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An Experimental Study to the Design of Pressure inside Fire-Resistant Concrete

A Thesis Submitted to

Mechanics and Equipment Department- University of Technology

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

(Applied Mechanics)

By

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(B.Sc. 2010)

(30.June.2013)

Joint Supervision

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2013 A.M. *1434 A.H.*

.. بسم الله الرحمن الرحيم .

.. يرفع الله الذين آمنوا مِنكم والذين أُتوا

العِلمَ دَرَجاتٍ والله بما تعملونَ خبيرٌ .

صدق الله العلي العظيم

سورة المجادلة , الآية 11

CERTIFICATION

I certify that this thesis entitled ***"An Experimental Study to the Design of Pressure inside Fire-Resistant Concrete"*** which prepared by ***"Ali Saad Mahmood"*** has been carried out completely under my supervision at the University of Technology - Mechanics and Equipment Department - Iraq and the Technical University of Freiberg - Institute of Thermal Engineering - Germany, in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

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We certify that this thesis entitled ***"An Experimental Study to the Design of Pressure inside Fire-Resistant Concrete"*** *and as examining committee, examined the student* ***"Ali Saad Mahmood"*** *in its contents and that in our opinion it meets the standard of thesis for the degree of Master of Science in Mechanical Engineering.*

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Dedication

I would like to dedicate this thesis to all for their support and encouragement

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(In The Name of Allah, the Gracious, the Merciful)

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Abstract

The developing steam-pressure inside fire-resistant concrete during first heating can exceed the strength of concrete and cause an explosive spalling. A technique for an experimental device was designed and used in this research for more understanding to the behavior of the pore-pressure-sensor under various conditions. This technique is able to measure the real amount of pore-pressure and able to compare and calibrate the pore-pressure sensors. In addition, a control program was designed for recording and measurement computerized for the obtained results.

Various studies have been carried-out on fire resistance concrete specimens by this technique, the specimens have different diameters (3.6, 4.3, 5.1, 6.6, 7 and 8.5 cm) and heights (5 and 7 cm), with a pressure and temperature up to 3 bar and 120 $°C$ respectively.

The results showed that the type and the volume of the fluid filling the space inside the tube-pressure-sensor have a highly influence on its response. In which, by the use of water instead of air as a fluid filling this space, the time delay was reduce by (75 %), also by reducing the space volume, a reduction of (67 %) in the time delay is achieved. In addition, the leakage between the tube and the concrete that initiated by shrinkage cracks have a high influence and cause a big error in the measurement.

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Nomenclature

D	Specimen diameter	mm
$d_{I.T}$	Inner tube diameter	mm
$d_{T.C}$	Thermo-couple diameter	mm
d_{th}	Theoretical diameter	mm
h	Specimen height	mm
L	Length	mm
P	Pressure	bar
t	Time	sec
T	Temperature	$°C$ or $°K$
V_{Cross}	Cross connector inner volume	mm^3
w	Moisture content	

Abbreviations

Al_2O_3	Aluminum oxide
CaO	Calcium oxide
Fe_2O_3	Iron oxide
HFRHSC	Hybrid-Fiber-Reinforced High Strength Concrete
HPC	High performance concrete
HSC	High strength concrete
K_2O	Potassium oxide
NSC	Normal strength concrete
OC	Ordinary concrete
PID	Proportional-Integral-Derivative Controller
P.V	Pressure vessel
RH	Relative humidity
SCC	Self-Compacting Concrete
SiO_2	Silicon dioxide
T.C	Thermo-couple

1 Chapter One: Introduction

1.1 Introduction

The most dangerous case that facing fire-resistant concrete that used to build the industrial furnaces occurs during first heating; this is caused by the creation of extremely high steam pressure inside the material. In contrast to prefabrication fire-resistant stones, the moisture content in the "green" material evaporates and creates a high steam-pressure inside the concrete. The ultimate raise level for this steam-pressure depends on the saturation and permeability of the concrete as well as the supplied heat rate. Industrial users intend to spend only a short time for first heating due to economic reasons, and damage of the fire-resistant occurs if the stream pressure exceeds certain limits given by the materials strength causing an explosive spalling. In addition, fire still remains one of the most serious risks for many civil engineering structures, such as bridges, high-rise buildings, tunnels and underground parks, especially those made of HSC [1] because of its superior performance compared to NSC. However, fire accidents that have occurred involving infrastructures and various studies have shown that the high strength concrete performance is highly susceptible to high temperature condition [2] because of its low permeability. Thermal instability leads to breaking off layers or pieces of concrete from the thermally exposed surface, and this significantly compromised the structural integrity of the concrete structures.

1.2 Scope of the Present Work:

The presented work has wide applications through the multi scientific, technological and industrial aspects, which can be summarized as follows:

1. Industrial applications: in producing the lining of industrial furnaces.
2. Petroleum industries: in producing the lining of the towers and boilers that use for oil refining.
3. Energy producing: in producing the lining of the nuclear power plant reactors, and the lining of steam boilers in thermal power plants.
4. Aerospace applications: in producing the outer shell of some parts of the spacecraft.
5. Civil and construction applications: In the development of the normal concrete that used in tunnels, towers, bridges and concrete pillars, in order to prevent the collapse under fire accidents, as well as fire-resistance bricks that use in thermal chimneys for homes and bakery ovens.

In addition, the Iraqi ministry of industry and minerals had started recently to build some new factories for the production of the fire resistance cement and bricks, and such scientific research has a significant contribution to development the quality of local production in order to compete with the international production.

1.3 The Objectives of the Present Work

This Master-Thesis will put a focus on the measuring of humidity, temperature and especially on the steam-pressure inside fire-resistance concrete walls that generate during first heating, including the above-mentioned phenomena that associated with drying of fire-resistant concrete.

In detail, the following summarized objectives will be done:-

1. Preparing a technique to build an experimental device that is able to compare and calibrate the pore-pressure-sensors.
2. Study and investigate the effect of different parameters on the pore pressure measurement.
3. Study the effect of fluid type and volume inside the tube-sensor-sensor.
4. Modify the pore-pressure-sensor.
5. Find the time delay in the response of pressure sensor.

1.4 Thesis's Construction

The following four detailed chapters are presented in this thesis:

Chapter Two: Literature Survey

A literature review for the important relevant experimental and numerical researches that handled the processes of high temperature drying of construction materials and methods to measure steam pressure, temperature and humidity inside porous materials.

Chapter Three: Experimental Work

A details description for the used experimental device, sensor and specimens and the different studies that done by this work on pore-pressure measurement.

Chapter Four: Results and Discussion

The effects of several parameters on the pore-pressure measurement based on the results obtained from the experimental work were presented and discussed in this chapter.

Chapter Five: Conclusions and Suggestions for Future works

At last, chapter five provides the main conclusions from the present work based on the results obtained from chapter six. In addition, the suggested recommendations for the future works have been summarized to modify the present research.

2 Chapter Two: Literature Survey

2.1 General Introduction

In the past few years, the subject of Drying Technology for Refractory Materials and Porous Media, and the theoretical and experimental methods for measuring the pore steam pressure and temperature inside these materials have received a considerable attention. Concrete as a structural material is considered as a multiphase medium [3], see figure 2-1 [3], comprises of three different phases; solid skeleton, liquid (water), and gaseous mixture (water vapor and air).

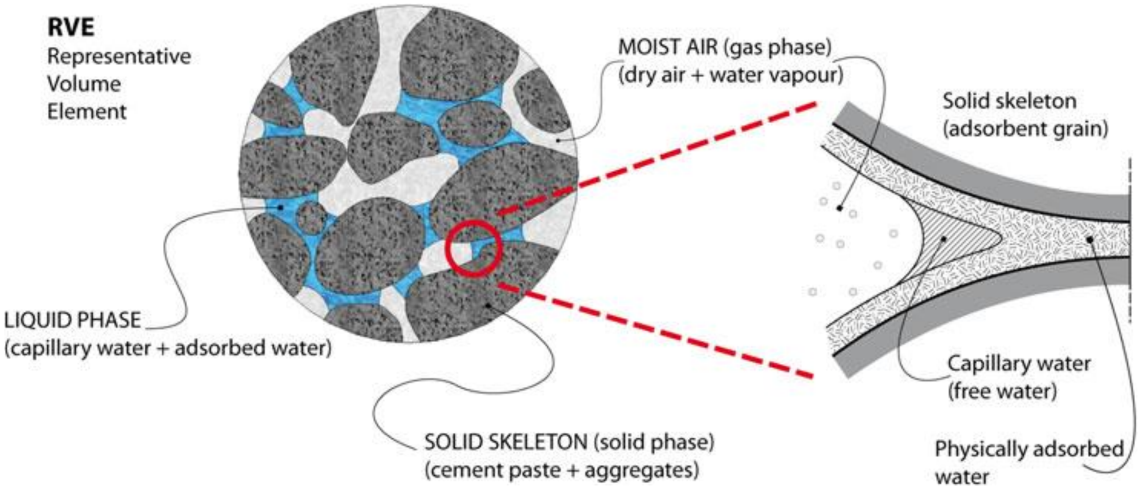


Figure 2-1 Scheme represents concrete as a multiphase porous material [3]

In the specific case, the fluids filling pore space are the moist air (mixture of dry air and vapor), capillary water and physically adsorbed water. The chemically bound water is considered to be part of the solid skeleton until it is released on heating [3]. The solid phase consists of cement paste and aggregate, both of which are porous. The cement paste contains very a small gel pores (diameter about 2 nm) and capillary pores (about 1 μm) [4]. The capillary pores may be fully filled (saturated concrete) or partially filled with water.

2.2 Drying of refractory concrete

To dry a product seems to be very simple: it is sufficient to supply energy to the product and to evacuate the vapor generated by this energy. Nevertheless, what is less simple is to obtain fast drying with good product quality and low cost (equipment and operation). Such a combination is very difficult to optimize, especially if one remembers the number of different possibilities and difficulties that exist [5]:

- Heat may be supplied by convection, conduction or radiation.
- Batch drying and continuous drying are possible.
- The products have different shapes and very different physical properties.
- The definition of the dried product quality requires many different objective and subjective criteria.

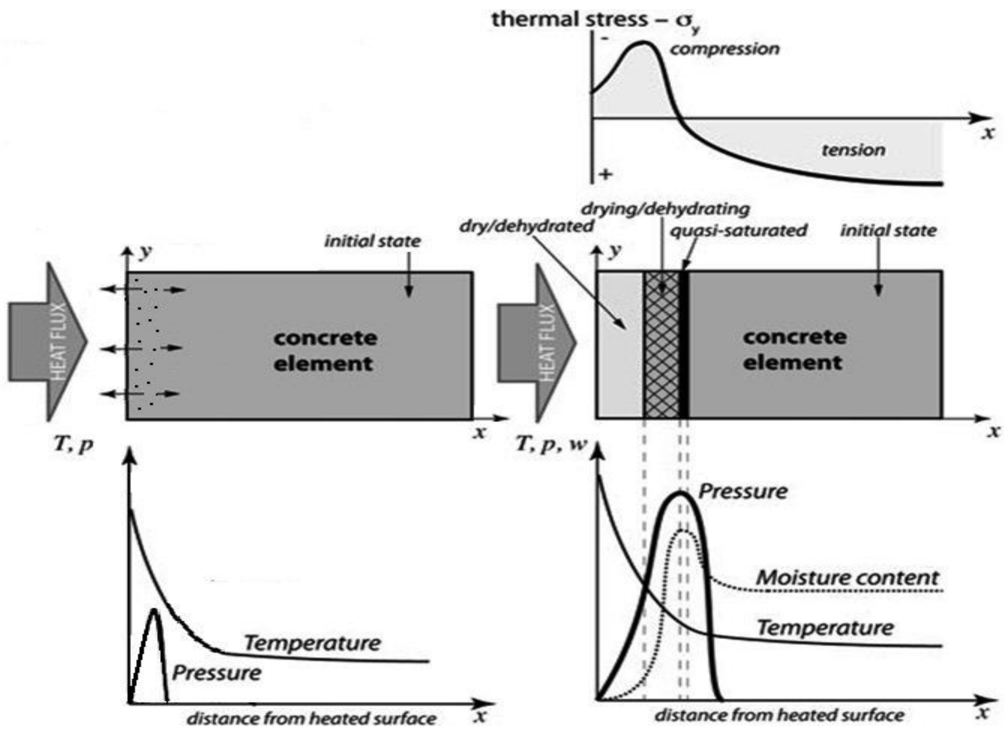


Figure 2-2 The four observed zones and the process for the build-up of pressure [3, 6]

Figure (2-2) [3, 6] shows the four observed zones (dry/dehydrated, drying/dehydrating, quasi-saturated and initial state) and the process for the build-up of pore pressure associated with the drying of concrete specimen. In addition, figure (2-2) [3, 6] shows the distribution of the temperature, moisture content and the thermal stress with the distance from the heated surface.

In work by **P. Perre et. al. [7],** a high temperature convective drying process was presented and investigated experimentally and theoretically for two drying fluids: moist and superheated steam, and for two materials: light concrete and softwood. The experimental investigation was made in an aerodynamic return flow wind tunnel. In addition, a numerical model was used to simulate the experimental test.

For **P. Perre, [5],** different drying configurations (convective drying with moist air and superheated steam, microwave drying and vacuum drying) on different materials were experimentally studied in order to model and visualize the evolution of internal pressure and temperature, also for measuring the average moisture. An analytical model was also provided to facilitate the better undemanding of internal phenomena.

The work of **F. Topin and L. Tadrist, [8]** focused on high-temperature convective drying (superheated steam drying). The process has been investigated both experimentally and numerically. The experimental analysis was carried out in an aerodynamic return-flow wind tunnel, with very small cylinders of cellular concrete. A numerical model for high temperature drying, using the finite elements method, in a 2-D configuration, was implemented and validated.

The paper of **M. Adam et. al. [9]** deals with the investigations carried out on the field of dewatering of refractory castable. Several grades of refractory castable have been prepared with different cement content including a self-leveling grade. In addition, it is provide how to dry out and heat up refractory castable to make the process effective and safer.

H. Taira and H. Nakamura, [10] developed in their work a combination method for drying monolithic refractories by using a microwaves and hot air. As a result, they found that:

(a) The hot air and microwave drying process makes it possible to significantly narrow down the temperature distribution inside the refractory material during drying.
(b) When the amount of water added is decreased, the porosity decreases, the steam pressure generated inside the refractory rises, and the drying time increases.

All the efficient processes use internal vaporization [5]. This means that during drying, the internal temperature of the concrete must be higher than the boiling point of water, if free water exists inside the medium, such temperature level always generates an overpressure inside the product. The resulting pressure gradient is a very efficient driving force for both liquid and vapor. This principle is common to many different drying procedures: high temperature convective drying, microwave drying, vacuum drying and contact drying. Only the temperature level and the way to supply energy distinguish these processes.

2.3 Spalling of Fire-Resistance Concrete

Particularly, previous studies have shown the important risk of thermal instability of concrete, phenomenon commonly called spalling. Spalling is the violent or non-violent breaking-off of layers or pieces of concrete from the surface of a structural element when it is exposed to high and rapidly rising temperatures. It can result in significant loss of section leading to reduction in load-bearing capacity, figure (2-3) [3] is an examples of spalling. Nowadays, concrete spalling is still a phenomenon not well explained and such risk is not predictable by models [11].

Figure 2-3 (a) Spalling of a tunnel due to a fire, (b) Corner spalling of a concrete column [3]

Spalling results from two main processes:

1- *Thermo-mechanical process:*

It is related to the thermal dilation gradients taking place in the structural element; the heating of a concrete element involves high temperature gradients, particularly in the first centimeters of the heated surface [12]. The thermal dilation generates tensile stresses perpendicular

to the heated face, see figure 2-4 [12]. Local strain incompatibilities between the cement paste and the aggregates also exist. While the aggregates dilate with increasing temperature until they are chemically degraded [6], the cement paste shrinks as soon as it loses water (by drying and dehydration). This differential thermal behavior can be very important in the case of a rapid heating and induce high compressive stresses close to the heated surface. These stresses can locally overtake the concrete strength and cause the ejection of pieces.

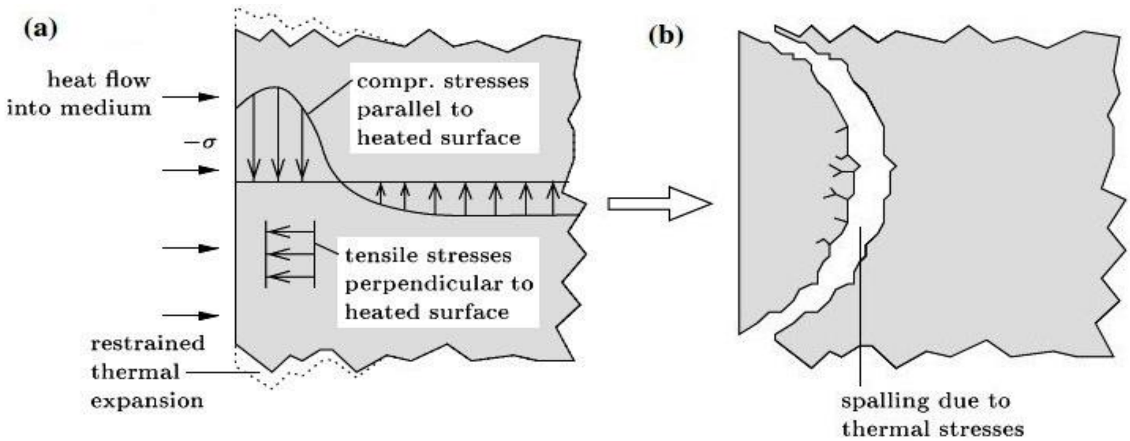


Figure 2-4 Illustration of spalling due to thermo-mechanical processes [12]

2- <u>Thermo-hygral process:</u>

The heating of a concrete element involves mass transport into the porous medium. As temperature increases, water is partly evaporated; also, the chemical bound water is released by dehydration and then evaporates. This evaporation generates a pressure in the porous network. Fluids that are present into concrete (free water, water vapor and dry air) are moving due to pressure and molar concentration gradients (Darcy and Fick laws) [13]. The water vapor transferred in two directions: (i) outward, where it escapes; (ii) inward, where it starts to condensate since these zones are

colder [14]. As a result, a quasi-saturated layer “moisture clog” is formed and blocking further movement in that direction [4]. Since this clog acts like a real barrier (an impermeable wall) to fluid's flow, pore pressures are increasing, figure (2-5) [4, 14, 13] shows the above mentioned phenomena. As is the case during fire, the rate of evaporation exceeds the rate of vapor migration, and this result in pore pressure buildup, this pressure can locally overtake the tensile strength of concrete and initiate the spalling.

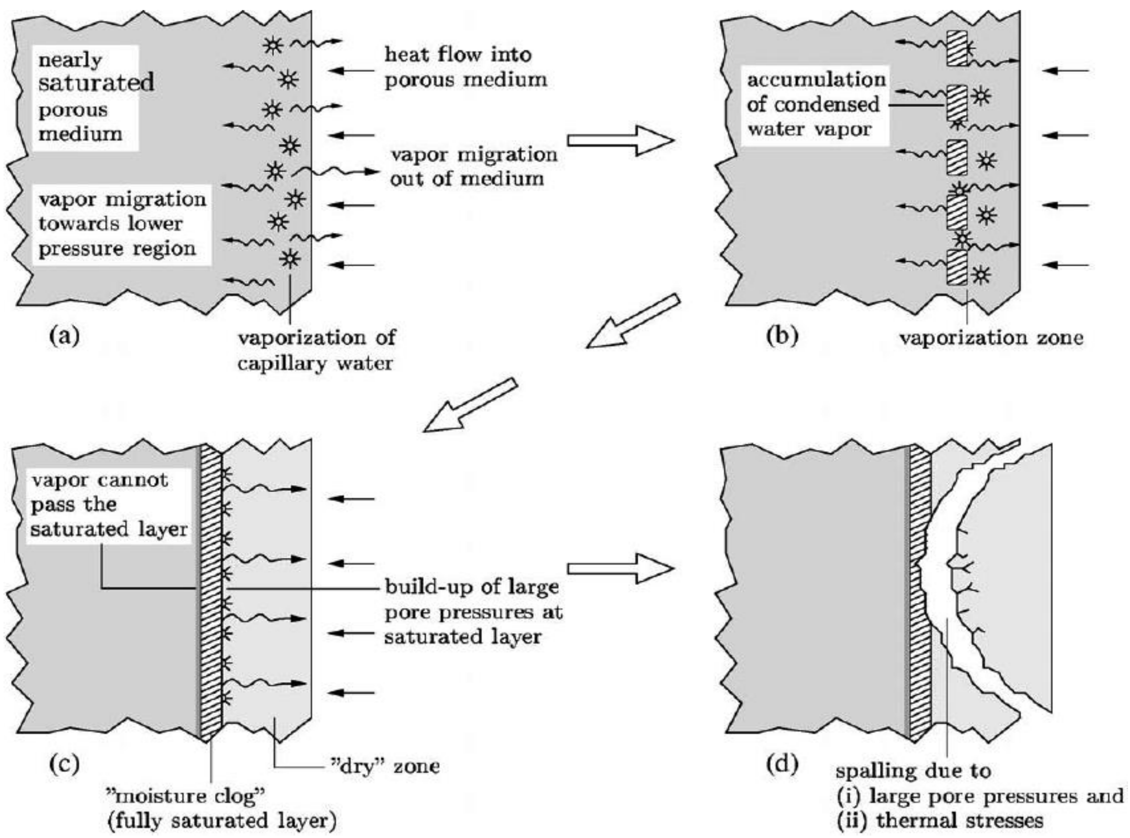


Figure 2-5 Illustration of spalling due to Thermo-hygral process [4, 14, 13]

Whether the first or second process is the dominant process that causes spalling, both of them are thermal-dependent and occurs synchronously. Spalling therefore results from a thermo-hydro-mechanical coupled process [6].

M. Zeiml et. al. [12] presented in their paper a new experimental insight into the spalling behavior. In which, spalling was recorded by a high-speed camera, the slow motion sequences allows to determine the size, shape, and velocity of the spalled-off pieces, with this information at hand, the released energy associated with every spalling event is computed and compared to the energies associated with pore-pressure and thermal-stress spalling. This comparison provides a batter insight into the impact of the various thermal, mechanical, and hydral processes controlling concrete spalling.

R. Jansson and L. Bostrom, [15] presented an investigation on the reason behind fire spalling of concrete by performing pressure measurements on SCC and a traditional vibrated concrete. The highest pressures in the two test series were measured in the concretes that did not exhibit spalling during fire. The conclusions from this work are:

(a) Pressure in the capillary system is not the driving force for spalling during fire exposure.
(b) Pressure is involved in the redistribution of moisture during fire exposure.
(c) A modified theory is proposed to explain the spalling reducing function of PP-fibers based on the presence and movement of moisture.

2.4 Experimental Techniques

All the experimental devices, which have previously used by different researchers, have mainly the same principles, in which:

- Heating-up the concrete specimen by various methods
- Measuring the generated steam pressure by various methods
- Measuring the pore temperature either simultaneous with the pressure gauge or separate.
- Measuring the average moisture content by simple weighting.

2.4.1 Experimental Technique No. 1

The following device is the most common experimental technique, which was used by different researchers [1, 2, 6, 11 and 16], in which:

- A thermal load is applied to the upper face of the brick concrete specimen, by means of a computer-controlled radiant heater placed 1-3 cm above the concrete specimen. The heater of power 5000 W exposes the whole surface of the specimen and generates maximum temperature of up to 600-800 °C.
- The lateral faces of the specimen are heat-insulated with porous ceramic blocks to ensure quasi-unidirectional thermal load upon it.
- The specimen is placed on a balance in order to measure its mass loss during heating. The mass loss of the specimen during heating is mainly due to the fluid's escape from concrete (water, vapor and dry air).

- The specimens were instrumented with five to six pressure-temperature gauges that placed at different depths during casting. The temperature-pressure gauge was described in details in section 2.5.1.

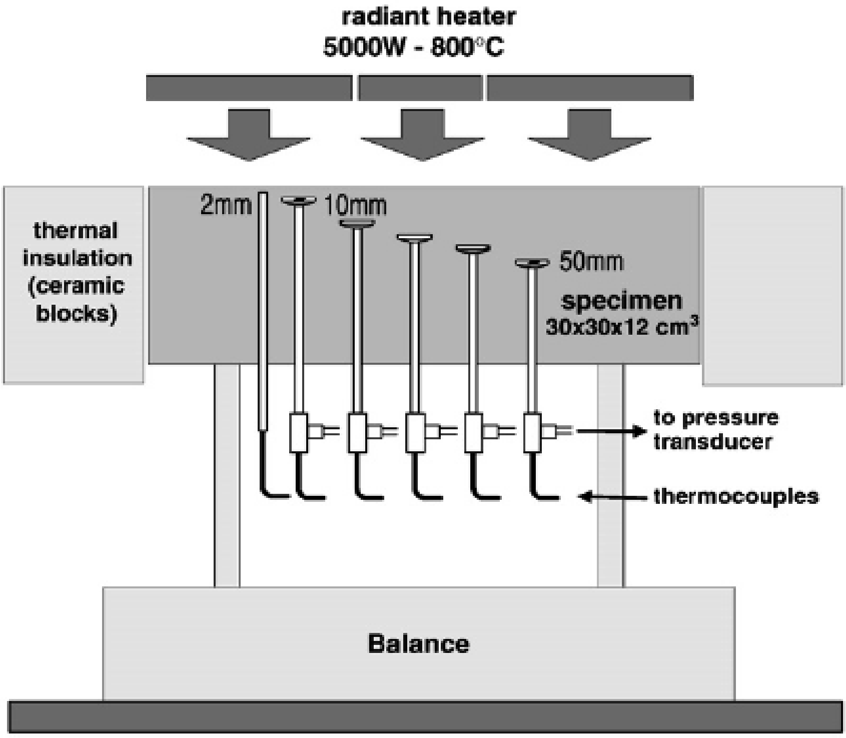


Figure 2-6 Scheme of the experimental set-up used in [6, 11, 16]

Some of the previous researchers [6, 11, 16] had inserted the thermocouples inside the tube (see figure 2-6 [6, 11, 16]), while others [1, 2] placed it outside but attached to the tube (see figure 2-7 [1, 2]), in order to insure that the temperature-pressure measurement is at the same point.

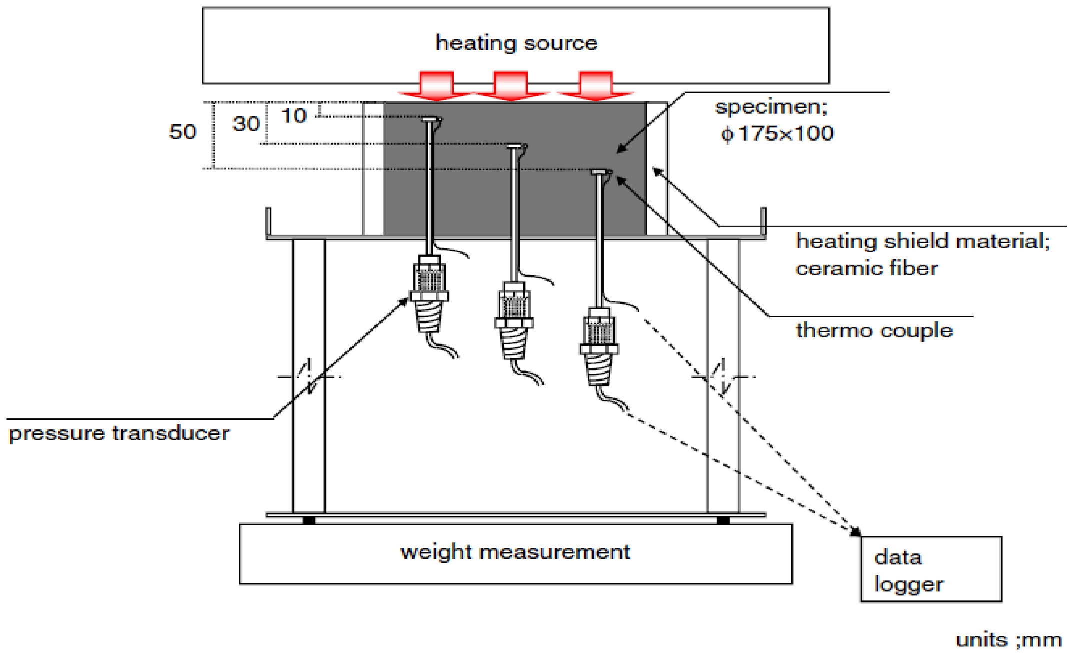


Figure 2-7 Scheme of the experimental set-up used in [1, 2]

In **P. Kalifa et al. [6]** work, an original device was designed in order to make simultaneous measurements of pressure and temperature in a concrete specimen ($30 \times 30 \times 12\ cm^3$) heated on one face up to 800°C. The specimen was also continuously weighed during the tests, the mass loss resulting mainly from water transport and loss.

J. Mindeguia et. al. [11] presented the results of an experimental study carried out on five different concrete mixtures. They used a device intended for measuring temperature, pore vapor pressure and mass loss of concrete specimens. In Moreover, based on their experimental observations, a numerical analysis of the influence of water content on the thermo-mechanical behavior of concrete during heating was done.

2.4.2 Experimental Technique No. 2

The **F. Topin et. al. [17]** work focused on heat and mass transfers with phase change in porous media. A method of temperature and pressure field visualization was developed to highlight the dynamics of transport phenomena. They showed two specific phenomena:

(a) Liquid outflow generated by the overpressure.
(b) Vaporization of the water inside a two-phase zone that progressively pervades the specimen.

"F. Topin and L. Tadrist [8]" and "F. Topin, O. Rahli and H. Tadrist [17]" used the device shown in Figure 2-8 [8, 17], in which:

- Aerodynamic return-flow wind tunnel operates by superheated air or steam at ambient pressure and temperature up to $200\ ℃$.
- The cylindrical samples were made of cellular concrete (3, 5, 10 cm in diameter). Long soaking in water humidified them.
- The samples were fitted with up to 20 thermocouples and 10 pressure sensors that described in details in section 2.5.1.2.
- After fitting the sensors, the sample is compressed between two Teflon plates to ensure a watertight fit at the extremities.
- Different superheated steam conditions: velocities 2.5, 8 m/sec and temperatures $120, 140, 160, 180\ ℃$ were carried-out.
- The mean moisture content of the sample was simultaneously measured by simple weighting.

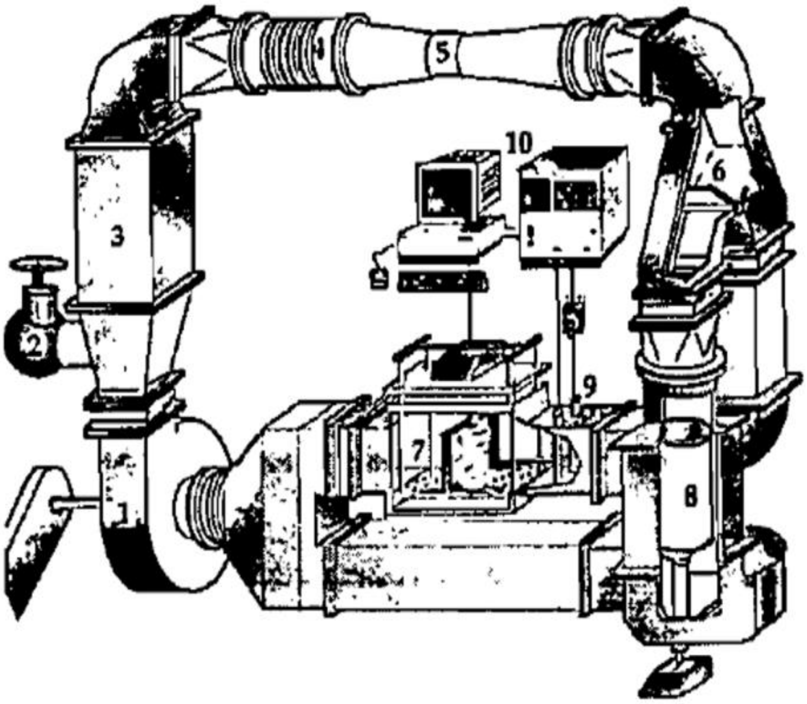


Figure 2-8 The return-flow wind tunnel used by [8, 17]

2.4.3 Experimental Technique No. 3

P. Perre et. al. [7], had used nearly the same previous experimental technique, but with some differences in the arrangement of the device components that can be shown in figure 2-9 [7], and the type of the specimen in which light concrete and soft wood specimens were used. In addition, a difference in the pore pressure-temperature measurement technique that described in details in section 2.5.1.3 can be noticed.

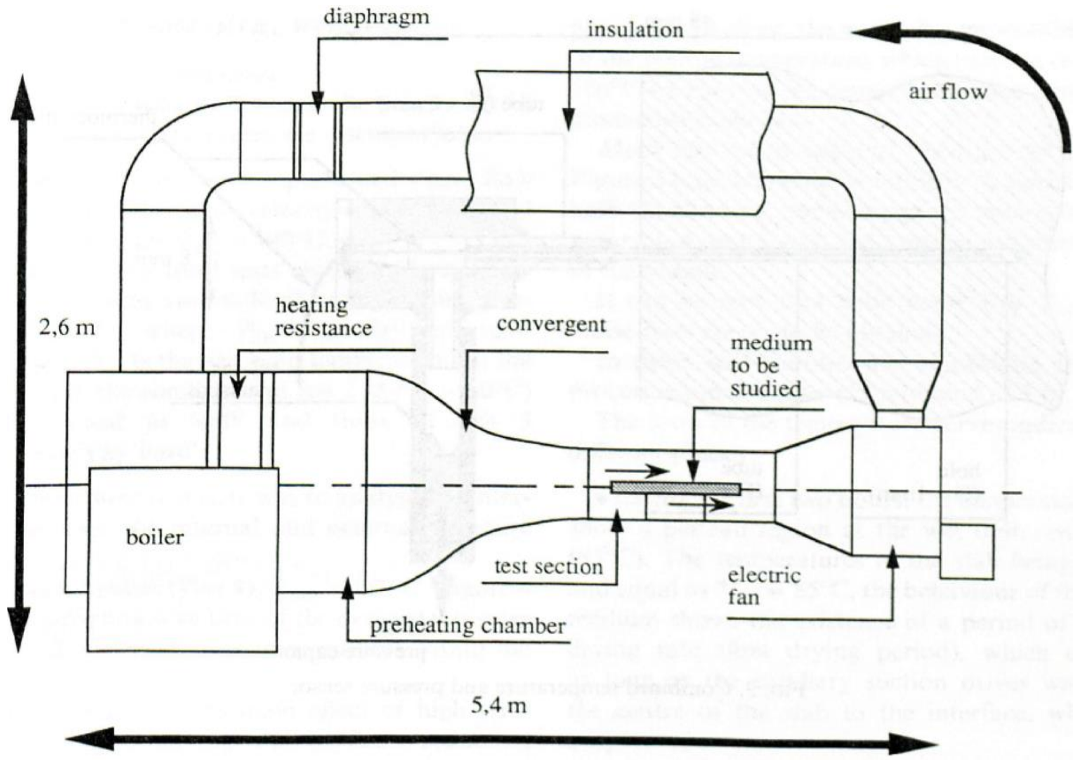


Figure 2-9 Scheme for the wind tunnel used by [7]

2.4.4 Experimental Technique No. 4

G. Consolazio et. al. [14] presented the experimental and numerical studies on the measurement and predication of pore pressure and moisture flow in concrete. Pore pressure data were presented for experimental tests, in which saturated cement specimens were subjected to a high temperature. A numerical modeling was then presented and was used to numerically simulate the experimental tests. Good agreement was shown between the pore pressure and temperature recorded experimentally and those predicated though simulation. They used the device shown in Figure 2-10 [14], in which:

- The specimens were instrumented with thermocouples and pore-pressure transducers by drilling holes from the bottom of the

specimen up to the desired position, later inserting and cementing them into the drilled holes.

- A portable cylindrical oven of approximately the same diameter as the specimens served as the radiant heat source. In which the sides of the oven walls consisted of heating element embedded in the ceramic material, while the top of the oven consisted of insulation.
- A thermo-couple was placed inside the oven near the top surface to monitor the transient air temperature in the oven.

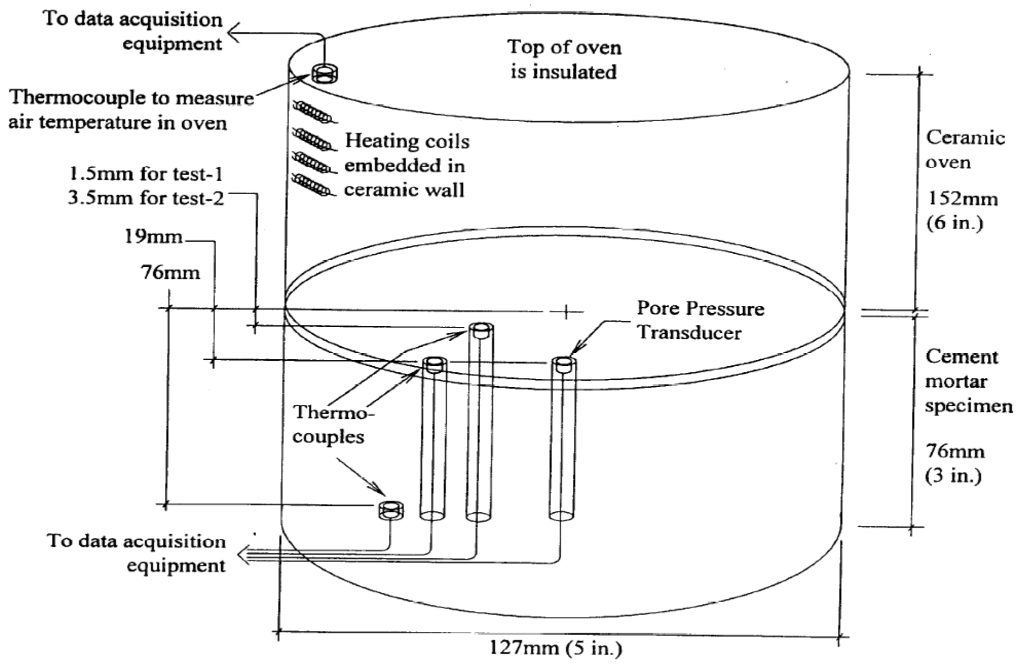


Figure 2-10 Scheme for the experimental device used by [14]

2.4.5 Experimental Technique No. 5

F. Toutlemonde, [18] paper presented the effects of elevated temperature exposure and various factors, including water-to-cement ratios (w/cm), curing conditions, heating rates, test methods, and polypropylene fibers, on: (a) Degradation of mechanical properties in (NSC) and (HSC).

(b) Pore pressure buildup and potential for explosive spalling. By the using of following experimental program:

A. Experimental device shown in figure (2-11 a) [18], for measuring the concrete mechanical properties at elevated temperature using 100 x 200 mm cylinders with three test methods, namely stressed, unstressed, and unstressed residual property test methods. In the stressed and unstressed test methods, the specimens were subjected to simultaneous application of loading and heating and loaded to failure under uniaxial compression. In the unstressed residual property test method, the specimens were heated to target temperatures, allowed to cool to room temperature, and then loaded to failure at room temperature.

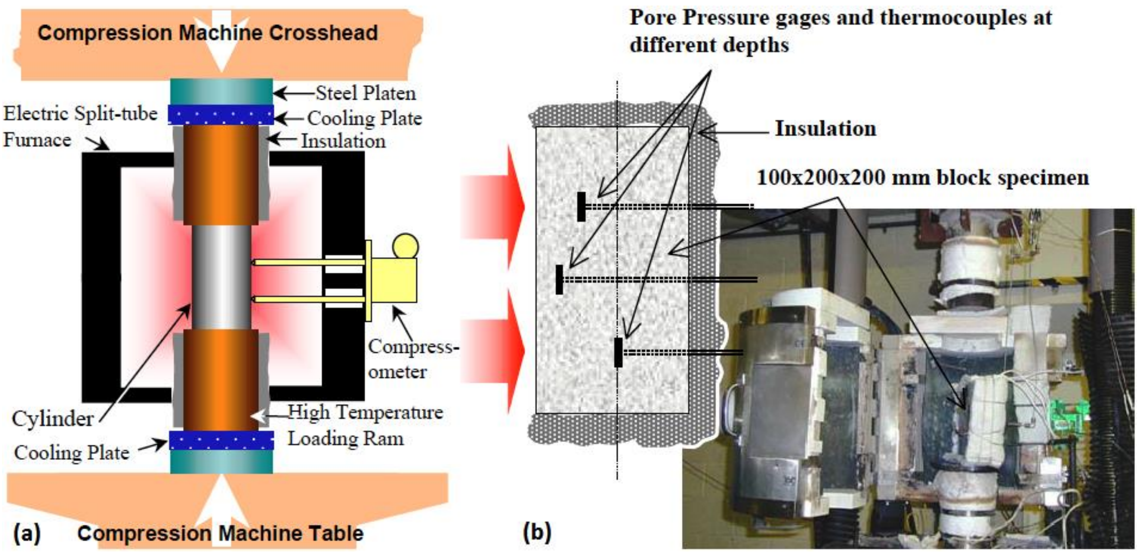


Figure 2-11 (a) mechanical property and (b) pore pressure test setups [18]

B. Experimental device shown in figure (2-11 b) [18], for measuring the heat-induced internal pore pressures in concrete by using 100 x 200 x 200 mm blocks, which insulated on all sides, except the face, and subjected only to heating without any mechanical loading.

2.5 Measurement

2.5.1 Pore Pressure- Temperature

Pore pressure measurement is very important to understand the thermo-hydral process and to validate the codes, very few experimental works were carried out. One author measured a pressure up to (31 bars), while a very low pressure (2 bars) in a specimen heated to 900 °C was measured by another [6]. These results are probably biased on the experimental procedure. Figure (2-12) [3] shows the gas pressure in a concrete specimen heated to a target temperature of 600 ℃ for both experimental and numerical results, it is shown that the pressure wave stays for short time, therefore the pressure sensor must by fast enough to measure it.

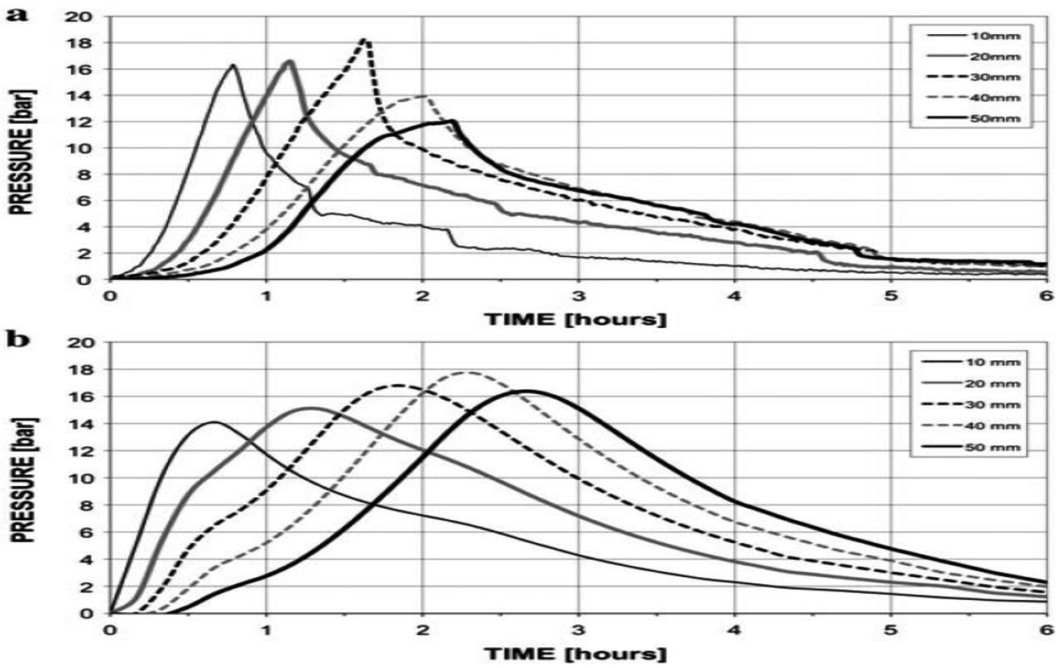


Figure 2-12 Pressure build-up:a) experimental b) numerical result [3]

2.5.1.1 Measurement technique No. 1

The technique in figure (2-13) [1, 2, 6, 11, 16, 18] is widely used for simultaneous pore pressure-temperature measurement [1, 2, 6, 11, 16, 18], in which the specimens were equipped during casting with gauges that made of:

- Disc of porous sintered metal (Ø 12 mm ×1 mm) with evenly distributed pores of diameter 2 μm.
- Metal cup encapsulates the sintered metal and weld to a metal tube.
- Metal tube with inner diameter of 1.6 to 2 mm.
- Piezoelectric pressure transducer.
- K-type thermocouples of diameter 1.5 mm that is, even inserted inside the metal tube or attached to the metal tube, in order to insure that the temperature-pressure measurement is at the same point.
- A tight connector is placed at the free end of the tube, it connects the metal tube to the transducer, and the thermo-couple is inserted into the tube through it down to the metal plate.

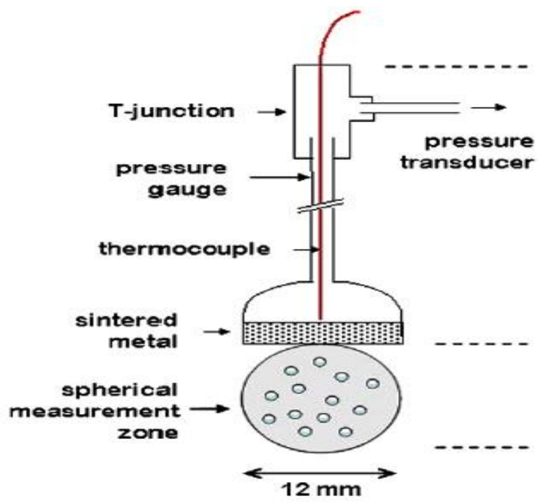


Figure 2-13 Pressure-temperature gauge used by [1, 2, 6, 11, 16, 18]

M. Bangi and T. Horiguchi, [1] investigated the build-up of pore pressure at different depths of (HSC) and (HFRHSC) when exposed to different heating rates. The effect of the measurement technique on the maximum pore pressures measured was evaluated. In which, the pressure measurement technique that utilized a sintered metal and silicon oil was found to be the most effective technique.

2.5.1.2 Measurement technique No. 2

F. Topin and L. Tadrist [8] and **F. Topin et. al. [17]** used the technique shown in figure (2-14) [8, 17], in which:

- The pressure and temperature sensors were implemented by pressing them into a needle (external diameter 0.9 mm, internal diameter 0.6 mm, and length 9 cm)
- The needle inserted into holes that had smaller diameters than the sensors, and it equipped with removable mandrels, which allowed to introduce the sensor without blocking the opening.
- Chromel-Alumel thermocouples of diameter 0.5 mm and of length 0.1 m inserted into the needle.
- The needles are connected to pressure sensors (Sencym SCX05) by a Teflon tube of diameter 0.4 mm.

Figure 2-14 Spinnal needle used for pressure and temperature sensor [8, 17]

2.5.1.3 Measurement technique No. 3

P. Perre et. al. [7], the pressure sensor shown in Figure 2-15 **[7]** was used by these researchers for a simultaneous pressure-temperature measurement of wood and light concrete, in which:

- A hole was made at each measurement location
- In case of wood, the hole was smaller than the diameter of the sensor, so that the latter was forced into the board with the aid of a hammer.
- In case of concrete, only temperature measurement was carried out.
- The 3 mm wide hole was filled with silicon glue, after the glue had been dried, the medium was saturated and the thermo-couples were inserted in the glue.
- By this instrument in wood a pressures up to three bar was measured.

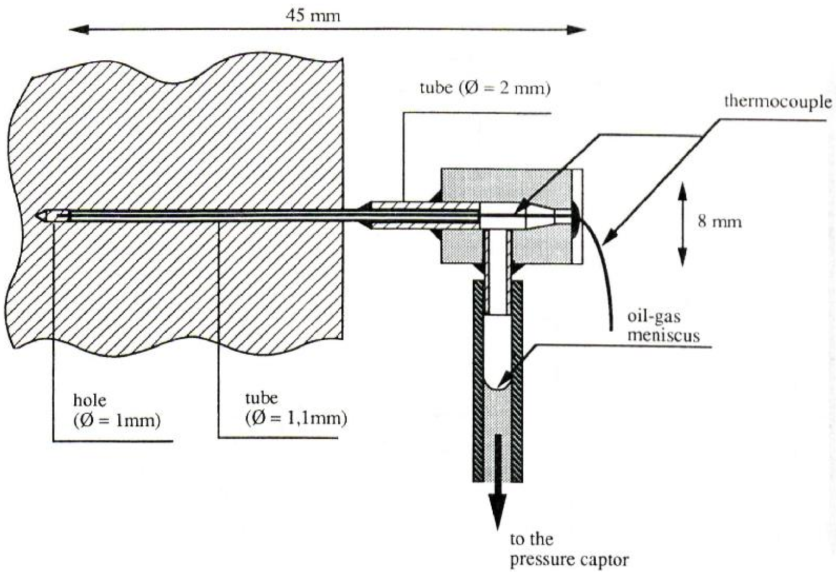


Figure 2-15 Combined temperature pressure sensor [7]

2.5.2 Moisture Content

Most of the previous researchers [1, 2, 6, 11, 16 and 18] measured the mean humidity of the concrete specimen simultaneously by simple weighing. In addition, the following techniques were used to measure the moisture distribution in the concrete:

2.5.2.1 Measurement technique No. 1

In **Z. Grasley et al. [19]** work, a developed internal RH measurement system was used to quantify the moisture gradient in early age concrete exposed to drying (see figure 2-17 [19]). Internal RH sensors were embedded in fresh concrete prisms using small plastic tubes with Gore-Tex caps (see figure 2-16 [20, 21]). The tubes were embedded using a special concrete mold. The tubes were inserted to various depths such that the measurements were being taken. The prisms were cast, and immediately the surface was sealed using plastic wrap. In addition, this technique was also used in [20, 21].

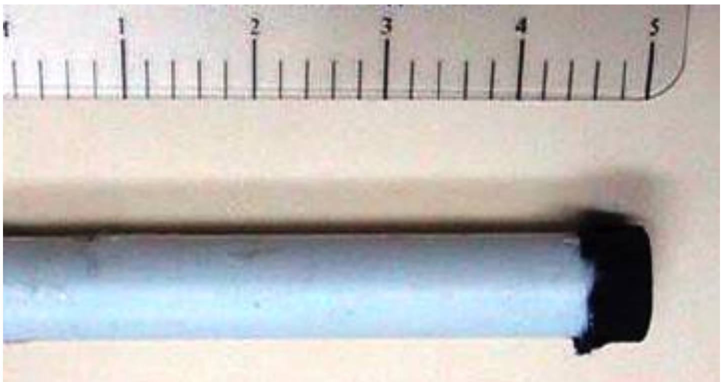


Figure 2-16 Packaged to be cast in concrete [20, 21]

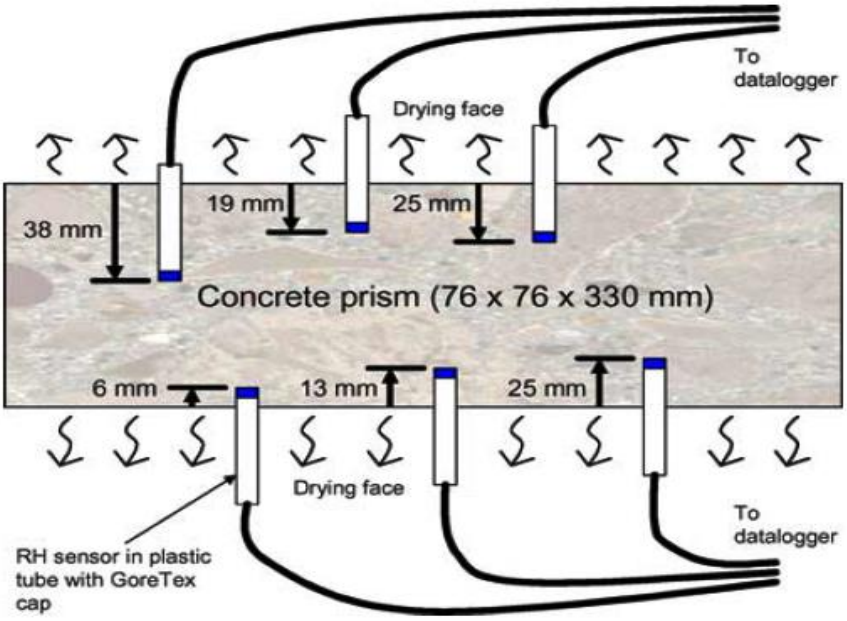


Figure 2-17 Measurement of internal RH gradient in concrete prism [19]

2.5.2.2 Measurement technique No. 2

Y. Theiner and G. Hofstetter [22] used a Multi-Ring-Sensor shown in figure (2-18) [22] with the respective measuring points, embedded in the concrete for determining the moisture distribution inside it at different levels.

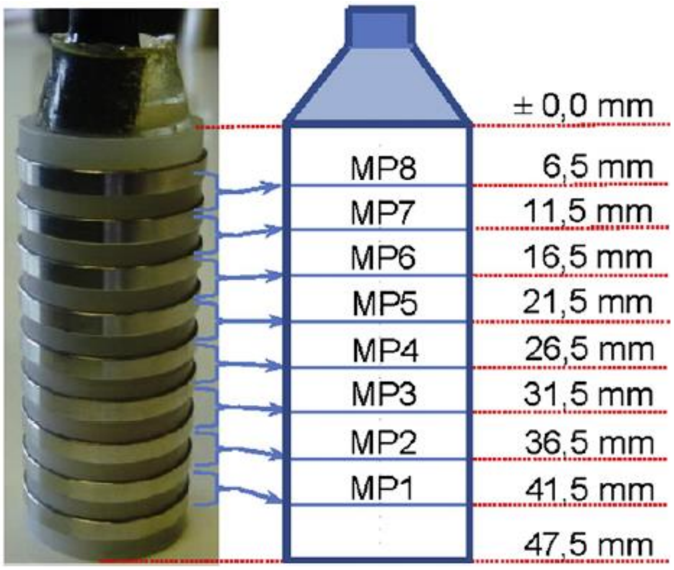


Figure 2-18 Multi-Ring-Sensor [22]

E. Waters, [23] reported the comparative measurements of the moisture content, during air drying, of concrete slabs as measured by:

(a) A commercial electrical resistance "moisture meter.
(b) Progressive weight loss to the atmosphere followed by oven drying.

The results from this work are:

(a) A wide divergence between the results from (a) and (b).
(b) No correlation could be found between cement composition and the resistance moisture relationships of the concrete.
(c) The use of electrical resistance meters to determine the moisture content of concrete may produce very misleading results unless the meter is calibrated with concrete having the same characteristics as that to be tested.

2.6 Concluding Remarks

Finally, from the previous works, the following conclusions on the pressure measurement inside fire-resistance-concrete can be summarized:

- Pore pressure isn’t easy to measure, and numerical works still need more experimental results to validate their assumptions.
- Studies by different researchers on the pressures measurement are not in agreement with each other, and they observed quite different maximum pore pressure.
- Most of the previous works which had dealt with the pressure measurement had used nearly the same technique, and they have a main problem, which is the unreliability of the measured pressure, if it's the real amount of pressure or a percentage of it.
- Due to the extremely important to modify and calibrate a pressure sensor that able to measure the real amount of pressure, it is very important to find a new technique that able to do that.

According to the previous concluding remarks, this thesis is concentrated on the modification and calibration of a pressure sensor and to study the behavior of such sensor in different conditions by the using of the technique that had been designed and manufactured by this research.

3 Chapter Three: Experimental Work

3.1 General Introduction

Most of the previous works, which had dealt with the measuring of the steam pressure inside fire-resistance concrete, had used nearly the same technique, which has been described in details in chapter two. This technique has a main problem, which is the uncertainty from the amount of the measured pressure, due to the unknowns of the actual amount of the pressure inside a concrete specimen subjected to a heating process, also the disadvantages of using such technique to modify and test the sensors are the relatively high cost and the long time require to prepare and carry out such experiments. While, the technique used in this research is able to measure the real amount of the pressure inside a concrete specimen, also for testing the available sensor and modify it, and to study the behavior of such sensor in different conditions.

3.2 Experimental Device

Figure 3-1 shows the experimental device that designed and used in this research, in order to measure the real amount of pressure and compare it to a reliable reference pressure to test and modify the available sensors. In which, a steel pressure pan was used as a pressure vessel, that allows to get a high pressure up to 3 bar by two ways, first; a high-pressure air which is supplied from a compressor through a hose connected to the pressure vessel with an on-off valve and another control valve to control the amount of the pressure inside the pressure vessel, second; a high-pressure steam that can be generated inside the pressure vessel by putting a water inside it, and put the pressure vessel on a heat plate.

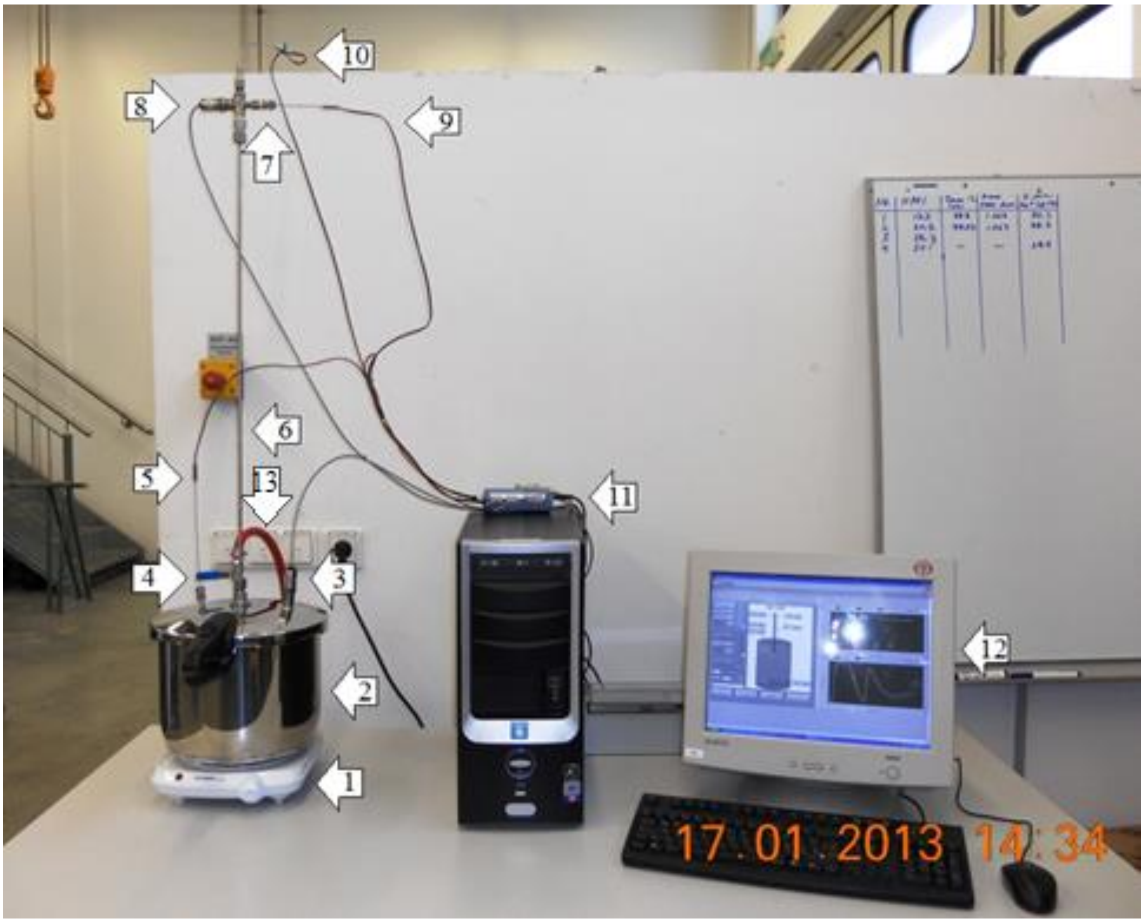


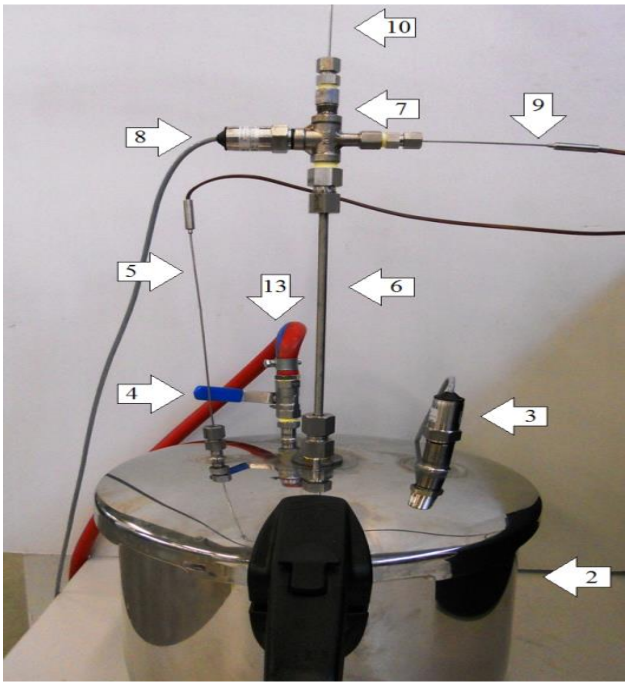
Figure 3-1 Experimental Device

1	Heat plate	2	Pressure vessel	3	Pressure gauge 1	4	On-off valve
5	Thermo-couple 1	6	Tube-sensor	7	Cross Connector	8	Pressure gauge 2
9	Thermo-couple 2	10	Thermo-couple 3	11	Data acquisition and processing unit		
12	Screen	13	Hose				

A flat tube (6 mm outer diameter and 2 mm inner diameter) is placed inside the concrete specimen during casting, a tight "Cross Connector" is placed at the free end of the tube, the cross connector does the following purposes:

- First, it is connecting the tube-sensor to a pressure gauge No. 2, in order to measure the pressure of the air or the steam inside the pressure vessel, which is passing through the concrete specimen.

- Second, a thermo-couple No. 2 (Ø 1.5 mm, 20 cm long) is placed in front of the pressure gauge No. 2, for measuring the temperature of the fluid (air, water, steam or oil) in front of the pressure gauge No. 2.
- Third, a thermo-couple No. 3 (Ø 1.5 mm, 1 m long) is inserted inside the tube-sensor through the connector down to the end of the tube, for measuring the temperature of the air or the steam inside the concrete specimen.



2	Pressure vessel
3	Pressure gauge No. 1
4	On-off valve
5	Thermo-couple No. 1
6	Tube-sensor
7	Cross Connector
8	Pressure gauge No. 2
9	Thermo-couple No. 2
10	Thermo-couple No. 3
13	Hose

Figure 3-2 Pressure Vessel

The pressure vessel in figure (3-2) was coupled with a thermo-couple No. 1 and a pressure gauge No. 1, in order to measure the temperature and the pressure of the air or the steam inside the pressure vessel. Figure (3-3) shows a block diagram for the excremental device that used in this research.

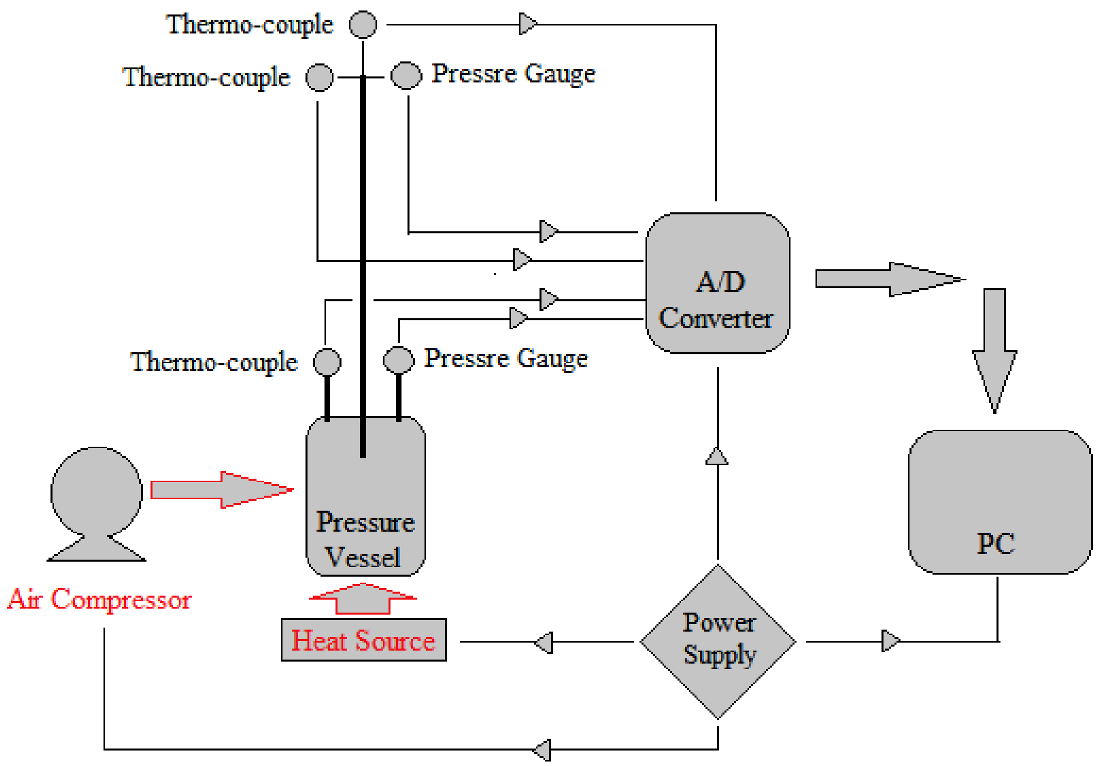


Figure 3-3 Block diagram for the experimental device.

Parts used to manufacture the Experimental Device

1- Heat plate (2000 W): for heating the water inside the pressure vessel, in order to get a high pressure steam.
2- Pressure pan: to use as a pressure vessel.
3- Two Piezoresistive pressure transmitters (3 bar, accuracy 0.25 %, total error in temperature range 20 - 120 °C is 0.8 %): used for measuring the pressure inside the pressure vessel by two ways, directly and through the tube-pressure-sensor.
4- Three thermo-couples T-type (Ø 1.5 mm): for measuring the temperature at three points; inside the pressure vessel, inside the concrete specimen and in front of the pressure gauge No. 2.
5- Cross Connector: for connecting the tube-sensor, thermo-couples and the pressure sensors to each other.

6- Measurement computing hardware: for converting the analog inputs, which is a voltage from the pressure sensors and a thermocouples input, into a readable signals for the computer.
7- Computer: for running the program that controls the experimental device, also for recording and showing the results.

3.3 Program used to Control the Experimental Device

A lab view program was used to control the experimental device (figure 3-4 shows the main screen of the program). In which, a thermocouple is measuring the temperature difference between the measurement-point and a reference junction, this reference junction is integrated inside an AD-converters. The thermocouple is measuring a voltage as an analog signal; the wire is connected to the AD-converter in which the reference junction is integrated. The AD-converter is converting the analog voltage signal to a digital signal (discrete signal).

Later the Labview program is reading that signal, since Labview is an graphical-program, so there are some "boxes" which do complicate operations, figure 3-5 shows example of these boxes. Simply there is one box for "read the signal" and a second one to make it visible.

For the pressure sensors, it is similar but the reference junction is not applicable, it is not used. The pressure-sensor gives just a voltage proportional to the pressure. The measured voltage is multiplied by a scale-factor to convert it to a pressure. For both of the temperature and pressure measurements, the program was measured 1 sample per second.

The heat plate is controlled by a solid-state-relay, which goes "on" and "off" 100 times per second. For example, 3% of heating power means that it was on for 3/100 seconds and off for 97/100 seconds. This is the way that the program is working.

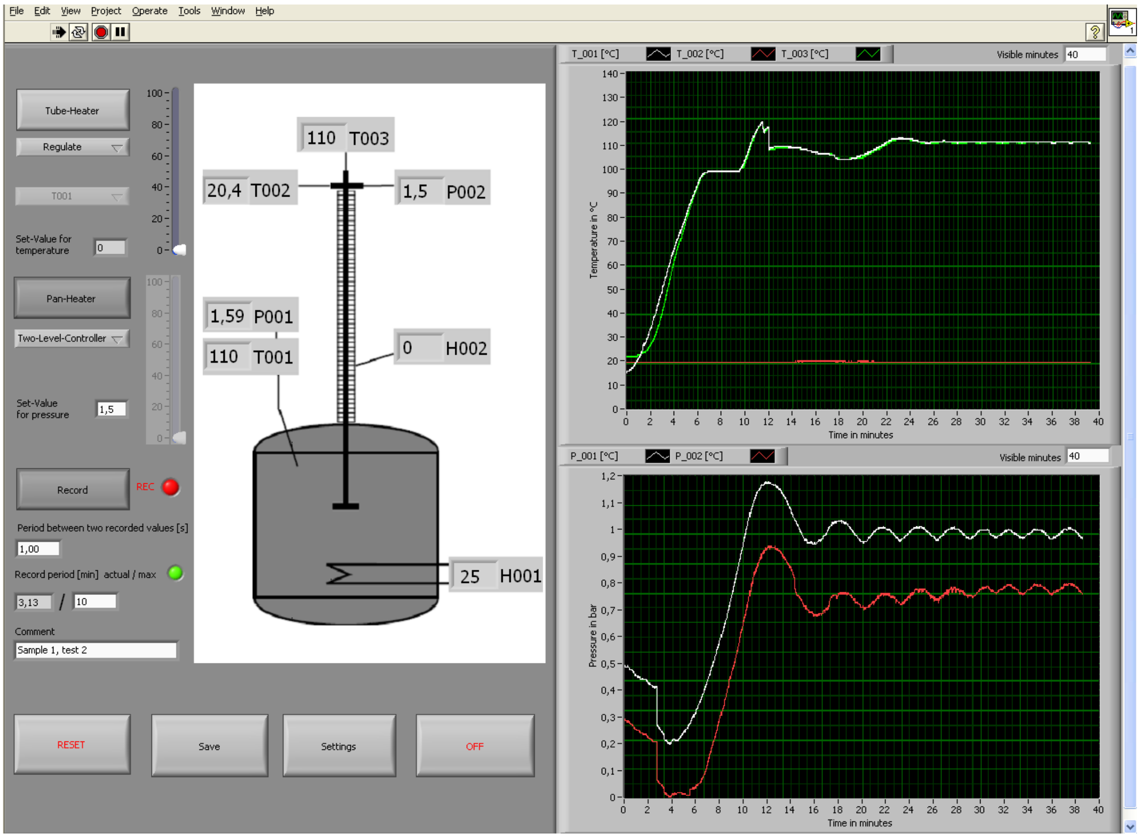


Figure 3-4 The main screen of the Lapview program

At first, the program was controlled the amount of heat supplied from the heat-plate to the pressure-vessel by controlling the amount of the power that supplied to the heat-plate by two ways, either by regulator or by the two-level control. For the regulator control of the heat plate, one can set the heat plate to 30% of its maximum power (for example) and wait to see how much steam-pressure inside the pressure-vessel will obtain. For the two-level control, one can set the pressure to the desired value 1.5 bar (for example) and the heat plat will work with its maximum power until the

pressure-gauge No. 1 measure the set-value of the pressure and then it turn-off, forevermore when the pressure became lower than the set-value, the heat-plate will turn-on again and so on.

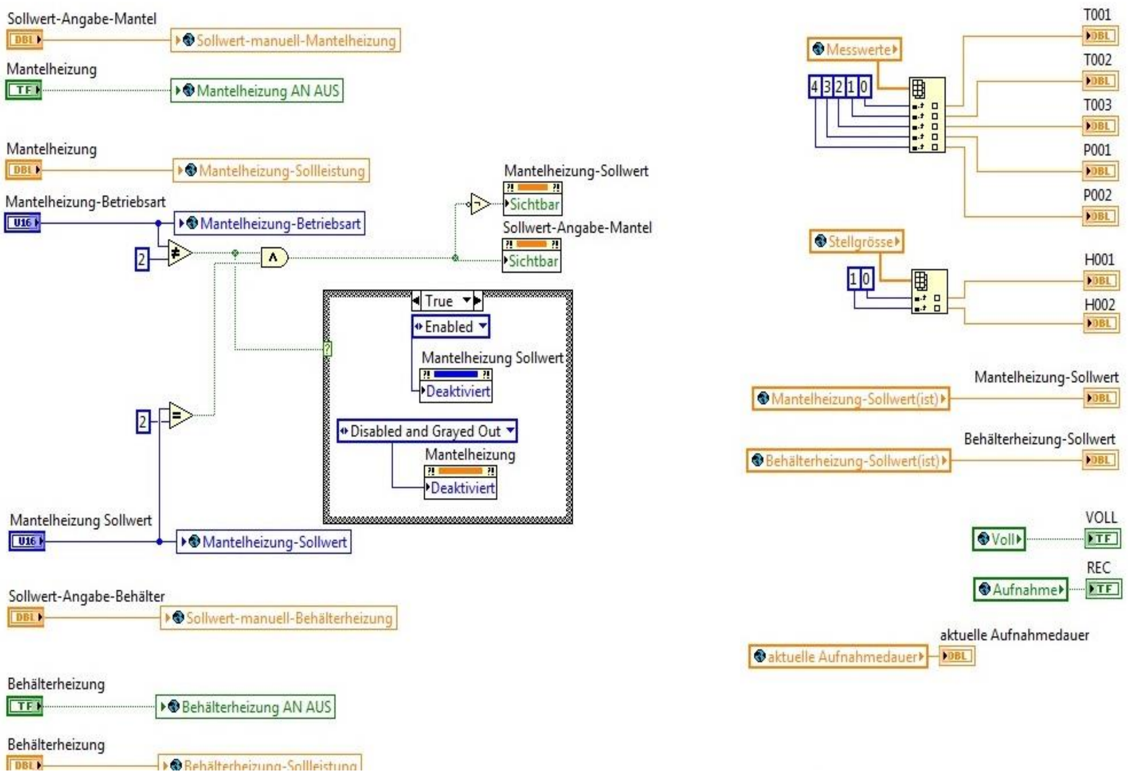


Figure 3-5 Example of the operation system of the program

The regulator and two-level control are suffered from the safety and low accuracy problem. For safe and accurate tests, it is very important to use a batter controller. In which, a PID was used to control the amount of heat supplied by the heat plate, an Empirical Tuning Rules according to Ziegler and Nichols was used to calculate the gain parameters for the PID controller.

3.4 Specimens

3.4.1 Properties of the Used Fire-Resistance Concrete

- Conventional refractory concrete, DIN EN ISO 1927-1.
- Can withstand up to 1450 ℃.
- Water/concrete ratio: 9.0 to 10.0 liters / 100 kg of dry material.

Chemical analysis:

Al_2O_3	SiO_2	Fe_2O_3	K_2O	CaO
72.0 %	15.0 %	1.5 %	0.2 %	7.5 %

3.4.2 Specimens Preparation

Six different specimen diameters (3.6, 4.3, 5.1, 6.6, 7 and 8.5 cm) and two different specimen heights (5 and 7 cm) that used in the presented experimental work, figure (3-6) shows an example of these specimens. These specimens were used for carrying out various studies on the behavior of the tube-pressure-sensor with different conditions such as drying time, wetting time, volume and type of fluid filling the space inside the tube-pressure-sensor and the “Cross Connector” and density of the fluid passing through the concrete, etc.

At the beginning of this experimental work, a manual mixing and casting processes were used to produce the specimens. Later, a mixer machine and vibrating table (see figure 3-7 (a) and (b)) were used to produce the specimens.

In addition, different molds were used for manual casting (figure 3-8) and for the vibrating table (figure 3-9).

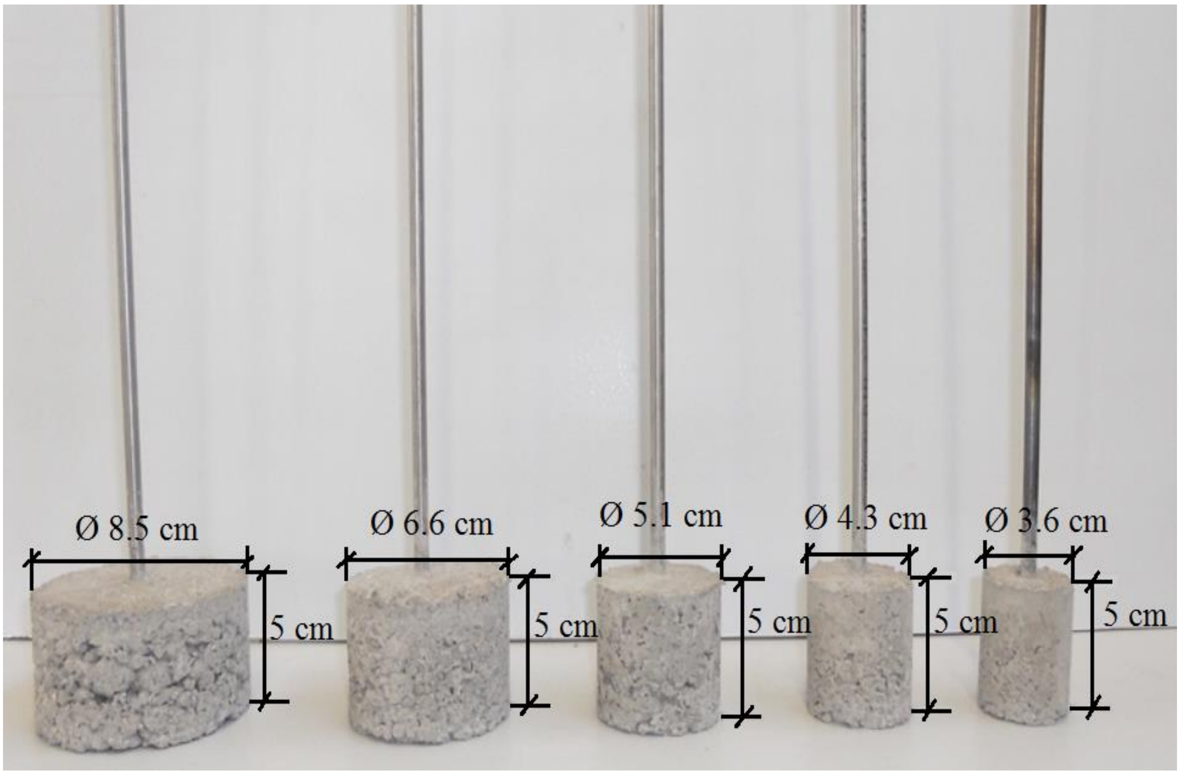


Figure 3-6 Different specimen diameters and heights

(a) **(b)**

Figure 3-7 (a)Mixer machine and (b)vibrating table used for casting

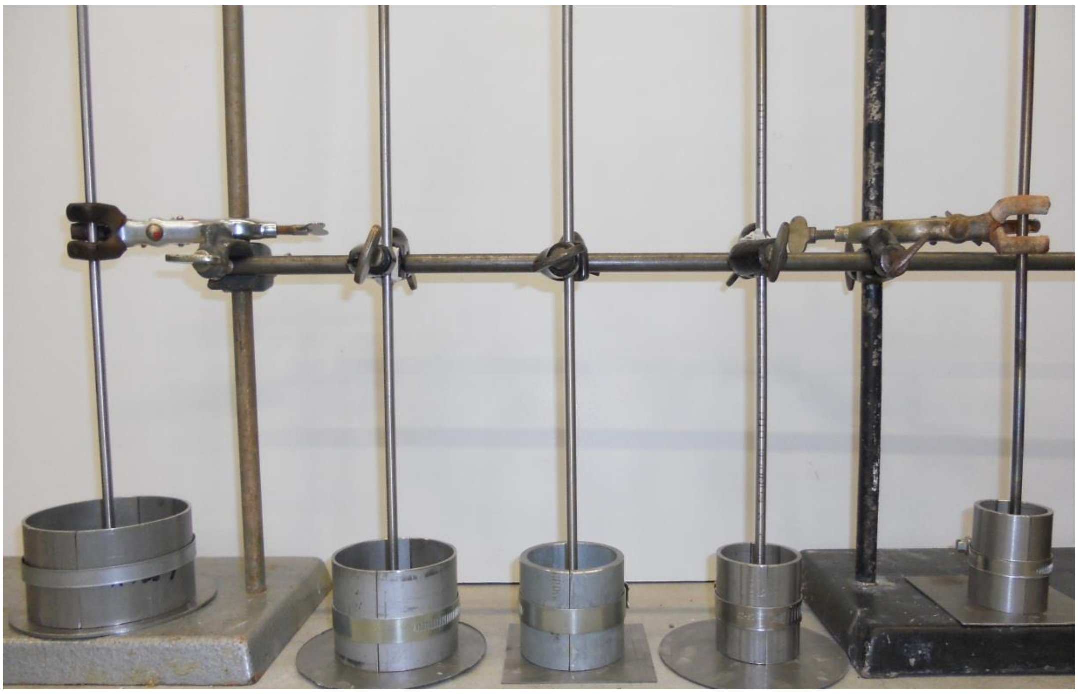


Figure 3-8 Different molds diameters used for manual casting

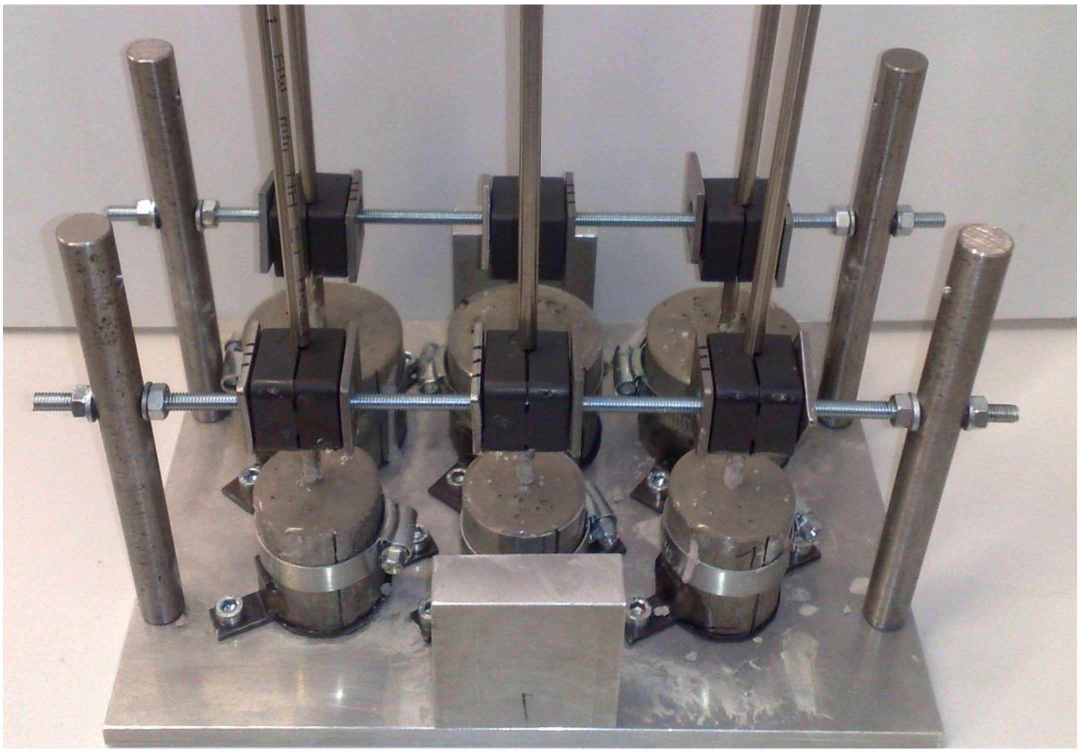


Figure 3-9 Two molds with different diameters used for the vibrating table

3.5 Studies Carried Out During the Experiments

3.5.1 The Possibility of Reusing the Available Sensor

As described in section 2.5.1, different researchers who used nearly the same pore-pressure technique (a sintered metal round plate crimped in a metal cup, and the metal cup welded to a thin metal tube) recorded a varying in the maximum pore-pressure. In addition, sometimes when this pressure-sensor was used for the first time by the company that supports our project, it measured nothing, and the explanation for such behavior was; the sintered metal round plate inside the metal cup will be closed after the casting process. This explanation wasn’t very clear, because sometimes the sensor measured something and sometimes not. Another reason for this study is the relatively high cost of the available sensor, keeping in our mind, that such kind of investigation needs to a series of tests (each test needs five to six sensors) to verify the obtained results, and the using of sensor for one time only will led to a very high overall cost.

Therefore, it is very important to check the possibility of reusing the sensor in more than one test, in order to clarify if the sintered metal will be close or not. If not, an explanation for such varying in the maximum pore-pressure that was recorded is needed, and why sometimes the pressure-sensor measured nothing. Furthermore, by the verifying of the possibility of reusing the sensor, a big reduction in the overall test cost will be achieved. With the technique used in this research, it was easy to do such check, because there is no need to cast concrete around the sensor, and heat the concrete in order to generate a high-pressure air or steam inside it. In

which the high-pressure air can be supplied to the pressure-vessel from an external source.

Two tube-pressure-sensors were tested; the first one is new, and the second one was used previously. Both tests were carried out at the same air pressure that supplied to the pressure vessel, also and all the remaining characteristics were the same.

3.5.2 Temperature Change in Thermo-Couple No. 2

As described before in section 3.2, a thermo-couple No. 2 was used for measuring the temperature of the fluid (air, water, steam or oil) inside the tube-pressure-sensor and the “Cross Connector”, specifically in front of the pressure gauge No. 2. In order to study the change in the temperature at this point, a test was carried out on the available sensor without casting any concrete around the metal cup containing the sintered metal, a high steam pressure is generated inside the pressure-vessel. This high steam pressure simulates the real case that happens in the heat-up experiment, in which the evaporation of the water droplet inside the concrete due to heating process will generate this high steam pressure.

3.5.3 The Possibility of Getting same Specimen Characteristic

In order to verify any obtained experimental results, and to be sure that is possible to consider this results as a general behavior for a specified phenomenon, it is needed to test more than one specimen and get nearly the same results from all these specimens, also the specimens should be identical in characteristics and properties.

The main object from this research is to modify a pressure-sensor, in a way to have an accurate and fast response to the change in steam pressure inside fire-resistance concrete. Therefore, some parameters should be change, such as (drying time, volume and type of fluid filling the space inside the tube-pressure-sensor and the “Cross Connector” and density of fluid passing through the concrete) following by studying and comparing the effect of these parameters on the pore-pressure measurement. In addition, there is a need to repeat these studies at least for two times, in order to verify the results obtained from this experimental work. So, one needs to cast four or more specimens have the same characteristics, such as specimen height, specimen diameter, length of the tube-pressure-sensor, drying time and many other things, but the important thing is to have the same properties of concrete mixture "water-cement ratio" and the mixing and casting processes. Therefore, it is very important to figure out if it is possible to get such identical specimens.

Two tests were carried out for this study; the first test was carried out on three specimens have the same diameter (5 cm) and height (5 cm) and all the remaining characteristics are the same. The second test was carried out on five specimens have five different diameters (3.6, 4.3, 5.1, 6.6 and 8.5 cm) and the same height (5 cm), and all the remaining characteristics are the same.

3.5.4 The Effect of Repeatability the same Specimen

From the previous study, it is found that it is difficult to get the identical specimens by the using of a manual mixing and casting process. And, due to the an availability of the mixer machine and the vibrating table

at this part of experimental work, the same specimen will be used for several tests. The using of the same specimen is more reliable to verify any obtaining experimental results, as well as to compare the effect of changing in some parameters on the pore-pressure measurement by repeating the tests on the same specimen.

Therefore, there is a need to figure out if the specimen will keep the same properties after more than one test or not, and if the specimen will have a residual pressure inside the pores of concrete or not.

For carrying out this study, one specimen was tested for three times directly one after another, the entire three tests were carried out at the same air pressure that supplied to the pressure vessel, also and all the remaining characteristics were the same.

3.5.5 The Effect of Dry out Time

For checking the effect of the drying time on the behavior of the specimen, One specimen was tested for two times with the same test conditions; the first is done after one day from casting, while the second test is done after 3 days from casting.

3.5.6 The Effect of Specimen Moistening

In most of the previous heat-up experiments that have done by different researchers, the specimens were placed in water before starting the heat-up process in order to get a homogenous and fully saturated concrete, some of them put the specimen in water for ten hours, and for three months in another research, and in another research for six months.

The heat-up experiment is not involved in the aims of the present work, but in order to take a general idea about: how the concrete will behave after moistening. Therefore, one specimen was tested for two times, the first test was carried out without make any change to the concrete specimen, while the second test was carried out on a specimen sinking in water for one hour, the same pressure and test conditions were applied for the two tests.

3.5.7 The Difference in Tube-sensor Diameter

It is very important to study the effect of the difference in the inside diameter of the tube-pressure-sensor, in order to recognize the effect of the difference in the volume of the fluid filling the space inside both of the tube-pressure-sensor and “Cross Connector”. This fluid volume has a high effect on the required time for measuring the pressure inside the pressure-vessel by the tube-pressure-sensor.

To do that, one needs to test two specimens have the same characteristics, as said before is not easy to get such thing. So, in order to get such difference in the inside diameter of the tube-pressure-sensor, the same specimen was used for two tests, the first test with the absence of the

thermo-couple inside the tube-pressure-sensor, and the second test with the existing of the thermo-couple, by simple calculation one can find the theoretical inside diameter in the second test:

$$Vol._{real} = Vol._{Theoretical} \quad (3\text{-}1)$$

$$\frac{\pi}{4}\left({d_{I.T}}^2 - {d_{T.C}}^2\right) \cdot h = \frac{\pi}{4}{d_{th}}^2 \cdot h \quad (3\text{-}2)$$

$$d_{th} = \sqrt{{d_{I.T}}^2 - {d_{T.C}}^2} = \sqrt{2^2 - 1.5^2} = 1.323\ mm \quad (3\text{-}3)$$

Therefore, by the removing of the thermo-couple from the tube-pressure-sensor, it is just like comparing two tube-sensors with two inside diameters, first test 2 mm, and the second test 1.323 mm.

3.5.8 The Difference in Fluid Volume inside the Tube-sensor

The previous study provides an introduction to a another study, which is the effect of the difference in the volume of fluid that fills the space inside both of the tube-pressure-sensor and the “Cross Connector”. The important thing in this study is; what is the volume of the fluid inside both of the tube-pressure-sensor and the "Cross Connector", no matter the length or the inside diameter of the used tube-sensor.

Because of the complexity of the inner shape of the “Cross Connector”, due to the welding processes and the different tube fittings that have been used to produce the “Cross Connector”, it is difficult to calculate the inner volume of “Cross Connector” by a geometrical method. Therefore, the mass of the water need to fill the “Cross Connector” was measured, and with the knowing of density of the water, one can calculate the inner volume of the “Cross connector” $V_{Cross} = 6343.8\ mm^3$.

Five different cases with five different fluid volumes were carried out on the same concrete specimen (to be sure that the specimen has exactly the same characteristics), by connecting different tubes to the tube which had been previously cast with the concrete specimen, also with the presence and absence of the thermo-couple inside the tube-pressure-sensor.

Case	Volume mm^3
1	6684.76
2	7327.12
3	9651.9
4	12971.84
5	14565.35

Table 3-1 Five different volume for the space inside the pressure-sensor and the "Cross Connector"

3.5.9 The Effect of Inverting the Test Situation

Most of the previous heating-up experiments that carried out by different authors, as described in section 3.2, were done by an opposite situation to the tests that done in the presented work, in which the heat is applied to the upper face of the concrete specimen, and the pressure gauges that placed during casting were come out of the bottom face of the specimen. Therefore, it is important to know if the inverting situation for testing will affect the behavior of the tube-sensor or not.

Figure 5-10 shows a scheme for the two tests that carried out on the same concrete specimen, and the same test conditions, the first test with the normal position (figure 5-10 A) and the second test with an opposite position (figure 5-10 B).

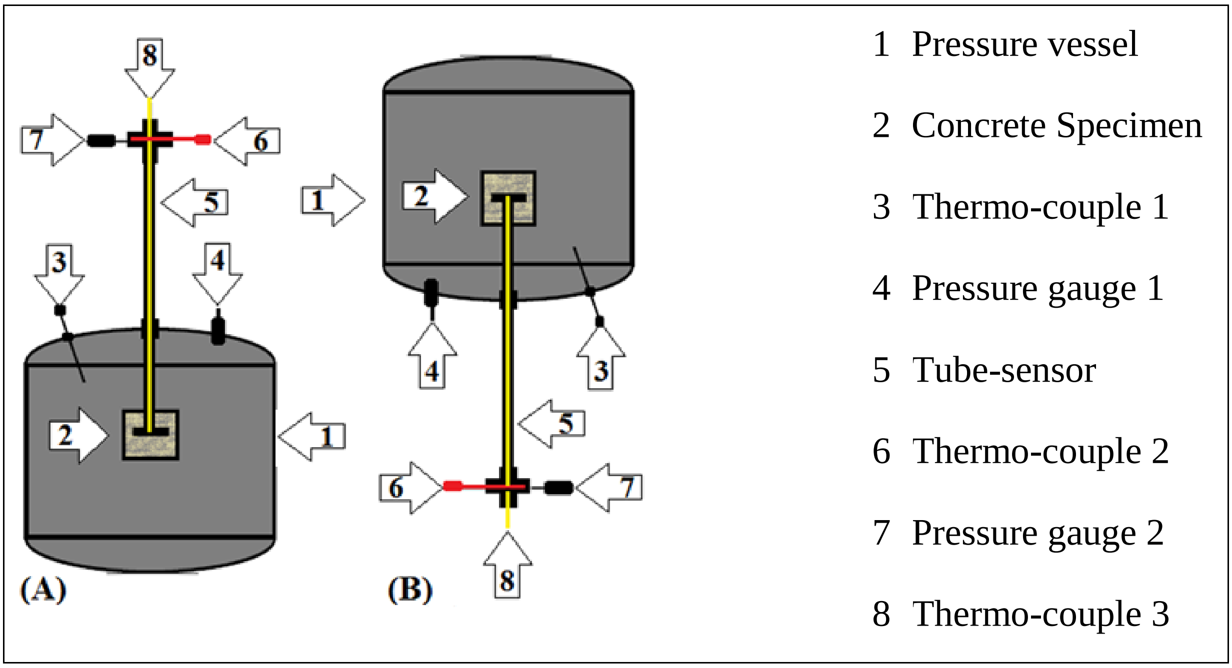


Figure 3-10 Experimental tests: (A) Normal positions, (B) Opposite position

3.5.10 Effect of the type of Fluid Passing through the Specimen

Most of previous tests were carried out by forcing the ambient air with high-pressure inside the pressure vessel to pass through the concrete specimens, while in the reality one will have a mixture of liquid water, water vapor and gaseous. According to Darcy's law of pressure driven flow, the change in the viscosity of the fluid that is passing through the specimen has a significant influence on the speed of transporting for the gaseous or the liquid water through a porous media. Therefore, it is important to study this effect in the presented experimental work.

One specimen was tested two times; the first test was carried out by forcing a high-pressure dry air to pass through the pores of the concrete specimen, by applying a pressure of (2.79 bar) inside the pressure vessel. The second test was carried out by forcing a water to pass through the

pores of the concrete, by filling the pressure vessel with water to a level enough to totally cover the specimen with water, and apply the same pressure ($2.79\ bar$).

3.6 Modification of the Tube-Pressure-Sensor

The major object from this research is to develop the tube-pressure-sensors, so that one gets a quick response to the change in pressure of air inside the concrete specimen. In the previous tests, the air was filling the space inside each of the tube-pressure-sensor and the “Cross Connector”, and these studies showed that: the different specimens gave different time delays. These time delays are due to two reasons or two parts. The first part is the time required for air with a high pressure inside the pressure-vessel to pass through pores in the concrete specimen. The second part is the time required to compress the air column inside both of the tube-pressure-sensor and the “Cross Connector” from the atmospheric pressure to pressure of air inside the pressure-vessel. Therefore, it is very important to reduce this time delay.

The first part of this time delay is uncontrollable, because it depends on the permeability of the concrete, but it is possible to control the second part of this time delay. One can control the second part of this time delay by two ways: either by the use of an incompressible fluid or a fluid has a very small compressibility, such as water inside the tube-pressure-sensor and the “Cross Connector”, or by reducing the volume of air inside the tube-pressure-sensor and the “Cross Connector”.

3.6.1 Changing the Type of Fluid inside the Tube-sensor

One specimen was tested for two times, the first was carried out with an air filling the space inside the tube-pressure-sensor and the “Cross Connector”, and the second test was carried out with water filling the space. In addition, the effect of changing in the type of the fluid filling the space inside the tube-sensor and the “Cross Connector” by the opposite position was carried-out. In which, one concrete specimen was tested for two times, one time with air filling this space and the second time with water filling this space, but in this time the “Cross Connector” is filled only, which represents the major part of the total fluid volume ($6684.76\ mm^3$); ($6218.3\ mm^3$) for the “Cross Connector” and ($466.46\ mm^3$) for the tube-sensor.

3.6.2 Changing the Volume of Fluid inside the Tube-sensor

As said before, the volume of fluid inside the tube-sensor and the “Cross Connector” has a big influence on the response of the tube-pressure-sensor, and the reducing of the total volume is an important matter. Therefore, a new connector was produced in order to reduce the inner volume of the connector. In addition, a thermo-couple with a diameter ($1.9\ mm$) bigger than the old one ($1.45\ mm$) was used for farther reduction in the fluid volume.

The new connector that shown in figure (3-11) has another feature, which is the elimination of the thermo-couple No. 2 (that used for measuring the temperature of the fluid (air, water, steam or oil) in front of the pressure gauge No. 2), this thermo-couple was eliminated according to the study in section 3.4.2, and the obtained results from this study.

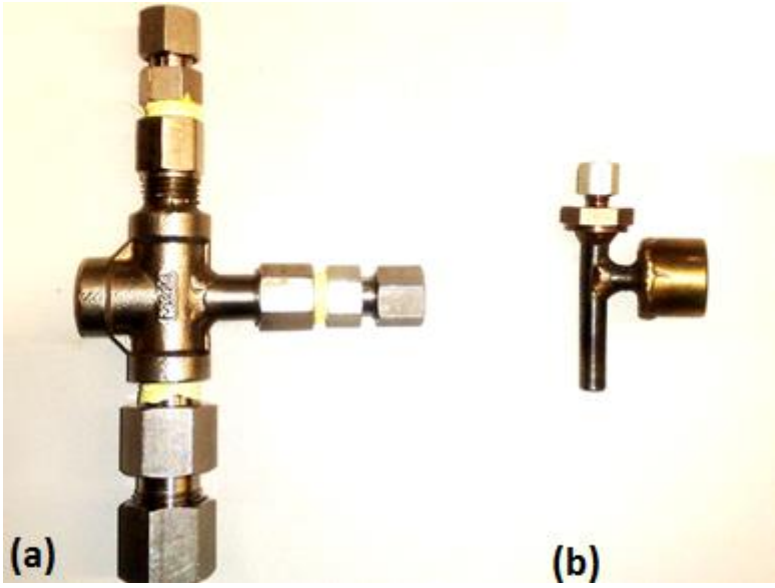


Figure 3-11 Pressure and thermo-couple connector: (a) Old one, (b) New one

The net fluid volume in the new connector is $(300.73\,mm)$, and comparing to the old "Cross Connector" $(6218.3\,mm)$, a reduction of (95 %) in the fluid volume is achieved.

Two tests were carried-out on the same specimen and the same test conditions, the first test by the use of the old "Cross Connector" and the old thermo-couple, and the second test by the use of the new connector and the new thermo-couple.

3.6.3 Modification on the Tube-Sensor Profile

Fire-resistance concrete (refractory concrete) suffers from the shrinkage problem as same as the Portland cement or the normal concrete. It is a normal behavior for most kinds of concrete, and the aim of this research is not to prevent or reduce this behavior, but the important thing for this research is the big problem caused by this shrinkage for the measuring of the pore pressure inside the fire-resistance concrete. In which the concrete that surrounded the tube-sensor will shrinking and create a crack along the part of the tube-sensor that is previously casted inside the concrete specimen. This crack will start from the surface of the specimen till the end of the tube-pressure-sensor inside the specimen, such a crack will works as a path for the high-pressure gaseous (gaseous that generating inside the concrete specimen due to the heating process) to leak out through this path to the surrounding, and not to fill the tube-sensor.

If such leakage accrues, the tube-sensor will measure a part from the actual pressure inside the concrete specimen and maybe it will measure nothing, depending on the size of the crack. In this case, the tube-sensor will have a lower sensitivity to the change of the pressure inside the concrete specimen, and if the crack is big enough the tube-sensor will have no sensitivity.

In the technique used in this research, the situation is little different, where the high-pressure air inside the pressure vessel will pass through the crack from the surface of the specimen down to the end of the tube-pressure-sensor, and then into the tube-sensor. Therefore, the tube-pressure-sensor will measure the pressure of air that pass through the crack

not through the porous of the concrete specimen. In this case, as much as the tube-sensor has a higher sensitivity to the change in pressure inside the pressure vessel, as much as there is a bigger crack between the tube-pressure-sensor and the concrete specimen.

Therefore, it was an extremely important to modify the tube-pressure-sensor in order to eliminate this leakage which came from the initiation of the crack due to the shrinkage effect. One of the ideas to modify the tube-pressure-sensor is the use of a circular barrier, in order to increase the contact area between the concrete and the tube-sensor, also to make the path of the crack more complicated.

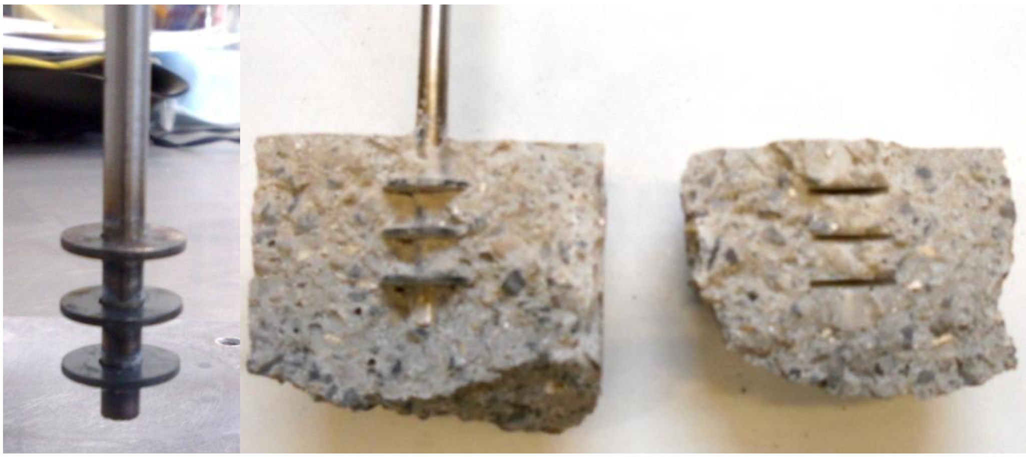


Figure 3-12 Modification on the tube-sensor, the use of three barriers

In order to check if the use of the three barriers welded to the casted end of the tube-sensor (as shown in figure 3-12) will improve the sensitivity of the tube-pressure-sensor or not, a test for a four specimens with this modification on the tube were carried out, with the same condition of testing.

4 Chapter Four: Results and Discussion

This chapter presented the obtained results from the different studies for the effect of different parameters on the pore pressure measurement, which have been carried out by the technique used in this research.

4.1 The Possibility of Reusing the Available Sensor

Figure 4-1 shows the result for this study. In which, the used sensor is still work and the sintered metal porous is still open, as shown there is a small time delay between the air pressure inside the pressure vessel that measured directly and through the tube-pressure-sensor, which is the time delay required to compress the air inside the tube. Therefore, the varying in the recorded maximum pore-pressure and the zero measured pressure in sometimes, were because of the leakage that initiated due to the shrinkage cracks in the concrete attached to the tube-pressure-sensor.

4.2 Temperature Change in Thermo-Couple No. 2

As seen in figure 4-2, there is no change in the temperature measured by the thermo-couple No. 2, while it has seen that the temperature measured inside the pressure vessel increased and reached to 110 ℃ by the generation of steam. In addition, one can notice that at the beginning of the test the temperature inside the pressure vessel is lower than the temperature measured by thermo-couple No. 2 due to the excited of the water inside the pressure vessel. Therefore, one can say that for this range of temperature $(0 - 120\ ℃)$ that the used pressure gauge can withstand it, there is no need for use this thermo-couple.

4.3 The Possibility of getting same Specimen Characteristic

For the first test, it is expected to get the same results for the three specimens, but as seen in figure 4-3, the specimens have a three different time delays.

For the second test, it was expected to get results that have the same behaviors but different time delays for the air of high pressure to pass through the different diameters of concrete specimens. As seen in figure 4-4, the results were random and not as expected, the arrangement of the specimen according to the time delay from the smallest to the largest value was as follow: D=8.5, 5.1, 4.3, 6.6 and 3.6 cm.

The unexpected behaviors for both of the previous two tests were because of the manual mixing and casting processes. Therefore, one needs to modify the mixing and casting processes by two ways; first, using of a mixer machine for mixing the row concrete with water. Second, using of a vibrating table for compacting the concrete, getting a homogenous concrete specimen, and also for releasing all the air bubbles inside the concrete.

4.4 The Effect of Repeatability the same Specimen

From this study, the same results were obtained for the three tests as seen in figure 4-5. Therefore, one can say that it is possible to retesting the specimen for more than one time, in order to make any comparison or study on the behaviors of pore-pressure-sensor in different conditions, and the obtained results from these studies are reliable and dependable.

4.5 The Effect of Dry out Time

For this study, it was expected that after three days from casting, the concrete specimen becomes drier, and it would have more pores, more pores generated from the evaporated water droplets inside the concrete, and the higher porosity led to higher permeability of the concrete.

But the result for these two tests came opposite to what was expected, figure 4-6 shows that after three days, the concrete specimen becomes less permeable, and the pressure rising becomes more slower.

4.6 The Effect of Specimen Moistening

It is seen from figure 4-7, after one hour moistening the concrete specimen by snaking in water, the concrete specimen and the tube-pressure-sensor need ($4.5\ min$) to transfer the pressure form the pressure vessel to the pressure gauge, while with the dry concrete specimen, it needs ($2\ min$). This means that, by sinking the specimen for one hour, an increment of ($55\ \%$) in the time delay is obtained. This increment in the time delay occurred due to the following reason: by sinking the specimen in water, the water will go deeply inside the concrete, and it will fill the pores and reduce the permeability of the concrete.

4.7 The Difference in Tube-sensor Diameter

The result of this study can be seen in figure 4-8, in which by increasing the inside diameter of the tube-pressure-sensor, more time delay in the rising time for the pressure of air that passed through the concrete specimen is achieved.

4.8 The Difference in Fluid Volume inside the Tube-sensor

As expected for this study, by increasing the volume of the fluid that filling the space inside both of the tube-pressure-sensor and the "Cross Connector", there is more time delay in the rising time for the pressure of air that passed through the concrete specimen is achieved, as seen in figure 4-9.

For more explanation of this study and for easy comparison between the five different cases of fluid volumes, one can calculate the time delay for each case by the using of the curve fitting approximation, the five different calculated time delays for the five different fluid volumes can be seen in figure 4-10. In which by the increase of fluid volume more time delay is obtained.

4.9 The Effect of Inverting the Test Situation

As seen in figure 4-11, the results of this study come as follow: the first test is coincided with the second test, and there is no effect in the inverting situation for the experimental device. In addition, all the previous studies that have done by the normal situation are reliable and dependable.

4.10 Effect of the type of Fluid Passing through the Specimen

As seen in figure 4-12, with the air test, the concrete specimen and the tube-pressure-sensor need ($17\ sec$) to transfer the pressure form the pressure vessel to the pressure sensor, while with the water test it needs ($10\ min$). The time needed for the water to pass through the specimen is more than the time needed for the dry air, and this is normal because the water has a higher viscosity than the air, and the viscosity is inversely proportional to the speed of transportation according to Darcy's law. In

addition, in the case of water, there is a steady error ($0.026\ bar$) between the pressure of air that measured directly inside the pressure-vessel and through the concrete specimen, one can explain this error as follow:

Before applying the pressure, the volume of air inside both of the tube-pressure-sensor and the "Cross Connector" is $8783.34\ mm^3$. After applying a pressure of ($2.79\ bar$), the air inside both of the tube-pressure-sensor and the "Cross Connector" will compressed, and the new volume of compressed air will be $3396.5\ mm^3$. The new volume of the compressed air ($3396.5\ mm^3$) is nearly half of the inner volume of the "Cross Connector" ($6343.8\ mm^3$), which means that the tube-pressure-sensor and half of the "Cross Connector" will fill with water which was forced to pass through the specimen. This water will apply an opposite pressure to the pressure inside the pressure vessel.

The column of water will be the length of the tube-sensor ($23.5\ cm$) adding to it a ($3\ cm$) which is approximately half of "Cross Connector", and the opposite pressure will be $P_{water} \approx 0.026\ bar$. This is exactly the steady error that obtained in the presented results.

4.11 Changing the Type of Fluid inside the Tube-sensor

As seen in figure 4-13, with the air test, the concrete specimen and the tube-pressure-sensor need ($16\ min$) to transfer the pressure of air form the pressure-vessel to the pressure gauge, while with the water test it needs ($4\ min$) to reach a study error of ($0.03562\ bar$). This steady error is due to the column of water that creates an opposite pressure to the pressure inside the pressure vessel. The column of water has a length of the tube-sensor

(31 cm) and the “Cross Connector” (5.5 cm), so the opposite pressure will be:

$P_{opp.} =\approx 0.0358\ bar$

This is almost the steady error that obtained in the presented results. Therefore, one can say that a reduction of (75 %) in the time delay is achieved by the use of water instead of air as fluid filling the space inside the tube-pressure-sensor and the “Cross Connector”.

One can see the result for the inverting position for the experimental device in figure 4-14 in which, with the air test, the concrete specimen and the tube-sensor need (18 min) to transfer the pressure form the pressure vessel to the pressure sensor, while with the water test it needs (3 min). As well as, it can be noticed that there is no steady error in this case, because there is no water column in the tube-sensor. Therefore, one can say that a reduction of (83 %) in the time delay is achieved by the use of water instead of air as a filling fluid.

4.12 Changing the Volume of Fluid inside the Tube-sensor

As seen in figure 4-15, with the old ‘Cross Connector” and the old thermo-couple, the concrete specimen and the tube-pressure-sensor need (3 min) to transfer the pressure of air form the pressure vessel to the pressure gauge, while with the use of the new connector and the new thermo-couple needs (1 min). Therefore, one can say that a reduction of (67 %) in the time delay is achieved by the use of the new connector and the new thermo-couple.

4.13 Modification on the Tube-Sensor Profile

The results for the four tests can be seen in figure 4-16, in which all the four specimens gave nearly the same time delay $(18\, sec)$ approximately. In addition, this is a very low time delay, which means that the specimens still have a big crack. In order to find how much these barriers improve the tube-pressure-sensor, a comparison between the barriers and non-barriers tube-pressure-sensor can be seen in figure 4-17. In which, the same time delay in the measured air pressure for both of the barriers and non-barriers tube-pressure-sensor, also it can be noticed that there is an intersection between the two curves, and this is due to the fluctuation in the high-pressure air that supplied from a compressor to the pressure vessel, and the manual control by the on-off valve. The result from this comparison is; there is no benefit from the use of these barriers, because it is nearly the same time delay for the two tests.

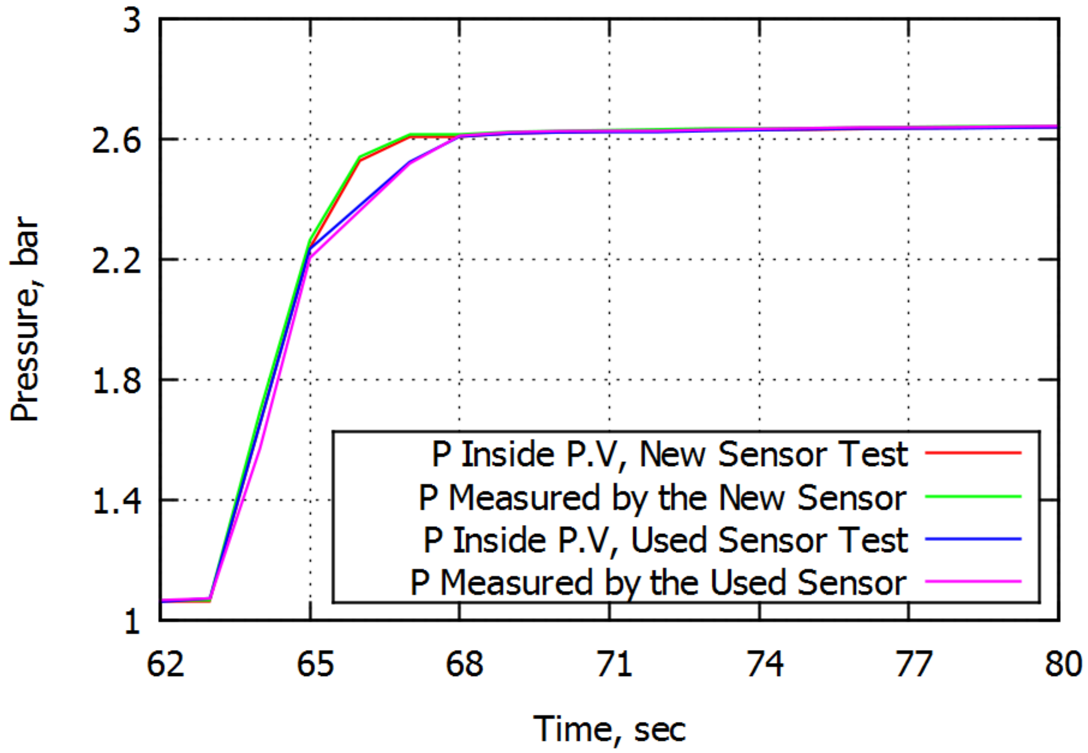


Figure 4-1 Comparison between the used and the new pressure sensor

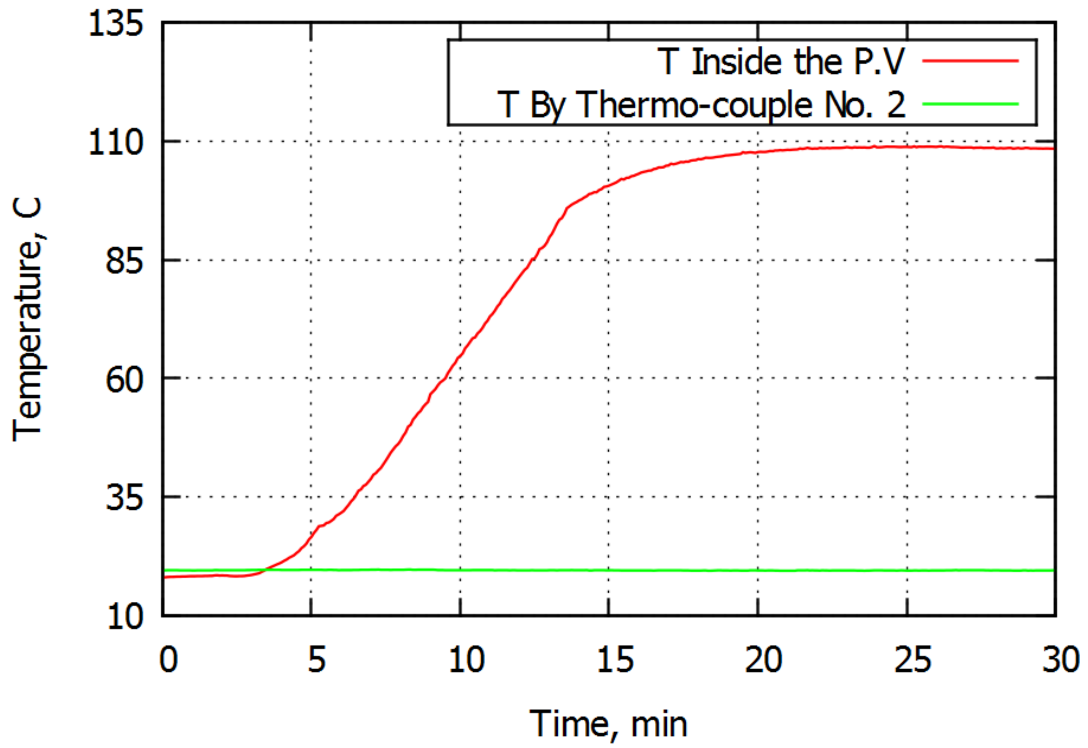


Figure 4-2 Steamtemperature change in thermo-couple No. 2

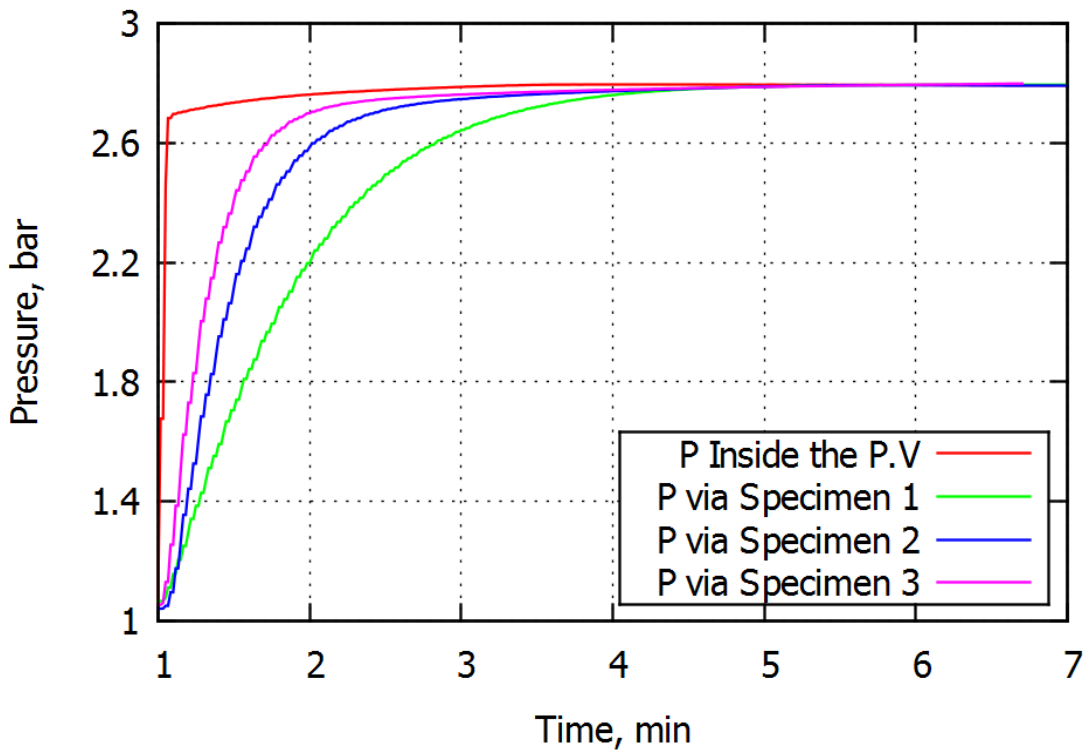


Figure 4-3 The relation between air pressure and time for three specimens with the same diameter

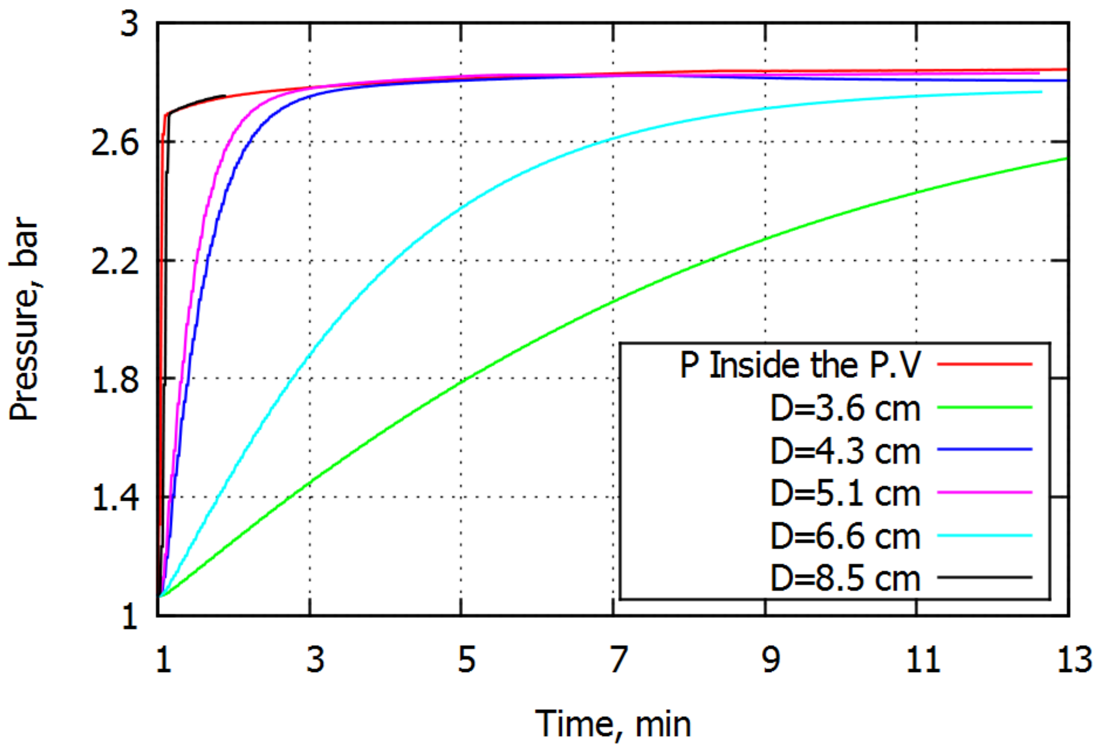


Figure 4-4 The relation between air pressure and time for five different specimn diameters

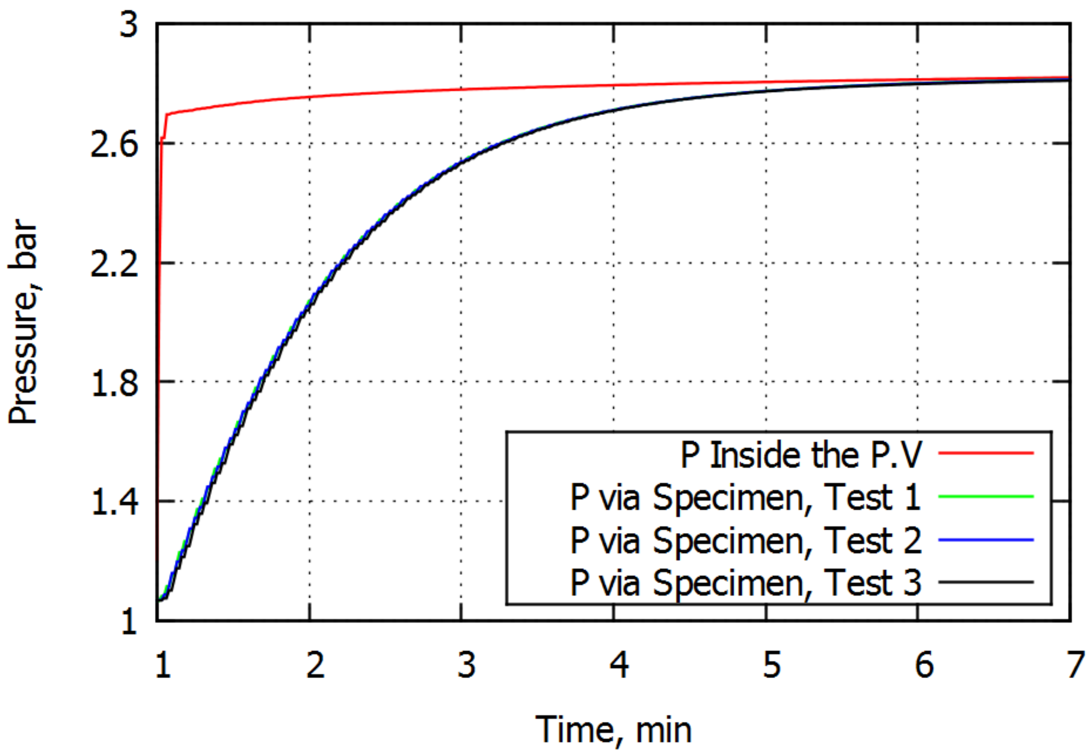


Figure 4-5 The relation between air pressure and time for three tests done on the same specimen

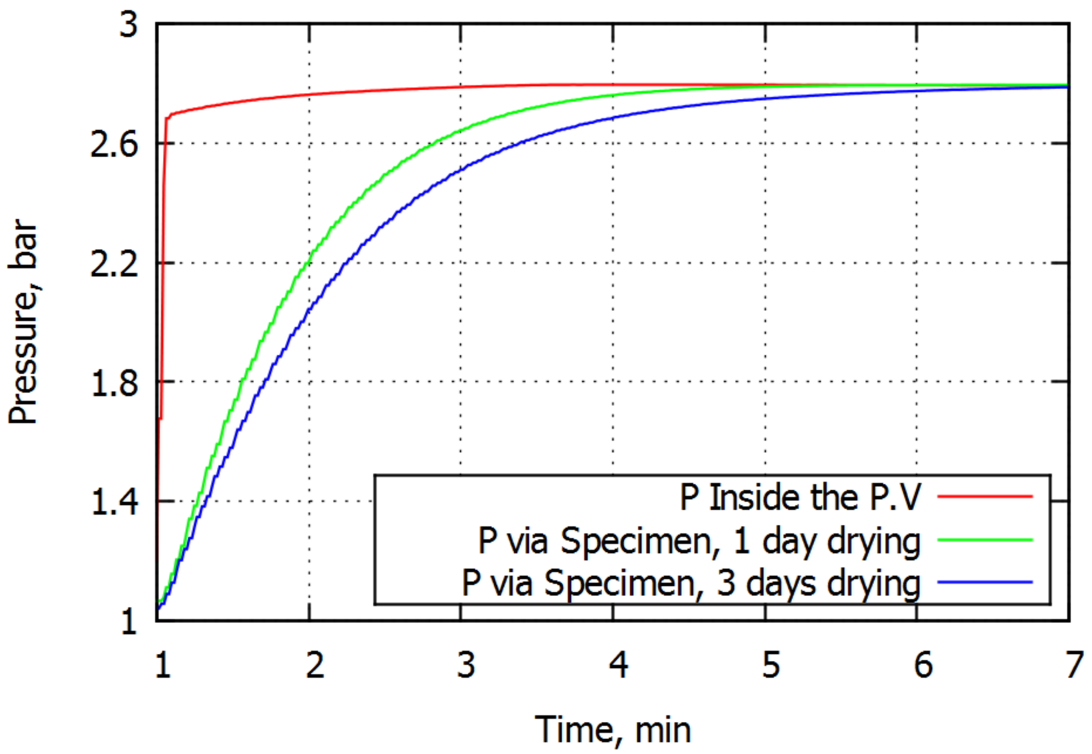


Figure 4-6 The effect of dry out time on air pressure for two different dry out time

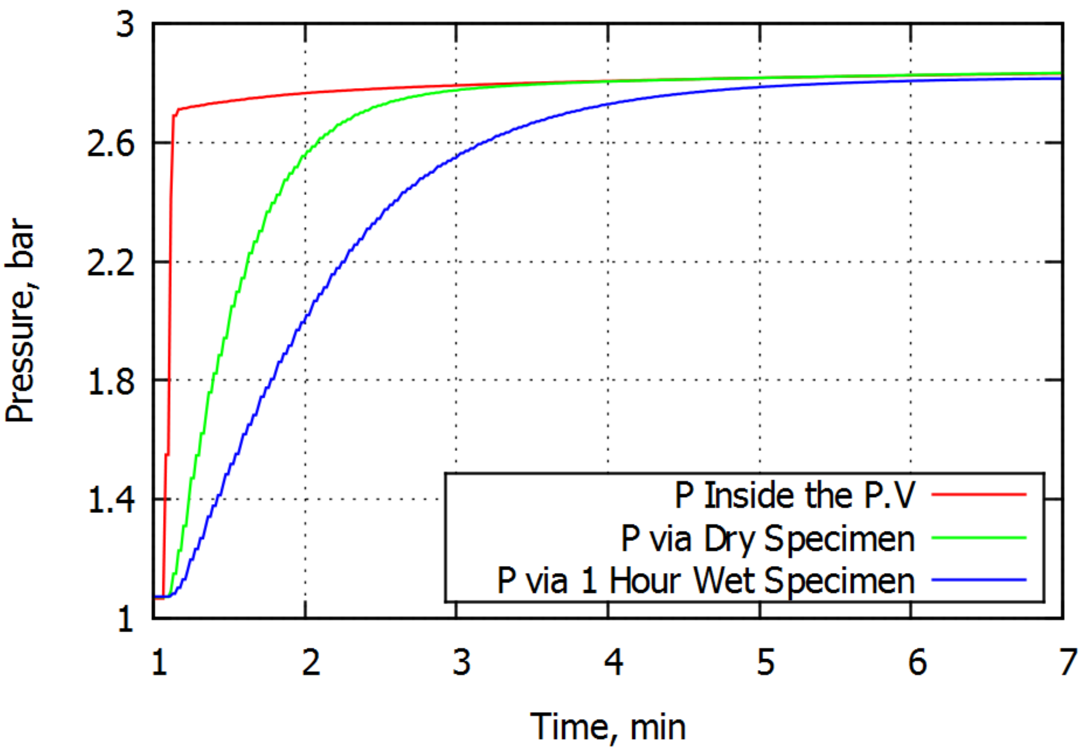


Figure 4-7 The effect of specimen moisting on air pressure

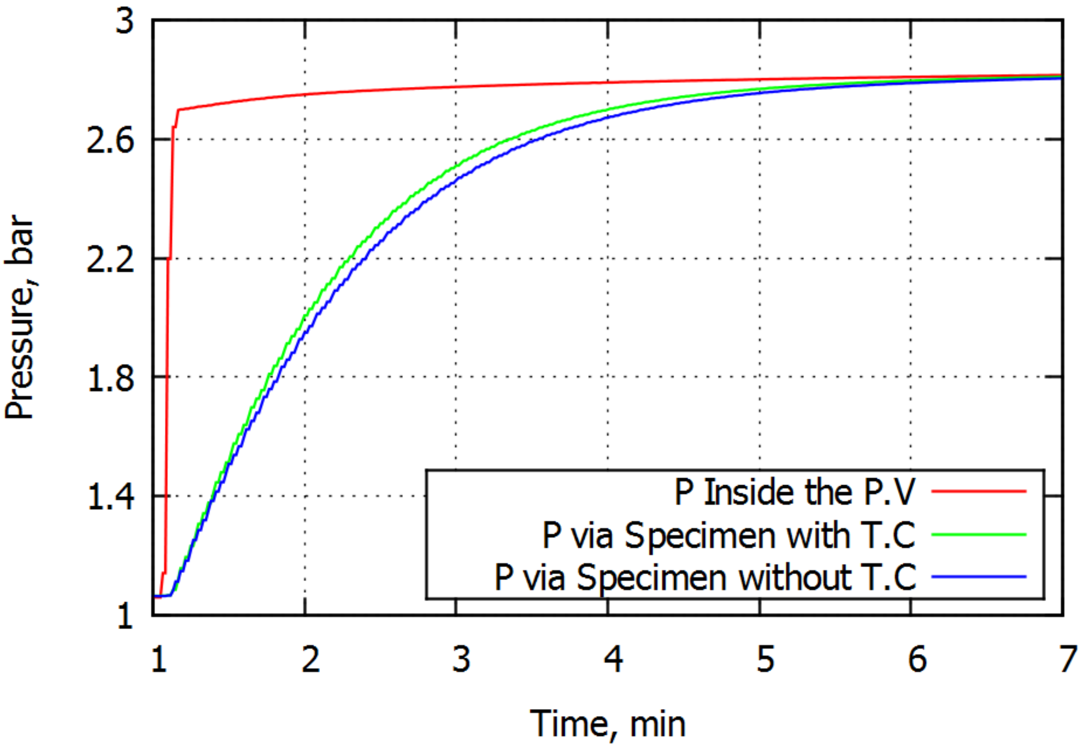


Figure 4-8 The relation between air pressure and time for two different diameters of tube sensor

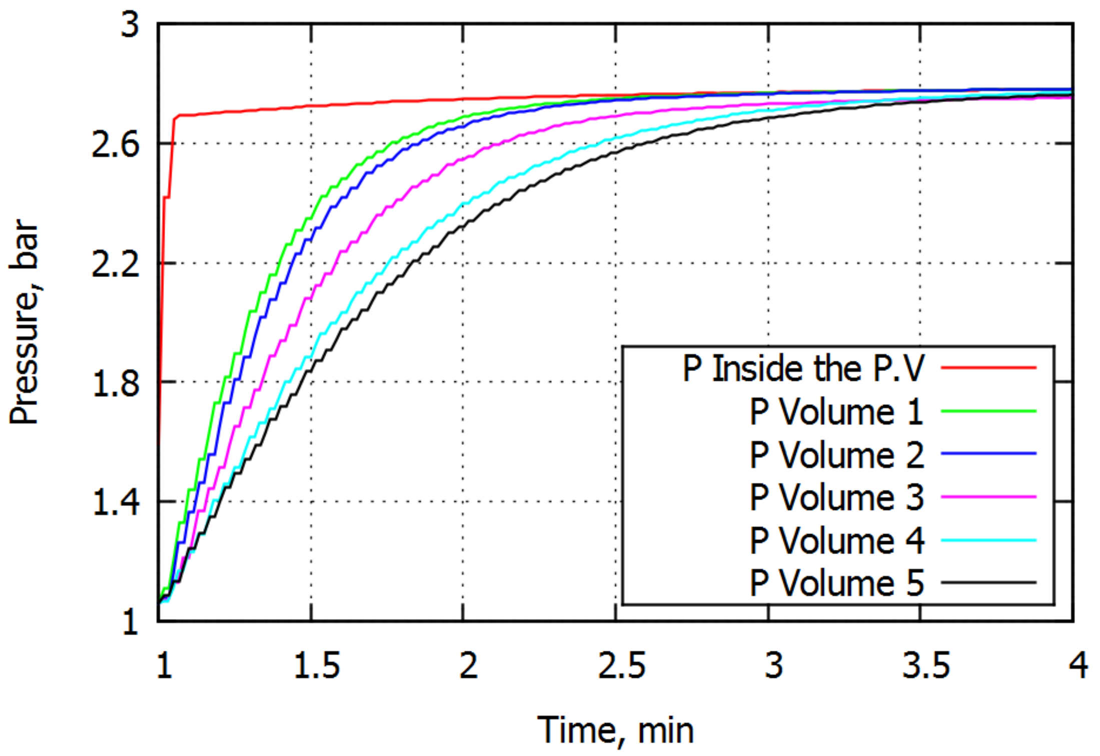


Figure 4-9 The relation between pressure and time for five different fluid volumes

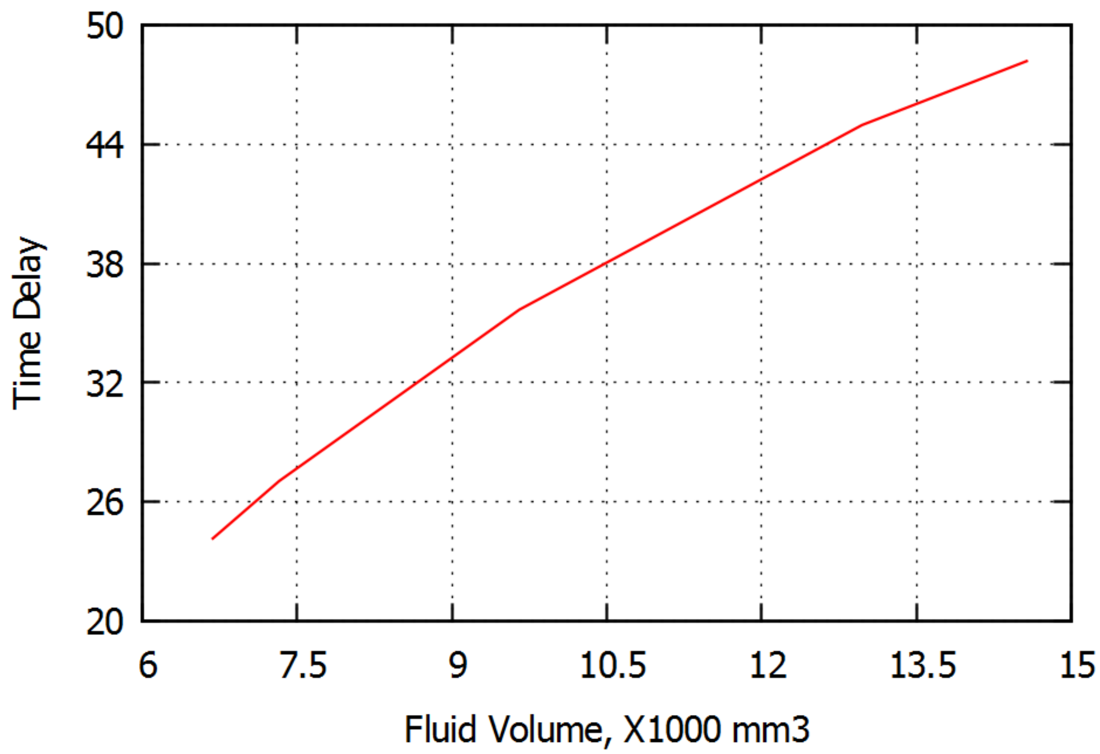


Figure 4-10 The relation between fluid volume and time delay

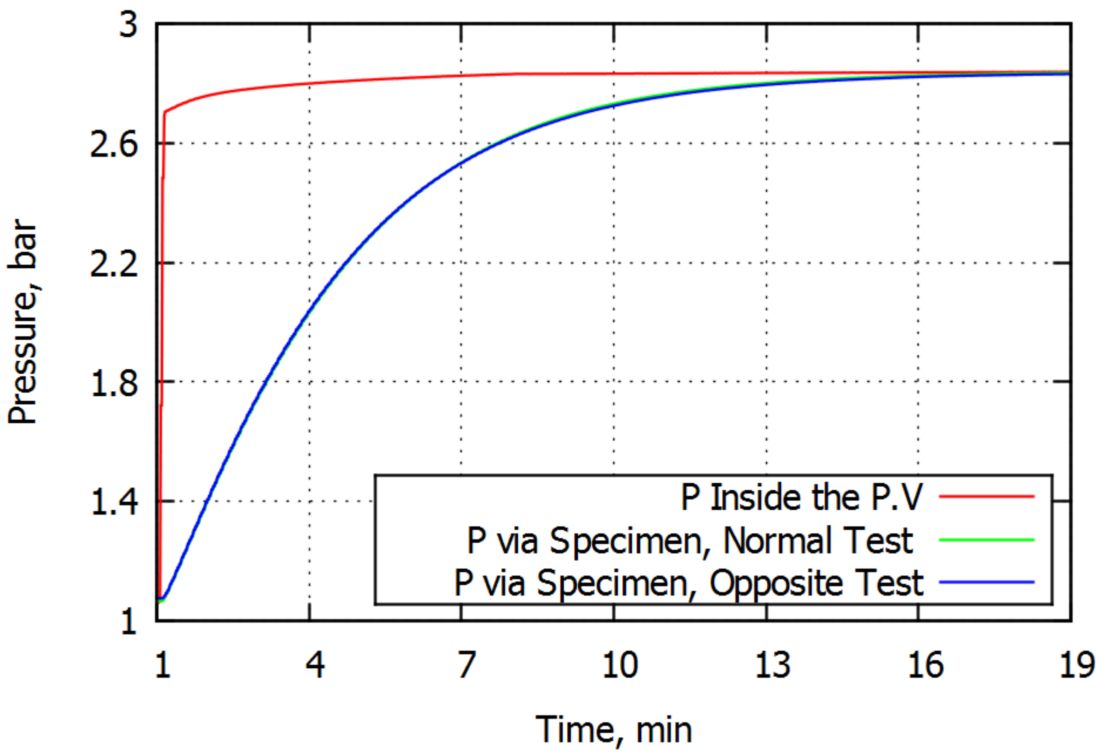


Figure 4-11 The relation between air pressure and time for normal and opposite position

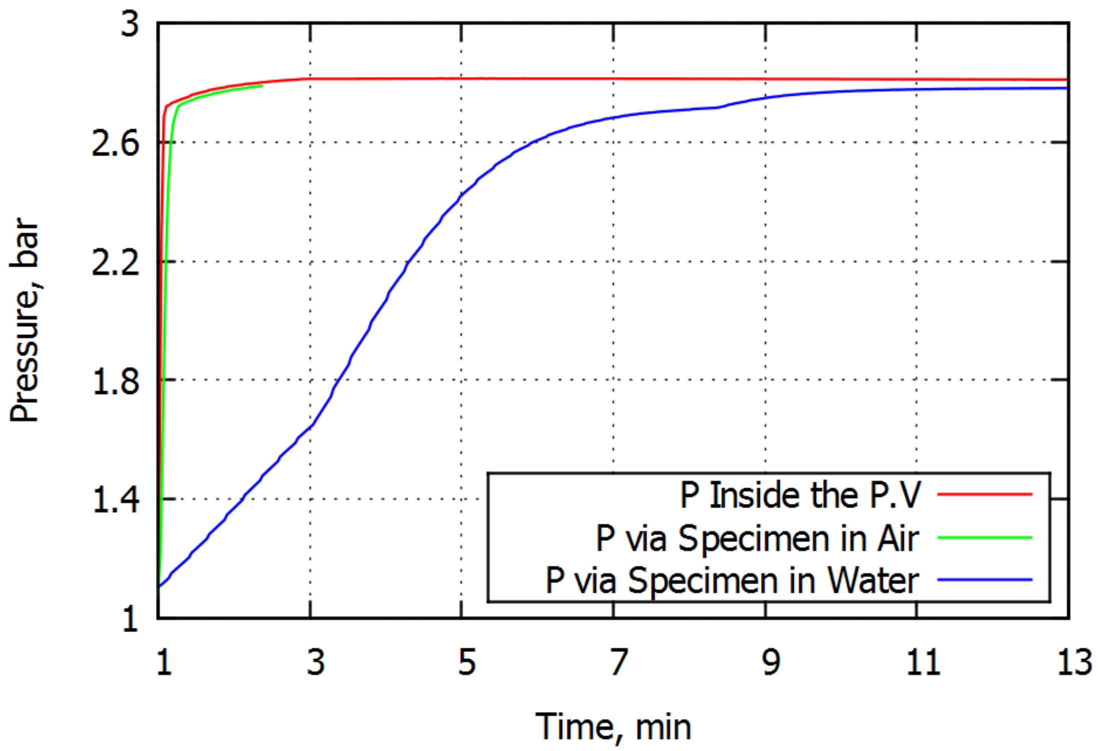


Figure 4-12 Effect of type of fluid (air/water) passing through the specimen

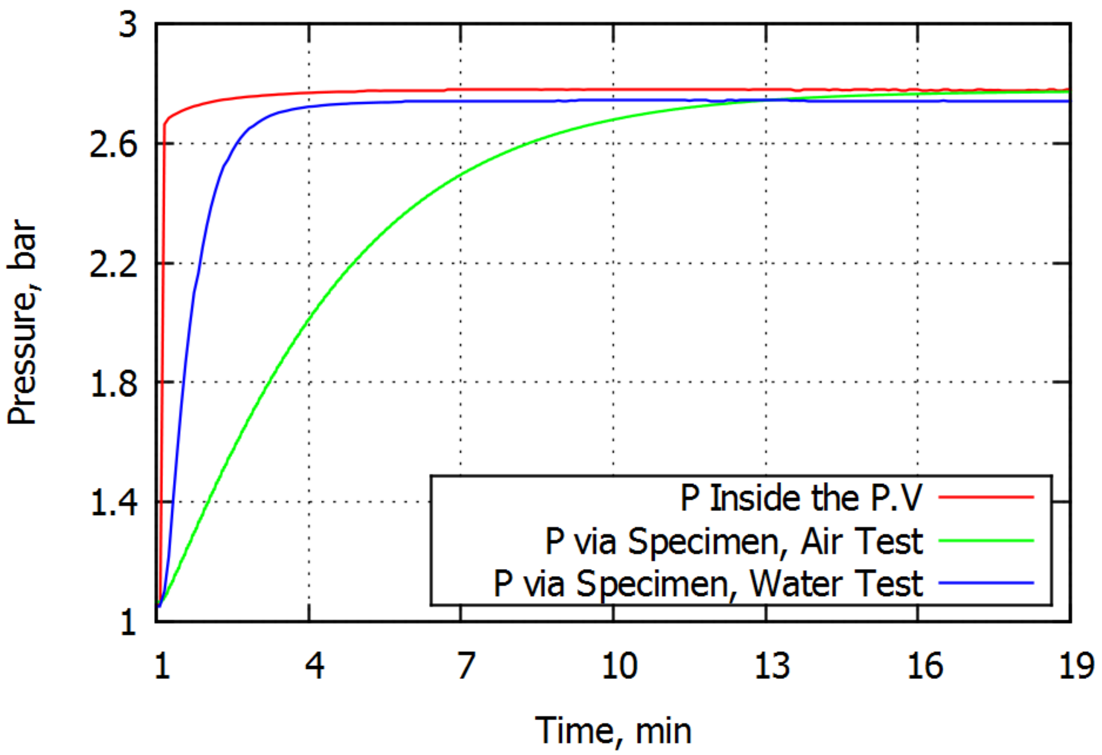


Figure 4-13 Effect of fluid type (air/water) inside the tube-pressure-sensor

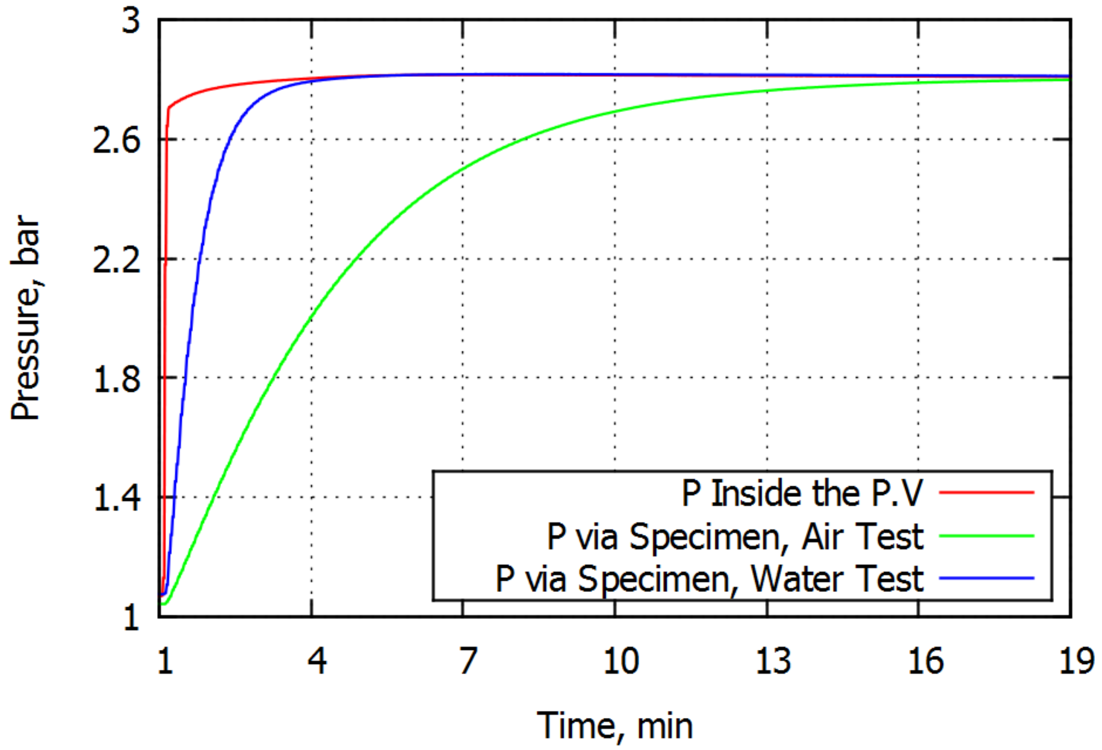


Figure 4-14 The relation between pressure and time for opposite position, air and water test

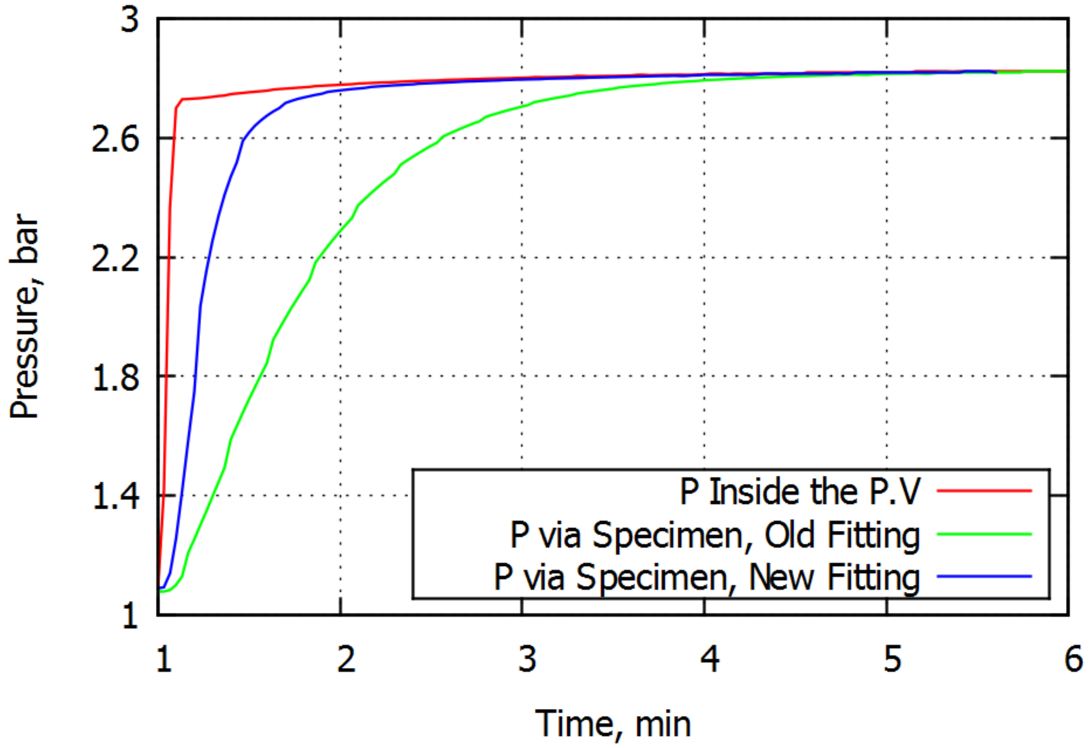


Figure 4-15 The effect of reducing the space volume inside the pressure-sensor; old and new connector

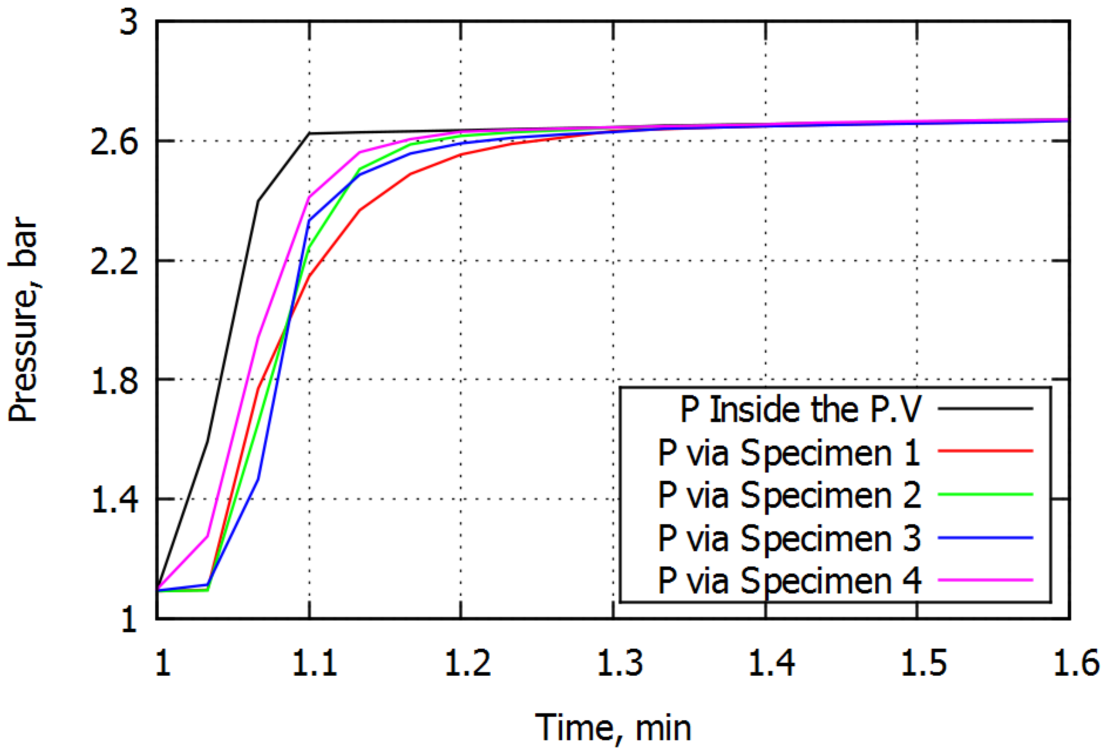


Figure 4-16 Four specimens with three barriers on tube-pressure-sensor

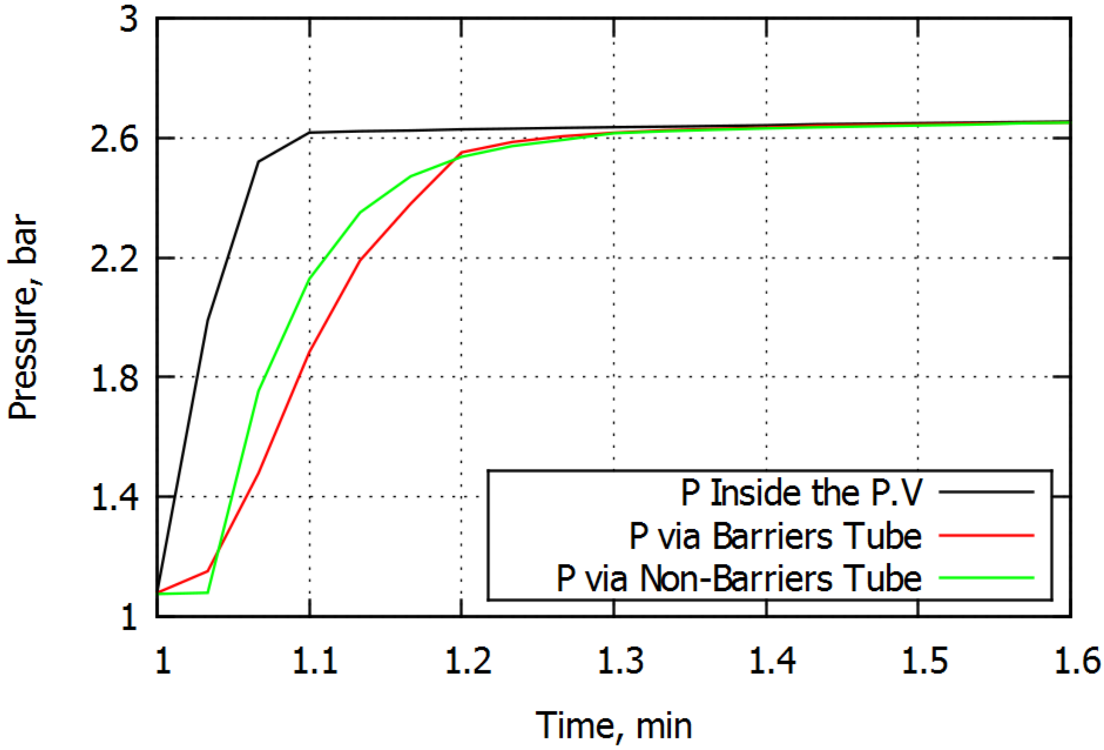


Figure 4-17 Barriers and non-barriers tube-pressure-sensor

5 Chapter Five: Conclusions & Recommendations

5.1 Conclusions

The conclusions of the present work, according to the analysis of the results obtained by the new technique that designed and used by this research, can be summarized as follows:

1. The tube-pressure-sensor or the sintered metal round plate in the sensor will not close by casting a concrete around it.
2. The concrete will become less permeable with the increase in dry out time as seen in the results 33 % increase in time delay was obtained with 3 days dry out.
3. By moistening the concrete, the permeability will decrease with the increase in the sinking time, in which an increment of 55 % in the time delay was obtained after one hour sinking.
4. The viscosity of the fluid passing through the pores of concrete plays an important role to control its transporting speed, 97 % increase in the time delay was obtained with water.
5. The type of the fluid filling the space inside the pressure-sensor have a highly influence on its response. In which, by the use of water instead of air as fluid filling this space, the time delay was reduce by (75 %).
6. The volume of the fluid filling the space inside the pressure-sensor have a highly influence on its response. In which, by reducing the volume of this space, the time delay was reduce by (67 %).

5.2 Recommendations for Future Work

The reported work can be considered as a fundamental approach into the high-temperature drying of fire-resistance concrete and the pore-pressure measurement. Therefore, based on the present research, it is suggested that further work should be carried out in this field to strengthen the full understanding of the behavior of such field. The further work suggestions may include the following:

1. Use of new pressure-vessel that can withstand a pressure up to $40\ bar$ and a temperature up to $600\ ℃$, in order to simulate the real amount of steam-pressure and temperature that generate inside the fire-resistance concrete by heating process.

2. In case of using a new pressure-vessel, repeat the studies that carried out by this research, but with the use of high-pressure steam instead of high-pressure air.

3. Close the side and bottom of the concrete specimen by using epoxy, in order to measure the amount of air pressure transfer through the crack between the concrete specimen and the tube-pressure sensor.

4. Study the possibility of using an extendable concrete in the area around the tube-pressure sensor, in order to eliminate the leakage that initiates by shrinkage cracks of normal concrete.

5. Compare the obtained results with a new numerical model that simulates the presented new pore-pressure measurement technique.

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الخلاصة

ان ضغط البخار المتولد داخل الخرسانة المقاومة للحرارة اثناء عملية التسخين الاولى يمكن أَن يتجاوز حد الاجهاد الذي تتحمله الخرسانة ويسبب تكسر انفجاري. تم تصميم واستخدام تقنية لجهاز تجريبي في هذا البحث من اجل فهم افضل لسلوك متحسس الضغط تحت ظروف مختلفة. ان هذه التقنية قادرة على قياس مقدار الضغط الحقيقي داخل المسام ومعايرة متحسسات الضغط المختلفة, وقد تم تصميم برنامج سيطرة من اجل عرض وتسجيل النتائج التي يتم الحصول عليها.

وقد أجريت دراسات عديدة على عينات الخرسانة المقاومة للحرارة بأستخدام هذه التقنية, تختلف العينات المستخدمة من حيث القطر (3.6, 4.3، 5.1، 6.6, 7 و 8.5 سم) والارتفاع مختلفين (5 و 7 سم) ، مع الضغط ودرجة الحرارة تصل إلى 3 بار و120 درجة مئوية.

وقد أظهرت النتائج أن نوع وحجم السائل الذي يملئ الحيز داخل متحسس الضغط يكون له تأثير كبير على دقة المتحسس، حيث تم تقليل زمن التأخر في استجابة المتحسس بنسبة (75 %) عن طريق ملء هذا الحيز بالماء بدلا من الهواء, وايضا تم تقليل زمن التأخر في استجابة المتحسس بنسبة (67 %) من خلال تقليل حجم هذا الحيز. بالإضافة الى ذلك فان التسرب بين الأنبوب والخرسانة الذي يتولد نتيجة شقوق الانكماش له تأثير كبير على دقة المتحسس والتي تسبب خطأ كبيرا في القياس.

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جامعة فرايبرغ
معهد الهندسة الحرارية

دراسة تجريبية لتصميم الضغط داخل الخرسانة المقاومة للحرارة

أطروحة مقدمة إلى
قسم هندسة المكائن والمعدات–الجامعة التكنولوجية
وهي جزء من متطلبات نيل درجةالماجستير في علوم الهندسة الميكانيكية
(ميكانيك تطبيقي)

تقدم بها
علي سعد محمود
(بكالوريوس في الهندسة الميكانيكية 2010)
(2013/06/30)

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