The University of Sheffield, Akdeniz University – Technical University "Gheorghe Asachi" Iasi – European Tyre Recycling Association, Aggregate Industries UK LTD, Antalya Greater Municipality, Compania Nationala di Drumuri Nationale din Romania - prin DRDP Iasi, Adriatica Riciclaggio e Ambiente s.r.l., Public Works Department, Cyprus University of Technology, Scott Wilson Ltd

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EcoLanes

Economical and Sustainable Pavement Infrastructure for Surface Transport

Specific Targeted Research Project

Priority 6.2 Sustainable Surface Transport

Publishable Final Activity Report

Period covered: 1 October 2008 to 30 September 2009 Date of preparation: 15 November 2009

Start date of project: 1 October 2006 Duration: 36 months

Project coordinator: Professor Kypros Pilakoutas

Project coordinator: The University of Sheffield Revision [1]

PROJECT EXECUTION

Executive Summary

EcoLanes demonstrated that recycled steel tyre-cord fibres (RSTCF) can be used to reinforced concrete for pavement applications. Steel, recycled from post-consumer tyres, has been produced following modifications to the manufacturing plant of ADRIA (a tyre recycling company in Italy) and post-processing the steel for cleaning and classification. For quality assurance purposes, Ecolanes developed various classifications of RSTCF. Using RSTCF and industrially-produced steel fibres, EcoLanes developed concrete mixes suitable for wet-consistency concrete and roller-compacted concrete (which has dry-consistency). Those mixes included different proportions of fibres, different types and proportions of cements as well as virgin and recycled aggregates. A selection of concrete mixes has been tested for durability and fatigue resistance. The results showed that RSTCF, at the right proportions, can perform as well as industrially-produced steel fibres, and are particularly good at reinforcing concrete made with recycled aggregates.

Large scale load tests, carried out at the Accelerated Load testing LIRA facility in Iasi Romania using simulated axle load, showed that pavements produced using Ecolanes' concrete could resist 1.5 millions 115kN-load cycles, which is equivalent to 20.5 million single-axis of normal traffic. Following extensive numerical and analytical work, a design framework and software were developed by UTI (Technical University 'Gheorghe Asachi' Iasi) for use by design engineers.

Environmental and cost life-cycle studies showed that the energy consumption of steel fibre reinforced roller compacted concrete pavements can be up to 40% less than of commonly used asphalt pavements and up to 12% cheaper.

Finally, EcoLanes produced the following four demonstration projects.

1) A series of access channels in the United Kingdom, constructed by Aggregate Industries UK.
2) Full rehabilitation of a heavily trafficked national road in Romania, constructed by Compania Nationala de Autostrazi si Drumuri Nationale din Romania, prin DRDP Iasi, Romania.
3) Full rehabilitation of a heavily trafficked urban road in Turkey, constructed by Antalya Municipality.
4) Rehabilitation of a rural road (subjected to ground movements) in Cyprus, constructed by the Public Works Department of the Ministry of Communications and Works.

Project Objectives

EcoLanes' main objectives were to develop, test and validate steel fibre reinforced concrete (SFRC) pavements that will contribute towards the strategic objectives of the thematic priority area of Sustainable Surface Transport. EcoLanes aimed to use roller-compaction techniques (based on existing asphalt laying equipment) as well as recycled materials to reduce construction costs in the range of 10-20%, construction time by 15% and energy consumption by up to 40%.

The project, which started in October 2006, comprised 9 work packages: 4 RTD, 3 demonstration, 1 dissemination and 1 management. The project drew expertise from six European countries and its consortium (shown below) comprises four universities, three industrial partners, a Recycling Association and three end-users.

- The University of Sheffield, UK *(Coordinator: Prof. Kypros Pilakoutas, Department of Civil and Structural Engineering, The University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, United Kingdom. k.pilakoutas@sheffield.ac.uk).*
- Akdeniz University, Turkey.
- Technical University ‘Gheorghe Asachi’ Iasi, Romania.
- European Tyre Recycling Association, France.
- Aggregate Industries UK Ltd, United Kingdom.
- Antalya Municipality, Turkey.
- Compania Nationala de Autostrazi si Drumuri Nationale din Romania, prin DRDP Iasi, Romania.
- Adriatica Riciclaggio e Ambiente s.r.l., Italy.
- Public Works Department, Ministry of Communications and Works, Cyprus.
- Cyprus University of Technology, Cyprus.
- Scott Wilson Ltd, United Kingdom.

In addition to the management and administration of the consortium, the following were the other main objectives of the project.

- Development and optimisation of techniques and equipment for cleaning, sorting and packaging recycled steel tyre-cord fibres, produced from the mechanical treatment of post-consumer tyres.
- Supply of recycled steel tyre-cord fibre reinforcement required for the activities of the other work packages.
- Development of wet and dry SFRC mixes, which have reduced energy requirements and use recycled materials.
- Experimental and theoretical investigation of mechanical behaviour and durability of wet and dry SFRC mixes, which have reduced energy requirements and use recycled materials.
- Development of the concept of the long lasting rigid pavements (LLRP) made with wet and dry SFRC.
- Experimental and theoretical validation of the concept of LLRP made with wet and dry SFRC.
- Development of design guidelines for LLRP made with wet and dry SFRC mixes.
- Review and development of life-cycle methodologies for the assessment of the environmental impact and cost of LLRP and site processes.
- Life cycle assessment of the environmental impact and cost of the four demonstration pavements made with dry SFRC.
- Development of equipment for fibre dispersion and site processes.
- Development of guidelines for producing LLRP made with dry SFRC.
- Problem investigation and design of the four demonstration pavements made with dry SFRC.
- Construction, and monitoring of the four demonstration pavements made with dry SFRC.

Project Management

During the three years of the project, the consortium had seven plenary management meetings as well as several technical meetings and dissemination activities. In addition to maintaining clear communication channels and coordinating the technical work, the project steering and management committee took very robust action (especially during 1st reporting period) to deal with some delays in the work progress of some contractors. In addition, two new partners were acceded to the project (at the beginning of the 2nd reporting period) to contribute to the delayed activities.

On the RTD side, the main strategy throughout the project duration was to tackle very quickly the areas that presented the highest technological risks, i.e. whether the recycled steel tyre-cord fibres could be sorted and classified on the medium scale and whether they could be included in sufficient quantities in wet and dry SFRC. A low level risk also existed in securing the supply of recycled steel tyre-cord fibres to the project specification and, hence, a provision was made to purchase (if necessary) steel fibres from external sources. The results from the SFRC mix development and fibre supply were positive, and that meant that the overall project technological risks were eliminated. The performed work and main outcomes of the 4 main RTD work packages are as follows.

Details of main work packages and results

Work Package 1 – Fibre Sorting

During the 1st reporting period, the steel fibres, recycled from various mechanical treatments of post-consumer tyres, were classified and the fibre balling mechanism was examined. These activities assessed the level of treatment that each type of steel fibres would require to fulfil the project requirements. In addition, various techniques were investigated for cleaning and sorting the steel tyre-cord fibres (Figure 1a). This study led to the development of a hardware prototype (Figure 1b), which was capable of producing sorted steel tyre-cord fibres (kilograms per hour).

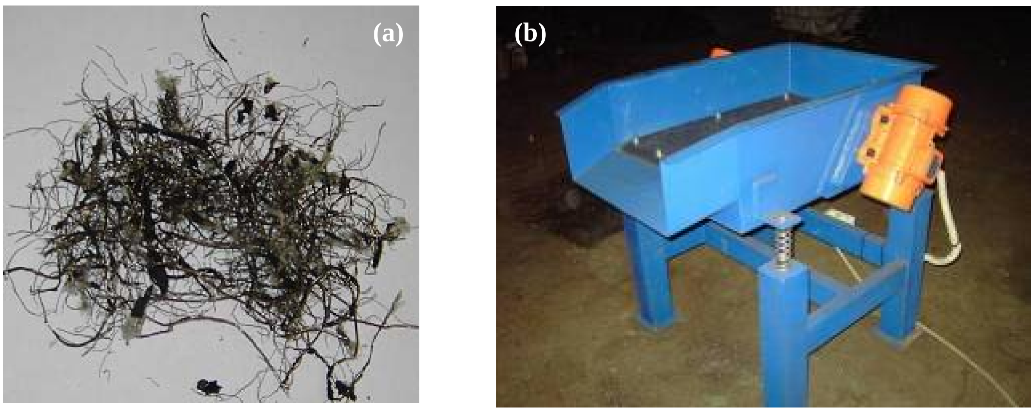

Figure 1 - (a) Unsorted steel tyre-cord fibres recycled from the mechanical treatment of post-consumer tyres, and (b) hardware prototype used for their sorting

The fibre cleaning and sorting processes were improved during the 2nd reporting period to increase the yield of useful steel tyre-cord fibres. This included refinement of the process and hardware used for the mechanical treatment of post-consumer tyres. A procedure was also developed for determining fibre length distributions for Q/A purposes. By the end of the 2nd reporting period, the cleaning and sorting techniques could produce (to the project specification, Figure 2a) tens of kilograms of recycled steel tyre-cord fibres per hour. Around 15 tonnes of recycled steel tyre-cord fibres were supplied for the pre-demonstration trials. During the 3rd reporting period, processes and equipment were also developed for the 25kg packaging of the recycled steel tyre-cord fibres (Figure 2b). In addition, formal specifications were developed (for Q/A purposes) for the production and classification of recycled steel tyre-cord fibres; the latter comprises three classes: “SHEF Class A”, “EcoLanes Class B” and “EcoLanes Class C”. By the end of the project, around 105 tonnes of recycled steel tyre-cord fibres were supplied for the RTD and demonstration activities.

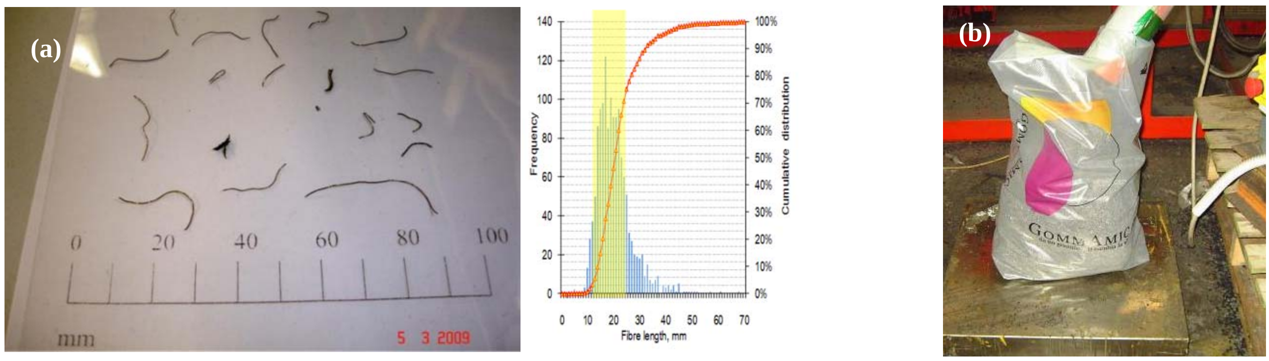

Figure 2 - Steel tyre-cord fibres, recycled from the mechanical treatment of post-consumer tyres: (a) sorted to the project specification, (b) 25kg packaging

Work Package 2 – Fibre Reinforced Concrete

At the beginning of the 1st reporting period, bending tests of SFRC prisms were undertaken (as part of a pilot study) to characterise concrete reinforced with industrially-produced and recycled steel tyre-cord fibres. The results of the study showed that industrially-produced fibres are more efficient in reinforcing concrete than steel tyre-cord fibres (Figure 3). However, it was shown that steel tyre-cord fibres have the potential to offer a viable alternative to the industrial fibres, if used in high amounts or blended with industrial fibres.

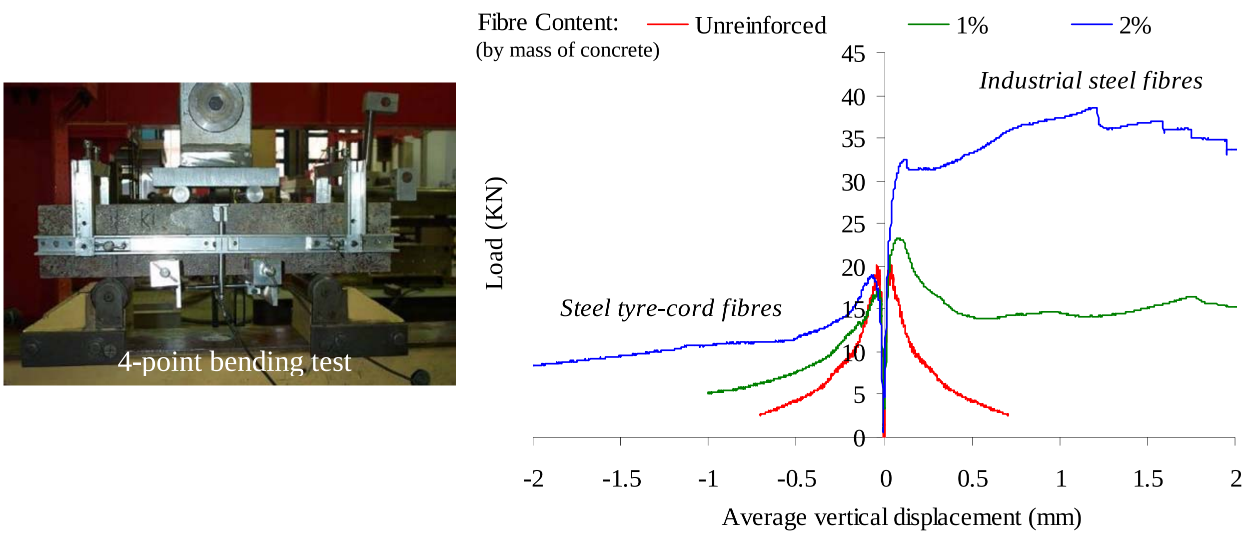

Figure 3 - Bending test results of dry SFRC prisms tested during a pilot study of WP2

The pilot study, which continued during the 2nd reporting period, included the development and optimisation of dry and wet SFRC mixes; different types of cement and steel fibres were examined. The fresh and hardened concrete properties were evaluated by undertaking laboratory tests, such as slump and compaction tests, air content test, as well as compressive and bending tests. The laboratory results indicated that, although the addition of steel fibres in concrete reduces its workability, it enhances the post-cracking behaviour of hardened concrete, (e.g. Figure 3).

A comprehensive experimental program was also initiated, during the 2nd reporting period, to study the durability of selected wet and dry SFRC mixes; this included accelerated corrosion, freeze-thaw and shrinkage tests. Compressive and bending tests were also carried out on specimens (Figure 4), which were initially exposed to accelerated corrosive environments (e.g. freeze-thaw cycles). Work was also carried out on the theoretical evaluation of the properties of the wet and dry SFRC mixes; this included evaluation of the flexural toughness of SFRC mixes as well as derivation of tensile stress-strains models that could be used in the analysis and design of LLRP made with wet and dry SFRC.

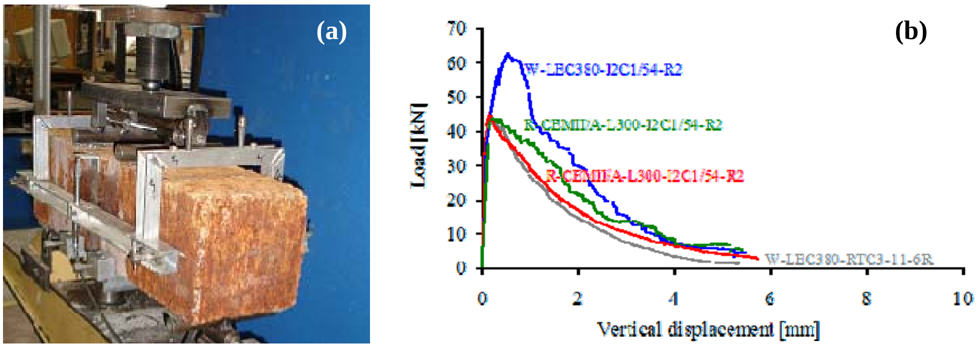

Figure 4 – Bending tests of prisms that initially sustained 5 months of wet-dry corrosion cycles: (a) test setup, (b) experimental results

During the 3rd reporting period, WP2 work comprised parametric studies that were undertaken to assess the effect of key parameters on the fresh and hardened properties of dry SFRC. These included the length, shape and tensile strength of industrially-produced steel fibres, content of recycled steel tyre-cord fibres, as well as content of recycled and natural aggregates. Experimental results indicate that the flexural behaviour of dry SFRC mixes, made with recycled concrete aggregates, is equivalent to the one obtained from SFRC mixes made with natural aggregates (e.g. Figure 5a). EcoLanes also collaborated with the Federal University of Rio Grande do Sul (in Brazil) to investigate the fatigue flexural behaviour (e.g. Figure 5b) of selected dry SFRC mixes; the results showed that dry SFRC containing 2% (by mass) recycled steel tyre-cord fibres has better fatigue performance than plain dry-concrete (at both low and high stress levels). Work was also continued on studying the durability of selected wet and dry SFRC mixes; this work also included chloride ingression, permeability and porosity tests. Experimental results indicated that dry SFRC mixes are more susceptible to corrosion and freeze-thaw (e.g. Figure 5c) than wet SFRC mixes. However, these results may be due to the boundary conditions used in the specific tests.

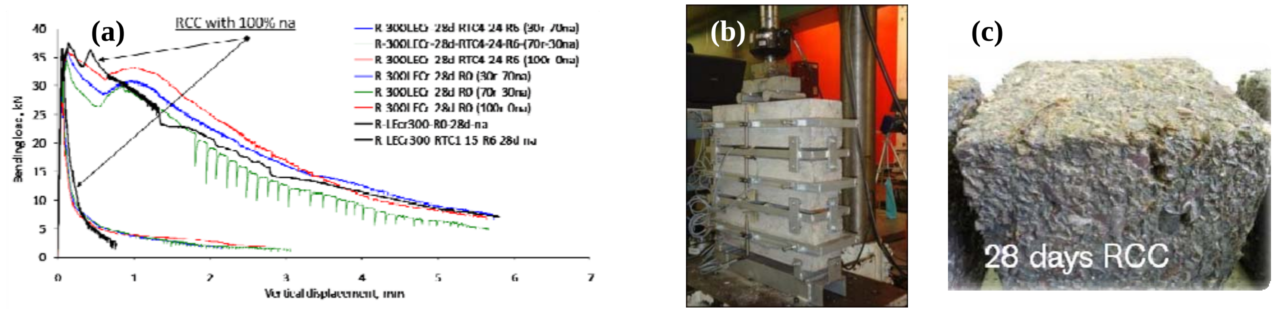

Figure 5 - WP2 experimental work: (a) Flexural behaviour of dry-consistency SFRC mixes made with recycled concrete aggregates, (b) Setup for fatigue bending tests, (c) dry-consistency SFRC samples after 28 days of freeze-thaw testing

Work Package 3 - Pavement testing, analysis and design

The design and construction of existing plain concrete and SFRC pavements were investigated during the 1st reporting period in order to develop the concept of LLRP, for which, a number of options for the construction materials and pavement layers were proposed. During the 2nd reporting period, trial wet and dry SFRC sectors were constructed and instrumented at the ALT LIRA facility in Romania (Figures 6a & 6b), in order to be tested under accelerated cyclic load (Figure 6c) and assess whether SFRC is a suitable construction material for LLRPs. By the end of the project, 1.5 million load cycles were accomplished. Experimental results indicated that there was no failure in any of the sectors, showing that (over a design life of 30 years) the proposed roads would survive at least 20.5 million-single-axis of traffic.

Figure 6 – (a and b) Construction of the trial SFRC sectors, ALT LIRA facility (c)

Extensive analytical and numerical (elastic and inelastic finite element) analyses of plain-concrete and SFRC pavements were also undertaken (during the 2nd and 3rd reporting periods) aiming to develop appropriate design tools and failure criteria for wet and dry SFRC pavements. Existing design methods for concrete pavements were also examined, and a design framework and software (Figure 7) were developed for LLRPs made with wet and dry SFRC.

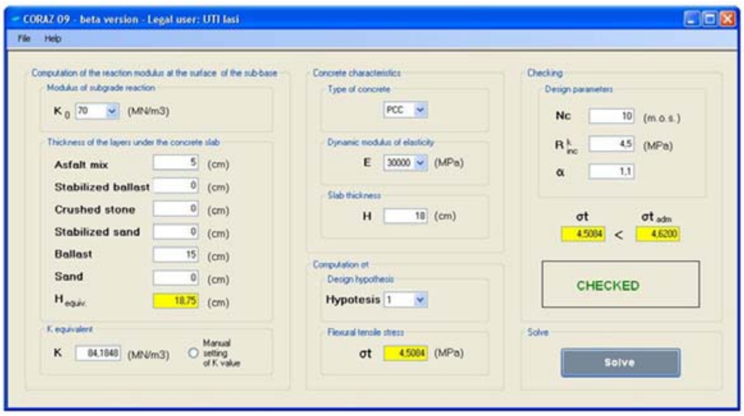

Figure 7 - Design software developed by WP3 for LLRP made with wet and dry SFRC

Work Package 4 - Environmental studies and site processes

The environmental impact and cost of concrete and asphalt pavements was reviewed during the 1st reporting period. In addition, methodologies were developed and continuously refined for the life cycle assessment (LCA) of the environmental impact and cost of LLRPs made with wet and dry SFRC. Comprehensive data was collected for the LCA of the demonstration pavements, constructed with dry SFRC in Cyprus, Romania, Turkey, and the United Kingdom. For comparison purposes, LCA was also undertaken for four alternative pavements (asphalt and three made with wet concrete). In addition, a parametric study was undertaken to examine the effect of key parameters on the LCA of pavements made with wet and dry SFRC. LCA results indicated that the energy consumption of SFR-RCC pavements can be up to 40% less than that of the commonly constructed asphalt pavements. The environmental impact of SFRC pavements improves by using local as well as recycled material (such as recycled concrete aggregates). It was also evaluated that the life cycle cost of dry SFRC pavements can be lower (up to 12%) than that of wet SFRC and asphalt pavements. It was also evaluated that the environmental and cost impact of dry SFRC pavements improves as the fibre content increases (due to the reduction in the pavement depth required to support the traffic loading).

The industrial dispersion of fibres in concrete was also examined as well as the processes and equipment currently used for roller-compacted concrete (Figure 8). During the 2nd and 3rd reporting periods, trials of dry SFRC pavement construction were carried out in the United Kingdom, Romania, Turkey, and Cyprus in order to assess these equipment and processes (e.g. Figure 9). The results of the trials showed that existing equipment, such as those used in ready mix concrete plants as well as asphalt pavers and rollers, can be used successfully for the construction of dry SFRC pavements. Based on the findings of these trials, guidelines were prepared for the production of pavements made with dry SFRC.

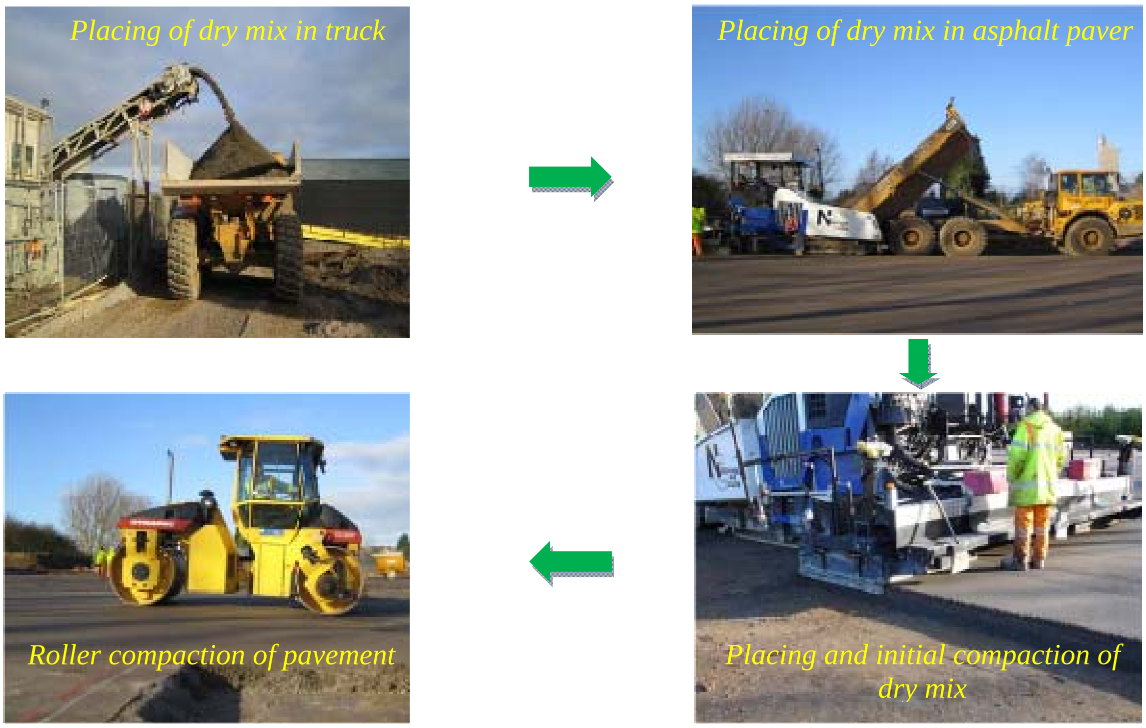

Figure 8 - Construction of roller-compacted plain-concrete pavements

(a) Pre-demonstration trial held in London (UK), June 2008.

(b) Pre-demonstration trial held in Gura Humorului (Romania), September 2008.

Figure 9 - WP4 trials of site processes: (a) at the United Kingdom, (b) in Romania

Work Package 5 to 7 - Demonstration Pavements

On the demonstration side, activities included design, construction, and monitoring of the four demonstration pavements. The pavements were designed utilising data from WP2 and 3, while roller-compaction techniques were adopted for the construction of the pavements. The monitoring of the pavements comprised testing of insitu samples as well as visual observations. “EcoLanes Class B” recycled steel tyre-cord fibres were used for the construction of the demonstration pavements.

The WP5 demonstration pavement (Figure 10) was constructed in London (UK) and comprised a series of access channels (surface area 300 m^2), subjected to controlled heavy goods traffic. The pavement was constructed in April 2009 and comprised three layers: foundation (150 mm deep of cement bound granular material), dry SFRC base (170 mm deep) containing 5% (by mass) recycled steel tyre-cord fibres, and asphalt overlay (70 mm deep).

Figure 10 - Demonstration pavement constructed in the United Kingdom

The WP6 demonstration pavement (Figure 11) was constructed between Campulung Moldovenesc and Gura Humorului (Romania) and comprised full rehabilitation of an existing heavily-trafficked national road (DN17). The pavement was constructed in May 2009 and comprised three layers: foundation, concrete base, and asphalt overlay. The foundation was made with ballast material (300 mm deep), whilst the concrete base comprised three sectors (180, 230 and 280 mm deep); the depth of the asphalt overlay was 100 mm. The demonstration pavement (150 m long and 9.5 m wide) comprised two lanes: one made with plain RCC and one made with dry SFRC, which contained 3% (by mass) recycled steel tyre-cord fibres. The concrete bases were jointed in both lanes (variable joint spacing was trialled: 4, 6, and 8 metres).

Figure 11 - Demonstration pavement constructed in Romania

Two demonstration pavements were constructed by WP7 in April 2009. The first WP7 demonstration pavement (150 m long and 8.6 m wide) was constructed in Antalya (Turkey) and comprised full rehabilitation of an existing urban road (Necip Fazıl Kısakürek Street). This required removal of the existing asphalt road and foundation. The demonstration pavement (Figure 12) comprised four layers: foundation (ballast, 200 mm deep), base course (broken stone, 100 mm), concrete base (190 mm deep), and asphalt overlay (40 mm deep). The concrete base was constructed in four joint-less sectors: sector A (70 m long, 5.1 m wide) was made with dry SFRC containing 3% (by mass) recycled steel tyre-cord fibres, sector B (40 m long, 5.1 m wide) was made with dry SFRC containing 2% (by mass) industrially-produced steel fibres, sector C (40 m long, 5.1 m wide) was made with plain dry-concrete, and sector D (150 m long, 3.5 m wide) was made with dry SFRC containing 3% (by mass) recycled steel tyre-cord fibres.

Figure 12 - Demonstration pavement constructed in Turkey

The second WP7 pavement (40 m long, 6 m wide) was constructed at a rural environment (old road leading to Galataria village in Pafos district at Troodos mountain) and comprised rehabilitation of the existing road, subjected to ground movements. The demonstration pavement (Figure 13) was placed over the existing asphalt pavement (to maintain the geotechnical equilibrium); however the asphalt pavement was slightly milled to provide better bond. The demonstration pavement comprised two layers: a dry SFRC base containing 2% (by mass) recycled steel tyre-cord fibres and asphalt overlay (100 mm deep).


Figure 13 - Demonstration pavement constructed in Cyprus

The consortium also undertook dissemination activities, such as publication of 46 press releases and 36 technical papers. Three industrial seminars were also held (May 2007 in Rome, Italy; October 2008 in Iasi, Romania; and April 2009 in Pafos, Cyprus).

Outcome

A number of results were produced from the work of the EcoLanes project.

- The project has developed small to medium scale industrial processes and machinery for sorting the steel tyre-cord fibres.
- The project developed SFRC mixtures, which use materials with low energy requirements.
- Analysis and design tools were also developed for the concept of LLRP made with wet/ dry SFRC.
- Methodologies were also developed for the LCA of LLRPs made with wet and dry SFRC.
- The construction of the demonstration pavements indicated that the developed technology can be practically applied in practice.

These results should provide: a) a sustainable market for the steel fibres recycled from post consumer tyres and, thus, encourage the material recovery of large amounts of tyres, b) open the way for the construction of LLRP, which are more economic and environmentally friendly.

The EcoLanes consortium has also developed an exploitation strategy of the project. Further information on the EcoLanes' activities and dissemination material may be obtained from http://ecolanes.shef.ac.uk.

Publishable Results

During the 3rd reporting period of the project, the EcoLanes consortium reviewed the knowledge, generated per work package, and concluded that most knowledge represents know-how and has good dissemination value. The potentially exploitable knowledge is presented below per work package.

WP1 - Fibre Sorting

Equipment for sorting recycled steel tyre-cord fibres:

- *Result description*: Hardware and processes for post-processing recycled steel tyre-cord fibres to the project specification ("SHEF Class A", "EcoLanes Class B", "EcoLanes Class C"). This result can convert a waste to a construction material for reinforced concrete applications (i.e. a product).
- *Possible market applications*: Tyre recycling, wire manufacturing, and construction.
- *Stage of development*: Laboratory prototype.
- *Collaboration sought or offered*: Manufacturing agreement, financial support or investment, information exchange, training, and consultancy.
- *Collaborator details*: Equipment manufacturer to produce the hardware.
- *Intellectual property rights:* Confidential know-how, but owner is currently seeking IPR protection.
- *Contact Details*: Dr Ettore Musacchi (ettore_musacchi@yahoo.it, Adriatica Riciclaggio e Ambiente s.r.l., Italy).

Work Package 2 - Fibre Reinforced Concrete

Recycled steel tyre-cord fibres:

- *Result description*: Recycled steel tyre-cord fibres for use in reinforced concrete applications. This result can lead to fibre reinforcement that costs less than industrially-produced steel fibres as well as to concrete with better performance.
- *Possible market applications:* Tyre recycling, wire manufacturing, and construction.
- *Stage of development*: Demonstrator.
- *Collaboration sought or offered*: Manufacturing agreement, IP licensing, consultancy, financial support and/ or investment.
- *Collaborator details*: Industry for post-processing/ selling / using the recycled steel tyre-cord fibres.
- *Intellectual property rights:* IPR[1] granted/ pending.
- *Contact Details*: Prof. Kypros Pilakoutas (k.pilakoutas@sheffield.ac.uk, The University of Sheffield, United Kingdom).

Work Package 3 - Pavement testing, analysis and design

- *Result description*: Algorithms and software for the design of long-lasting rigid pavements. This result can be used for the design of steel fibre-reinforced concrete pavements, which (over their life cycle) consume less energy, are cheaper, and perform better than asphalt or plain concrete pavements.
- *Possible market applications:* Construction and transportation engineering.
- *Stage of development*: Demonstrator.
- *Collaboration sought or offered*: IP licensing, consultancy, financial support and/ or investment.
- *Collaborator details:* Industry for selling / using the developed software.
- *Intellectual property rights:* Confidential know-how, but owner is currently seeking IPR protection.
- *Contact Details*: Prof. Radu Andrei (radu.andrei.d@gmail.com, Technical University "Gh. Asachi" Iasi, Romania).

[1] http://www.shef.ac.uk/tyre-recycling/com/exploitation.html