ÖRESUND BRIDGE. TEMPERATURE AND CRACKING CONTROL OF THE DECK SLAB CONCRETE AT EARLY AGES

Fernando Hue*, Guillermo Serrano*, Juan Antonio Bolaño**

*Dragados y Construcciones, S.A. (DRAGADOS). Dragados Group. (Spain)

**Geotecnia yCimientos, S.A. (GEOCISA). Dragados Group. (Spain)

SUMMARY

High performance features are required of the concrete for the deck slab of the bridge over Öresund Straight between Denmark and Sweden and, among them, great durability. To guarantee this, it is necessary to assure in advance and control during the construction of the deck slabs, that the maximum temperatures and the traction stresses in the deck slab will not be greater than the allowable values and to control these factors during the construction process. Before beginning construction, the deck slab was calculated using a program of finite elements that considers the heat generated, the shrinkage and creep of the concrete and the ambient conditions. To control the temperature during construction, temperature sensors are installed in various sections of each of the 49 deck spans and the temperatures produced during the first days of hardening are recorded on computer. The temperatures of the components are also measured in order to estimate the temperature of the fresh concrete.

1. INTRODUCTION

The Örcsund Straight crossing, of which the Öresund Bridge forms a part, will join the island where Copenhagen is located with the Scandinavian Peninsula. This job is a continuation of the Great Belt Straight crossing that joins the island with the continent. Together, these two jobs will connect Sweden and the continental part of Denmark by land, establishing a direct passage between the Scandinavian countries and the center of Europe without having to go around the Baltic Sea. The 49 spans 140 and 120 meters long that will form the two access sections to the main suspension section of the Öresund Bridge are being built at a plant in Cadiz. They are being shipped by sea and installed on piers using a huge floating crane.

Therefore, this bridge is located across a straight separating two important land masses of the European continent that are very different, in a damp and saline marine environment, with significant wind, frost and atmospheric temperature variation and, to make it worse, salt will have to be spread on the roadways to prevent ice from forming and reduce it. Under these conditions and considering that this is a large, important job, a minimum functional life of 100 years has been foreseen for the concrete. For this reason, during each phase of the design and construction, great attention and care have been given to all the factors that can affect the concrete's durability.

The cross section of the spans is formed of an upper deck slab and a lower steel truss structure. This structure has a height slightly greater than 10 meters and houses a dual railroad track. It is formed of two rectangular chords 1.50 m high by 1.30 m wide joined by rectangular diagonals, all formed of stiffened plate boxes. The deck slab for road traffic has two roadways, each with two lanes of traffic plus one for emergency, separated by a guard rail. The upper surface slopes downwards from the center outwards. The slab is of concrete that is transversally pre-stressed and longitudinally reinforced, almost 25 meters wide, with a varying thickness averaging some 30 cm except in the areas where it is joined to the steel structure where it is approximately 70 cm. thick.

When the concrete is hardening, it lets off heat due to the setting reaction of the concrete and other binding materials that it may contain. This heat is eliminated from the concrete through the exterior surfaces of the element. The heat generated increases the concrete's temperature in the first stages of the process in an uneven manner as it dissipates outwards, producing expansions. Other deformations arc also produced by shrinkage and creeping. These deformations are restricted by surrounding conditions such as the shape of the
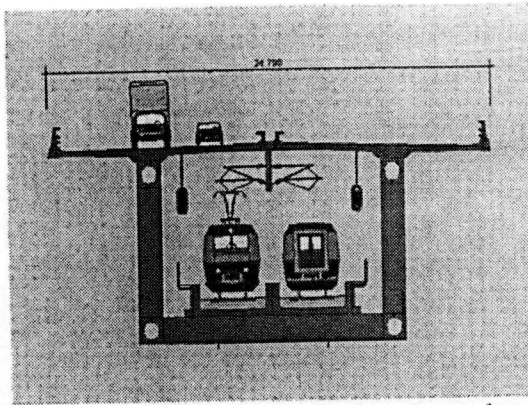
element, supports, areas already concreted and Figure 1.1.: Transversal section of the access spans to the main bridge

partially or totally hardened, or union with other structures. These restrictions produce stresses that are added to those produced by exterior loads or other causes. The tensile stresses can cause cracks if they exceed the stresses that the concrete is allow to resist during the hardening process and they reduce the durability because they provide a way of entry from the outside. Also, the temperature reached during the hardening process affects durability. If it is high, it helps other compounds to be formed later, like etringite, that slowly deteriorates the concrete.

The specifications for the concrete require that, before starting to build the deck slab elements, it must be demonstrated by means of a temperature and stress simulation analysis using a program based on the Finite Elements Method, that the construction method guarantees that the temperature will not be greater than 60°C and that there does not exist any risk of cracking for all the expected weather conditions. It also requires that adequate measurements be used to control and guarantee that the limits specified are met during the construction process.

2. CALCULATION OF TEMPERATURES AND RISK OF CRACKING

2.1. Calculation Method

The program used is the CIMS-2D Version 1.11 for Windows, developed by the Construction Technology Department of the Danish Technology Institute that was developed for the construction of the bridge crossing the Great Belt Straight.

The program automatically performs the iterative process in the time it takes to generate heat in the concrete and transmit it between elements and to the exterior and modifies for each element and

moment, the characteristics of the concrete according to its maturity, in order to structurally calculate the element at that moment. It is designed to determine how the temperatures and stresses vary in time in two dimensions, in one element or a set of modelized elements. It is also possible to simulate stress-deformation conditions in the third axis perpendicular to the section and different lengths of the elements, but not for variations in the section in this third axis whereby the calculation is done in two and a half dimensions. The properties of the concrete that hardens are variables in function of its maturity and are constant in other types of materials. The grid of elements is generated automatically. The elements are triangular with quadratic, parametric formulation.

First, the thermal analysis is made based on the heat generated by the concrete, the concreting process if it is done in various stages, the exterior surrounding temperature, the insulation conditions of the surfaces and the existence of cooling pipes or heating wires, all with time variation. The temperature and maturities are calculated as functions of the position and time from the start of the first concreting. After the thermal calculations, the structural calculations can be made, based on the thermal calculation done before, the exterior loads and the supports, the variations in the concrete's properties in function of the maturity reached in each element and the shrinkage and creep of the concrete.

The results can be seen on the screen and/or printed out and give the geometry of the grid generated, the curves for the variation in temperature, age, stresses and risk of cracking over time and the isocurves of these values for any age from the start of concreting. The curves in time can be of maximum, minimum and average values of the volume defined or in points of the volume. These curves can also be obtained in numerical format in files.

2.2 Model used for the deck

Since the transversal section of the deck is symmetrical with respect to the central vertical axis, only half the section was modelized, establishing symmetrical support conditions for the axis. To take into account the longitudinal restriction that the steel structure produces in the concrete slab because it is stiffly joined to it by a large number of embedded connectors, a complete model was introduced into the program with the concrete slab and the steel structure joined to it.

The data of the concrete characteristics was obtained from the characterisation tests run during the stage prior to building the deck spans, such as heat generation, heat transmission coefficient, modulus of elasticity, compression and tensile strengths, and shrinkage and creep coefficients for early ages. These tests were run for various ages of concrete. For the shrinkage and creep tests, it was necessary to perfect a test method in collaboration with Geocisa of the Dragados Group and the Eduardo Torroja Institute, since this characteristic is not usually determined for a project.
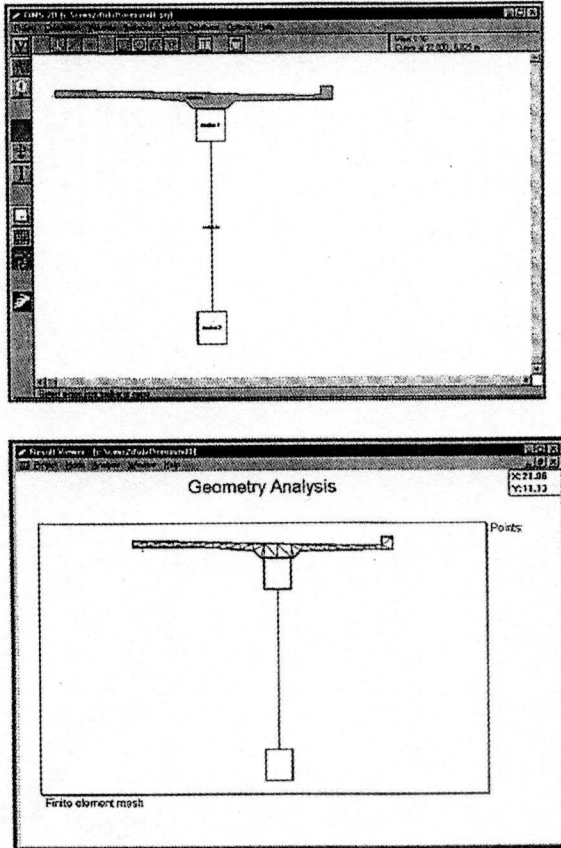
Figure 2.1: Model used for the deck and grid of finite elements generated

A study was made of data on the weather gathered by the Cadiz Weather Observatory between 1961 and 1995 and it was estimated that during the hottest day the maximum temperature would be 35°C and the minimum 25°C and that during the coldest day the maximum would be 10°C and the minimum 5°C, considering that every two weeks one slab is concreted continuously during two complete days. It has also been estimated that the during the hottest day, the concrete made without using any cooling process would reach a temperature greater than 25°C.

2.3. Results of the simulation program

The following data was entered into the simulation program: temperature of the fresh concrete, workshop ambient temperature, heat generated by the concrete during hardening, specific and insulation heat values for all the elements involved in the process and the other data mentioned above.
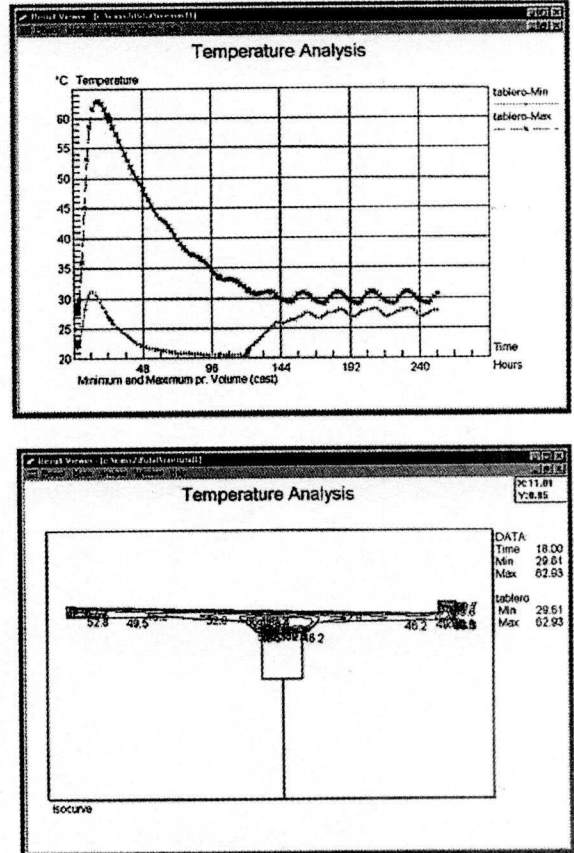

Figure 2.2: Example of the results of temeperature isocurves and diagrams

By simulation, the maximum temperature obtained during the hottest day was 66°C and there was also a risk of cracking during the coldest day, whereby temperature control measures must be taken during both summer and winter in order to meet the specifications on temperature limits and risk of cracking at an early age.

3. TEMPERATURE CONTROL DURING CONSTRUCTION

3.1. Design of the temperature control system

To prevent exceeding the specified limits for maximum temperature and risk of cracking during the concrete hardening process in extreme conditions during summer and winter, it is

necessary to control this process by artificial systems. There are different methods for this.
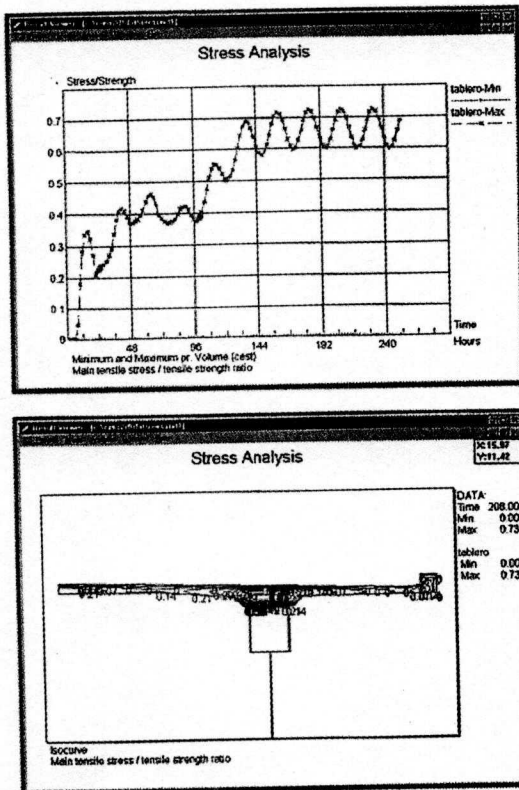

Figure 2.3: Example of the results on diagrams and isocurves of risk of cracking

One method consists of making the fresh concrete colder by cooling the materials used to make it such as the cement, silica fume, water, aggregates and agents and/or the mix itself in the mixer. This slows the concrete maturity rate and also slows the heat generation process in the concrete, making its evacuation easier.

Another method is to control the ambient temperature where the concrete hardens. Due to the way the construction of these elements is foreseen, it is possible to control this on the upper face of the slab that is going to be concreted in an industrial bay. It is much more difficult to control the air temperature of the lower face of the deck slab since the steel structure must be passed through the two wider sides of the bay before concreting the slab and the entire section must be returned through them after it has been concreted. Plus, the form of the inner zone between the steel structure has to pass through the two shorter sides.

In addition to the temperature control, it is necessary to also prevent water from evaporating from the concrete during the hardening process. The best way of doing this is to place a sheet of plastic over the surface of the slab so that no water can leave the concrete. In winter an insulating blanket can also be placed on the surface of the deck slab to reduce the heat gradients in the slab and with it the risk of cracking, and making it possible to take the concreted slab out of the bay.

As a last resort, it is possible to use cooling pipes embedded in the concrete through which water flows at a controlled temperature. In addition to being expensive because of the non-recoverable piping, this method has certain inconveniences. In general, a pipe is a discontinuity in the concrete and strong heat gradients are produced in it. This does not precisely help to cracking control. Furthermore, due to the slab's particular geometry and the longitudinal process of concreting, there is the problem of where to place the pipes.

The two basic measures used for the construction system are to control the air temperature on the upper face of the slab and to make concrete with controlled temperature, cooling the components in general. These measures were designed and calculated starting with the simulation process with the program mentioned above, so that, in the foreseen extreme atmospheric conditions as mentioned above, the specified limits are not exceeded. The concreting bay was air conditioned so that the air temperature of the upper face of the slab would be kept at 20°C in hot weather and 15°C in cold weather. Furthermore, in extreme winter, the upper surface of the deck slab must be covered with an insulating blanket before removing the section from the bay in order to reduce the heat gradients and the risk of cracking.
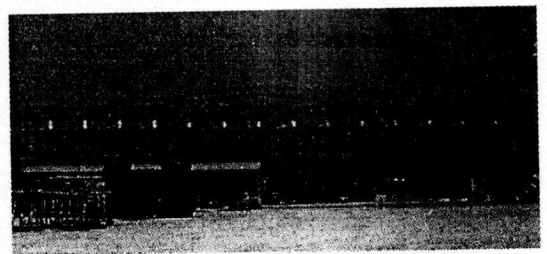

Figure 3.1: Picture of the concreting bay with the air conditioning system

The fresh concrete temperature is limited to between 25°C and 15°C, although in extreme conditions in summer, it is limited to a maximum of 22°C in the fresh concrete used for the thickest areas of the slab. In certain extreme conditions in winter, it has to be limited to 18°C in order to not exceed the acceptable risk of cracking. Since the control of the air temperature on the lower face of the slab is much more difficult, this is not done. The lower face of the steel slab form is subjected to the

exterior air temperature since in this lower area there is natural ventilation.

3.2. System to estimate the temperature of the fresh concrete

The system controls the temperature in the hoppers and in the storage silos for the different components used to make fresh concrete and estimates the final mixing temperature in either of the two existing plants.

The system's elements are: temperature sensors, electronic control and application software for monitoring. Digital sensors (range -55° to 125°, increasing by 0.5°). Each of these sensors has a characteristic identification number. We installed: 1 sensor in the unloading area, 2 sensors in each of the main aggregate silos, 2 sensors in each of the main cement silos, 2 sensors in each of the unloading hoppers and 1 sensor in the water tank.

The different sensors are connected to the control electronics located in boxes using a common bus. Four control boxes are used. Each box receives the sensors that are physically closest to it. Each control box is governed by an 8 bits microprocessor (8052) that acts as an interface between the application for PC and the temperature sensors. All the control boxes are connected by an RS485 line to a PC from where the control program is executed.

On the screen, the control software application shows a diagram of the concrete plant and the location of the temperature sensors in the hoppers and silos. Periodically (approximately once every minute), the program sends a command to each control box requesting the temperature of the sensors connected to it. Each box asks the sensors connected to it and sends the information to the main program. From the temperatures obtained and using the information on the location of the sensors in the silos, the main program estimates the final temperature, using the average figure weighted with the mass used in the concrete batch of the product of the temperature by the specific heat of the material by an adjustment factor.

The data on the temperatures measured is stored in a file in order to keep a historical record of the evolution of the temperatures. They are also given in a graph of the evolution during the last 24 hours and during the last few minutes.
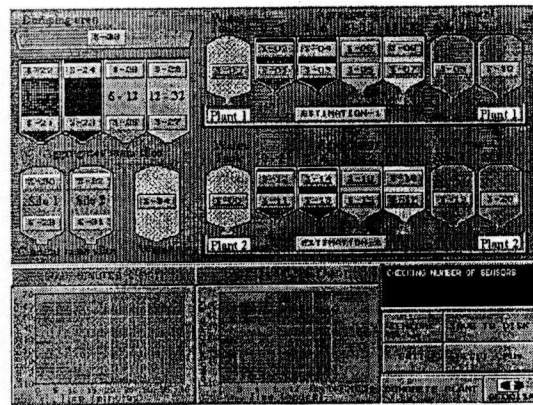

Figure 3.2: Screen showing the component and estimated temperatures

4. TEMPERATURE MEASUREMENTS

4.1. Temperature measuring system

The system developed and used allows us to obtain and record the temperature of the concrete during the hardening process at various points of the deck slab. It also monitors the ambient temperature and humidity and the wind speed. Furthermore, it is possible to make an estimate of the concrete's maturity in the setting process.

The elements of the system are: temperature sensors embedded in the concrete, ambient temperature and humidity sensors, wind gages, electronic control and software application for collecting, presenting and recording the data.

Digital sensors are used (range -55° to 125°, increasing by 0.5°). To embed the sensors in the concrete, strips or test frames are made. Each of these strips contains three temperature sensors at different heights using plastic resin. Before pouring the fresh concrete, the strips are installed in pre-established positions to take measurements at different points of the reinforcing cage. The sensors of each strip are joined to a common bus with three wires that connect them to a control box. Each sensor has its own characteristic identification number. The identification of the sensor and verification that it is working correctly are done using a portable unit that is connected to the corresponding bus.
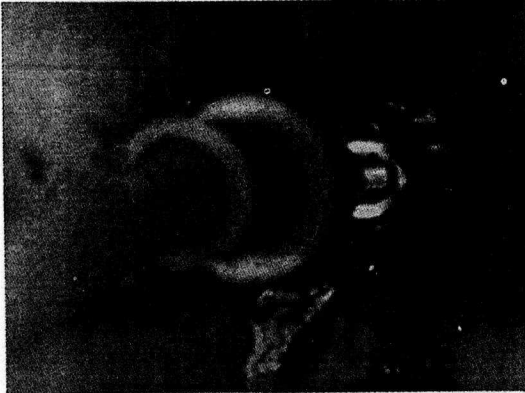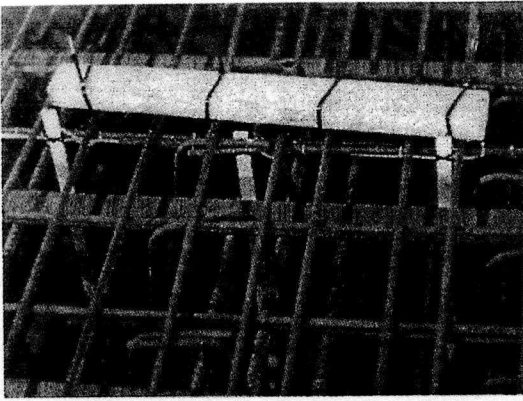
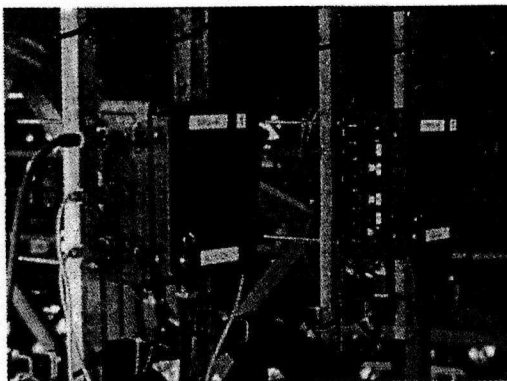Figure 4.1: Pictures of the interior sensors and of the forms in place
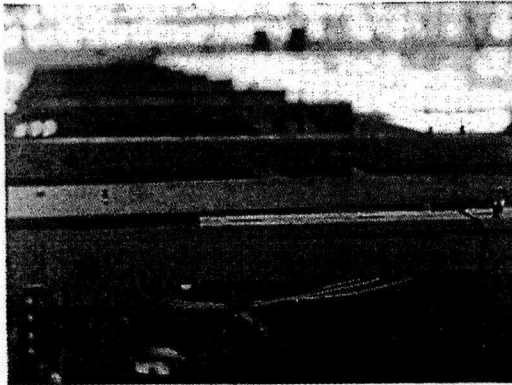

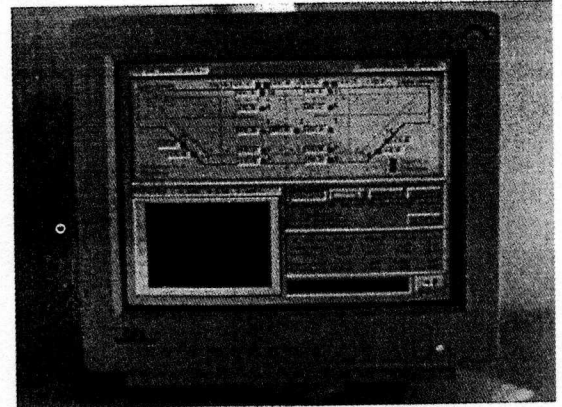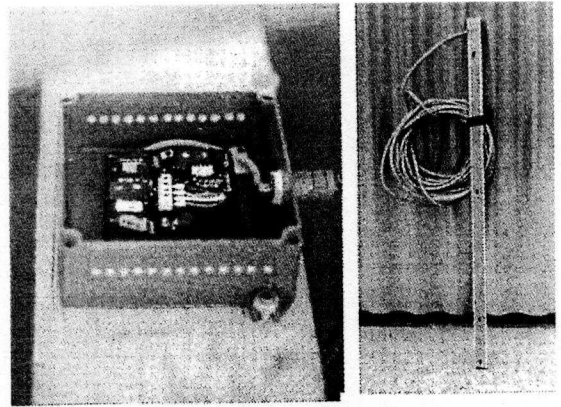Figure 4.2: Pictures of the upper sensors not yet in place and of the control boxes

Figure 4.3: Pictures of the ambient sensors, sensors strip and computer

The strips are distributed in the deck in sections. All the sensors of one section are connected through a bus with three wires to a control box. The control box contains a microprocessor and the corresponding electronics that periodically capture the data on the temperature from the sensors and transmit this information to a computer to which it is joined by an RS485 line.

In addition to the four control boxes that supervise the concrete temperature sensors, there are another two control boxes to which the air temperature sensors, the humidity sensors and the wind gages are connected. These boxes are also connected to the main computer by the RS485 line.

The software application program obtains, presents and records the temperature data throughout the concrete setting process. Periodically, the program asks the control boxes to send the temperatures read by its sensors. The main screen of the program shows a drawing of the deck slab that is being concreted, indicating the location of the heat sensors in it. The information on the temperature at these points is updated every time the computer asks the control boxes for information.
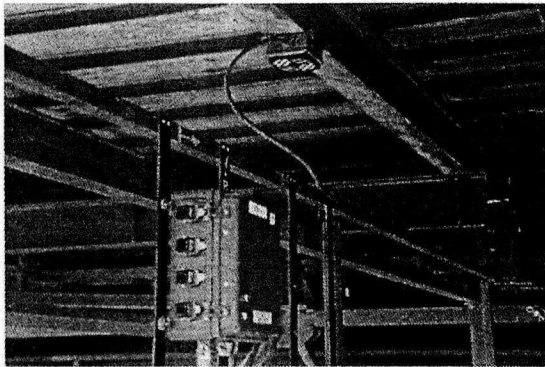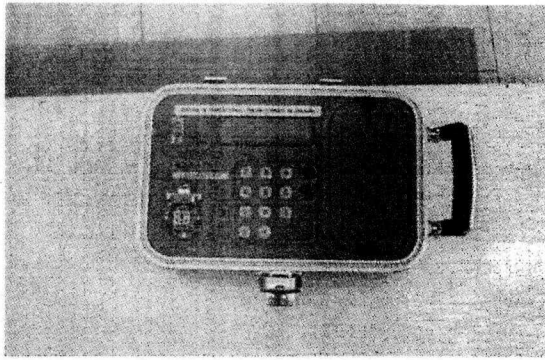
Figure 4.4: Pictures of the portable unit and control box and ambient sensors

It is possible to select from the program any of the sensors being monitored and a graph will appear on the screen showing the evolution of the average temperature taken by that sensor since the beginning of the process. Alternatively, it is also possible to see an estimate of the maturity of the concrete at that point. The screen also indicates the averages of the ambient temperature and humidity as well as the wind speed. All of this data is recorded and stored in a file to keep a history of the evolution of the temperatures during the process. All of the installation and the program to identify the sensors and to gather, present and record the temperatures were developed by Geocisa.

4.2. Measurements during the full size tests

To verify the entire construction system, various full size tests were run concreting in each test various adjacent sections of deck slab, each with their full width and a length of 2 meters. To check and adjust the simulation program and verify the system of taking temperatures to be installed during construction, two sections were instrumented in the first test and one in the second. Nineteen temperature sensors were placed in each section, in the area where they are joined to the steel structure, 7 in the interior of the zone, 1 located 1 cm from

the lower surface, 1 located 1 cm. below the upper surface, 4 on the steel form and 4 on the upper surface. In addition, 2 were placed in the air outside of the concrete under the slab and another 2 in the air in the bay above it.

With the data gathered in the three sections of the two tests, the modelization system was adjusted and it was verified that the results of the program and real concrete readings coincided sufficiently, whereby the modelization done was correct and could serve to control the quality of the deck slabs during their construction.

4.3. Measurements during the construction of the decks

In order to be able to check that the deck sections were being correctly built and to meet the conditions of the specifications, two sections of temperature sensors were installed in each of the 49 elements to be built. In this case, in each section we installed 13 sensors, 9 in the thick area of the slab at its union with the upper steel chord, of which 3 are in the centre of the zone, 2 are 1 cm from the lower surface, 2 are 1 cm below the supper surface and 2 on the steel forms, 3 in the thinnest section of the slab of which one is in the centre, 1 at 1 cm below the upper surface and the third on the steel form and the thirteenth is on the form of the outer edge of the slab. There are six ambient sensors, three located under the form and three in the bay. Two hot wire type wind speed gage are located under the form to modelize better the forms surface transmission coefficient.

The reading program was adjusted to the new distribution of the sensors and was complemented with the maturity calculation in function of the temperature of each sensor, since the form removal and pre-stressing operations are done when the concrete has reached a certain maturity.

5. CONCLUSIONS

The temperature produced during the setting and hardening process and the cracking that this temperature and the shrinkage in these early ages can produce have a great influence on the durability of a concrete for which high performance is required.

To control this risk and know the steps that must be taken so that the risk is not greater than allowable, a simulation of the structure can be used with the Finite Elements Method, considering all the stages
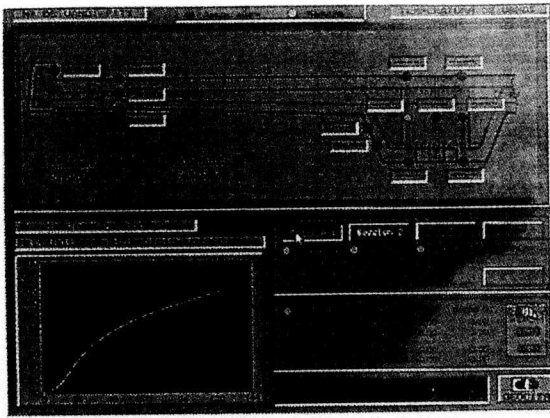
Figure 4.5: Computer control screen

and characteristics of the job to be carried out. The calculation gives a sufficiently close prediction of the structure's real behaviour.

The goodness and approximation of the simulation of the temperatures in the field can be controlled by installing sensors and taking measurements in full scale models and by controlling the construction of the structure itself.