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EXPERIMENTAL PROCEDURE TO EVALUATE AIR LEAKAGE THROUGH DIFFERENT BUILDING MATERIALS

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ABSTRACT

EXPERIMENTAL PROCEDURE TO EVALUATE AIR LEAKAGE THROUGH DIFFERENT BUILDING MATERIALS

This work deals with the evaluation of air flow rate through different building materials used in the construction of building envelope. Experimental measurements of the air flow through and static pressure difference across building walls were carried out. For this purpose a new test configuration consisting of pressurization chambers was designed and developed.

In order to validate the new experimental setup developed, the leakage parameters of some common building materials such as gypsum board and plywood sheathing were evaluated and compared with literature values with satisfactory results.

The experimental approach developed in this study was then used to evaluate the air leakage characteristics (resistance, permeance, equivalent leakage area) of brick, impregnated brick and composite walls. Different building envelope configurations were compared in order to assess the airtightness performance and recommend appropriate improvements.

This study confirmed that under pressure differentials of 10 to 150 Pa, the air flow regime through rigid building materials is mainly laminar. The research also dealt with the evaluation of the air flow characteristics through a composite system in order to estimate the general envelope performance, by considering the air flow rate through each component layer.

The building component airtightness measurements using the proposed experimental configuration were performed under controlled laboratory conditions. This system has the advantage that a large number of rigid specimens can be examined under similar conditions. However, results obtained under laboratory conditions may be significantly different from those of similar components on site evaluation. This is attributed to the effect of workmanship on the airtightness performance of the building envelope.

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CHAPTER 1

INTRODUCTION

The role of the building envelope is to maintain comfortable interior conditions by affecting the heat, moisture and air transfer. If the envelope does not perform adequately, the excessive transfer of heat, air or moisture leads to increased energy consumption in the occupied space and deterioration of envelope materials. On the other hand, too little fresh air may create health-related problems to the people living and/or working in a building.

The building envelope materials must provide some performance requirements or "constraints" in terms of thermal resistance, structural conditions, resistance to the air leakage etc, in order to realise an acceptable level of performance based on standards and codes. These requirements deal with air flow control, heat flow control, water and vapour flow control, fire resistance, durability, noise control, strength and rigidity, aesthetic and economical aspects.

The unrestricted air flow passages within the envelope wall cause problems including air exchange between the building interior and the envelope, between the envelope system and the outdoor and the air movement within the envelope system itself. Sometimes vertical air spaces are designed into wall system, for example, between the wall board and the cladding wall. In this wall system the masonry layer constitutes one of the major components of the wall.

One of the functions of the building envelopes is to separate the indoor from the outdoor environment and some flow of air is permitted through them. Air exchange between indoors and outdoors of the building is divided into ventilation (natural and forced) and infiltration (unintentional and uncontrolled). It is determined by pressure differences caused by wind or stack effects.

Natural ventilation is airflow through open windows, doors and other intentional openings in the building envelope. Forced ventilation is intentional powered air exchange by fan and blower through intake and/or exhaust vents that are designed for ventilation. Infiltration is uncontrolled air flow through pores of materials, holes, cracks, interstices and other unintentional openings [ASHRAE Fundamentals Handbook, 1993].

Air leakage is considered as a very important parameter in the analysis of the building performance. The air leakage of building characterizes the relationship between the pressure difference across the building envelope and the air flow through the envelope [ASHRAE Fundamentals Handbook, 1993]. This is a physical property of the envelope and is affected by its design, construction, seasonal effects and deterioration over time.

Several factors contribute to the air flow through the building envelope. The present work aims at the experimental evaluation of the general elements concerning the air flow through various building materials used in the envelope design, and the comparison of the air leakage among these materials in order to improve their performance characteristics.

The main aspects of this research program are:

a) To review the present knowledge of air leakage behaviour of some building materials used in the envelope design.

b) To propose, design, develop and validate an experimental set-up for the determination of airtightness of rigid building materials by measuring the air flow with reasonable accuracy.

c) To measure the air leakage at various static pressure differentials by using the proposed test set-up. The determination of air leakage achieved by this study would be helpful in the selection of building materials in order to build a good air barrier system.

d) To investigate the improvement of brick airtightness by using the impregnation method.

e) To evaluate the air flow resistance of a composite wall system, by taking into account the resistance to air flow through each component material of the system.

CHAPTER 2

PREVIOUS WORK ON AIR LEAKAGE CHARACTERISTICS OF THE BUILDING ENVELOPE

Airtightness may vary widely from one form of construction to another. The airtightness of building materials increases by using plaster or rendering inner wall, gasketed or caulked joints, impregnation etc. The air leakage and air change rate depend upon a variety of influencing factors such as wind, temperature, HVAC system, etc [Charlesworth, 1988]. In order to obtain the relationship between the air flow through and the pressure differential across the building envelope, it is useful to analyse individual building components or building materials [Shultz, and Saxhof, 1994].

The earliest investigations in air leakage characteristics of walls concerned masonry walls. Several works have been carried out and mentioned by Building Code Requirements for Engineering (1969, 1970), Specifications for the Design and Construction of Load Bearing Concrete Masonry, "Construction" (1970), Persily and Grot (1986) and Persily (1993) who released reports on experiments testing light weight concrete masonry walls.

By analyzing different Swedish research efforts, Kronwall (1980) gave some information on air leakage characteristics of different types of masonry walls. The airtightness of different walls for factory buildings was investigated by the same author. Experimental data indicated that it is possible to achieve a relatively high degree of airtightness of such walls. Results proved that the lack of airtightness of building components is mainly due to concentrated air leakage at joints in the wall and between the wall and other components (windows, doors etc.).

Air flow through and within masonry walls was analyzed by Dickson (1981). The air flow through walls was investigated by sealing a box with 0.5 m^2 vertical cross area against a brick wall and measuring the relationship between air flow and applied pressure (Figure 2.1). In this experiment, the measurable air flow was achieved with conditions of ordinary wind pressure and with negligible effects of ventilation rate and thermal performance [CMHC, 1992].

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Fundamentals Handbook specifies the air leakage of masonry walls, the increase of airtightness by the plastering process for some brick walls (thickness ranging between 0.2 and 0.33 m), and the effective leakage areas of building components. The air leakage resistance of common building materials in New Zealand has been presented by Mong and Trethowen (1992), with results obtained from experimental measurements conducted under dry-air conditions (23 degree C, and 55% RH). This study shows the advantages of using coating procedures in increasing the air leakage resistance.

Malcolm, Liddament and Wilson (1994) published a study and data summary regarding the component and whole building air leakage based on measurements in over 2700 buildings. In order to use these data for design and evaluation purposes, the authors identified the construction techniques and materials that may contribute to airthightness performance but concluded that more investigations about the masonry wall must be carried out.

Studies of airtightness and infiltration through the exterior walls of small and tall buildings were made by Tamura and Shaw (1982) and Shaw (1986). CMHC released data concerning the air barrier systems for wood frame walls and the air permeance of common building materials (1988), methods to evaluate air barrier membranes for masonry walls (1989) and the air leakage characteristics of building envelopes (1992). Such measurements establish the contribution to airtightness of various components of the envelope assembly. Figure 2.2 shows the schematic drawing of a test chamber including the main experimental components, the test panel and the assembly method. A single testing box is used in order to create a pressure difference on the envelope sides. This pressure difference produces an airflow through the envelope components.

Researchers at the NRC (National Research Council of Canada) analyzed the building envelope [NRC 1984, 1989] and published partial results for the air leakage in concrete blocks [NRC 1994], and other selected building materials, which have been used for comparison in the present study.

Tests conducted across Canada indicate that improvements in construction need to be made. A house can be well insulated but if it is not properly sealed against air leakage, it will lose a significant portion of its heat (30% or more). The indoor air leaking into the shell can cause condensation damage to the insulation and structural components. The purpose in the construction industry today is to have homes better sealed against air leakage than ever before. Naturally, excessive reduction of air leakage through the envelopes can cause indoor air quality problems if it is not combined with a proper ventilation system. The goal for the "Perfect house" [Tsongas, 1992], or the R-2000 home [CMHC, 1992] proposition is for the new constructions to combine air sealing with continuous ventilation, assuming lower energy bills and better indoor air quality. Therefore, airtightness and infiltration rates are very important for design purposes. Wind, stack, exhaust fan and HVAC systems are the most common pressure producers. Pressure difference is the main parameter creating the movement of air across the building envelope. Recent studies investigating this parameter conclude that pressure differentials as high as 37 Pa and as low as -32 Pa relative to outdoor may be measured within the building envelope [Liddament 1994].

A study [Persily 1993] examined 371 homes in USA and found pressure as high as 35 Pa and as low as -16 Pa relative to outdoors. The differences between these absolute numbers depend upon wind speeds which appears to be one of the major natural factor in infiltration. By considering this, in the present experimental work the air leakage through some rigid building materials under static pressure differentials ranging from 0 to 150 Pa (with good accuracy) is analyzed. This pressure differential can cover the natural pressure effects and other causes that can create pressure differences (HVAC, ventilation, fireplaces, etc), [Mong and Trethowen 1992].

In order to analyse the heat storage in building products by using various substances such as Phase Change Materials (PCMs), which absorb and release heat much more than conventional building materials, a comprehensive study was carried out at Concordia University (SFB), by Hawes, Banu, Feldman (1989, 1992, 1993) and Feldman, Hawes, Banu (1991). The main results concerning PCMs revealed the better energy storage capacity of envelopes using impregnated materials. In the present experimental program the airtightness parameters of some building materials used in the building envelope design (gypsum board, plywood sheathing, brick wall etc) are analyzed by using an experimental method proposed for rigid materials. The performance of impregnated bricks with PCMs is also examined in order to improve the airtightness of building envelope. This procedure permits to determine the air leakage parameters for a single building material or for a multilayer wall.

By considering the non-linear relationship between air leakage and pressure differences across a building wall, the great variety of wall sections and building materials as well as construction techniques and workmanship, in the literature there is only a limited amount of air-leakage data related to specific building materials.

Taking into account the obtained results in previous works and the need to obtain more data concerning the numerous parameters which influence the air leakage through the building envelope, the present study has, as main goal, to study air infiltration by using and validating a new test method and to select the best material for a wall based on the measurement of air flow rate per unit area.

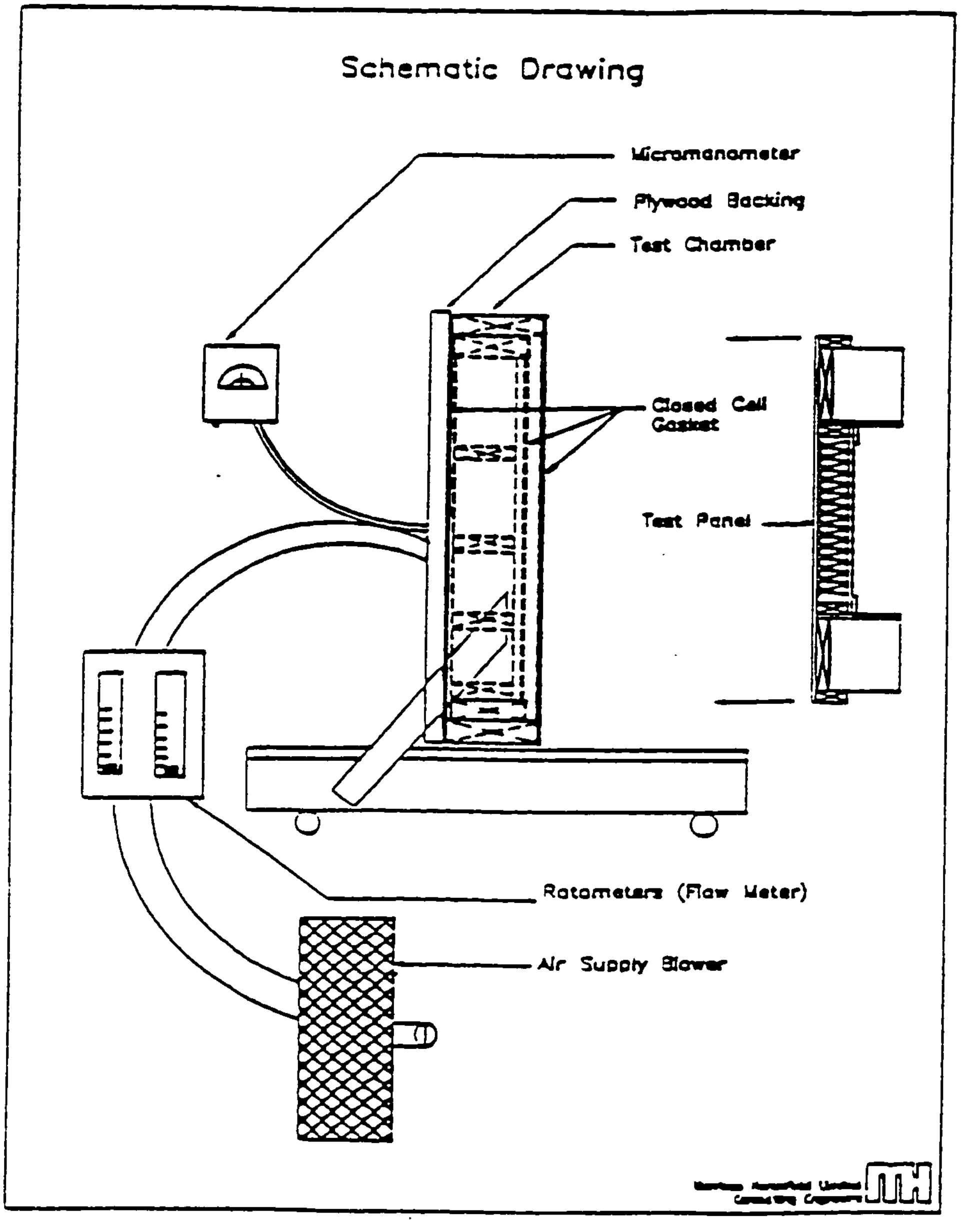


Fig. 2.1 Schematic Drawing of the Test Assembly, CMHC, 1992

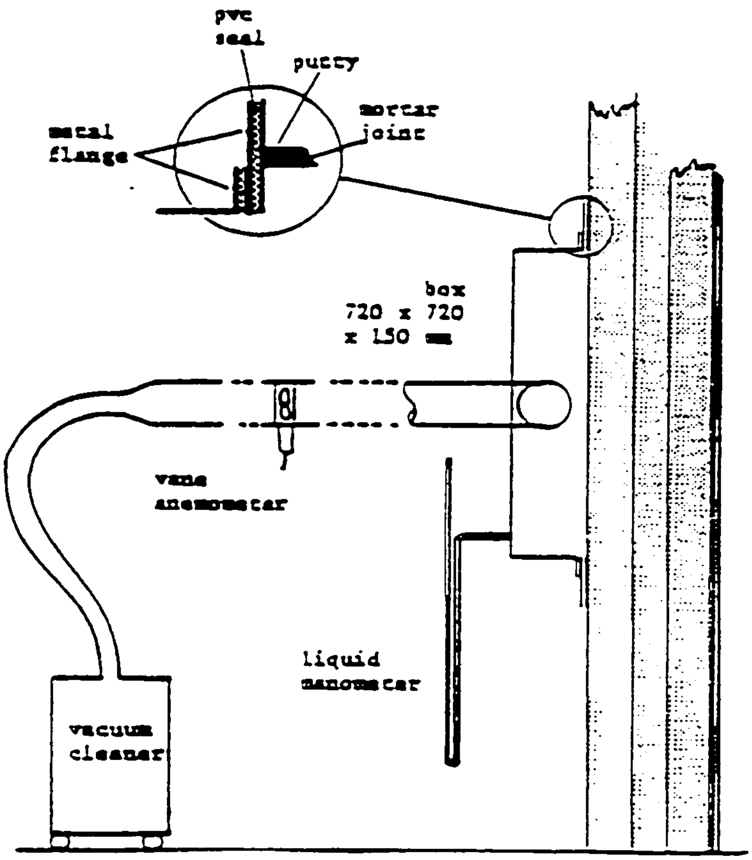


Fig. 2.2 Wall Permeability Apparatus, after Dickson 1991

CHAPTER 3

INFILTRATION AND AIR LEAKAGE

3.1 General

Building materials have cracks and gaps which form the route for air infiltration. The size and flow characteristics of such gaps depend on the type of joints, the material used and the quality of manufacturing and fitting. It is possible that similar components may be expected to have a variety of leakage characteristics. It is the in-situ performance of components that will define the airtightness, or air leakage of the whole structure [Liddament 1994].

The leakage performance of a typical construction material plays a very important role in the determination of air infiltration through a wall. The air infiltration characteristics of a multilayer wall is function of each building material airtightness. In this research program the method used to establish the airtightness performance of the material itself or of the multilayer wall helps test the samples at incremental changes in artificially-induced air flow rate and measure the corresponding variation of pressure.

Knowledge of building materials airtightness may be used to confirm the infiltration performance of each material and to improve eventually their infiltration performance by impregnation, coating, etc.

The relationship between air flow rate and pressure difference, presented by a Power Law Equation and the expression of air flow rate at an artificially induced pressure of 50 Pa or 75 Pa have been used as a basis of airtightness standards [CAN/CGSB 149-10-M86, ASTM E 283-83].

3.2 Flow Coefficient and Flow Exponent

The method of expressing the airtightness measurement results is applicable both to the building envelope as a whole and to the building envelope components. Determining the air leakage induced by a given pressure difference allows to predict the ventilation related energy consumption (the typical amount of heat loss due to air leakage is between 20% and 40% of the total heat loss of the residence - Liddament 1994) and the quality of indoor air.

By making pressure difference and flow rate measurements the following generalized leakage function can be determined [ASHRAE Fundamentals Handbook, 1993]:

$$Q = CA(\Delta P)^n \quad (m^3s^{-1}) \qquad (3.1)$$

where:

Q = Air flow rate, (m^3s^{-1})

ΔP= Pressure differential, (Pa)

C = Flow coefficient, volumetric flow rate per unit area at a unit pressure difference

A = Cross sectional surface area normal to the flow (m^2)

n = Flow exponent

Coefficients C and n describe the air leakage parameters of the tested envelope or component over the range of examined flows and pressure differentials. Figure 3.1 illustrates the power law function presented in Equation 3.1. [ASHRAE Fundamentals Handbook, 1993].

3.3 Modes of Air Flow

A unidirectional steady flow of air through a permeable material is presented in Figure 3.2.

A building can be either pressurized or depressurized and the flow is measured as a function of pressure difference between inside and outside. As mentioned in Chapter 2, typical design leakage rates are at 50 Pa (0.2 in. H_2O) in Canadian Standards and 75 Pa (0.3 in. H_2O) in American Standards.

3.4 Laminar and Turbulent Flow

The rate of air flow through a permeable material can be expressed by Equation 3.1, in which $n = 1$ for laminar flow and $n = 1/2$ for turbulent flow.

Building materials are heterogeneous by nature. The mode of air flow through a material may change from laminar to turbulent at several locations within it. In order to cover all cases, the flow exponent n is defined as $0.5 < n < 1.0$. A graphical representation of various modes of air flow through a permeable material is shown in Figure 3.3.

3.5 Air Permeance of Building Materials

The air permeance of a building material is defined as the rate of air flow (L/s), per unit area (m^2) and per unit static pressure differential (Pa).

$$\text{Air permeance} = p = Q / (A\Delta P),\ (\text{L/s-m}^2\text{-Pa}) \text{ or } (\text{m/s-Pa})/10^3 \qquad (3.2)$$

3.6 Resistance to Air Flow Provided by Building Materials

The resistance to air flow provided by a building material (R) is the reciprocal of air permeance.

$$R = 1/p \ \ (\text{s-Pa/m})10^3 \qquad (3.3)$$

3.7 Equivalent Leakage Area (E.L.A.)

The building envelope has numerous cracks and crevices (penetrations) which allow air to flow through them. The equivalent leakage area (E.L.A.) is a measure of the total area of all the cracks in the envelope. It is calculated as the area of a sharp edge orifice which would pass the same air flow volume as the one passing through the building envelope at a given pressure difference.

Following Equation 3.1 with n= 1/2 (turbulent flow), the evaluation of the E.L.A. (m^2) is given by the equation:

$$E.L.A. = Q / [C(2\Delta P/\rho)^{1/2}] \qquad (3.4)$$

where:

C = Flow coefficient = 0.6

ρ = Density of air, (kg/m^3)

ΔP= Pressure differential, (Pa)

Equations 3.1 - 3.4 have been utilized as the analytical basis in the present research. The parameters contained in these equations describe the characteristics of building materials with respect to the air infiltration behaviour.

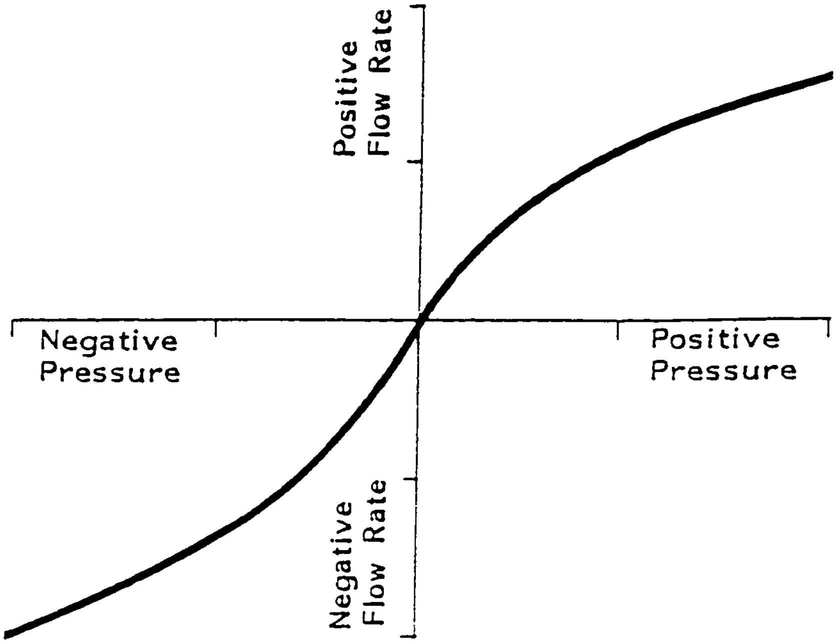


Fig. 3.1 Air Flow Rate Versus Static Pressure Difference, after ASHRAE Fundamentals Handbook, 1993

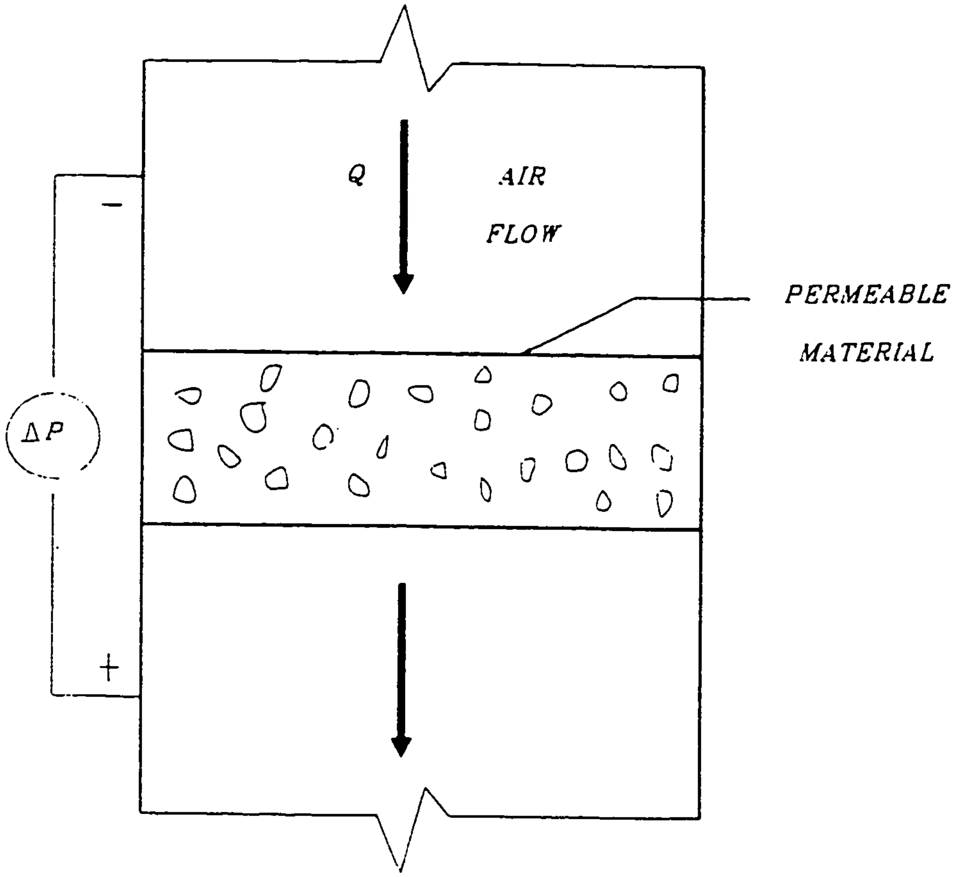


Fig. 3.2 Flow of Air Through a Permeable Material, after CMHC, 1981

Laminar Flow

$Q = CA\Delta P$

Turbulent Flow

$Q = CA(\Delta P)^{1/2}$

Transition Zone

$Q = CA(\Delta P)^{n}$

$0.5 < n < 1.0$

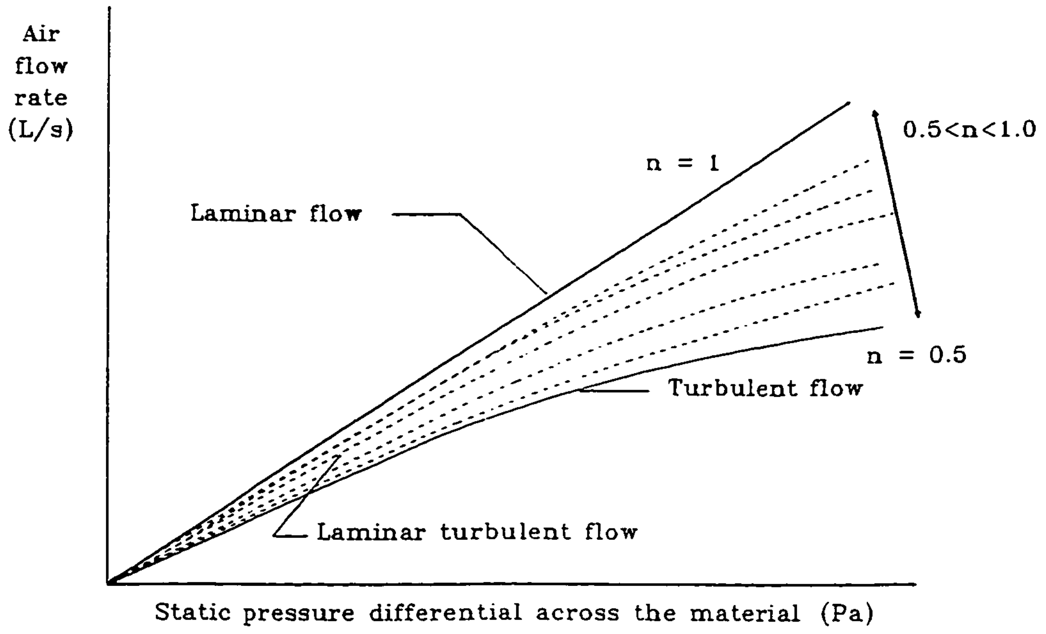


Fig. 3.3 Mode of Air Flow Through a Permeable Material, after CMHC, 1988

CHAPTER 4

LABORATORY TEST METHOD

The proposed testing apparatus and procedures have been developed according to ASTM-E283, 1991 and can be used to study the air infiltration characteristics of various components of the building envelope.

The present experimental laboratory methodology consists of sealing a test specimen between two specially made chambers (boxes), exhausting air to maintain the specified air flow rate and to measure the resulting static pressure difference across the specimen. The air leakage rates for different pressure differences are used for comparison purposes.

The testing parameters for this laboratory method have been calibrated according to reference standard conditions and are defined as: dry air at pressure 101.3 KPa, temperature 21.8 ^{0}C and air density 1.202 kg/m^3 . The specified air leakage (Q) is the volume of air flowing per unit of time through the closed specimen, expressed as (L/s-m^2) and the test pressure difference is the difference in static air pressure across the locked or fixed specimen, expressed in Pa.

A single air leakage value measured at a pressure differential of 50, 75, 100 or 150 Pa could be used to calculate the air flow through a material at other pressure differentials.

The test specimen is the entire assembled unit submitted for test and it shall be of sufficient size to determine the performance of all typical parts of the wall system. If the wall is constructed with prefabricated units, the specimen width shall not be less than two typical units plus the connection elements at both sides, and the height of the specimen must include at least one full horizontal joint, as well as the connection at top and bottom of the unit (ASTM E 283-91). All parts of the wall test specimen shall be full size. The conditions for a structural support or frame support in which or against which the tested material was built (brick wall) or sealed (gypsum wallboard, plywood sheathing, or "three layer" component wall) shall be simulated as accurately as possible.

In order to verify the repeatability of the manufacturing process, a minimum number of two specimens were selected to test the air permeance of building materials. This minimum number of specimens (two or three usually) was used because for same materials, air flow may vary by as much as 30% to 50% from the average flow. These variations are not caused by erroneous data, but rather by inhomogeneity of the material under investigation.

4.1 Design, Construction and Calibration of the Airtightness Test Chamber

The analysis of the suitability of the test chamber used to measure the airtightness of rigid building materials involves two aspects, namely design of the test chambers and validation of the equipment.

a) Design of the test chamber

The chamber is required to be much more airtight and stiffer than the actual building envelope, in order to allow the calibration for further experimental analysis of mainly rigid building materials used in the building envelope design (gypsum board, plywood sheathing etc).

In this study it was decided to design two 1.00 m high, 1.00 m long and 0.50 m wide wood boxes with a sealing frame, so that leakage occurs only through the specimen. Figure 4.1 shows the new, simple apparatus for air infiltration testing.

The different components of the test apparatus are shown in Figure 4.2 and Figure 4.3. The system includes:

- A test chamber composed of two boxes between which the tested specimen is installed;
- Flow measuring devices;
- Pressure measuring devices;

- Flow control devices;
- System to create pressure inside the chamber (oxygen reservoir).

The different parts of the test apparatus are:

- The already mentioned boxes between which the specimen is installed;
- A wood frame with the inside surface of 1.00m by 1.00m in which the specimen is installed;
- Two clamping devices on opposite sides of the boxes to compress the frame and the specimen;
- Two systems (one for each box) to join the pipe connected to the test chamber leading to the flow measuring devices and to the pressurization system.

The two boxes of the test system have been constructed by 19 mm thick plywood with density equal to 580 kg/m^3. The edges of the plywood panels were reinforced with timber battens and all joints were carefully sealed in order to resist the air leakage and the possible deflection created by an accidental increase of pressure during the experimental work. Both faces of chambers were equipped by two U channels to attach the rods and to join the two boxes through the frame for the specimen. The upper faces of the boxes were equipped by two fittings connecting the plastic holes to the compressed air and to the pressure measuring devices, in order to measure the pressure variation in each box by means of a pressure transducer. The two boxes and the frame have been carefully treated inside and outside with several coats of paint in order to avoid the air leakage through the plywood from which the boxes were made of.

The pressurization method was used to realize the increase and decrease of pressure within the limits imposed by standards and other research programs that analyze the building material operations [Phaff, 1987, Tsongas, 1992].

In order to detect possible differences between the boxes, the pressurization for the two boxes and the frame was carried out under the following conditions:

- that the frame and the material under consideration will be sealed in the same way and with the same sealant in each experiment, and
- that the frame will be rigid during the experimental work and not subjected to any movement due to the pressure variation in the range of measurements imposed by this method (between 0 and 300 Pa).

b) Validation of the equipment

The chamber was carefully built and when the frame containing the sample was installed, the four clamps compressed the two boxes against the frame. Closed cell foam gaskets were used as a seal between the chambers and the frame and each joint and screw hole was sealed with silicon sealant.

In order to check the tightness of the boxes against leak, the system was pressurized at different air flow rates required to obtain the pressure differences between 0 and 300 Pa. The pressure decay was measured by a pressure transducer connected to a Uniform Wave Form Analyzer (DATA 6000). These values have been used to obtain the pressure difference for each air flow rate chosen similarly to the procedure followed by Alkhaddar and Dewsbury (1990).

The calibration of the test chamber will be well suited for the development of pressurization system for airtightness measurements of other building materials at low pressure difference. The chamber was calibrated by using an impermeable material poly(vinyl-chloride) PVC, (ASTM D 1434/D 3985).

4.2 Instrumentation and Calibration

a) Measurement of pressure

The pressure measurement was obtained by means of pressure transducers through a device that uses a 160 PC pressure sensor manufactured by Micro-switch (a Honeywell Division), that provides output voltage proportional to the applied pressure. This transducer operates from a single, positive supply voltage ranging from 6.0 to 12.0 Volts. Details about the pressure transducer used in the present study are shown in Appendix A. The pressure transducer was calibrated in the Building Aerodynamics Laboratory of the School for Building, Concordia University.

The calibration set-up of pressure measuring device is shown in Figure 4.4. The calibration is done by using a Micromanometer type Microtector (Dwyer Instrument Inc.- 46360), accurate to + 0.01 Pa. With the help of a syringe, tubing and a T-joint, pressure is applied and measured by the manometer as shown in Figure 4.5. For each pressure level applied, the corresponding output voltage is recorded and a graph is plotted between pressure in Pa and output in volts. Figure 4.6 shows a typical calibration curve.

b) Measurement of Air Flow

The air flow measurements were done by using an air flow controller transducer flowmeter (Matheson Model 8270) that has been designed to allow operation on any gas having a known molar specific heat [Matheson Gas Products 1990]. The flow controller is a self-contained, closed-loop control system which measures the rate of gaseous flow through the instrument and compares it with an externally commanded flow rate by means of the Flow Control Boxes. It adjusts the valve to control the flow to the recommended level imposed by the Control Box. The basic elements of the flow controller that accomplish this function are the flow sensor, the full scale flow range of the measuring section, the control valve and the electronic component shown in Figure 4.7 and Figure 4.8.

The environmental requirements for maximum performance of the instrument are the ambient temperature between 0 and 50°C, and the maximum operated pressure of 1500 Pa which includes the testing conditions up to 300 Pa, 21°C temperature and 40% humidity across the specimen.

The instrument was calibrated for the specific flow range, and specific gas (compressed air) using a precision calibrated equipment Hastings Mini-Flo Calibrator, Model LHBM-1A (HBM-1A Mini-Flow Calibrator, Specification Sheet, 1990).

c) Data acquisition and instrumentation

The objective of the measurements was to evaluate the static pressure for each air flow rate imposed by the flowmeter. The pressure variation and the mean value obtained in a specified delay of time (one hour for each measurement), was calculated using the DATA 6000. This high accurate analyzer has four input channels but in the present experimentation only two connections were used. Two programs were written, one for calibration and the other for evaluation of the mean pressure.

Table 4.1 summarizes the apparatus used in the present experimental work.

Table 4.1 Typical Measuring Instruments

Measured value	Method or instrument	Accuracy
Actual flow	Flowmeter No.1 Range 0-10.10^{-5} m^3/s	±0.5%
Actual flow	Flowmeter No.2 Range 0-400.10^{-5} m^3/s	±0.5%
ΔP Flowmeter	Micromanometer " Air Ltd." Scale 0-19.99 in.H_2O	±1.0%
ΔP Upstream	Micromanometer "Air Ltd." Scale 0-19.99 in.H_2O	±1.0%
Barometric pressure	Environment Canada	±0.5%
ΔP Specimen	DATA 6000	±0.001mV
Specimen width	Measurement device	±1 mm on the width
Specimen length	Measurement device	±1 mm on the length

4.3 Validation of the Applied Method

Different building materials were analyzed in laboratory at standard conditions (temperature and humidity), in order to measure the amount of air leakage resulting at different pressure differences. Gypsum board and plywood sheathing are two materials commonly used in the building envelope design such as in brick walls and in EIFS (exterior insulation finish system).

Table 4.2 and Table 4.3 present a list of air flow rates versus static pressure differences of selected building materials (gypsum board and plywood sheathing) which were analyzed previously in laboratory conditions (CMHC-1988) and which were chosen as comparative values in the present experimental validation measurements.

Table 4.2 Plywood Sheathing 8mm, (Q versus ΔP), after CMHC-1988

No.	Air flow rate (avg.) (L/s-m^2)10^{-2}	Static pressure difference (Pa)
1	0.24	25
2	0.45	50
3	0.67	75
4	0.87	100

Table 4.3 Gypsum Board 12.7mm, (Q versus ΔP), after CMHC-1988

No.	Air flow rate(avg.) (L/s-m^2)*10^{-2}	Static pressure difference (Pa)
1	0.66	25
2	1.31	50
3	1.96	75
4	2.61	100

In order to measure the accuracy of the air flow rate versus static pressure difference in the present validation measurement for the two materials studied previously, two samples of each material were analyzed. The panels were installed inside the wood frame, and caulked carefully around the perimeter.

The test experiment was conducted for each sample seven times and mean values were calculated in order to verify the repeatability of the measurements. Box 1 was pressurized and box 2 was open to the atmosphere during the first set of measurements. Box 2 was then pressurized and box 1 was open to the atmosphere. A general mean value of static pressure difference was considered for each set of measurements. Figure 4.9 presents the mean experimental values of static pressures obtained for gypsum board 12.7mm samples which are shown in Figure 4.10. Similarly, Figure 4.11 presents the air flow rate versus static pressure difference for plywood sheathing 8mm sample shown in Figure 4.12.

The airtightness comparative analysis between the experimental values obtained in the CMHC research and the present work shows only 7% to 15% difference for the measurable static pressure for both tested materials (see Figures 4.9 and 4.11).

4.4 Advantages of the Present Experimental Method

As shown previously, the proposed laboratory procedure respects the procedure of the current standards. Other research works used the similar basic principles in their laboratory tests, as described in Chapter 2 . The present testing methodology allows a complex experimental study for a given material. By using two pressurized chambers it is possible to investigate the air leakage characteristics in a large variety of conditions. One chamber may be used as "outdoor" and the other as "indoor" environment. The advantage of the present research work is the possibility to use both chambers as indoor or outdoor environment respectively. Also, the system allows to vary, besides the air pressure, other parameters such as air temperature and humidity, which may be considered for further research.

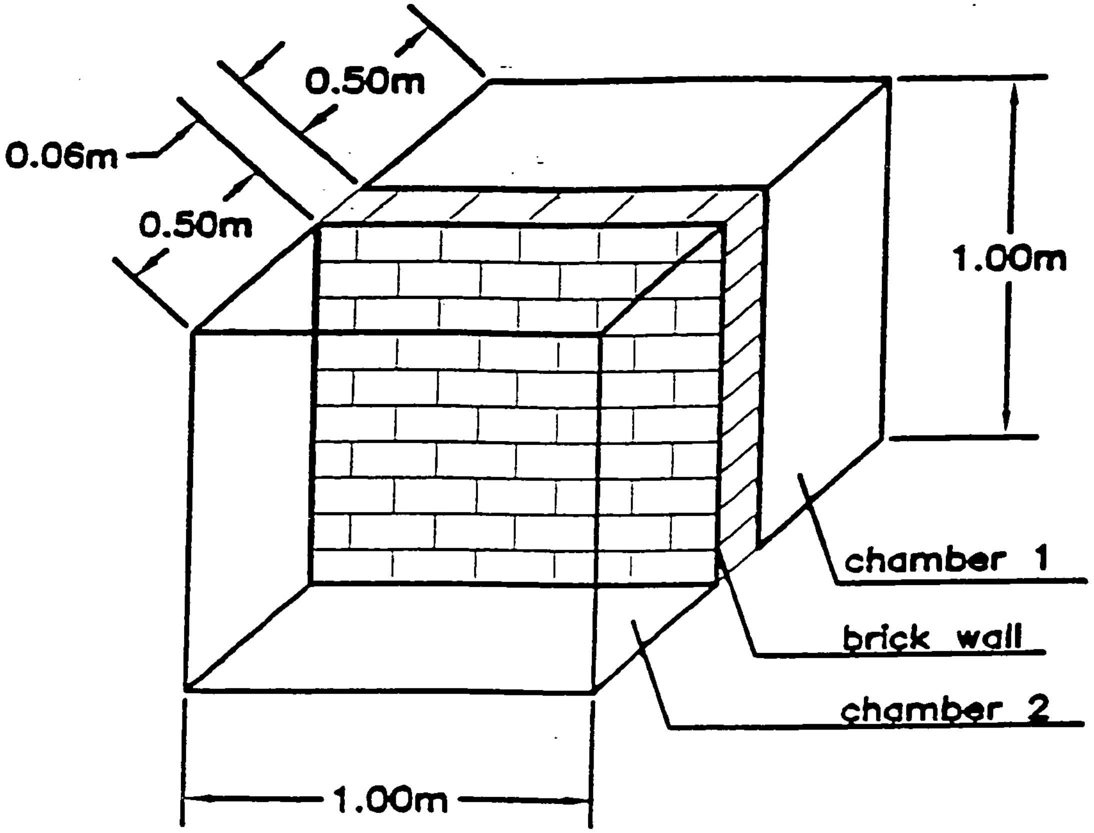
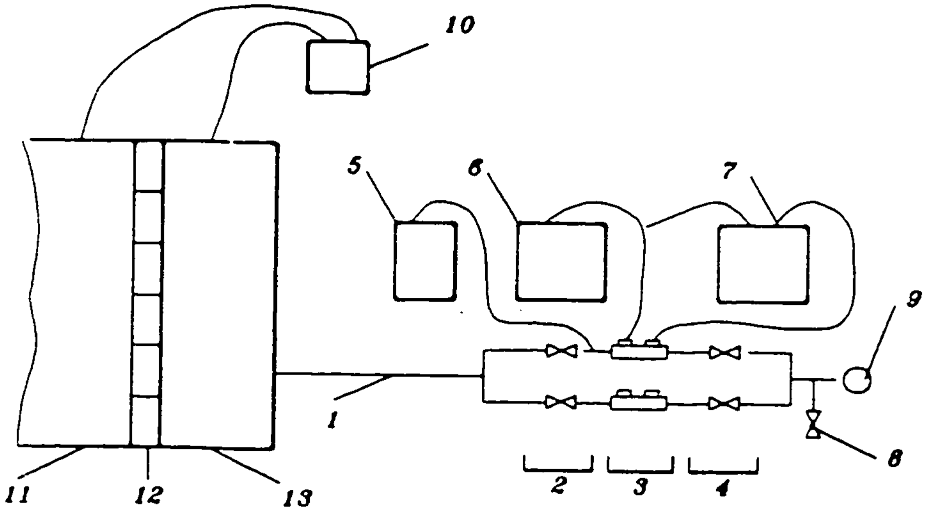


Fig. 4.1 Experimental Laboratory Test Chamber



Legend 1 Pipe

2 and 4 Control Valves

3 Laminar Flowmeter

5 Temperature Measuring Devices

6 and 7 Micromanometers

8 Bypass Valve

9 Blower

10 Pressure measuring Devices

11 and 13 Test Boxes

12 Test Specimen

Fig. 4.2 Laboratory Testing Set-up

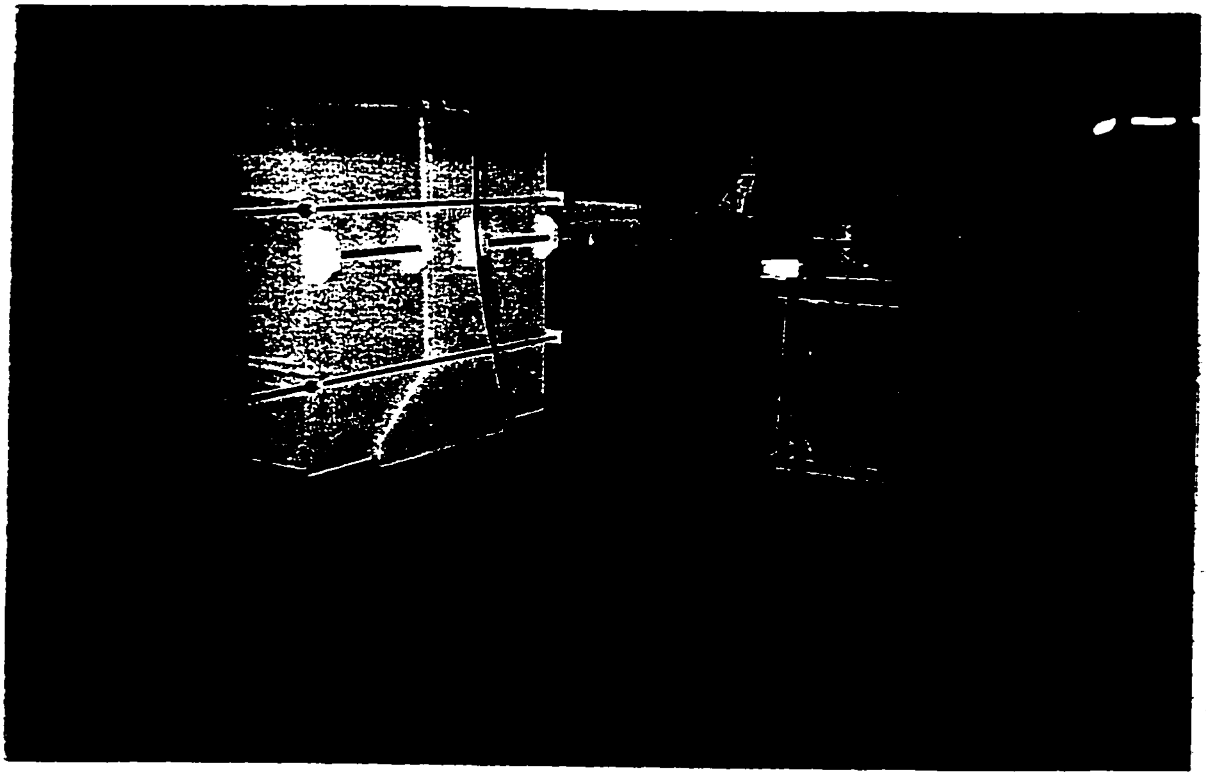


Fig. 4.3 Laboratory Model

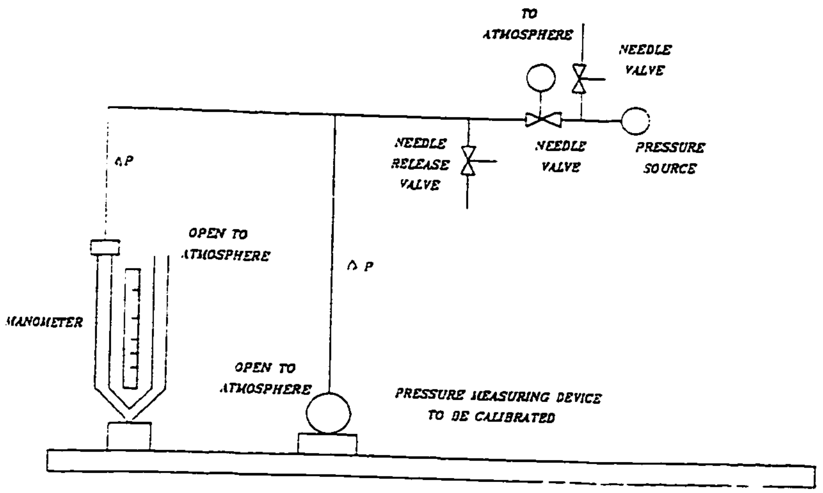


Fig. 4.4 Set-up for Calibration of Pressure Measuring Device

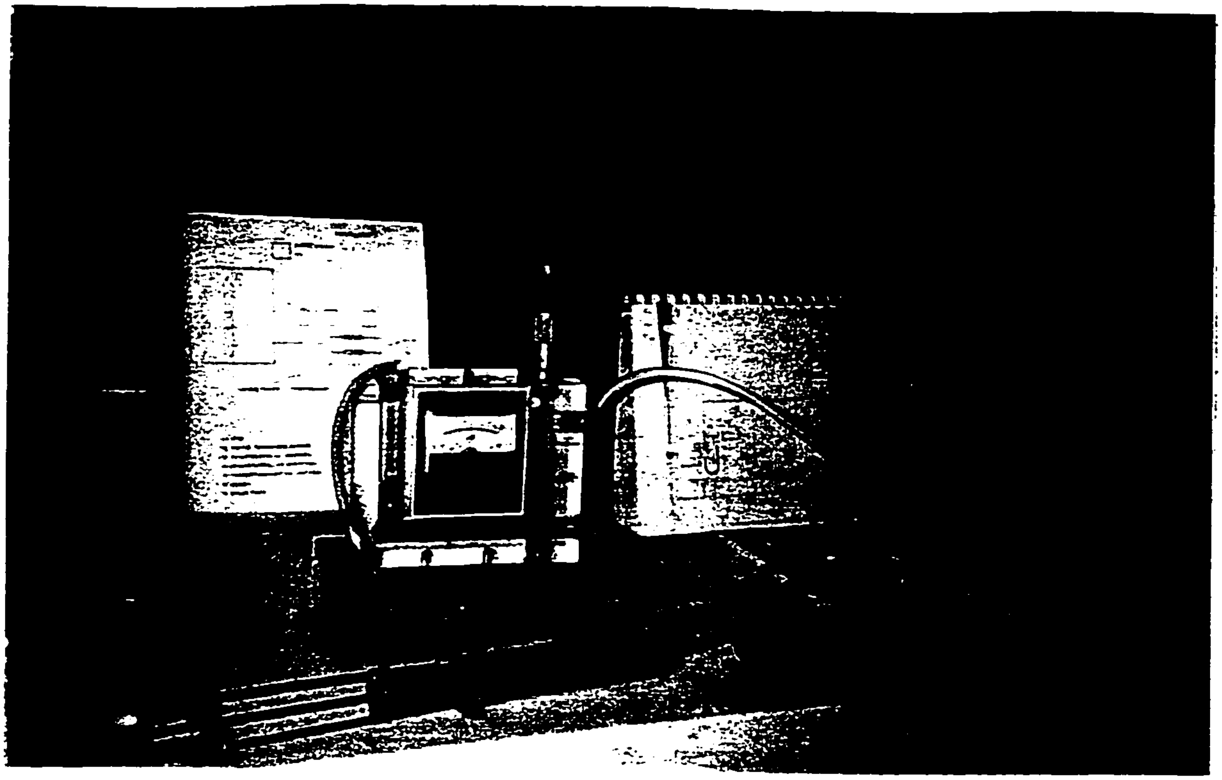


Fig. 4.5 Calibration of Pressure Measuring Device Using a Micromanometer Type Microtector

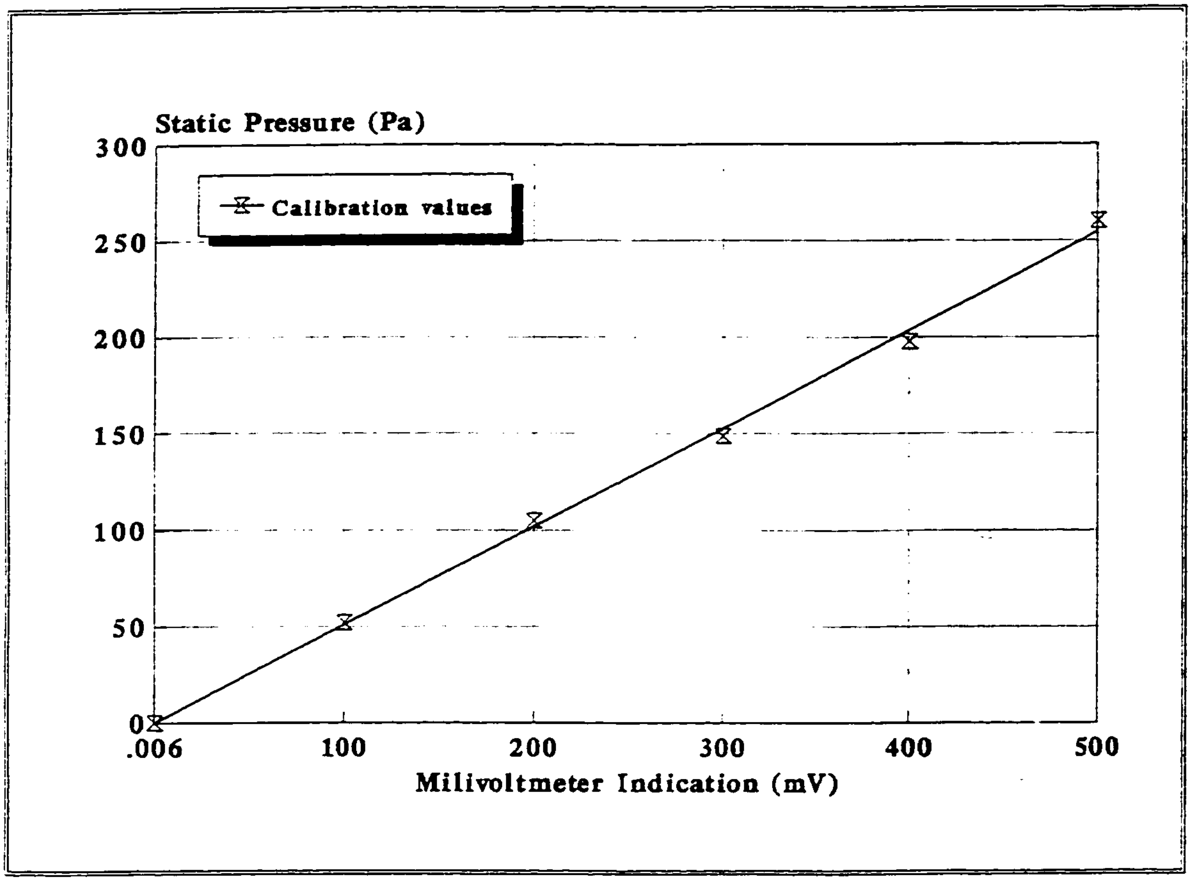


Fig. 4.6 Pressure Transducer Calibration

Fig. 4.7 Hastings Mini-Flow Calibrator Model HBM-1

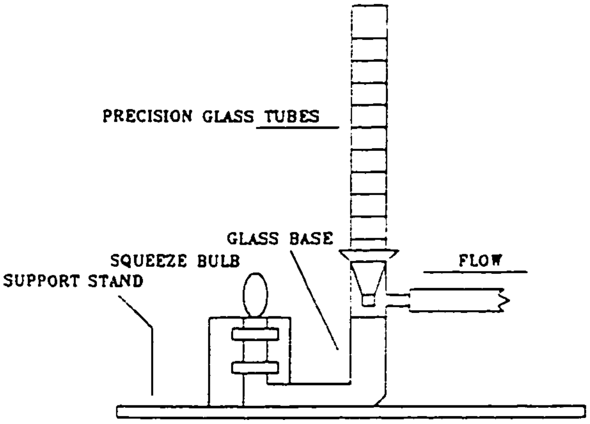


Fig. 4.8 Set-up for Calibration of Air Flow Rate

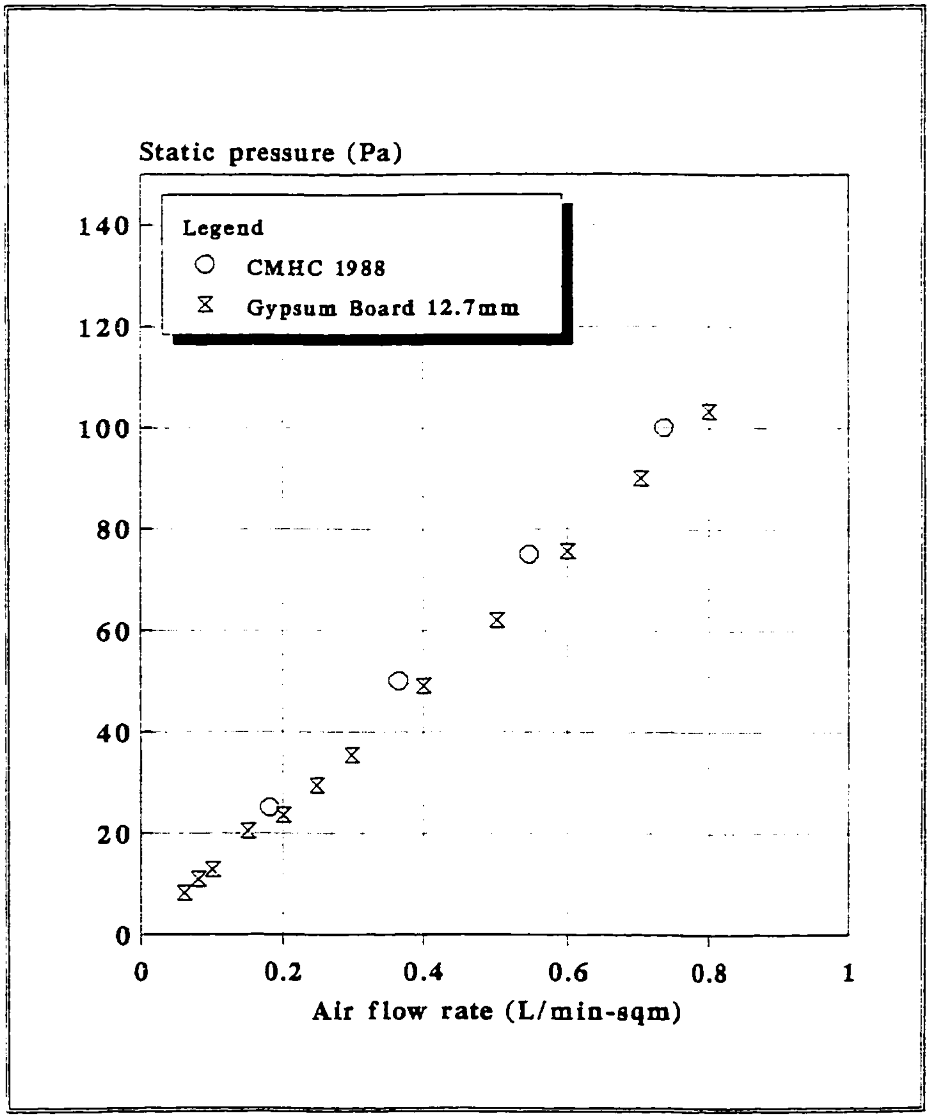


Fig. 4.9 Air Flow Rate Versus Static Pressure Difference (Experimental Values) for Gypsum Board 12.7 mm

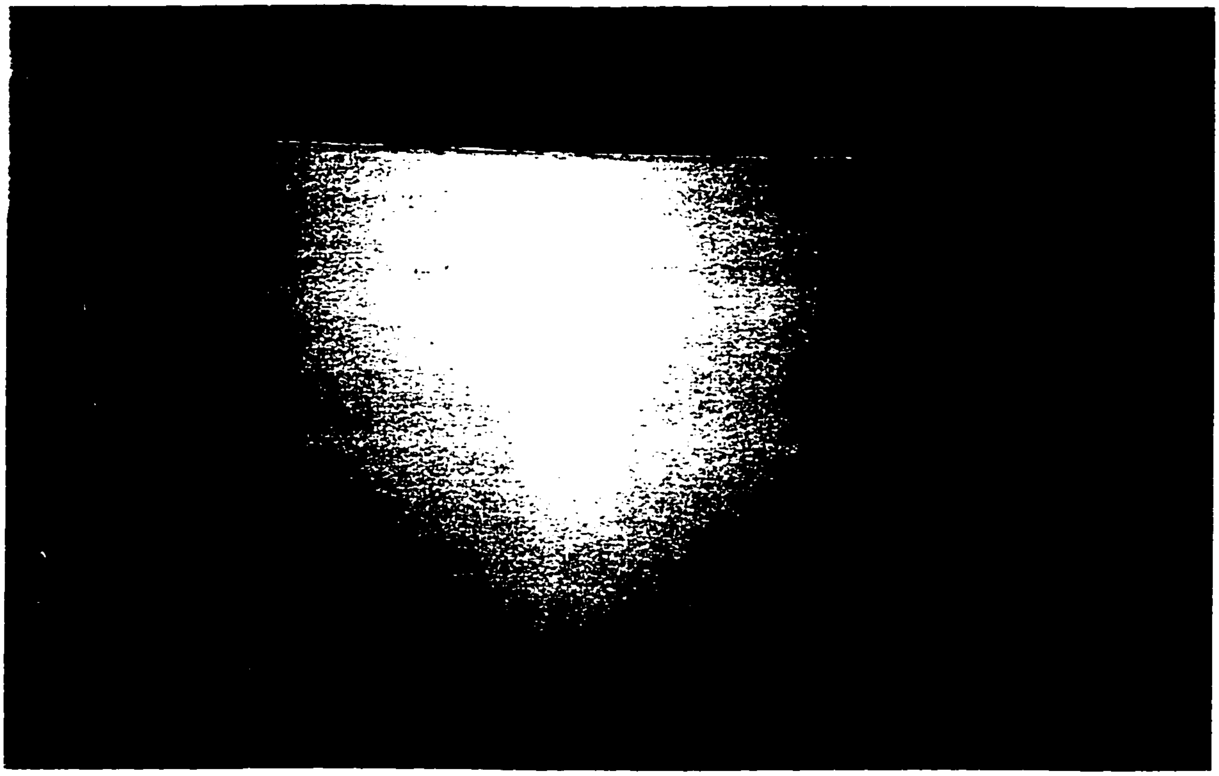


Fig. 4.10. Gypsum Board 12.7 mm (Sample Tested in the Present Experimental Work)

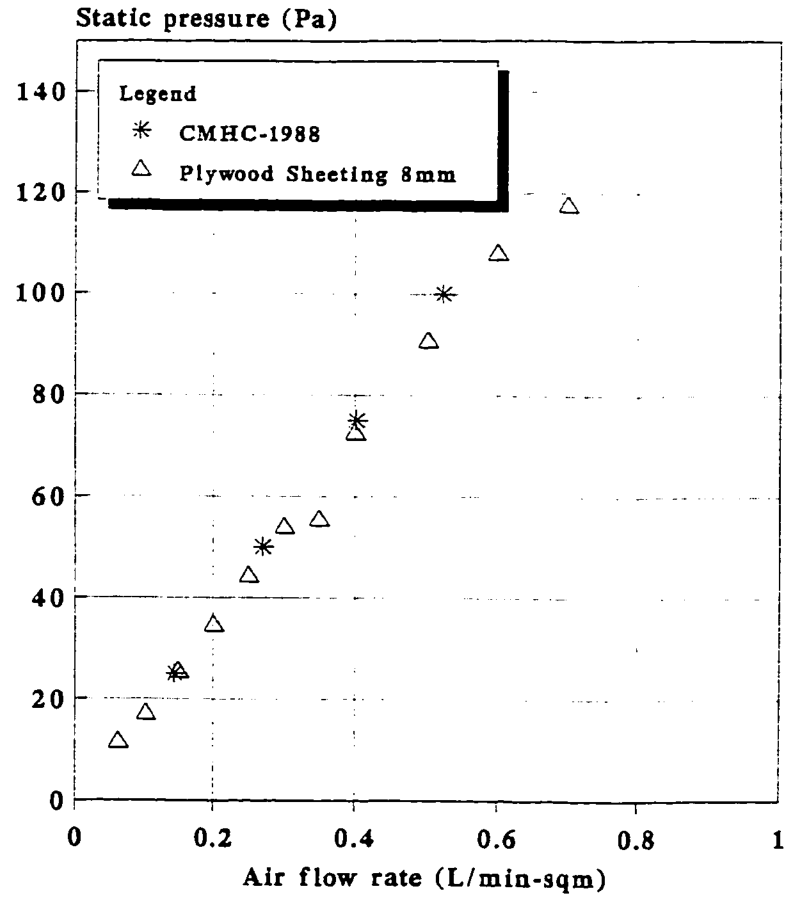


Fig. 4.11 Air Flow Rate Versus Static Pressure Difference (Experimental Values) for Plywood Sheathing 8 mm

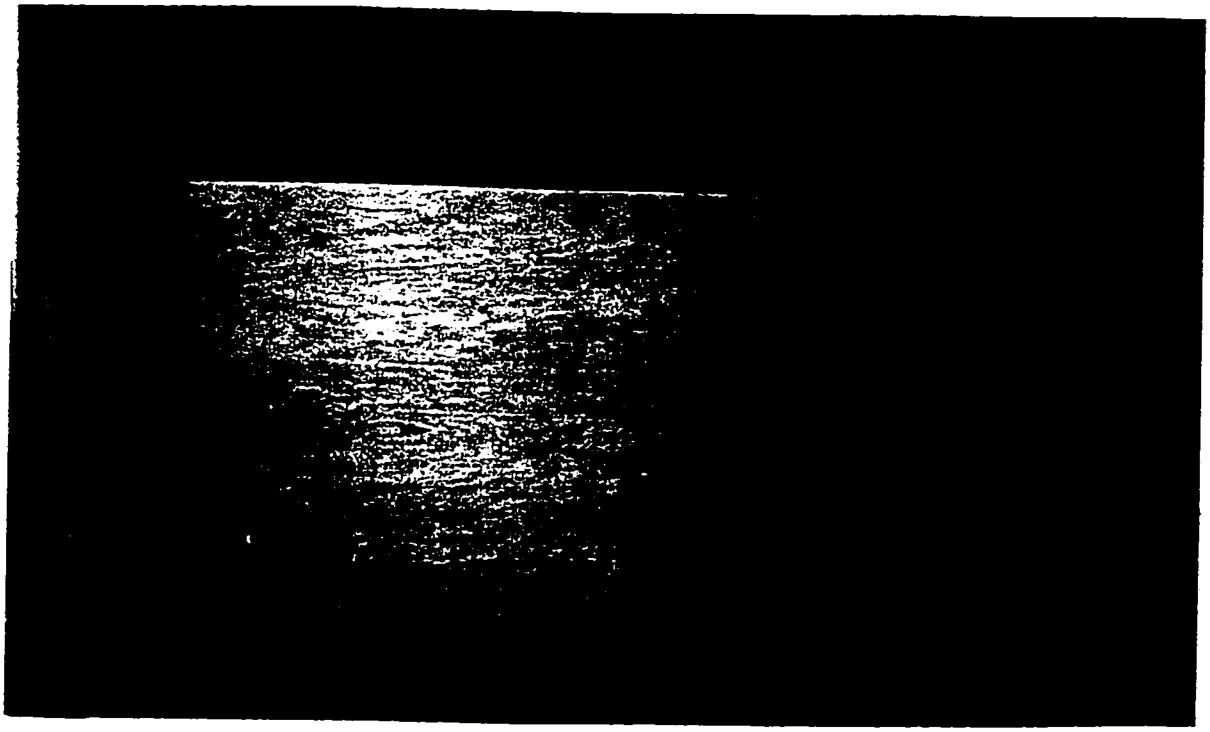


Fig. 4.12 Plywood Sheathing 8 mm (Sample Tested in the Present Experimental Work)

CHAPTER 5

DESCRIPTION OF THE TESTED BUILDING MATERIALS

5.1 Brick Wall and Impregnated Brick Wall

Brick or masonry walls are porous and permeable to air. These porous materials provide a source of air leakage which can have a considerable impact on overall building airtightness. A cavity wall consists of an outer masonry layer and an inner element based on different components. The function of masonry is to protect the interior elements and at the same time to create a face for the building. The experimental work performed till now has shown that it is almost impossible to obtain a watertight and airtight masonry leaf [Keneth, 1993].

Usually the masonry wall is considered and designed as a cold wall. Examples of traditional cavity walls designed for northern countries are presented in Figure 5.1 and Figure 5.2. As it is shown, both walls are provided with an outer masonry leaf and inner elements made of gypsum board, insulation and plywood sheathing.

One of the methods to protect the construction and to ensure a good indoor air quality for the building occupants is the reduction of the air infiltration and implicitly the vapour transport through the masonry to the inner side. This may be achieved by increasing the wall airtightness by the impregnation of the brick units with different materials including Phase Change Materials (PCMs) normally recommended for energy conservation in buildings.

A masonry construction must provide a good barrier against sound, heat transfer, moisture and fire resistance efficiency. A brick wall is made of brick and mortar that bonds the masonry units together. The characteristics of the brick material include physical properties related to architectural needs and engineering properties related to its structural capabilities.

One of the most used materials in brick construction is clay, which consists of silica, alumina and impurities of metallic oxides. The three types of clay brick commonly used in construction and ASTM designations are presented in Table 5.1.

Table 5.1 Clay Brick Unit, after Syllabus on Structural Masonry, 1984

Type of Unit	ASTM Designation
Solid Load Bearing Block	C 145
Hollow Load Bearing Block	C 90
Hollow Non-Load Bearing Block	C 129

Design procedures for brick masonry and concrete masonry in the US and Canada are specified by the Brick Institute of America (BIA), American Concrete Institute (ACI) and standards developed by the American Society for Testing of

Materials (ASTM); in Canada, the National Building Code Committee has adopted mainly the BIA Code. The TCMA-TEK2A Sizes and Shapes of Concrete Masonry units and the Masonry Handbook, published by the Portland Cement Association, provide information about the physical and engineering properties of such units.

Previous research shows that the air infiltration through the hollow brick units is lower than in plain brick units of similar size, and that the rendering on the masonry walls reduces the air leakage substantially. Also, the density, the thickness and the workmanship have a great importance in air infiltration. Table 5.2 presents some information about air leakage analysis for different types of brick walls [Kronwall, 1980].

Table 5.2 Air Leakage of Masonry Walls, after Kronwall, 1980.

No	Thickness (m)	Joint rendering	Air Leakage ($m^3.s^{-1}.m^{-2}$)at 75 Pa	Brick	Density ($Kg.m^{-3}$)
1	0.38	2R	3.1 10^{-5}	S	1100
2	0.38	2R	3.9 10^{-5}	H	1600
3	0.38	2R	4.7 10^{-5}	H	1400
4	0.30	2R	5.0 10^{-5}	H	1200
5	0.38	1R	8.3 10^{-5}	H	1600
6	0.38	0	2.8 10^{-4}	H	1600
7	0.38	1R	1.7 10^{-4}	H	1600
8	0.38	2R	6.9 10^{-5}	H	1600
9	0.25	0	5.5 10^{-4}	H	1600
10	0.25	1R	2.5 10^{-4}	H	1600
11	0.25	2R	8.9 10^{-5}	H	1600

H = hollow brick

1R = rendering on one side

S = solid brick

2R = rendering on two sides

0 = no rendering

Three types of facing brick commonly used in North America are:

1) Type FBS - brick for general use in exposed exterior and interior masonry walls and partitions ;

2) Type FBX - brick for general use in exposed exterior and interior masonry walls and partitions where a high degree of mechanical perfection and minimum permissible variation in size are required;

3) Type FBA - brick manufactured and selected to produce characteristic architectural effects resulting from nonuniformity in size, colour and texture of individual units.

When the type is not specified, the requirements for Type FBS shall govern. In fact, the brick type tested in the present research program has been manufactured according to the ASTM C-216-81, Type F.B.S.- Standard, rendering one side, with the dimensions presented in Table 5.3, for severe weathering regions as shown in Figure 5.3.

Table 5.3 Dimensions of the Clay Masonry Unit, after Brickwork Design Profile, 1992.

Description	Thickness in.(cm)	Height in.(cm)	Length in.(cm)
Standard	2 3/8 (6.03)	2 1/4 (5.72)	8 (20.32)
Oversize	2 3/8 (6.03)	2 3/4 (6.98)	8 (20.32)
Oversize modular	2 3/8 (6.03)	2 3/4 (6.98)	7 5/8 (19.37)

The tolerances for the various unit dimensions are typically:

- Thickness -1/8 to +1/8 in, (-0.32 to +0.32 cm);
- Height -3/32 to +3/32 in, (-0.24 to +0.24 cm);
- Length -1/4 to +1/4 in, (-0.64 to +0.64 cm).

The materials, methods and workmanship used in the construction of the brick wall test specimen were representative of the building [Construction of Brick Masonry Building Code, 1969], [Construction, 1970]. The brick wall which consists of 85 bricks and mortar (surface 1 m^2) was built in the corresponding wood frame as shown in Figure 5.4. Mortar specifications by volume proportion of material are indicated in Table 5.4.

Table 5.4 Mortar Specifications, after Syllabus on Structural Masonry, 1984.

Mortar Type	Portland Cement (parts by volume)	Hydrated Lime (parts by volume)
M	1	1/4
S	1	1/2
N	1	1
O	1	2

Note: The aggregate must be not less than 2.25 and not more than 3 times the sum of the volumes of the cement and lime used.

The curing process took place under laboratory conditions (air temperature 20-26 ^{0}C and RH 30-60 %) during 30 days (the standard condition requirements are no less than 28 days and no more than 60 days) [Syllabus on Structural Masonry 1984].

The frame containing the wall was installed between the two boxes, the system was clamped together, sealed carefully and an imposed delay of 24 hours was taken before starting the test.

5.2 Phase Change Materials (PCMs)

The behaviour of the building materials can be expressed by different parameters such as thermal capacity, thermal resistance between the indoor and the outdoor environment, thermal resistance between the indoor environment and the thermal mass of the envelope, air leakage etc. Some properties of different building materials (concrete, brick, gypsum board etc.) can be greatly enhanced by impregnating them with PCMs.

Prior research at the Centre for Building Studies, Concordia University has demonstrated a great increase of the heat storage capacity of concrete building product in the case of impregnation of concrete with PCMs [Hawes, Banu, and Feldman, 1993]. A very important consideration in the manufacturing and use of these thermal storage building products is the stability of the PCMs in the concrete throughout its service.

Types of PCMs

1) Inorganic PCMs (salt-hydrates). These materials have some useful characteristics :

- They change state within useful temperature ranges;
- They have relatively high latent heat per volume unit;
- There is no flammability hazard;

- They are relatively inexpensive;

They are corrosive and require special containment as well as space for the containers.

2) Organic PCMs offer a number of important advantages:

- The components melt congruently and do not become segregated;
- Many do not have a supercooling problem;
- Most are chemically stable;
- They can be incorporated in the building material without containment;
- The overall cost is competitive with that of inorganic PCMs;
- They have low thermal conductivity.

Appropriate PCMs are selected by evaluating criteria in which the following characteristics were examined :

1) Thermodynamic considerations:

- latent heat of fusion;
- heat transfer properties;
- transition temperature;
- phase equilibrium;
- vapour pressure.

2) Physical properties:

- appearance;

- volumetric change;

- density.

3) Stability considerations.

4) Economic considerations.

Taking into account the good thermodynamic properties of these materials and their economical advantages, it might be useful to investigate also their air leakage properties, perhaps in combination with different air leakage barrier systems.

On the basis of the updated criterion from the study of the referenced literature and on the basis of previous works [Hawes, Banu and Feldman, 1989], [Feldman, Hawes, and Banu, 1991] the following materials can be used in the impregnation analysis of building materials:

a) Butyl stearate (BS) : $CH_3\text{-}(CH_2)_{16}\text{-}COO(CH_2)_3\text{-}CH_3$

b) 1-Dodecanol (DD) : $CH_3\text{-}(CH_2)_{11}\text{-}OH$

c) Polyethylene Glycol (PEG) : $H(OCH_2\text{-}CH_2)_n\text{-}OH$ Carbovax 600

d) 1-Tetradecanol (TD) : $CH_3\text{-}(CH_2)_{13}\text{-}OH$ EPAL 14 Alcohol

e) Paraffin (PAR) : $CH_3\text{-}(CH_2)_n\text{-}CH_3$

f) Dimethyl Sulfoxide (DS) : $(CH_3)_2\text{-}SO$.

Taking into account the characteristics of these substances, in order to analyze the infiltration through building materials (brick, gypsum board, wood etc.) paraffin was selected for use in the present work.

Paraffin, CH_3- $(CH_2)_n$-CH_3, is a macrocrystalline wax derived from petroleum and is a by-product of the oil refining process consisting principally of normal alkane. It is produced in large quantities and is readily available throughout the world. By considering its thermal and airtightness characteristics, paraffin is also suitable in order to improve the material (brick, wood, concrete etc.) properties, due to its stability, low cost and easy availability.

Paraffin is particularly useful for thermal storage applications where low cost heat is available from sources such as solar collectors or exothermic processes. Some of the relevant characteristics of paraffin are presented in Table 5.5:

Table 5.5 Paraffin Characteristics, after Feldman, Hawes and Banu, 1991.

Melting point	60^0 C
Latent heat	200 J/Kg
Viscosity	0.0053 Ns^{2}m at 80^0 C
Molecular weight	400
Density	915 Kg/m^3
Flash point	232^0C (ASTM D 92)
Cost	0.88 Cdn$/Kg, 1993

The technology of bricks impregnation followed the next steps:

1) Heating in drying stove. Each brick was kept in the drying stove for two hours at a constant temperature of 95^0C (Figure 5.5).

2) Impregnation. At this temperature (95^0C) the bricks were introduced in the paraffin bath for one hour. The constant temperature of paraffin (86^0C) was controlled by a thermostat (Figure 5.6).

The specimens (55 bricks) were weighed before and after impregnation and the results are presented in Appendix B.

The impregnation changes the mass of brick wall as follows:
Total weight of brick wall : 107 Kg
Total weight of impregnated brick wall : 110 Kg
Percentage of weight increasing: 2.8 %

The previously analyzed bricks have been used for the construction of two different walls wich served to the study of infiltration of single layer and multilayer envelopes (Chapters 6 and 7).

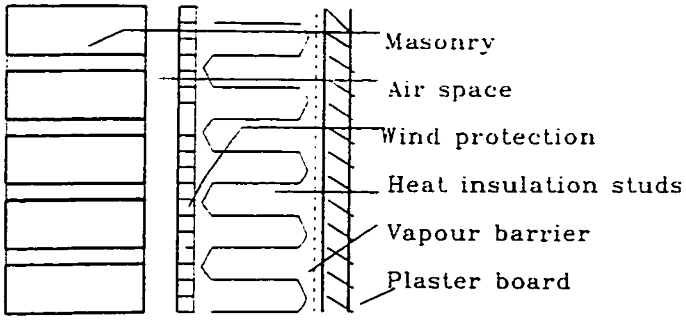


Fig. 5.1 Swedish Cavity Wall

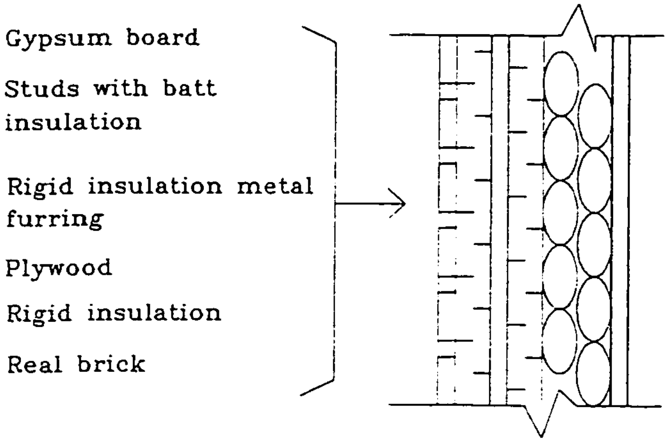


Fig. 5.2 Canadian Cavity Wall

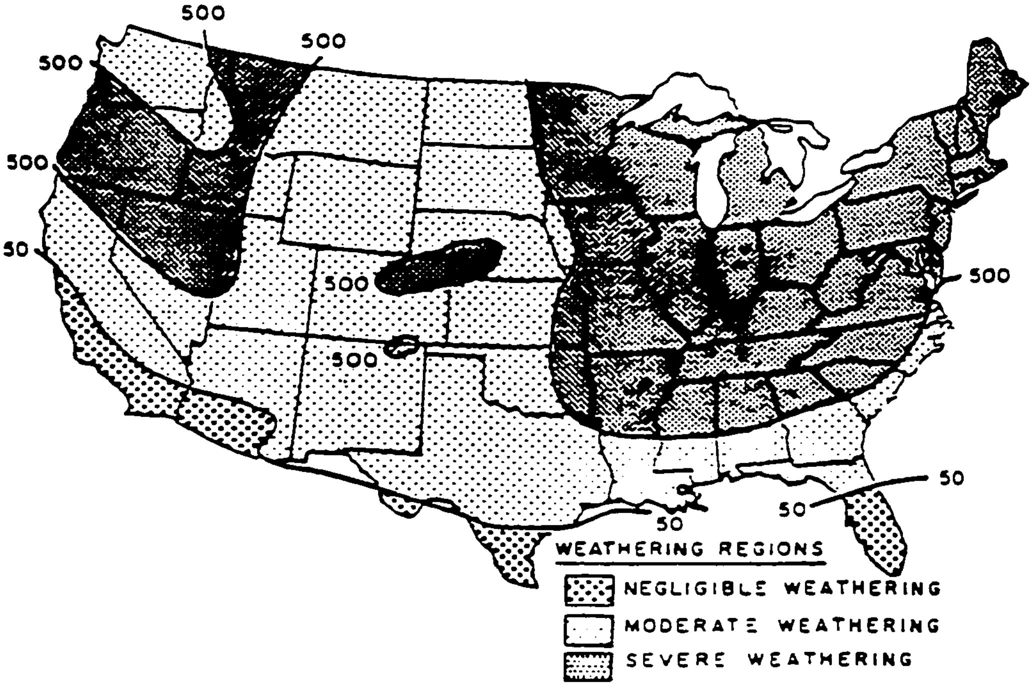


Fig. 5.3 Weathering Regions (Severe Weathering - ASTM C216-81) Facing Brick Masonry units type FBS Standard, Made from Clay

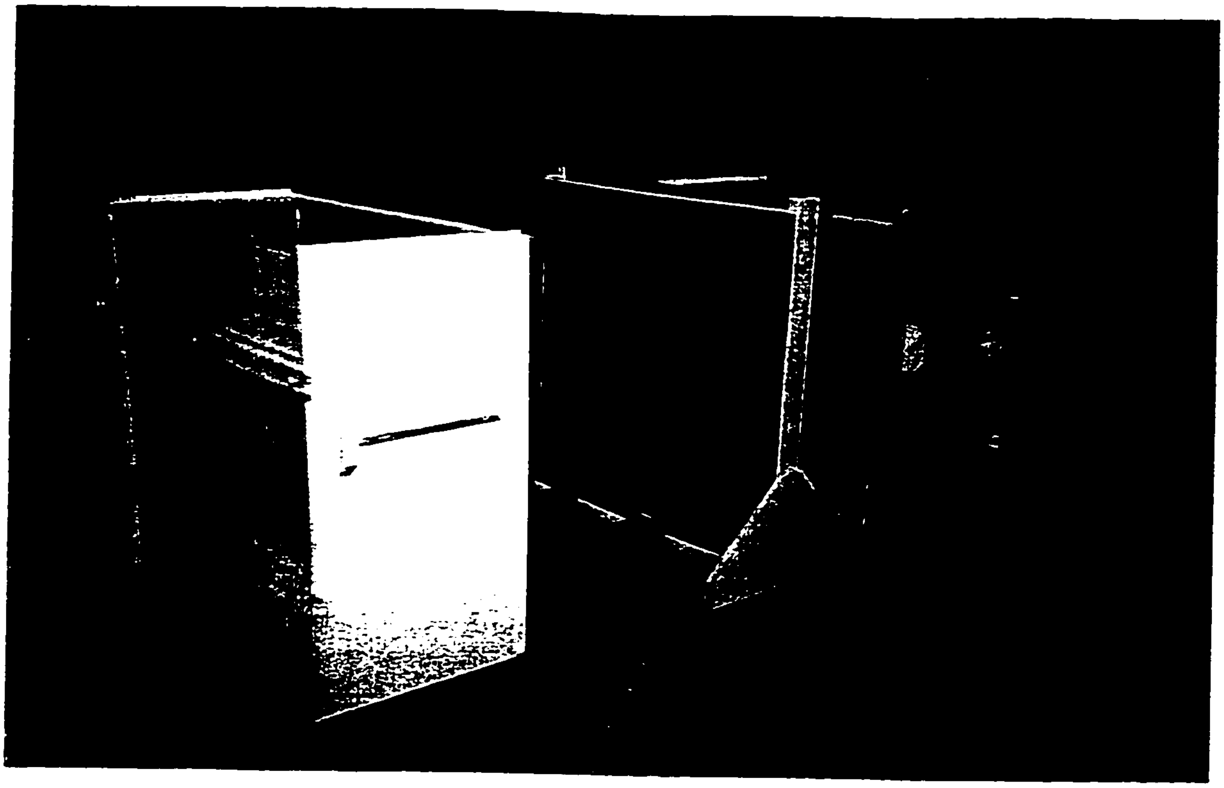


Fig. 5.4 Brick Wall. Experimental Model

Fig.5.5 Heating in Drying Stove

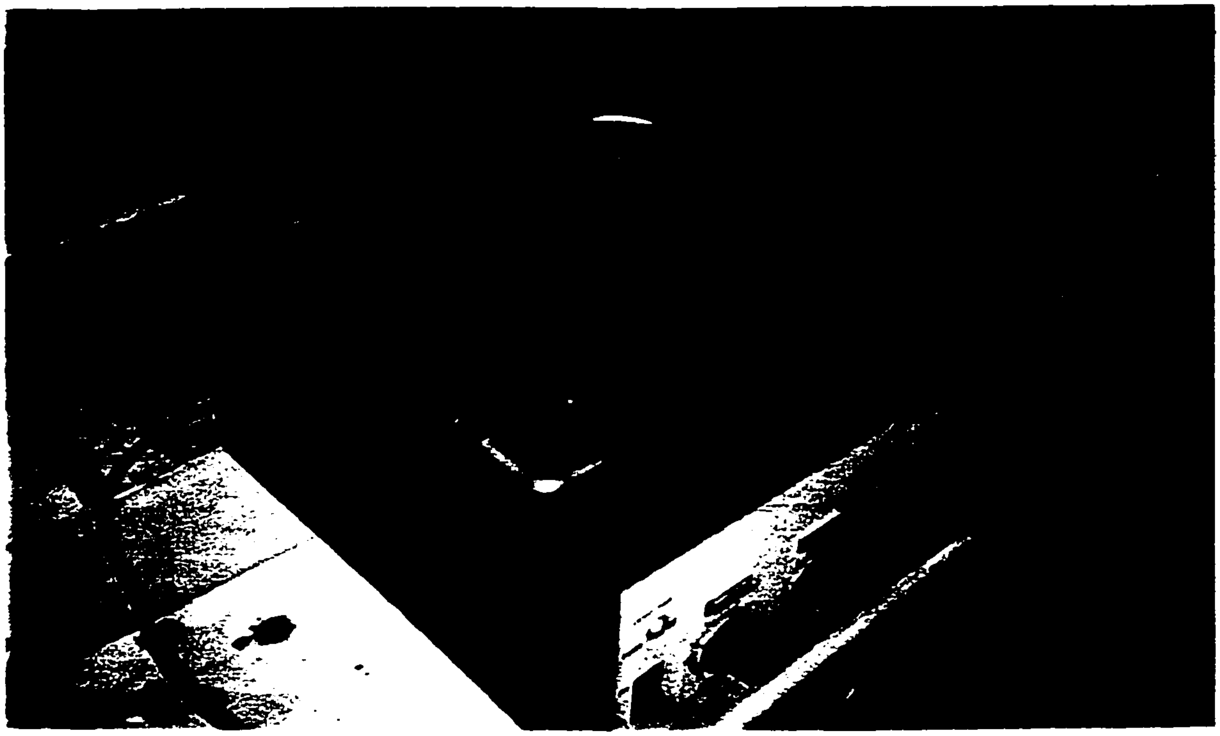


Fig. 5.6 Impregnation Procedure

CHAPTER 6

SINGLE LAYER ENVELOPE

EXPERIMENTAL RESULTS AND DISCUSSION

This chapter presents an airtightness analysis of brick walls and impregnated brick walls. Values are presented in terms of flow rate across unit areas of material, i.e. $m^3.s^{-1}.m^{-2}$,or $L.min^{-1}.m^{-2}$. This analysis does not include air vents, and service penetration.

The infiltration test was conducted by keeping box 1 pressurized and box 2 open to the atmosphere (as shown in Chapter 5, Figure 5.4). The air flow rate values were imposed by using the Flow Control Box devices, and the resulting pressure was measured. Because of the fact that the system works at relatively low pressure values (0-200 Pa), the fluctuations of pressure are relatively high. In order to obtain accurate results, the pressure values were recorded during each testing hour, and an average was calculated for each value of air flow rate imposed. In order to verify the repeatability of the operations, seven sets of similar measurements were carried out.

The same analysis (seven more tests) was repeated for the pressurized box 2 when box 1 was open to the atmosphere. The experimental results of the mean pressure values obtained for the brick wall are presented in Appendix C for the two sets of the experimental tests. All the seven experimental curves show a good repeatability of the results. This demonstrates the accuracy of the proposed testing method.

6.1 Airtightness Measurements of Brick Wall

A general mean value for all the pressure measurements presents the reference values of Q and ΔP, which will be considered in calculations of air leakage characteristics: permeance (P), resistance (R) and equivalent leakage area (ELA). Table 6.1 shows values of these parameters for the tested brick wall, determined for 12 representative cases, at pressures ranging from 0 to 100Pa. The permeance and resistance presented in Table 6.1 will be used in the comparative analysis between air leakage characteristics of brick wall and impregnated brick wall (Figure 6.1).

Table 6.1 Brick Wall, Leakage Parameters

No	Air Flow Rate (avg)(L/sm^2)*10^{-2}	Permeance (avg) (L/s-m^2-Pa)*10^{-5}	Resistance (avg) (s-m^2-Pa/L)*100
1	0.66	110.73	9.03
2	1.00	118.2	8.46
3	1.33	113.6	7.32
4	1.66	167.7	5.96
5	2.00	174.5	5.72
6	2.33	195.8	5.10
7	2.66	209.5	4.77
8	3.00	200.9	4.98
9	3.33	202.8	4.93
10	5.00	180.5	5.30
11	6.66	180.9	5.53
12	8.33	170.34	5.77

6.2 Airtightness Measurements of Impregnated Brick Wall

The measurements of air leakage through the impregnated brick wall were carried out by the pressurization methodology proposed for the airtightness analysis of building materials used in the building envelope design. The impregnated brick wall was built with the same materials (cement, sand etc.) and under the same conditions as the non-impregnated brick wall. The experimental results are presented in Appendix D. Following the same procedure used for the brick wall, seven similar air infiltration tests were carried out. As demonstrated in the previous tests for the brick wall, the obtained values show good repeatability. Mean values for the pressure measurements of impregnated brick wall shown in Figure 6.1 with the corresponding values of Q and ΔP, will be considered as reference values in calculation of air leakage characteristics, permeance (P) and resistance (R), presented in Table 6.2. In order to comply with the limits of the pressure measurements accuracy of the proposed experimental method, a maximum of 6.66×10^{-2} L/s-m^2 air flow rate was considered (14 increasing values).

Table 6.2 Impregnated Brick Wall, Leakage Characteristics.

No	Air Flow Rate (avg) (L/s-m^2)*10^{-2}	Permeance (avg.) (L/s-m^2-Pa)*10^{-5}	Resistance (avg.) (s-m^2-Pa)*100
1	0.13	21.24	47.08
2	0.17	20.93	47.76
3	0.33	20.88	47.87
4	0.66	22.23	43.03
5	1.00	23.02	41.80
6	1.33	23.18	43.15
7	1.66	23.17	43.65
8	2.00	22.42	44.59
9	2.33	22.45	44.54
10	2.66	21.98	45.48
11	3.00	22.88	45.68
12	3.33	23.30	46.93
13	5.00	25.10	39.81
14	6.66	28.64	35.82

6.3 Brick Wall. Impregnated Brick Wall. Airtightness Comparative Analysis

Comparison between the experimental results obtained for the brick wall and for the impregnated brick wall is shown in Figure 6.1 in terms of air flow rate versus static pressure variation. The efficiency of brick impregnation in terms of wall airtightness is apparent for all ranges of the air flow rate (0 to 8 L/min-sqm). At specific static pressure differences of 50 Pa and 75 Pa, the air flow rate is 8.7 and 5.6 times greater, respectively, in the case of brick wall in comparison with impregnated brick wall.

For the same range of air flow rate, Figures 6.2 (brick wall) and 6.3 (impregnated brick wall) present the permeance and resistance variation. The comparison concerning the behaviour of the brick wall and the impregnated brick wall in terms of permeance, resistance and ELA shows, as expected, the following trends:

- the increase of the permeance (Figures 6.2a and 6.3a) and the decreasing of the resistance (Figures 6.2b and 6.3b), for both walls, with the increase of air flow rate.
- the permeance of the impregnated brick wall has been found 7.8, 7.6 and 7.7 times lower than of that of the non-impregnated brick wall for 10 Pa, 50 Pa and 75 Pa static pressure differences respectively (Figure 6.4);
- the resistance of the impregnated brick wall is 8.3, 7.3 and 7.4 times greater than of that of the non-impregnated brick wall for the same values of static pressure differences (Figure 6.5).

The Equivalent Leakage Area (ELA) was calculated by using the equations discussed in Chapter 3. The results of this analysis are presented in Figure 6.6, as a function of different static pressure differences (0-100 Pa for brick wall and 0-200 Pa for impregnated brick wall). The graphs indicate that at low pressure differences the ELA decreases significantly in both cases, as expected.

A comparison between ELA of both walls is shown in Figure 6.7; for 10 Pa and 50 Pa the values of ELA present significant differences which increase with the increase of static pressure difference. For the impregnated brick wall, the ELA was 7.5 times lower at 10 Pa and 6.8 times lower at 50 Pa. It can be seen that the variation of ELA with result to the static pressure is much more significant for brick wall than that for the impregnated brick wall and this can be summarized as follows:

- for an increase of the static pressure from 10 Pa to 50 Pa, the increase of ELA of the brick wall was 2 times;
- for the same increase of the static pressure, the increase of the ELA of the impregnated brick wall was only 1.14 times.

6.4 Airtightness Comparative Analysis with Other Research Programs

The air permeable material permits air to flow through it under the influence of pressure gradient. The airtightness of different walls for factory buildings was investigated by Kronwall [1980], and his results indicate that a relatively high degree of airtightness of brick walls (leakage rate of approximately 0.1 L/s-m^2 at 50 Pa) was achieved. In the present experimental programme, the air leakage curve of brick wall is presented in Figure 6.8 where the points (a), (b) and (c) represent the values of air leakage rate at 50 Pa for masonry walls, hollow brick, rendering on one side, 0.12 m thickness, high sorption, good workmanship (a), low sorption, good workmanship (b), and masonry wall, low sorption, retested after 5 months, (c). The values obtained in the present experimental programme for 50 Pa static pressure difference are included in the range of the results indicated in the literature [Kronwall, 1980] (Figure 6.8).

ASHRAE Fundamentals Handbook 1993 gives information data about the infiltration through brick and frame wall. Table 6.3 presents the air leakage through plastered and frame walls as a function of the type of brick, for different pressure differences in the range of 12 Pa and 75 Pa. These values are compared in Figure 6.9 with those of the impregnated brick wall used in the present study.

Table 6.3 Air leakage through walls in (L/ min-sqm), after ASHRAE 1993

Type of Wall	Pressure Difference 12 Pa	Pressure Difference 25 Pa	Pressure Difference 50 Pa	Pressure Difference 75 Pa
brick wall 0.22m plastered	0.24	0.42	0.72	1.02
brick wall 0.33m plastered	0.06	0.24	0.24	0.4
frame wall plastered	0.48	0.78	1.14	1.5

Figure 6.9 represents a comparative analysis for air leakage values of the impregnated brick wall of the present experimental work, the brick wall plastered 0.22m, and plastered brick wall 0.33m. It may be underlined that the impregnation procedure represents an economical method in order to improve the airtightness of the brick wall. This comparative analysis shows that, in the range of 12 Pa to 75 Pa, the air flow rate for 0.06m impregnated brick wall (the present experimental programme) has a similar behaviour with that of 0.22m plastered brick wall (ASHRAE 1993).

The main purpose of this analysis was to establish a comparison between the main air leakage characteristics of the brick wall and impregnated brick wall.

The conclusion of this experimental programme is that the impregnation procedure reduces the permeance of the impregnated wall by about 7.5 times at 50 Pa and by about 8 times at 75 Pa, as it was expected. One can also draw the conclusion that the material impregnation methods can be applied successfully to porous materials with high air leakage rate.

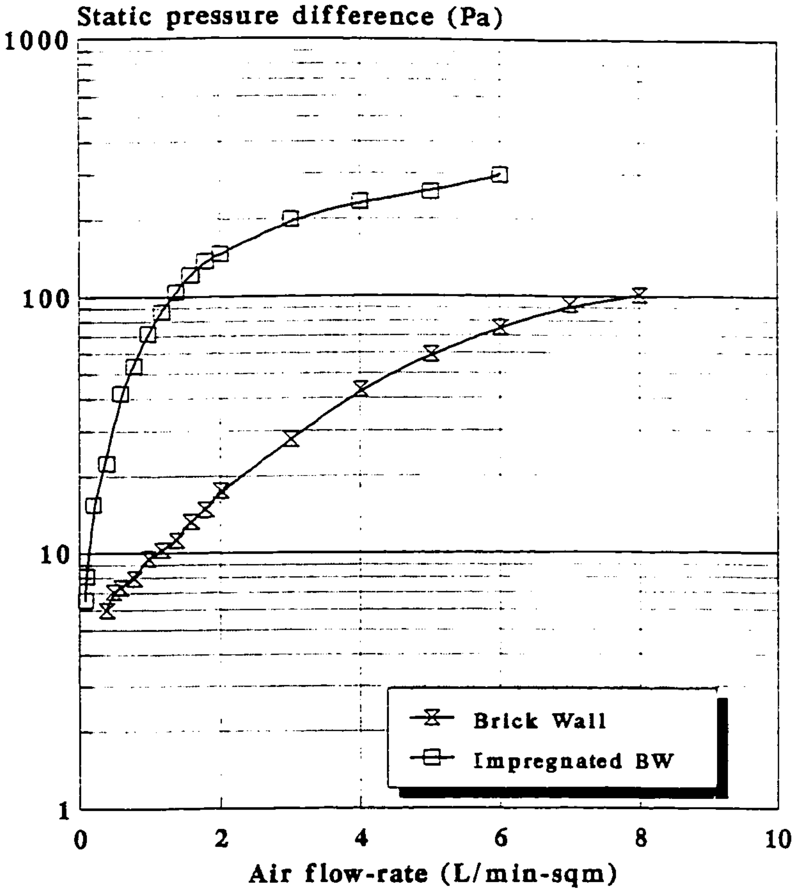


Fig. 6.1 Air Flow Rate Versus Static Pressure Difference for Brick Wall and Impregnated Brick Wall

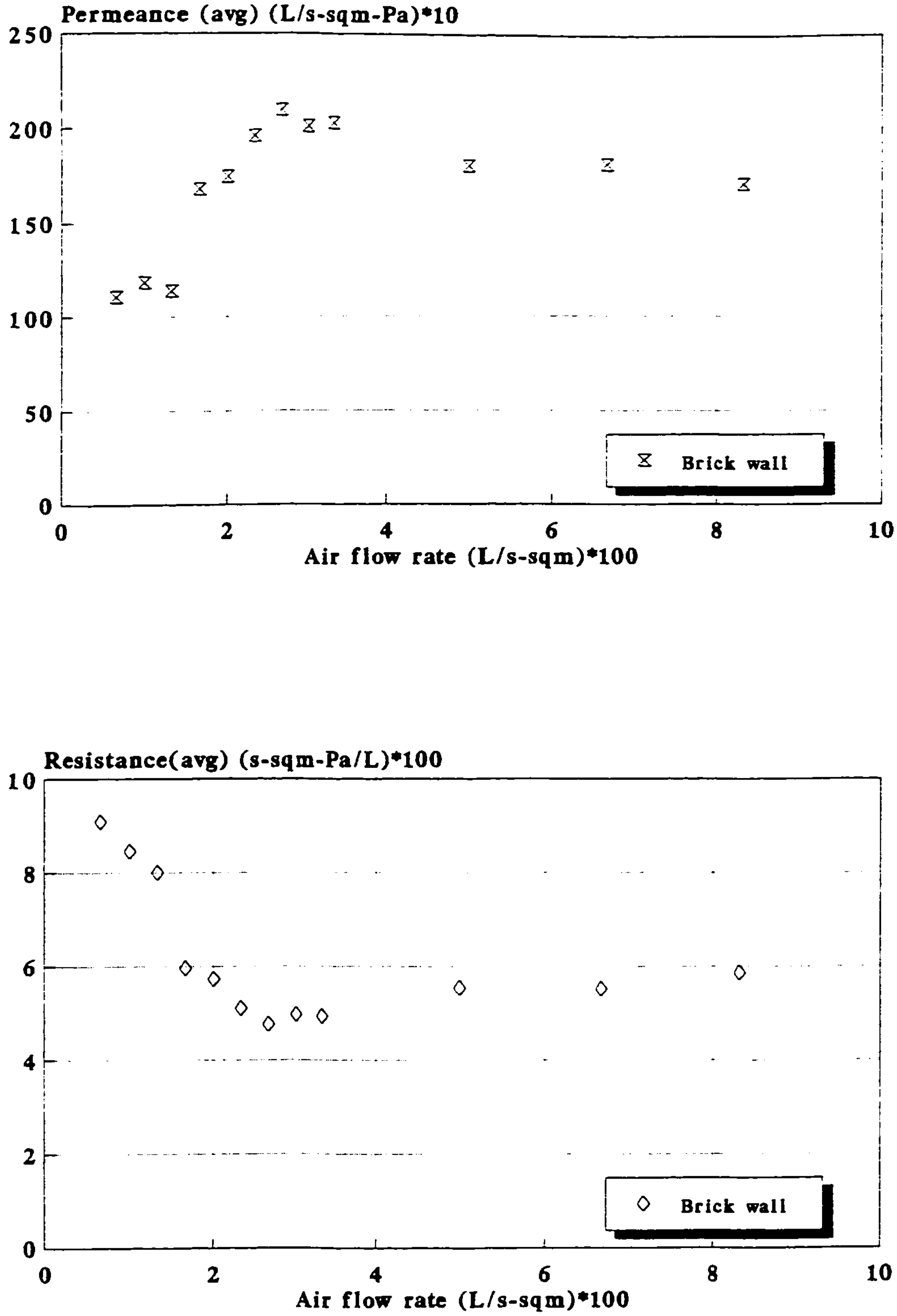
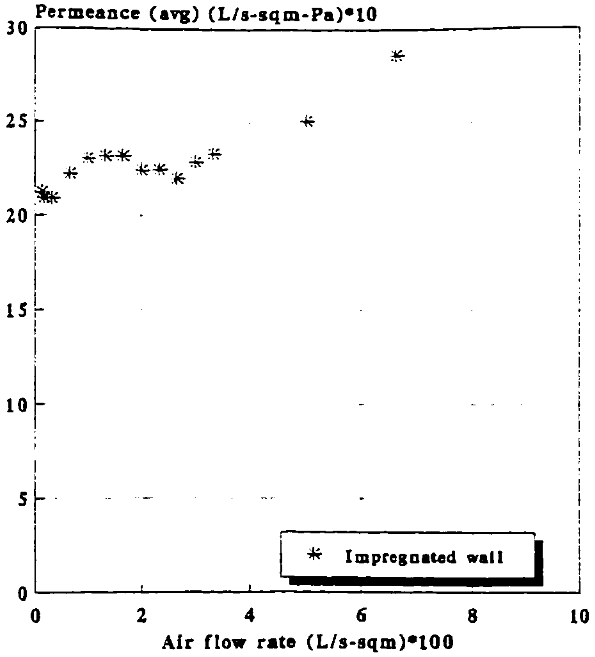


Fig. 6.2 Brick Wall. Permeance and Resistance Parameters as a Function of the Air Flow Rate (Experimental Values)



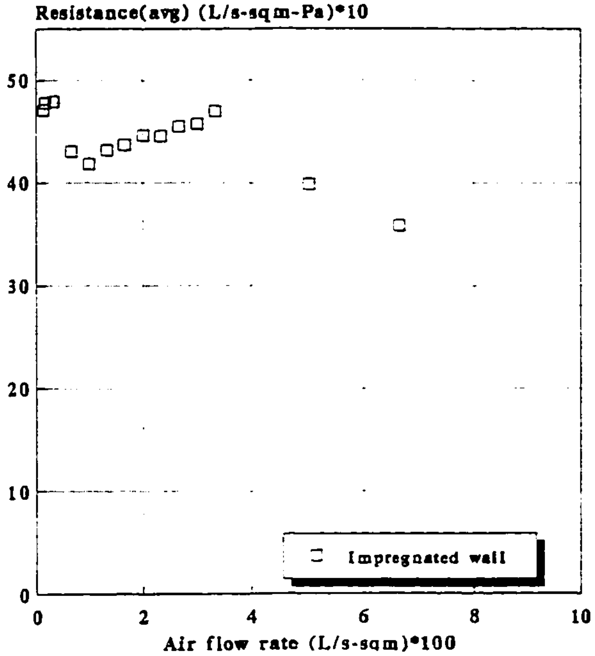


Fig. 6.3 Impregnated Brick Wall. Permeance and Resistance Parameters as a Function of the Air Flow Rate (Experimental Values)

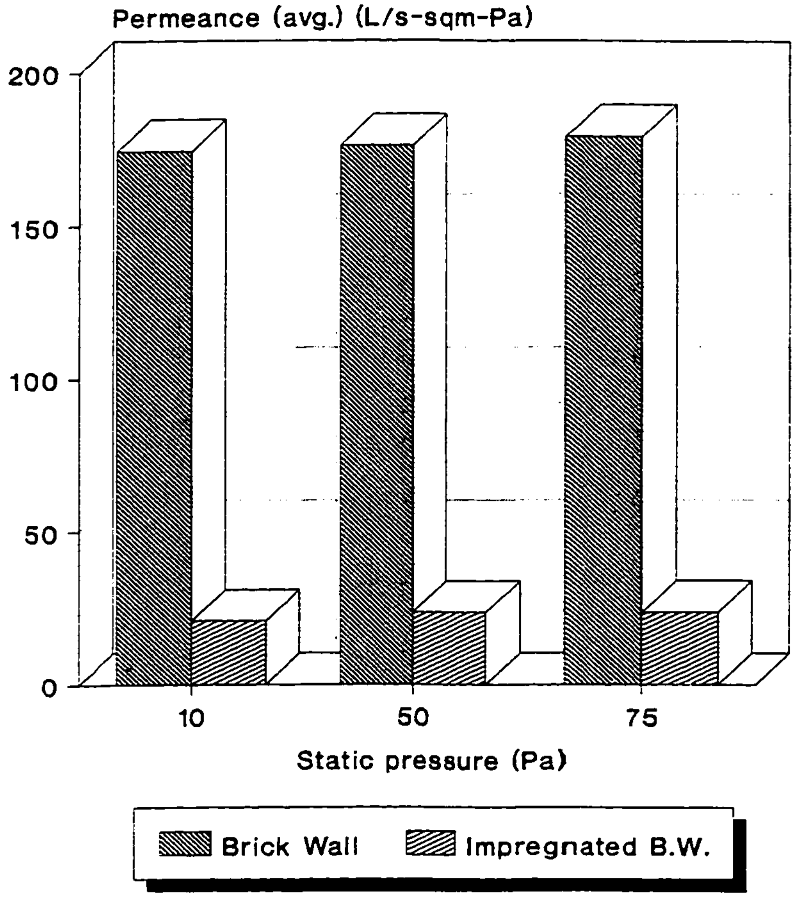


Fig. 6.4 Brick Wall and Impregnated Brick Wall. Comparative Analysis in Terms of Permeance for 10, 50, 75 Pa

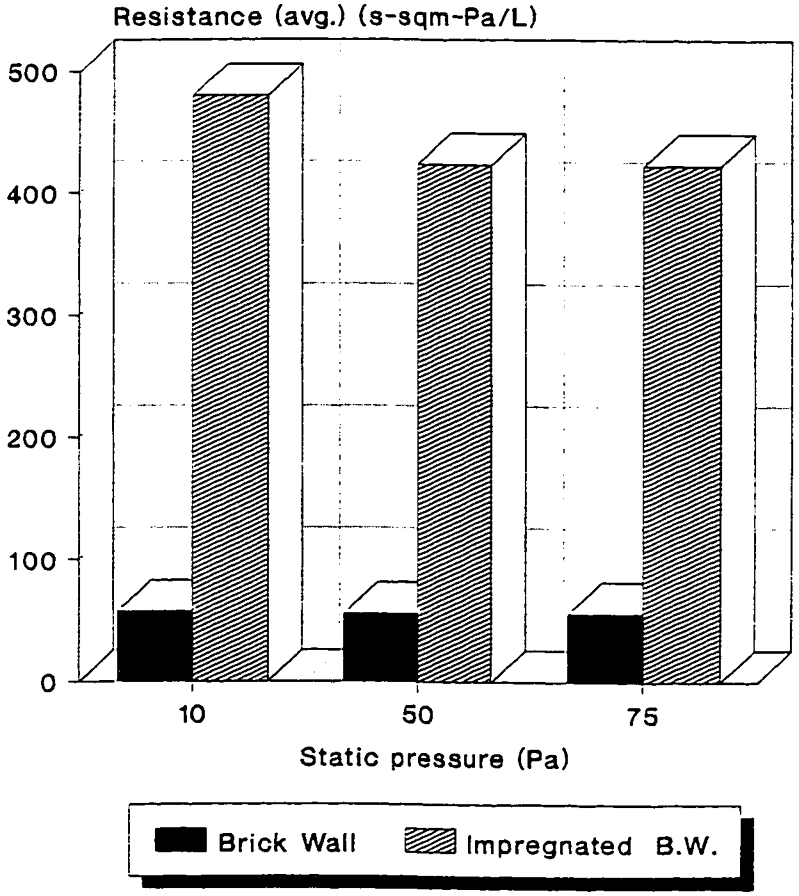
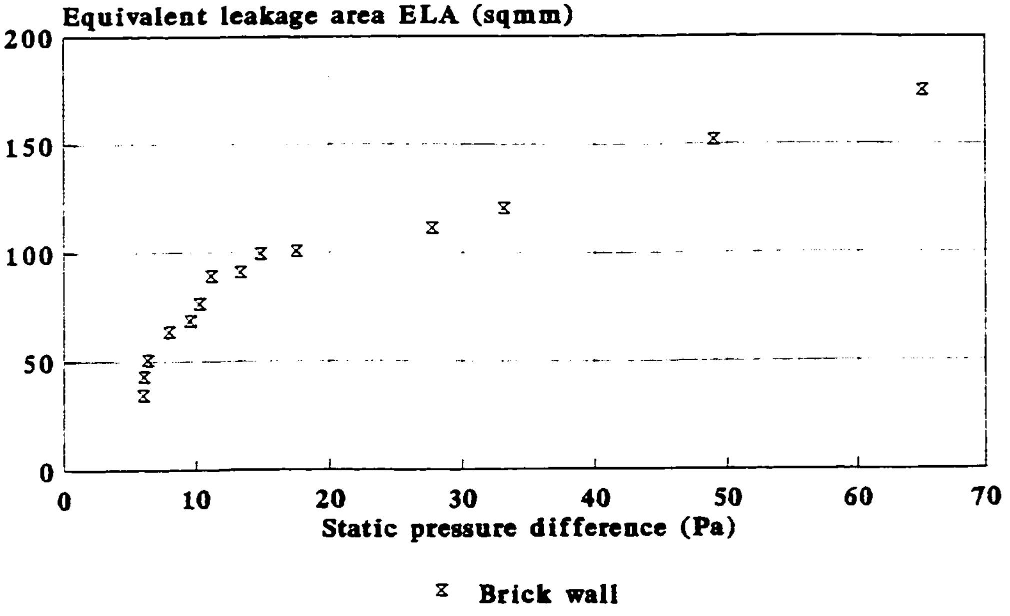


Fig. 6.5 Brick Wall and Impregnated Brick Wall. Comparative Analysis in Terms of Resistance for 10, 50, 75 Pa



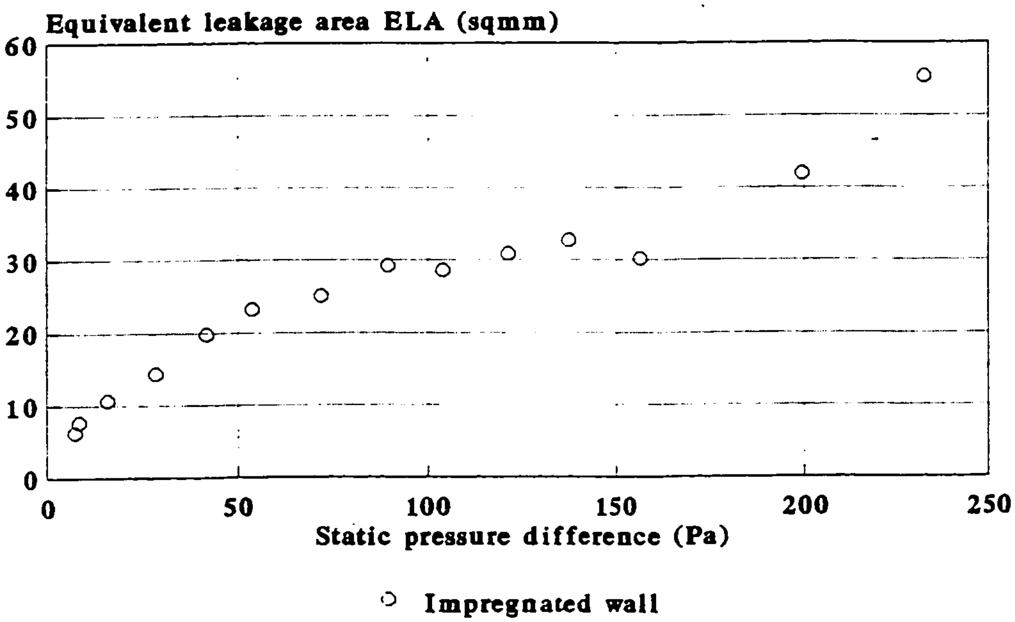


Fig. 6.6 Brick Wall and Impregnated Brick Wall. Comparative Analysis in Terms of ELA

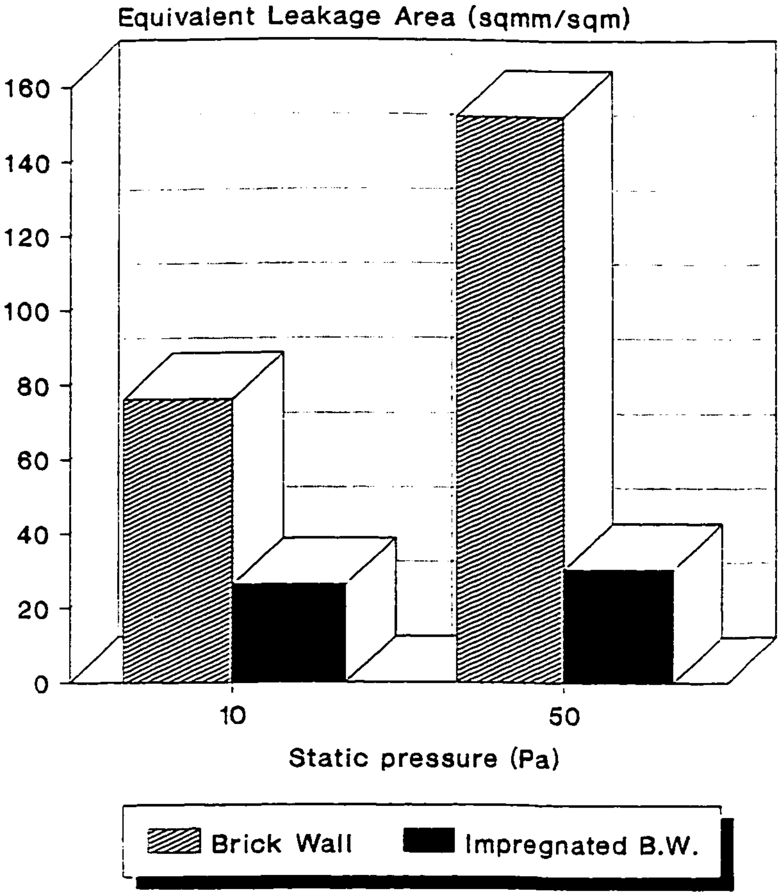


Fig. 6.7 Brick Wall and Impregnated Brick Wall. Comparative Analysis in Terms of ELA for 10 and 50 Pa

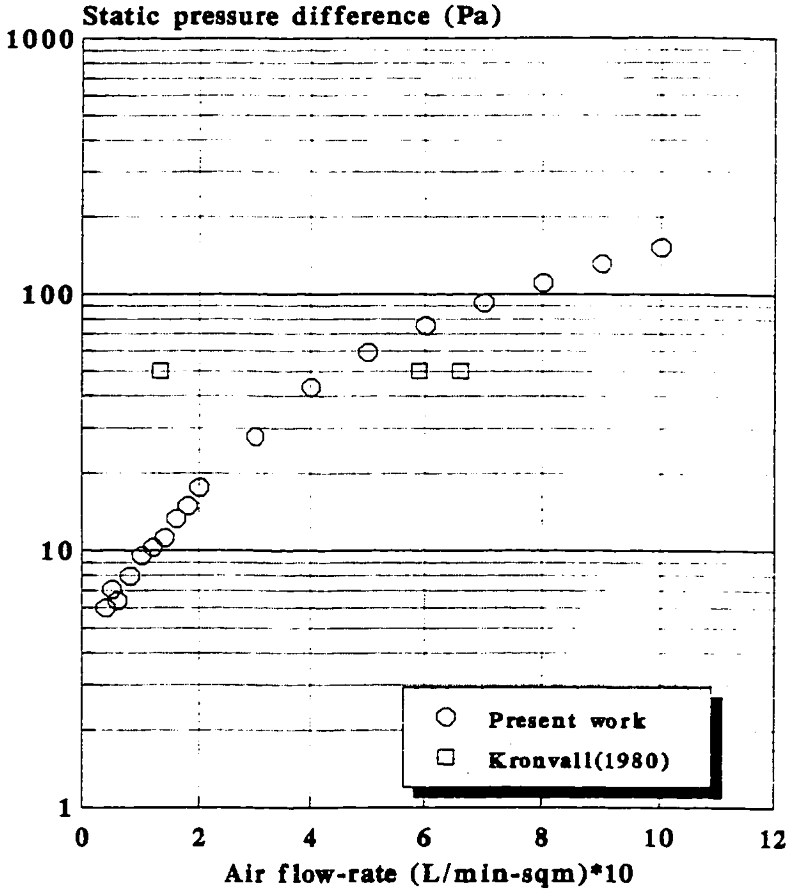


Fig. 6.8 Airtightness Comparative Analysis Between the Tested Brick Wall Model (Mean Experimental Values) and Kronwall, J. 1980

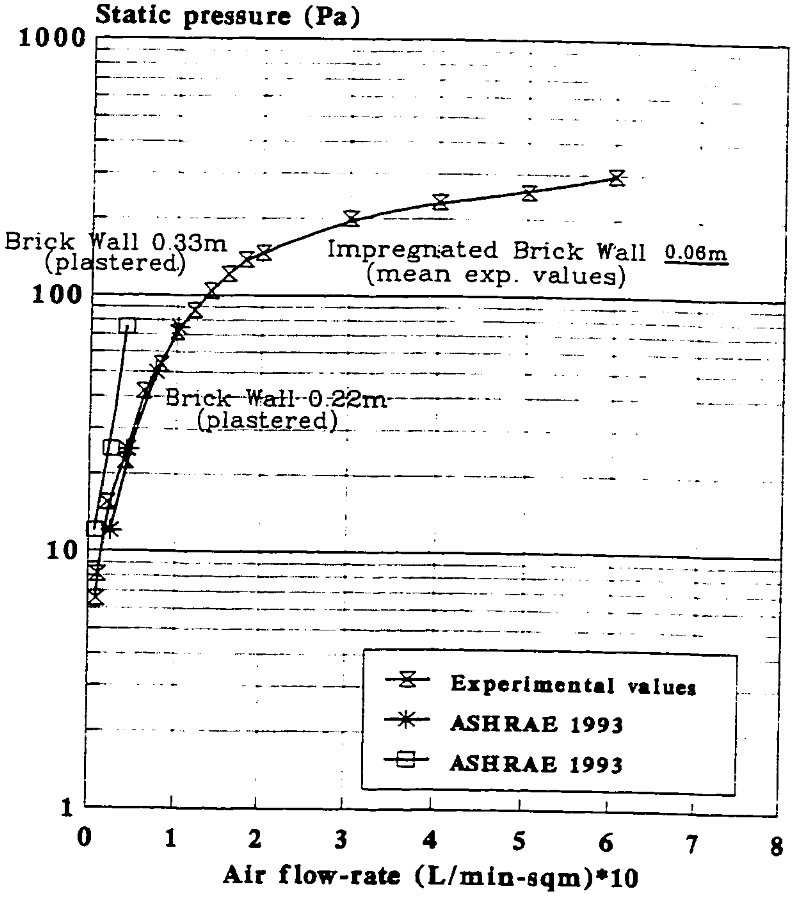


Fig. 6.9 Airtightness Comparative Analysis Between the Tested Impregnated Brick Wall (Mean Experimental Values) and ASHRAE 1993

CHAPTER 7

MULTILAYER ENVELOPE
EXPERIMENTAL RESULTS AND DISCUSSION

There are many quite different systems that can be included under the category of masonry walls. These systems can range from a single wythe with no exterior or interior finish, to a double wythe cavity wall with brick veneer and interior finish of furring and gypsum. In the North American climate, a typical exterior wall consists of many layers of different materials, such as exterior cladding, insulation, vapour barrier, air barrier and interior finishes [Fazio, et al. 1992].

The hierarchy of building envelope components is presented in Figure 7.1 but usually the term envelope is used for the external wall, which represents the main component of the envelope. In order to study the performance of the building envelope, by taking into account the air leakage characteristics, the present research work focused on the measurement of infiltration of composite walls. Gypsum board, plywood sheathing, brick and impregnated brick (discussed in Chapters 5 and 6) were used as layers in different combinations as usually employed in the envelope design.

7.1 Three-layer Wall System (gypsum board, insulation, plywood sheathing)

Many research programmes focused on the air leakage characteristics of building materials by using different design approaches. Figure 7.2 presents four design approaches used in Canadian envelope construction, where gypsum board, insulation and plywood sheathing represent component layers. The National Research Council of Canada (NRC) has published envelope building design data, [NRC 1994] wich were used in the present study for comparison purposes. All four panels presented in Figure 8.2 were realised of 3.8 mm by 8.9 mm wood framing with an indoor sheathing of 12 mm gypsum board. Exterior sheathing was 50 mm semi-rigid fiberboard for POLY and ADA approaches, 12 mm chipboard for the conventional approach, and a layer of spun bonded olefin film (Tyvec) sandwiched between two sheets of 12 mm fibreboard for the EASE approach [CMHC 1992].

All four different approaches to joist construction were subjected to an air leakage analysis in the test chamber. The traditional approach (see Figure 7.2), provided the most air leakage (1.12 L/s-sqm at 75 Pa) and the ADA detail achieved the lowest leakage (0.12 L/s-sqm at 75 Pa). The maximum acceptable level of air leakage through construction details has not yet been defined.

In the present work the airtightness and the air leakage characteristics of the multilayer envelope with brick wall or impregnated brick wall were determined under controlled laboratory conditions. The study concerning these parameters is based on the results obtained previously for each material which composes the system (see Chapters 5 and 6).

The composite wall was subjected to a series of air flow rates (in the air leakage test chamber), ranging from 0 to 1.2 $L.min^{-1}.m^{-2}$. in order to obtain values for the static pressure difference, and also to have the possibility to draw the air leakage curves. The air leakage rate was measured at each layer in order to determine the contribution of each material to the airtightness of the whole system. For this reason, the composite wall was designed without a vapour barrier and without exterior sheathing paper.

For the experimental test, the three layer wall (Figure 6.3) was constructed inside the wood framing with an inner surface of 1 m^2. The indoor sheathing was a 12.7 mm gypsum board and the exterior sheathing was a plywood sheeting of 8 mm thickness. The samples used in order to form this three strata envelope were those tested previously - see Chapter 4. The space between gypsum board and plywood sheeting was filled with dense glass fibre batts (RSI-2.47, R-14, one of the most used in building envelope design), manufactured by Manville Canada. This insulation contains up to 30% recycled glass. The corners and perimeter between the wood frame and the threelayer wall were well sealed in order to minimize the air leakage on the perimeter (Figure 7.3). The experimental three layer wall specimen is presented in Figure 7.4.

The mean experimental data, obtained after the pressurization of the chamber No.1 and chamber No.2 respectively are presented in Table 7.1.

Table 7.1 Mean Experimental Values for Pressurization Measurements of Three Layer Approach (gypsum board, insulation and plywood sheathing)

Air flow rate L/min/m^2	Gypsum board Static pressure (Pa)	Plywood sheathing Static pressure (Pa)	Three layer Static pressure (Pa)
0.06	8.13	11.45	11.78
0.08	10.87	-	-
0.10	12.84	17.04	18.02
0.15	20.45	25.45	25.91
0.2	23.50	34.52	35.54
0.25	29.41	44.25	47.40
0.30	35.39	53.96	56.91
0.40	49.00	72.42	75.90
0.50	62.02	90.63	95.00
0.60	75.63	108.00	110.90
0.70	90.03	117.51	120.10

As expected, the multilayer envelope airtightness is strongly dependent on the air leakage characteristics of the component layers with the highest airtightness. In the present analysis this layer is represented by the 8 mm plywood sheathing (Figure 7.5).

7.2 Composite Wall

The present study analyzes composite walls by considering the following layer combinations:

1) Three layer approach and ordinary brick cladding (composite wall-1), and
2) Three layer approach and impregnated brick cladding (composite wall-2).

The experimental model is composed by the three layer approach and the ordinary or impregnated brick wall separated by 2.5 cm air space.

The testing procedure, as presented in Chapter 4, was applied for the composite wall (three layer approach frame and the brick frame) for both 1) and 2) models. The two boxes have been pressurized alternatively for different air flow rates in order to study both the infiltration and exfiltration for the same sample. The results of the experimental analysis for the two combinations, in terms of air flow rate versus static pressure differences are presented in Figure 7.6. Clearly the impregnation provides an increase of the airtightness in the case of the composite wall-2. This increase is available for the entire range of the measured air flow rate

(0 to 6.0 L/min/m^2) and the corresponding static pressure differences (0 to 300 Pa).

The experimental programme has been conducted for the two types of composite walls. Composite Wall-1 had as components threelayer and brick cladding (Figure 7.7) while the Composite Wall-2 was composed of the same threelayer and impregnated brick wall (Figure 7.8). The composite wall response represents, in both cases, the greater value in terms of airtightness (Figures 7.7 and 7.8). The efficiency of the impregnated brick wall on the airtightness of the composite wall is clear especially for air flow rates higher than 2.0 L/min/m^2 (Figure 7.8).

The leakage characteristics, permeance and resistance of the analyzed data are presented in Tables 7.2 and 7.3 and in Figures 7.9 and 7.10.

Table 7.2 Composite Wall-1, Leakage Characteristics

No	Air Flow Rate $(L/s\text{-}m^2)*10^{-2}$	Permeance $(L/s\text{-}m^2\text{-}Pa)*10^{-5}$	Resistance $(s\text{-}m^2\text{-}Pa/L)*100$
1	0.17	-	111.17
2	0.33	8.95	93.98
3	0.66	11.85	84.33
4	1.00	-	-
5	1.30	14.67	68.14
6	1.60	13.47	74.19
7	2.00	14.95	66.88
8	2.30	15.75	63.38
9	2.60	15.78	63.46
10	3.00	16.36	61.10
11	3.30	17.57	56.89
12	5.00	17.42	57.40
13	6.60	22.19	45.06

Table 7.3 Composite Wall-2, Leakage Characteristics

No	Air flow rate (L/s-m^2)*10^{-2}	Permeance (L/s-m^2-Pa)*10^{-5}	Resistance (s-m^2-Pa/L)*100
1	0.13	6.33	157.74
2	0.16	4.30	232.22
3	0.33	5.95	168.06
4	0.66	9.18	108.83
5	1.00	9.22	108.45
6	1.30	10.78	92.73
7	1.60	11.50	86.92
8	2.00	12.51	79.90
9	2.30	13.59	73.56
10	2.60	13.76	72.62
11	3.00	16.00	62.49
12	3.30	19.00	51.26
13	5.00	22.10	45.34
14	6.60	26.00	37.37

The testing program has been performed for an air flow rate ranging from 0 L/s-m^2 to 6.6 L/s-m^2. The permeance values increase to a maximum of 22.19x10^{-5} L/s-m^2-Pa in case of composite wall-1 and to a maximum of 26.0x10^{-5}L/s-m^2-Pa for the composite wall-2. In Tables 7.2 and 7.3 the corresponding resistance values are 45.06x10^2 s-m^2-Pa/L for composite wall-1 and 37.37x10^{2}s-m^2-Pa/L respectively. It may be noted that the composite wall-1 permeance has higher values for the entire air flow rate range (Figure 7.9), while its resistance has lower values for the same range (Figure 7.10).

Figures 7.11 and 7.12 present a comparative analysis between the two composite wall combinations in terms of permeance and ELA for two different pressure differences (50 and 75 Pa respectively).

The obtained results indicate that the permeance of the composite wall-2 (three layer approach and impregnated brick cladding) is 2 times lower than that of the composite wall-1 (three layer approach and ordinary brick cladding) at 50 Pa pressure difference. For 75 Pa static pressure difference the permeance of the composite wall-2 is 1.5 times lower than the permeance of the wall-1 (Figure 7.11).

Figure 7.12 shows the comparative analysis in terms of ELA as a function of the static pressure difference of 50 Pa and 75 Pa. In this case the ELA$_{50}$ (Equivalent Leakage Area for 50 Pa) for the threelayer approach and impregnated brick

Leakage Area for 50 Pa) for the threelayer approach and impregnated brick cladding (composite wall-2) is 1.7 times lower than the ELA_{50} of the three layer approach and ordinary brick cladding (composite wall-1). For ELA_{75} (Equivalent Leakage Area for 75 Pa), the same ratio is 1.3 (Figure 7.12).

Consequently, the impregnation procedure, which is an inexpensive and efficient method, reduces significantly the air leakage through the building envelope.

7.3 Comparative Airtightness Analysis Between the Present Testing Program and Previous Research

These experiments constitute only the first step in defining the air leakage characteristics of some building materials and the combinations of different building materials commonly used in the envelope design. In the actual building envelope the vapour barrier and air barrier must be taken into account as well as the construction details. Further research is needed in order to observe and measure, under controlled laboratory conditions, the air leakage characteristics of construction details represented according to the design approaches.

The National Research Council of Canada recommends maximum leakage rates for the entire building envelope of 2 $L/min/m^2$. These values are expressed in litres per minute per square metre of panel for a pressure differential of 75 Pa inducing air infiltration and exfiltration.

Figure 7.13 presents the comparative analysis of the mean experimental values obtained in this research programme for the composite wall in both cases, and the results published in ASHRAE 1993. Clearly the composite wall-2 composed of threelayer approach and impregnated brick wall has a superior airtightness for all the values in the range of 0 to 200 Pa.

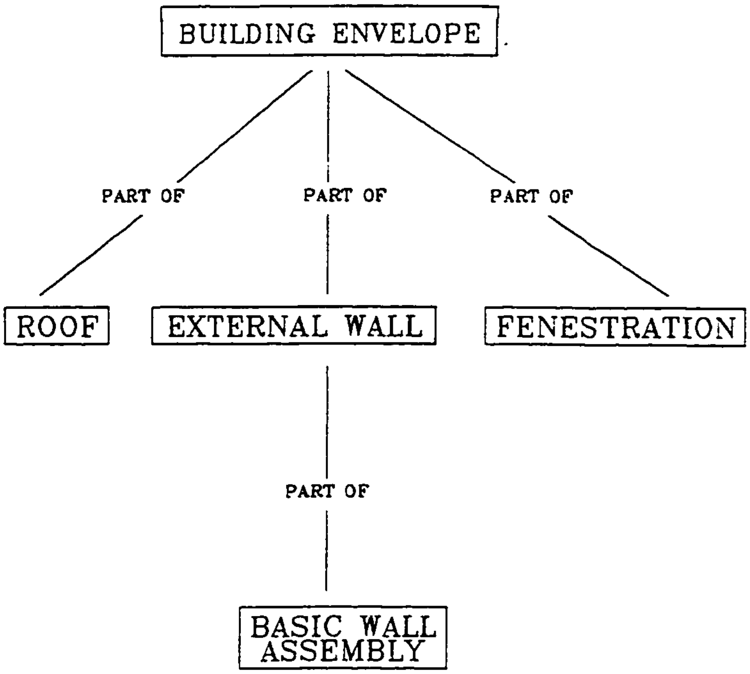
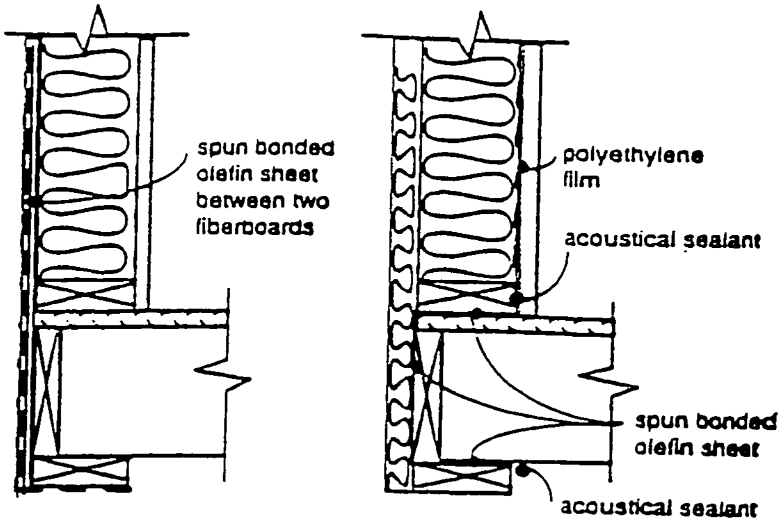


Fig. 7.1 Hierarchy of Building Envelope Components

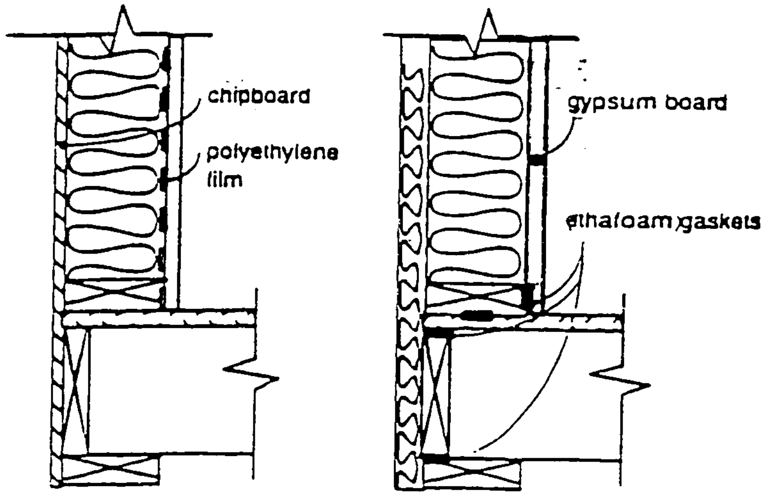


Traditional Approach

1.12 L/s/m^2 at 75 Pa

ADA Approach

0.12 L/s/m^2 at 75 Pa



EASE Approach

0.20 L/s/m^2 at 75 Pa

Poly Approach

0.29 L/s/m^2 at 75 Pa

Fig. 7.2 Three Layer Approach Used in the Canadian Envelope Constructions, after CMHC, 1995

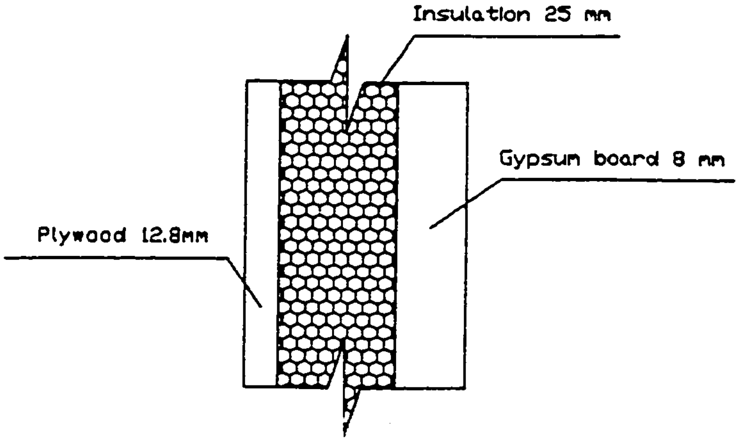


Fig. 7.3 Cross Section of Three Layer Approach Analysed in the Present Study

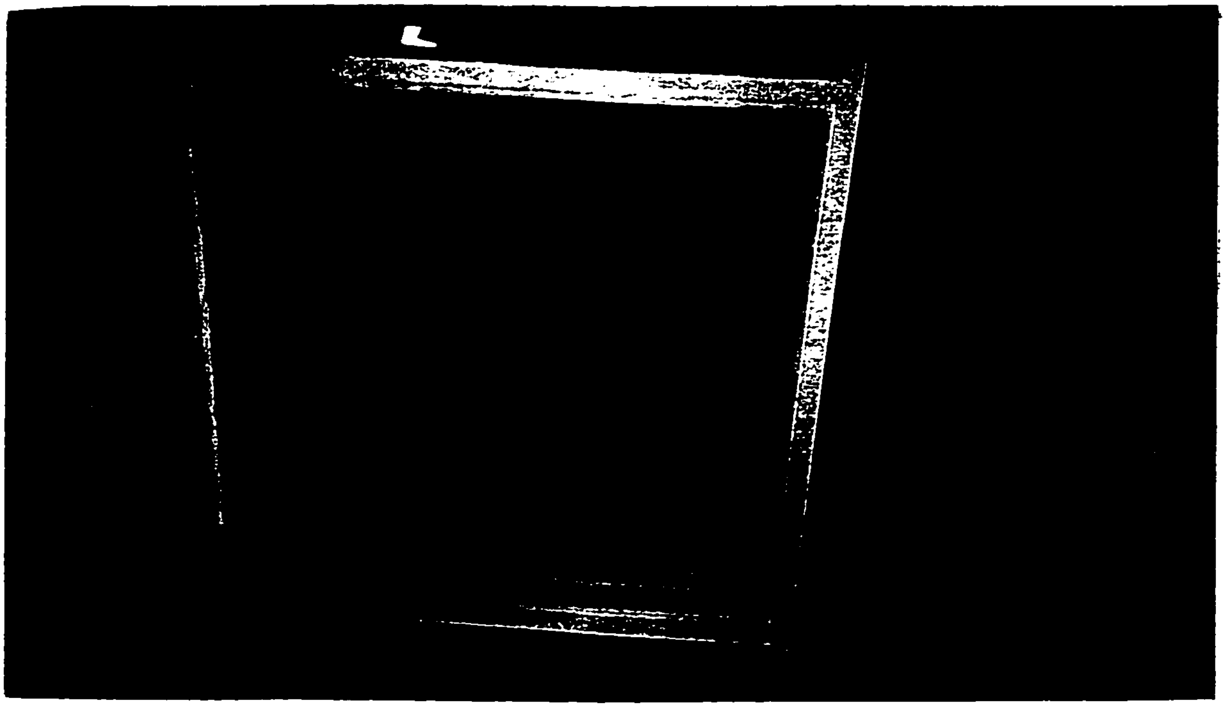


Fig. 7.4 Experimental Sample of Three Layer Approach (Insulation and Plywood Sheathing - Back Face - Gypsum Wallboard)

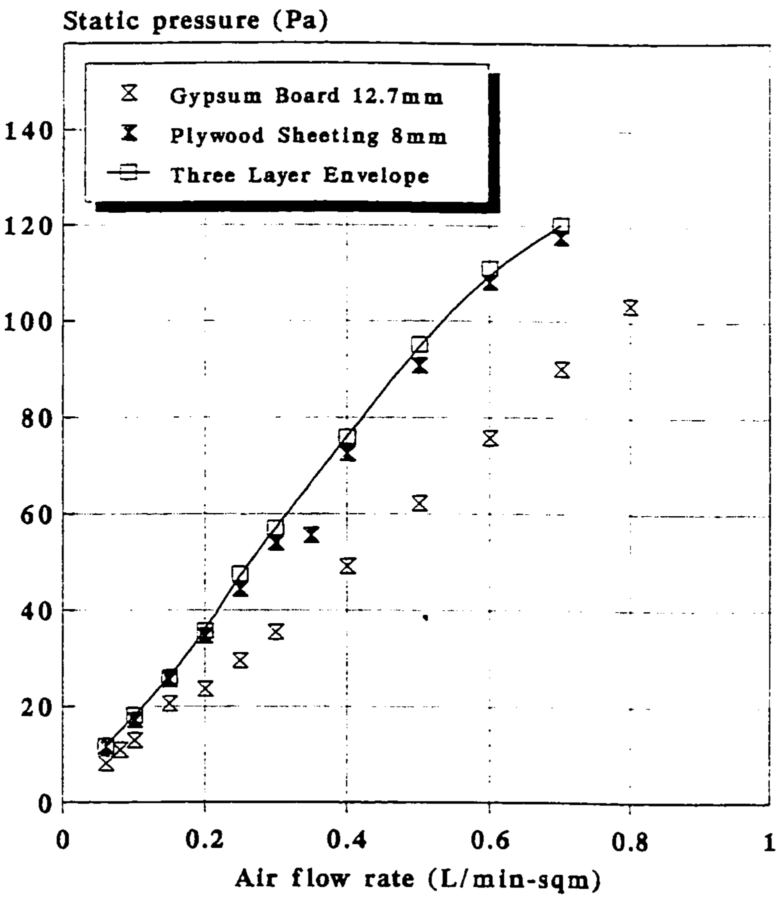


Fig. 7.5 Airtightness Comparative Analysis Between Gypsum Board, Plywood Sheathing and Threelayer

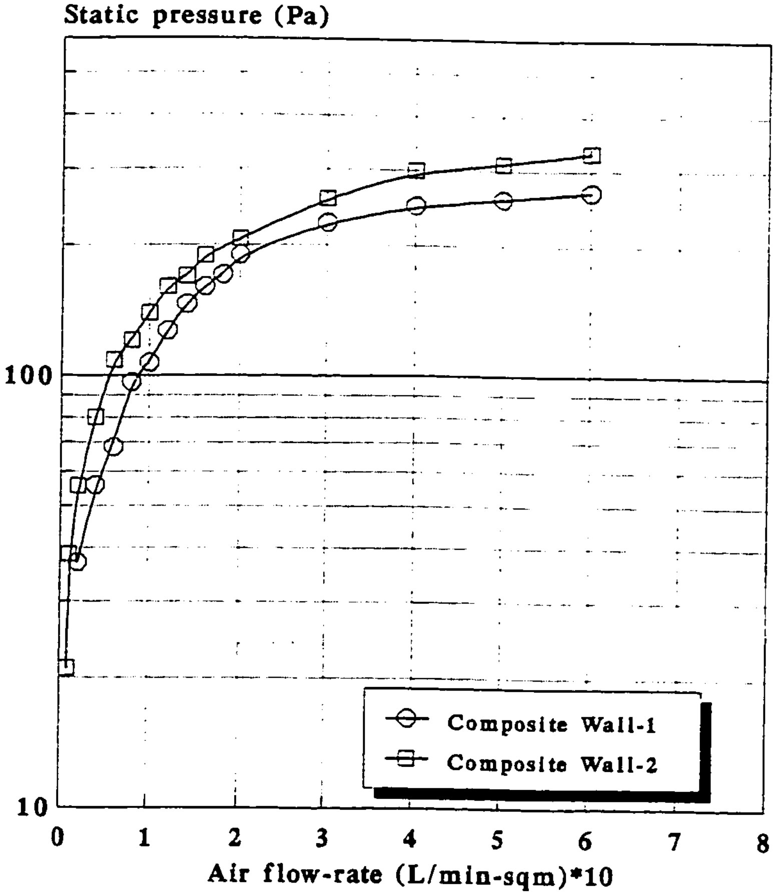


Fig. 7.6 Airtightness Comparative Analysis for the Composite Wall 1 and Composite Wall 2

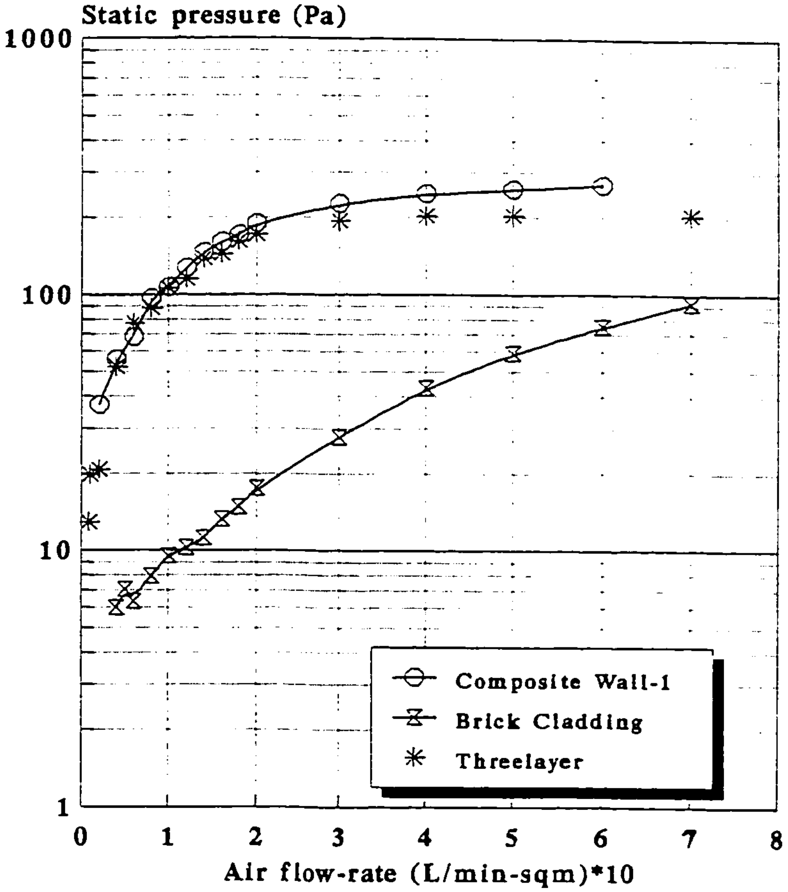


Fig. 7.7 Composite Wall 1, Brick Cladding and Threelayer

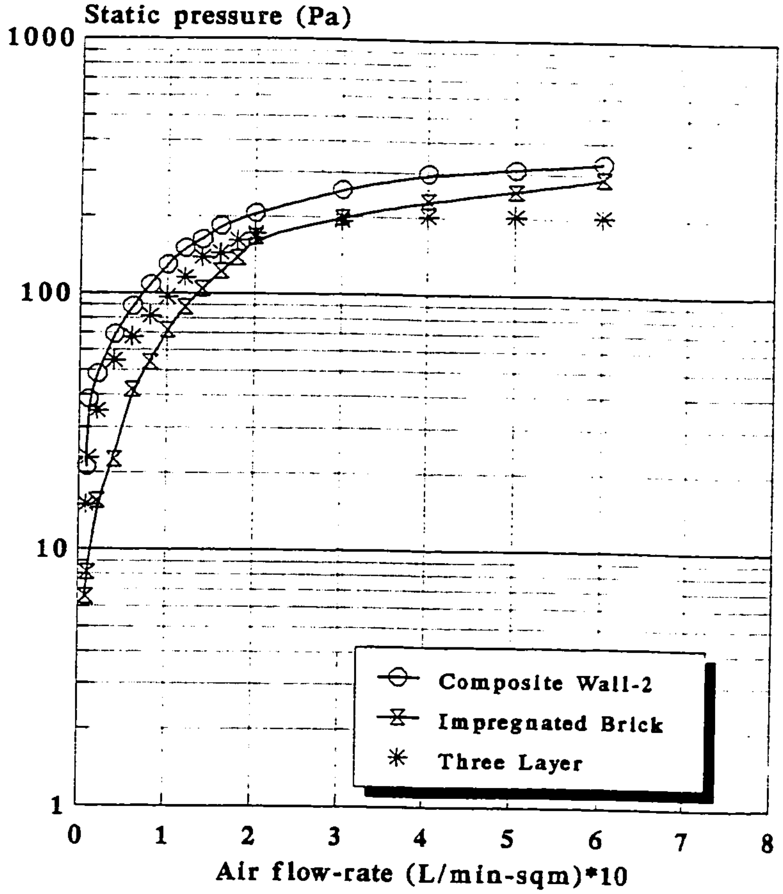


Fig. 7.8 Composite Wall 2, Impregnated Brick and Threelayer

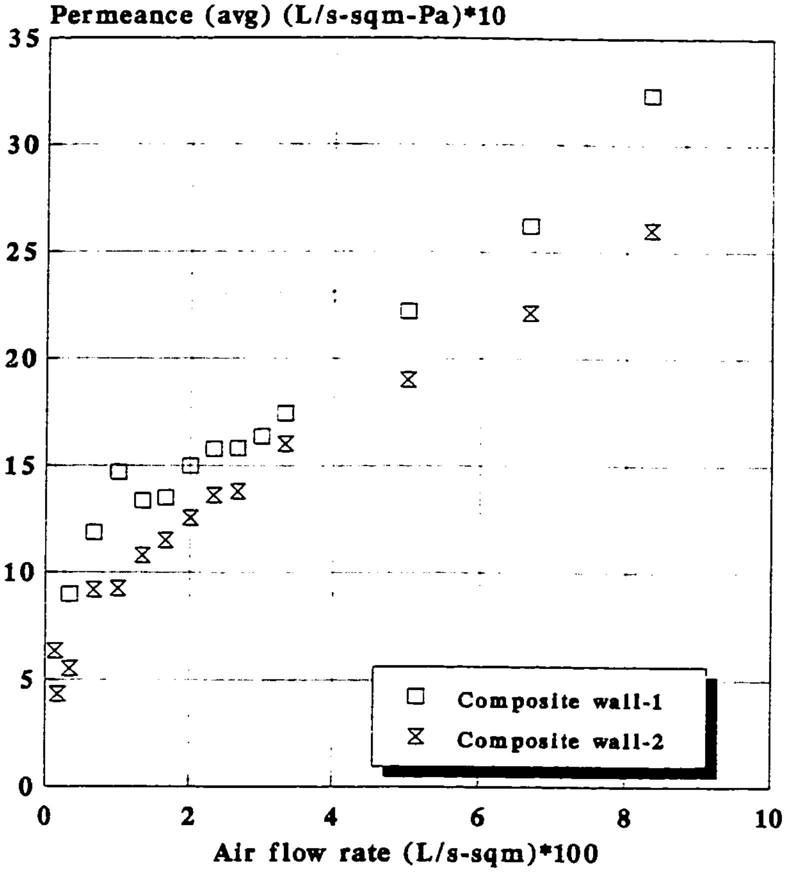


Fig. 7.9 Composite Wall 1 and Composite Wall 2. Comparative Analysis in Terms of Permeance

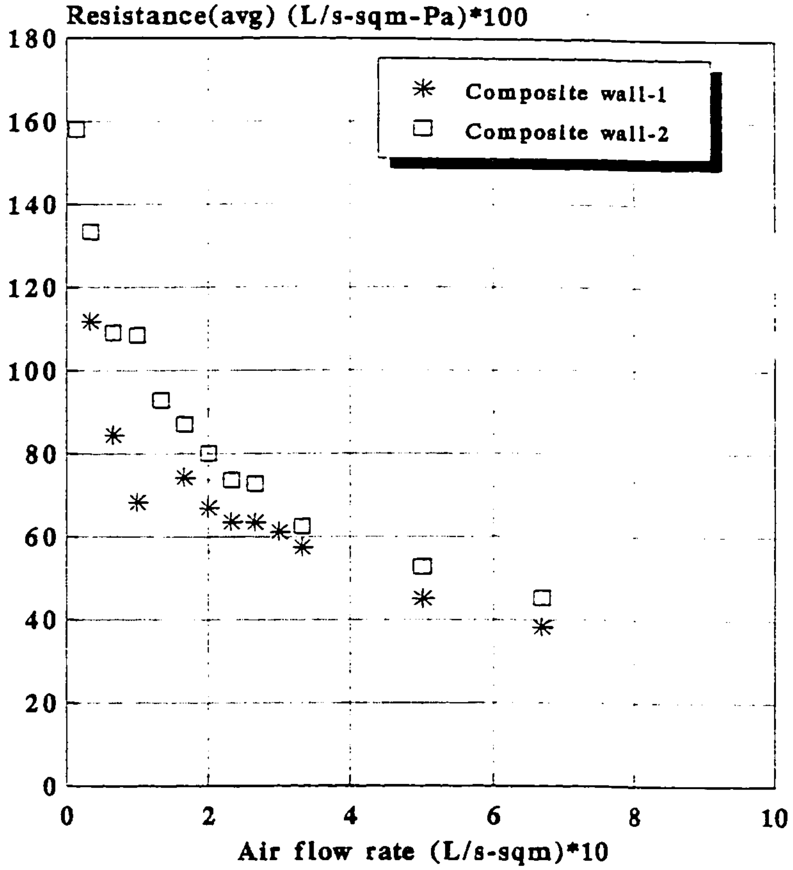


Fig. 7.10 Composite Wall 1 and Composite Wall 2. Comparative Analysis in Terms of Resistance

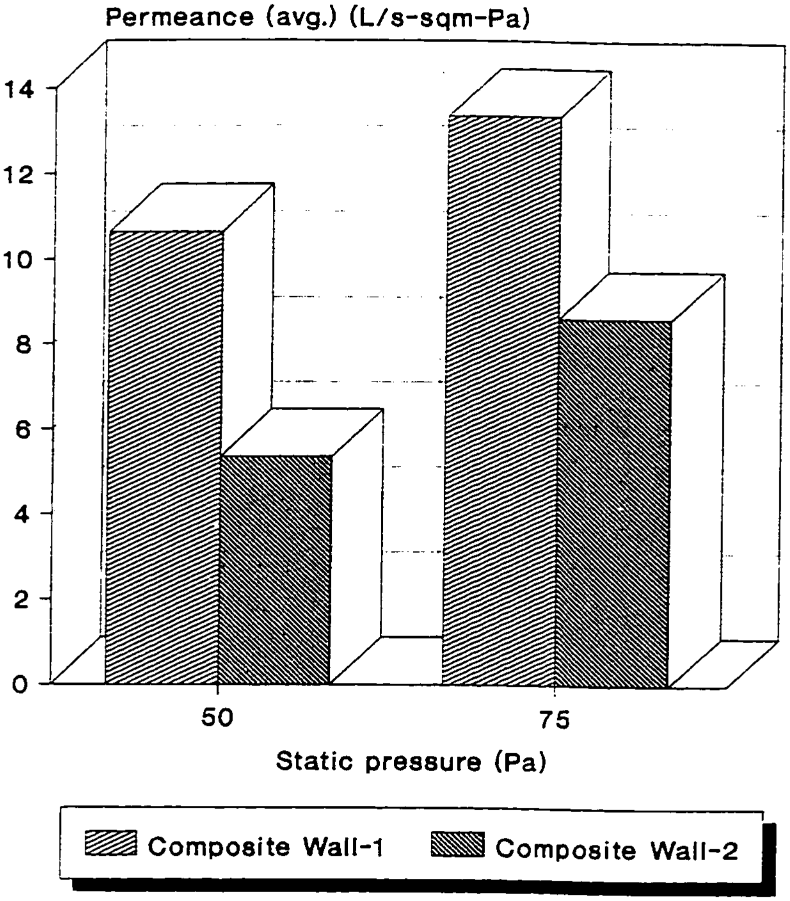


Fig. 7.11 Composite Wall 1 and Composite Wall 2. Comparative Analysis in Terms of Permeance for 50 and 75 Pa

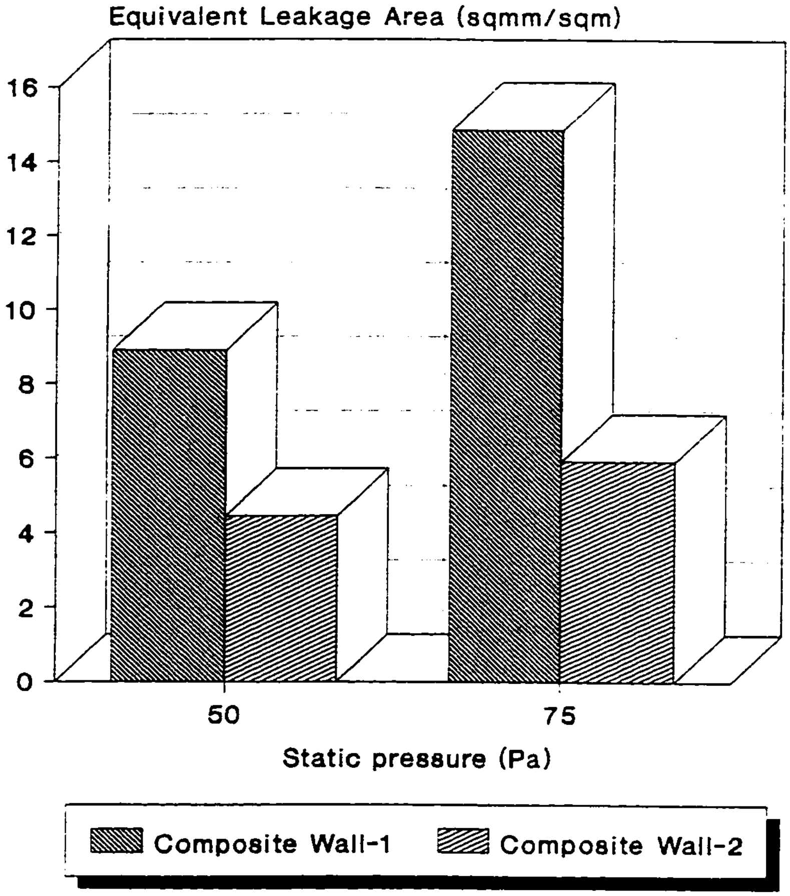


Fig. 7.12 Composite Wall 1 and Composite Wall 2. Comparative Analysis in Terms of ELA for 50 and 75 Pa

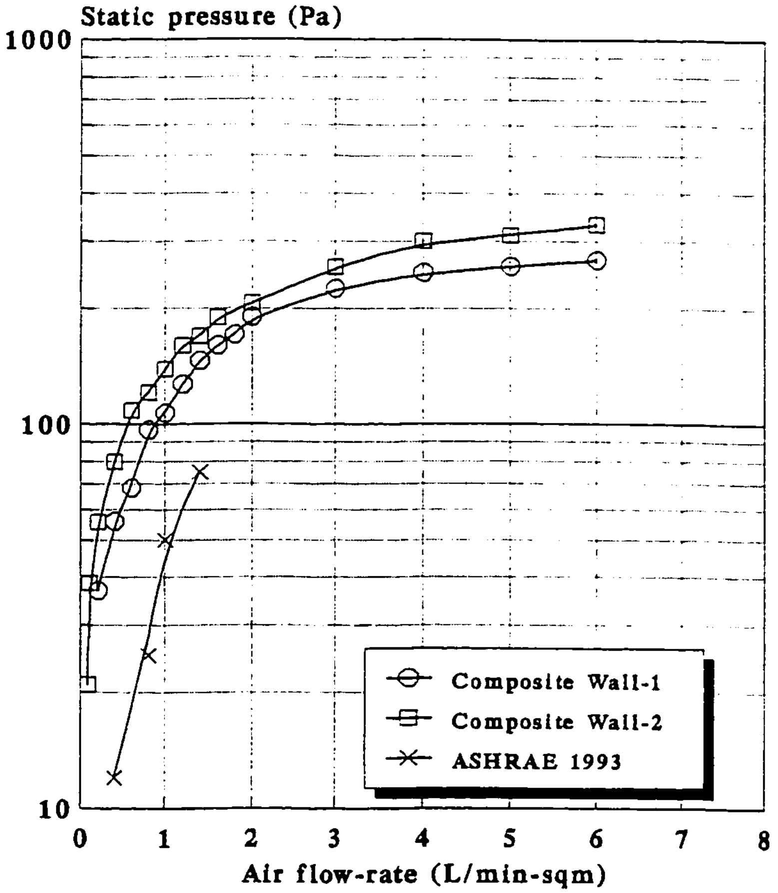


Fig. 7.13 Airtightness Comparative Analysis Between the Present Testing Program and Previous Research

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

A new simple apparatus has been designed, fabricated, calibrated and tested at the School for Building of Concordia University to determine the air leakage through building envelope components such as simple or composite wall.
The experimental results of air flow through and static pressure difference across building envelope have been found in good agreement with literature information.

The experiments carried out in this study constitute a step in determining air leakage characteristics of building materials commonly used in the envelope design. The proposed experimental method gives an accessible tool to determine the air infiltration, by considering a static variation of pressure difference through a building envelope.

Results of these tests can be used by designers to estimate air infiltration rates in determining heating and cooling loads or to calculate energy consumption. The experimental program has found that the apparatus is capable of measuring the air infiltration through a simple and composite envelope accurately and efficiently for engineering purposes.

The test panels were carefully assembled under laboratory conditions and the effectiveness of various building materials used in the envelope systems as constructed under field conditions requires further assessment. The experimental program employed tapes and gaskets to achieve airtightness. The efforts for ensuring the airtightness of the apparatus have resulted in experimental data in good agreement with published results. Studies to ensure the durability of these components over their anticipated service life require consideration.

The experimental program has been carried out on single layer as well as on multilayer building envelopes by using different rigid materials. The airtightness of the composite envelope depends on the air leakage characteristics of the component layer with the highest airtightness.

The technique of impregnation proved that it is possible to build walls with higher levels of airtightness and implicit thermal efficiency as required by the North American and European standards.

The proposed experimental model can be used in the analysis of different types of rigid building materials and suitable combinations of these materials. By making some adjustments in the general arrangement of the testing boxes (regardless to the clamped and sealed system against the wall) the apparatus can be used to measure the air flow through and within building envelopes in site.

On the basis of the experimental results and the good agreement with other research it can be concluded that the proposed technique may be useful for a wide range of pressure differences and for a multitude of materials. However, more experimental results are required in order to expand research by taking into account the role of other parameters, such as temperature and humidity, on the envelope airtightness.

Finally, the experimental study of the fluctuating pressure differences as a function of wind influence, would be a further important step in the more complex analysis of the air leakage characteristics of the envelope components or the envelope as a whole.

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APPENDIX A
PRESSURE SENSOR USED IN THE PRESENT STUDY

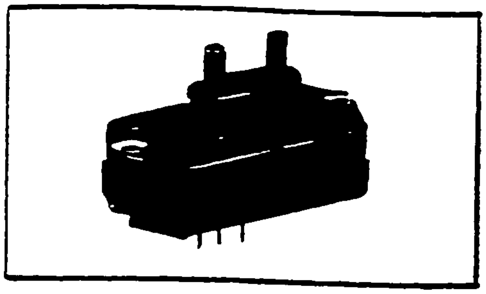
MICRO SWITCH
a Honeywell Division

1 psi pressure sensors

PK 8772 3

GENERAL INFORMATION

160PC 1 psi sensors provide an output voltage proportional to applied pressure. They operate from a single, positive supply voltage ranging from 6.0 to 12VDC. Signal conditioning results in directly usable outputs; temperature compensation results in predicable performance over specified temperature ranges.



160PC SPECIFICATIONS at 8.0 ± 0.01VDC, 25° C

PARAMETER	Min	Typ.	Max.	UNITS
F S O. (Full Scale Output)*	4.85	5.00	5.15	Volts
Null Offset	0.95	1.00	1.05	Volts
Excitation	6.0	8.00	12.0	VDC
Output Current Source Sink	 10.0 5.0			mA
Supply Current (10K ohm load)		8.0	20.0	mA
Overpressure			5	psi
Operating Temperature	-40° C to +85° C (-40° F to +185° F)			
Storage Temperature	-55° C to +125° C (-65° F to +257° F)			

*F.S.O. is the algebraic difference between end points (null and full pressure outputs).
Output voltage at full pressure equals 6.0 ± 0.20 volts at 8.0VDC.

APPENDIX B

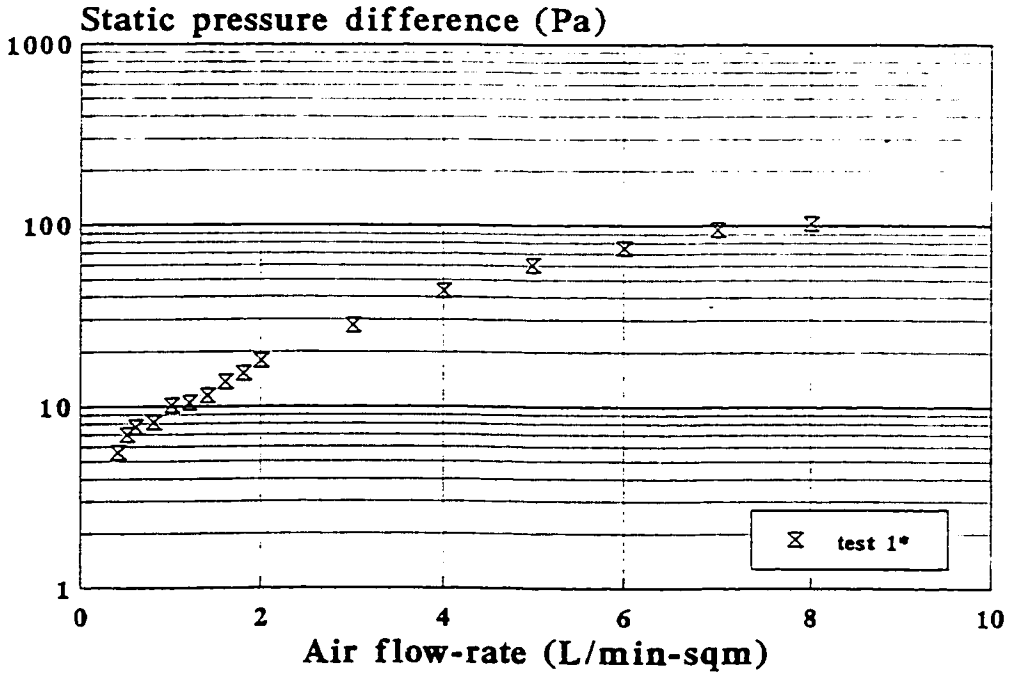
IMPREGNATED BRICK WALL. TESTING RESULTS

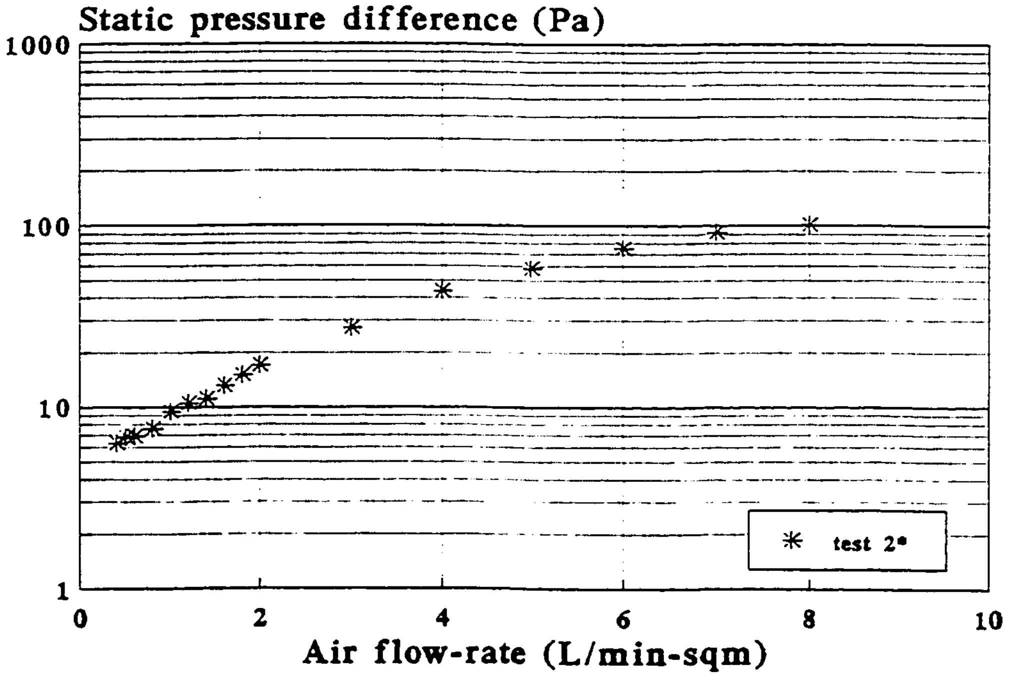
No.	Weight Before Impregnation G_1 (kg)*10^{-3}	Weight After Impregnation G_2 (Kg)*10^{-3}	G_2-G_1 (Kg)*10^{-3}
1	2152.5	2210.8	58.3
2	2130.0	2166.2	36.2
3	2142.1	2214.2	72.1
4	2162.3	2218.7	56.4
5	2135.2	2207.2	72.0
6	2123.0	2191.0	68.0
7	2128.1	2187.7	59.6
8	2132.6	2194.9	62.3
9	2126.2	2177.2	51.0
10	2136.3	2200.5	64.2
11	2161.1	2240.0	78.9
12	2136.0	2207.1	71.1
13	2123.2	2169.0	45.8
14	2128.1	2207.1	79.0
15	2132.5	2187.1	54.6
16	2124.3	2204.0	79.7
17	2136.4	2190.3	53.9
18	2126.0	2186.2	60.2

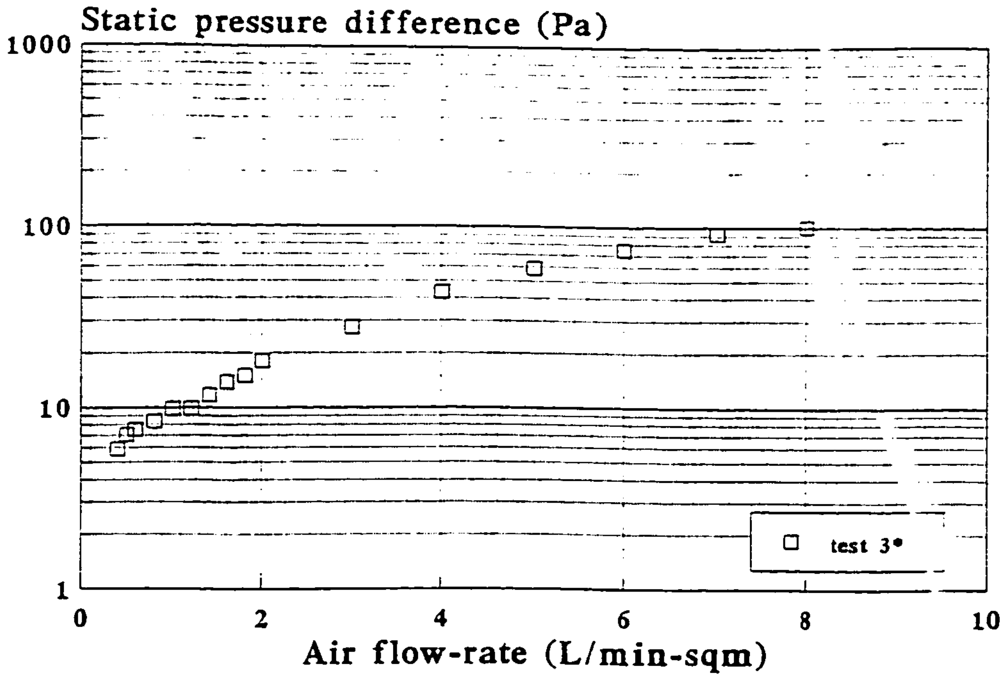
19	2128.1	2194.0	65.9
20	2167.2	2229.1	61.9
21	2148.1	2165.1	17.0
22	2149.0	2183.0	34.0
23	2139.0	2210.1	71.1
24	2126.1	2214.3	88.2
25	2118.3	2184.2	65.9
26	2123.2	2210.0	86.8
27	2136.1	2218.3	82.3
28	2117.0	2216.2	99.2
29	2151.0	2183.2	32.2
30	2170.1	2211.1	41.0
31	2150.6	2198.6	48.0
32	2162.1	2220.0	57.9
33	2141.2	2223.1	81.9
34	2154.3	2236.2	81.9
35	2130.0	2186.0	56.0
36	2128.0	2191.1	63.1
37	2138.0	2197.2	59.2
38	2126.1	2191.2	65.1
39	2128.2	2184.4	56.2
40	2130.0	2195.3	65.3
41	2129.5	2185.3	55.8

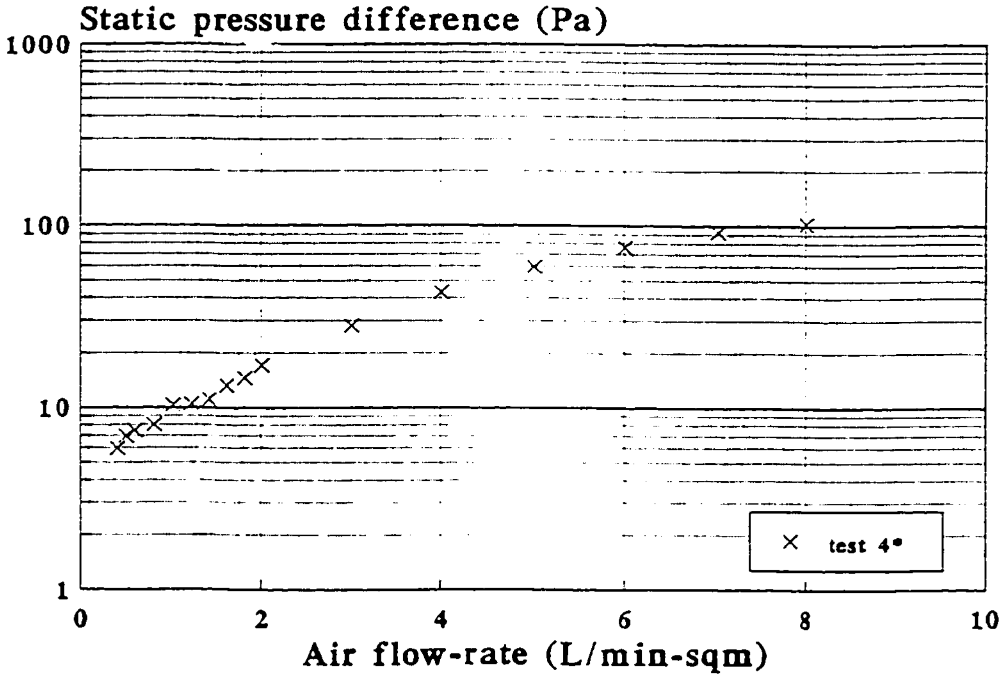
42	2128.6	2190.9	62.3
43	2130.1	2165.8	35.7
44	2129.2	2178.1	48.9
45	2126.8	2182.0	55.2
46	1192.5	1163.0	29.5
47	1079.6	1106.5	26.9
48	1075.4	1106.3	30.9
49	1082.7	1103.2	20.5
50	1082.3	1103.5	21.2
51	1146.2	1174.2	28.0
52	1035.4	1068.0	32.6
53	1025.2	1035.2	28.0
54	1065.4	1092.0	26.6
55	1060.7	1096.2	35.5

APPENDIX C
BRICK WALL






Static pressure difference (Pa)
1000
100
10
1
0
2
4
6
8
10
Air flow-rate (L/min-sqm)
test 3*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10
1
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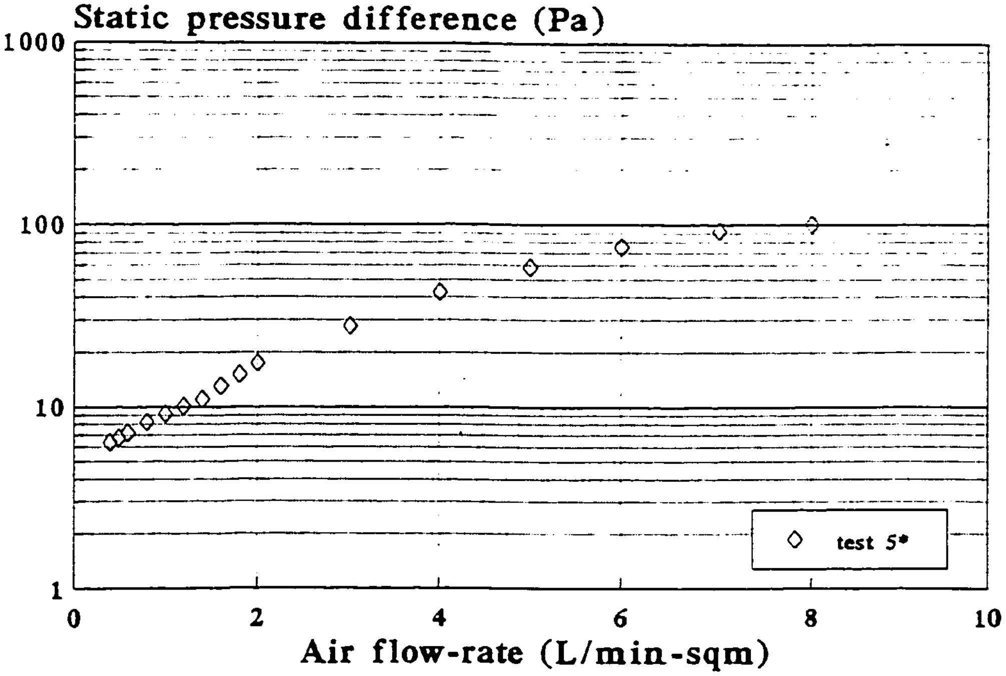
2
4
6
8
10
Air flow-rate (L/min-sqm)
test 4*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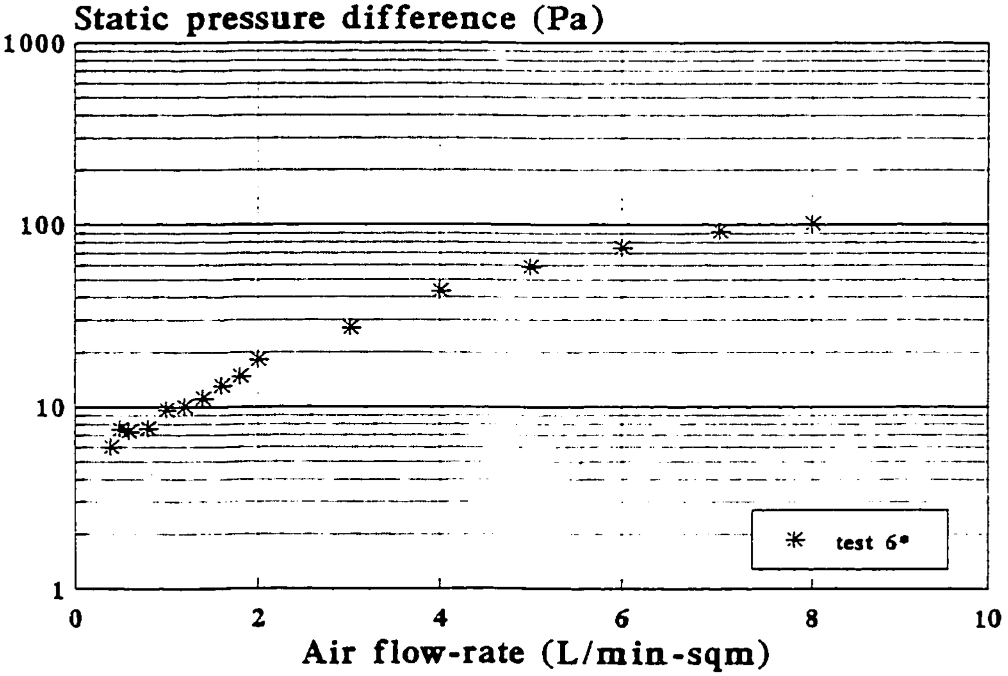
10
1
0
2
4
6
8
10
Air flow-rate (L/min-sqm)
◇ test 5*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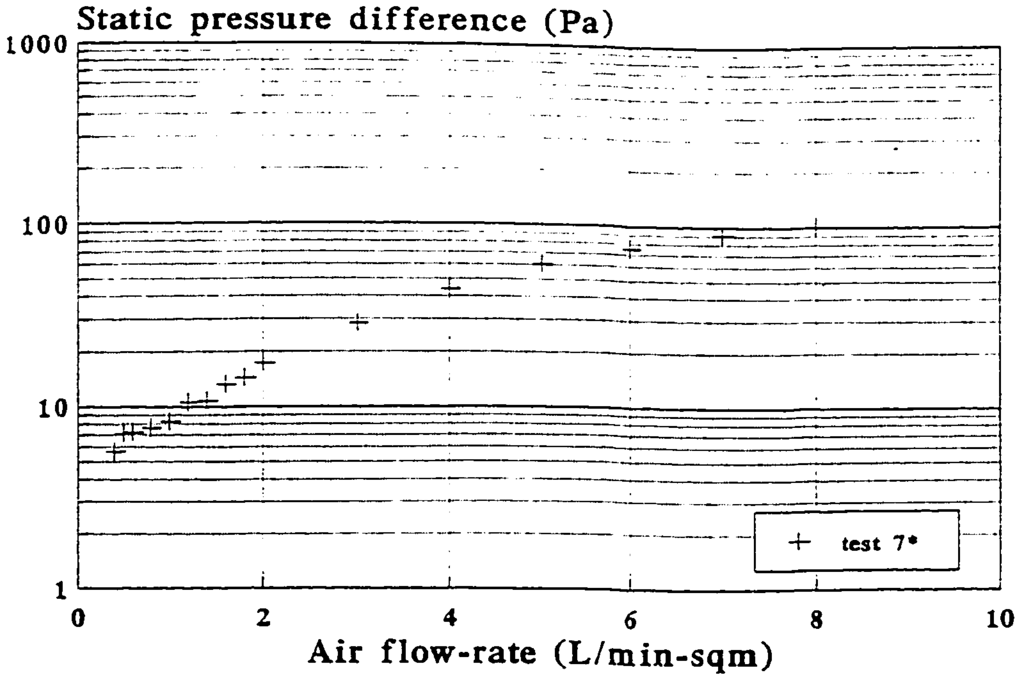
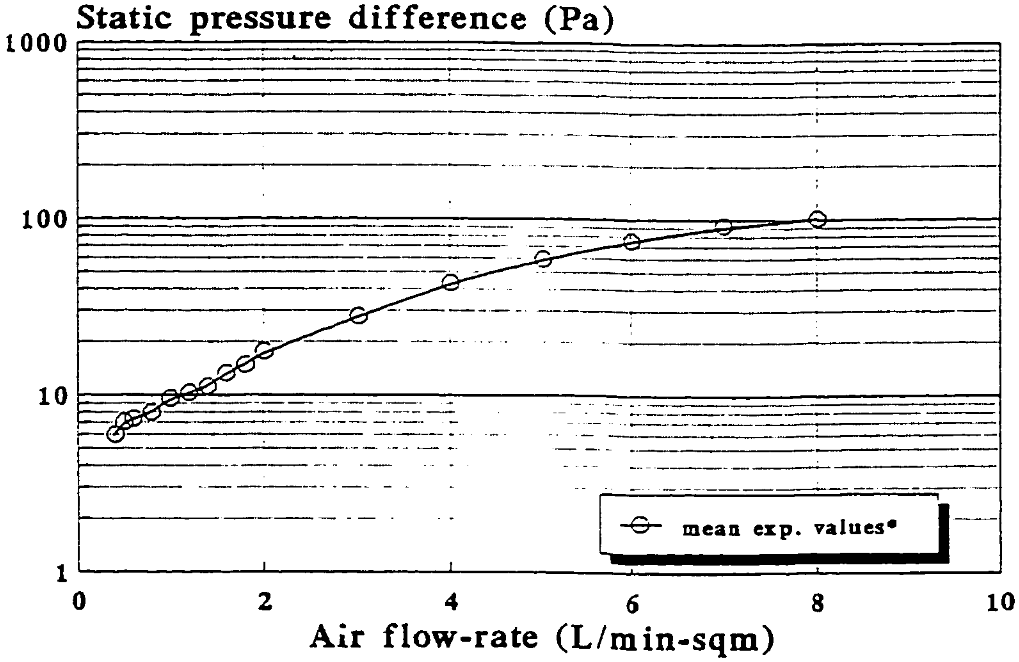
100
10
1
0
2
4
6
8
10
Air flow-rate (L/min-sqm)
✳ test 6*


Static pressure difference (Pa)
1000
100
10
1
0
2
4
6
8
10
Air flow-rate (L/min-sqm)
test 7*

Brick Wall


Static pressure difference (Pa)
1000
100
10
1
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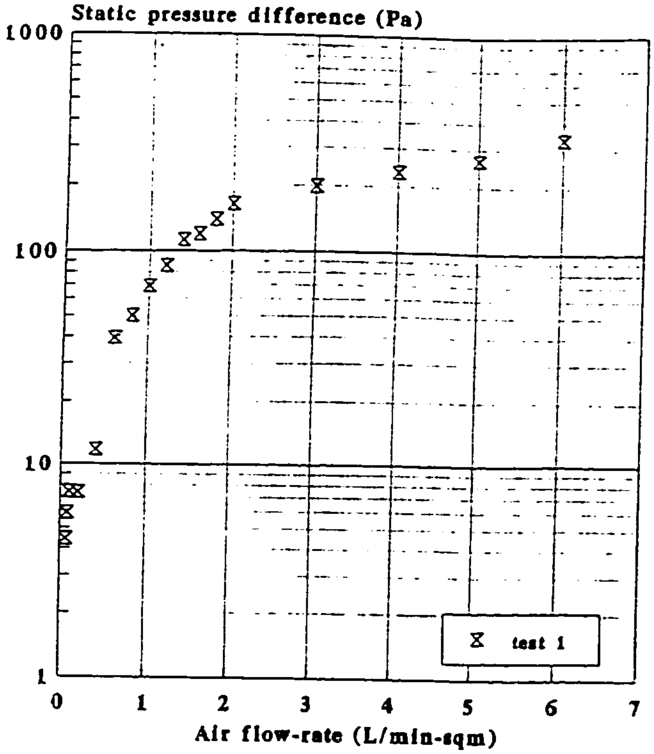
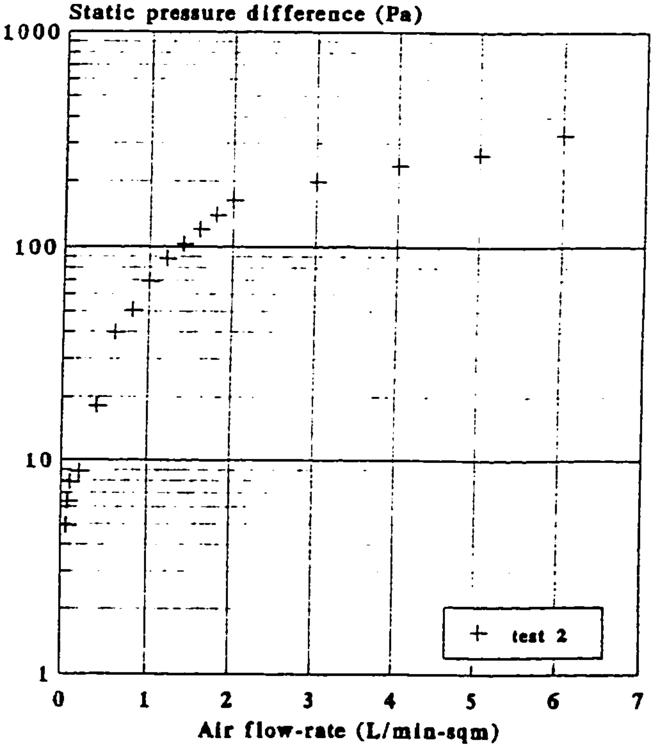
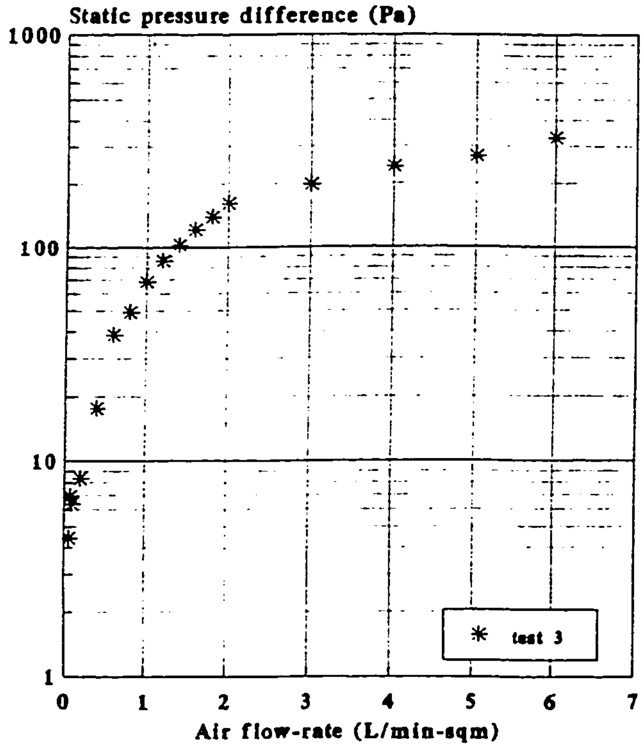
2
4
6
8
10
Air flow-rate (L/min-sqm)
mean exp. values*

APPENDIX D
IMPREGNATED BRICK WALL






Static pressure difference (Pa)
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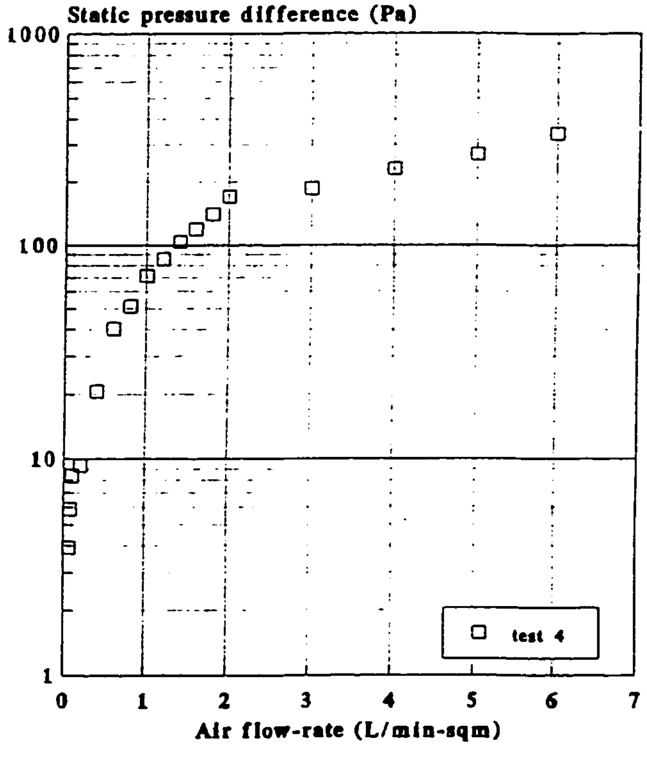
10
1
0
1
2
3
4
5
6
7
Air flow-rate (L/min-sqm)
✳ test 3


Static pressure difference (Pa)
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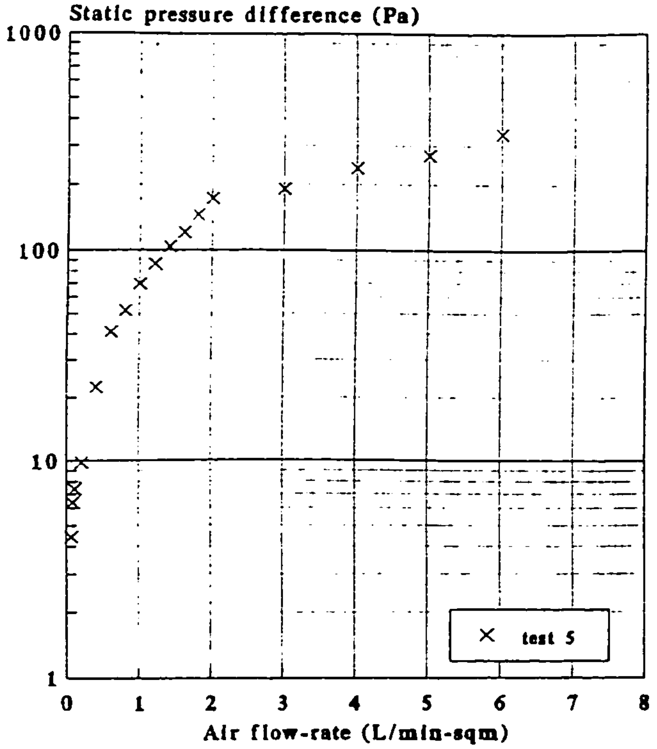
100
10
1
0
1
2
3
4
5
6
7
Air flow-rate (L/min-sqm)
□ test 4


Static pressure difference (Pa)
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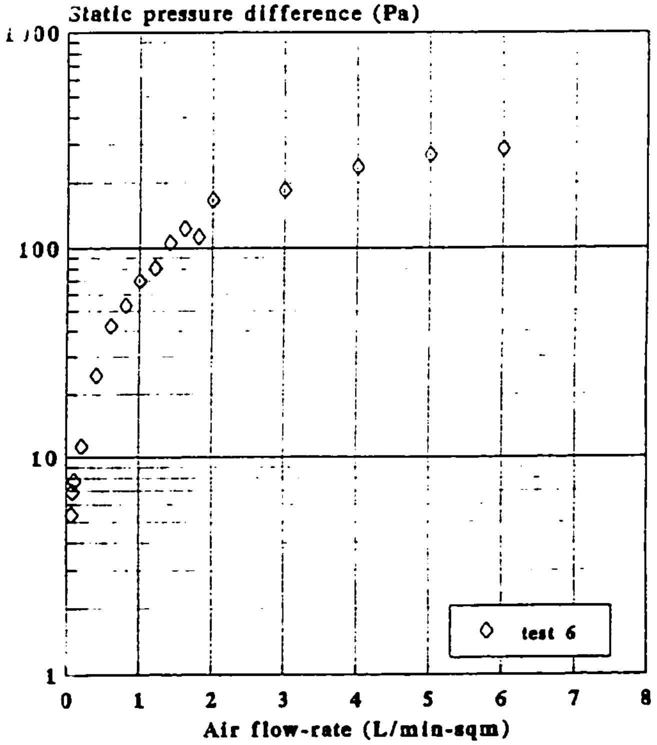
100
10
1
0
1
2
3
4
5
6
7
8
Air flow-rate (L/min-sqm)
× test 5


Static pressure difference (Pa)
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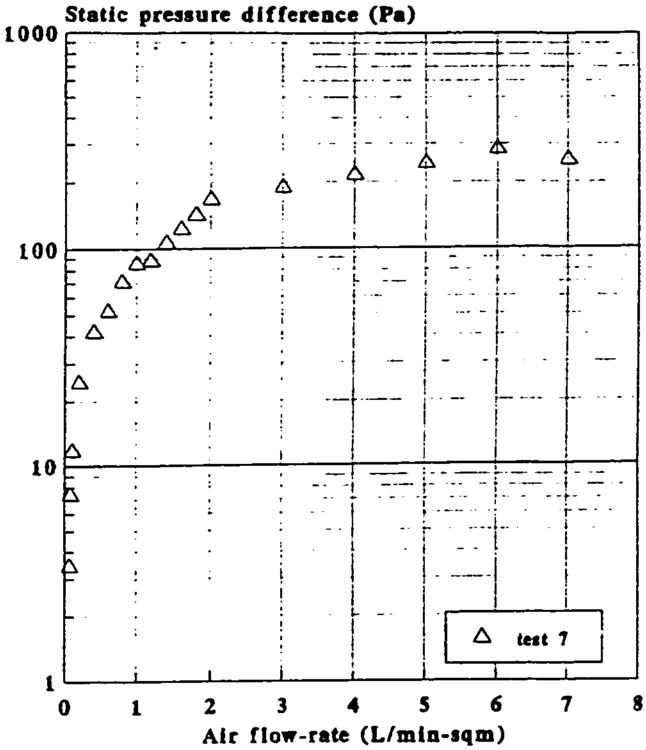
100
10
1
0
1
2
3
4
5
6
7
8
Air flow-rate (L/min-sqm)
◇ test 6



Impregnated Brick Wall