SUSTAINABLE ASPHALT PAVEMENTS – PAS

Christian cortés[1], Carolina rios[1], Juan Manuel Cadenas[1], Carlos García[2], Pablo Pascual[3], Daniel Castro[3], Amaya Vega[3], Juan José Potti[4]
1 SERVIÀ CANTÓ SA, ccortesfu@fcc.es
2 COLLOSA
3 GITECO DEPARTMENT, UNIVERSIDAD DE CANTABRIA
4 FENIX AIE

ABSTRACT

The Spanish road network is made up of 163,577 kilometres of motorways, dual carriageways and conventional roads that are only used for the transporting of merchandise and people. There are studies which show that the surface areas of Spanish roads receive solar radiation equivalent to 7,000 Gwh every day of the summer. However, there is no procedure for making use of the energy received on the surface of the roads.

The Sustainable Asphalt Pavements (SAP) that are described in this document, is a system designed to capture and store the solar energy radiated on road surfaces in the form of heat so it can be used later on. The PAS system comprises three main parts: solar capture, heat storage and energy efficiency.

The experimental work done below was focused on studying energy capture performance levels on the basis of the different variables studied (fluid flows, characteristics of the bituminous mixes, etc.). In a parallel way, a study was done about how to store the heat-carrying fluid, minimising energy losses and studying the evolution and particular characteristics of the fluid over time. In the same way, an actual-scale test stretch has been carried out in order to check the results of the research.

The main conclusion of the work carried out is that it is feasible to extract part of the energy irradiated by the sun on a surface area of asphalt blacktop and moreover to store and use this energy for different applications.

Keywords: Sustainable, Asphalt, Pavements, Heat,

1. INTRODUCTION

There are studies that indicate that the surfaces of Spanish roads receive solar radiation equivalent to 7,000 Gwh every day of the summer. This quantity is 200 times greater than the daily energy generated by the Santa María de Garoña, Burgos (Spain) nuclear plant. However, there is no procedure that makes it possible to make use of this energy.

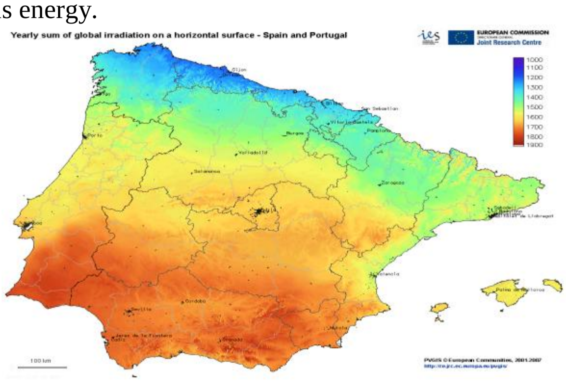

Figure 1: Image with the irradiance received on the surface of the Iberian Peninsula.

Different types of energy come together/ participate on the roads during their useful life that could be the subject of re-utilisation or of usage. These different types of energy can be classified into the solar energy that the surface of the asphalt blacktop receives. Thermal energy also comes from the sun and this produces a temperature gradient on the thick part of the road. We can lastly consider the mechanical energy from the loads and vibrations of the vehicles that travel along the road surfaces. The concept of Energy Harvesting consists of the possible usage of these types of energy for other purposes, in this way providing added value to the roads.

In this case, and considering the fact that the temperature of the surface of the pavement is generally between 20 and 30ºC higher than the air due to the absorption of solar energy, especially in summer [2]. Hence it is possible to propose the possibility of making use of this type of energy. In this work context the idea of capturing sun energy in order to store it and use it some time after is applied, as well as that of making hot water circulate under the surface of the pavement so as to make use of its thermal energy.

Although rare, there are diverse backgrounds to benefit from solar energy received by the pavements.

Sokolov and Reshef [3] by placing concrete pipes embedded enbloques proposed the use of these assets as solar collectors, energy suppliers, for example, heat water or heat a low uncoste housing . Bilgen and Richard [4], however, experimental and theoretical studies of solar radiation laacción on a concrete slab (functioning as passive solar collector), establishing the relative influence of some parameters on its thermal behavior.

The first reference to practical application of these techniques found among the literature comes from the late seventies in the United States where a patent titled "Paving and solar energy system" (Wendel, 1979) shows a method for heating water this pool circulating through tubes that pass beneath a pavement in the sun.

Since 1994, SERS pilot plant, located in Switzerland, prevents the formation of ice on a motorway bridge. This system captures the heat absorbed by the pavement in summer by a metal pipe embedded in it and stores it in pipes drilled into the mountain at a certain depth. During the winter, the heat keeps the temperature of the bridge above the freezing point.

In Japan, the system called GAIA operating successfully in Ninohe City since 1995. This installation consists of a pipe embedded in the pavement that capture of solar energy absorbed by it, transporting it to a coaxial heat exchanger buried in the surroundings where it is stored. In winter, this heat energy passes through a heat pump and is circulated through pipes located under the floor to avoid freezing.

But the main advances made in this field since to date has come from the hand of using this energy for air conditioning of buildings. Netherlands and the UK have been the spearheads of this technology in Europe.

In the Netherlands, the research carried out by companies and universities has been extensive. It should be noted first study conducted by Van Bijsterveld et al. [6], which analyzes the behavior of an asphalt collector tubes made of polymeric material on the inside and the influence on the temperature distribution through the asphalt of parameters such as depth of the tube, the distance between them or fluid flow through them. From this work, asphalt born collectors called "Road Energy System (RES)." This system, developed between 1997 and 2001, consists of a bituminous layer reinforced by a grid (grid) and crossed by pipes for water conveyance. Furthermore, the development of RES brings a deeper structural analysis that previously performed (Van Bijsterveld and De Bondt, [7]).

In the UK, the evolution of these systems has been very even in the Netherlands and the technology called "Interseasonal Heat Transfer" is the biggest advancement in this field. This system uses an asphalt pavement to capture energy from the sun and stores it in the ground so it can be used to condition buildings in winter. The system also works in reverse, cooling buildings in summer. One such project, implemented in the Howe Dell Primary School (ICAX, 2007), provides heating and cooling the building during the year.

Besides the use of stored energy for subsequent conditioning of buildings, another advantage of this type of collector is the maintenance of the road (eg prevention of cracks), not forgetting, of course, reducing CO_2 emissions by the reduced use of fossil fuels.

All references cited above are based on the use of some type of pipe embedded in the matrix of the pavement. Some authors (Van Bijsterveld et al.[6]) have focused on investigating the effect that the presence of polyethylene pipe causes the pavement structure. The analysis by Van Bijsterveld and De Bondt coincides with the previous article to determine the presence of pipes in the asphalt has a negative effect on the durability of the pavement structure.

Furthermore, these systems have significant technological and functional problems to solve. The first is the low efficiency offered by these systems capture, which is around 25%. This is mainly due to poor performance of heat transfer caused by the reduced contact area between the tubes through which circulates the heat transfer fluid and the material that forms the pavement. That is, it misses much of the potential area of irradiation.

The second problem is the difficulty resulting from constructively having to embed the piping below the pavement surface. The current technique requires placing the tubes in a folded to maximize surface contact and use a mesh support is poured until the paving material (bituminous or concrete) which is the main base of the pavement. Also, the tubes can not be placed very near the surface because the weight of vehicles could cause damage, so it must be placed at a certain depth, which negatively impacts system performance.

The third problem are the difficulties of maintenance and low operational reliability. Any fault in the pipe network, however small, involves having to lift the pavement, replace or repair the damaged pipeline and to pave the affected area again. In turn, the breaking of a single tube cut all the circulation of heat transfer fluid, causing a general breakdown means the interruption of the whole system. To these difficulties must be added the difficulties to recycle any materials from the pipe network, since its separation from the pavement is complicated, and often destructive.

Given this background, the development of work covered by this publication is structured according to the following sequence:

- Experimental verification of the models capture and transfer of heat.
- Development and evaluation of systems for thermal solar energy capture and subsequent storage.
- Design and construction of a prototype floor sensor equipped with energy monitoring and control systems.

2. DEVELOPMENT OF NEW SYSTEMS OF COLLECTION AND STORAGE

2.1. Collection system

A form of technology has been developed in recent years that is able to capture thermal energy from the sun in summer by means of the use of a suitable surface to do this, such as asphalt, and store it on the land so as to heat buildings in winter. Thus, solar energy is converted into energy that can be used over time. In this case a system of capture is used that is composed of a network of pipes under the asphalt which water travels through and a storage system comprising another network of pipes (see figure 2).

Figure 2 – Asphalt collector in Rotterdam [3].

A thermal and structural study has been done in order to specify the necessary variables and parameters in a pavement in order to achieve the goal set. The thermal study mostly determines the thermal properties of the materials and the ambient circumstances. As regards the structural study, this analyses the mechanical response of the heat capture systems to the loads applied by the vehicles that travel on the pavement and the distribution of the temperatures that are present. The conclusions to this analysis are based on the results obtained from the computer simulation with programmes of finite elements and the carrying out of different laboratory tests.

As regards the system of pipes used in the experiments described in the bibliography, in addition to achieving energy saving, the implementation of this technology would make it possible to increase the life of the pavement. However, it is necessary to take account of the fact that in turn elements that weaken it are being introduced. Van Bijsterveld et al. [4] focus themselves on investigating the effect that the presence of polyethylene pipes causes on the structure of the pavement. The analysis done by Van Bijsterveld and De Bondt [5] coincides with the previous article in determining that the presence of pipes in the asphalt has a negative influence on the durability of the structure of the pavement.

The first phase of research focused on studying the thermal behavior of bituminous mixtures under different solar radiation conditions similar to those we can find in Spain. These studies of Pascual et al. [7,8,9] were intended to model the thermal behavior of a pavement when subjected to solar radiation and when it ceases. Among the variables studied include studying the influence of the type of asphalt, the temperature distribution in function of depth or intensity of black color on the surface.

Next to thermal analysis of the selected designs are also carried out a structural analysis to verify the mechanical response of the feedback systems of heat to the loads applied by vehicles driving on the pavement. The findings of this analysis are based on the results of computer simulation with finite element software and conducting various laboratory tests.

The conclusion reached was that the development of solar thermal tube based embedded within the pavement had severe contraindications and that even improving existing designs, there loomed a remarkable capacity for improvement. The main limitation of pipes based systems is the lack of surface contact between the heat transfer fluid and the pavement in addition to the additional drawback is the placement of the tubes at a relatively large depth further reduces heat collection performance.

Given these considerations the idea of combining the hydraulic carrying capacity of the porous mixtures with other types of asphalt mixtures. The possibility arises of combining the know-how of the companies taking part in the research with the capacity for innovation of the university. In the context of the project, the idea arises of combining the drainage capacity of certain types of asphalt blacktop designed for the fast release of rainwater from the road surface with the capturing of heat from black surfaces. This combination of properties led to the emergence of the concept of pavement "sandwich" consisting of:

- an upper layer configured so as to absorb the solar energy irradiated on the capture surface area;
- an intermediate layer of a porous nature arranged under the upper layer, configured to allow for the free flow of a heat-carrying flow through it that receives the solar energy absorbed by the upper layer and which transports this to a storage module or directly to an energy usage module;
- a lower impermeable base with carrying capacity set under the intermediate layer, configured so as to stop the leaking of the heat-carrying fluid that flows onto that lower base and in order to support the weight of all of the layers that are above it, as well as all of the loads envisaged to be used.

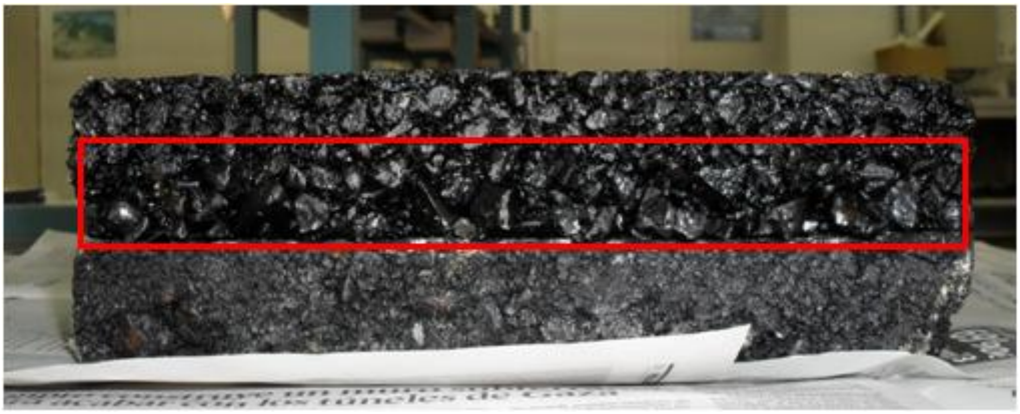

Figure 3 – Sandwich pavement test mould

The essential characteristic is that the heat-carrying fluid travels freely through the intermediate layer, flowing over the lower base to the storage or energy usage module, with no need to use a network of pipes to do this. In this way the heat-carrying fluid makes use of the whole of the capture surface area, receiving the solar energy absorbed by the upper layer.

The next phase of experimentation involved the construction of specimens under the concept of pavement sandwich. With these specimens are looking for study, laboratory scale, the ability to capture thermal fluid flowing through the drainage layer. The trial mould used is a sandwich test mould such as the one described above of 30x40 cm and which contains gaps of between 23% and 27%. The duration of each lab test was 6 hours. Data about the surface temperature of the test mould, the temperature of the water at the entrance and the exit points, the ambient humidity and temperature and the flow of the water to the exit point of the test mould were continuously recorded during the trials. The energy irradiated by the lamp onto the test mould depends on each trial: for the sort test mould with 23% of gaps 300,380 and 450 W/sq.m. was used; while for the short and long test moulds with 27%, 380 W/sq.m. was used, because the goal was to achieve a flow increase as compared to the previous trials.

Figure 4 – thermal-hydraulic trial.

The results, obtained for the test moulds with 23% and 27% of gaps can be observed in the figure below.

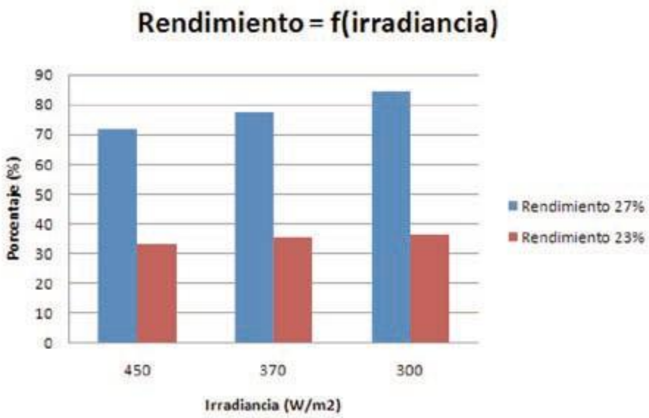

Figure 5 – Comparison of the performance levelsof the two types of test moulds

From the data shown in Figure 5, highlights the percentage of yield obtained, reaching 80% get radiated energy. It is also noted that increasing the flow rate (increasing the percentage of voids in the porous mixture) significantly enhances the thermal efficiency of uptake.

During the development of this test series was a need to examine other variables that could be critical in the scaling process. The first was the possibility of increasing the flow of water through a slight pressurization (0.06 bar). The second was to check the linearity of the flow depending on the path.

To address these issues new probes were constructed in which, keeping the percentage of voids in the porous mix, doubled the length (30x80cm) and waterproofed with asphalt to prevent leakage of fluid to pressurize the water circulation. This last experiment was not successful and appeared numerous water leaks. The results of flow variation with time are shown in Figure 6 (unpressurized specimens)

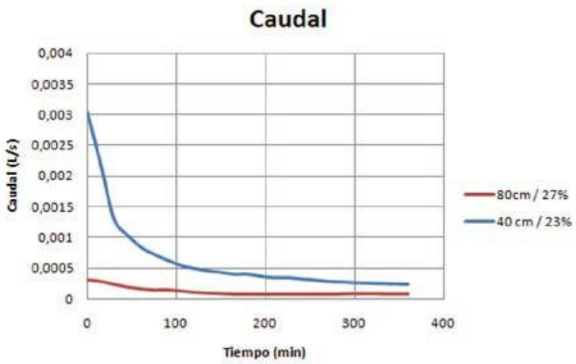

Figure 6 – Representation of the flow in the test moulds of 40 cm and 23% Gaps and 80 cm and 27% Gaps.

The results obtained make it possible to conclude that after 2 hours of the trial, the values of the flow, of the temperature gradient and output power obtained for the long test mould with 27% gaps, these come close to those obtained in the trials obtained for the short test mould with 23% of gaps.

2.2. Storage system

Energy from the sun is intermittent (meteorology, night and day cycles, land transfer movements, etc.) and so most of the solar energy capture systems are connected to a storage system so as to meet the energy demands at the time at which these are required. In this way fluctuations from this source are stopped, making it possible to use the energy after it has been captured. It also provides greater effectiveness to the thermal systems, reducing the losses of residual heat as there is a means of storage.

The heat storage systems are varied and they relate to different technologies developed in the solar energy and geo-thermal energy. Storage of the solar energy can be done [6]:

- In the form of sensitive heat, in which the heat stored increases the temperature of a liquid, solid or gaseous medium.
- In the form of latent heat, such as the energy stored until the temperature at which the change in state of a substance takes place.
- In the form of sensitive and latent heat, in which the stored heat undergoes a variation in temperature and a change of state of the receptor system (solid or liquid); the restoration of the heat corresponds to the inverse change of state.
- In the form of chemical energy originating in some chemical reactions.
- In the form of mechanical energy that can be transformed into potential energy by means of the storage of fluids at certain heights.
- In the form of substances obtained in non-energy solar processes, such as distilled water in a solar distiller that can be stored in tanks to be used later on.

The possibility of storing sensitive heat in the sub-base of a permeable foundation, composed of gravel and water, is studied. A mould is constructed at the trial stage of dimensions 0.5 m x 0.5 m x 0.68 m of rigid and impermeable material covered by insulating materials (rigid panels, compact or projected covers) on all of its sides except for the surface. The mould will be filled with layers corresponding to that which is found in the permeable layers, with identical thicknesses and materials to those used for the actual-scale construction of the same.

Figure 7 –Laboratory thermal energy storage tank.

The first layer on the surface concerns the permeable pavement used in the study: porous asphalt. The successive layers are made up of road metal, separation geo-textiles and drainage aggregate.

A source of heat is applied from the inside of the sub-base by means of electrical resistance that simulates the introduction of a heat exchanger, through which the hot water that comes from the solar collector travels. Temperature measurements will be continuously compiled at different distances from the surface throughout the permeable foundation.

Temperature measurements are also done at different points depending on the heat flows applied. Water level measurements will also be complied at the sub-base of the permeable foundation so as to obtain data about the loss of heat due to water evaporation, as well as data about the air temperature and humidity.

The temperatures programmed for the trials are: 30ºC and 50ºC; and heating takes place until the temperature programmed in the four probes is approximately reached. The cooling curves are compiled from the moment at which the three upper temperature probes reach the temperature established for each trial during the heating, assuming that the tank is in a stationary state in relation to the corresponding equilibrium temperature. The representation of the temperature reached at the level of the four probes during the periods of the heating and cooling of the tank reflect the low degree of stratification taking place, that is to say, fluids with slow convective flows where it can be assumed that the prevailing phenomenon of heat transfer is due to conduction, and the mixed model of the laws of mix in the appropriate heat transfer. The results of the calculation of the performance of the system during the heating for each trial carried out are shown in figure 8.

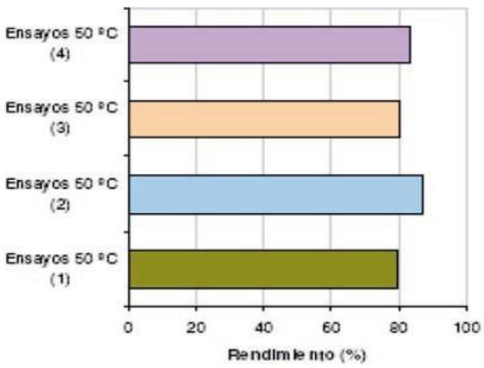

Figure 8 - Performance of heat stored during the heating.

2.3. Heat usage

After analyzing the data collected in laboratory studies, they concluded that it was possible to scale the process. The completion of the test section was based on a design that integrates the collection and storage. The circuit design consists of a primary circuit in which the energy captured by the capture module is sent to a storage module capable of yielding power to the domestic water system of a building (Figure 9). The circuit designed is a primary circuit in which the energy captured by the capture module is going to be sent to a storage module in such a way that the energy is transferred to the sanitary water of a changing room.

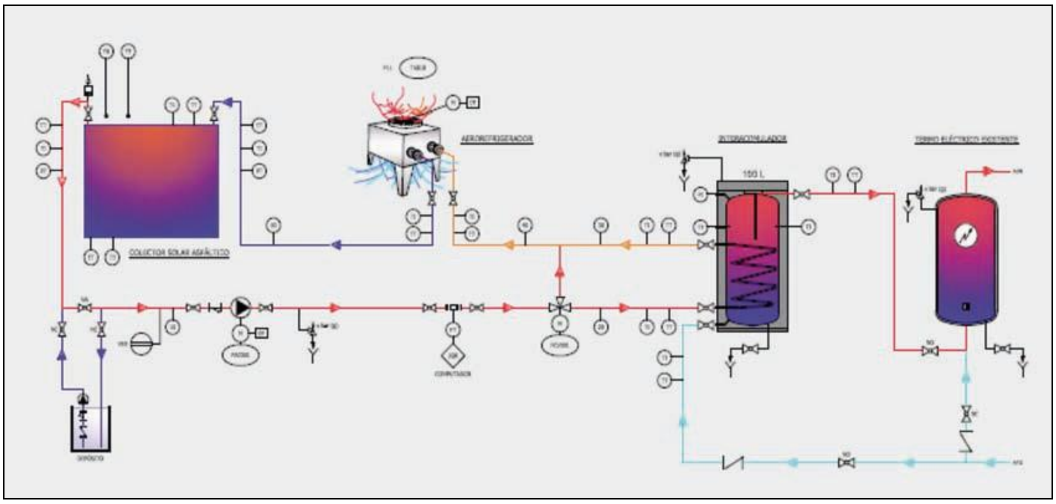

Figure 9: Diagram of the system

The capture module consists of a 6x8 m plate that holds the solar irradiation and transfers the energy to the heat-carrying flow. This fluid exchange the energy received with the ACS in the storage module. In addition, an aerogenerator has been including in the system that enables us to modify the final energy demand that the system requires of it. In this way and using the control probes installed, we can study the energy performance of the whole system. This module is sub-divided into 4 sections in order to study different actual-scale energy capture scenarios. The drainage layer of the first section has 35% gaps content. This section works with a pressure rate of 0.7 bars. The next sections work with no pressure and the second and the third ones comprise a drainage lawyer with 35% and 30% of gaps respectively. The last section corresponds to a later of gravel with 45% gaps.

Figure 10: Details of the four sections of the stretch.

The control of the system is based on a SIEMENS PLC S7-200 and the interface PC-based user through the program of Siemens WinCC which ahve de following functions:

- Execute control loops and control
- Governing plant automatically and securely
- Serve as interface between system operators and

- Show help resolve anomalies and failures
- Helping plant maintenance
- Collect data that can be further processed
- Generate reports operating

The monitoring system or HMI consists of a series of images represent the process of friendly and intuitive way described below.

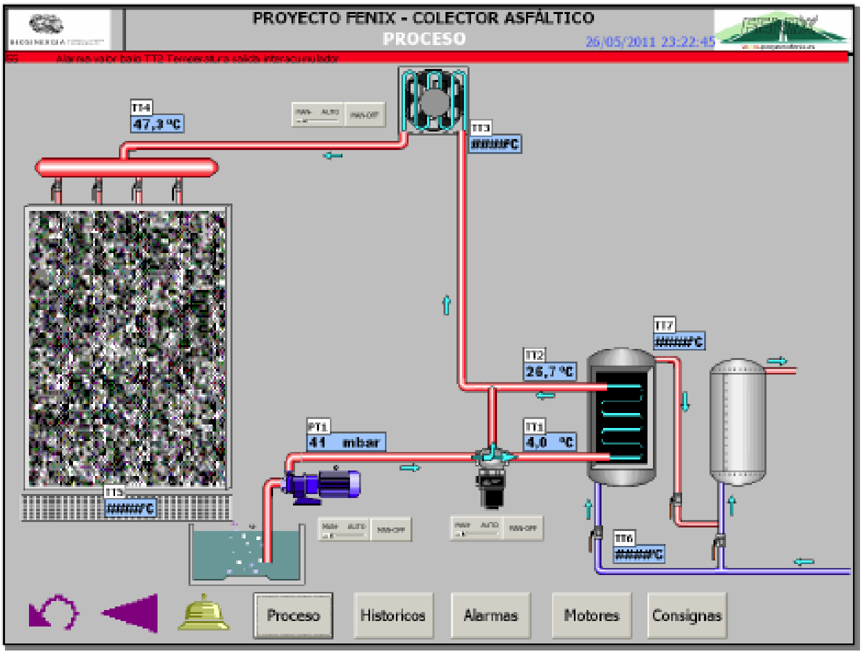

Figure 11: Sanpshot of the monitoring system.

In order to achieve the proper functioning of the capture module, the base of the stretch and of the drainage layers have been waterproofed. The test module has been designed so that each section can work with or without pressure and independently of the rest.

The results obtained so far allow to certify that it is feasible to extract energy from asphalt radiated by the sun. We are currently monitoring the test section at different external environmental conditions and we obtain very positive results. For instance, with an irradiance of 800 W/m2 we can heat the water of the system up to 35ºC, when the atmosphere temperature was 24ºC which represents a ΔT of 11ºC. More test at different weather conditions have been executed and will be executed in a close future.

3. Conclusions

The main conclusions of the study carried out are extracted below.

- The performance levels obtained in the different trials undertaken with the sandwich test mould are very high, with values of around 80% for the configuration of the one with 27% gaps in the 40 cm test mould.
- The flow value obtained when the test mould attains the permanent or quasi-permanent procedure is very small.
- The low flow values serve to reduce the SAP performance level, even with the increase of the radiation on the test mould.
- The results show that a heat performance level of 70-80% provided to the system can be obtained during the heating, to the maximum temperature of the range of operation.
- After 2 hours of the trial, the flow values, temperature gradient and output power for the long test mould with 27% gaps come close to those obtained in the trial with the short test mould with 23% gaps.

4. Aknowledgments

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