring programmes to ascertain the correct operation of wildlife protection measures, the Spanish Highways Department, under the auspices of the Ministry of Development, are currently preparing specific monitoring contracts. The controls are conducted by means of infrared-activated camera images and animal track detection on substrates of marble dust, set in specific wildlife crossings and in culverts and tunnels.

Monitoring controls have also been installed to establish roadkill statistics.

Working group on habitat fragmentation caused by transport infrastructre

The Working Group forms part of the National Commission for Nature Protection and includes representatives from all transport and natural environment authorities, both in the Autonomous Communities and in the Central Administration, as well as from other associated organizations. Meetings are held at the *Department of Biodiversity* under the auspices of the *Ministry of the Environment*, who act as the technical secretariat of the Group.

Photo 4. *Exit system.*

In the most recent meeting, attended by a representative from the Highways Department, the Ministry of the Environment and Rural and Marine Affairs presented the Technical Specifications for the design of wildlife crossing structures and perimeter fencing[VI], drafted on the basis of the specifications of the *European Handbook COST 341 Wildlife and Traffic*. A second publication is currently being drafted regarding the technical specifications for the monitoring and evaluation of the efficiency of wildlife crossings. The publication of a document on the prevention of habitat fragmentation in the planning stage of infrastructures is due out in 2008.

The Technical Specifications for the design of wildlife crossing structures and perimeter fencing[VI], include a series of files with photographs of completed work and the technical specifications for the correct design of eleven types of wildlife crossing structures adapted to different species and landscapes. The specifications include the minimum dimensions and recommendations for each type of passage. These specifications similarly:

- Detail the dimensions and characteristics of accesses (file 112) and the surface of the passage,
- Show examples of more common errors and poor practice which undermine the efficiency of these structures, and
- Include files on:
    - perimeter fencing (No. 13 for large mammals and No. 14 for small animals),
    - exit systems (File 15, see Photo 4),
    - roadside vegetation management (file 16)
    - reinforcement of warning signs (file 17),
    - dissuasive systems (file 18)
    - signalling of transparent screens to prevent bird collision (file 19), and
    - adaptation of collection boxes, ditches and other elements that may cause wildlife mortality (file 20).

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Comparative study of fatigue in bitumens and asphalt mixes

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ABSTRACT

One of the most common failures of asphalt mixes is that of fatigue and many authors have subsequently investigated this factor on the basis of individual studies of the bitumen itself or that of the asphalt mix. The object of this study is to establish a correlation between the fatigue behaviour of bitumen and that of the asphalt mixes incorporating the same. The fatigue limits of the bitumen were obtained by dynamic shear rheometer (DSR) testing and those of the mixes by the three point bending flexural test.

Keywords: *Fatigue, Bitumen, Asphalt mix, Critical deformation, Rheology, Polymer modified bitumen (PMB), Dynamic sheer rheometer (DSR),Three-point bending test.*

In the majority of tests, the failure of an asphalt mix by fatigue cracking does not tend to occur in an abrupt manner, with the total cracking of the material, and which would then make it easy to establish the number of cycles associated with the fatigue failure. Instead, the material progressively detriorates without causing the complete cracking of the specimen. The fatigue failure of asphalt mixes can be established in two ways and, namely, by stress controlled testing or testing at controlled strain or displacement.

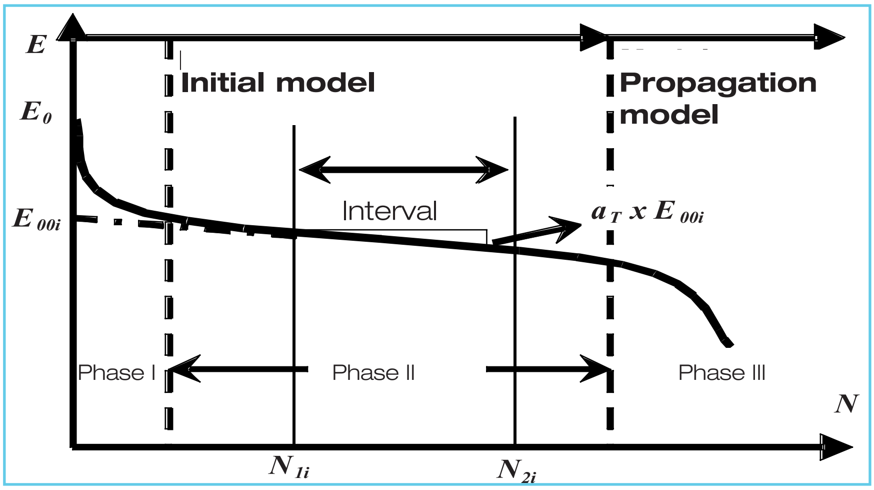

Figure 1. *Evolution of asphalt mix modulus with load cycles*

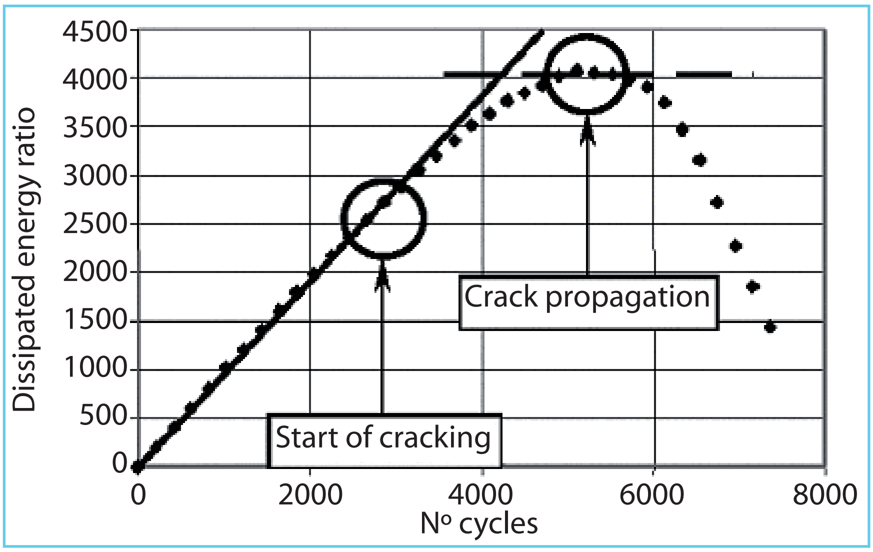

Figure 2. *Variation in dissipated energy ratio under controlled stress*

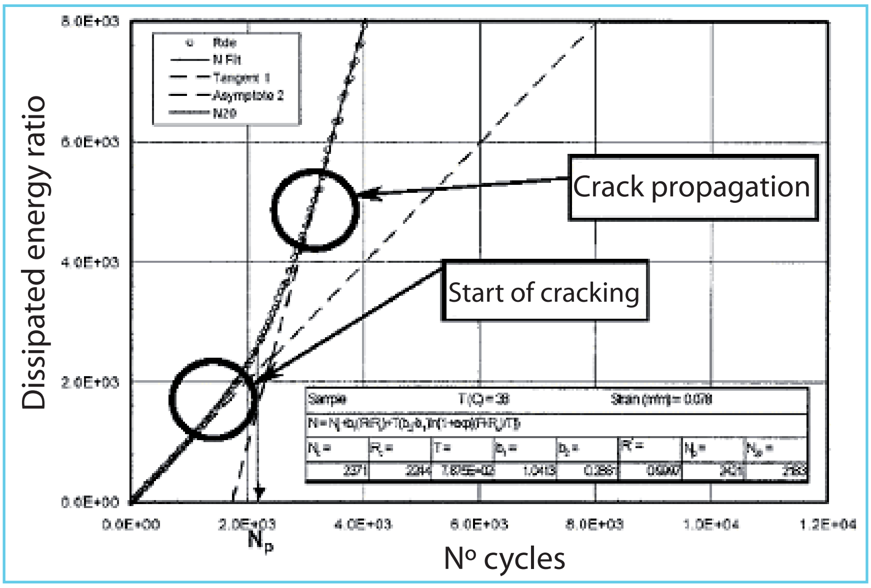

Figure 3. *Variation in dissipated energy ratio under controlled strain*

In the case of stress controlled testing, a measurement is made of the strain occurring in a specimen on the application of a constant stress or load. The fatigue strength of the material is associated with fracture or when the modulus of the mix is reduced by 10%. In the case of controlled strain or displacement testing, recordings are made of the development of the load during testing. Fatigue failure is taken to occur when the load or the modulus of the test material is reduced by half. These same types of tests and criteria are employed in the fatigue characterization of asphalt binders.

In spite of the ease with which we may define fatigue failure criteria, it is not so easy to apply in practice, mainly on account of the form of the curves showing the development of the parameters indicating fatigue failure. These curves take the form of an "S" and according to various authors [I, II, III] three different stages may be distinguished in the fatigue process (See Fig. 1).

During the first stage there is a rapid decrease in the modulus of the mix which, according to Di Benedetto et al.[I], is due to the heating of the mix on account of its viscous behaviour and which gives rise to a loss of modulus which is also influenced by thixotrophy and local phenomena. The second stage is shown by a continuous loss of modulus and this, according to these authors, is the stage that should really be associated with the fatigue process. It is in this stage that small faults and microcracking appear in the mix. In the third stage the failure density increases and cracking appears, leading to a rapid drop in the mix modulus.

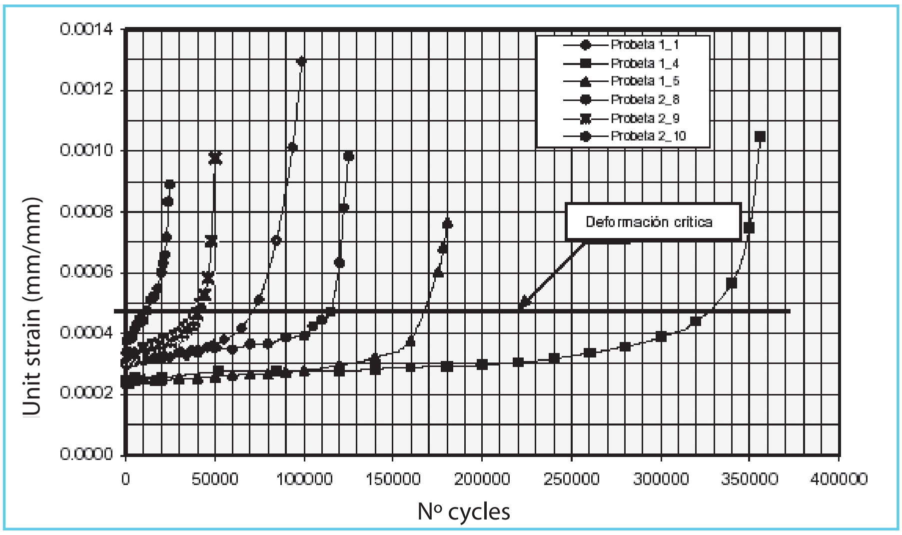

Figure 4. *Critical strain of an asphalt mix*

Khalid and other authors[IV, V] have studied the fatigue process of mixes on the basis of the energy dissipated by the material under each load cycle, determined in accordance with the stress-strain state affecting the material, and have recorded how this increases in the stress-controlled test when the specimen starts to fail, but decreases in the strain-controlled fatigue test.

In the case of cyclic loaded stress or strain controlled tests, the energy dissipated in each cycle is given by the following expression:

$$w = \pi \sigma \varepsilon \operatorname{sen} \theta \qquad [1]$$

where:

w = Dissipated energy,

σ = Applied stress,

ε = Applied strain, and

θ = Phase angle.

This process makes it easier to obtain the fatigue failure of the specimen, particularly in the case of the stress-controlled test. Furthermore, this failure corresponds in both cases to a physical state of the specimen where the density of microcracking is very high and where the cracking and rapid fracture of the specimen starts to occur.

Delgadillo and Bahia[VI] also applied the concepts described above to the study of fatigue in asphalt binders. Both authors have studied fatigue by dynamic shear rheometer testing, through the analysis of the dissipated energy (equation No. 1) and the dissipated energy ratio (equation No. 2), and have established that on plotting the dissipated energy ratio with respect to the controlled strain or load cycles, a curve then leads off from a constant sloping line and then separates after various cycles, at the point where cracking starts.

In stress-controlled tests the separation occurs in a downward direction, reaching a maximum value at the point where cracking spreads and the specimen fails by fatigue, Figure 2. In strain-controlled fatigue testing the separation is ascendant and reaches the point of fatigue failure when the separation reaches a value of 20% with respect to the trend line, Figure 3. This criteria is employed by Bahia and Delgadillo to determine the fatigue failure of bitumens.

$$DER = \frac{\sum_{1}^{n} \pi \sigma_i \varepsilon_i \operatorname{sen}\phi_i}{\pi \sigma_n \varepsilon_n \operatorname{sen}\phi_n} \qquad [2]$$

where:

DER = Dissipated energy ratio at cycle i

σ = Applied stress at cycle i

ε = Applied strain at cycle i, and

θ = Phase angle at cycle i

Pérez and others [VIII, IX, X] have investigated the fatigue behaviour of asphalt mixes by three point bending test with controlled displacement, focusing primarily on the study of the strain development. From the results obtained, they have demonstrated that, regardless of the level of displacement imposed on the mix and the material employed in its manufacture (virgin and recycled material), there is a level of strain at which the specimen deforms rapidly and produces failure. This strain has been referred to as the critical strain, Figure 4. Furthermore, it has been observed that the slope of the fatigue curve becomes lower as the modulus of the binder or the mix is increased.

Studies performed

The study consisted of establishing the fatigue failure of different types of bitumen, Table 1, by dynamic sheer rheometer (DSR) and the three-point bending flexural test for different mixes with the same grain size, Figure 5, made with these binders. Two of the bitumens are conventional types, B13/22 and B60/70, and the third is a polymer modified bitumen (PMB), type BM-3b.

Characteristics	Unit	NLT Standard	Bitumen type		
			B13/22	B-60/70	BM-3b
Penetration at 25°C, 100 g	0.1 mm	124/84	17	64	60
Penetration index		181/88	0.1	-0.5	2.4
Softening point A y B	°C	125/84	67.3	50.6	64.4
Fraass breaking point	°C	182/84	5	-13	–
Density	gr/cm^3	122/91	–	1,034	–

Table 1. *Characteristics of bitumens employed*

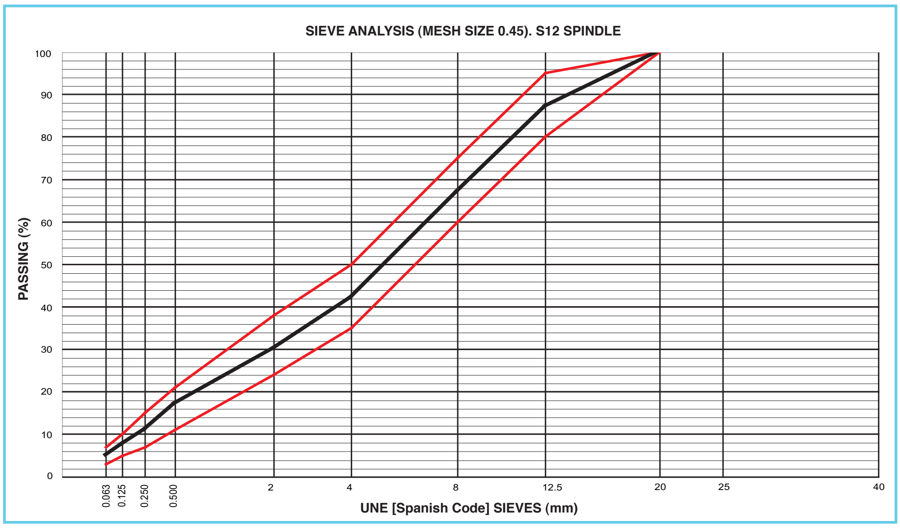

Figure 5. *Granulometric curve of mix S-12*

1. Dynamic shear rheometer testing

In order to obtain the fatigue limits of the bitumens in question, controlled stress tests, between 1,000 and 9,000 Pa, were conducted in the dynamic shear rheometer which plotted the development of strain with increased load cycles (see Photograph 1).

The DSR tests were conducted on 8 mm diameter and 2 mm high cylindrical specimens at a frequency of 1.59 Hz and at 20°C. A sinusoidal load function was employed at controlled stress and the strain was calculated in accordance with the ratio between the height and the angle of rotation in the upper part of the same, as may be seen in Figure 7.

The failure criteria employed to establish fatigue limits consisted of calculating the maximum value of the dissipated energy ratio (DER, equation No. 2), Figure 8 at the cycle where the material showed fatigue. The fatigue limits of the three bitumens studied (conventional B13/22 and B 60/70 and modified BM 3-b) is shown on logarithmic scale, relating the number of cycles to failure with the initial deformation, Figure 9.

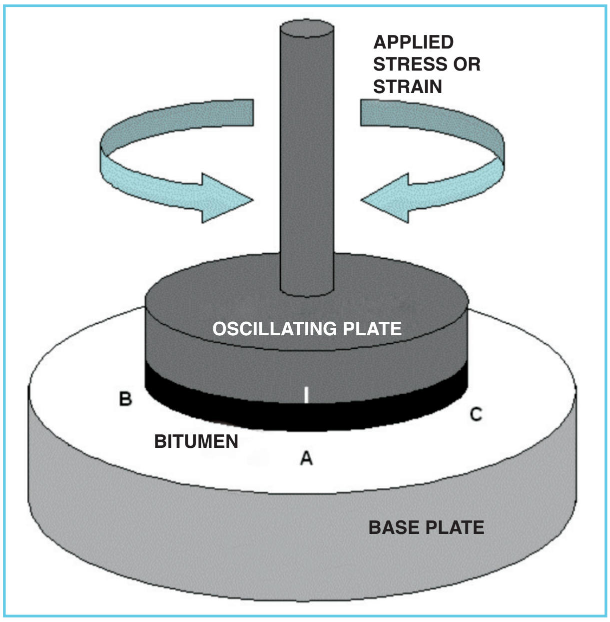

Figure 6. *Schematic representation of Dynamic shear rheometer (DSR) bitumen fatigue testing*

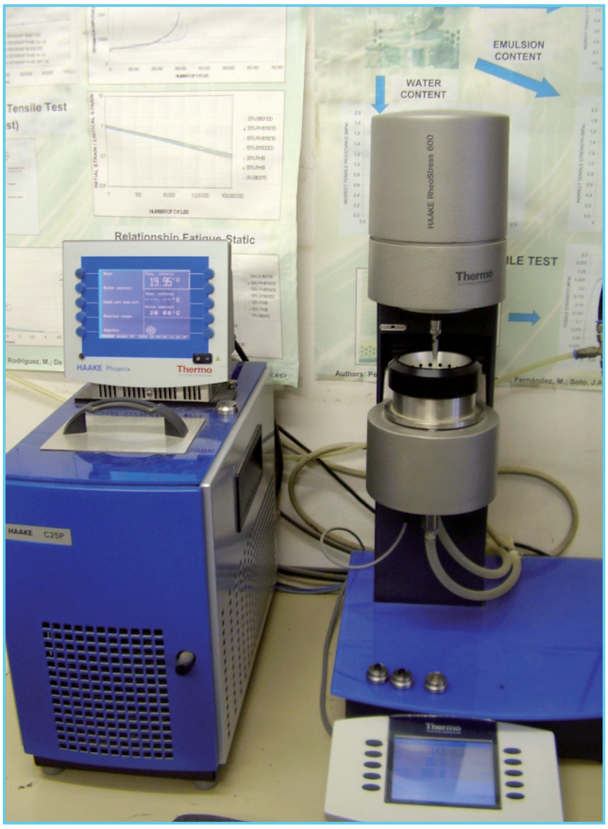

Photo 1. *Dynamic shear rheometer (DSR) equipment*

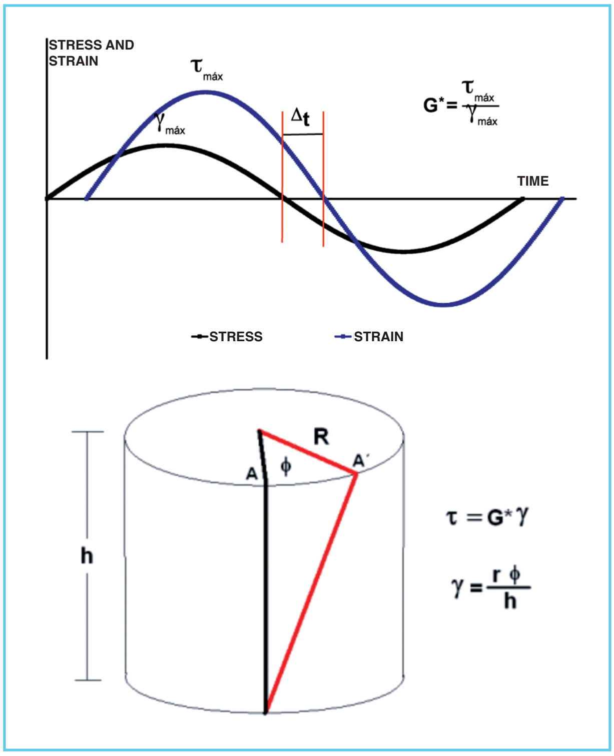

Figure 7. *Load function and strain calculation in DSR testing*

The strain development during the testing of the three bitumens, Figures 10, 11 and 12, was also recorded. From these figures it may be seen that practically all the specimens yielded at the same level of strain, which in the case of the modified bitumen was seen to be between 0.15 and 0.20, and in the case of the conventional bitumens between 0.08 and 0.12 for the B-60/70 bitumen and between 0.04 and 0.06 for the B-13/22 bitumen.

If these results are then compared with the fatigue limits obtained, Figure 9, the modified bitumen, set in the upper part of the figure, is seen to be capable of withstanding the greatest number of load applications for the same initial strain and, subsequently, required the highest number of load applications to reach its level of deterioration. To the other extent, the B-13/22 required very few load applications to reach its level of deformation.

It is also of interest to analyse the slopes of the strain development curves of the B-60/70 and B-13/22 bitumens. In the case of the softest bitumen, with a

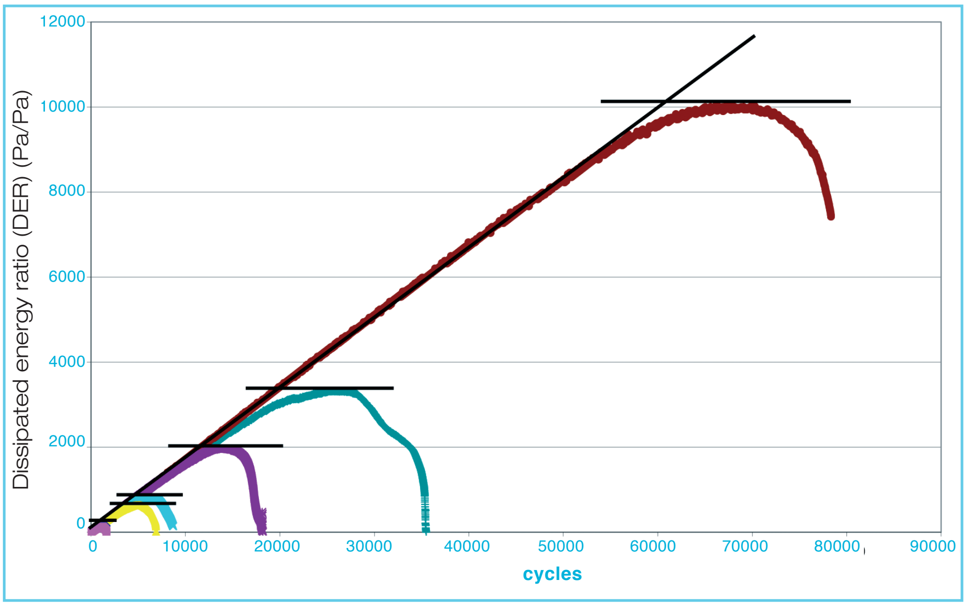

Figure 8. *Failure cycle with calculation of dissipated energy ratio*

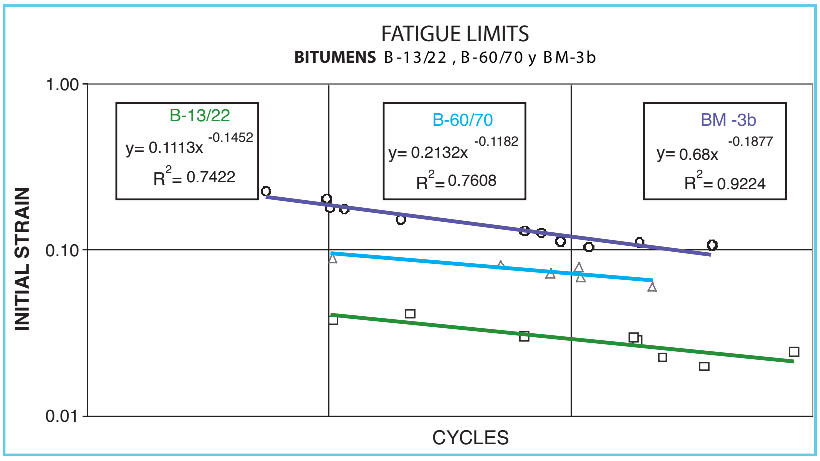

Figure 9. *Fatigue limits for different bitumens*

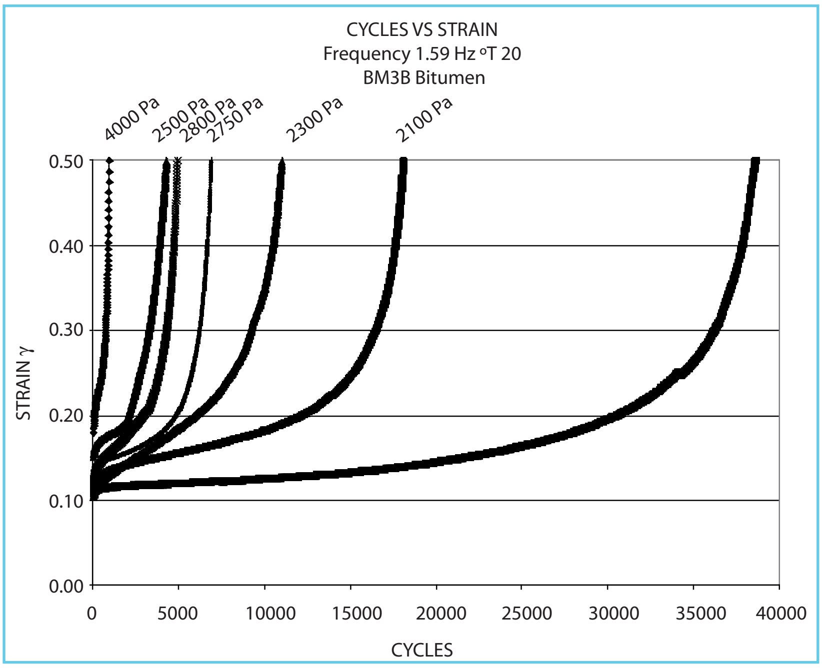

Figure 10. *Evolution of strain with load cycles. BM-3 b Bitumen*

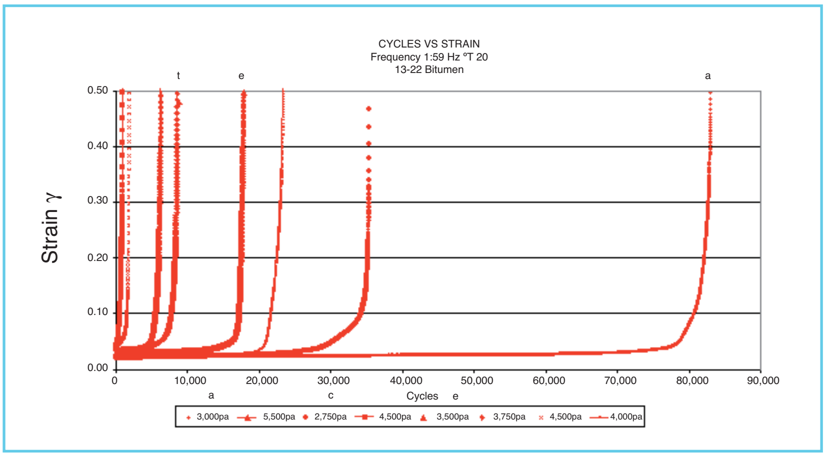

Figure 11. *Evolution of strain with load cycles. B-13/22 Bitumen*

lower stiffness modulus, these curves are steeper and each load application implies greater deformation. However, in the case of the B-13/22 bitumen, with a higher stiffness modulus, there was a far lower increase in deformation under each cycle. This then means that the higher the stiffness module, the lower the slope of the fatigue limit shown in logarithmic scale (lower than b).

2. Tests on mixes

The fatigue limits have been established with displacement control through three-point bending flexural testing, in accordance with the Spanish code NLT-350/90 (see Photo 2).

The test consists of the preparation of a prismatic specimen and supporting this at both ends of the longer side. A sinusoidal load is then applied under displacement control at the centre of the specimen and the ensuing strain is established at the end opposite to load application, Figure 13.

The fatigue failure criteria is given when the modulus falls to half its initial value, Figure 14. Figure 15 shows the fatigue limits obtained for these three mixes.

These tests also reveal the development of strain in the lower fibre of the specimen, as may be seen in Figures 16 and 17 for bitumens B-60/70 and B-13/22 respectively. From these tables it may be seen that fatigue failure occurs at a same level of strain regardless of the initial stress or strain. The mix made with B-60/70 bitumen failed at a higher unit strain than the B-13/22 mix, failing at 0.0008 and 0.0005 mm/mm respectively.

The mix made with modified bitumen failed at a critical strain of around 0.0012 mm/mm. On establishing the fatigue limits (Figure 15), the mix made with modified bitumen is then seen to be set in the upper part of the figure, while the mix made with B-13/22 bitumen is set in the lower part of the same. This then means that the mixes are set in the same order as that of their respective binders.

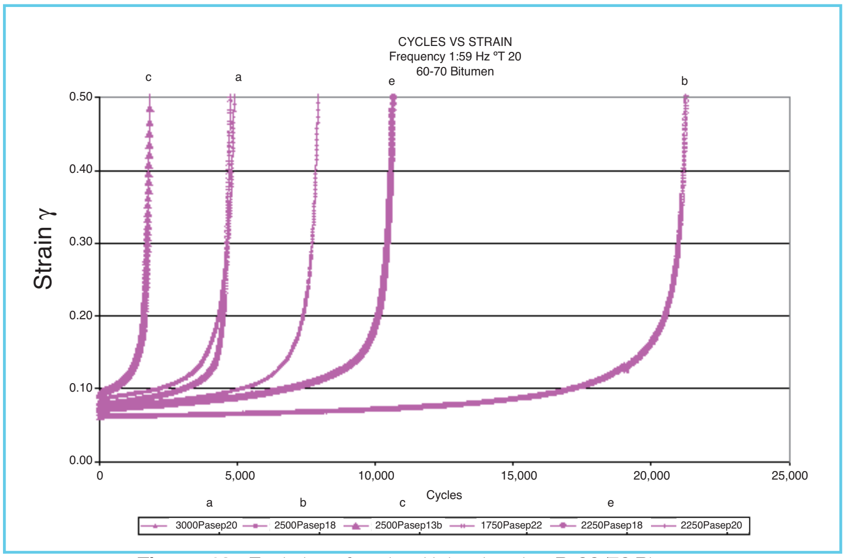

Figure 12. *Evolution of strain with load cycles. B-60/70 Bitumen*

Conclusions

The study confirms that indicated in the introduction to this article with regard to the very important effect of the modulus and the critical strain on the fatigue failure of binders and asphalt mixes. The fatigue behaviour of binders with the same modulus improves with the increased critical strain of the same.

There was also seen to be a degree of dependence between the fatigue behaviour of the mix and that of the binder employed in the same. In spite of its low relative content in the mix, of just 4.5% in weight, the type of binder employed has a very significant effect on the response of the mix.

This critical strain has been shown in other studies and is related to the ductility of the binder. In binders of the same modulus, fatigue performance is improved with the added ductility of the binder.

Photo 2. *Three-point bending flexural test*

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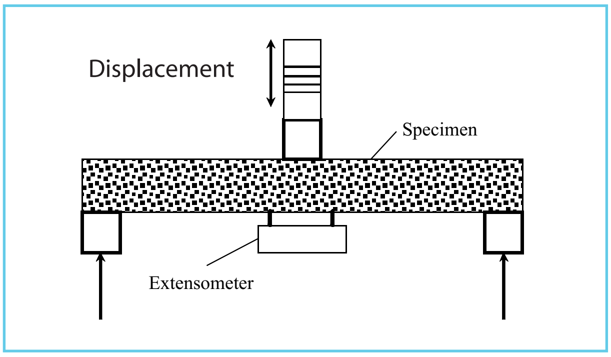

Figure 13. *Set up of three-point bending flexural test*

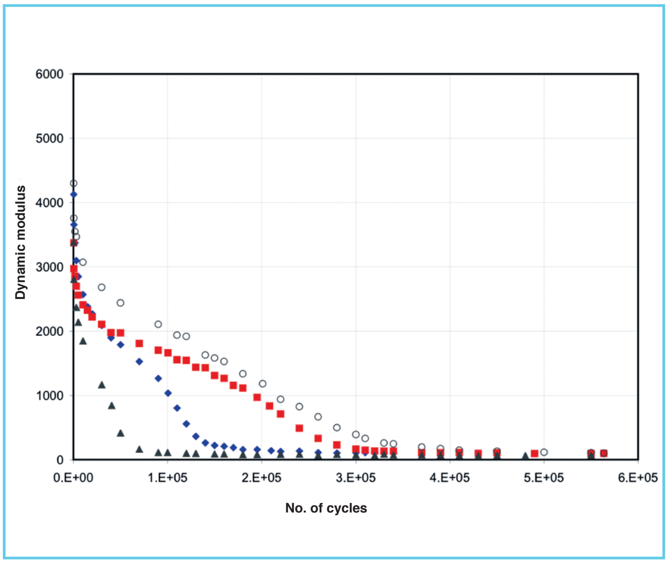

Figure 14. *Evolution of modulus with load cycles. Bitumen B-60/70*

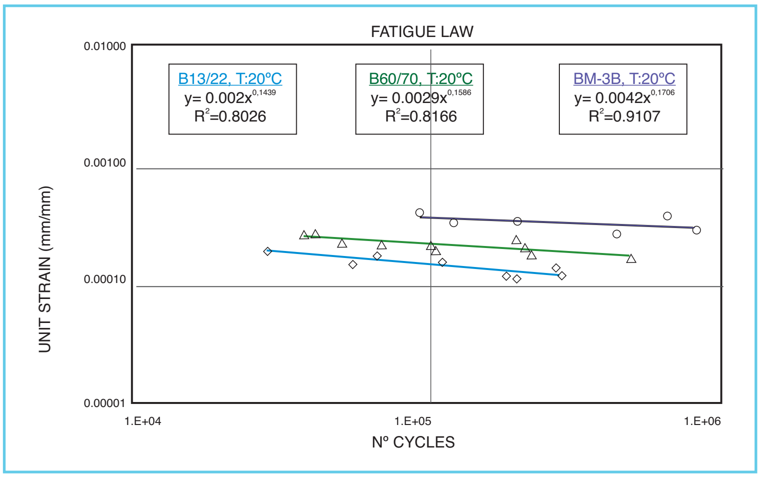

Figure 15. *Fatigue limits of asphalt mixes*

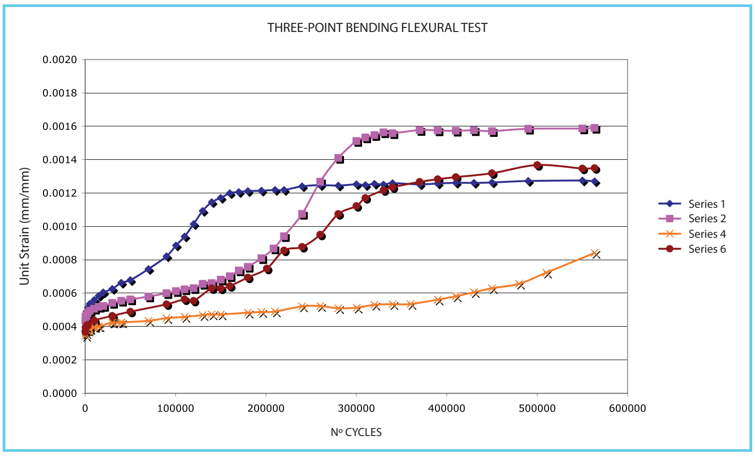

Figure 16. *Strain development under load cycles for asphalt mix with B-60/70 binder*

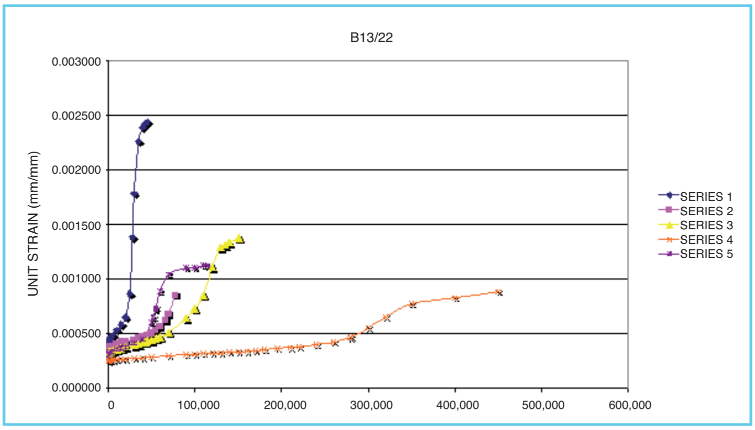

Figure 17. *Strain development under load cycles for asphalt mix with B-13/22 binder*

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Tunnels built with TBMs. The world's largest tunnelling machines (I)

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ABSTRACT

The two works for the Southern By-pass of the M-30 ring road used two 15-m diameter tunnels excavated by tunnelling machine to create a by-pass that decongested the southern section of this urban ring road by separating off from it the traffic not involved in the junctions forming part of the Southern Interchange.

This article describes the characteristics and execution of the South Tunnel and the Tizona tunnelling machine used, which at the time, and together with its partner Dulcinea, formed the largest tunnelling machine in the world. Worth highlighting is the fact that the excavation of the 3,660-m long South Tunnel took just 200 days (April 11, 2006/ October 27, 2006) with some peak output levels of 46 m/day and average levels of 557 m/month that were exceptional for a machine of this diameter and when the work involved difficult advancing conditions and logistics crossing under existing buildings.

Key words: *Tunnel, Tunnelling machine, M-30, Segments, Southern By-pass, Excavation crown.*

The M-30 ring road in Madrid encloses an area of 42 square kilometres and a population of around one million people. The ring road was built over different stages throughout the 1960s and 1980s. The road building criteria followed during these stages was not always uniform and this gave rise to certain sections controlled by traffic lights and others that had the characteristics of a motorway. The presence of complicated intersections, that were not always evident, and continuous changes in the number of lanes on the main carriageways has caused numerous traffic accidents over the years together with enormous traffic jams during morning and evening rush hours. A further, unwanted consequence of the ring road has been the enormous environmental impact and noise pollution caused in residential areas of the capital.

At the start of the 2003-2007 legislation and on the basis of socio-economic and environmental criteria, the Mayor of Madrid took the decision to rebuild the M-30 ring road in accordance with the principles of sustainable development listed below:

- Convert the majority of the new ring road and intersections as underground routes in order to form new green areas on the surface and reduce environmental impact.
- Increase traffic capacity and flow.
- Increase traffic safety by clearly visible information panels and by preventing dangerous manoeuvres.
- The remodelling of interchanges with six radial roads and with other exits and approach roads.

The total cost of the remodelling project amounted to Euros 3.7 billion, though following the completion of the project in mid-2007, it was expected that 14 million hours would be saved in transit, representing an annual saving of 4.5 million euros in fuel consumption. Further, and no less important, effects would be the reduction in pollution of 35,000 tons of CO_2 emissions per year and a prevision of some 400 less accidents occurring on the ring road each year. All these forecasts were predicted to rise even more substantially over following years.

The west of Madrid, the area where the River Manzanares runs parallel to the M-30, will reap the most benefits from this transformation as the San Isidro fields will regain their former splendour and the barriers imposed by the existing layout will be removed.

Cross-section of the south by-pass tunnels

One of the major challenges of this remodelling work does not lie with the ring road itself, but in the intersection with the A-3 Levante highway. This is the busiest intersection on the entire route and has one of the highest traffic densities in all Spain, with over 250,000 vehicles passing through each day. The remodelling of this intersection is one of the main objectives of the South By-Pass, and is the subject of another article appearing in this special edition of the *Carreteras* journal.

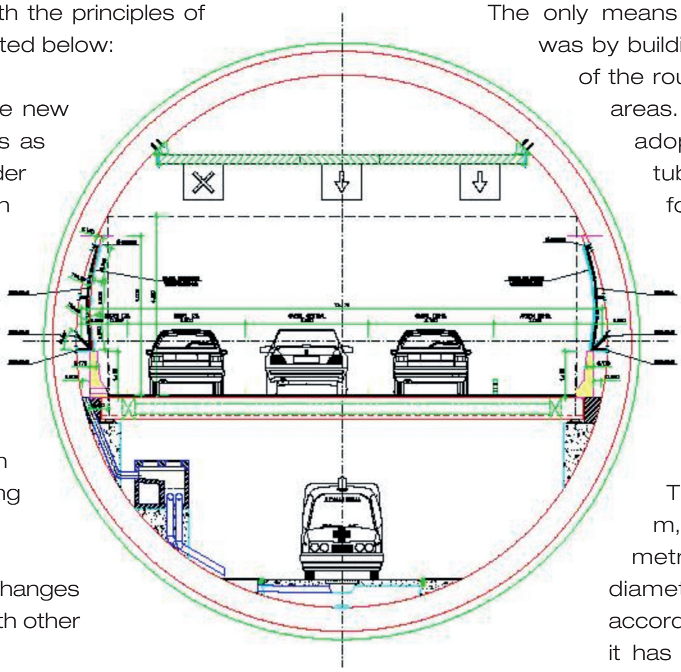

Figure 1. *Cross-section of the tunnel*

The only means of resolving this problem was by building a tunnel as a large part of the route runs through residential areas. The final solution that was adopted consisted of a twin tube tunnel, with one tube for each direction of traffic and capable of carrying both light and heavy vehicles. The lanes are 3.5 m wide, the shoulders 0.5 m and the footways 0.8 m (see Figure 1).

The height clearance is 4.5 m, with the roadway set one metre below the horizontal diameter of the tunnels. In accordance with these premises it has been necessary to design tunnels with a 13.45 m internal diameter. On account of the circular arrangement, it is also possible to house two emergency lanes in the lower part of the tube (5.5 x 4 m).

The total length of each tube is 3,660 m which are interconnected by 8 cross connections, three of which serving for vehicles and five exclusively for pedestrians (Figure 2). Each tube has its own ventilation shaft set within the central third of the route. The fire protection of these urban tunnel has been resolved by incorporating polypropylene fibres within the concrete lining.

The maximum cover of these tunnels is 65 m and the average cover is 30 m, equivalent to at least two diameters. The portals at each end of the tunnel were designed as rectangular shafts with a cover of under 15 m in order to reduce height. This then made it necessary to make ground improvement at both portals and over the initial run of the tunnel.

Selected excavation method

1. Excavation method

As mentioned earlier, part of the new layout of *Calle 30* has been set underground. In order to do so, several excavation systems or techniques have been employed, ranging from the *Madrid method* to the *false tunnel* method and obviously employing *TBMs*.

The *false tunnel* or cut-and-cover method, consisting of diaphragm walls and concrete slab, is the most economical in view of the soil conditions in Madrid. However, it does present a series of inconveniences such as the relocation of affected services in densely populated areas, the greater volume of excavation required and ensuing transport to land fill sites which are becoming increasingly scarce in the vicinity of the city and which, subsequently make this option less favourable than a bored option. This latter solution also allow the route to be maintained below buildings and historic monuments.

The *Madrid method* is a traditional excavating method without the use of tunnel boring machines and is successfully employed in the capital for small tunnels, caverns and galleries. The method is based on excavating by stages and perfectly adapts to variations in the geometry of the excavated structures.

With regard to the south By-pass tunnels, and on account that these had an excavation diameter of 15 m, it was not possible to resort to a cut-and-cover method, particularly in view of the very short period available for construction.

The soil conditions in Madrid lend themselves perfectly to the use of EPB (Earth Pressure Balance) type boring machines as has been confirmed by the work conducted on the Madrid Metro over preceding years.

In July 2004 an order was subsequently issued for the construction of two 15 m diameter EPB tunnelling machines, which were the largest in the world at the time.

The geology of Madrid, and particularly in the area where the South by-pass tunnels are located, have the following characteristics:

- Alluvial deposits down to depths of 20 m,
- Sandy clays (known locally as Peñuela clay) with thicknesses of 20 to 30 m, and
- 20 to 25 m hard clay with gypsum levels.

With regard to the geotechnical parameters, the "peñuela" clay has a cohesion of τ = 60 kPa, an internal angle of friction of ϕ' = 28° and a deformation modulus of E = 220 Mpa. The content of fines passing through a 200 sieve is between 85-95%. The tunnels were built below the phreatic level and with a maximum hydrostatic load of 40 m.

The lining was formed by nine 60 cm thick by 2 m wide segments formed in a universal type ring. The segments are bolted together by three bolts and each segment is fixed to the adjacent ring by a further four bolts. Two dowels are placed on each segments at the joint with the ring to ensure correct positioning.

The longer segments, measuring 4.76 m on the outer side, weigh 13.1 tons and the total weight of the entire ring is 125 tons. The ring is supplemented by a concrete base plate (insert) which is employed to support the provisional work platforms.

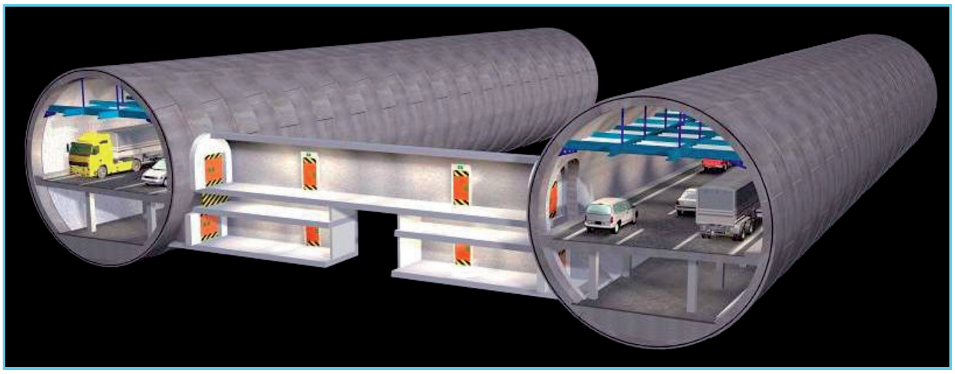

Figure 2. *3D view of tunnels and cross passages*

2. Prior experience on the Madrid Metro

Experience with EPB type tunnelling machines was first gained in 1995, when a 7.38 m diameter (DRAGADOS) LOVAT machine was employed in the extension of Line 4 of the Madrid Metro which included a crossing below the Manzanares River with just 2 m overlay. From this time on and over successive extensions to the Metro conducted over 1995-1999, 1999-2003 and 2003-2007, more than 140 km of tunnels have been built by this procedure, with average advance rates of over 600 m/month and a peak rate of 1,230 m in just one month.

A high level of expertise in this type of tunnelling has subsequently been gained as a result of the experience accumulated over the last decade. The analysis of the results obtained and particularly that of unproductive periods, has allowed the design of new machines to obtain even greater efficiency.

It is common knowledge that these types of machine do not employ more than 50% of their working time in actually excavating and placing the ring lining, while the other 50% of the time is spent on maintenance and repair, cutter changing, extending pipes and cables, surveying, soil treatment from the machine, etc.

Additional time is also lost as a result of the frequent derailment of convoys travelling between the portal and the tunnelling machine, supplying segments and removing excavated muck or soil.

Experience has shown that the change of cutter tools is an aspect that still has to be addressed, in spite of recent progress that allows these cutters to be changed from inside the cutterhead without exposing workers to the risks of falling rock or spoil. The narrow access to the chamber, the provisional scaffolding and difficulty involved in removing bolts, etc., all make this a slow and laborious operation.

The breakdown of TBMs is, in the majority of cases, directly related to their operation at the maximum of their electromechanical capacities. As a result, the provision of certain technical specifications over and above those strictly required then allows a wider scope of operation and an increase in production. This solution is also applicable to the back-up[a] system or trailing equipment such as the grouting pumps, ventilation, drainage and other auxiliary equipment.

The third cause of loss of performance through stoppages is related to the frequent derailment of muck convoys. The current and recommended trend is to employ conveyor belt systems for the removal of muck and soil as the convoys are then only required to transport lining segments, grouting material (mortar or gravel) and other materials. This then leads to a considerable reduction in the number of derailments.

As no adverse geological conditions were expected to be encountered in the south By-pass tunnels, the tunnel boring machines were designed to operate in EPB mode and this together with a detailed study of the three main causes of loss of production time detailed above and subsequent improvements made have all ensured a considerable increase in production and a reduction in stoppages during operation.

Technical specifications of the TBMs

The technical specifications of the TBMs were based on those requested for the Madrid Metro work, where very similar ground conditions were encountered, but adapted to incorporate larger diameters and increased capacity in order to reduce the risk of breakdown and improve performance.

1. Excavation diameter

The excavation diameter is conditioned by the free internal diameter referred to above. When adding the thickness of the segmental lining to the 13.45 clear diameter, this then gives an outer diameter of 14.65 m. When considering the gap[b] of the overcut required to prevent the risk of trapping the machine and to allow curves of 350 m radius, this then gives a final excavation diameter of over 15 m. The minimum radius tolerance was defined to correct possible errors in guidance as the alignment restricted the minimum radius to 500 m.

Each manufacturer proposed their own design which then gave rise to different excavation diameters. Herrenknecht proposed a sandwich type design for the tail shield which offered a diameter of 15.08 m, while the Japanese manufacturer, Mitsubishi, considered a 15.01 m diameter which complied with the required specifications.

(a) Train of trailing units behind the excavator carrying all installations necessary for operation. The 134 m long back-up system to the Tizona TBM was formed by eight 2-3 deck trailers.
(b) Ring-shaped gap between the excavation tunnel and the exterior diameter of the shield allowing the movement of the machine and small pitching movement to form the curves of the layout. This has an influence on the settlement that may be cause by the TBM.

2. Maximum thrust

Thrust or propulsion is provided by a set of hydraulic cylinders that push against the last ring of segments installed. These should be capable of meeting the following objectives (Figure 3):

- Preventing horizontal deformation at the tunnel face,
- Compensate the effective horizontal ground pressure,
- Compensate the interstitial groundwater pressure,
- Eliminate vertical settlement of the ground ahead of the tunnel face, and
- Overcome shield friction during the advance of the TBM.

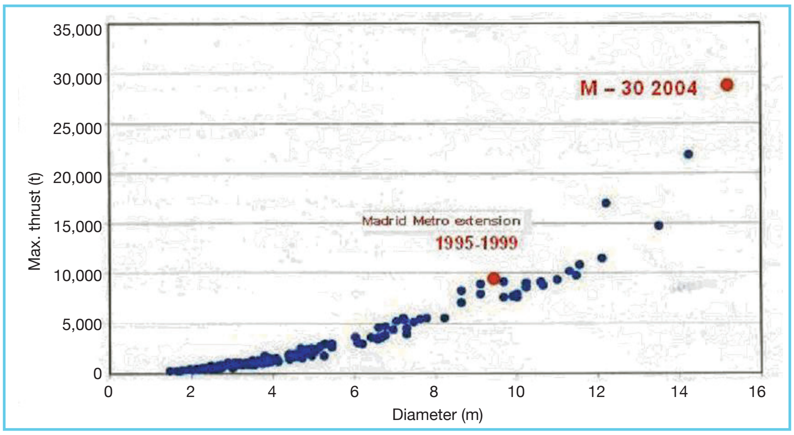

Figure 3. *Maximum thrust vs. Diameter*

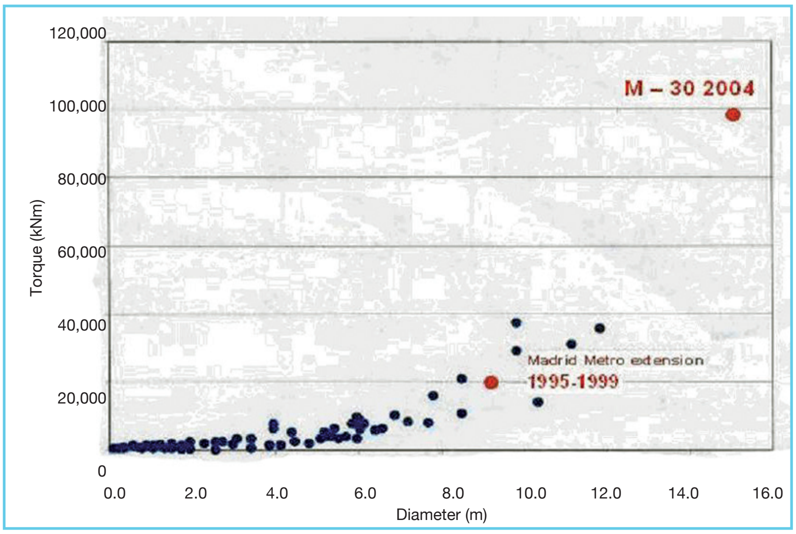

Figure 4. *Torque vs. diameter*

The TBMs employed in the extension to the Madrid Metro had a maximum thrust of 100,000 kN with a 9.4 m excavation diameter. As the ratio of the areas is 2.5, the manufacturers were requested to provide a maximum thrust of over 250,000 kN in the knowledge that problems could otherwise occur due to the excessive friction in the TBM shields

The Mitsubishi TBM proposal enabled a maximum thrust of 285,000 kN, provided by 57 cylinders of 500 t each, while the Herrenknecht TBM offered a 276,390 kN maximum thrust, using 57 cylinders of 485 tons each.

3. Maximum torque

The maximum torque was estimated for the Madrid Metro work in accordance with the following equation:

$$T = (2/3)\ \pi\ \tau\ R^3$$

where π is the soil cohesion (100 kPa or 10 T/m^2) and which then implies a torque of 2,175 mT, though one of 2,000 mT was finally selected (figure 4).

A ratio of excavated volumes was employed to establish the minimum specifications for the TBMs used on the M-30 work:

$$T=2,000\ (15.1/9.4)\ 3 = 8,240 \text{ mT}$$

This torque makes it possible to:

- Excavate the ground by drag bits and other cutter tools
- Overcome the fiction between the ground and cutterhead
- Overcome radial and tangential stress on the main bearing,
- Overcome the friction of the sealing rings, and

Homogenise the soil within the working chamber

4. Other specifications

In accordance with the geological characteristics of the soil envisaged in this project, the manufacturers were requested to meet the following specifications:

- Working pressure in the lower part of the chamber of 6 bar
- Cutterhead opening ratio of over 30%
- At least 6 earth pressure sensors in the chamber for the correct control of the excavation process
- Advance rate of 65 mm/min, equivalent to one 2 m ring every 30 minutes.
- Maximum size passing through screw conveyor of 700 x 300 x 300 mm
- 1000 m3/hr foam injection capacity for soil conditioning
- Annulus grouting pump capacity of over 50 m3/hr
- Over three rows of wire brushes to prevent entry of water
- Rescue chamber providing refuge to 20 people for up to 12 hours.

Double design

The South By-pass project was divided into two independent contracts and each joint venture was awarded the construction of its TBM, one going to Herrenknecht and the other to Mitsubishi-Duro Felguera. As this concerned new design-build TBMs and in order to comply with the strict specifications established by the client and very restricted construction schedule, both TBM manufacturers considered the introduction of highly innovative solutions.

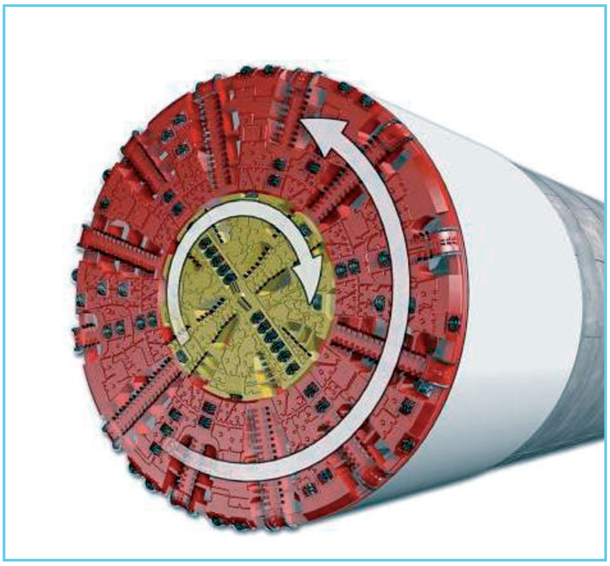

Figure 5. *Opposing directions of inner and outer cutter wheel*

The high excavations rates resulting from the torque and thrust specifications, indicated above, together with revolutionary designs for the cutterheads and new concepts applied to reduce the time necessary for lining installation made it possible to meet the stipulated schedule.

In our opinion, the proposals of both manufacturers have paved the way for future development of large TBMs capable of excavating large tunnels quickly and safely.

1. German design

The German design sought to prevent the counter-rotation of the machine on account of the enormous torque at the cutterhead when excavating faces of 181.5 m^2.

This effect has been overcome by splitting the cutterhead into two concentric cutting wheels which turn in opposite directions during excavation. In this way the torque generated by the outer cutting wheel is partially offset by the opposing torque of the inner wheel and this considerably reduces any risk of the turning of the machine in the event of the blocking of the cutterhead (see Figure 5).

The inner cutting wheel or active cutting centre has a diameter of 7 m and a face of 38.5 m^2 arranged in the form of six radial arms equipped with drag bits and disk cutters and may advance independently from the rest of the cutterhead, thereby allowing the prior excavation of the central section in a drive that facilitates the excavation of the rest of the section by the outer cutting wheel.

The 143 m^2 outer cutting wheel is fitted with 12 radial arms, all equipped with the pertinent cutting tools. This wheel contains a total of 57 double 17” disk cutters, 332 bits, 24 scrapers and a central cutter, and has a cutterhead opening ratio of 31.6%.

The concept of the double cutterhead has been used by Herrenknecht on earlier hydro shield type machines, though this was the first time that the technology had been employed on an EPB machine. The inner cutting wheel has a higher rotating speed than the outer wheel in order to prevent the risk of hardening and blocking of excavated material in the central part of the chamber. This is due to the low speed of rotation in this area together with water evaporation caused by the high temperatures generated by friction and drive.

The cutterhead is hydraulically driven with 10 drive motors in the inner cutting wheel and double gearing in the outer wheel with 24 and 32 drive units respectively. In view of the loss of output of hydraulic drive, of around 32%, the 15.8 MW installed capacity provided 10,700 kW to the cutterhead.

This drive power provides a torque of 9,600 mT at 0.81 rpm in the outer cutting wheel and one of 8,450 mT at 1.5 rpm in the inner wheel. Maximum torques of 12,527 mT and 10,890 mT are obtained for the outer and inner wheels respectively

The shield is 11.51 m long without articulation and includes three rows of wire brushes at the tail shield and excavated material is removed by three screw conveyors. A somewhat smaller 700 mm diameter conveyor is employed for the mucking of the central area, while two larger 1200 mm screw conveyors remove excavated materials from the lower part of the cutter chamber. Segments are installed by a standard vacuum segment erector.

2. Japanese design

The Japanese design is substantially different from that of its German counterpart. The cutterhead is formed as a single wheel equipped with 44 triple 17" disk cutters, 678 bits of different format and a central cutter. The TBM has a cutterhead opening ratio of 43% and significantly higher than that of the Herrenknecht machine (see Photo 1).

The TBM is electrically driven by twenty-seven 358 kW variable frequency drive motors, providing a total of 10 MW. As this type of drive has a smaller loss of transmission in the kinematic chain, the nominal torque transmitted to the cutterhead is 8,570 mT at 1.05 rpm and a maximum torque of 12,700 mT.

In order to prevent the counter rotation or rolling of the machine, adjustable thrust cylinders were placed in conjunction with steel profiles set on the lower part of the shield and acting as guides. The turning direction of the cutterhead was repeatedly changed during excavation to further prevent the risk of rolling.

As the rotation speed of these types of machine is very low, being around 1 rpm, there is a risk that the central area of the chamber becomes plugged with excavated material. In order to offset this problem, Mitsubishi decided to install a centre agitator formed by three arms and with a 5 m diameter, which was hydraulically driven to remove the material accumulated in the

Photo 1. *Mitsubishi – DF EPB*

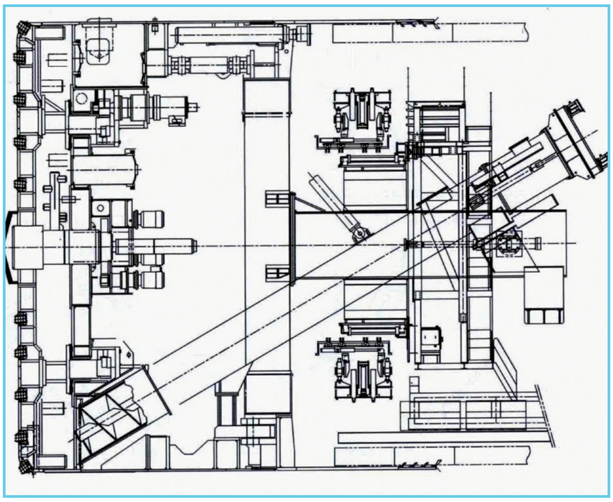

Figure 6. *Longitudinal section of Mitsubishi EPB*

centre of the chamber and to prevent clogging. This agitator can rotate at 2 rpm, which is more than sufficient to offset these problems.

The shield is 12.22 m long and has active articulation. The tail shield is fitted with four rows of wire brushes and spoil is removed by a single screw conveyor (Figure 6).

A further innovation introduced in this machine is the double segment erector. The erector was built with two vacuum plates set either end of the erector arm and in such a way that the plate closer to the segment feeder be the one taking the segment for placement in the lining ring. This system reduces the assembly cycle of the rings by the time necessary to move the erector from the position of the last segment installed back to the feeder.

Planning of work

Once independent contracts had been awarded for each of the tubes, work was then scheduled to last 33 months as from July 2004. The manufacturers had previously been given a 6 month contract in which to prepare the design of the machines and to confirm viability in accordance with the specific requirements of the client (see Photo 2).

The Herrenknecht TBM was assembled in 12 months and the Mitsubishi in 17 months. During this time, two launch shafts, 40 x 100 x 30 m deep, were excavated at either end of the route. The plan was to separate the activities of each Joint Venture to avoid potential interference caused by simultaneous work from just one launch shaft.

The forecasted excavation rate was 12 m/day or 360 m/month, which implied a period of 10 months to excavate each of the tubes.

The rest of the work, such as the intermediate slab or cross passages, was carried out in parallel to the excavation, a few hundred metres behind the tunnel face, in order to meet the very tight schedule of the respective contracts.

Work on the south tunnel

The contract for the South tunnel was awarded to the Joint Venture formed by DRAGADOS and FCC who, in turn, awarded the construction of their TBM to MHI-DF, an association between Mitsubishi and the Spanish company Duro Felguera, in order to ensure the manufacture of the largest possible number of components in Spain and this latter company took responsibility for back-up design.

The delays arising in the construction of the TBM were partly due to the limited number of factories in

Photo 2. *Mitsubishi TBM at the Duo Felguera factory during trials*

Europe capable of building the enormous components of this machine, such as the main drive, together with the fact that the Duro Felguera installations were not entirely appropriate for the construction of the "largest TBM in the world". This then gave rise to a number of unforeseen circumstances and changes in the initial planning of the construction. However, the expedience of the design and the build quality all went to ensure the construction of a truly competitive TBM and allowed the contractor to recover the time that had been lost.

It took one month to transport the TBM from the Barros factory in Asturias to Madrid and a further three months to construct the launch shaft, these being considered reasonable times in view of the dimension of the equipment and the restrictions and bottlenecks at accesses and on site. Photograph 3 shows the construction of the launch shaft beside the existing M-30 ring road and where rush hour traffic considerably affected the normal progress of the work..

1. Excavation of the South Tunnel

Excavation work on the South tunnel began on 11 April 2006 using temporary soil removal systems as the restrictions of the launch shaft did not allow the complete assembly of the TBM or the installation of conveyor belts for the removal of excavated material. After 10 days work and excavating 64 m of tunnel (including the passage below the conservatories seen at the bottom right of Photo 3), it was then necessary to halt excavation for one week in order to continue with the assembly of the back-up system and auxiliary installations.

The progress over the first 240 m, as may be seen from Figure 7, was partly conditioned by the learning curve required of the entire team and the conservative approach in the handling of the machine in order to weigh up its performance. Here it is of note that the largest EPB ever to be employed prior to this particular work was that used on Line 9 of the Barcelona Metro which had "just" a 12 m diameter. This 50% plus increase in size more than justified this cautious approach over the initial stages of the excavation.

On 17 May it was necessary to make a further stoppage of 15 days in order to complete the assembly of a permanent muck haulage system, remove the drive structure and complete the track system in the launch shaft. There was also a failure in the hoist transporting segments at the back-up between the unloading point of the train and the segment feeder which, subsequently, required the complete redesign of this component by the manufacturer.

Constant and continuous progress was made from this moment on (as may be seen from the chart in Figure 7), largely on account of the highly qualified crew handling the TBM and the experience gained through successive work on the Madrid Metro and on the excavation of the 28 km long Guadarrama tunnels, among other projects. This aspect is more than revealed by the advance rates that were finally achieved.

The following performance figures were achieved on the completion of the tunnel::

- Average daily performance: 18.3 metres/day
- Average monthly performance: 557 metres/month
- Best daily performance: 46 m (9 October 2006),
- Best monthly performance: 791 m (October 2006),
- Best 30-day performance: 928 m (from 22 September to 21 October)

The figures speak for themselves and after 200 days work this spectacular excavation, which started on 11 April was culminated with the breakthrough on 27 October 2006 (see Photo 4).

Photo 3. *Launch shaft of the South tunnel*

It is worth mentioning that if the site conditions at the launch portal has not been quite so restrictive in terms of space and if it had been possible to assemble both the TBM and all the permanent installations as from the very first day, this would have prevented the 21 day stoppage and the final performance would have risen to 20.5 m/day and would have exceeded 615 m/month.

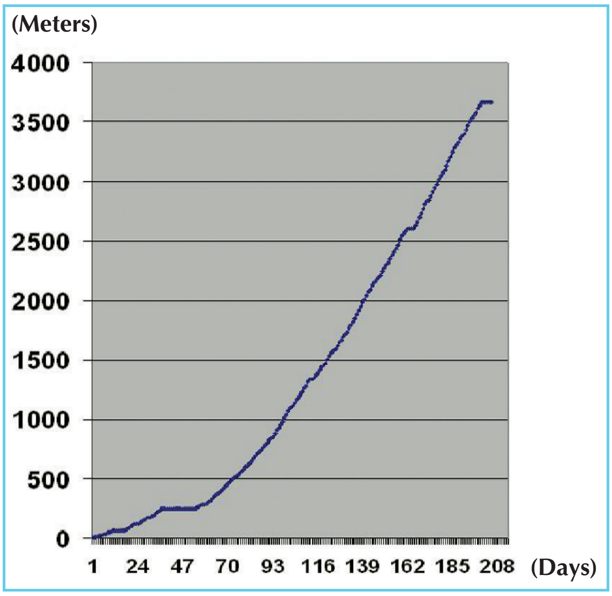

Figure 7. *Accumulated performance on South tunnel*

2. Lessons learned from the excavation

The excavation of the south tunnel of the Calle 30 South By-pass project came up to out highest expectations regarding large diameter tunnels and their tunnelling. One conclusion that should be taken into account in future projects is that the speed of excavation (performance) is not conditioned by the tunnel diameter but by the correct choice of machinery with regards to the expected geological conditions throughout the route, by the design of installations that can match this performance and by suitable management of the entire procedure by a highly qualified team of professionals.

The reserve power of the cutterhead and of the torque and thrust of the TBM have all shown to be highly efficient fallbacks when the soil conditions have deteriorated and have subsequently prevented breakdowns and unexpected stoppages.

The central agitator designed to homogenize the soil and prevent plugging in the central part of the chamber has proved to be a simple yet very efficient tool in large diameter machines.

Photo 4. *Breakthrough of the South tunnel*

The double erector has been employed more as a stand-by erector than for its original design purpose as described in section 2 Japanese Design. The time employed in reversing the controls in order to use the opposing vacuum plate to that in use at any given time is greater than the time implied by a smaller movement of the same to place the corresponding segment. However, the fact that a second vacuum plate was available has prevented any stoppages during the lining assembly cycle due to a failure of the plate and any such failures have been repaired during the excavation of the following cycle or during scheduled maintenance stops. This has all lead to improved performance (Photo 5)

3. Intermediate roadway slab

The original design of the tunnel considered an intermediate slab cast in-situ, supported by two central columns and resting on cantilevered supports set along both sides (see Figure 2). This design was modified by another design that gave the same end result but simplified construction and left the lower part of the tunnel completely clear, as may be seen in Figure 1.

A 24 m long sliding formwork structure made it possible to erect identical lengths of cantilever support every day (Photo 6). The reinforcement was placed by an independent shuttle wagon set between the sliding form

Photo 5. *Segment erector*

and the back-up of the TBM. From the rear of the back-up, perforations were made in the segments to house starter bars which would then be connected to the tunnel lining.

The concrete for the cantilever supports was supplied by trucks moving along the slab and leaving the two tracks below the slab clear for the supply of materials to the TBM. A distance of around 200 m was kept between the slab and cantilever supports and a concrete pump set on the slab piped the mix to the cantilever formwork.

The operation was followed up by the placing of neoprene bearing pads which served to support the prefabricated slabs. These 2 m wide slabs were transported from the portal by tractor and trailer and placed in position with the aid of a fork lift (Photo 7).

As the slab was placed, the concrete pump and pipelines were moved forward to maintain the distances between the different work faces, thereby ensuring that all work was conducted from the upper slab. The 200 m gap was necessary to ensure the necessary hardening of the concrete cantilevers in order to support the slab.

The concreting of these cantilevers conditioned the progress of the entire operation and this then allowed 24 metres of slab to be completed each day.

Another important activity was the construction of the cross passages which were formed by the "Madrid Method" and excavated from the roadway slab until breaking through the adjacent tunnel and connecting with the lower area, as be the case.

Conclusions

The use of the largest ever EPB tunnel boring machines on the Calle 30 project serves as an enormous step forward in the state-of-the-art of tunnel construction, not only on account of their high performance in terms of power, torque and thrust, but also because of the complexity of the installations and services required to attend to the requirements generated by a tunnel of these dimensions.

With this in mind and based on the earlier experience of the Madrid Metro, the Madrid City Council has successfully brought off this imposing project that will undoubtedly

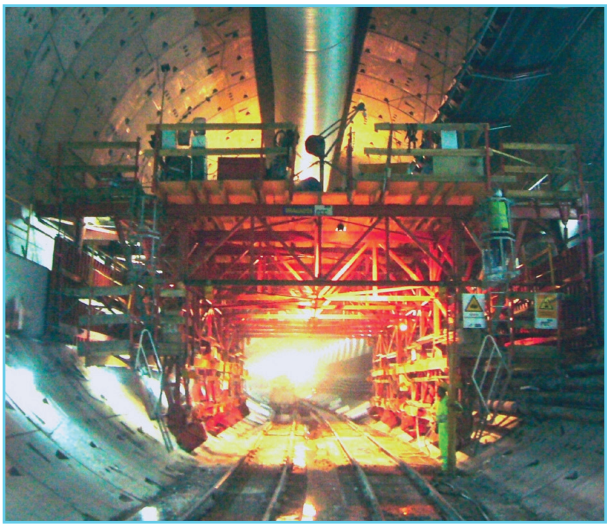

Photo 6. *Formwork for the construction of cantilevered supports*

Photo 7. *Laying of prefabricated slab*

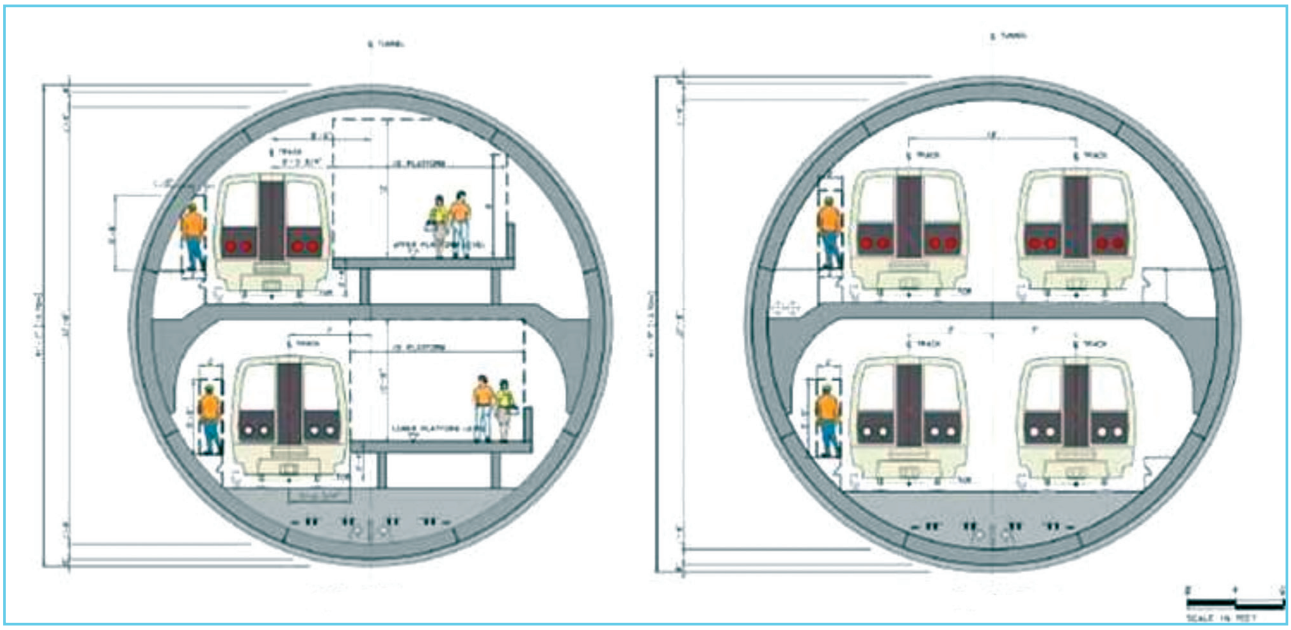

Figure 8. *Tunnel alternative for Tysons Corner*

ease traffic congestion and improve road safety while at the same time opening up much needed park areas in the city.

The *Calle 30* project considered similar action for the North By pass and where the current route passing along the Avda. de la Ilustración, controlled by traffic lights, would be replaced by an underground route which would connect up with the N-1 highway in the vicinity of the M-40 orbital ring road. The closing of the M-50 orbital through the Monte del Pardo woodlands is a further project where this type of solution could be applied, given the environmental restrictions on this specially protected area.

However, this type of project is not restricted to road tunnels alone and could be employed in multifunctional solutions where the entire inner area of the circular section created by the TBM could be employed to house roads, railways, light rail systems and tramways, emergency routes and, obviously, water, electricity or telecommunication services to allow new development of urban tunnels. If infrastructure is set underground and reclaimed land allocated to green areas and parks, this will all contribute to more sustainable development and improve the quality of life of the town's inhabitants.

Examples of multi-use tunnels abound, such as the SMART project in Kuala Lumpur, where the lower part of a road tunnel is employed as a stormwater diversion and where the entire tunnel can be employed to carry flood water in the event of major storms; the Port of Miami tunnel project, between Dodge and Watson Island; or the proposed underground alternative to the aerial monorail alignment to Tysons Corner within the new Dulles Corridor Metrorail Project between Washington D.C. and Dulles International Airport (Virginia) are new solutions to overcome problems in densely populated urban areas.

Recent development in TBM technology and innovative engineering designs, made to meet customer demands and transformed from paper into reality by proficient building contractors have opened up new avenues in the construction of tunnels, that go far beyond even the most optimistic expectations.

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Tunnels built with TBMs. The world's largest tunnelling machines (II)

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ABSTRACT

The article begins by describing the work on the SOUTH BY-PASS employing the 15.20 m diameter Dulcinea TBM and describing the groundplan layout, cross-section and soil conditions. After commenting on the development of cutting wheel diameters of TBMs, a description is given of the machine's technical specifications and a summary of the most relevant technological advances incorporated within the Dulcinea, such as: the twin cutterhead, the advancing system for the first trailer, the tool changing device, the double drive of the outer wheel, the lining ring and the turning rate.

The article goes on to give the performance rates of the tunnelling machine and describes the installations necessary in the launch shaft, while underlining the logistic problems entailed in this type of urban work. The article concludes with a comment on the use of these types of machine in future road tunnel projects.

Key words: *M-30, South By-pass, TBM, Cutting wheel, Launch shaft.*

Background

The Dulcinea Earth Pressure Balance shield (EPB) TBM, built in Germany by Herrenknecht and ordered by the South By Pass North Tunnel Joint Venture formed by Ferrovial-Agromán and Acciona Infraestructuras, was used in the construction of the north tunnel of the South By Pass to the M-30 ring road in Madrid (Left-hand carriageway of the connection from Paseo de Santa Maria de la Cabeza with the N-III highway, corresponding to the South By-Pass of the M30).

The work came within the Plan for the Remodelling and Integral Management of the M-30 inner ring road and concerned the south section of the same. This ambitious project aimed to ease passage through the city, reduce accidents and pollution, introduce new parks and green areas, to reclaim the Manzanares River and improve traffic flow.

1. Description of the work

The M-30 ring road South By-Pass, which is dealt with in more detail in a further article within this special edition, is a underground section of road formed by twin single-direction tunnels.

The north tunnel (see Figure 1) started off from a launch shaft built on the M-30 between the two bridges known as the Puente de Mediterráneo and the Puente de Vallecas. The route runs alongside the abutments of the Puente de Los Tres Ojos and parallel to the viaduct over the Avenida de la Albufera. The two tunnels run alongside the M-30 at

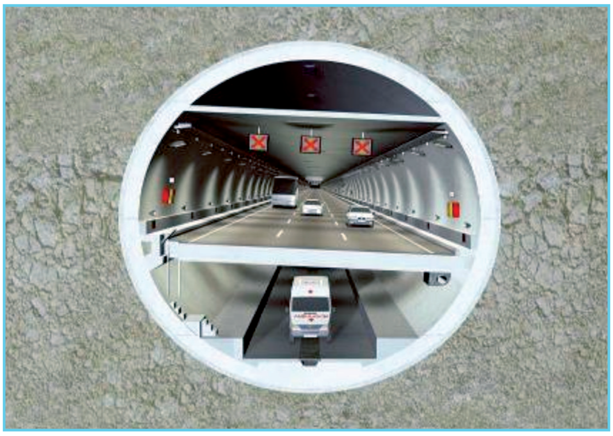

Figure 2. *Cross-section of the tunnel, with ventilation system, roadway and emergency escape.*

a distance of 30 metres and then cross under the Enrique Tierno Galván Park at the deepest section of the tunnels.

The tunnels continue below the Legazpi and Delicias districts, the Paseo de la Chopera and the Matadero de Arganzuela Park, before ending at a shaft set in the La Arganzuela Park close to the Palacio de Cristal conservatory (launch shaft of the TBM for the south tunnel) where they connect up with the following underground section of the M-30 ring road.

2. Cross section

The roadway has three 3.5 m wide lanes, 0.20 m shoulders and 0.90 m walkways, which give a horizontal clearance of 12.70 m (see Figure 2) The internal diameter of the built and lined tunnel is 13.45 m and the clear vertical height is 4.50 m to allow the passage of heavy vehicles.

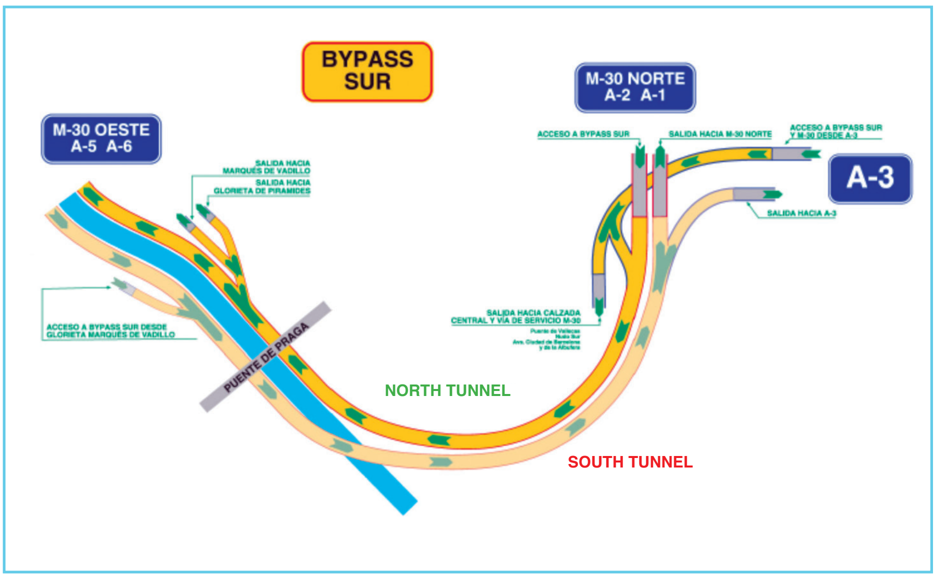

Figure 1. *Plan of the north and south tunnels of the M-30 South By Pass.*

The upper part of the section is allocated to ventilation ducts which extract the polluted air from the tunnel and channel it away through ventilation shafts.

Clean air is drawn in from the exterior by the ventilation shafts and circulates through the lower part of the tunnel, below the roadway itself, before passing through ventilation grilles set in the sides of the tunnel and into the roadway area. This lower section is also employed as an escape route in the case of fire and to allow emergency vehicles to attend any potential incident.

Geology

The tunnel passes through the tertiary soil of the Madrid basin, largely formed by varying layers of clay, peñuelas or sandy clays and hard clay with gypsum, going down to 40 m at the north of the route and 15 m at the south.

The gypsum bearing layers are always interspersed with the peñuelas or sandy clays. These formations are covered by:

- Alluvial quaternary sediments formed by weak sand and soft loams in layers of no more than 6-7 m, and
- Anthropic infill of diverse nature, in variable layers between 5-6 m thick, except in the Enrique Tierno Galván Park where layers reach up to 20 m.

Design of the TBM

1. Development in the diameter of cutting wheels

There has been a constant development in TBM technology over recent years. From the experience gained from earlier tunnel projects, both designers and manufacturers have undertaken to progressively increase the diameter of these machines in order to tackle increasingly ambitious projects that would have been unthinkable not so long ago.

Figure 4. *Development in cutting wheel diameters*

Figure 4 shows this development in Spain, starting from the TBM employed in the 6.52 m diameter single track Valencia Metro, the TBMs used in the 9.40 m diameter double-track Madrid Metro, those used to bore the 12.06 m diameter tunnels for the double-track Barcelona Metro and housing station platforms at two higher levels. The experience gained from all these projects has subsequently made it possible to tackle the design, construction and execution of the By Pass works with a 15.20 m diameter TBM.

2. Technical characteristics

The main characteristics of the TBM employed in the South By Pass tunnel are as indicated in Table 1.

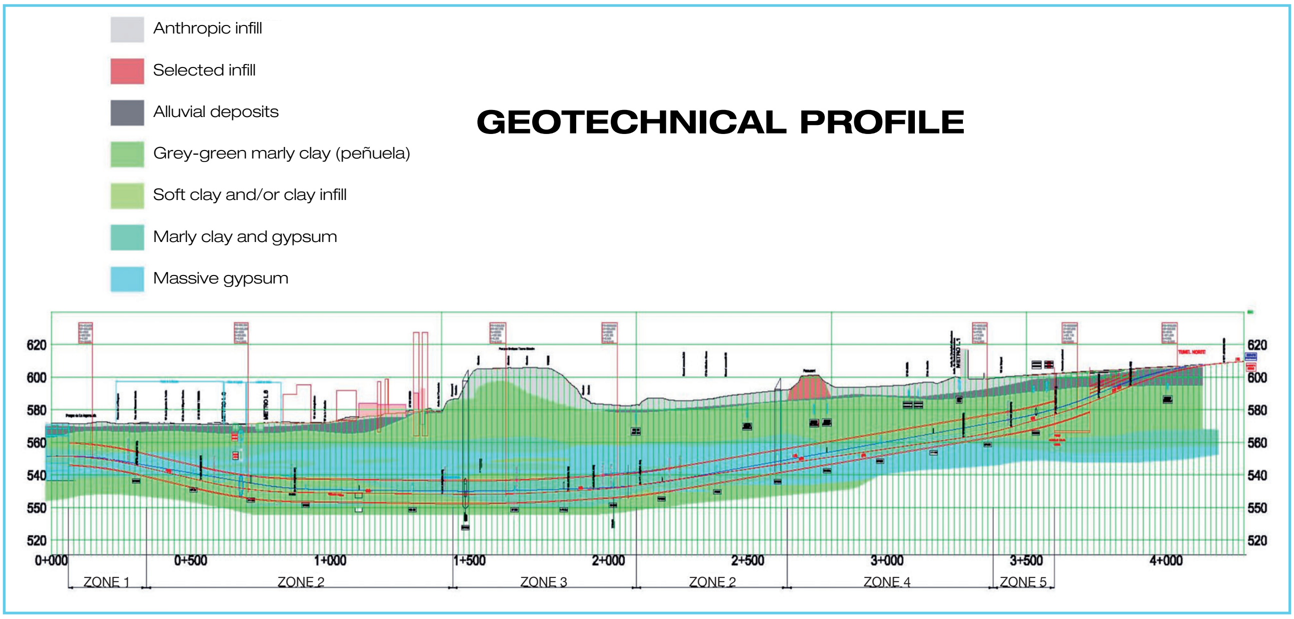

Figure 3. *Geotechnical profile of the tunnel area*

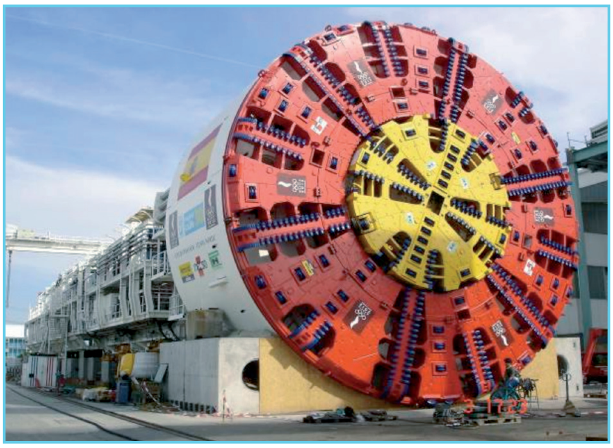

Photo 1. *View of the cutterhead, with double (inner and outer) cutting wheel*

3. Leading technical development

The following sections provide a brief summary of the main technological developments of the TBM employed in the tunnel work.

3.1. Double cutterhead, outer and inner cutting wheels

The double cutterhead is formed by independently rotating outer and inner cutting wheels that may turn in opposing directions or the same direction. Work tends to be conducted with counter rotating movement as this minimises the turning torque of the shield during excavation by partially offsetting the resultant torques of both wheels (see Photo 1).

The nominal torque of the inner cutting wheel is 845 txm and that of the outer wheel 9,600 txm (interrelated by the cube of the diameter). A torque reduction of 17% is provided by the counter-rotation of both cutting wheels.

The outer cutting wheel has an opening ratio of 32% and the inner wheel a ratio of some 30%.

Control of the advance of the inner cutting wheel: it is also possible to set the inner cutting wheel by up to 400 mm in advance of the outer cutting wheel. This then acts as an advance pilot tunnel which aids the excavation of the remaining section, until completing the 15.16 m diameter.

3.2. Advance system of the 1st trailer (segmental lining)

The first trailer (housing silos, grout pumps and transformers) is the heavier of the 510 t back-up system and the first to set against recently positioned lining segments.

Excavation diameter	15.20 m
Shield length	11.50 m
Shield weight	2,565 t
Maximum thrust	315,880 Kw
Maximum penetration speed	65 mm/min
Cutting wheel power	14,000 Kw
Nº of thrust jacks	57 ud
Cutter tools: Knife-edge bits Drag bits Cutters	 372 32 66
Open surface	32%
Total length (shield + trailers)	110 m
Weight of back-up [a]	1,800 t
Maximum torque	125 MN/m
Maximum rotation speed	2 rpm
Nº hydraulic motors	50 on outer wheel 10 on inner wheel
Screw conveyors	2 x 1,250 mm diameter 1 x 600 mm diameter
Screw conveyor capacity	2,050 m^3/h
Conveyor belt capacity	2,884 t/h
Foam injection capacity at face and chamber	417 m^3/h
Grouting of gap [b]	12 apertures (6 pumps)
Passive articulation cylinders between forward shield and tail shield	

(a) Train of trailing units behind the excavator carrying all installations necessary for operation. The 134 m long back-up system to the Tizona TBM was formed by eight 2-3 deck trailers..
(b) Ring-shaped gap between the excavation tunnel and the exterior diameter of the shield allowing the movement of the machine and small pitching movement to form the curves of the layout. This has an influence on the settlement that may be cause by the TBM.

Table 1- *Technical details of the TBM employed in the South By Pass*

In order to guarantee an even distribution of loads on the segment ring, a jacking system was installed, consisting of eight fixed supports and eight mobile supports which were alternated when supporting the trailer. The fixed supports held this in place during the placing of the ring and when the machine was stopped; and the mobile supports were employed during the excavation stage and while the machine was moving.

The mobile jacks had a total longitudinal extension of 2 m for each excavation stage and once the load had been transferred to the fixed supports, they then returned to their original housed position.

3.3. Tool changing systems

One aspect that took on particular importance with regards to the diameter of the tunnel was the increase in the number of cutting tools and their possible repercussions on stopping periods required to change these tools.

Here reference is made to the heavier of the cutting tools and, namely, the disc cutters. These are twin 17" discs similar to those employed by the Madrid Metro TBMs, but with 66 discs (16 on the central wheel and 50 on the outer wheel) instead of the 20 installed on the earlier TBMs. The combined weight of disc and fastening was 160 kg.

As a result, the sequence of operations for changing these tools was examined in the design stage to ensure that this task could be systematically and proficiently performed by the worker within a reasonable space of time.

The system consisted of the following arrangements (see Figure 5):

- 2 hydraulic mountings with articulated arms to allow the handling of tools within the shield.
- 2 man locks (hyperbaric chambers) for access of personnel to the pressurized chamber and 3 material locks
- Sliding work platforms providing access of personnel to the excavation chamber during cutter change and inspections.
- 2 auxiliary pulley arrangements within the excavation chamber to allow ease of handling of tools
- The disc cutters mountings were designed to allow ease of fixing from inside the excavation chamber.

3.4. Double gearing of the outer wheel

One of the essential aspects of the design of the TBM was the installation of drive motors capable of obtaining the torque requested by the client (10,700 t x m maximum service torque). This then required the installation of 60 hydraulic motors: 10 in the central cutting wheel and 50 in the outer wheel (Photo 3).

Twenty-nine of the fifty motors in the outer cutting wheel were set on the outer face of the wheel and 21 on the inside face (Photo 4).

This arrangement provided a 7500/6140 mm diameter mechanized outer wheel with double gearing for pinion movement on both sides. This being the largest machined arrangement of its kind in Europe.

Photo 2. *First trailer, with fixed and mobile supports*

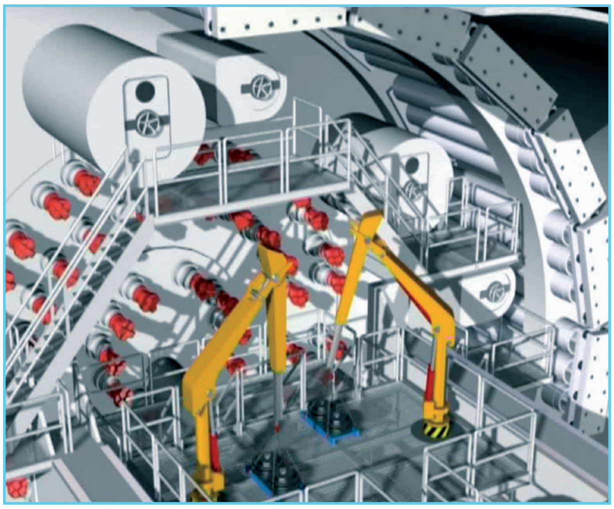

Figure 5. *Design system for the change of disc cutters*

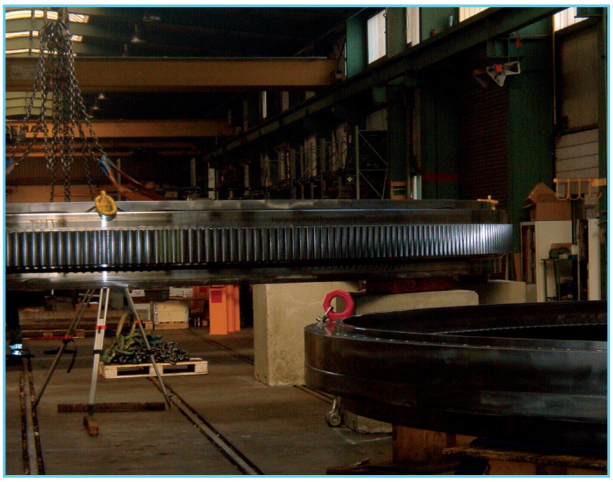

Photo 3. *Positioning of drive motors on the cutting wheel. 60 motors in total*

3.5. Ring bearing

A ring bearing was installed between the shield and the drive. This is a closed ring formed by two components which support the six sections of the shield. This structure distributes the thrust and torque forces between the shield and the drive (see Photo 5).

3.6. Rotary coupling

The rotary coupling is a sealed connection between the cutting wheel (rotating) and the axis of the machine (stationary); which incorporates water, foam or polymer feeds to the cutting wheel (see Photo 6).

Two rotary couplings were fitted on account of the two cutting wheels:

- A conventional 0.44 m diameter coupling was set on the inner wheel to provide the following supplies:
  - Foams, polymers and bentonite suspension: 8 supply lines (8 bar),
  - High pressure water: 2 lines (300 bar),
  - Hydraulic system for over cutters: 5 lines (300 bar), and
  - Electric system: routed on other side
- The coupling on the outer wheel has a 4 m diameter, though with this diameter there is no means of sealing a 300 bar line and this was only fitted with 8 bar lines for foams, polymers and bentonite suspensions (14 lines in total).

Performance

The tunnel had a total excavated length of 3,526 m and it took 230 days from the time of starting up the TBM to the final breakthrough, which then gives an average performance of 15.33 m per day (7.67 rings per day, see Figure 6).

The maximum length of lined tunnel performed in any single day was 36 m (18 ring, achieved during the second half of May).

The average progress achieved over any continuous 30 day period was 25 m per day (12.5 rings per day, see Figure 6), equivalent to 375 rings and 750 m advance a month.

The TBM required three months to assemble and a further 2 months to dismantle.

Photo 4. *The outer wheel has 50 motors, 29 on the outside face and 21 on the inside face*

Photo 5. *Ring bearing, formed by two parts that support the shield sections*

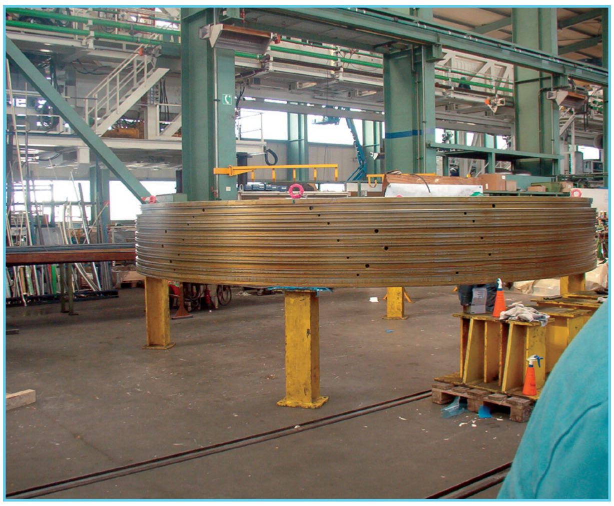

Photo 6. *Rotary coupling, incorporating water, foam or polymer piping*

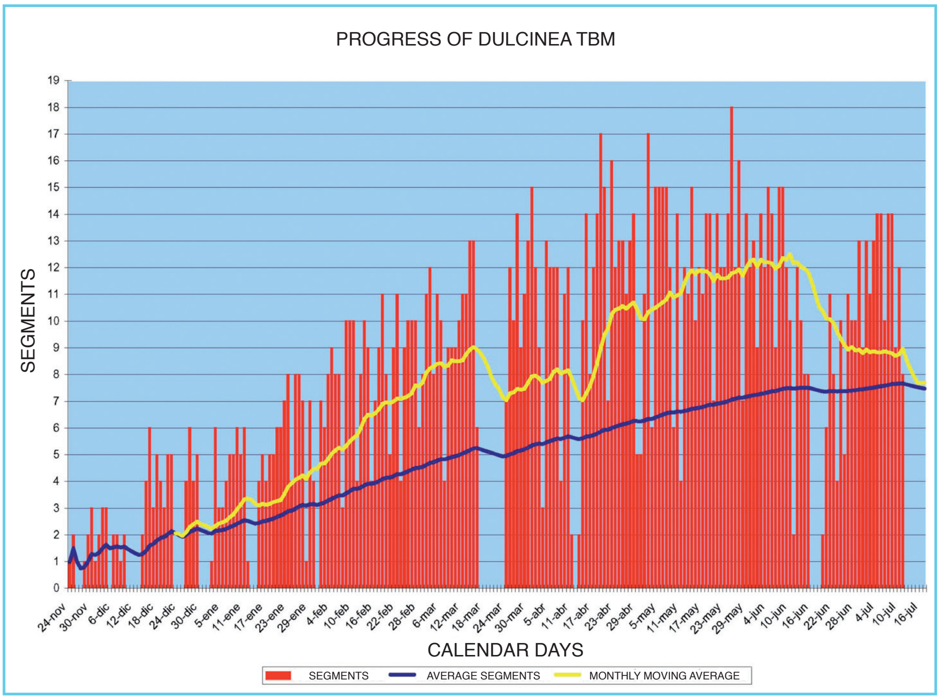

Figure 6. *Daily performance in terms of segment installation*

Installation of launch shaft. Logistics

The basic problem involved in these types of work in the centre of a city is one of logistics. In this case the launch shaft for the TBM was 95 m long, 30 m wide and 35 m deep and was built by pile driving and shoring the different levels with reinforced concrete cross beams.

Within the launch shaft itself (see Photo 7), it is necessary to reserve space for: the assembly of the TBM; the storage of segments; the electricity sub-station; the storage of spare parts for the TBM; storage of beams forming the roadway slab and the prefabricated hollow core slabs for the upper deck; site offices; a provisional deposit for excavated material; storage of refrigerated water fro the TBM; and space for all access routes both for trucks and the special cars supplying prefabricated components (segments, beams, slabs, etc.).

The initial project considered the installation of the two TBMs within the same launch shaft, which would have doubled the problem of space and made the project practically unfeasible. It was subsequently decided to build a new launch shaft on the M-30 near the Puente del Mediterráneo, so that the TBMs would then be advancing in opposite directions.

If we employ the 30-day performance rates of 12.5 rings per day (25 m per day) as a means of dimensioning the installations, this then implies an excavation of 180 m^3 of the face per lineal metre, which when foamed or conditioned would then give 300 m^3 per lineal metre. As such, some 7,000 m^3 of conditioned material were excavated every day (working 24 hours a day), which implied that a truck loaded with excavated material had to leave the site every 2 minutes (and be replaced by an empty truck).

In terms of the tunnel lining, it was necessary to install 125 segments every day, which then implies the entry of approximately 60 special cars as well as those required for the supply of beams, slabs, grout, etc.

As a result, the design of the access routes on site required a detailed study of these internal movements.

Two 60 ton gantries were set over the launch shafts to aid the supply of tunnel materials (segments, mortar, beams, slabs, etc.).

The excavated materials was extracted by conveyor belt from a screw conveyor to the excavation pit in the outside of the launch shaft. The conveyor belt was 1.60 m wide and had a capacity of 2,884 tons per hour.

A rail yard was set at the bottom of the launch shaft for the entry and exit of train cars and for maintenance of the same. Other installations in this area included the thrust wall necessary for the excavation of the initial section of the tunnel, the mortar silos and part of the storage area necessary for the segments.

Conclusions

On the basis of prior experience in the construction of large diameter tunnels with EPBs that had been gained over eight years during the extension of the Madrid Metro, the Madrid Council engineers decided to employ the largest TBMs ever built for the construction of the tunnels to the South By Pass of the M-30 ring road.

Photo 7. *View of launch shaft and surroundings*

The leap into the unknown implied by an increase in diameter from 9 m to 15 m led to considerable uncertainty at the start of the project as the scale effect did not necessarily guarantee the success of the operation.

The detailed plans introduced to overcome logistical problems, the correct decision to change the direction of one of the TBMs by forming a second launch shaft, the design quality, technical assistance offered to site management, the effectiveness of the soil treatment designed with the aid of leading geotechnical advisors, the speed and effectiveness of the decision-making process by site management and the quality, experience and dedication provided by Ferrovial-Agromán and Acciona Infraestructuras to the Joint Venture entrusted with the work, all ensured that the work was completed with performances that were unthinkable at the start of the project.

In view of the excellent results obtained in the construction of this tunnel, the authorities and designers should take this experience on board in order to employ these types of TBM in the design and construction of large three-lane road tunnels.

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