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LATENT AND SENSIBLE HEAT STORAGE IN CONCRETE BLOCKS

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A Thesis
in the
School For Building

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ABSTRACT

LATENT AND SENSIBLE HEAT STORAGE IN CONCRETE BLOCKS

TACHEN LEE

It is a practical approach to store energy in building materials by incorporating Phase Change Materials (PCMs) into their structures.

The intend of this present work is to address this achievement. Concrete blocks (both regular and autoclaved), the widely used construction material, were selected as ideal candidate for the experimental evaluation.

Followed by previous laboratory work, both Butyl Stearate (BS) and Paraffin (PAR) were selected as PCM due to the fact that they are representing the lower and higher melting temperature ranges.

The weight percentages vary with different PCMs and the types of block; furthermore, the adopted incorporating technique is by immersing.

The experimental studies were conducted in a thermally insulated wooden box. Twelve identical blocks were laid contiguously to allow continuous air flow through the tunnels formed by their hollow cores. In addition, their temperatures were recorded by digital data logger.

Heating and cooling cycle were provided by two sets of microcomputer controlled air conditioning systems. Three different heating and cooling temperature ranges were applied on different combinations. The mean air flow velocities were also set between 2 to 3 m/s.

The results showed that:

- Paraffin impregnated autoclaved blocks (AP) present the highest total storable heat to storable sensible heat in block ratio;
- the appropriate heating and cooling temperature ranges should be set according to the melting and freezing points of the PCM;
- it is possible to predict the required charging and discharging time for a designated heating and cooling process.

The results exhibited the concept of latent heat storage in concrete blocks is workable and that a higher amount of heat can be stored.

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LIST OF ABBREVIATIONS

A	Unimpregnated autoclaved concrete blocks
ABS	Autoclaved concrete blocks impregnated with Butyl Stearate
AP	Autoclaved concrete blocks impregnated with Paraffin
ASTM	American Society for Testing and Materials
BS	Butyl Stearate
CBS	Center for Building Studies
CMU	Concrete Masonry Unit
CSH	Calcium Silicate Hydrate ($C_3S_2H_3$)
DSC	Differential Scanning Calorimetry
HDPE	High Density Polytethylene
HVAC	Heating, Ventilating and Air Conditioning
NBCC	National Building Code of Canada
PAR	Paraffin
PCM	Phase Change Material
PU	Polyurethane
PVC	Poly (Vinyl Chloride)
PVA	Poly (Vinyl Alcohol)
R	Unimpregnated regular concrete blocks
RP	Regular concrete blocks impregnated with Paraffin
C_{p1}	Specific heat, KJ / Kg · °C
C_{p2}	Average specific heat between T_1 and T_2, KJ / Kg · °C
fp	Freezing point, °C
mp	Melting point, °C
m_1	Mass of heat storage medium, Kg
m_2	The mass of the phase change material, Kg
Q_l	latent heat stored, KJ
Qs	sensible heat stored, KJ

T_1	Initial temperature, °C
T_2	Final temperature, °C
λ	Latent heat of phase change material, KJ/Kg

CHAPTER 1. INTRODUCTION

1.1 Energy storage in building materials

Mechanical heating systems in buildings consume a major part of their overall energy consumption, so improvements in energy efficiency play an important role in overall building energy conservation.

In Canadian climates, space heating takes up to 61% (840 petajoules) of residential building energy consumption and 53.5% (503 petajoules) of commercial building energy consumption, based on the energy efficiency trend of Canada during 1990-1995 [4]. After the early 70's energy crisis produced an awareness that abundant fossil fuel was in diminishing supply and was not cheap enough to depend on for heating requirements. Researchers also made massive efforts to conserve fuel and develop other energy sources and to reduce energy consumption by improving the air tightness of building enclosures, by increasing insulation and the efficiency of HVAC systems and appliances. There were also significant researches focusing on: (1) renewable energy resources, such as solar energy and wind power. (2) energy storage, such as sensible and latent heat storage and thermochemical storage.

Energy efficiency and time-variable peak load demands could be achieved by utilizing energy storage in building materials. In this case energy costs are generally low and the pay back periods may be extended. However, the efficient use of energy could be stressed as a mitigation approach in reducing green house gas emissions as well.

The use of thermal storage in building materials has the following advantages [17, 29]:

a) It could utilize the heat produced from passive or active solar heating and waste heat which comes from exothermic process;
b) It could enable the use of energy at lower cost during off-peak periods for storage and discharge at times when full rates would otherwise be charged;
c) It permits the use of a smaller HVAC equipment size and more efficient operation;
d) It reduces furnace cycling;
e) It widens the thermostat dead band.

1.2 Sensible heat

Sensible heat is the heat stored in a material due to temperature change [26]. The amount of heat depends on the mass of the storage material, the heat capacity of the medium and the range of the temperature change. The quantity of heat stored (Q_s) can be calculated with the following equation:

$$Q_s = \int_{T1}^{T2} m_1 \cdot C_{p1} \cdot dT = m_1 \cdot C_{p2} \cdot (T_2 - T_1)$$

Q_s= sensible heat stored, KJ

T_1= Initial temperature, °C

T_2= Final temperature, °C

m_1= Mass of heat storage medium, Kg

C_{p1}=Specific heat, KJ / Kg · °C

C_{p2}= Averaged specific heat between T_1 and T_2, KJ / Kg · °C.

Water, ice, iron, granite and other rocks, concrete and bricks are the most commonly used building materials in energy storage practices and air, water or thermal transfer liquids serve as the heat transfer fluids [28]. Low specific heat and significant void volume in this heat storage media result in huge volume requirements when they are used as heat storage materials.

1.3 Latent heat

Latent heat is the heat required or released when a material undergoes a phase change [26]. The materials used for storing energy as latent heats are called Phase Change Materials (PCMs). The amount of energy stored depends on the amount of phase change material and latent heat of phase change material. In this case the quantity of latent heat stored (Q_l) can be calculated with the following equation:

$$Q_l = m_2 \cdot \lambda$$

Q_l= latent heat stored, KJ

m_2= The mass of the phase change material, Kg

λ= Latent heat of phase change material, KJ / Kg.

Energy storage is achieved by melting PCMs. Melting represents the process of changing from the solid (crystalline) to the liquid phase and is characterized by heat absorption which is the latent heat. Conversely, in changing from liquid to solid phase (crystallization), the stored latent heat is released by PCMs. In practice, heat storage also makes use of sensible heat capacity in the system.

Latent heat storage is a more efficient method of storing heat than using sensible heat. This is because the thermal energy absorbed per unit of mass in melting the crystalline compounds is several times greater than that stored by raising the sensible heat of substance through a small temperature range (6 ~ 8°C) through the PCM melting temperature.

1.4 The advantage of using latent heat storage

Compared with sensible heat storage, latent heat storage in building materials has the following advantages [17]:

a) It stores larger amount of energy per unit mass;
b) It is adaptable to conventional structural mass while sensible heat storage requires a larger mass to store the same amount of energy;

c) Thermal storage can be achieved in the thermal comfort temperature range;

d) It stores energy within a small temperature swing, thus uncomfortable temperature variation is avoided;

e) It provides much broader design application;

f) It achieves more efficient energy management.

CHAPTER 2. OBJECTIVES

The objectives of this research are focusing on:

1. to experimentally evaluate the storage and recovery of sensible and latent heat in and from PCM impregnated concrete blocks and compare their thermal storage performance with unimpregnated concrete blocks;
2. to evaluate the influence of air temperature and air flow velocity on the effectiveness of thermal storage and heat release so that appropriate means of control can be achieved in respect to the storage capacity and rate of heat exchange in both heating and cooling mode;
3. to ascertain the temperature at various points in the concrete block surfaces for both unimpregnated and PCM impregnated concrete specimens during heating and cooling cycles to determine the degree of potential thermal storage utilized;
4. to conduct the foregoing research for both a low temperature range (15°C to 25°C for Butyl Stearate) and a high temperature range (22°C to 60°C and 45°C to 60°C for Paraffin) in both regular and autoclaved blocks.

Chapter 1 presents the advantages of using thermal storage in building materials, the differences between sensible and latent heat storage and the advantages of using latent heat storage.

Chapter 2 discusses the objectives of this research.

Chapter 3 is a general review on the developments, advantages and disadvantages of latent heat storage in both inorganic and organic phase change materials. Furthermore, PCM selection criteria are also discussed. The building material used for PCM impregnation in the experiments is briefly introduced. Three techniques of incorporating PCM into blocks are also compared and determined.

Chapter 4 describes the method of the experimental study for evaluating thermal performance between unimpregnated and PCM impregnated blocks. The characteristics of the two PCMs used in the experiments and the procedures for incorporating PCMs into blocks are also presented. The experiments were conducted by installing twelve identical blocks in a thermally insulated wooden box and controlling the required conditions by a computerized data acquisition system and two sets of digital microprocessor controlled HVAC systems. Three groups were tested and compared:

- autoclaved blocks impregnated with Butyl Stearate (ABS)
- autoclaved blocks impregnated with Paraffin (AP)
- regular blocks impregnated with Paraffin (RP)

in forced heating and cooling modes at air flow velocities of 2, 2.5 and 3 m/s. A natural cooling mode was also performed and compared. The average weight percentages of PCMs used in the experiments were:

- 5.6 for autoclaved blocks impregnated with Butyl Stearate (ABS)
- 8.4 for autoclaved blocks impregnated with Paraffin (AP)
- 3.9 for regular blocks impregnated with Paraffin (RP).

Chapter 5 discusses the results obtained from the comparative experiments. The advantages of using only latent heat range are presented. The stability of PCMs in concrete after 20 heating and cooling cycles is investigated as well. The air flow velocity prediction charts for charging and discharging periods in a designated time were established.

The conclusions and recommendations are reserved till chapter 6.

CHAPTER 3. LITERATURE REVIEW

3.1 Development of latent heat storage

In the past 60 years, the use of phase change materials for storing thermal energy has evolved rapidly. Both mathematical modeling and practical experiments were used in various aspects in order to study and develop it. The impetus for this development has been several recent episodes which have demonstrated the fallibility of our fossil fuel supplies. Ambient energy, solar heating and renewable resources increasingly promise to serve our future needs.

In the early studies, inorganic PCMs were principally considered, especially salt hydrates. Dr. Maria Telkes, one of many pioneers PCM researchers, attempted the first practical application in late fall, 1948. A one story, five room house of 135 m^2 (1456 ft^2) was constructed. Eighteen solar collectors were arranged as a vertical south wall for the attic. Heat was removed by circulating air through ducts behind the absorber plates to three heat storage bins located between the rooms. Each bin contained 5-gal cans filled with Glauber's salt ($Na_2SO_4 \cdot 10H_2O$) [21]. The next similar practical experiment was conducted in Las Cruces, New Mexico by L. Gardenhire in 1953. The house was a one story and a half building of 102 m^2 (1100 ft^2). Gardenhire used Glauber's salt as well but mixed with borax as nucleating agent. Followed by this house, Glauber's salt was tried once again in a 111 m^2 (1200 ft^2) solar house in Princeton, New Jersey by R. Huley of Curtis Wright Corp. Both borax and chromate were added to act as nucleating agent and corrosion inhibitor. Unfortunately, all three cases failed over periods range from several months to 3 years due to leakage, segregation and supercooling of PCMs.

Several researchers have examined many aspects related to PCM applications since then, such as Feldman, Shapiro (1983, Canada), Abhat (1982, Germany), Van Galen (1986, The Netherlands), Lane, Salyer (1983, 1985, USA), Hawes, Feldman and Banu (1989, Canada).

Due to the presence of supercooling and segregation of inorganic PCMs and the tendency to cause leakage, the search for suitable PCMs began to shift to organic materials as early as 1930, although many improvements have been effected since then.

As early as in 1932, A.A.H. Douglas invented a heat storage apparatus comprising a container filled with PCM, such as paraffin or stearic acid. The heat stored was charged with off-peak electrical power [21]. Later on, the Apollo 15 Lunar Rover Vehicle employed paraffin as heat storage medium which functioned in three systems of the space mission in 1960 [29]. Recent researchers, such as Bannister and Bentilla were among the first to conduct studies and publish results for paraffins as thermal controllers (1966) [22]. Pujado, Stermode and Golden developed a mathematical model (1969) [22]. Lyons and Russell have shown that paraffin can successfully be used as a wall component to damp out exterior temperature fluctuation by its low thermal diffusivity (1977) [22]. De Jong A.G. concluded that to make full use of the heat of fusion of paraffinic materials the secondary recrystallization temperature should be brought near to the melting point by adding suitable crystallization aids (1981) [5]. Green and Vliet have used a baffled, shell and tube heat exchanger with water as the heat transfer fluid on the shell side (1981) [15]. Salyer and Abe et al. developed a direct contact storage unit using HDPE pellets form-stabilized by electron beam irradiation (1978, 1984). Farid has suggested the idea of using PCMs with different melting temperatures to improve heat transfer rates in a storage unit with rectangular encapsulation (1990) [7]. Tomlinson and Heberle have analyzed a passive solar building which indicated that the optimal PCM concentration is about 10 percent by weight and the pay back resulting from annual energy saving in a building heated by an electric heat pump is three to five years (1990) [27]. Stovall considered the PCMs whose melting temperature can be tailored to suit a particular application would be desirable (1995) [27].

At the Center for Building Studies (CBS) of the School for Building of Concordia University, various organic PCMs have been studied for several years. Most of these researches focus mainly on incorporating of various PCMs into different building materials, such as gypsum wallboard, brick, tile and concrete block (Feldman et al., 1984, 1985, 1986, 1989, 1991, 1995, 1996, Hawes et al., 1989) [8, 9, 10, 11, 12, 13, 14].

Interesting topics cover the followings: using PVC, PVA, etc. as matrix for PCMs [9]; latent heat storage in concrete tiles and searching for new kind of composites based on coarse aggregates, gypsum, cement, sawdust, etc. at different ratios [11]. Moreover, directly incorporating Butyl Stearate into gypsum wallboard and full scale thermal testing in gypsum wallboard were studied as well in recent years with encouraging results [13, 25].

3.2 Phase change material categories

Phase change materials can be divided into two categories, inorganic and organic. Both inorganic and organic materials are available for thermal storage at low, medium and high temperature but with different characteristics and performances.

3.2.1 Inorganic

In the early years, research on PCMs were focused on inorganic materials, especially salt hydrates which store and release heat by a reversible hydration and dehydration process. At temperatures below the hydration point, the anhydrate becomes hydrated and crystallizes with the evolution of heat. Upon heating, the crystal dissolves in its water of hydration, thereby absorbing heat [18].

Table 3.1 shows some well known salt hydrates which possess appropriate phase transition temperatures for space heating and cooling. Glauber's salt, $Na_2SO_4 \cdot 10H_2O$, one of the cheapest and most easily available materials, was extensively studied and put into full scale house experiments because of its high latent heat of fusion in the late 40's [21].

Material	Melting Point (°C)	Latent Heat (J/g)
$KF \cdot 4H_2O$	18.5	231
$CaCl_2 \cdot 6H_2O$	29.7	171
$Na_2SO_4 \cdot 10H_2O$	32.4	254
$Na_2HPO_4 \cdot 12H_2O$	35	281
$Zn(NO_3)_2 \cdot 6H_2O$	36.4	147
$Na_2S_2O_3 \cdot 5H_2O$	48	201
$Ba(OH)_2 \cdot 8H_2O$	78	267
$MgCl_2 \cdot 6H_2O$	116	165

Table 3.1 Thermal properties of some inorganic phase change materials [18]

Salt hydrates have the following major advantages:

a) phase transition points within appropriate temperature ranges;

b) high latent heats per unit volume;

c) no flammability hazard;

d) inexpensive and readily available.

Some disadvantages limited salt hydrates' applications [1], these are:

a) They are corrosive, therefore, higher costs for a special container are expected;

b) They have a tendency to supercool;

c) They do not melt congruently and segregation may occur;

d) Additives used to prevent incongruent melting reduce the latent heat per unit volume of a package storage module up to 25 percent;

e) They may lose the hydration water after many freeze-thaw cycles and consequently, their thermal characteristics are changed.

3.2.2 Organic

Obtained primarily from natural fats, oils or petrochemical products, organic phase change materials also present some advantages which cannot be found in inorganic phase change materials. They are:

a) They melt congruently and do not segregate;

b) Many of them do not have a supercooling problem;

c) They are chemically stable;

d) They can be directly incorporated into building materials;

e) There is a wide selection.

However, organic phase change materials have some disadvantages as well. These are:

a) possibility of flammability and smoke generation;

b) a few have appreciable volume change during phase change;

c) some have a strong odor;

d) some cause an oily exudation at the building material surfaces.

Organic PCMs have different melting temperatures. Their thermal conductivity in the solid phase is in the range of 0.16 to 0.24 W/m×°C and in the liquid state is around 0.20 W/m×°C. It is important to consider that the desirable melting temperature depends on whether we are heating or cooling, on the local climate and on the type of thermostatic control [14]. It becomes obvious that one must select a PCM with a melting temperature which can be tailored to suit a particular application. In the case of using mixtures of different organic materials, the melting temperature can be adjusted by mixing homologues of the same series.

If building materials and PCMs are carefully selected and applied, greater thermal storage can be expected. Table 3.2 lists many PCMs studied at the CBS suit for thermal storage [18].

Material	Melting Range (°C)	Latent Heat (J/g)
Octadecane (99% pure)	27-32	253
Commercial Wax	35-47	147
Palmitic acid	52-60	193
Stearic acid	55-71	191
Butyl Stearate	17-21	140
1-Dodecanol	49-60	200
45/55 Capric-lauric acid (mixture)	17-21	143
Propyl palmitate	20	190

Table 3.2 Thermal properties of some organic phase change materials [18]

3.3 Phase change material selection criteria

The selected PCMs must be satisfactory with respect to thermal, physical, chemical and economical aspects [1, 10, 18, 28]. In order to maximize the greatest uses of PCMs in building materials, they should be stable and compatible with other building materials with which they may come in contact and suitable for use in HVAC systems so that the air quality is not adversely affected.

3.3.1 Thermal properties

a) Suitable phase transition temperature: It is critical to match the phase transition temperature with the heating and cooling temperature ranges for a particular application.

b) High latent heat of transition: The selected PCMs must have the highest possible latent heat of transition. The higher the latent heat of transition, the more heat could be stored and released.

3.3.2 Physical properties

a) Lower vapor pressure: It is suggested that in order to have a low vapor pressure in operation, the PCM candidates must have a high boiling point with a difference of around 200°C higher than the intended heating and cooling range [18].

b) Small volume change: It is important to make sure that the volumetric change related to the phase change during the heating or cooling process will not damage the PCM carriers. If the PCMs were introduced to the carriers in the liquid state, the volumetric change is not likely to cause problems at temperatures below the immersion temperature.

c) High density: The higher the density of a given PCM the greater will be the amount of heat stored. Therefore, it is desirable to choose PCMs with the greatest density so that the heat that can be stored per unit volume is maximized.

3.3.3 Kinetic properties

a) When the latent heat of a PCM is not released, even if the temperature is below the freezing point, the respective PCM undergoes supercooling. For inorganic PCMs, this is a problem but organic PCMs such as Paraffins and Fatty Acids, Fatty Esters or Fatty Alcohols are not susceptible to supercooling.

b) Sufficient crystalline rate: crystallization begins with the formation of tiny crystallite nuclei on which the rest of the solid develops. For inorganic PCMs, such as salt hydrates, this process has to be induced with nucleating additives to produce satisfactory results.

3.3.4 Chemical properties

a) Long term chemical stability: The incorporated PCMs in the building materials must exhibit the same service life as the building itself. Therefore, oxidation, thermal decomposition, hydrolysis and other reactions must be at as low a rate as possible.

b) Compatibility with other construction materials: Many construction materials may contact the impregnated PCMs. Consequently the PCMs must be inert.

c) Nontoxic: The selected PCMs should be nontoxic and not affect the skin at contact.

d) No fire hazard: The building materials incorporated with PCMs must not cause fire or fume hazard, therefore, PCMs should be non-flammable and fire-resistant.

e) No nuisance factor: The PCMs should not present a nuisance in respect to odor or any other factor.

3.3.5 Economic

The chemicals or their raw materials for producing PCMs should be sufficiently abundant, readily available or obtained from renewable sources or by products.

3.4 The nature of concrete blocks

A PCM storage matrix in a building application should be simple and inexpensive. This means impregnating PCMs into porous building materials. Concrete products are ideal building materials to be used as PCMs carriers [17, 20].

Concrete Masonry Units (CMUs) provide a wide range of sizes, shapes, colors and textures for practical uses and have many applications in masonry construction [24].
For example:

a) Exterior and interior load-bearing walls;
b) Partitions, panel walls and solar screens;
c) Backing systems for brick or stone veneers;
d) Fire wall, party wall and curtain walls;
e) Fire safe enclosures for stairwells or elevator shafts, storage vaults and fire hazardous work areas;

f) Piers, pilasters and columns;

g) Retaining walls, slope protection and ornamental garden walls;

h) Chimneys and fireplaces.

In this research, a concrete block wall system is used to establish the efficiency of energy storage with PCMs.

3.4.1 Raw materials

The raw materials and manufacturing process used in concrete units directly affect the quality and characteristics of the final products. Concrete masonry units are mainly made of graded aggregates, portland cement and water.

(1). Aggregates

Aggregates in concrete blocks can occupy as much as 70% of their composition. Two categories of aggregates are now been used in the market, normal weight and light weight. The normal weight aggregates are well-graded sand, gravel, crushed stone, or air cooled blast furnace slag. The light-weight aggregates include expanded shale, clay, slate, slag for low-density concrete purposes and pumice, scoria, perlite, or vermiculite for insulating concrete purposes.

Light-weight CMUs increase the thermal and fire resistance, but the sound transmission ratings are decreased because of lower density [3].

(2). Cements

The main components of portland cement are $3CaO{\cdot}SiO_2$ and $2CaO{\cdot}SiO_2$. In general, Type I all purpose portland cement is the most commonly used cementitious material in concrete masonry. If early strength is essential during the curing process, Type III high-early-strength cement can be used to avoid distortion [3, 23].

3.4.2 Manufacturing process

The manufacturing processes of concrete masonry consist of six steps: (1) raw materials receiving and storage, (2) batching and mixing, (3) molding, (4) curing, (5) cubing, (6) delivery. One of the most important steps is the curing process. Adequate moisture, appropriate temperature and time required to achieve adequate strengths are the three important factors which affect the final quality. There are two different curing techniques used in this process: low-pressure steam curing and high-pressure steam curing.

(1). Low-pressure steam curing (Regular)

This process has three major phases:

a) Preset period lasts for one to three hours for attaining initial hardening at 20 to 40°C.

b) Heating period, the saturated steam is injected into the kiln at 90°C and the required time is determined by the composition of the cements and aggregates. Regular concrete blocks used in the experiments were heated up to 100°C for about 7 hours [33].

c) Soaking period begins once the maximum temperature is reached. The supplied steam is also shut off.

And the chemical reaction process is as follow [18]:

$(3CaO{\cdot}SiO_2 + 2CaO{\cdot}SiO_2) + H_2O \rightarrow 3CaO{\cdot}2SiO_2{\cdot}3H_2O + 2Ca(OH)_2$

(2). High-pressure steam curing (Autoclaved)

There are four phases to complete whole cycle.

a) The low-heat preset period.

b) Temperature rise period, gradually increasing pressure and temperature for 5 to 10 hours.

c) Constant temperature and pressure period.

d) Quick release causes rapid loss of moisture quickly from the CMUs without shrinkage cracks.

Instead of curing in the usual way, autoclaved blocks go through an accelerated hardening process consisting of treatment at 100% humidity at temperatures of 176°C to 185°C (350 °F to 365°F) in a huge cylinder at a pressure of 1,034 to 1,103 KPa (150 to 160 psi.). Five hours of curing under these conditions produces concrete of maximum strength which is hardened throughout. The sudden release of pressure at the end of the cycle causes the humidity to drop to 3% producing blocks that are perfectly dry. The retail listed price for each 20×20×40 autoclaved block is CDN $1.58 in 1998 which is 7 cents higher than regular's [33].

Autoclaved concrete blocks provide more stable and less volume change caused by surrounding moisture variation [3].

Chemical reaction process is as follow [18]:

$$(3CaO{\cdot}SiO_2 + 2CaO{\cdot}SiO_2) + 4\ SiO_2 + H_2O \rightarrow 3CaO{\cdot}2SiO_2{\cdot}3H_2O + 2Ca(OH)_2 + 4SiO_2$$

$$\rightarrow CSH$$

$$\rightarrow 5CaO{\cdot}6SiO_2{\cdot}5H_2O$$

It is important to note that autoclaved concrete block has no lime [$Ca(OH)_2$]. Consequently its alkalinity is much lower than that of regular concrete blocks [18].

3.4.3 Block types

With a wide range of selections from water absorption, weights, sizes and shapes, concrete blocks are capable of meeting a wide range of architectural, structural and economical demands.

(1). Water absorption rate

This is one of many factors which will affect the percentages of PCMs that can be impregnated into CMUs. According to the specification from the manufacturer, the percentages of water absorption for regular and autoclaved concrete blocks are 6.2% and 11.3% respectively. Therefore, it follows that more liquid PCMs can be impregnated into autoclaved concrete blocks than in regular blocks.

(2). Weight

The weight classifications for concrete blocks are derived from the density of the aggregates. The weight of light-weight CMU is 20 to 45 % lighter than that of normal-weight CMUs, but in general, local availability decides the use of light or normal weight aggregates.

(3). Hollow and solid units

A hollow unit is one where the net cross sectional area of the load-bearing face is less than 75% of the gross cross sectional area.

Owing to their lighter weight, easier handling and lower cost, hollow units are much more popular in the industry. However, the solid units are used for special needs, such as higher stress or fire protection requirements and the top or load-bearing course of a load-bearing wall [3].

(4). Sizes

The most popular modules for the concrete masonry unit dimensions are 10 to 20 cm (4 to 8 inch). The predominant nominal block size in this industry is 20×20×40 cm (8×8×16 inch) which was the size used in these experiments.

(5). Shapes

The wide range of application of concrete masonry in construction is made possible by the availability of a wide range of structural shapes so it is quite feasible for designers to use them to satisfy special needs. Briefly introducing eleven common shapes used on sites, they are steel sash unit, wood sash unit, bullnose unit, capping unit, control joint unit, header unit, plumbing unit, lintel unit, conduit unit, corner unit and joist unit.

3.5 Techniques of PCM incorporation

There are three major techniques of introducing PCMs into building materials [2, 18].

a) Direct incorporation: incorporating PCMs along with other components during the mixing process;

b) Encapsulation: comprises the inclusion of PCM in a high molecular weight polymeric film (capsule) which is mixed with other components of building materials;

c) Immersion: incorporating PCMs by immersion of building materials directly into a container which is filled with liquid PCMs at elevated temperatures (60°C~80°C).

The various techniques of incorporating PCMs into building materials have been studied for several years at CBS. The aforementioned three techniques have both advantages and disadvantages.

a) The advantages of direct incorporation are that the process is fast and inexpensive. In the case of cement concrete products, the main disadvantage is that care must be taken to avoid hydration reactions [13];

b) For encapsulation, the advantage is the flexibility to accommodate volume change in the PCMs while the disadvantages are additional cost and the fact that the thicker film will slow down the heat transfer process during the heating and cooling cycles;

c) Immersion is a very convenient and simple technique. A main advantage of this concept is that it can be used to impregnate blocks from storage as well as a step in the in line production. A disadvantage is that hydration reactions must be avoided.

Tests have shown that PCMs, even in their melted state, adhere to the large surface area provided by the dendritic structures comprising the core of concrete block [27]. This was the principal technique used at CBS in the studies of storing energy in gypsum wallboard and concrete and was the one used in this research for incorporating PCMs into concrete blocks.

CHAPTER 4. EXPERIMENTAL STUDIES FOR CONCRETE BLOCKS IMPREGNATED WITH PCMs

Two types of concrete blocks, low-pressure steam cured (regular) and high-pressure steam cured (autoclaved), were impregnated with Butyl Stearate (BS, EMEREST 2326, mp=17°C, fp = 20°C, latent heat = 138 J/g in melting) and Paraffin (PAR, UNICERE 55, mp =45°C, fp = 54°C, latent heat = 189 J/g in melting) respectively.

The comparisons related to the thermal storage in concrete blocks were made between the following three groups:

a) Autoclaved concrete blocks, unimpregnated (A) versus autoclaved concrete blocks impregnated with BS (ABS).

b) Autoclaved concrete blocks, unimpregnated (A) versus autoclaved concrete blocks impregnated with PAR (AP).

c) Regular concrete blocks, unimpregnated (R) versus regular concrete blocks impregnated with PAR (RP).

4.1 Test facility

The thermal performance of PCM impregnated concrete blocks was studied in a test facility, consisting of twelve identical 20×20×40 cm unimpregnated or PCM impregnated concrete blocks.

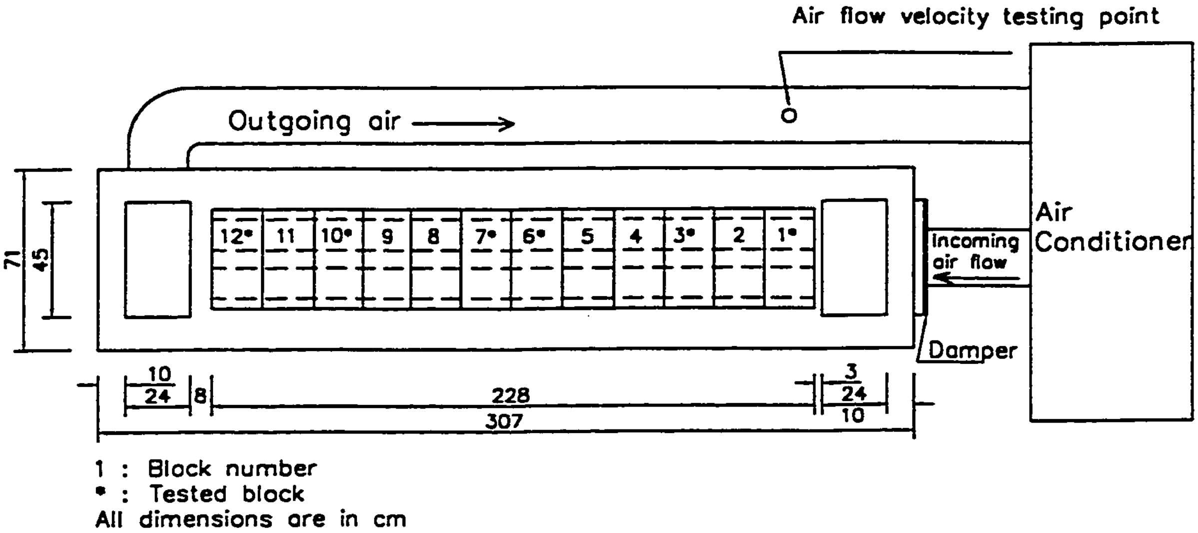
The twelve concrete blocks were laid contiguously to allow continuous air flow through the tunnels formed by their hollow cores. By varying the air temperatures, the blocks were heated or cooled through the desired temperature ranges.

In order to limit the heat losses, the twelve concrete blocks were installed in a thermally insulated wooden box with 311cm (length) × 75cm (width) × 67 cm (height) as shown in Figure 4.1.

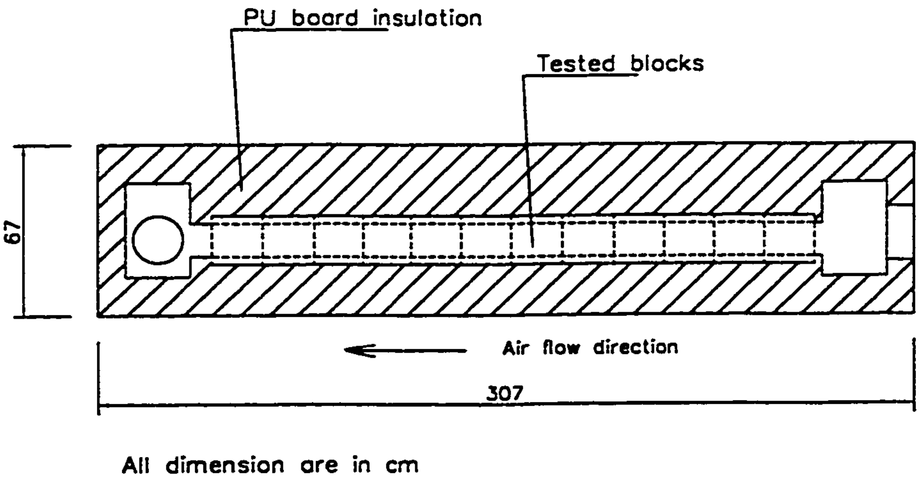
The insulation around the concrete blocks consisted of one ply 1.2 cm and two plies 2.5 cm PU board wrapped with aluminum foil and one ply 9 cm fiberglass with aluminum foil facing on each side. The top of the tunnel formed by the blocks was insulated with one ply 1.2 cm PU board wrapped with aluminum foil and two plies 9 cm fiberglass with aluminum foil facing. Its bottom was filled with three plies 1.2 cm PU board wrapped with aluminum foil.

The heating and cooling processes were performed by two sets of air conditioning systems and were monitored and controlled by microprocessor based digital controllers.

For controlling the incoming air flow volume and the tunnel air flow velocities, a damper was installed at the front of the box.



Schematic plan



Sectional plan

Figure 4.1 Schematic plan

Air flow velocities were measured by a Pitot tube at the outgoing air flow pipe at about 10 times the pipe diameter away from the end of the box. Mean air flow velocities were obtained after 20 testing points were averaged. The air flow velocities were calculated by equating the area-to-velocity ratio of the pipe and tunnels. The mean air flow velocities range inside the tunnels were 1 to 3 m/s while 2, 2.5 and 3 m/s were the velocities tested and compared in these experiments. Moreover, a boost fan was installed in the final experiment phase to verify the prediction of time using 3.9 m/s air flow rate for autoclaved concrete blocks impregnated with PAR. In this arrangement, air is assumed to be well mixed, so that its temperature varies only in the flow direction.

Two buffer spaces were also placed at the entrance and exit of the box to guide and evenly distribute the air flow into each tunnel.

The measured temperatures of the concrete blocks were collected through an OMEGA-5000 data logger and monitored by a computer. Temperatures were measured at 36 locations (testing points) which included the inside and outside surfaces of 6 blocks as well as room temperature (shown in Figure 4.2). Temperatures were recorded every 6 minutes for a 1 second dwell time.

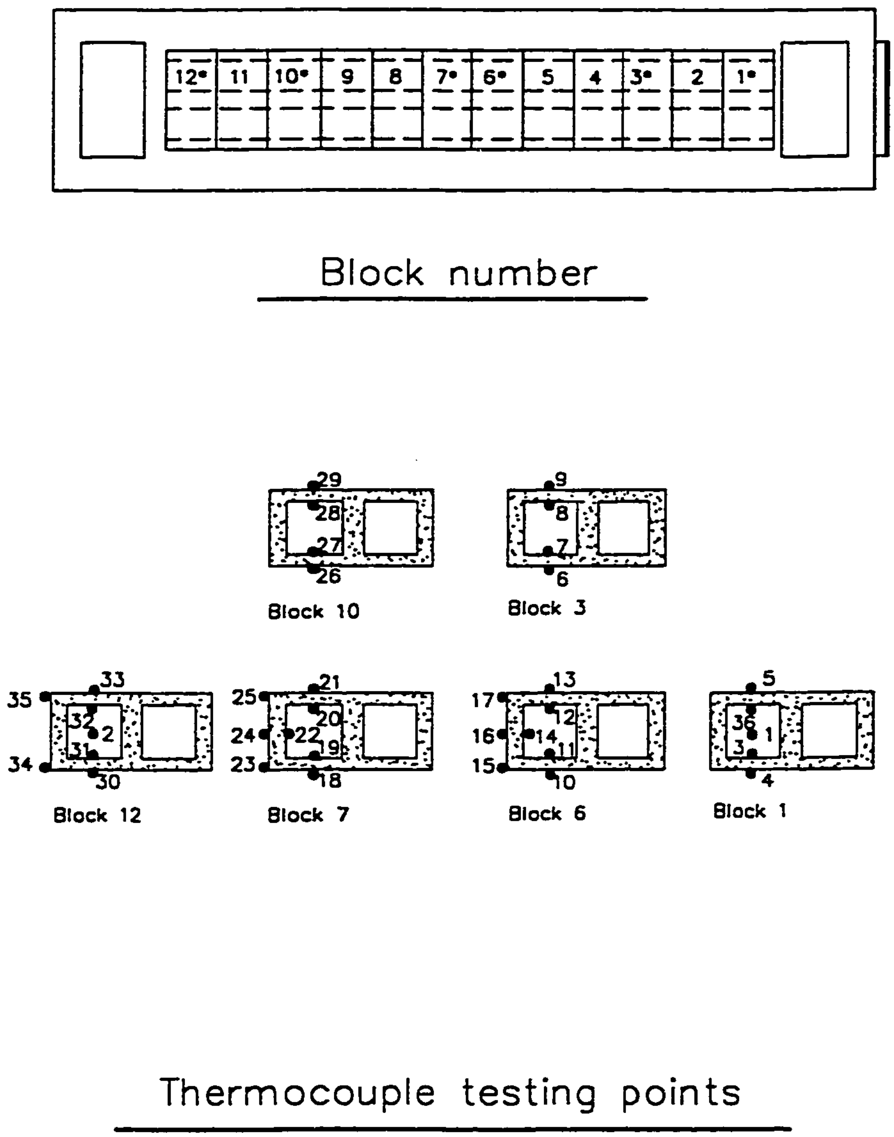


Figure 4.2 Thermocouple testing points

4.2 Test materials

All concrete blocks used in the experiments were provided by PERMACON INC., Montreal and meet C.S.A.- A165.1 requirements.

Both regular and autoclaved concrete blocks were selected as test media for PCM impregnation. The autoclaved blocks were impregnated with an average of 5.6% of BS and 8.4% of PAR. The regular blocks were impregnated with an average of 3.9% of PAR.

The Butyl Stearate meets the most criteria for low temperature heat storage. It has a low melting point and a high latent heat of transition per unit mass. It does not supercool during freezing and has a good chemical stability. Moreover, it is non-toxic, non-corrosive and odorless [13].

BS is obtained from renewable sources, such as oil seeds and tallow and already produced in large amounts for plastics, cosmetics, textiles, soaps as well as lubricants [10, 32]. It was analyzed by Differential Scanning Calorimetry (DSC), using a DuPont 910 Differential Calorimeter connected with a DuPont 1090 Thermal Analyzer. A 2 °C/min heating and cooling rate was considered optimal. Figure 4.3 shows a typical DSC diagram for BS with latent heat 138 J/g in melting and 135.5 J/g in freezing.

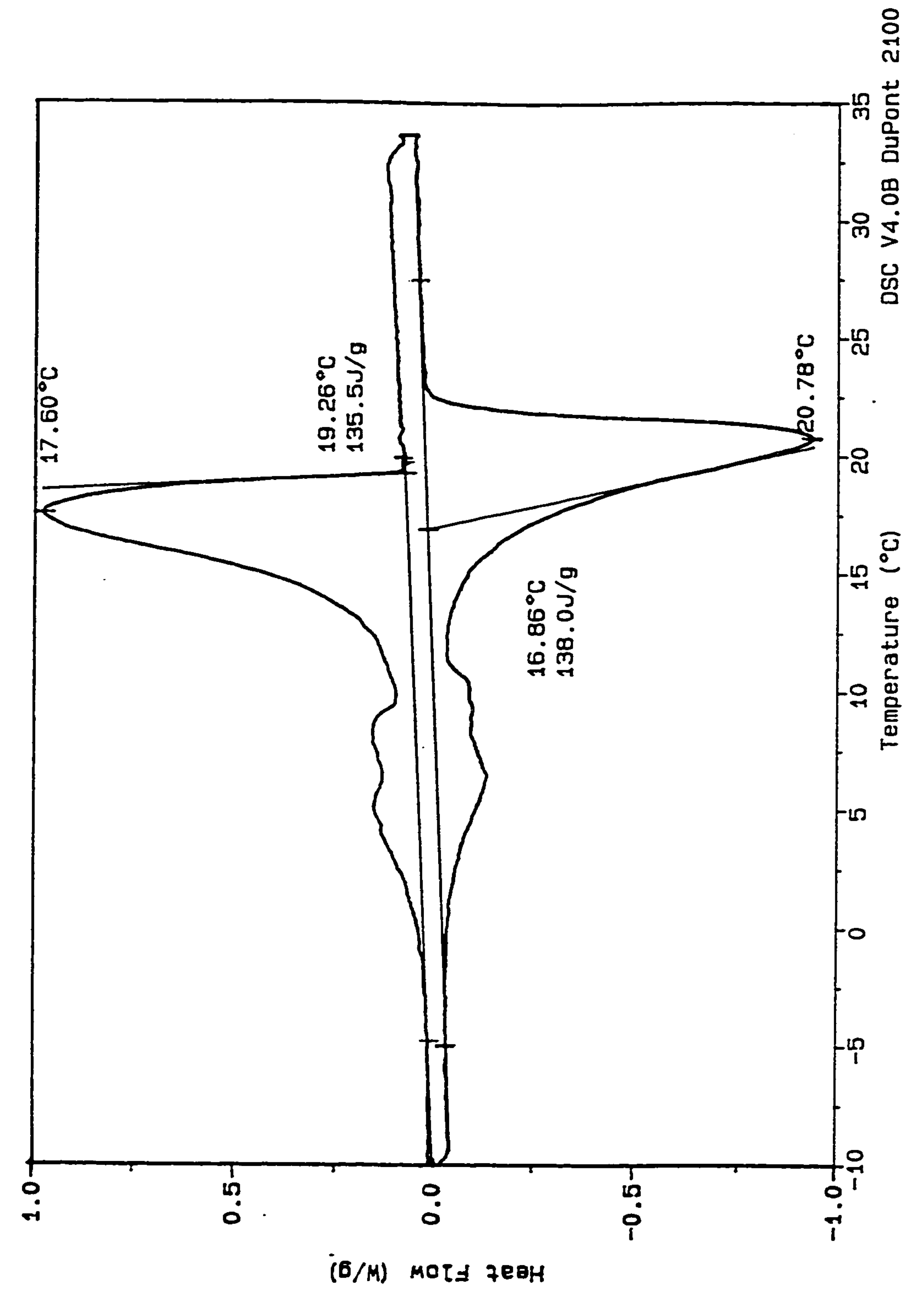


Figure 4.3 EMEREST 2326 DSC diagram

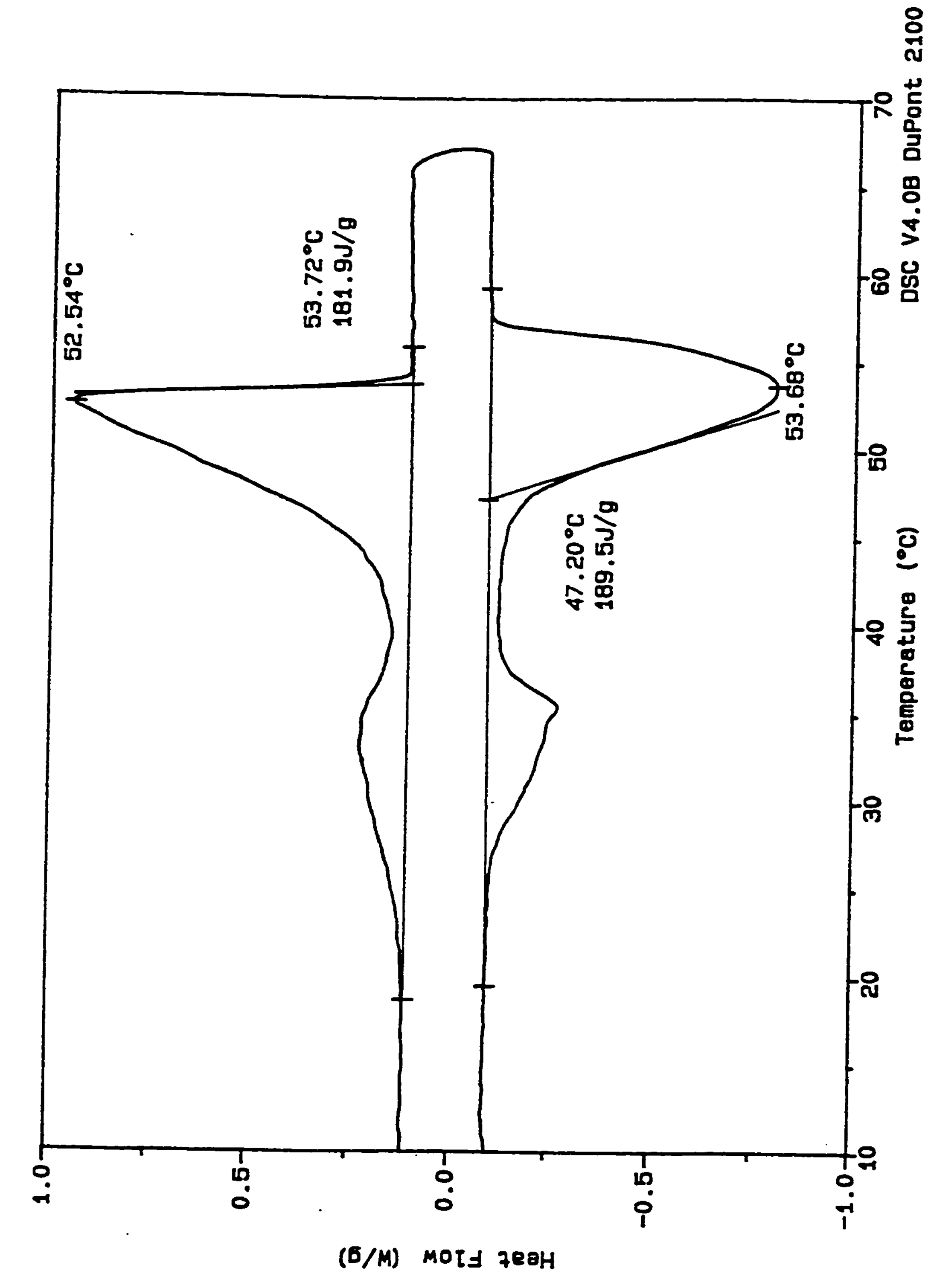


Figure 4.4 UNICERE 55 DSC diagram

The Paraffin, which is the by-product of the petrochemical industry and is a mixture of different hydrocarbons with different melting points [6, 31]. The melting point of the PAR, in the neighborhood of 53°C, is sufficiently high to provide a heated air supply for space heating. Figure 4.4 presents the DSC diagram of PAR with a latent heat 171 J/g in melting and 176 J/g in freezing.

4.3 Impregnation of concrete blocks

The impregnation of concrete blocks with PCM was performed in a steel container with the diameter of 35 cm and the height of 50 cm filled with BS or PAR at temperature of 80°C ± 5°C. A total of twelve autoclaved and twelve regular concrete blocks were impregnated with PAR and other twelve autoclaved blocks were impregnated with BS. The immersion time in the melted PCMs varied between 1 and 6 hours, depending on the characteristics of the concrete blocks and PCMs being used.

All the concrete blocks were weighed before and after immersion to obtain the percentages of absorption of the PCMs. Table 4.1 presents the weight of unimpregnated autoclaved and regular blocks. Tables 4.2 to 4.4 show the weights of autoclaved and regular blocks and the percentages of the impregnated autoclaved concrete blocks with BS, PAR and impregnated regular concrete blocks with PAR.

The immersion time for impregnating autoclaved blocks with BS and PAR varies from 40 minutes to 1 hour while impregnating regular blocks with PAR requires about 6 hours. The reason for the different immersion times is that the porosity or the degree of absorption of autoclaved concrete blocks is higher than those of regular concrete blocks. According to obtained data after impregnation, the content of PAR in autoclaved is higher than the content of BS. At 80°C the viscosity of PAR is higher (0.0053 Ns/m^2) than the viscosity of BS (0.0028 Ns/m^2). Because of a much lower porosity, the impregnation of regular blocks with PAR takes longer time than that of autoclaved ones and also the loading (3.9 % compared to 8.4 %) is lower.

We did not proceed to the impregnation of regular blocks with BS because of the potential interactions of this PCM with the alkalinity of concrete.

Autoclaved		Regular	
No. of Blocks	Dry Weight (Kg)	No. of Blocks	Dry Weight (Kg)
AR1	13.36	R1	18.38
AR2	13.14	R2	18.31
AR3	13.32	R3	18.48
AR4	13.37	R4	18.50
AR5	13.36	R5	18.43
AR6	13.37	R6	18.55
AR7	13.36	R7	18.51
AR8	13.18	R8	18.47
AR9	13.40	R9	18.78
AR10	13.49	R10	18.55
AR11	13.24	R11	18.43
AR12	13.40	R12	18.69
Total	159.99	Total	222.08

Table 4.1 Dry weight of unimpregnated autoclaved and regular concrete blocks

Block designation	Dry weight at 22°C (Kg)	Impregnated weight (Kg)	BS in concrete	
			Kg	%
AC1	13.47	14.38	0.91	6.3
AC2	13.52	14.30	0.78	5.5
AC3	13.47	14.39	0.92	6.4
AC4	13.47	14.21	0.74	5.2
AC5	13.67	14.49	0.82	5.7
AC6	13.53	14.31	0.78	5.5
AC7	13.32	14.13	0.81	5.7
AC8	13.49	14.19	0.70	4.9
AC9	13.79	14.46	0.67	4.6
AC10	13.49	14.41	0.92	6.4
AC11	13.44	14.29	0.85	5.9
AC12	13.57	14.34	0.77	5.4
Total / Average	162.23	171.90		5.6

Table 4.2 Butyl Stearate percentages in autoclaved concrete blocks (immersion time 60 ~ 120 mins.)

Block designation	Dry weight at 22°C (Kg)	Impregnated weight (Kg)	PAR in concrete	
			Kg	%
WA1	13.22	14.38	1.16	8.1
WA2	13.12	14.32	1.20	8.4
WA3	13.47	14.64	1.17	8.0
WA4	13.15	14.40	1.25	8.7
WA5	13.26	14.50	1.24	8.6
WA6	13.22	14.48	1.26	8.7
WA7	13.31	14.58	1.27	8.7
WA8	13.14	14.42	1.28	8.9
WA9	13.26	14.48	1.22	8.4
WA10	13.65	14.82	1.17	7.9
WA11	13.37	14.64	1.27	8.7
WA12	13.43	14.60	1.17	8.0
Total / Average	159.60	174.26		8.4

Table 4.3 Paraffin percentages in autoclaved concrete blocks (immersion time: 40 mins.)

Block designation	Dry weight at 22°C (Kg)	Impregnated weight (Kg)	PAR in concrete	
			Kg	%
RP1	18.80	19.52	0.72	3.7
RP2	18.35	19.08	0.73	3.8
RP3	18.73	19.48	0.75	3.9
RP4	18.72	19.54	0.82	4.2
RP5	18.71	19.42	0.71	3.7
RP6	18.3	19.04	0.74	3.9
RP7	18.56	19.29	0.73	3.8
RP8	18.31	19.10	0.79	4.1
RP9	18.28	19.14	0.86	4.5
RP10	18.81	19.56	0.75	3.8
RP11	18.56	19.26	0.70	3.6
RP12	18.68	19.47	0.79	4.1
Total / Average	222.81	231.90		3.9

Table 4.4 Paraffin percentages in regular concrete blocks (immersion time 360 mins.)

4.4 Experimental techniques

Three types of experiments were conducted:

- forced heating mode (circulating warm air)
- forced cooling mode (circulating cool air)
- natural cooling mode.

The purpose of these experiments was to charge and discharge heat into and from the concrete blocks and hence to evaluate the thermal storage and release performances of the regular and autoclaved PCM impregnated concrete blocks versus the unimpregnated ones. Experimental temperatures ranges were set:

- between 15°C and 25°C for blocks impregnated with BS;
- between 22°C and 60°C for the autoclaved blocks impregnated with PAR;
- between 45°C and 60°C for regular and autoclaved blocks impregnated with PAR.

For comparison, the unimpregnated concrete blocks were tested in the same temperature ranges. In every experiment, the blocks were first heated up to the upper temperature limits and then cooled down to the lower temperature limits. These experiments were repeated for all abovementioned cases for at least three times.

The purpose of setting two different temperature ranges (22°C to 60°C and 45°C to 60°C) for autoclaved blocks impregnated with PAR at 3 m/s air flow velocity is to investigate the PCM thermal storage and release performance when utilizing both sensible and latent heat capacity as well as latent heat only.

In order to maintain a stable temperature air flow supply, modified air conditioning systems were employed. Firstly, during the forced heating mode (charging heat into the blocks) in the high temperature ranges (both 22°C to 60°C and 45°C to 60°C), two heaters were turned on to gain sufficient heating power while the single air conditioner (chiller) was turned off. In the lower temperature range (15°C to 25°C), two heaters were turned on and the air conditioner was turned on as well. Secondly, in the forced cooling mode (discharging heat from blocks), from 60°C to 22°C, the air conditioner was run continuously when the heaters were used as required to effect the desired temperature modification. For the 60°C to 45°C range, only the two heaters were required to maintain a stable temperature supply. For the lower temperature range (25°C to 15°C), both two heaters and the air conditioner were used to maintain a controlled temperature air supply.

The termination of heating and cooling processes was determined by the fact that the temperature in blocks did not change (increase or decrease) in two hours; then, the time required to reach that temperature was considered the final point. In fact, at such points temperatures were still increasing or decreasing but since it takes hours until the thermal storage and the heat loss were completely balanced. A two hour equilibration period was selected as a reasonable compromise for the purpose of this research.

4.4.1 Forced heating mode

The term heating means charging heat into the tunnels consisting of the twelve concrete blocks for later release to the room. This process can use heat from an external source or be used to cool the room by selecting appropriate PCM and operating ranges.

Affected by the incoming hot air flow (25°C for A, ABS and 60°C for A, AP, R, RP), the temperatures of unimpregnated concrete blocks increase steadily as the sensible heat is stored. In the case of PCM impregnated concrete blocks, in addition to the sensible heat, the PCM latent heat is also stored. When temperatures rise through the solid-liquid transition ranges (17°C to 20°C for BS and 47°C to 54°C for PAR), the PCMs melt. At this point, the temperatures of the blocks rise continuously at a much slower rate. As the latent heat of melting is thus absorbed and stored by the PCM while the sensible heat content of both PCM and concrete are increased in accordance with the rise in temperature. In the case of concrete block, even this small temperature rise comprises a significant portion of the thermal energy storage.

In the case of the unimpregnated concrete blocks, since only sensible heat was stored, the heating mode required less time.

Figures 4.5 and 4.6 present profiles for the heating mode in BS and PAR impregnated block number 1 (bottom part). As described above, once the increasing temperature reached the PCM melting points 17°C in the BS and 47°C in the case of PAR impregnated blocks, the absorption of heat by the PCM started to affect the rate of temperature rise in the block. This phenomenon can be compared with the greater temperature increase rates for the unimpregnated blocks.

The greater amount of heat absorbed by the impregnated blocks means that, in this case, a greater amount of heat can be stored for the same mass.

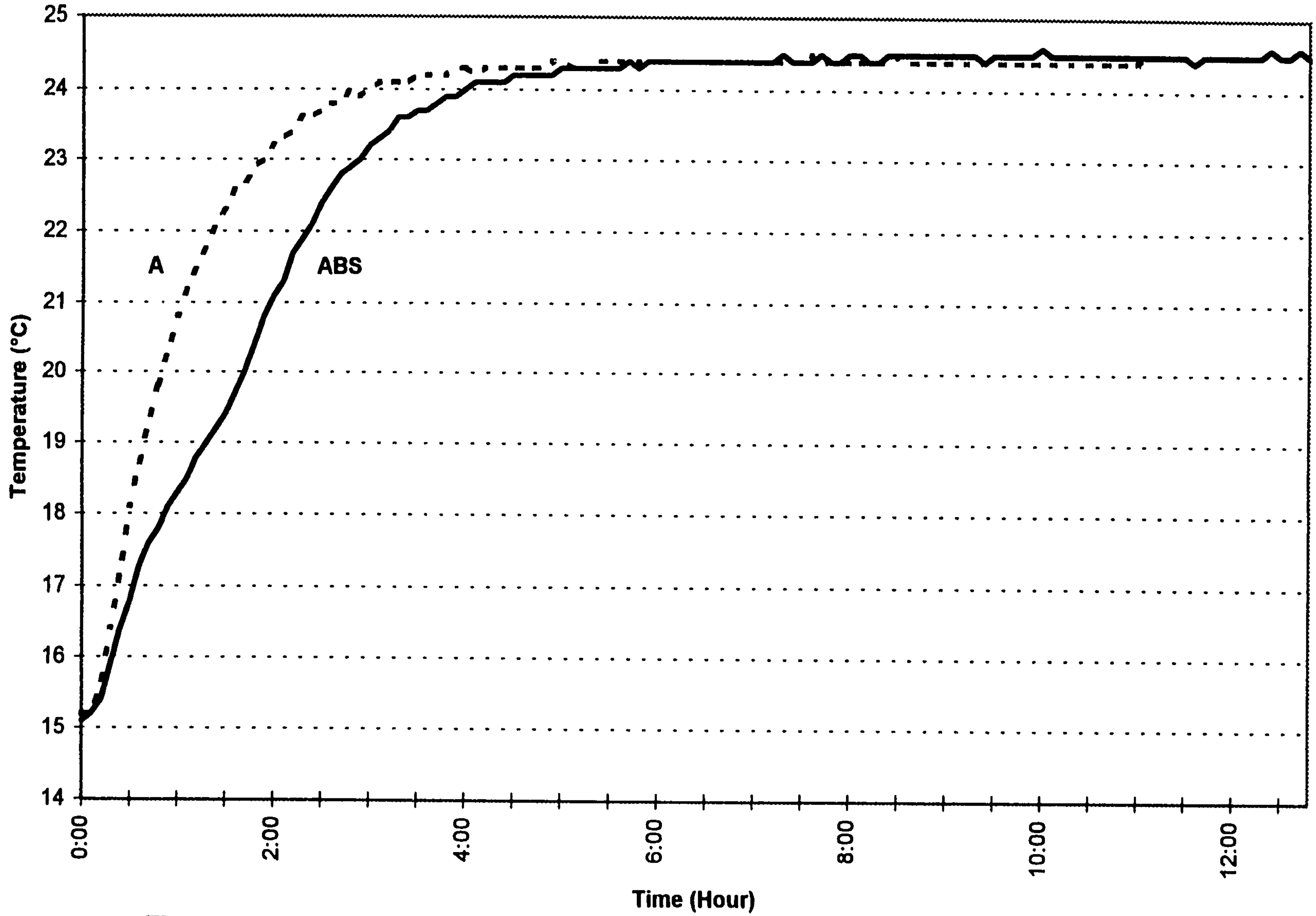


Figure 4.5 Time-temperature curves for unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 1 at 3 m/s air flow velocity in heating mode

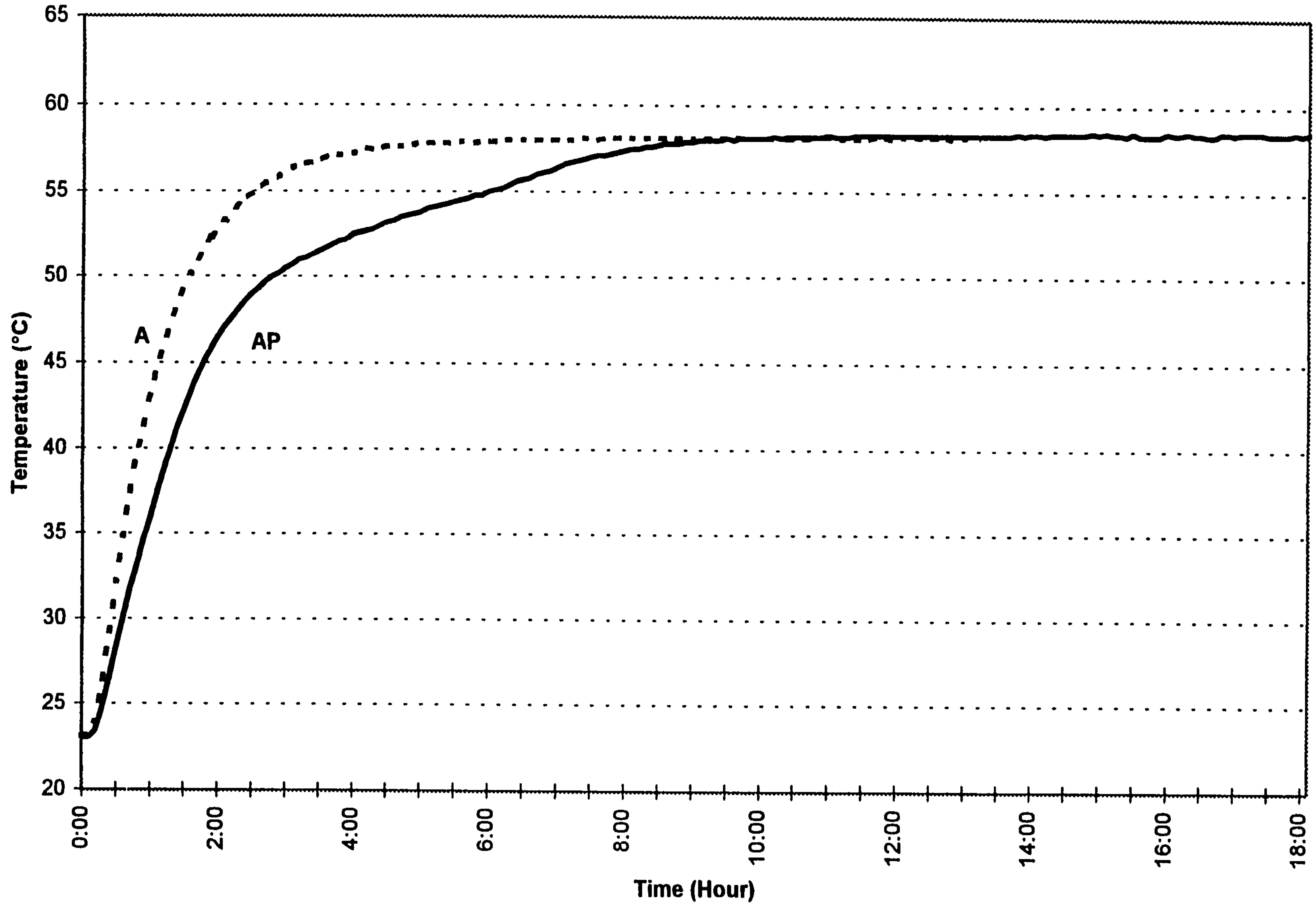


Figure 4.6 Time-temperature curves for unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 1 at 3 m/s air flow velocity in heating mode

4.4.2 Forced cooling mode

Cooling means the discharging heat from the tunnels made of twelve concrete blocks unimpregnated or impregnated with PCMs. This process cools the blocks and transfers heat to the room.

The cooling mode was started immediately after completing the heating mode. By blowing colder air (15°C for A, ABS, 22°C for A, AP and 45°C for R, RP) through the blocks. The heat previously stored in the blocks was removed and discharged to the room. The temperature profiles of the PCM impregnated blocks versus the unimpregnated ones indicate that the time for releasing stored heat is much longer for PCM impregnated blocks in comparison with unimpregnated blocks. In practice, the cool air would be that returned in the normal manner by the HVAC distribution system.

Figures 4.7 and 4.8 clearly show that the beginning of the crystallization starts at about 20°C for Butyl Stearate and 54°C for Paraffin impregnated concrete blocks. For both unimpregnated autoclaved and regular concrete blocks, the block temperature decreases faster in the cooling process. This faster temperature change characteristic of concrete block having only sensible heat storage was previously observed in the heating experiments.

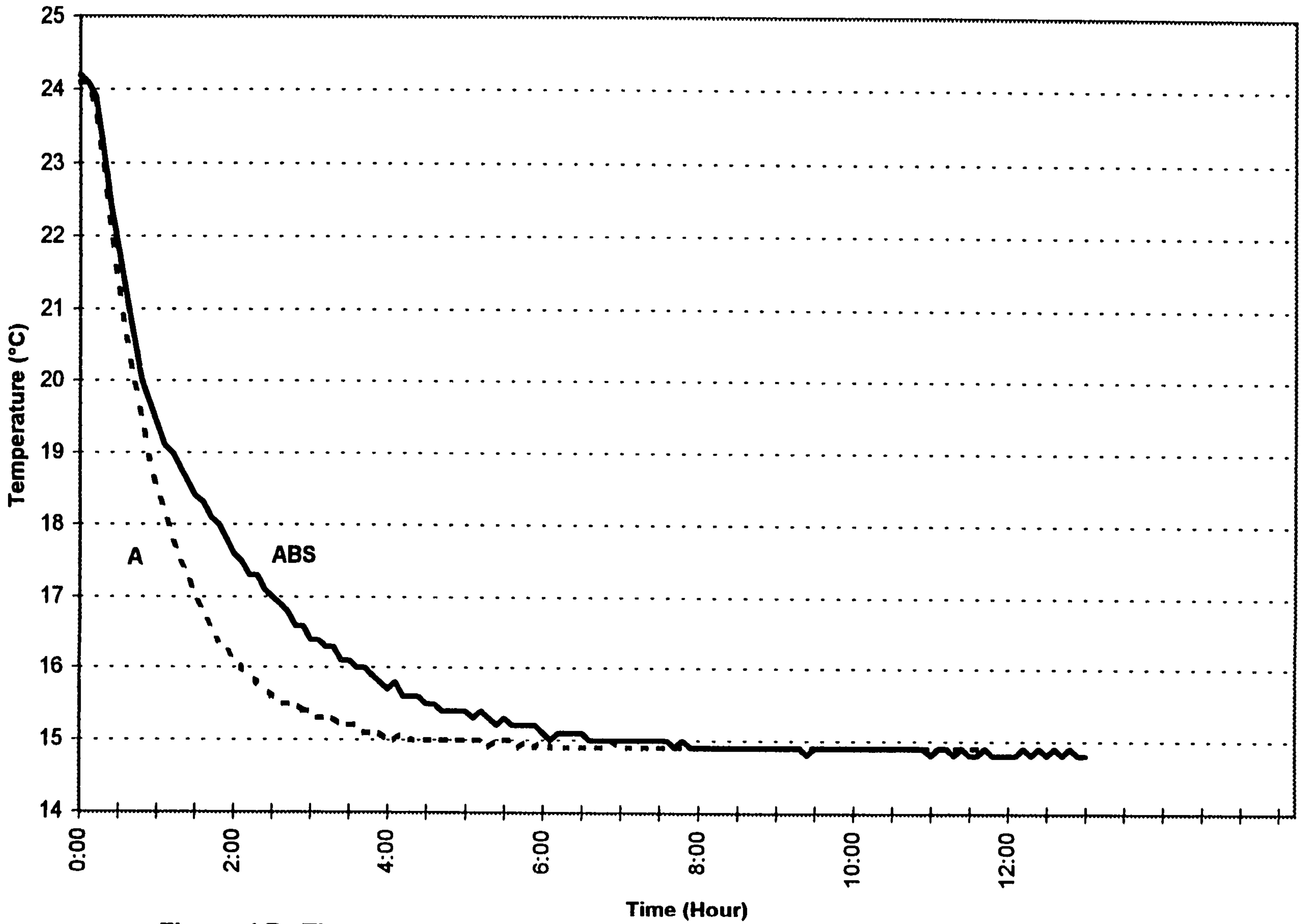


Figure 4.7 Time-temperature curves for unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 1 at 3 m/s air flow velocity in cooling mode

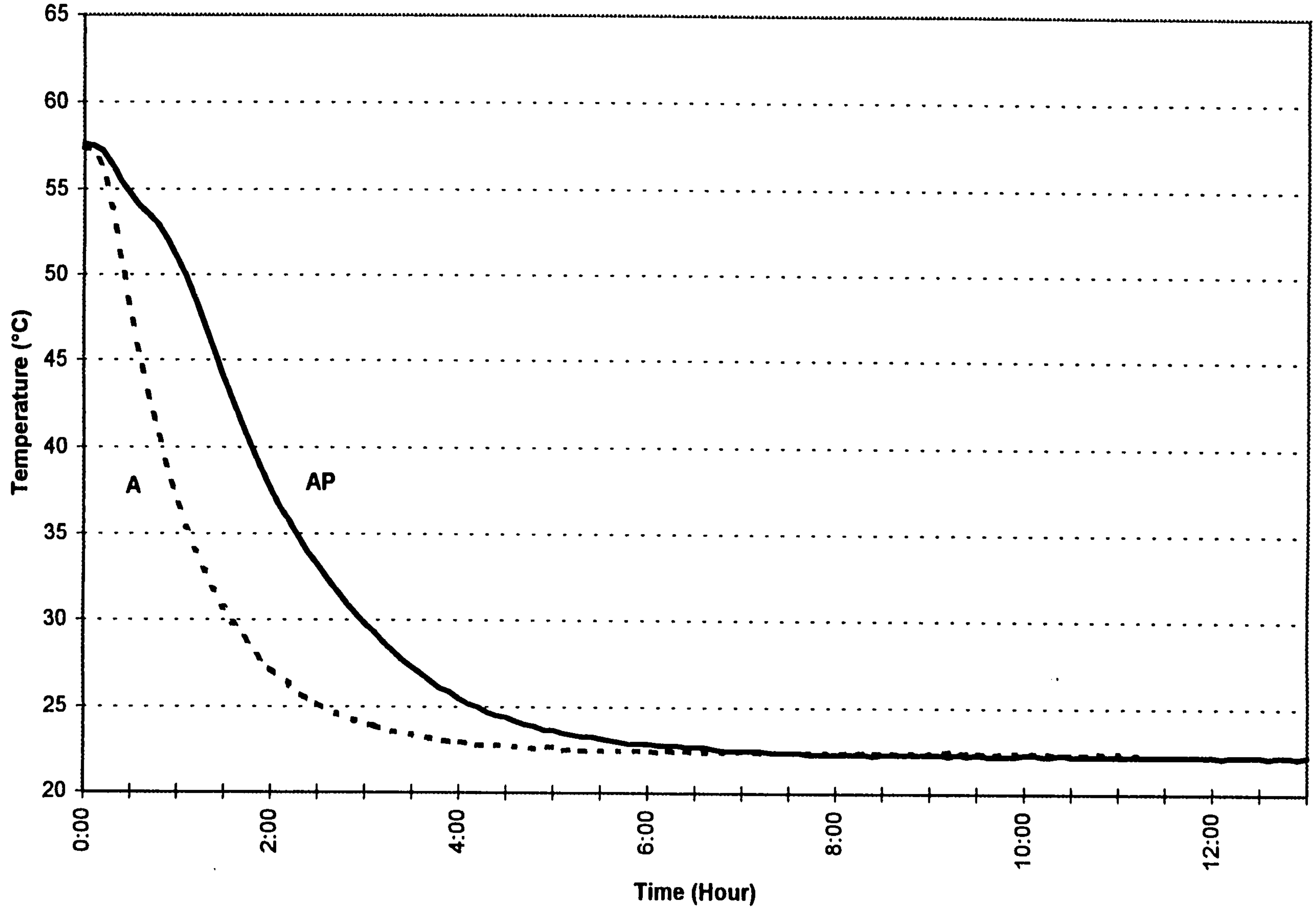


Figure 4.8 Time-temperature curves for unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 1 at 3 m/s air flow velocity in cooling mode

It will be seen from the foregoing that the impregnated blocks have greater thermal storage capacity than the unimpreganted blocks and are therefore, able to function as a more efficient and stable heat source.

One of many advantages gained by utilizing latent heat storage in concrete blocks is that the heat can thus be stored by using off-peak electrical power, solar energy or any other convenient source of low cost thermal energy. Then, when this energy is subsequently required for space heating, the building air can be passed through the impregnated concrete blocks where the heat is exchanged and circulated by the air conditioning system.

4.4.3 Natural cooling mode

Natural cooling was performed from 60°C to room temperature, for:

-unimpregnated autoclaved blocks (A);

-unimpregnated regular blocks (R);

-Paraffin impregnated autoclaved blocks (AP);

-Paraffin impregnated regular blocks (RP).

At the beginning, all twelve concrete blocks were heated up to 60°C, then, the air conditioning systems were turned off and cooled to the surrounding room temperature which swings between 22°C and 23°C.

CHAPTER 5. PERFORMANCE ANALYSIS OF PCM IMPREGNATED CONCRETE BLOCKS

The thermal performances of unimpregnated and PCM impregnated concrete blocks were determined and evaluated in three conditions:

- forced heating mode
- forced cooling mode
- natural cooling mode.

In each case, the effects of varying the air flow velocities on the thermal performances of the unimpregnated and PCM impregnated blocks were also investigated. For such evaluation, time-temperature diagrams were drawn. Based on the obtained data of these consecutive experiments average curves were established.

The temperature profiles of PCM impregnated blocks through the temperature transition ranges were correlated with data obtained from DSC analysis for PCMs alone.

When the extra thermal storage capacity provided by the latent heat of an incorporated PCM is involved, the heating mode was prolonged. In this process, once the concrete block temperatures are raised above the PCM melting point, both latent and sensible heats are stored together. Similarly, in the cooling mode, when the block temperature is lowered below the PCM freezing point, both latent and sensible heats are released.

5.1 Forced heating mode

In the forced heating mode, hot air was introduced (25°C for A, ABS and 60°C for A, AP, R, RP) into the tunnels made of the core of the twelve concrete blocks. The temperature of the blocks was gradually increased and as it was raised above the melting point through the solid-liquid phase range, the PCM was gradually melted. The energy thus absorbed comprised the sensible heats of the PCM and the concrete as well as the latent heat of the PCM which is crucial to the process.

To evaluate and compare the forced heating performance of unimpregnated and PCM impregnated blocks, the following experiments were made:

a) Time comparison: the time required to charge heat into the bottom part of the blocks at 2, 2.5 and 3 m/s air flow velocities and in a special case 3.9 m/s was determined.
b) Comparison between upper and bottom parts (block number 1, 3, 6, 7, 10 and 12) of tunnels made of unimpregnated and PCM impregnated concrete blocks at various air flow velocities.
c) The variation of the tunnel temperatures were followed during charging processes depending on the time and air flow velocities. In all these experiments, the bottom part of central block number 7 was considered.
d) Outgoing air temperature profiles (at block number 12).

5.1.1 Autoclaved concrete blocks unimpregnated (A) and impregnated with Butyl Stearate (ABS)

The average percentage of BS impregnated in autoclaved concrete blocks was about 5.6. An operating air temperature of 25°C was used to raised the temperature of the blocks from 15°C.

a). Time comparison was done taking into account the bottom part of the blocks.
The faster the air flow velocity, the shorter was the observed charging time required. Figure 5.1 and 5.2 clearly explained this phenomenon. The total heat storage in the BS impregnated autoclaved blocks (2638 KJ) was about twice that measured in the unimpregnated blocks (1428 KJ). As expected, the required charging time was found to be about 1.3 times longer for the impregnated blocks (723 min.) than for the unimpregnated ones (534 min.).

b). Comparison between unimpregnated and BS impregnated concrete blocks (upper and bottom part) at various air flow velocities:
It took about 3 hours longer to charge the BS impregnated blocks from 15°C to 25°C than for the unimpregnated blocks at various air flow velocities, as shown in Figures 5.3, 5.4 and 5.5. It will be noted that the time difference diminishes significantly as the velocity increases in the case of the impregnated blocks but less so for the unimpregnated blocks. This is because the greater thermal conductivity in the former case allows for better absorption of the increased heat supply resulting when the higher velocity is used.

In Figures 5.3, 5.4 and 5.5, each point represents the time needed for the various testings to reach the set temperature. It was observed that the bottom parts of the twelve concrete blocks required a longer time to reach the upper temperature limit than the upper part of the blocks. This was deemed to be due to convection and potential air leakage routes toward the upper cap of the box. It was also noted that the higher air flow velocities took less time to achieve the final set temperatures than the lower velocities did. This was to be expected because the greater air flow through the blocks carried more heat per unit time and the scrubbing effect was greater at the higher velocities which effected more efficient heat exchange.

c).From Figures 5.6, 5.7 and 5.8, we can observed that BS impregnated concrete blocks took approximately 13, 11 and 10 hours at 2, 2.5 and 3 m/s air flow velocities respectively to charge the necessary heat into the blocks due to the necessity of melting the PCM. However, for unimpregnated concrete blocks, it only took about 9, 8 and 7.5 hours at the same air flow velocities. This represents an average of 3 hours longer to charge impregnated blocks as compared to unimpregnated ones. This is principally due to the additional thermal energy required to charge the latent heat storage capacity provided by the impregnated PCM. In the case of BS impregnated blocks, we can see that the temperature in the block number 7 is 3°C lower for around 5 hours.

d). Outgoing air temperature profiles (block number 12):

The air temperature at various air flow velocities measured in block number 12 does not exhibit substantial differences between the two types of blocks. However, lower air flow velocities tend to maintain higher outgoing air temperature for a longer period of time. This effect is indicating a less efficient heat transfer at the lower velocities as previously discussed in section 5.1, shown in Figures 5.9, 5.10 and 5.11.

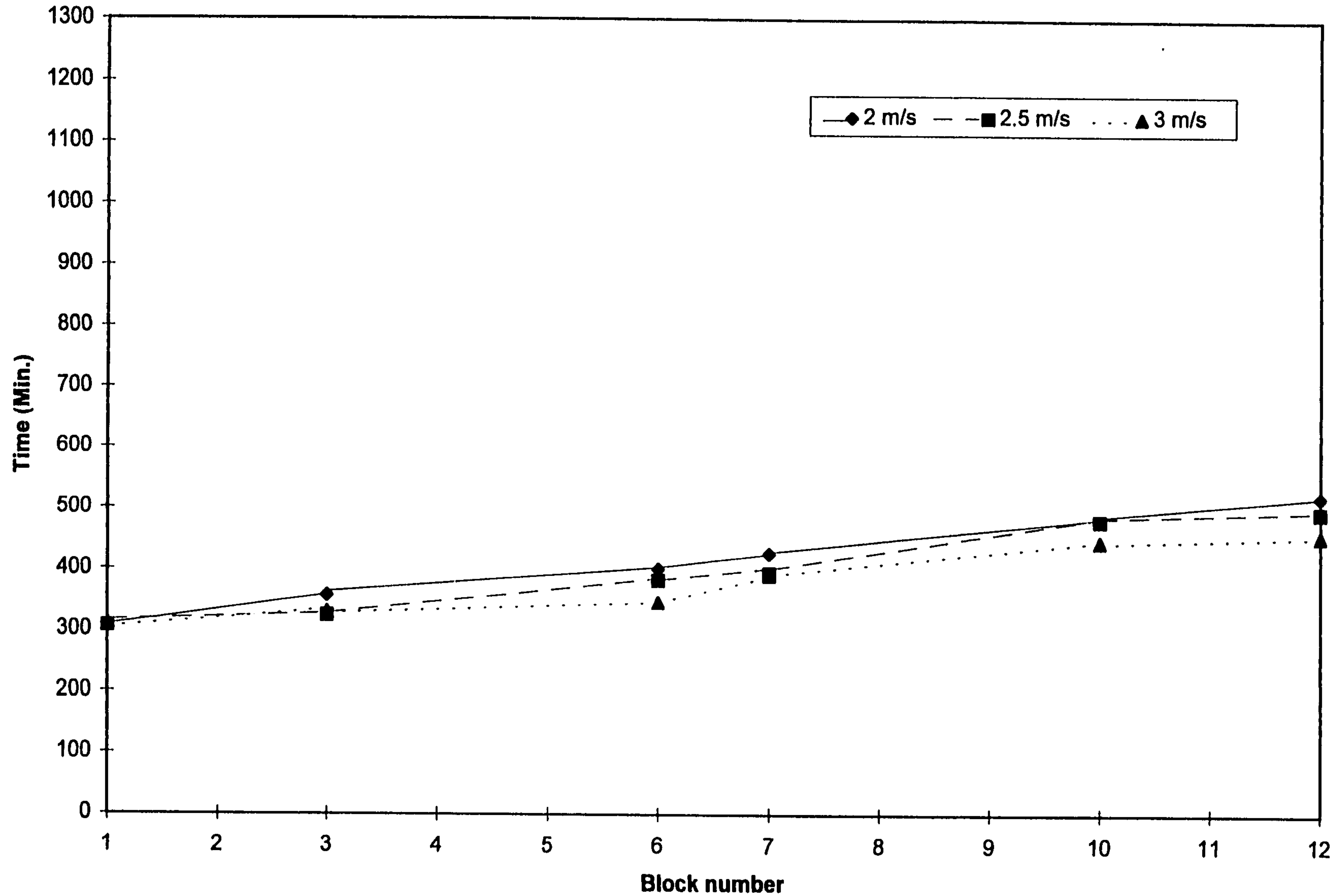


Figure 5.1 Time required for heating unimpregnated autoclaved blocks from 15°C to 25°C at different air flow velocities [A - Heating - Bottom]

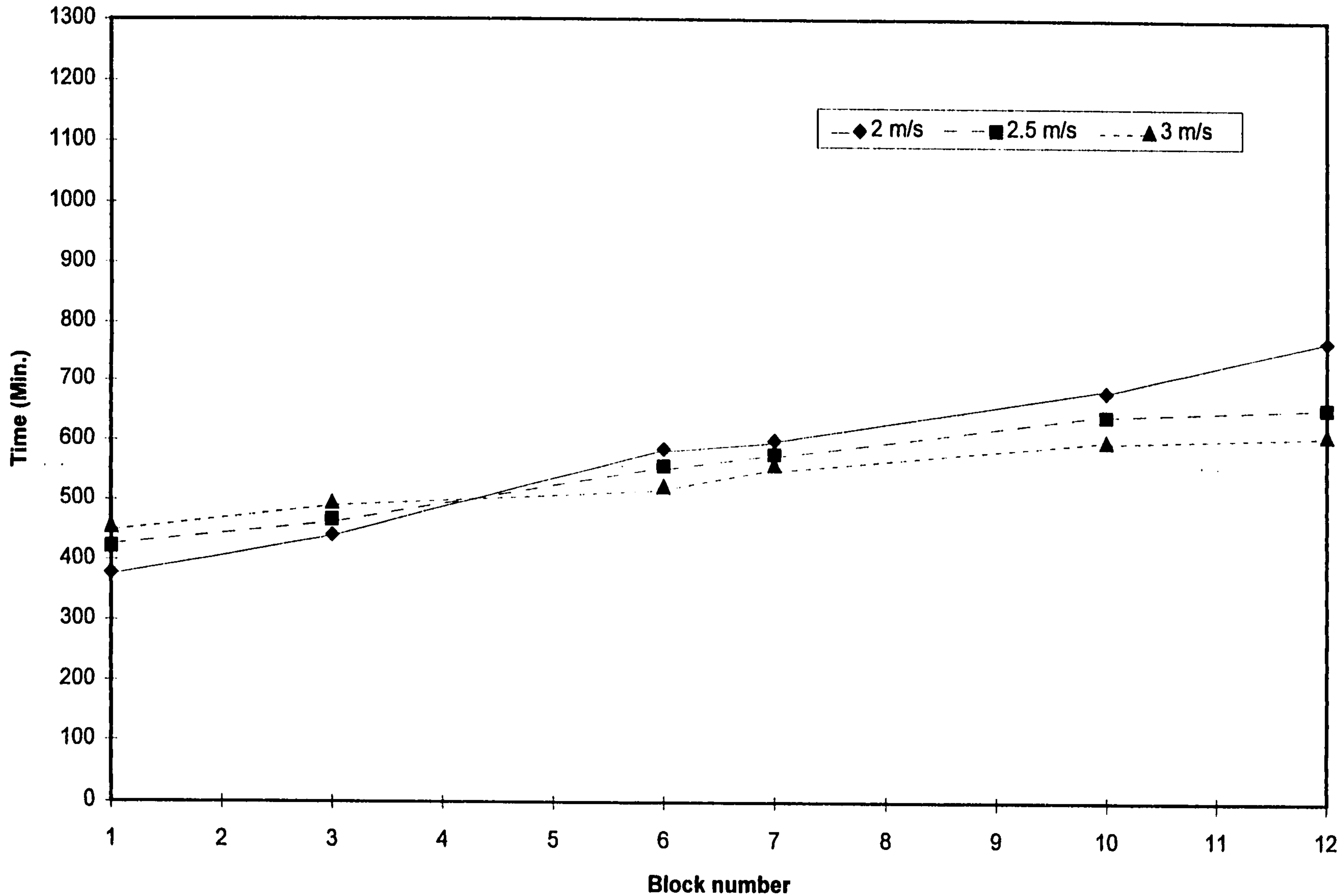


Figure 5.2 Time required for heating from 15°C of unimpregnated autoclaved blocks to reach 25°C at different air flow velocities [ABS - Heating - Bottom]

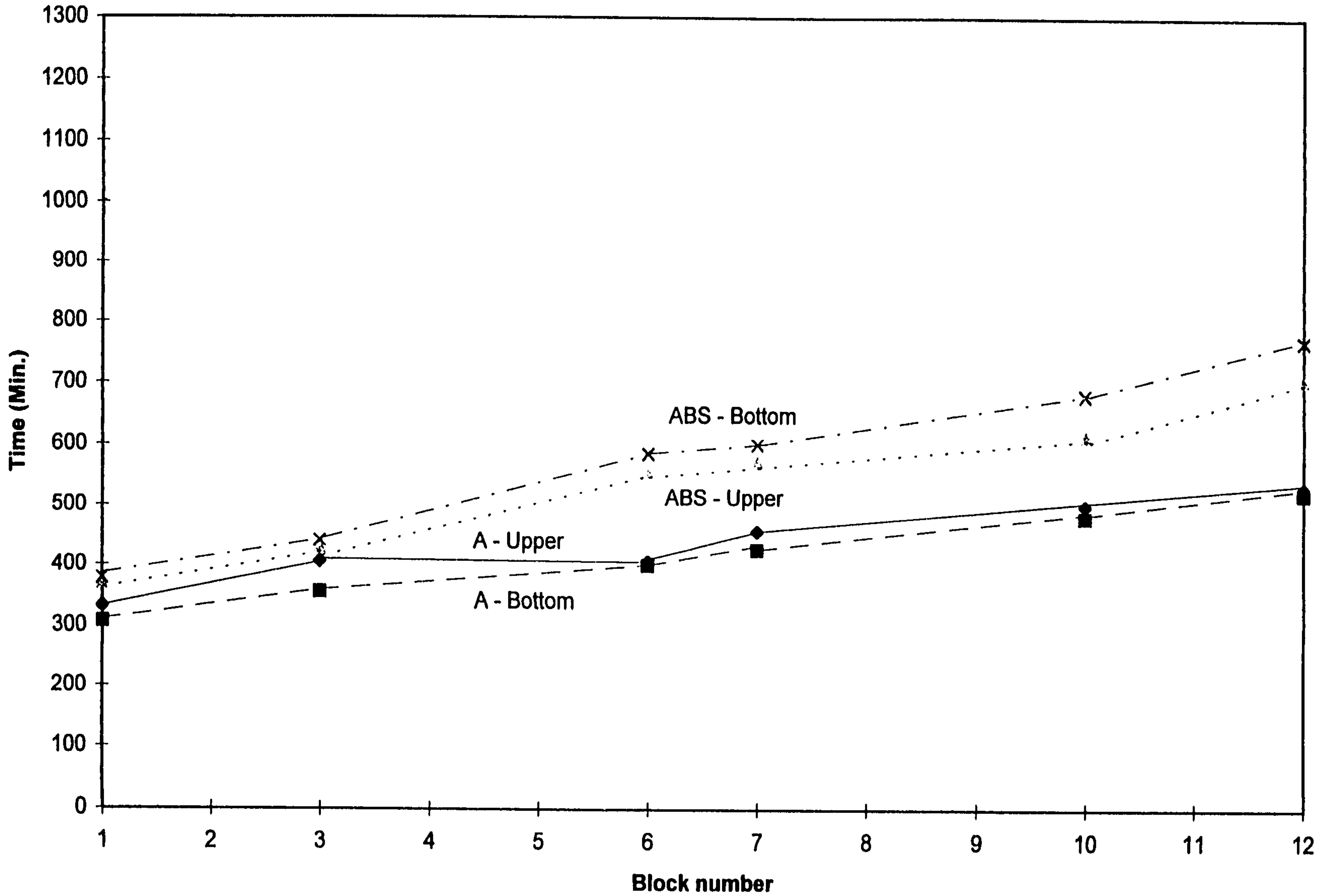


Figure 5.3 Comparison between the time required for heating unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved blocks from 15°C to 25°C at 2 m/s air flow velocity

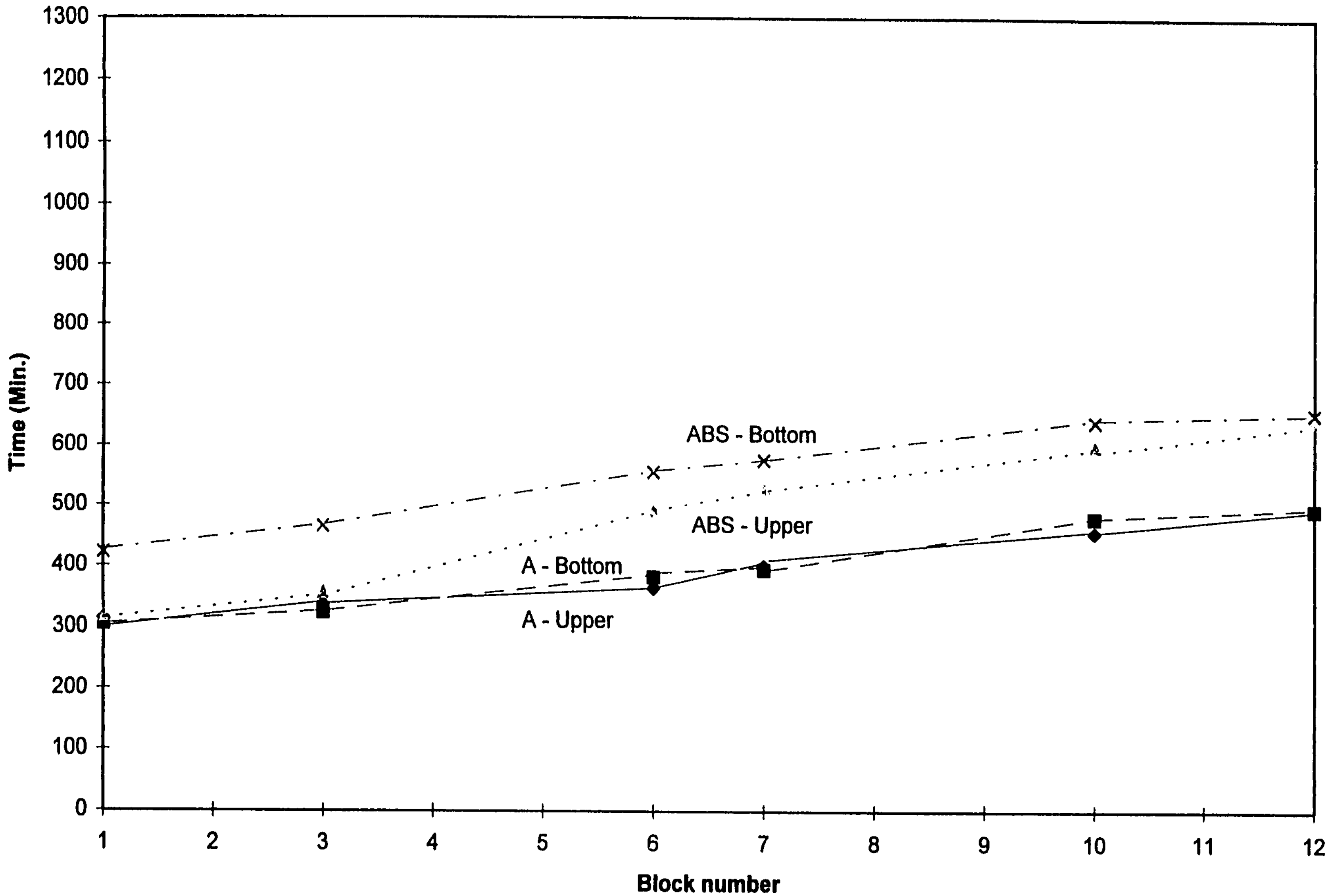


Figure 5.4 Comparison between the time required for heating unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved blocks from 15°C to 25°C at 2.5 m/s air flow velocity

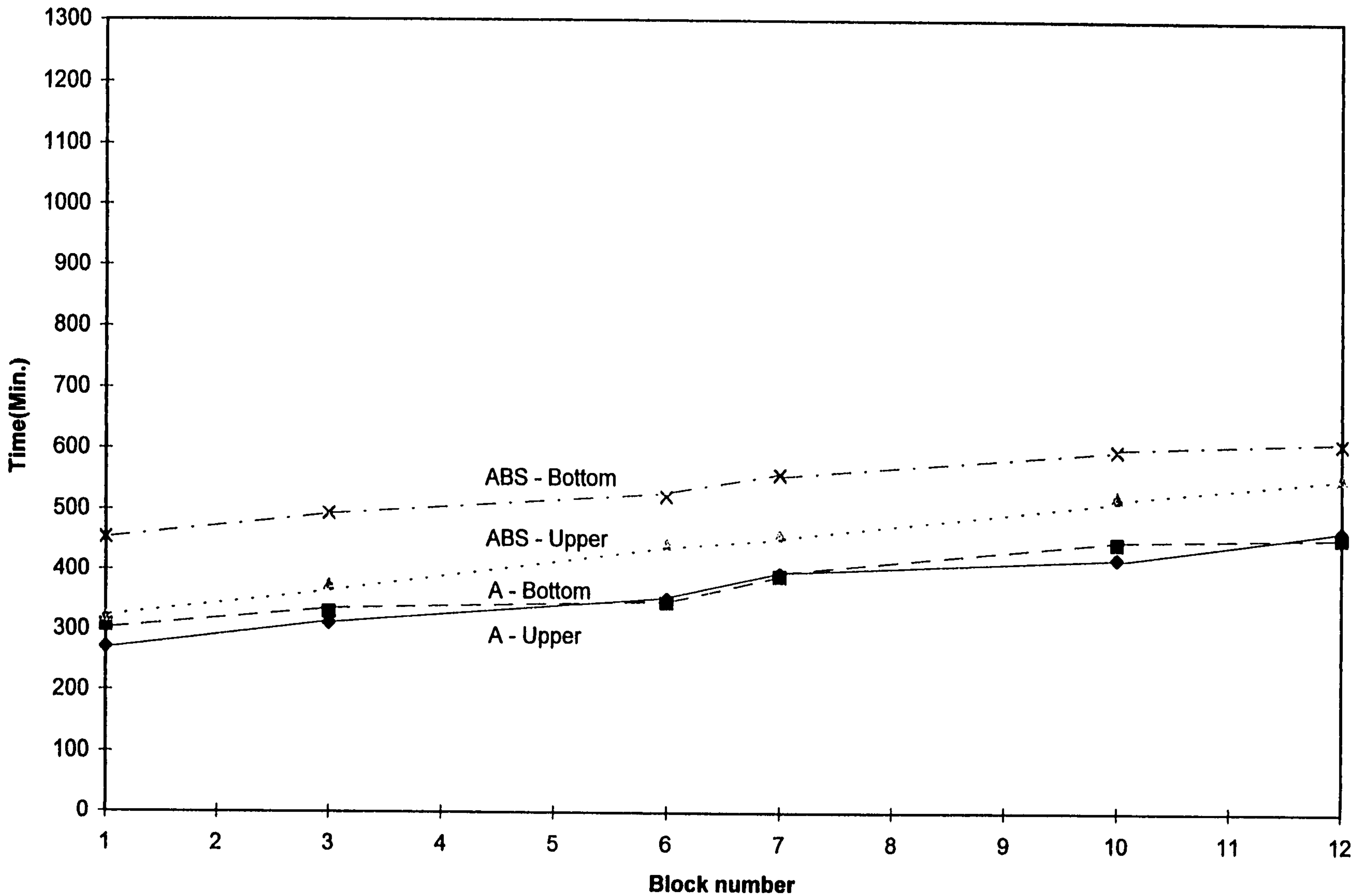


Figure 5.5 Comparison between the time required for heating unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved blocks from 15°C to 25°C at 3 m/s air flow velocity

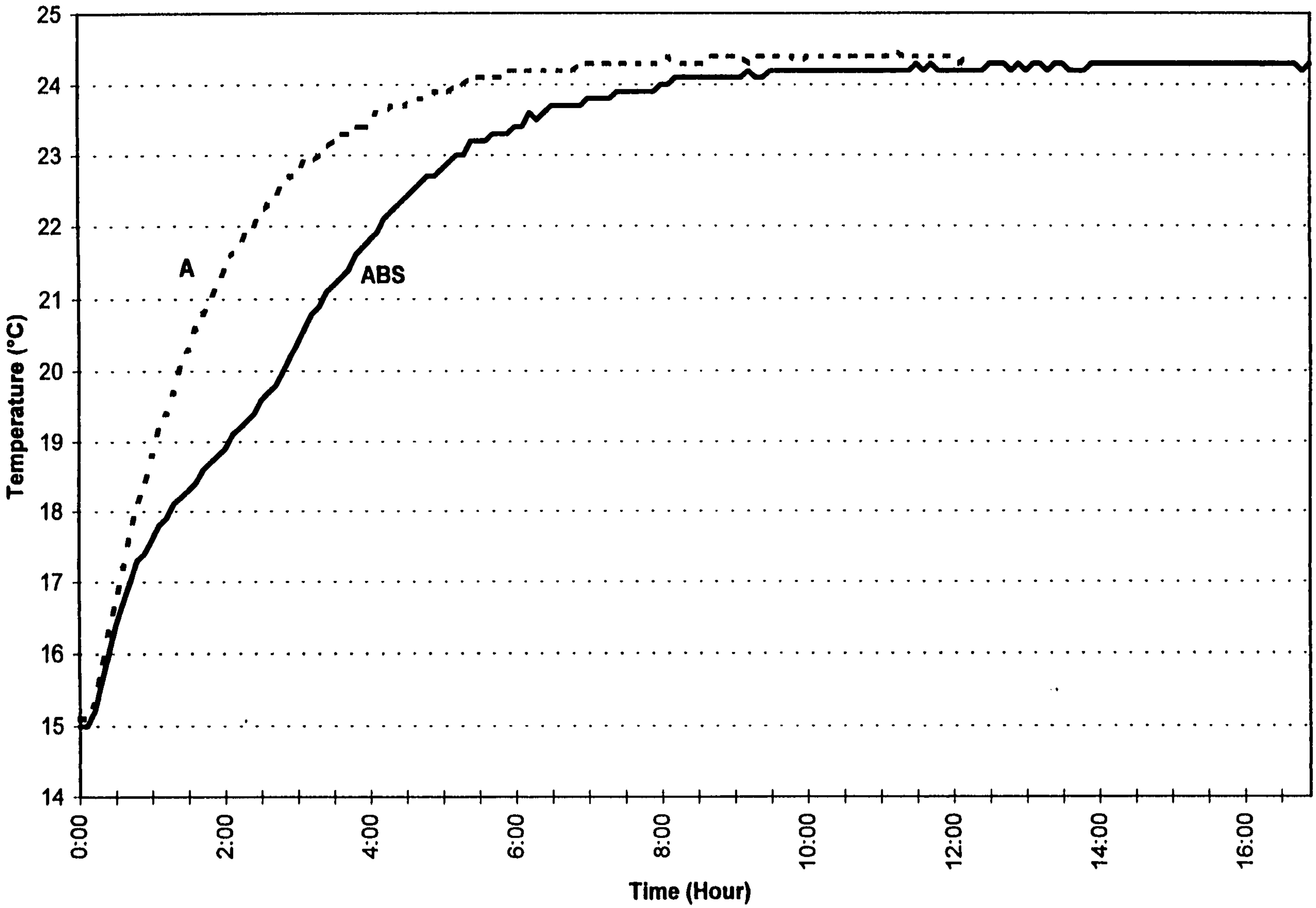


Figure 5.6 Time-temperature curves for unimpregnated (A) and Butyl Stearate impregnated (ABS) autocalved block number 7 at 2 m/s air flow velocity

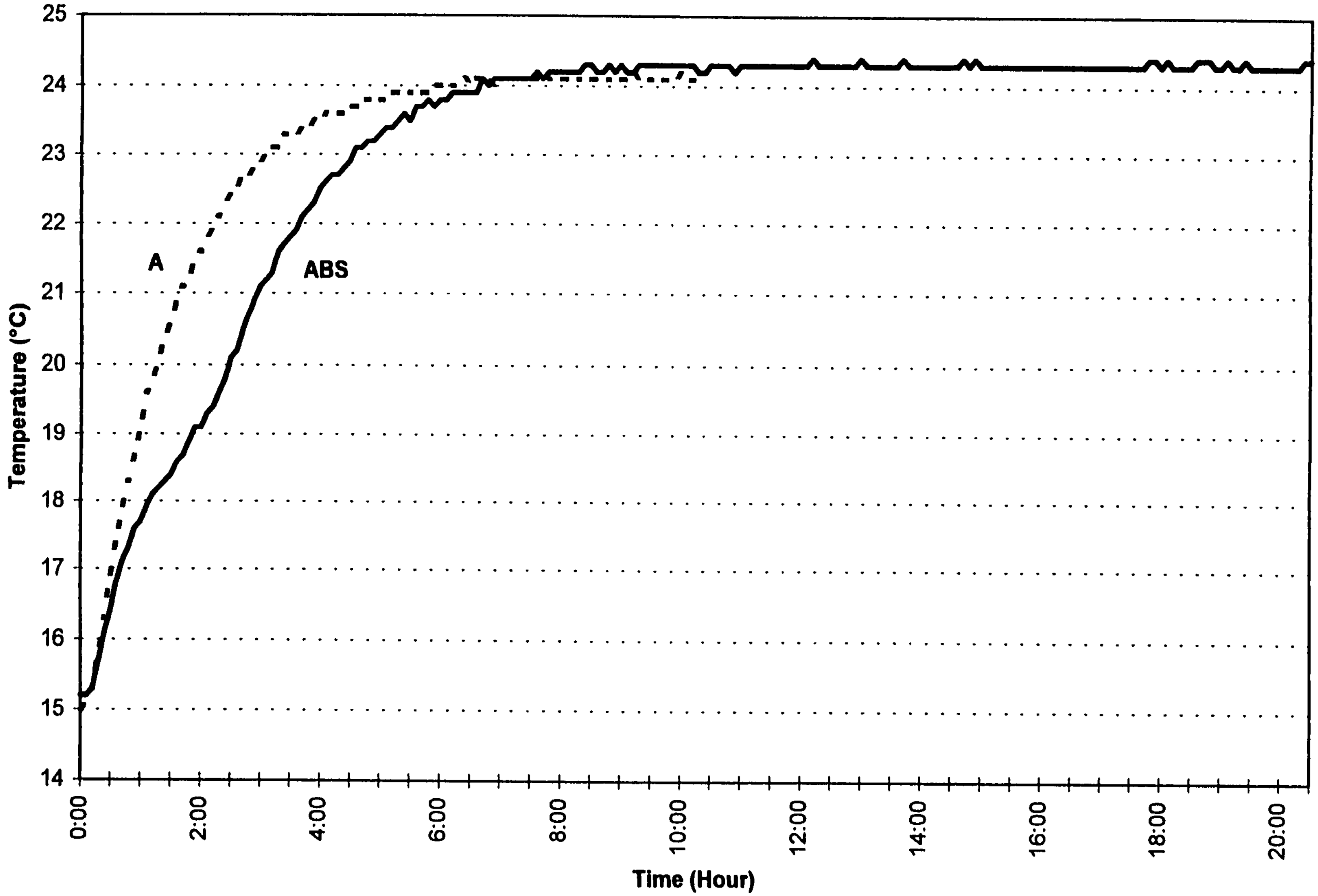


Figure 5.7 Time-temperature curves for unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 7 at 2.5 m/s air flow velocity

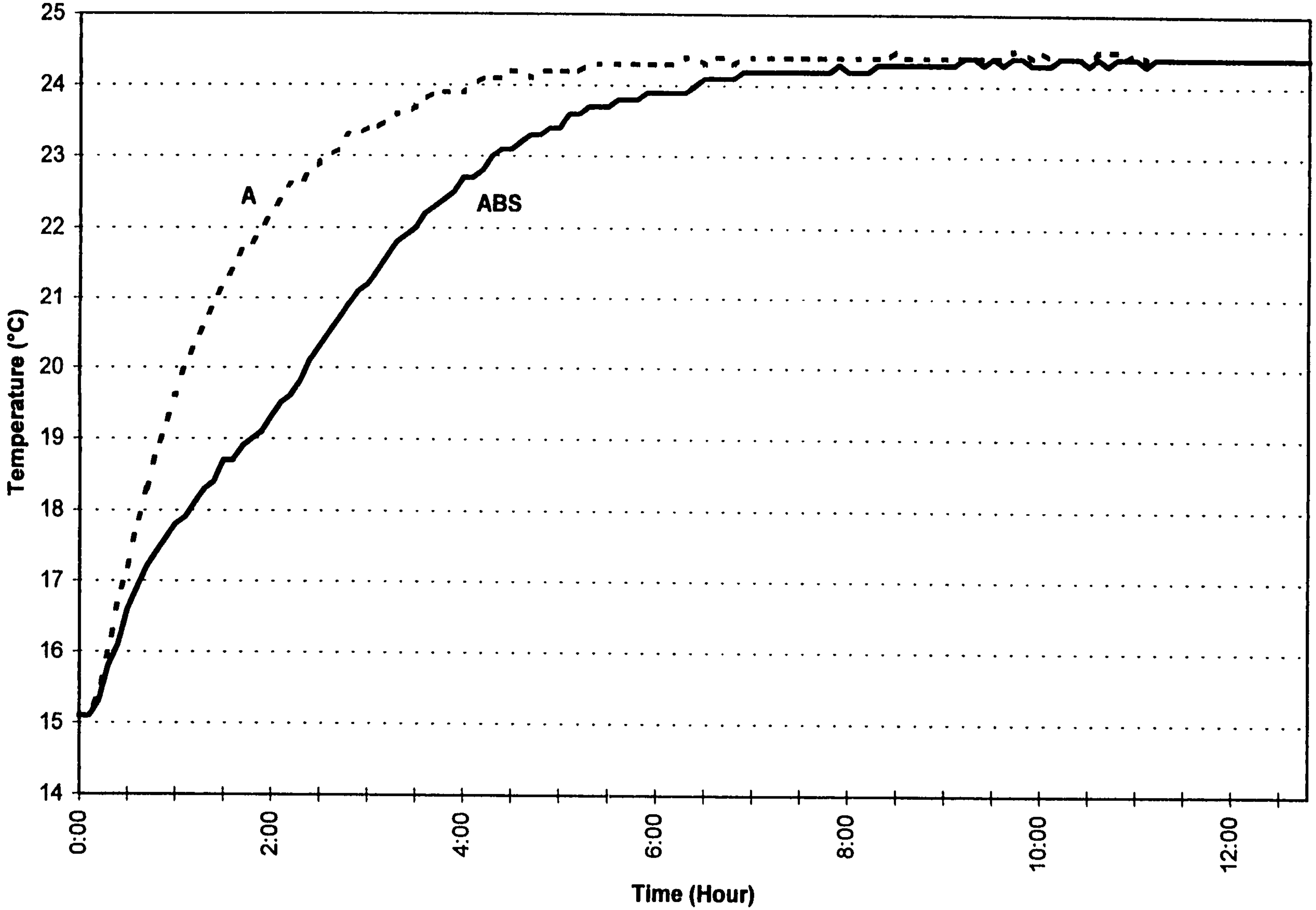


Figure 5.8 Time-temperature curves for unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 7 at 3 m/s air flow velocity

Figure 5.9 Time-temperature curves for the outgoing air from unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 12 at 2 m/s air flow velocity

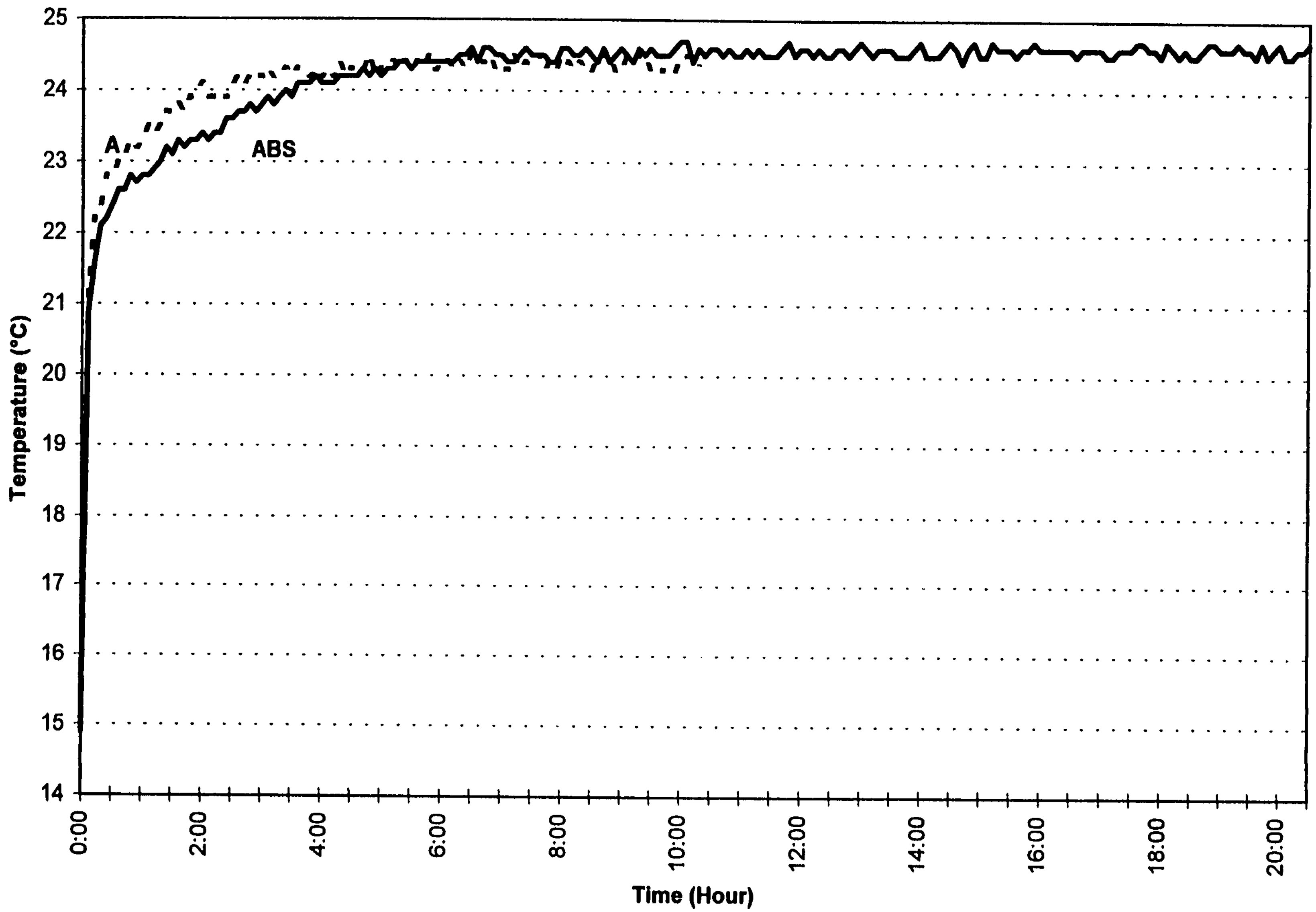


Figure 5.10 Time-temperature curves for the outgoing air from unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 12 at 2.5 m/s air flow velocity

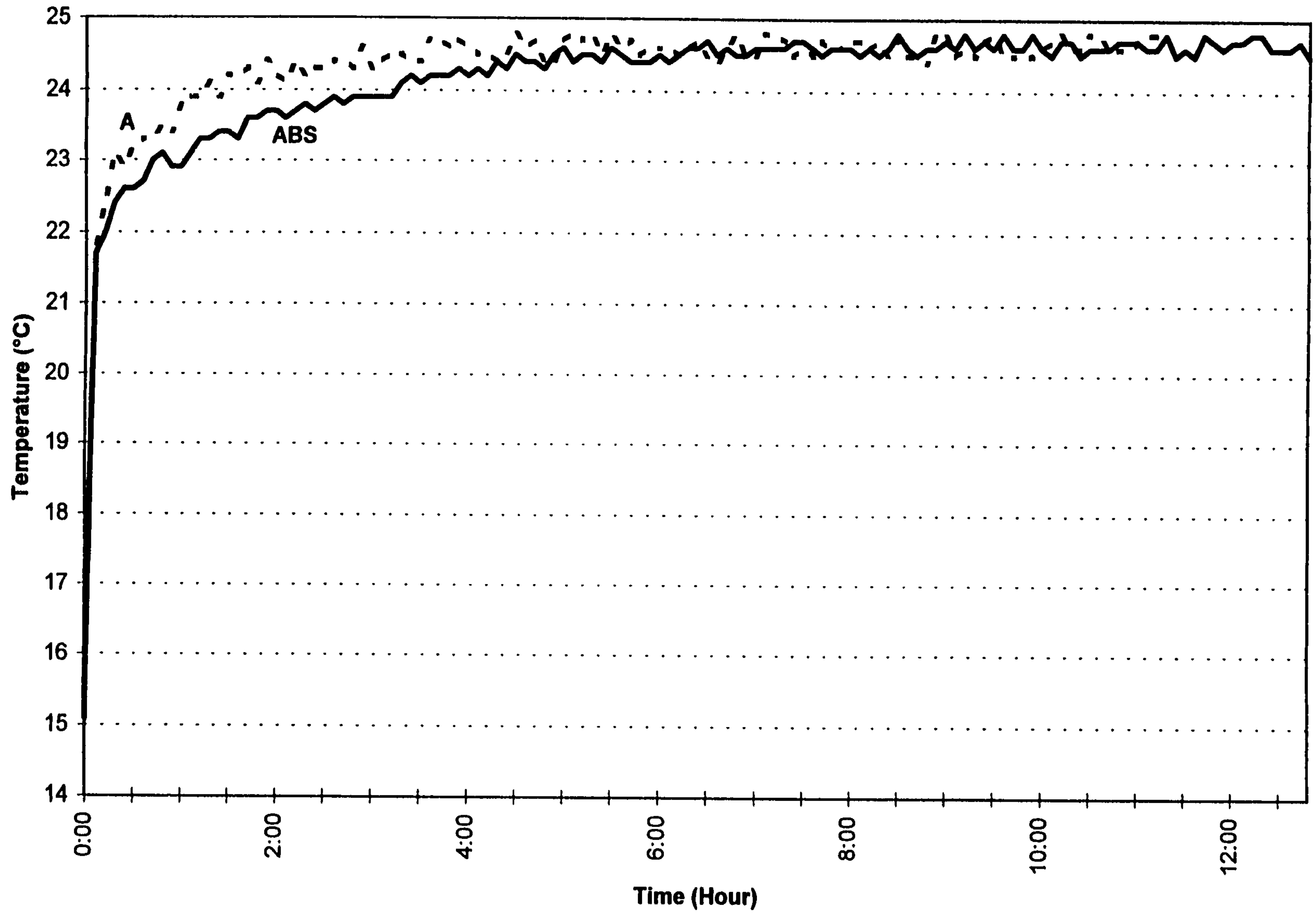


Figure 5.11 Time-temperature curves for the outgoing air from unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 12 at 3 m/s air flow velocity

5.1.2 Autoclaved concrete blocks unimpregnated (A) and impregnated with Paraffin (AP)

The average percentage of Paraffin impregnated in autoclaved concrete blocks was about 8.4 and the air temperature used to heat up the blocks was 60°C from 22°C. In addition, a shorter temperature range (45°C to 60°C) was also evaluated to compare with the aforementioned temperature range (22°C to 60°C).

a). Time comparison:

Figures 5.12 and 5.13 represent the time needed to heat each test block up to the set temperature. It was found that, as expected, the faster air flow required less time to reach the set temperature in both unimpregnated and paraffin impregnated concrete blocks.

Paraffin impregnated blocks had about 1.7 times more heat storage capacity (9244 KJ) than the unimpregnated blocks (5337 KJ), but the time required to charge the impregnated blocks to the upper set temperature was 1.6 times longer (1068 min. to 690 min.).

b). Comparison between upper and bottom parts of the blocks for reaching 60°C:

The variation of heating time for unimpregnated blocks and those impregnated with Paraffin depended on the position of the numbered blocks and the air flow velocities as shown in Figures 5.14, 5.15 and 5.16. It will be seen that, in this case, it took longer time to complete the whole heating process for the twelve PAR impregnated blocks than for the unimpregnated ones. The difference was approximately 9 hours at an air velocity of 2 m/s, 5.6 hours at 2.5 m/s and 4.6 hours at 3 m/s.

c). From Figures 5.17, 5.18 and 5.19, it was observed that PAR impregnated block number 7 took about 21, 18 and 16 hours to charge heat at 2, 2.5 and 3 m/s air flow velocities respectively due to the necessity of melting the PCM. However, for unimpregnated block number 7, it only took about 12, 12 and 11 hours at the same air flow velocities. The time difference between the two sets was due to the latent heat storage.

d). Outgoing air temperature profiles (block number 12):

As shown in Figures 5.20, 5.21 and 5.22, equilibrium is attained earlier as the air velocity is increased. However, it is also evident that the heat charging process will require a higher air velocity so that this cycle may be completed in eight hours or less. This problem may also be reduced by a change in the air flow distribution through the blocks. It is evident that further study will be required to ascertain the best technic or combination of technics required to effect the desired result.

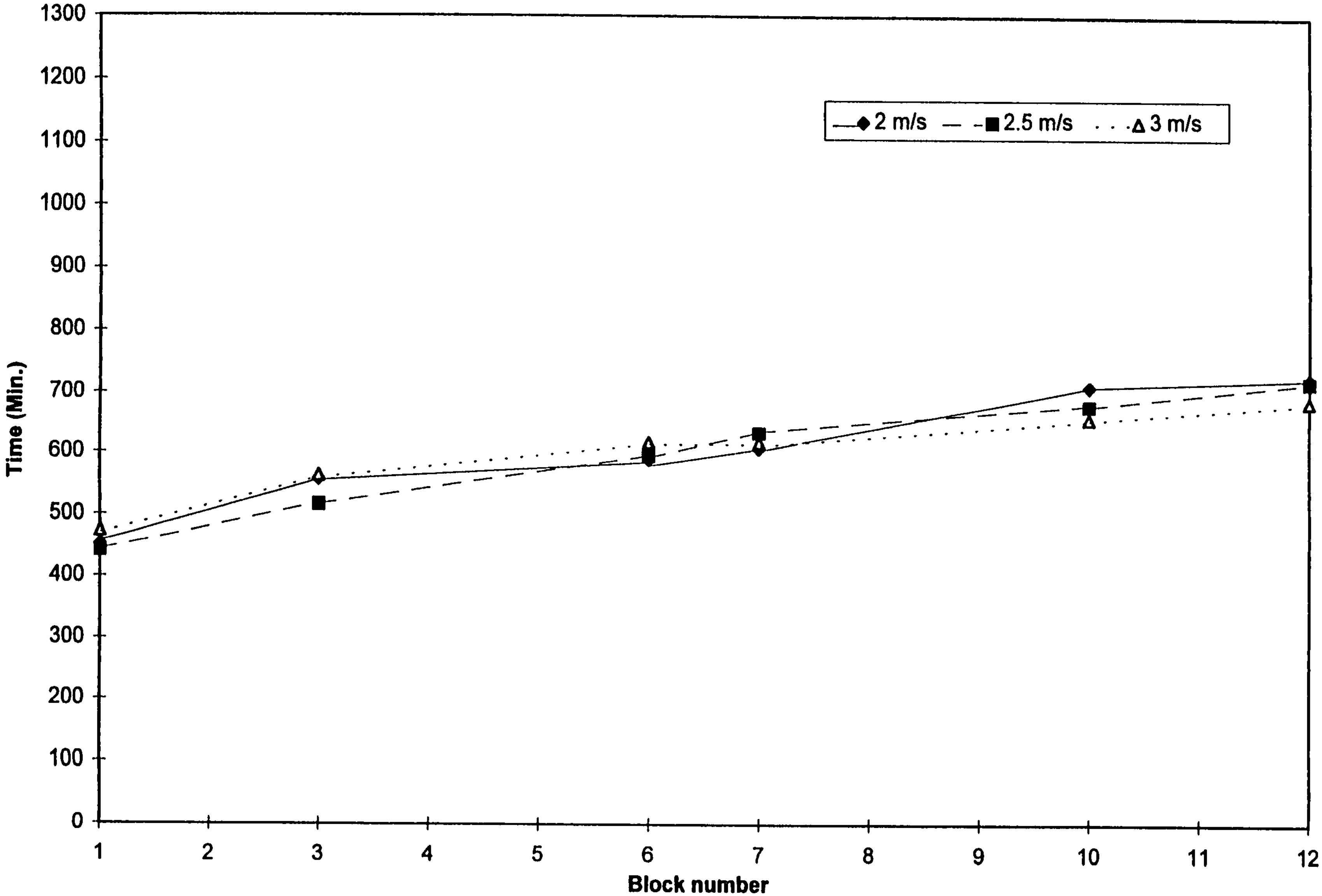


Figure 5.12 Time required for heating unimpregnated autoclaved blocks (A) from 22°C to 60°C at different air flow velocities [A - Heating - Bottom]

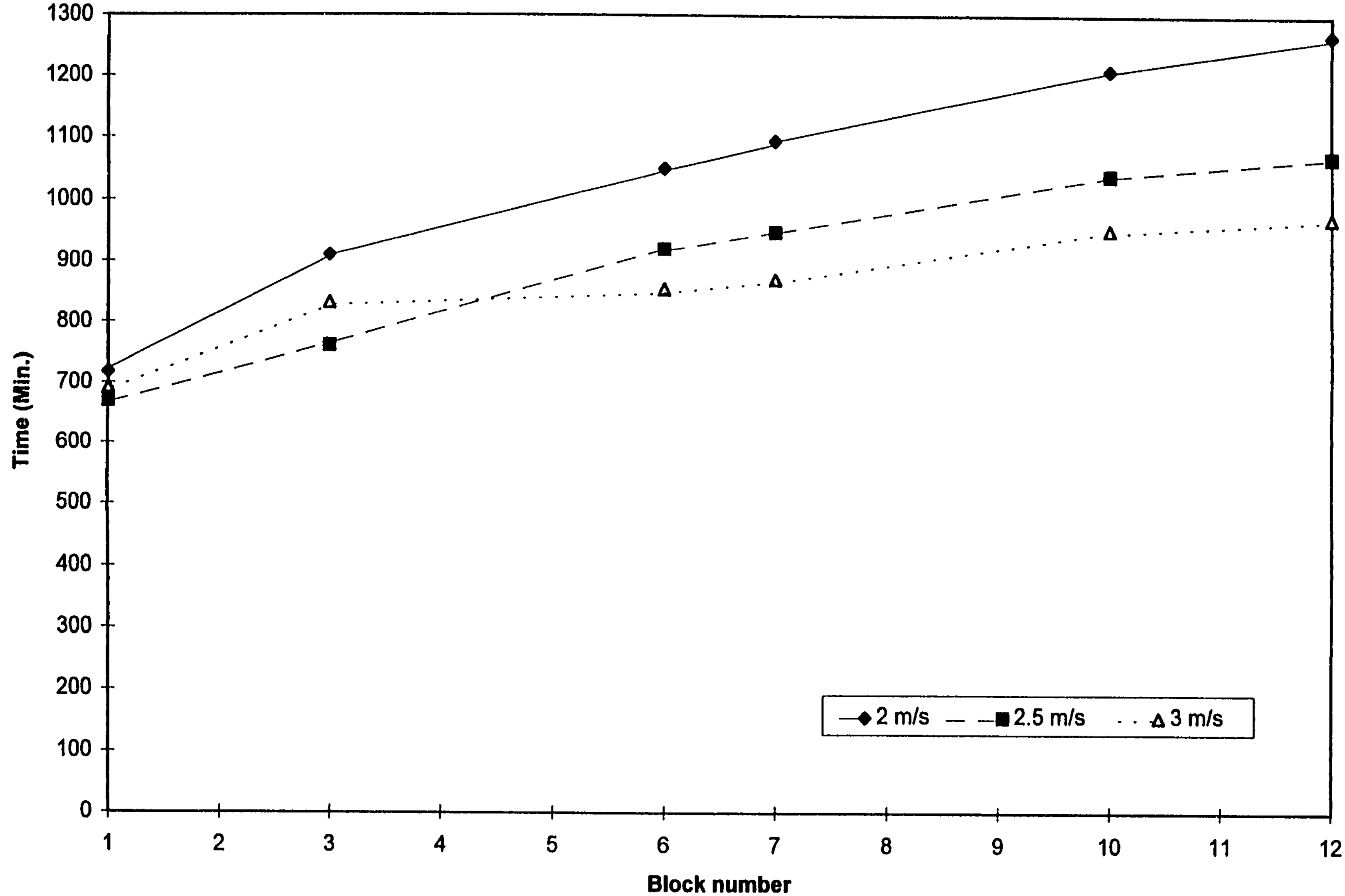


Figure 5.13 Time required for heating PAR impregnated autoclaved blocks (AP) from 22°C to 60°C at different air flow velocities [AP - Heating - Bottom]

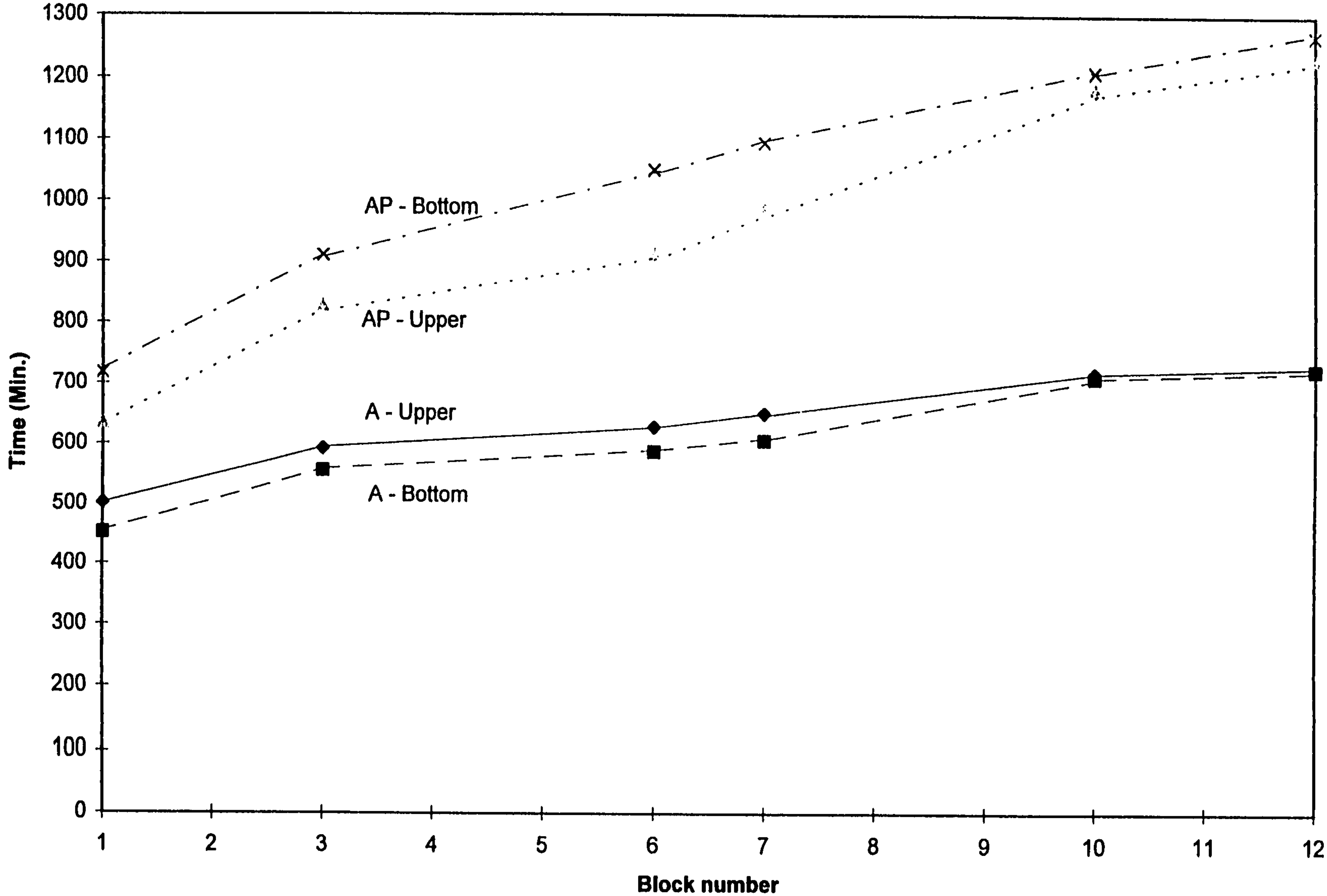


Figure 5.14 Comparison between the time required for heating unimpregnated (A) and Paraffin impregnated (AP) autoclaved blocks from 22°C to 60°C at 2 m/s air flow velocity

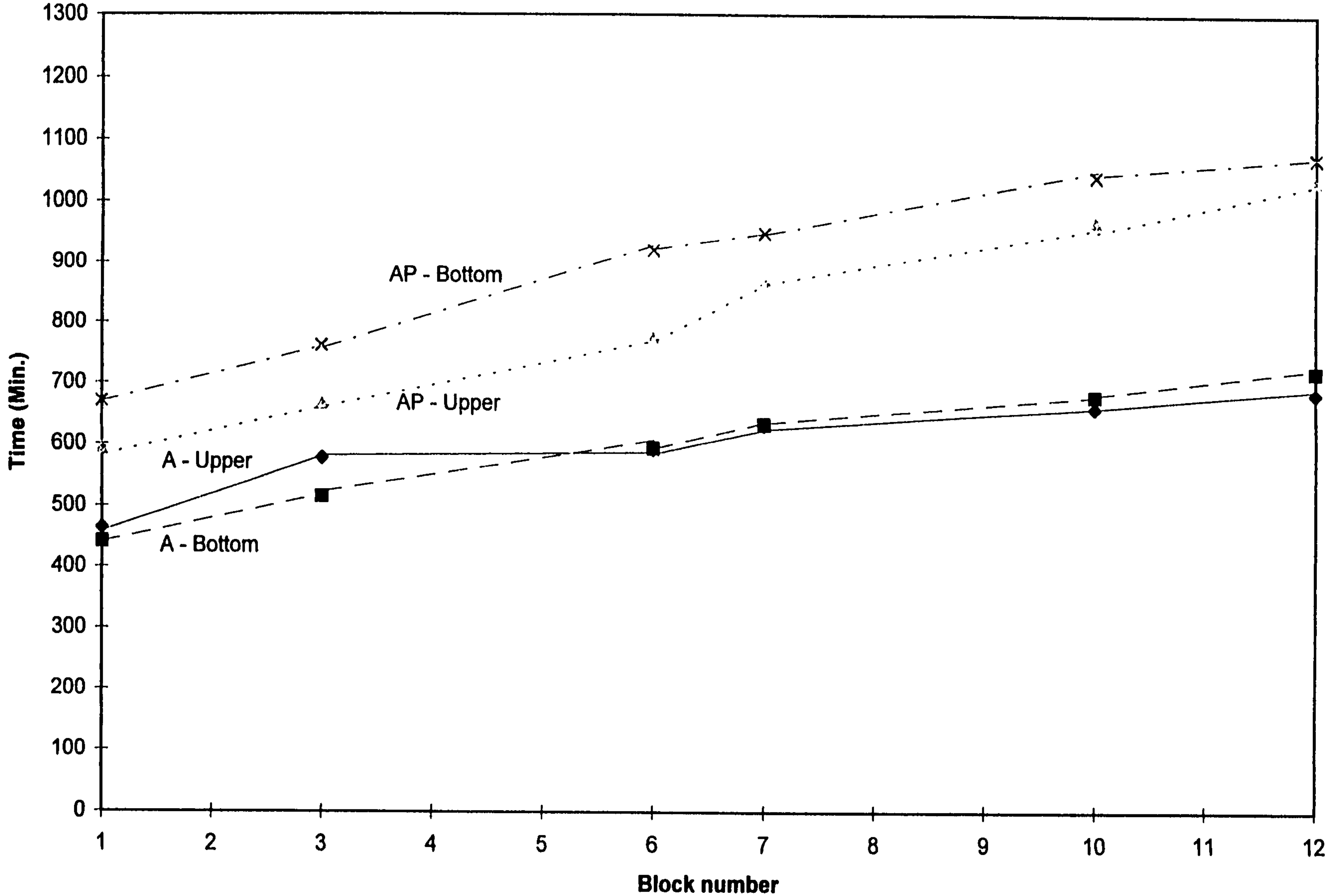


Figure 5.15 Comparison between the time required for heating unimpregnated (A) and Paraffin impregnated (AP) autoclaved blocks from 22°C to 60°C at 2.5 m/s air flow velocity

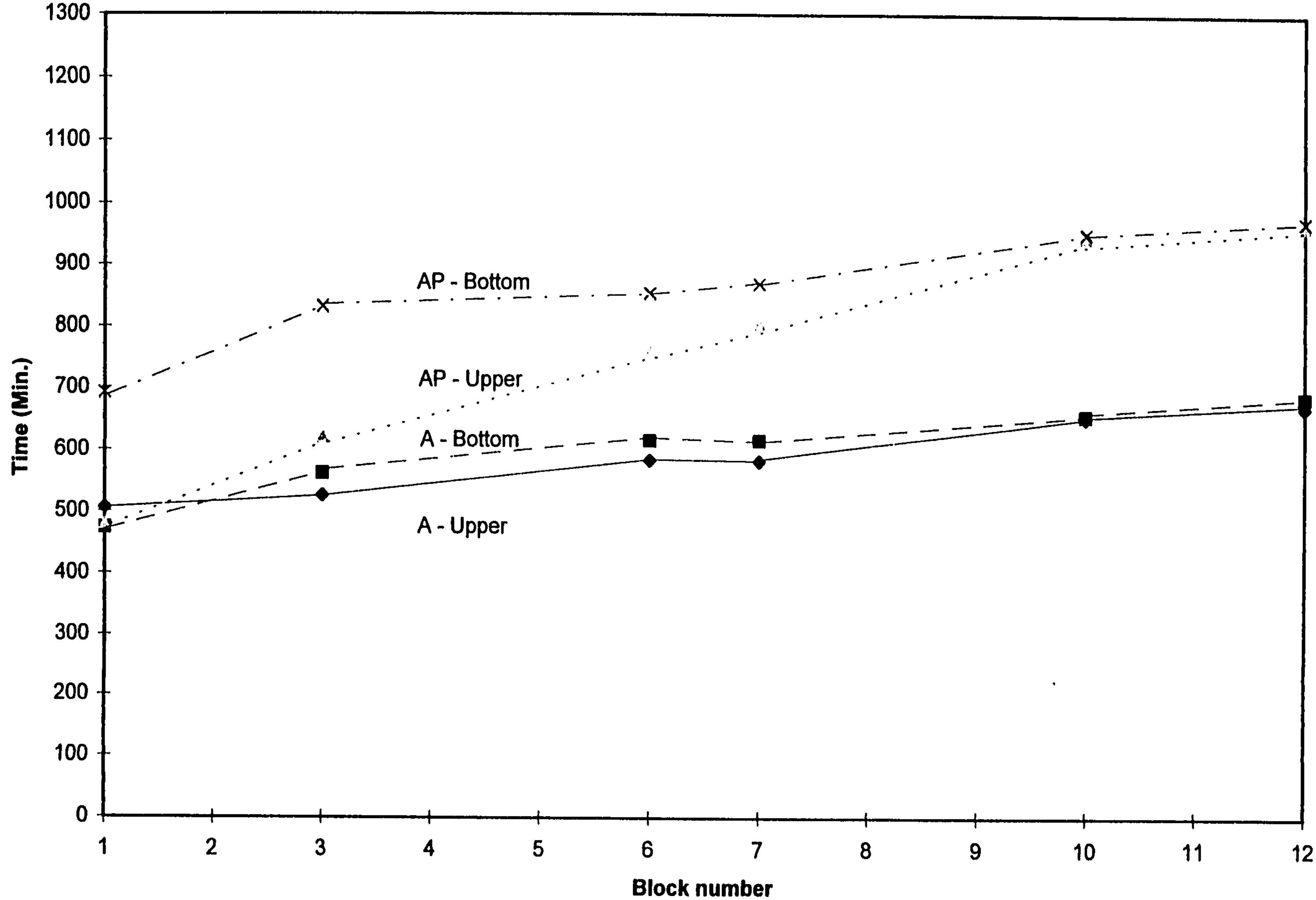


Figure 5.16 Comparison between the time required for heating unimpregnated (A) and Paraffin impregnated (AP) autoclaved blocks from 22°C to 60°C at 3 m/s air flow velocity

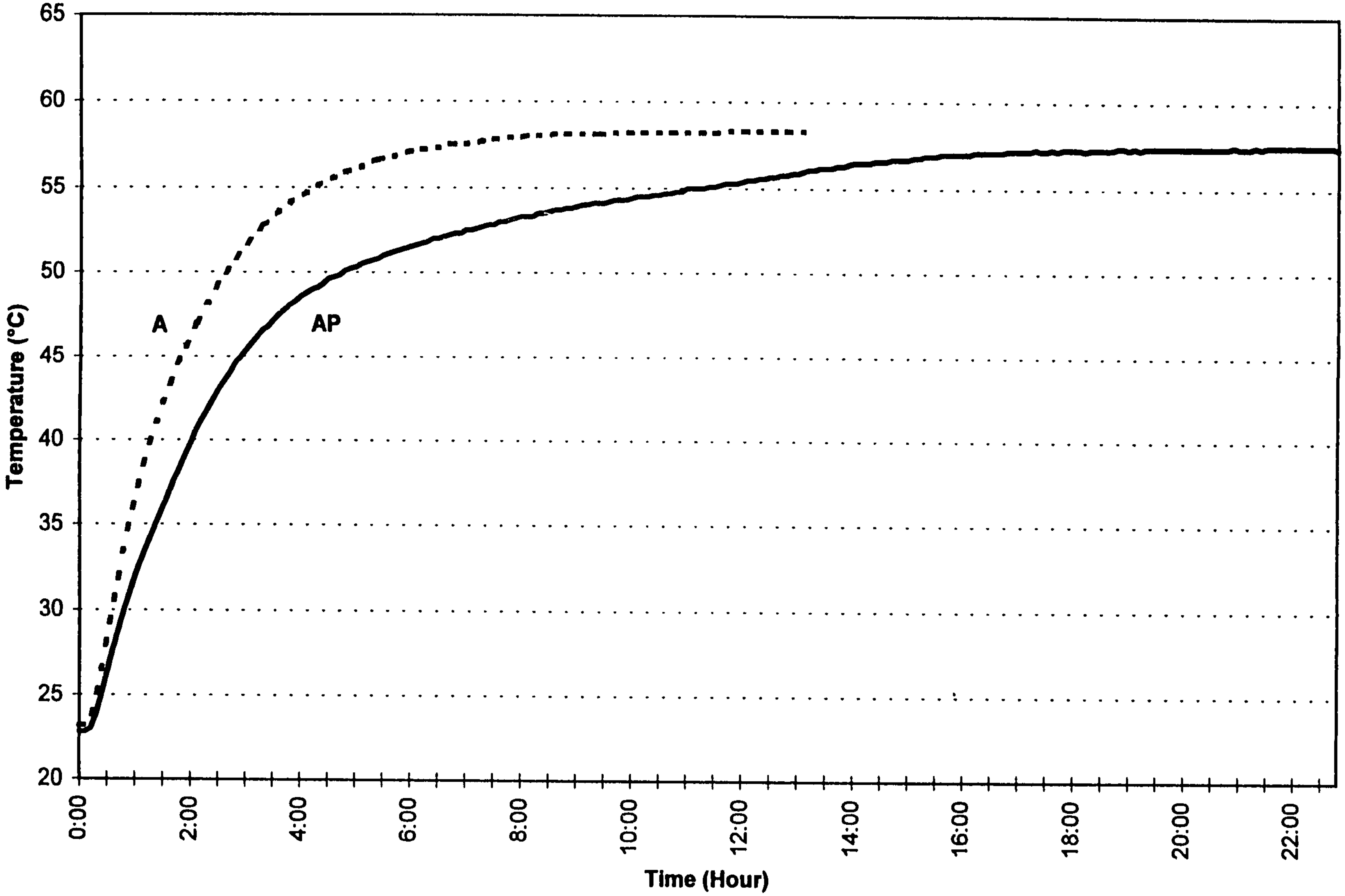


Figure 5.17 Time-temperature curves for unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 7 at 2 m/s air flow velocity

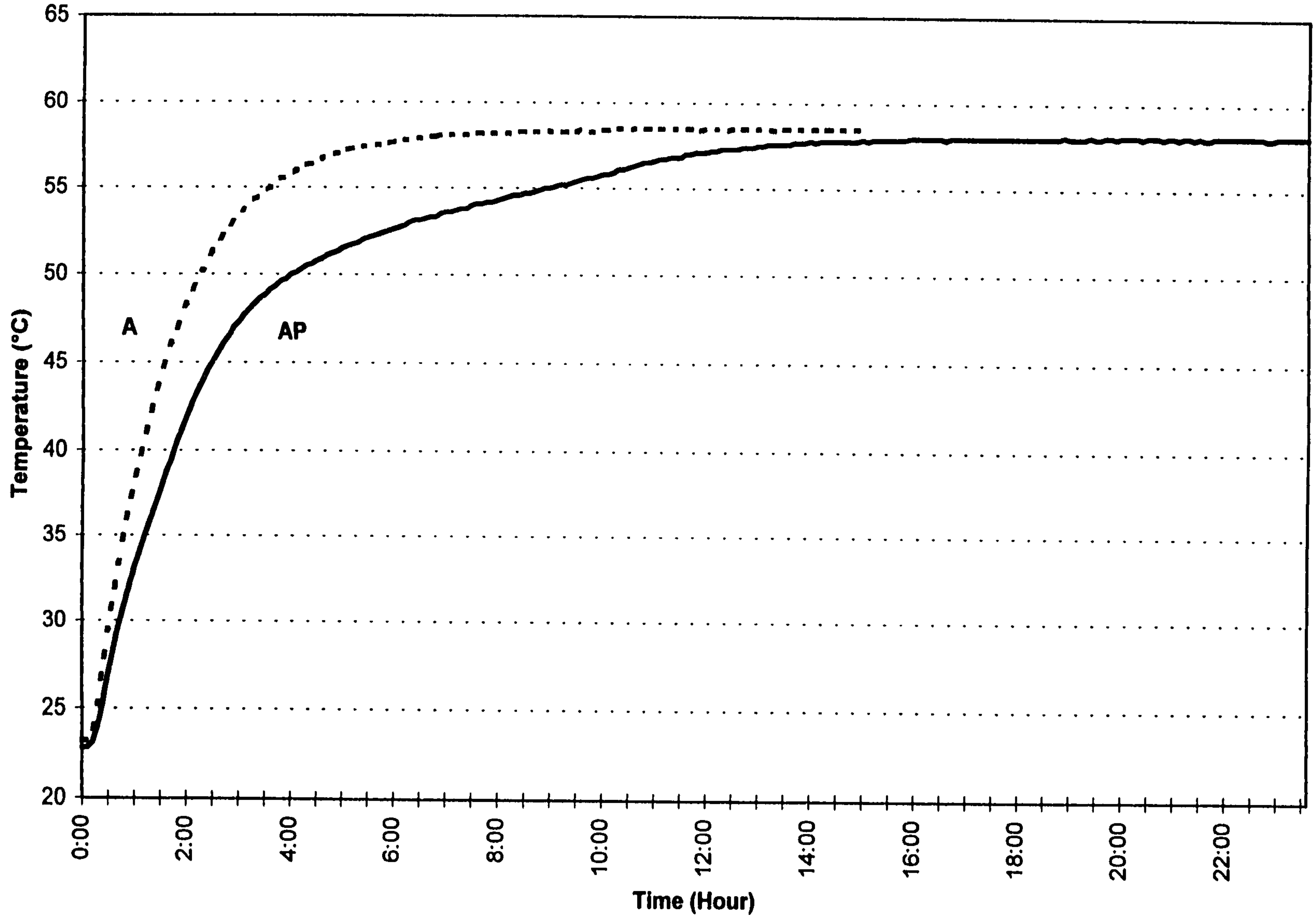


Figure 5.18 Time-temperature curves for unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 7 at 2.5 m/s air flow velocity

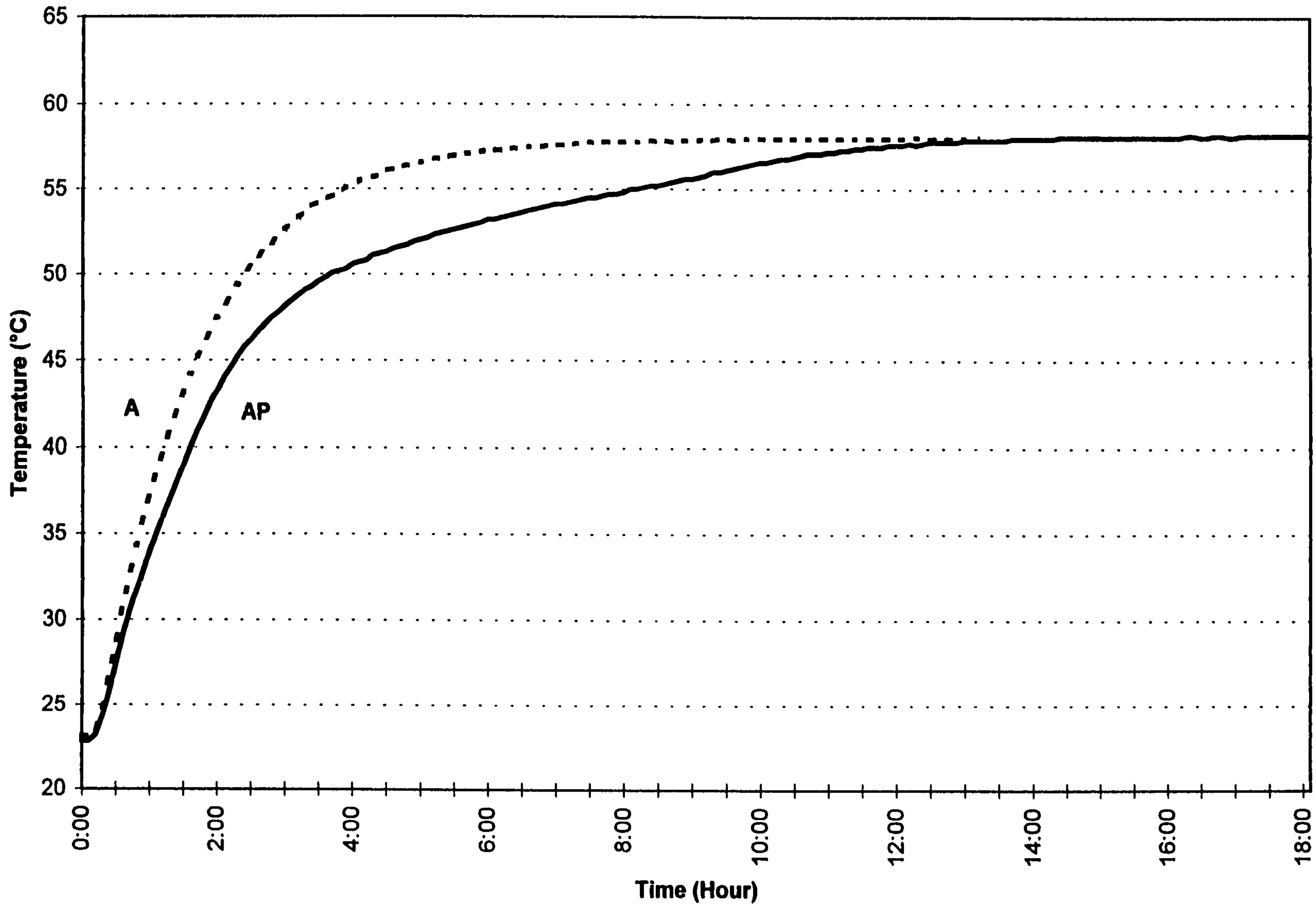


Figure 5.19 Time-temperature curves for unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 7 at 3 m/s air flow velocity

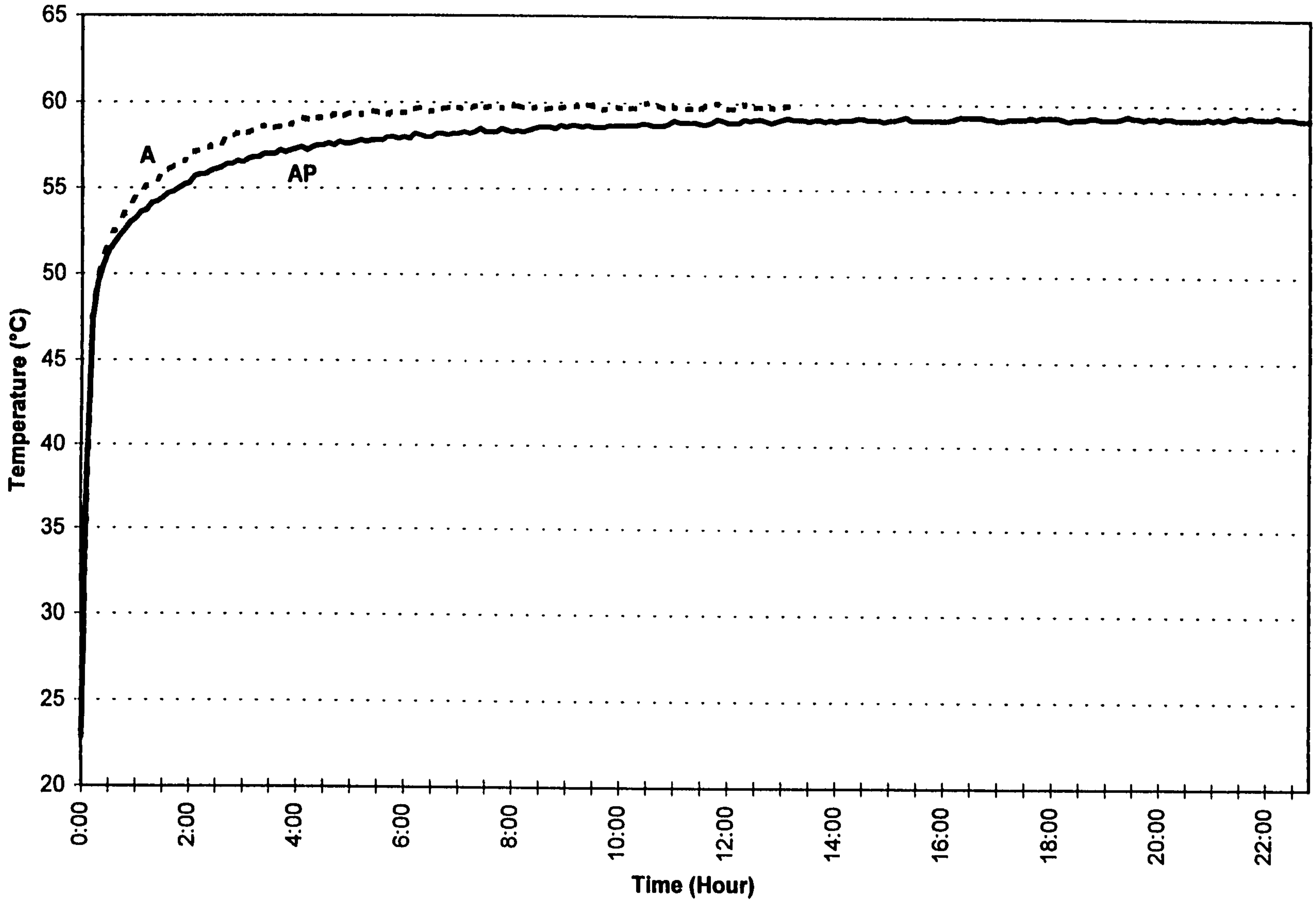


Figure 5.20 Time-temperature curves for the outgoing air from unimpregnated (A) and Butyl Stearate impregnated (AP) autoclaved block number 12 at 2 m/s air flow velocity

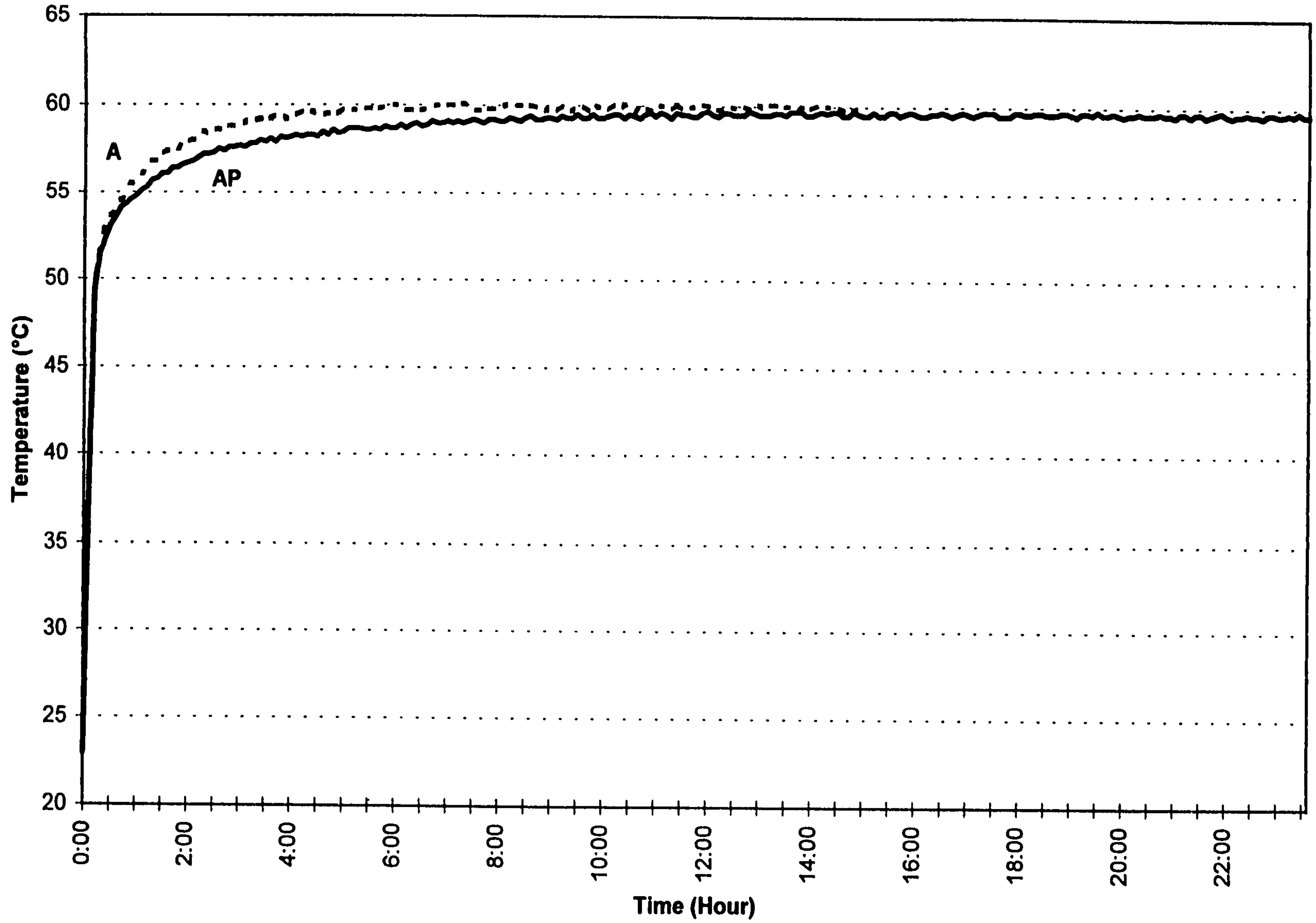


Figure 5.21 Time-temperature curves for the outgoing air from unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 12 at 2.5 m/s air flow velocity

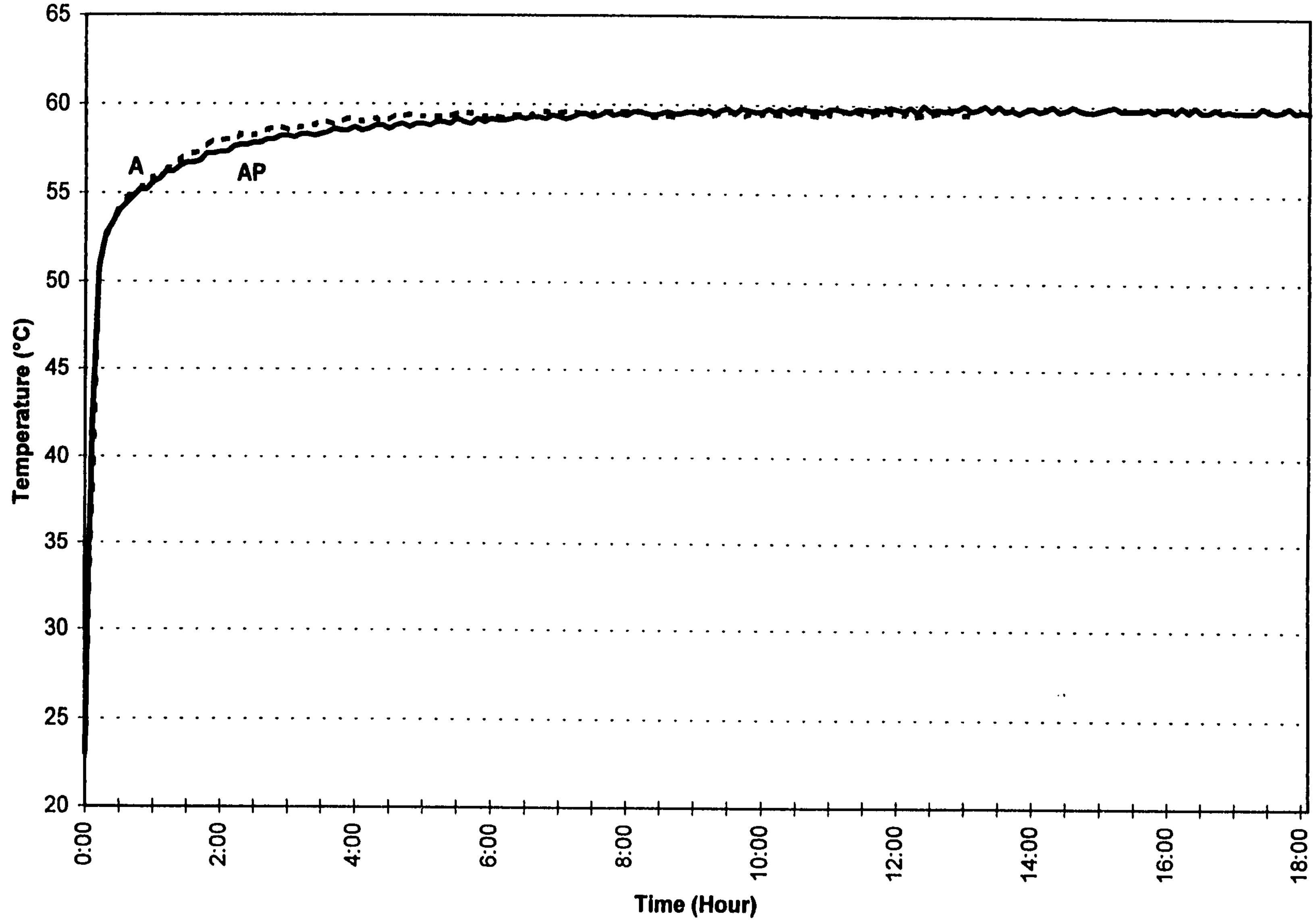


Figure 5.22 Time-temperature curves for the outgoing air from unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 12 at 3 m/s air flow velocity

5.1.3 Regular concrete blocks unimpregnated (R) and impregnated with Paraffin (RP)

The average percentage of paraffin impregnated regular blocks was about 3.9 and the operating air temperature is 60°C to heat up concrete blocks up from 45°C.

a). Figures 5.23 and 5.24 represent the time needed to charge heat into each block to the set temperature. As in the former case, it can be found that at faster air flow velocity less time is necessary to reach the set temperature in both unimpregnated and impregnated concrete blocks. Paraffin impregnated regular blocks (4510 KJ) store 1.5 times more heat than unimpregnated blocks (2941 KJ). However, these impregnated blocks also need about 1.3 times longer time (792 min. to 579 min.) to complete the heating mode.

b). Comparison between upper and bottom parts of the blocks:

The heating time for blocks unimpregnated and impregnated with Paraffin depended on the position in the tunnel (i.e. the block number) and the air flow velocity, as shown in Figures 5.25, 5.26 and 5.27. It seems that even RP blocks (conductivity=0.8384 W/m×°C) possess higher conductivity than AP blocks (conductivity=0.549 W/m×°C), they still exceed the designated charging time (8 hours). The possible solutions are increasing the air flow velocity or heat transfer surface areas.

c). Figures 5.28, 5.29 and 5.30 show that for Paraffin impregnated regular blocks took about 15, 14 and 13 hours at 2, 2.5 and 3 m/s air flow velocities respectively to charge heat. However, for unimpregnated concrete blocks, it takes only about 11, 10 and 10 hours at the same air flow velocities. This is an average of 3.5 hours longer. For the same Figures, we noticed that PAR impregnated blocks presented up to 4°C lower temperature during the first 8 hours of the process. In addition, the temperature-time rate of the R blocks decreased drastically with the decreasing air temperature difference between the air and block surface. The RP block number 7 presents steady lower surface temperature for a longer period of time. This is because both sensible and latent heat were stored.

d). Outgoing air temperature profiles (block number 12):

No significant differences were found at various air flow velocities, as shown in Figures 5.31, 5.32 and 5.33. The difference between these results and those shown in the Figures 5.20, 5.21 and 5.22 for the autoclaved block number 12 is attributable to the greater amount of PCM in the impregnated autoclaved block than in the impregnated regular one.

e). As in the case of autoclaved blocks, an increase in air velocity or better means of air distribution through the blocks will be required so that the heat charging cycle can be completed within the desired time limits.

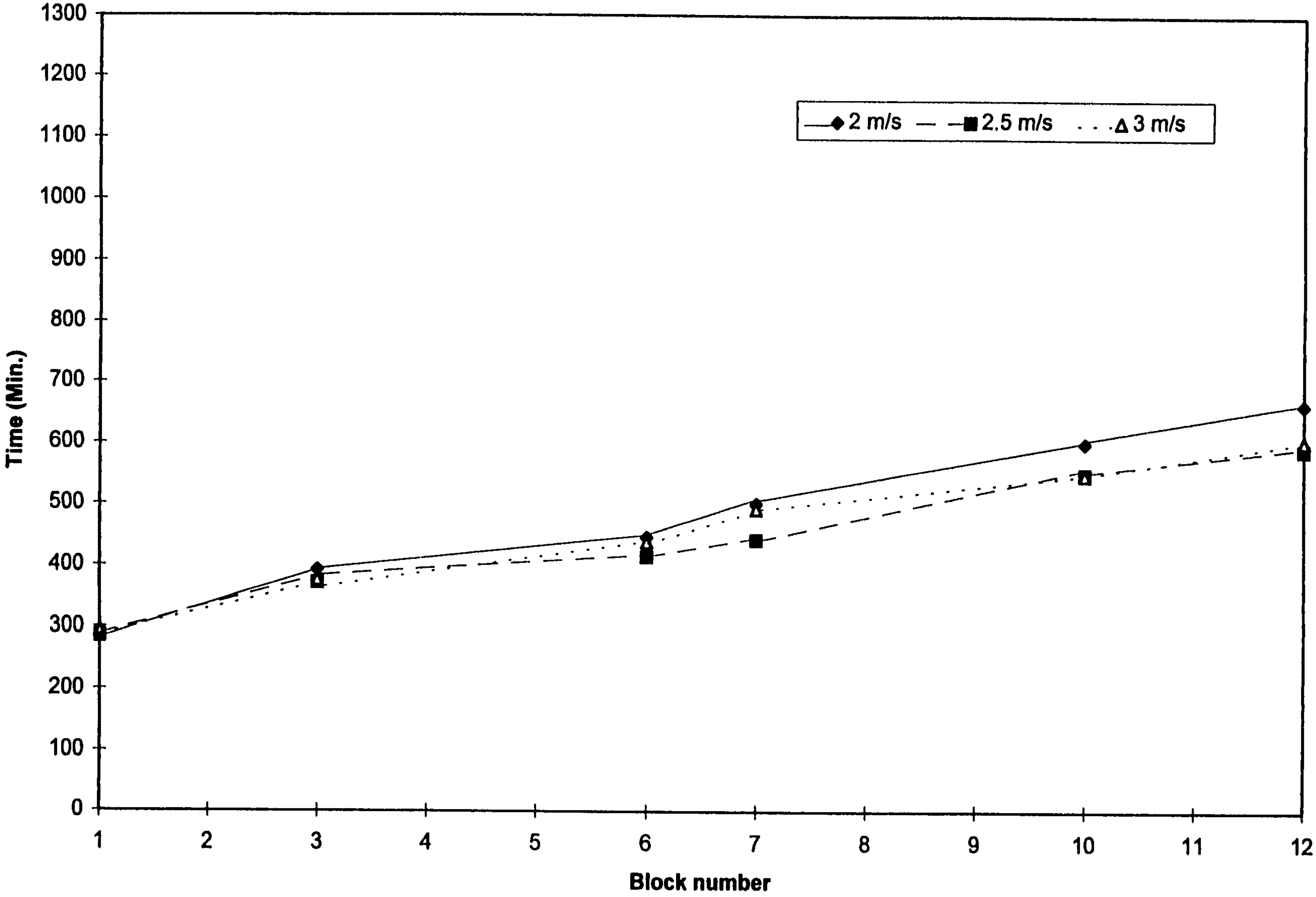


Figure 5.23 Time required for heating unimpregnated regular blocks from 45°C to 60°C at different air flow velocities [R - Heating - Bottom]

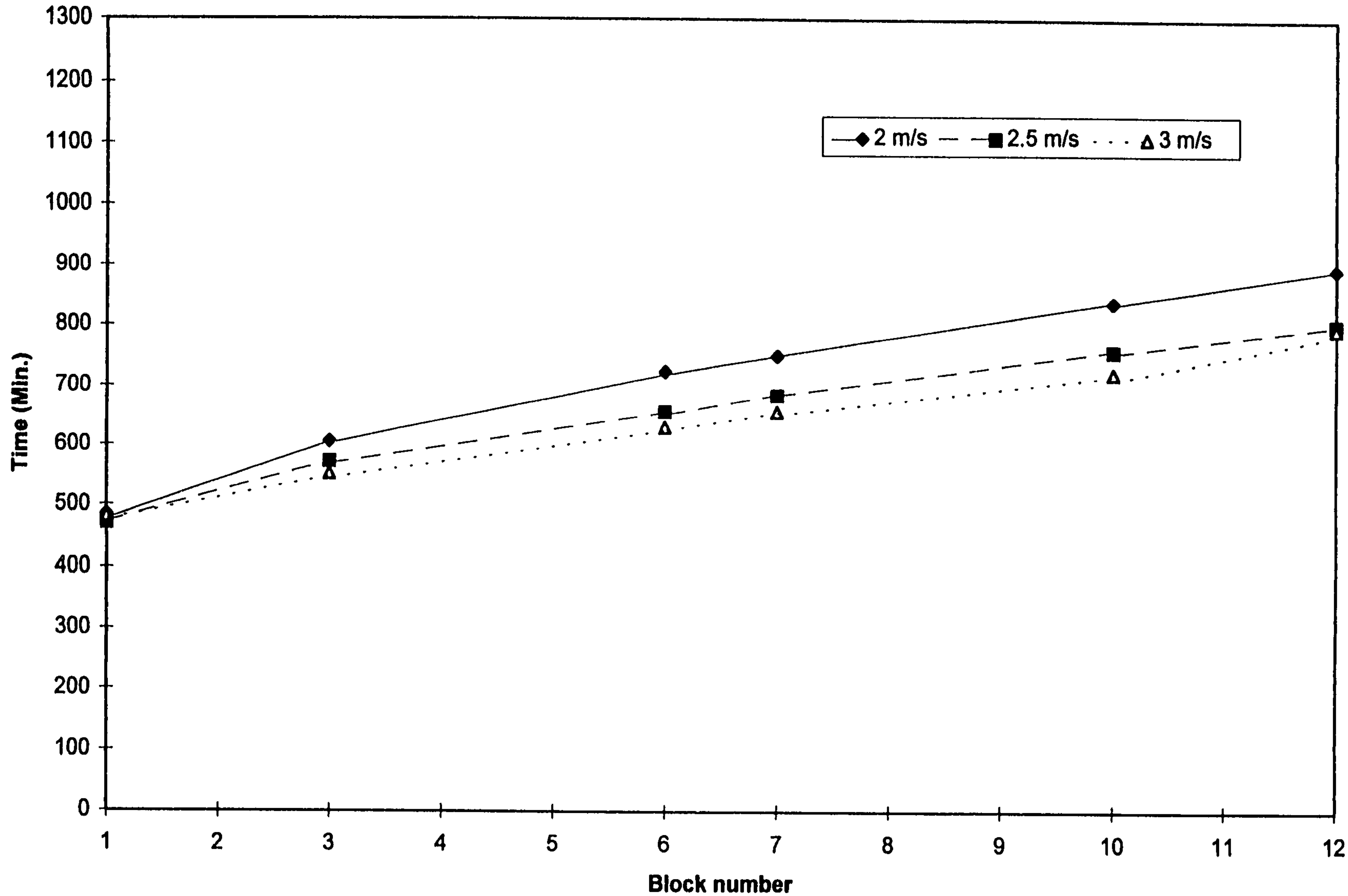


Figure 5.24 Time required for heating PAR impregnated regular blocks from 45°C to reach 60°C at different air flow velocities [RP - Heating - Bottom]

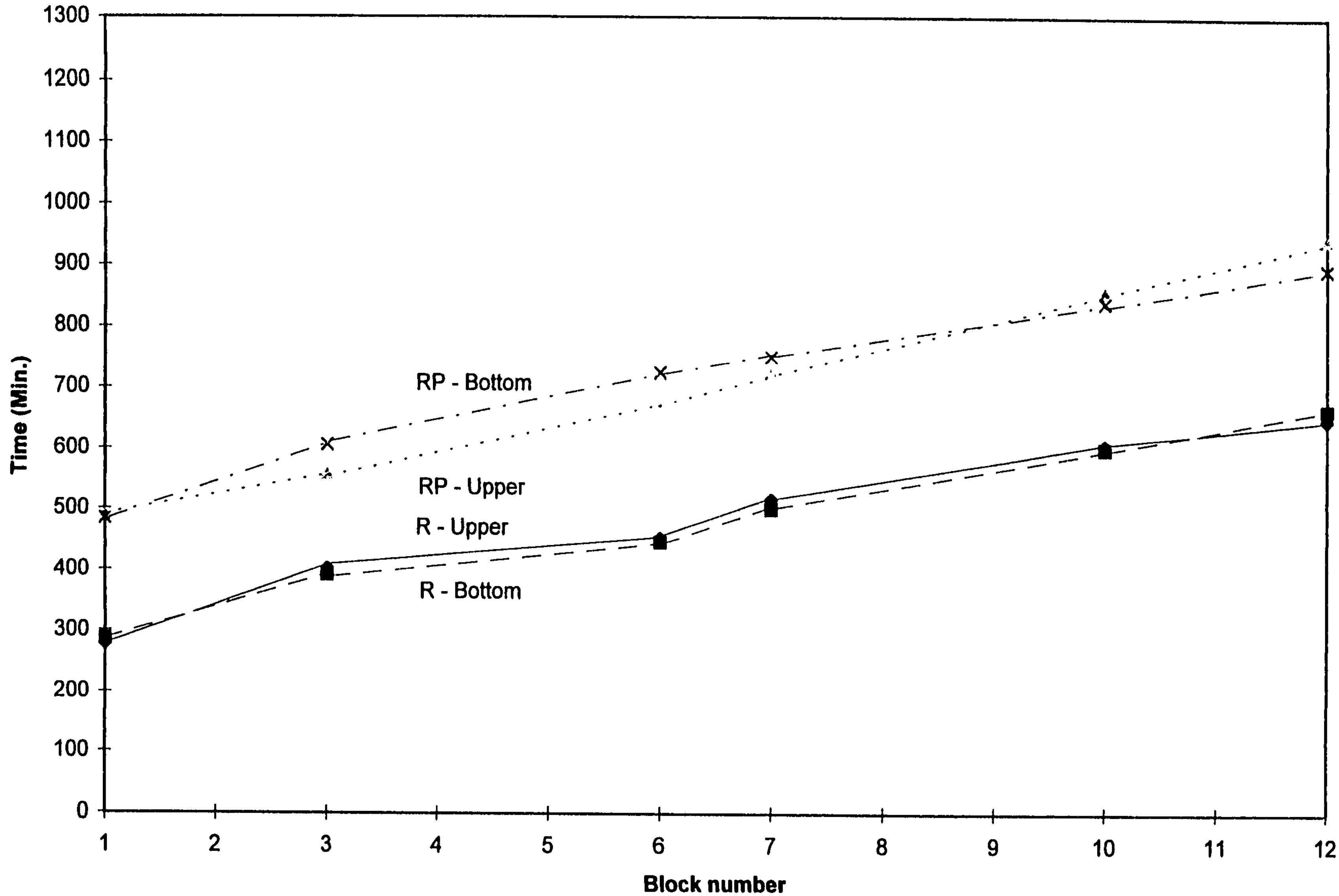


Figure 5.25 Comparison between the time required for heating unimpregnated (R) and Paraffin impregnated (RP) regular blocks from 45°C to 60°C at 2 m/s air flow velocity

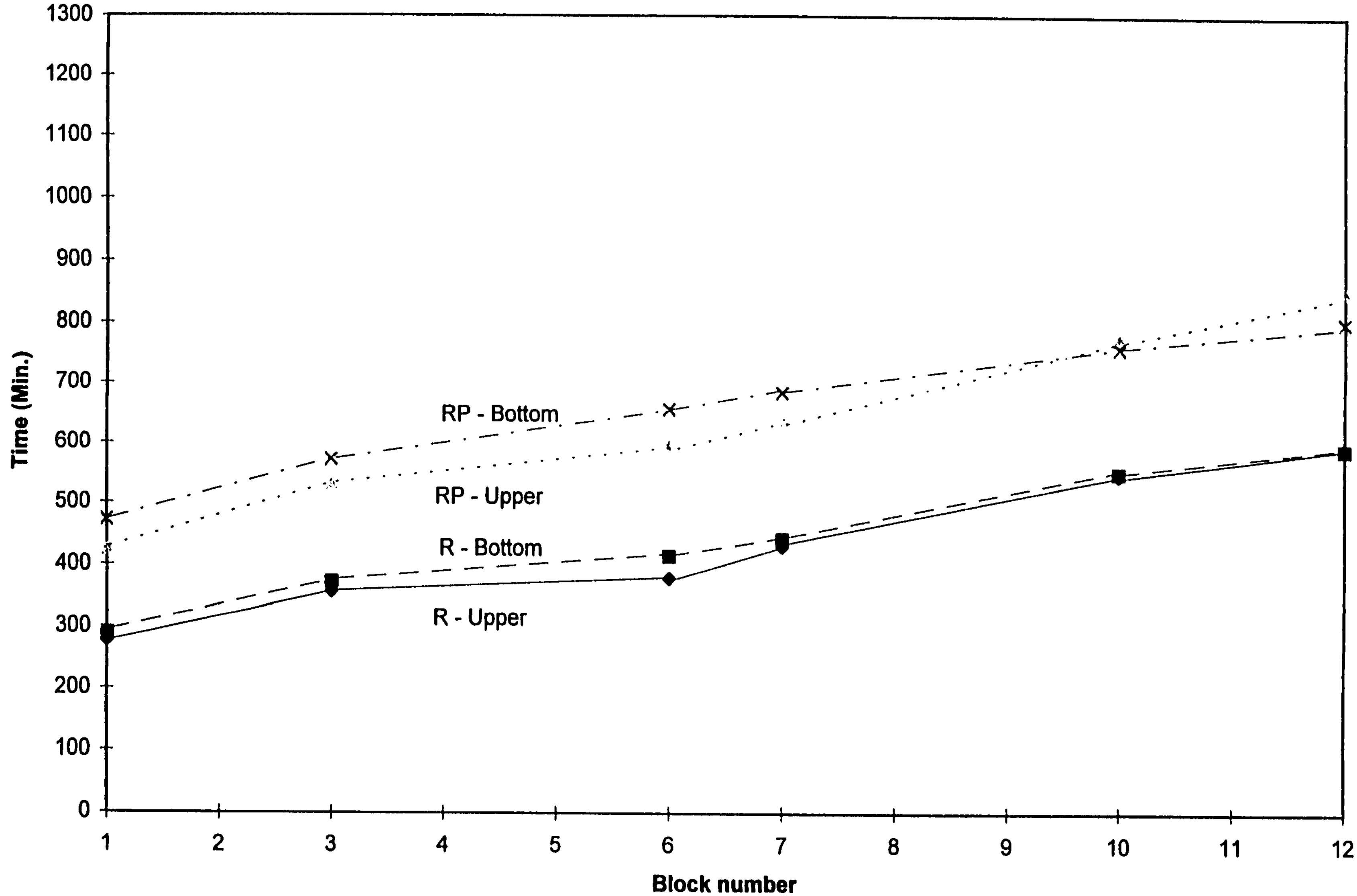


Figure 5.26 Comparison between the time required for heating unimpregnated (R) and Paraffin impregnated (RP) regular blocks from 45°C to 60°C at 2.5 m/s air flow velocity

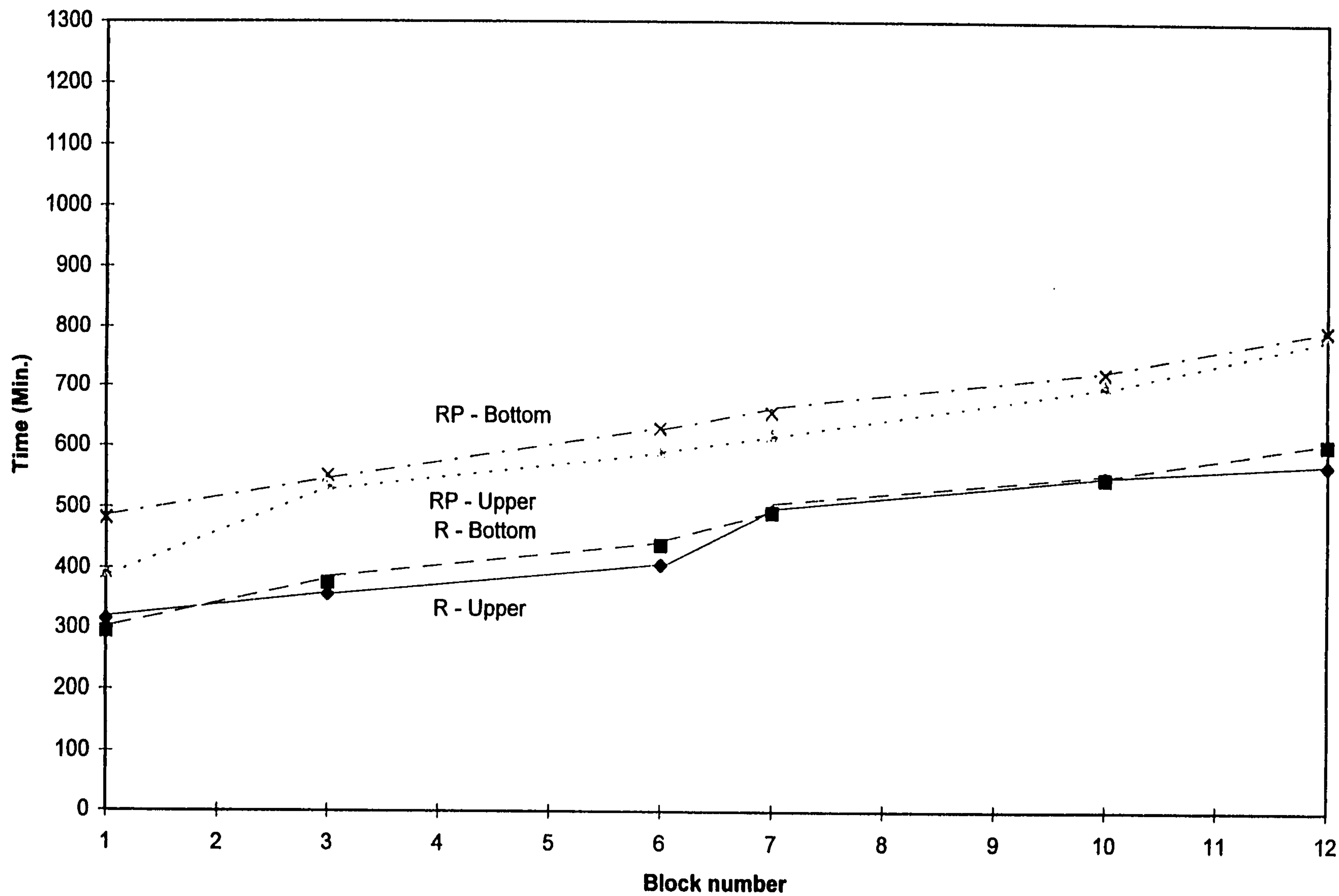


Figure 5.27 Comparison between the time required for heating unimpregnated (R) and Paraffin impregnated (RP) regular blocks from 45°C to 60°C at 3 m/s air flow velocity

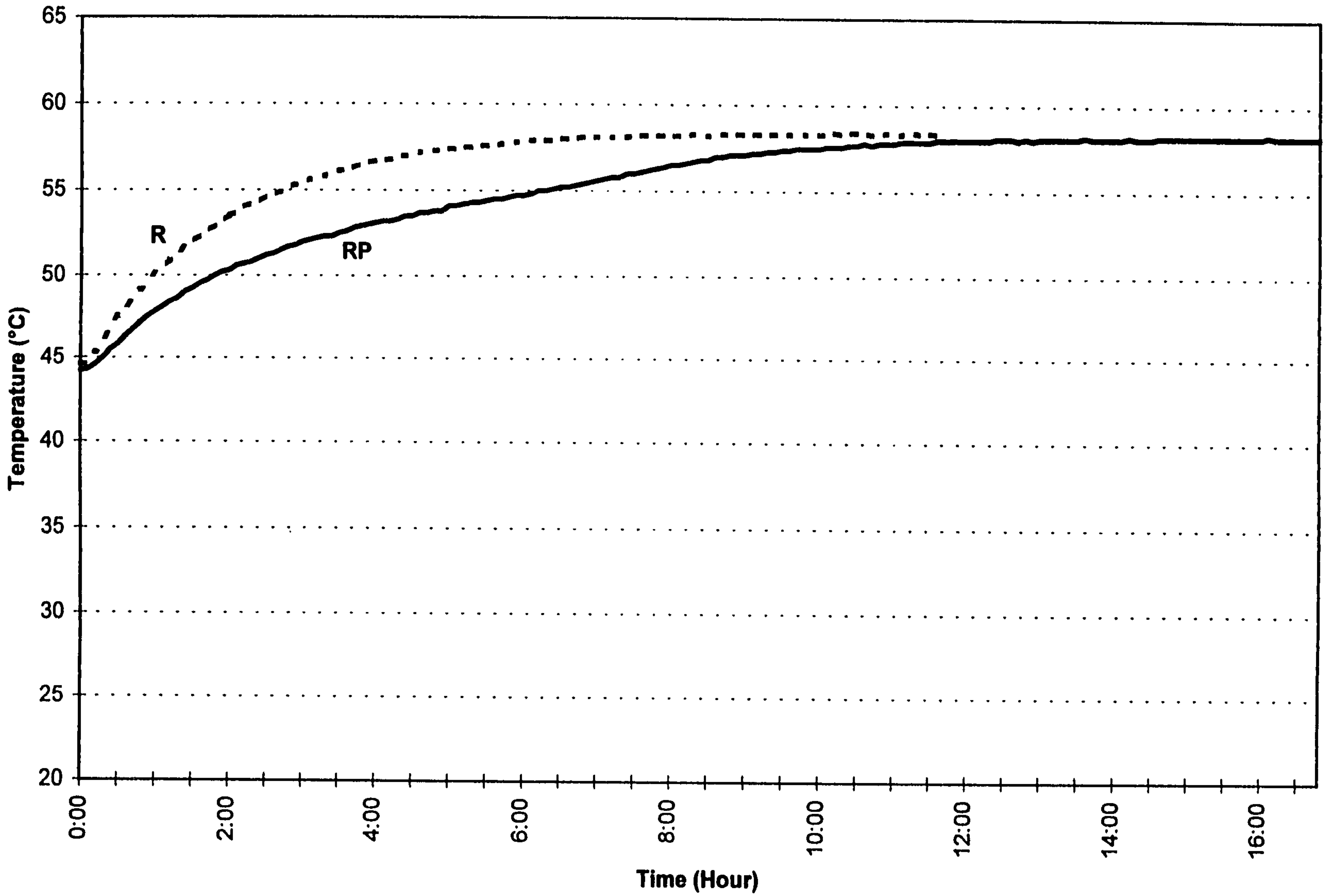


Figure 5.28 Time-temperature curves for unimpregnated (R) and Paraffin impregnated (RP) regular block number 7 at 2 m/s air flow velocity

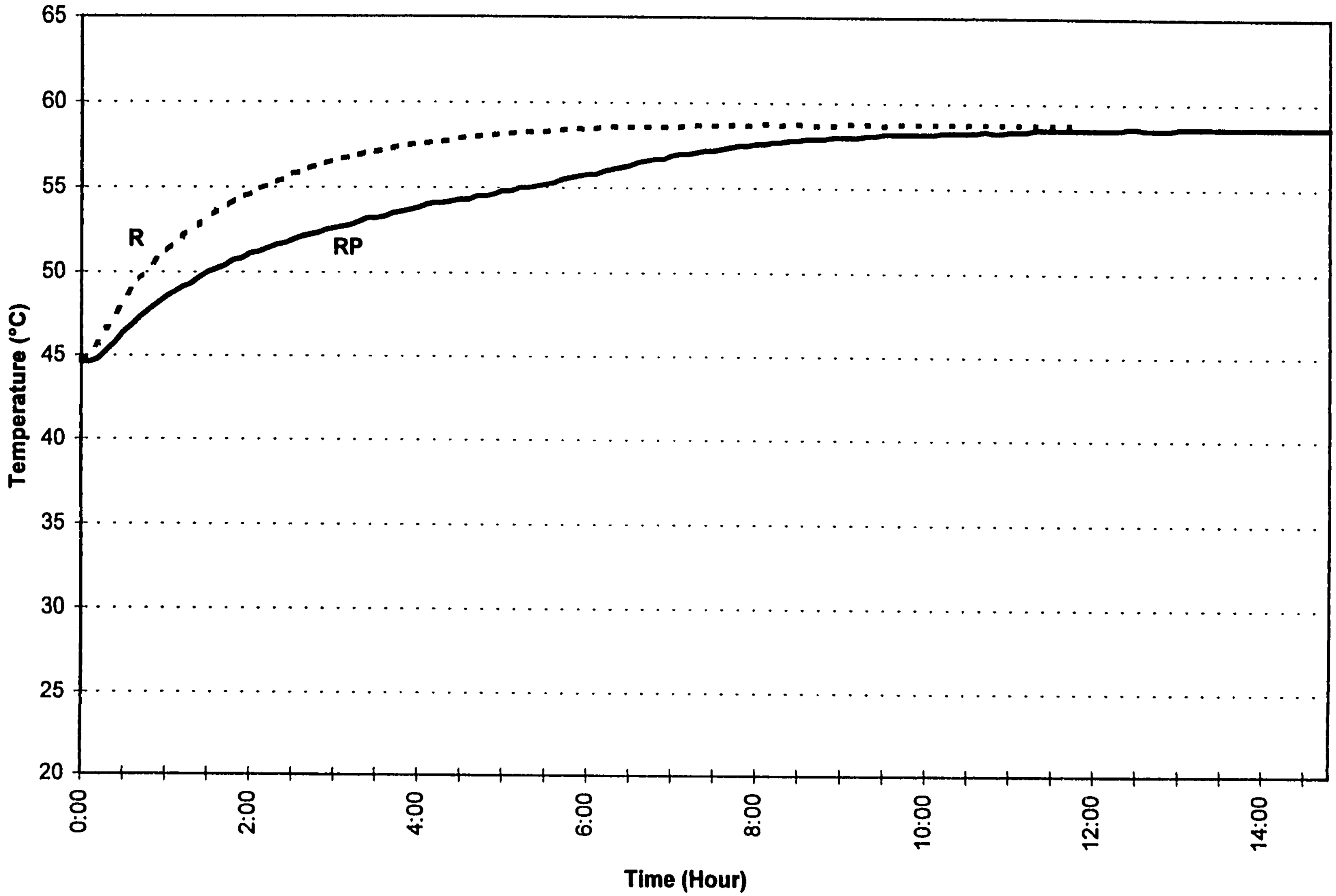


Figure 5.29 Time-temperature curves for unimpregnated (R) and Paraffin impregnated (RP) regular block number 7 at 2.5 m/s air flow velocity

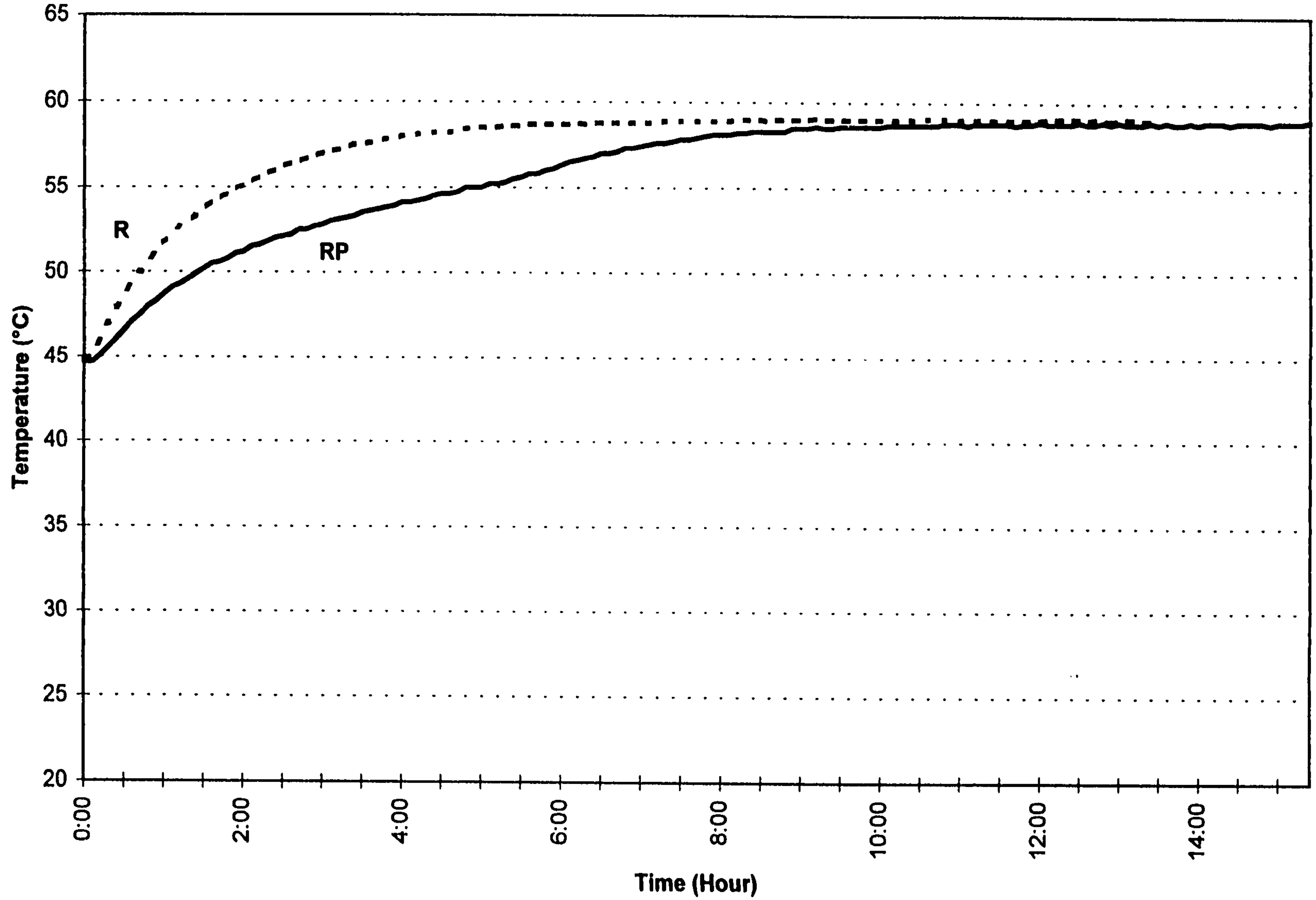


Figure 5.30 Time-temperature curves for unimpregnated (R) and Paraffin impregnated (RP) regular block number 7 at 3 m/s air flow velocity

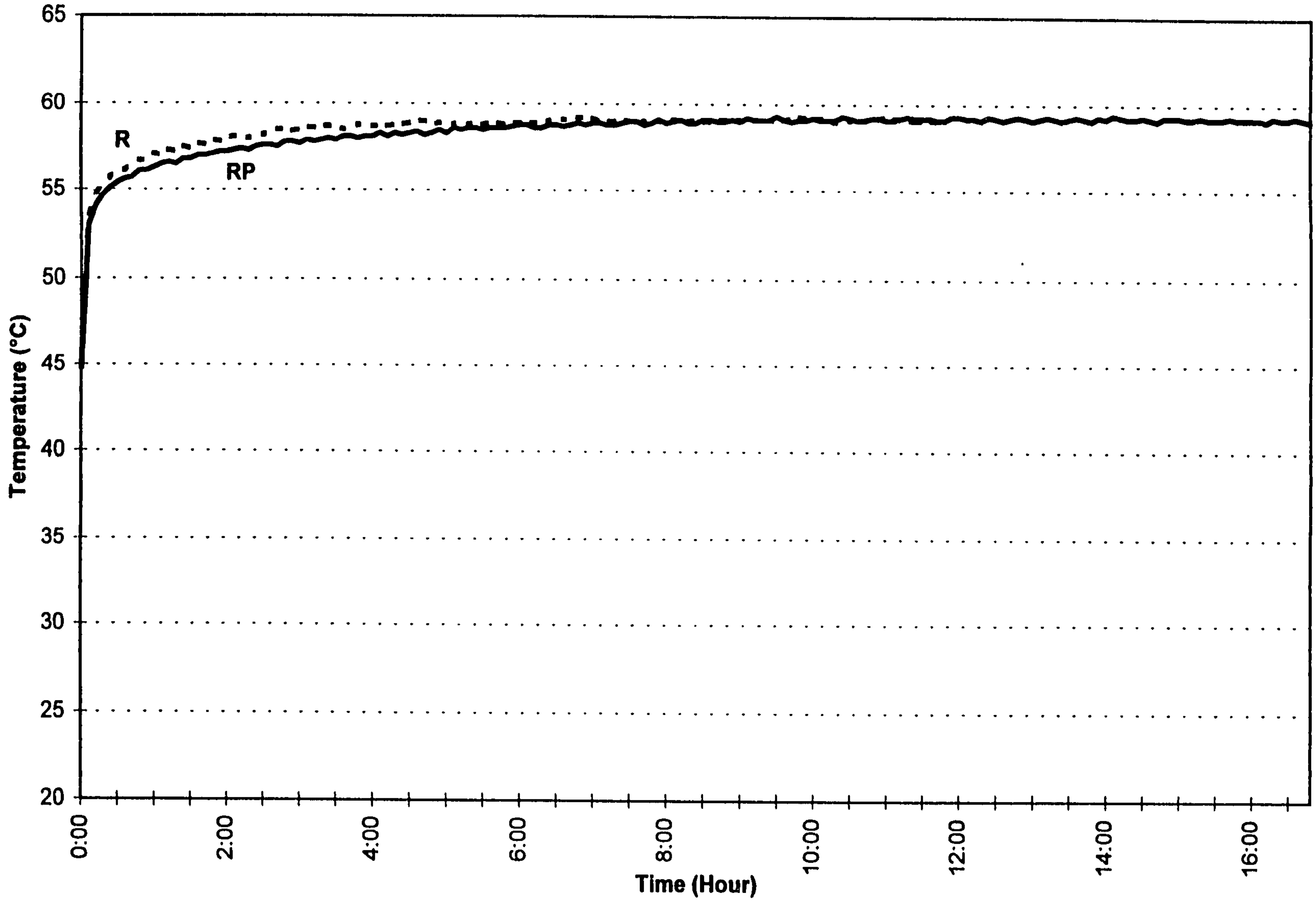


Figure 5.31 Time-temperature curves for the outgoing air from unimpregnated (R) and Paraffin impregnated (RP) regular block number 12 at 2 m/s air flow velocity

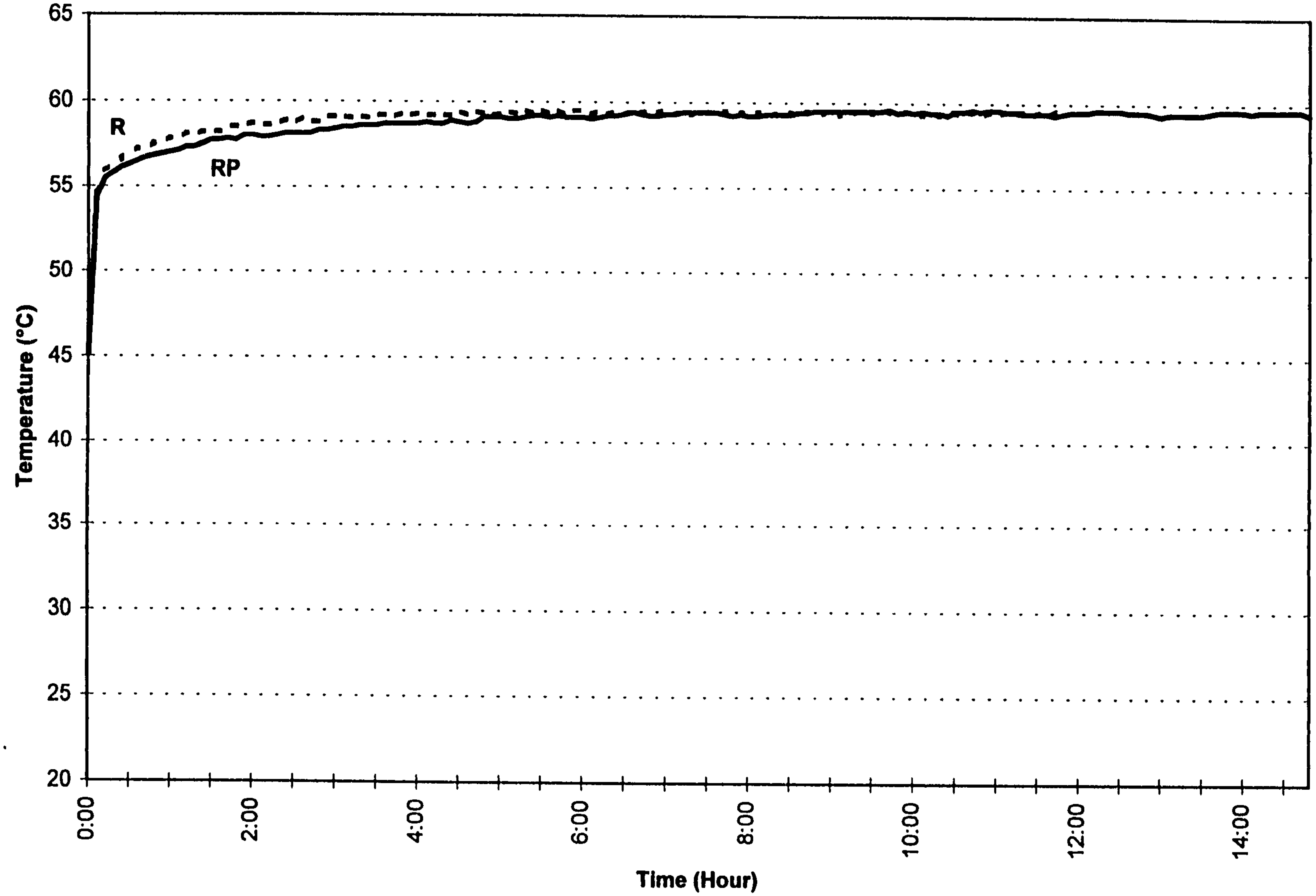


Figure 5.32 Time-temperature curves for the outgoing air from unimpregnated (R) and Paraffin impregnated (RP) regular block number 12 at 2.5 m/s air flow velocity

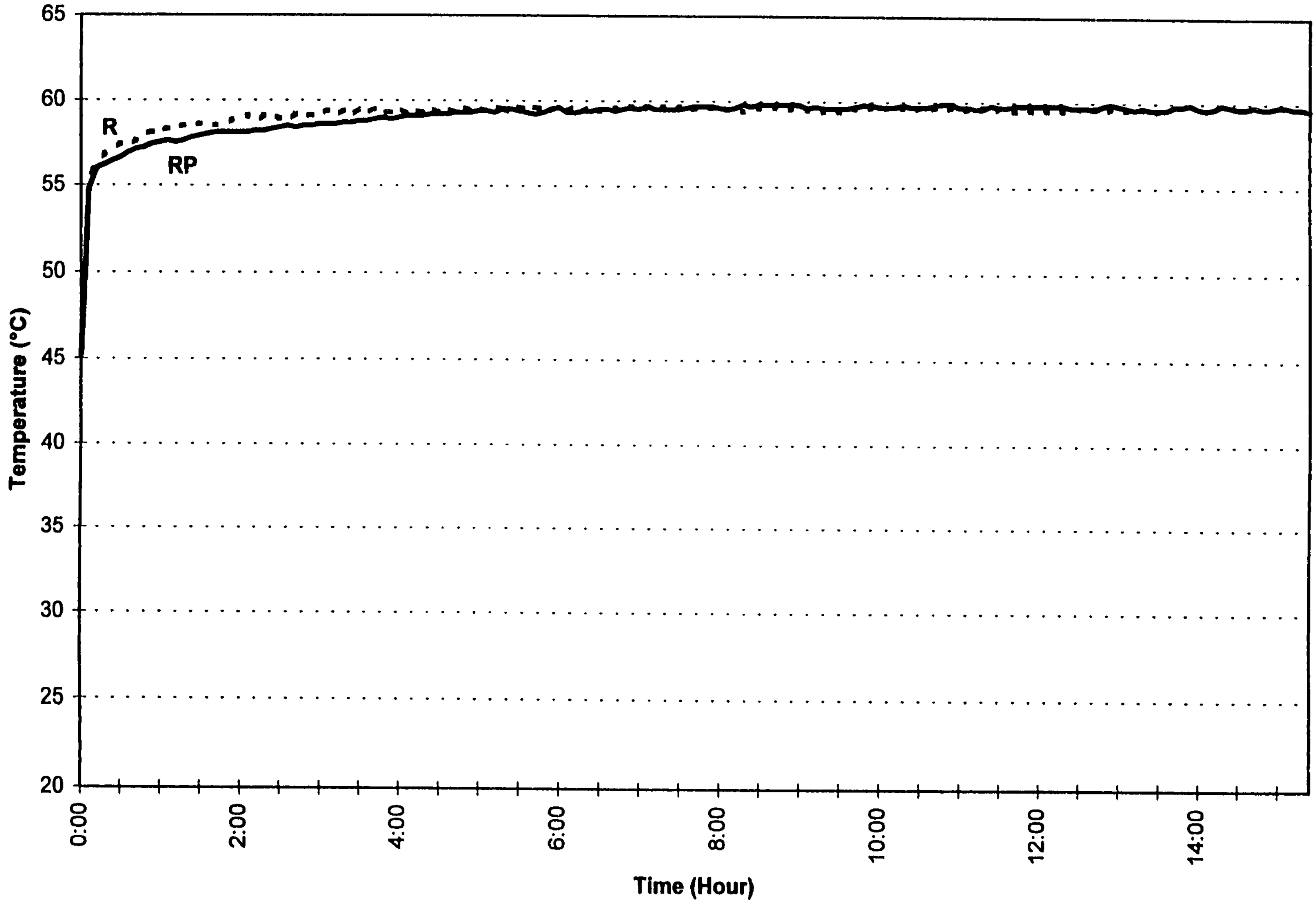


Figure 5.33 Time-temperature curves for the outgoing air from unimpregnated (R) and Paraffin impregnated (RP) regular block number 12 at 3 m/s air flow velocity

5.2 Forced cooling mode

During the forced cooling mode, due to colder air flow blown in (15°C for A, ABS and 22°C for A, AP and 45°C for R, RP), concrete block temperatures began to decrease from the inside surface toward outside. Due to the fact that the air temperature is lower than the PCM's freezing points (18°C for BS and 54°C for PAR from DSC analysis), the PCMs started to crystallize. In this process, heat is released as solidification taking place and the heat transfers slowly outward. This prevents any sharp temperature drop in PCM impregnated concrete blocks [16]. Heat discharged from these blocks can supply stored heat to the room over a longer period of time than ordinary blocks because the heat content previously stored includes latent heat as well as sensible heat.

In the cooling mode, four different experiments were made to evaluate and compare unimpregnated with PCM impregnated tunnels made of concrete blocks. They are:

a) Time comparison: the time required to discharge heat previously stored in the lower part of the blocks at 2, 2.5 and 3 m/s and in a special case 3.9 m/s air flow velocities.

b) Discharging time comparison between upper and bottom parts blocks (block number 1, 3, 6, 7, 10 and 12) made of unimpregnated and PCM impregnated concrete blocks at various air flow velocities.

c) The variation of the block temperatures were followed during discharging processes depending on the time and air flow velocities. In all these experiments the bottom part of central block number 7 was considered.

d) Outgoing air temperature profiles (at block number 12).

5.2.1 Autoclaved concrete blocks unimpregnated (A) and impregnated with Butyl Stearate (ABS)

The average weight percentage of Butyl Stearate impregnated in autoclaved concrete blocks was about 5.6 and the operating air temperature used to cool down concrete blocks from 25°C to 15°C.

a). Time comparison:

The variation of cooling time at the bottom side of the tunnels depends on the position (number) of the blocks and the air flow velocities. (The results obtained for the upper side are not represented). Figures 5.34 and 5.35 represent the time needed to cool each testing block down to the set temperature. It was found that the faster air flow took a shorter time to reach the set temperature in both unimpregnated and BS impregnated concrete blocks. The maximum stored heat in impregnated blocks (2638 KJ) is 1.9 times as high as that in the unimpregnated blocks (1428 KJ). For the impregnated block, the time required for the complete discharge of heat to the desired temperature for the two higher velocities was about 9 hours, which is too fast, while that at the lowest velocities was very close to the ideal maximum discharge time of 16 hours.

b). Comparison between upper and bottom parts (block number 1, 3, 6, 7, 10 and 12):

From Figures 5.36, 5.37 and 5.38, we may see that it will take about 5 hours longer than for the unimpregnated ones to complete the cooling mode for the twelve BS impregnated concrete blocks at various air flow velocities. At the lowest air flow velocity the longer discharge period coincides with the objective period of heat discharge to the room.

c). Discharging temperature profiles (block number 7):

From Figures 5.39, 5.40 and 5.41, BS impregnated block took about 12, 11 and 10 hours at 2, 2.5 and 3 m/s air flow velocities respectively to complete the discharging of the stored energy. However, for unimpregnated concrete block, it only took about 7, 6 and 5 hours at 2, 2.5 and 3 m/s air flow velocities. This is an average of 5 hours longer for the same operating procedures and conditions due to the extra time necessary for the crystallization of BS. For this application, an even lower air flow would have extended the discharge period closer to the objective of 16 hours.

d). discharging temperature profiles (block number 12):

The above mentioned difference was established also in the different air flow temperatures in block number 12. The air temperatures at various air flow velocities do not exhibit many differences. As expected, the lower air flow velocities tend to maintain higher outgoing air temperatures for a longer period of time. As may be seen in Figures 5.42, 5.43 and 5.44, the air temperature at 2, 2.5, 3 m/s air flow velocity was kept above 15°C for about 6, 5 and 4 hours respectively. As mentioned before, these discharge times are too short for practical application so it is obvious that a lower air flow velocity would be required in practice. In alternative air flow arrangement which could be arranged in a building structure but can not easily achieved in the test apparatus used.

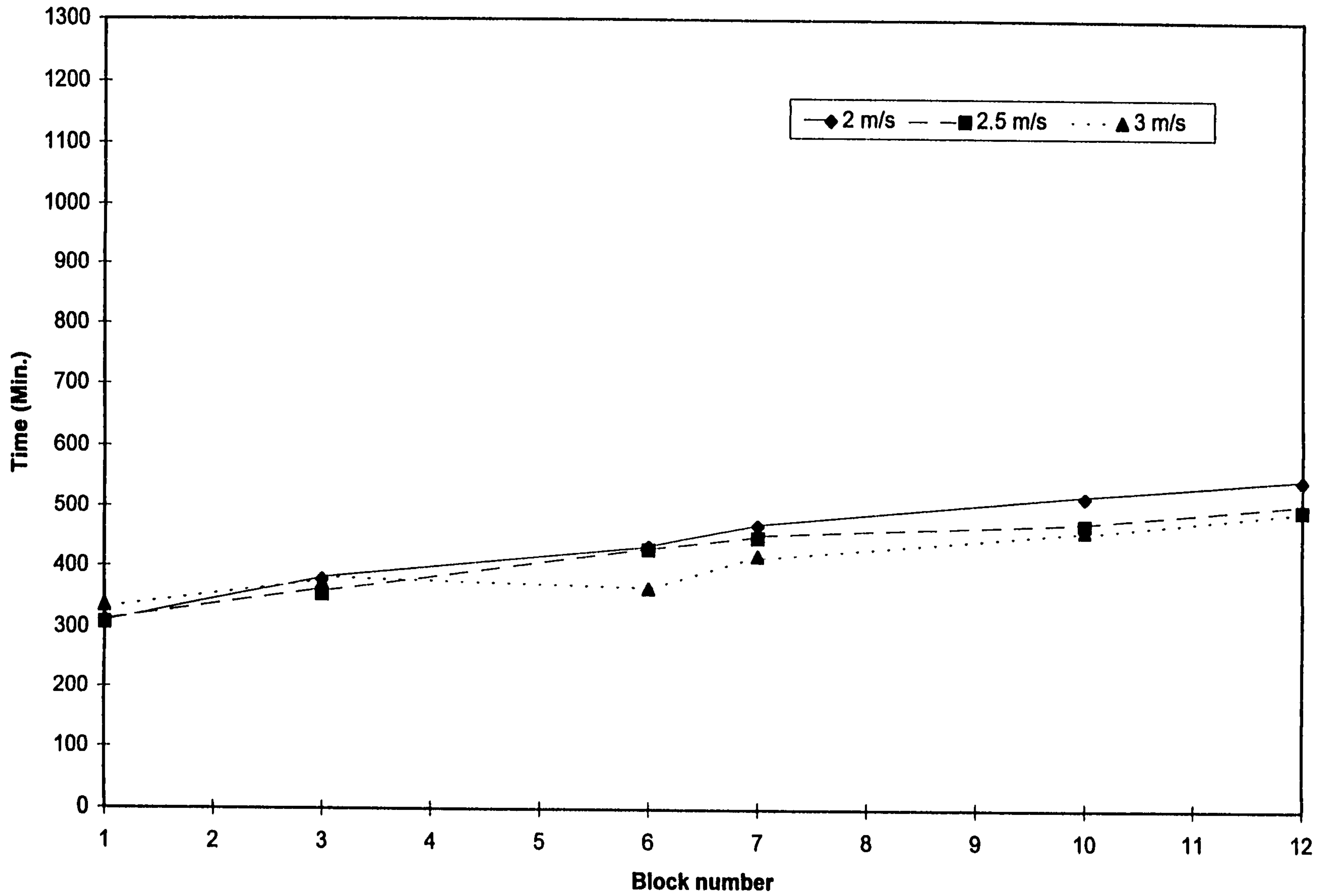


Figure 5.34 Time required for cooling unimpregnated autoclaved blocks from 25°C to 15°C at different air flow velocities [A - Cooling - Bottom]

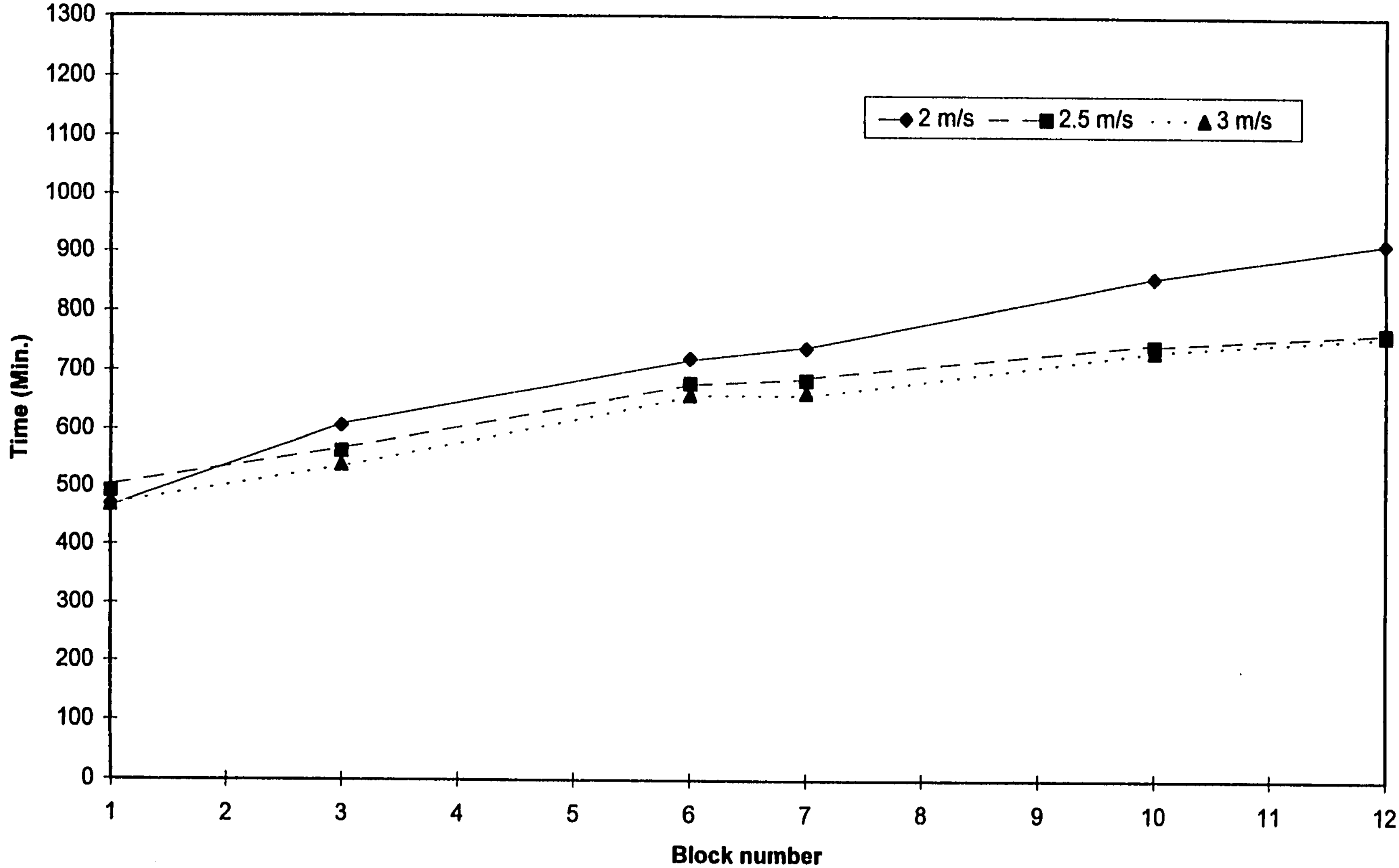


Figure 5.35 Time required for cooling BS impregnated autoclaved blocks (ABS) from 25°C to 15°C at different air flow velocities [ABS - Cooling - Bottom]

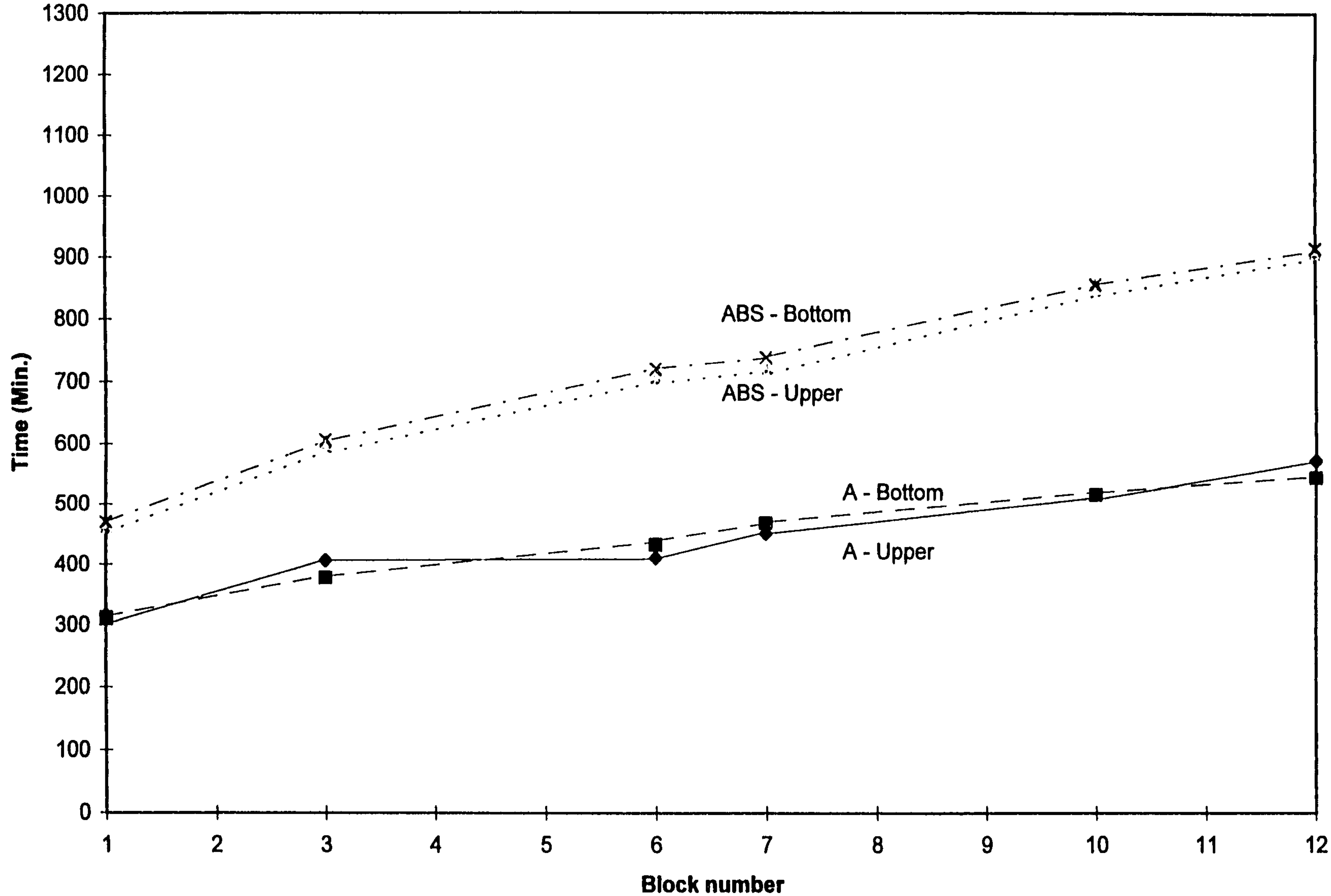


Figure 5.36 Comparison between the time required for cooling unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved blocks from 25°C to 15°C at 2 m/s air flow velocity

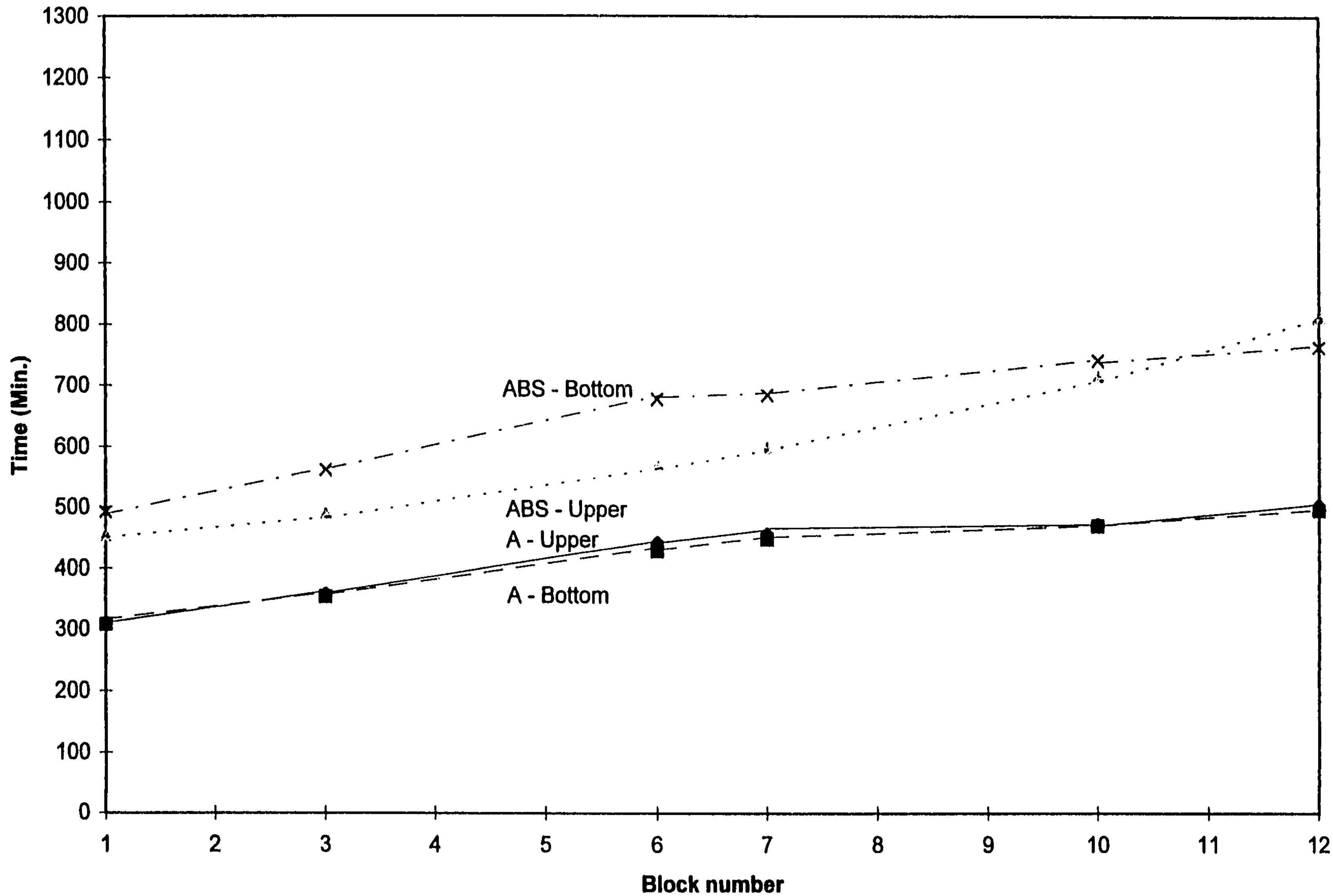


Figure 5.37 Comparison between the time required for cooling unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved blocks from 25°C to 15°C at 2.5 m/s air flow velocity

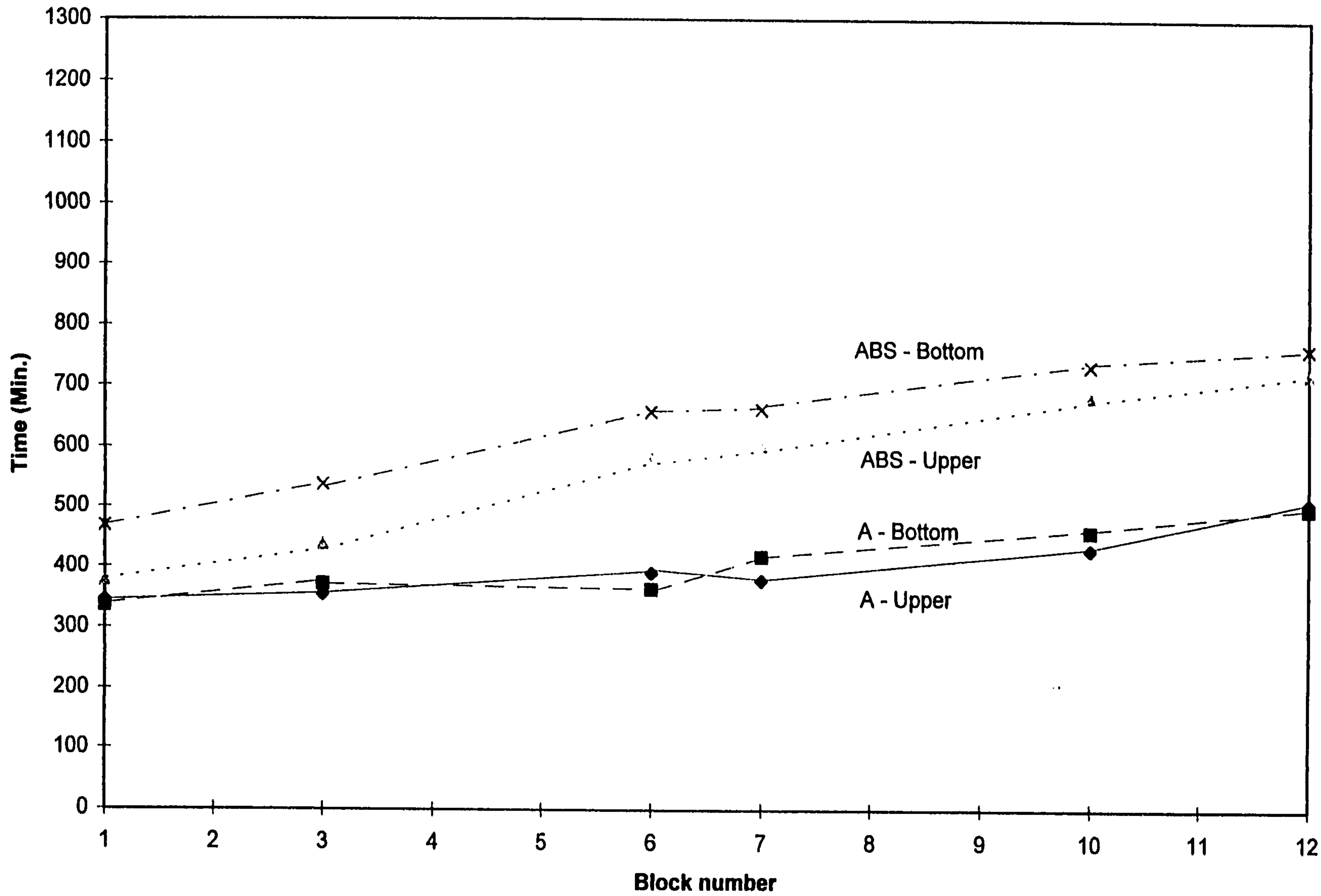


Figure 5.38 Comparison between the time required for cooling unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved blocks from 25°C to 15°C at 3 m/s air flow velocity

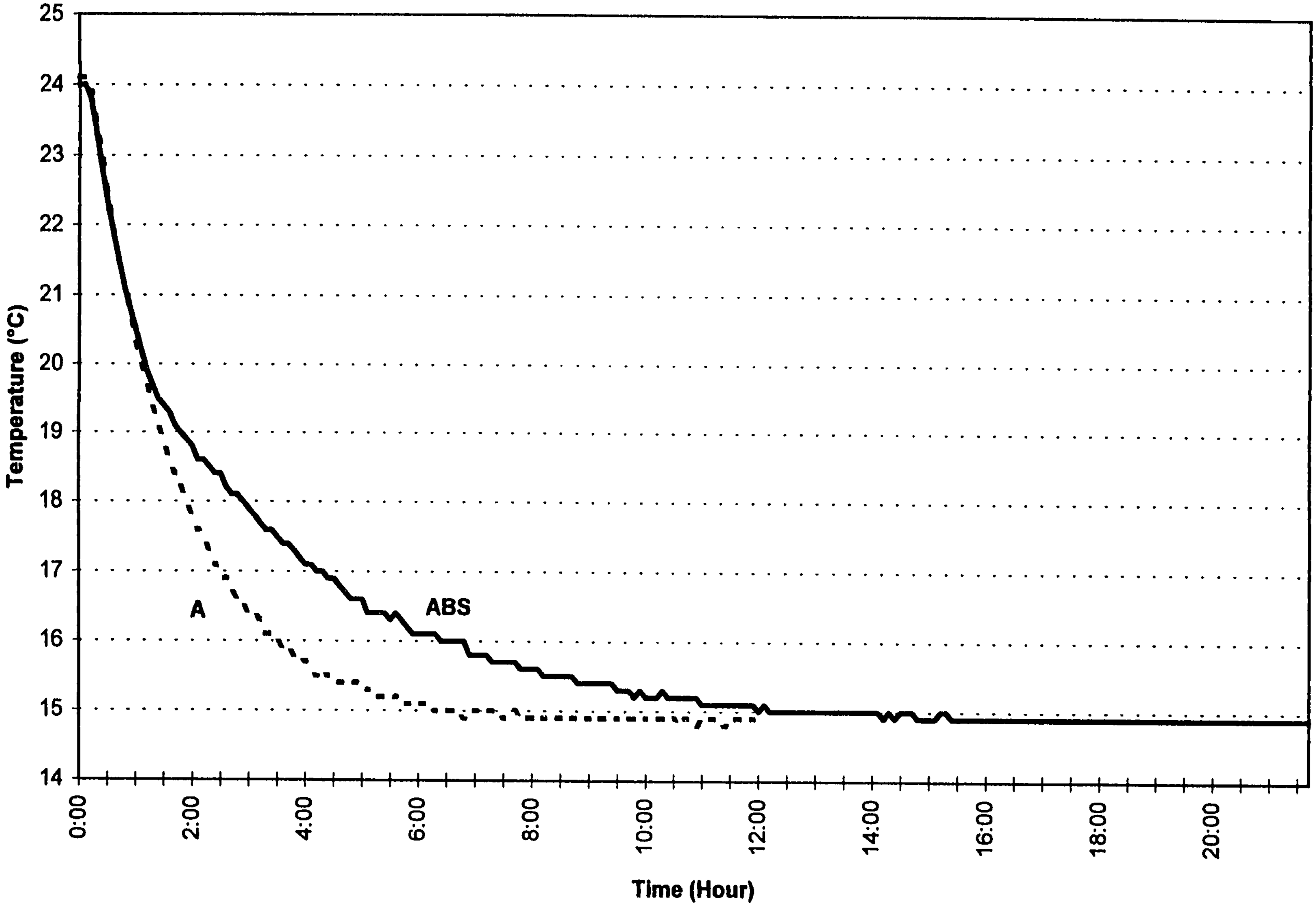


Figure 5.39 Time-temperature curves for unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 7 at 2 m/s air flow velocity

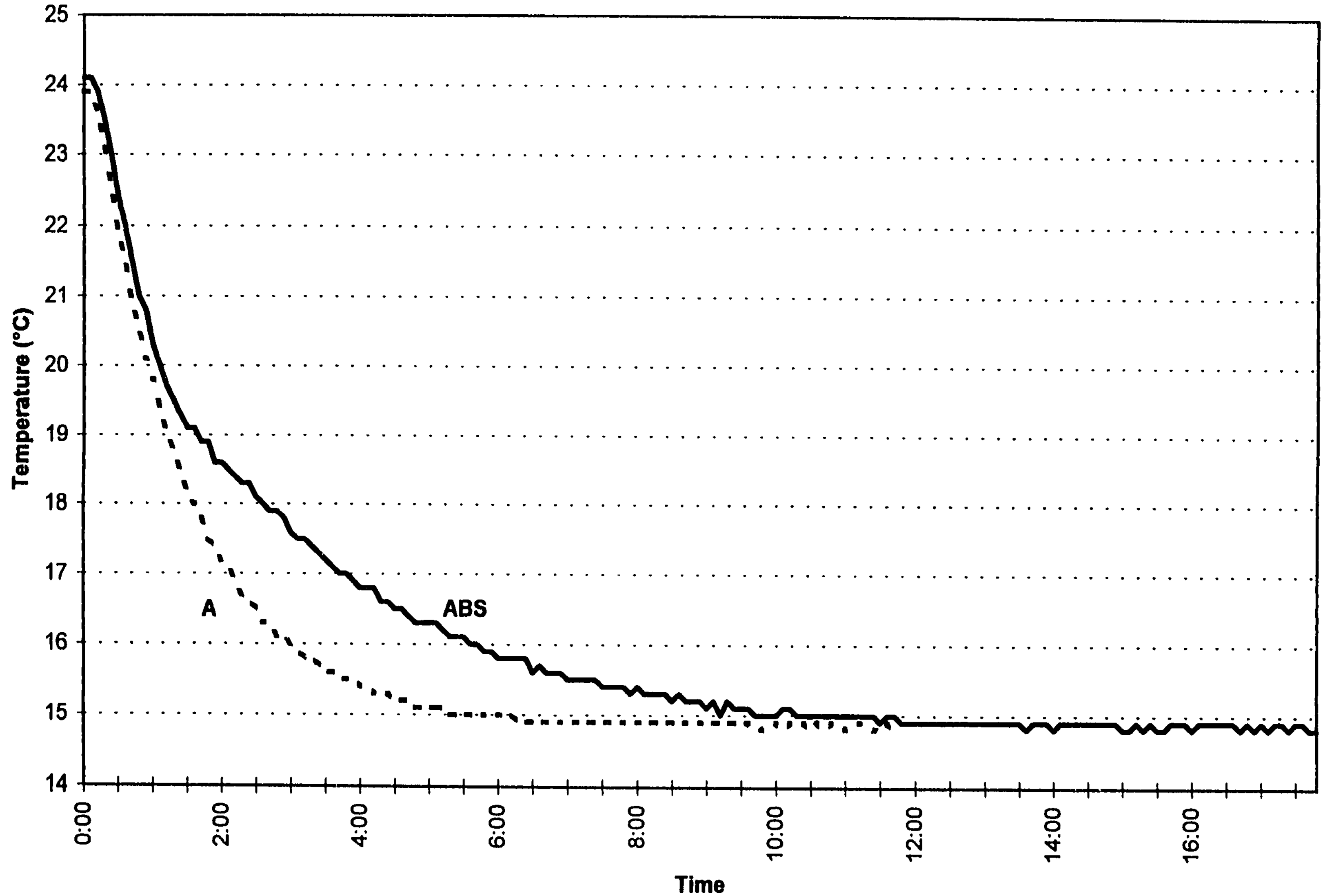


Figure 5.40 Time-temperature curves for unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 7 at 2.5 m/s air flow velocity

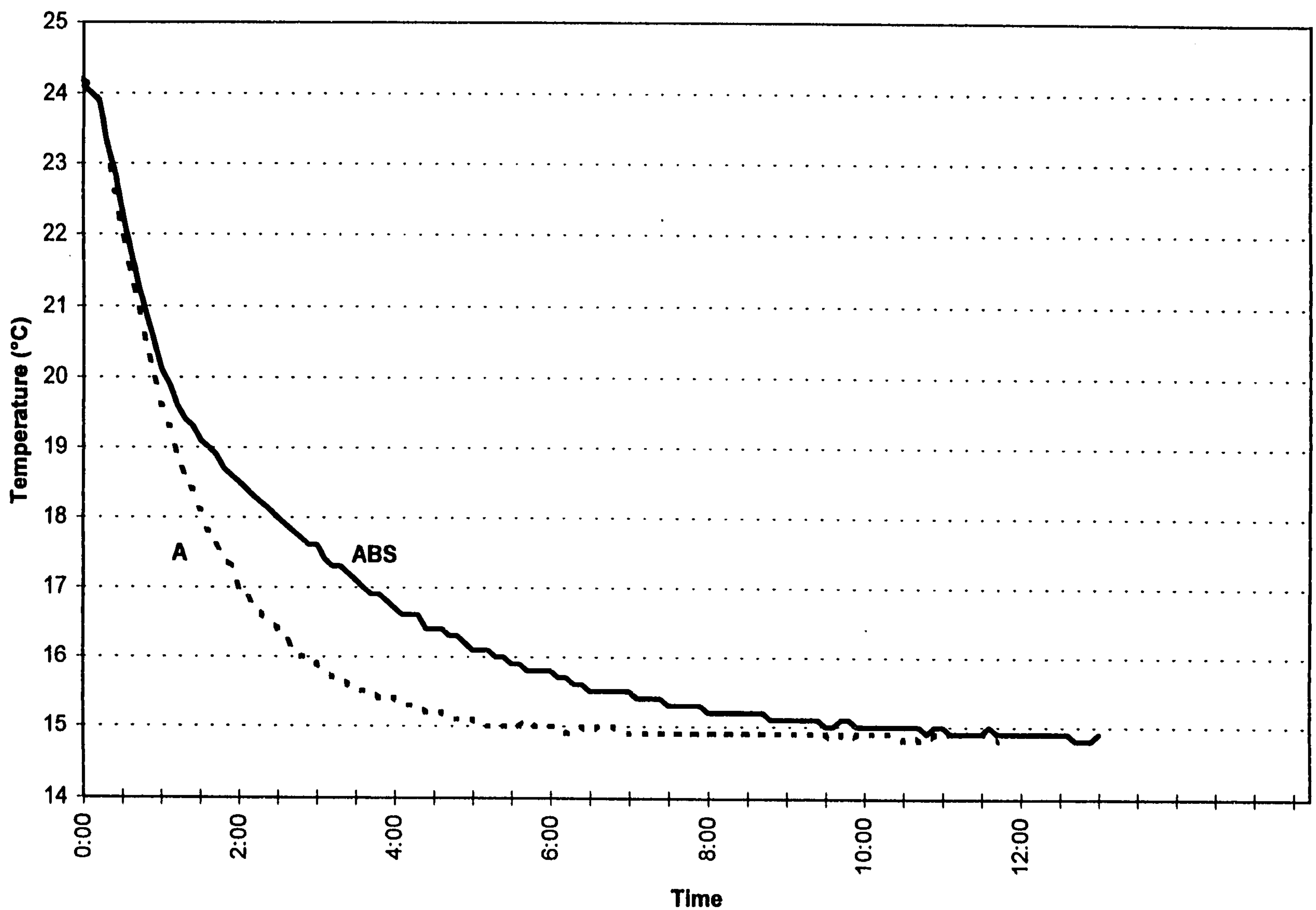


Figure 5.41 Time-temperature curves for unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 7 at 3 m/s air flow velocity

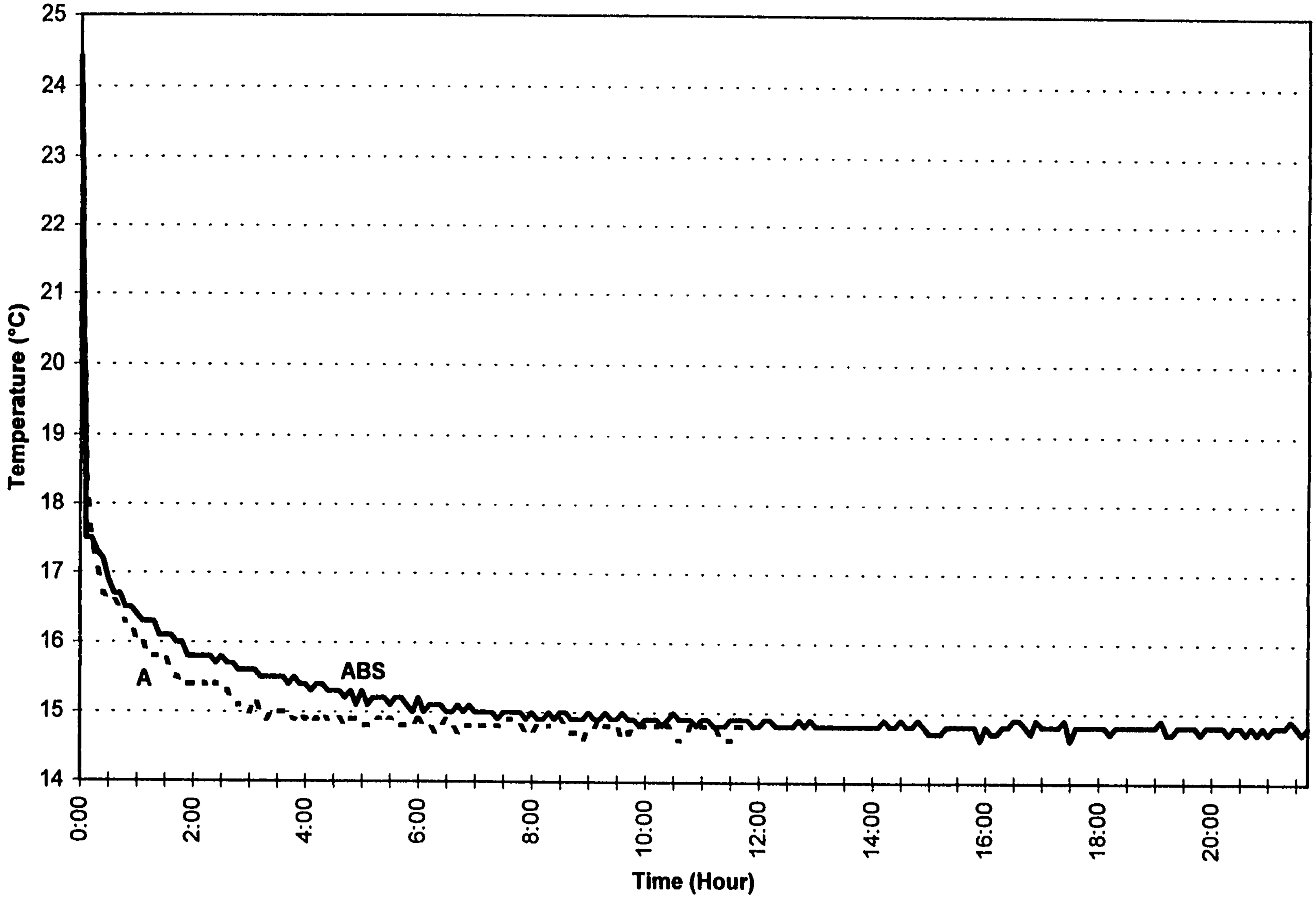


Figure 5.42 Time-temperature curves for the outgoing air from unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 12 at 2 m/s air flow velocity

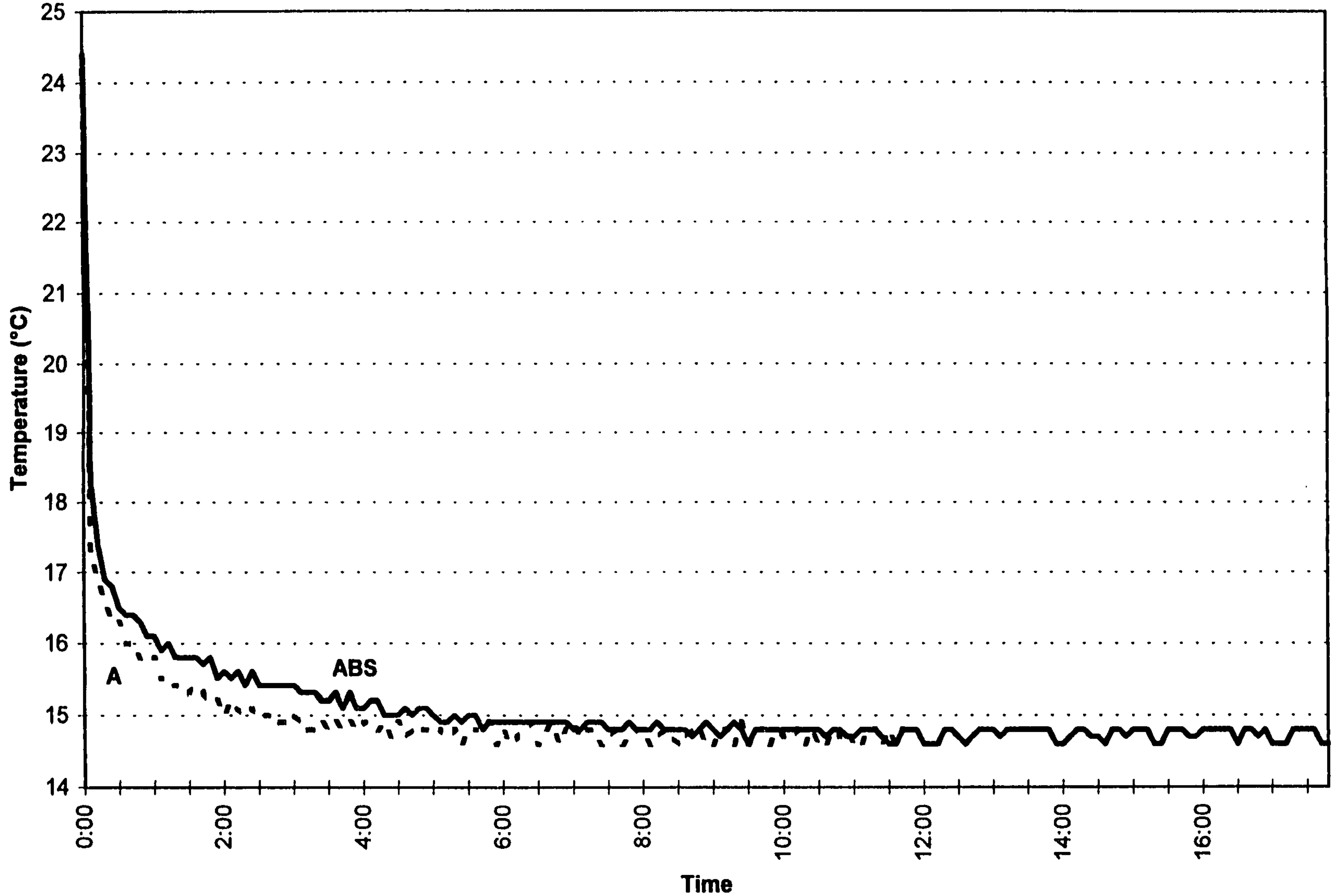


Figure 5.43 Time-temperature curves for the outgoing air from unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 12 at 2.5 m/s air flow velocity

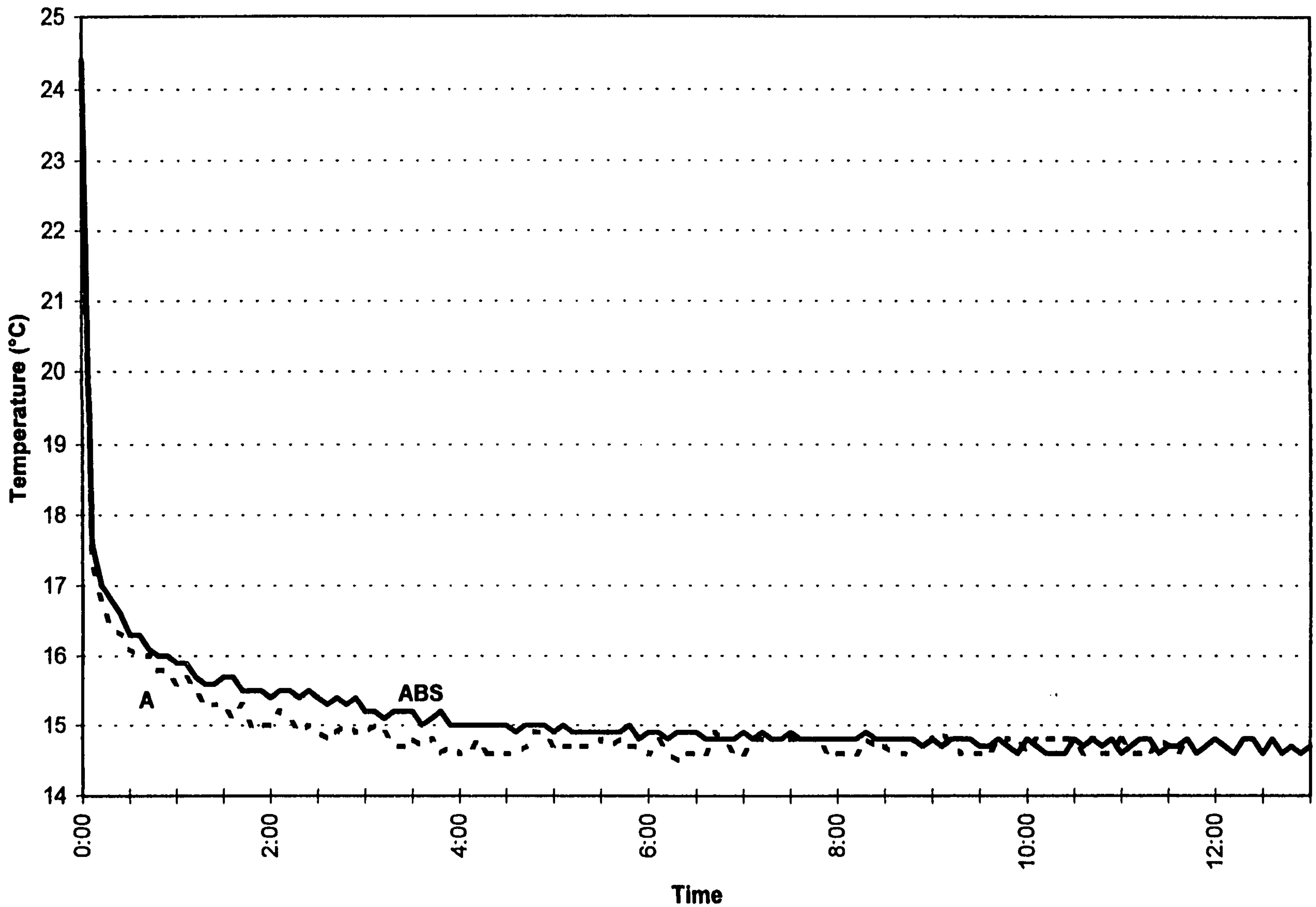


Figure 5.44 Time-temperature curves for the outgoing air from unimpregnated (A) and Butyl Stearate impregnated (ABS) autoclaved block number 12 at 3 m/s air flow velocity

5.2.2 Autoclaved concrete blocks unimpregnated (A) and impregnated with Paraffin (AP)

The average percentage of Paraffin impregnated in autoclaved concrete blocks is about 8.4 and an operating air temperature of 22°C was used to cool the concrete blocks from 60°C.

a). Time comparison:

Figures 5.45 and 5.46 present the results of various air flow velocities. The faster the air flow velocities, the sooner the cooling cycle is completed. The energy that could be stored in the Paraffin impregnated blocks (9244 KJ) is about 1.7 times greater than that in unimpregnated blocks (5337 KJ). However, it is estimated that the amount of heat storage and recovery can be improved by subsequent experimentation with reconfigured block structures and with improved air flow control.

b). Comparison between upper and bottom parts (block number 1, 3, 6, 7, 10 and 12):

From Figures 5.47, 5.48 and 5.49, one can see that at three different air flow velocities, it took about 3 hours longer to complete the whole cooling mode for the Paraffin impregnated concrete blocks. While a velocity of 2 m/s provides a satisfactory discharge time for heat recovery from the upper part of the block, that from the lower part of the block needs same improvement as mentioned in the preceding paragraph.

c). From the time-temperature diagrams (Figures 5.50, 5.51 and 5.52), one can observe that the Paraffin impregnated autoclaved block number 7 took about 16, 12.5 and 12 hours at 2, 2.5 and 3 m/s air flow velocities respectively to discharge the stored energy. However, for unimpregnated blocks, it only required about 12, 10 and 10 hours at the same air flow velocities. The differences are due to the latent heat storage. From the same figures, we noticed that Paraffin impregnated blocks presented up to 7°C higher temperature for about 4 hours.

d). Outgoing air temperature profiles (block number 12):

The air temperature differences at various air flow velocities exhibit characteristic difference in this case. As before, lower air flow velocities tend to result in higher outgoing air temperatures for longer periods of time. The PAR impregnated blocks were kept at 1 to 2°C higher temperature for almost 4 hours longer than the unimpregnated blocks, as shown in Figures 5.53, 5.54 and 5.55.

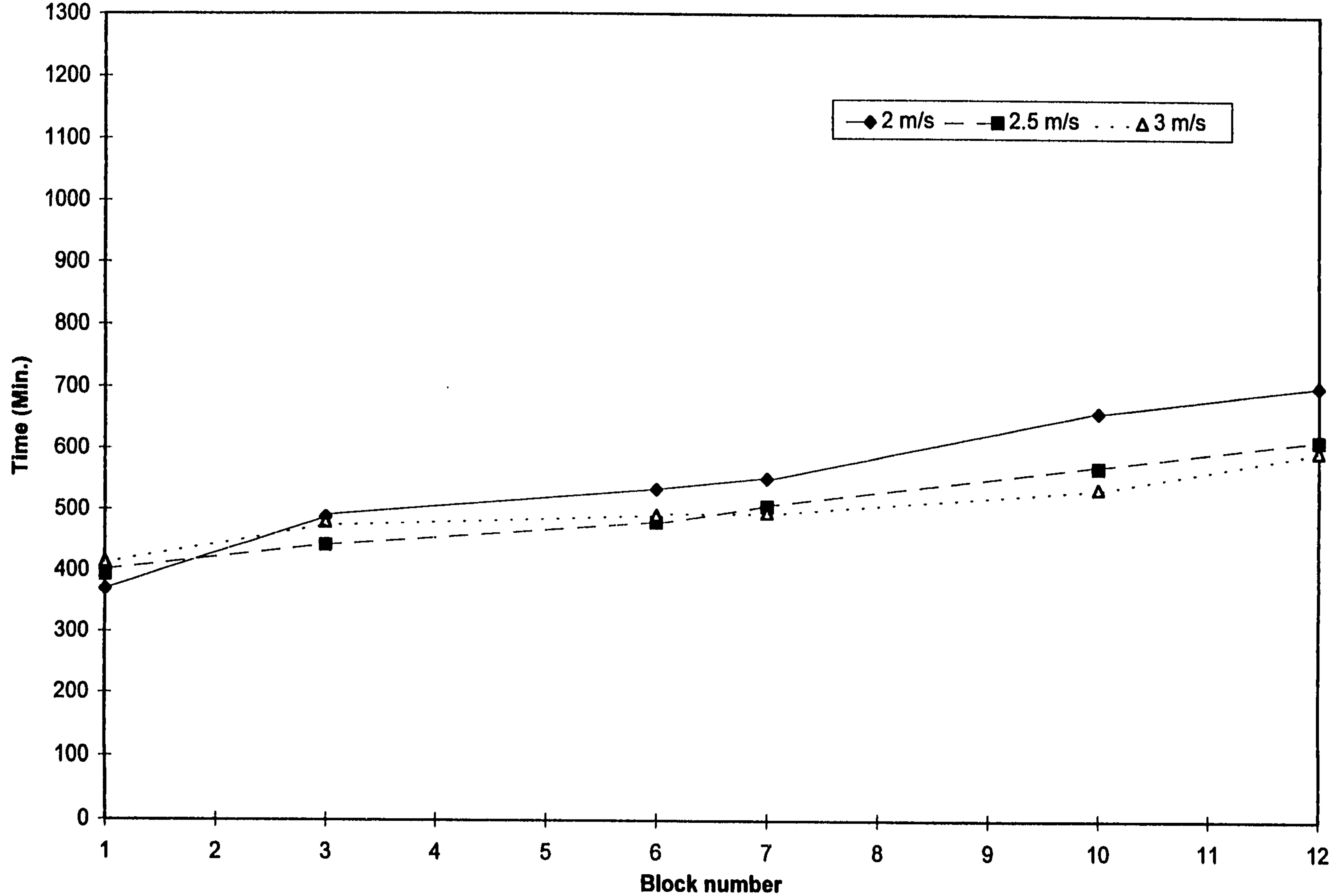


Figure 5.45 Time required for cooling unimpregnated autoclaved blocks (A) from 60°C to 22°C at different air flow velocities [A - Cooling - Bottom]

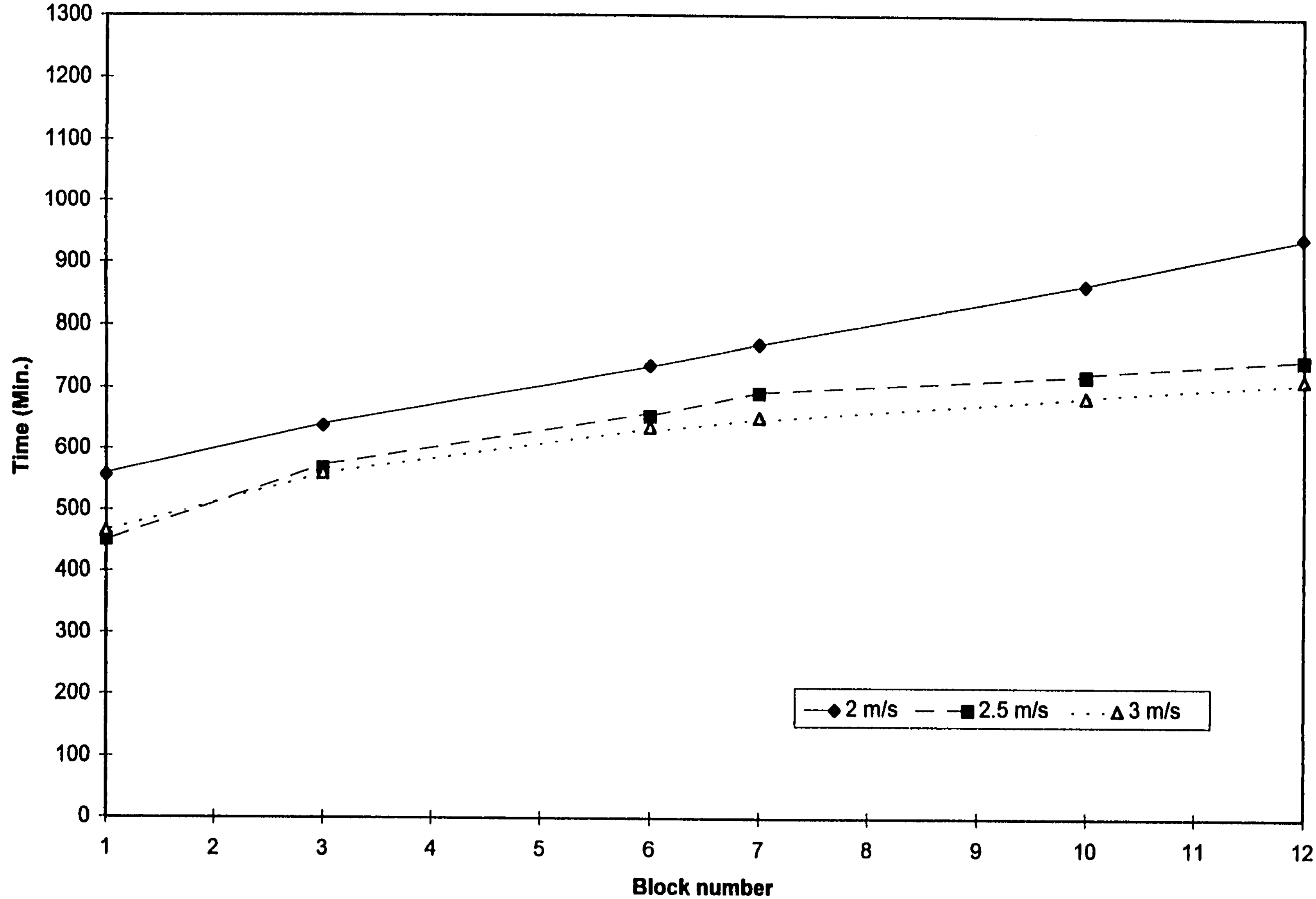


Figure 5.46 Time required for cooling PAR impregnated autoclaved blocks (AP) from 60°C to reach 22°C at different air flow velocities [AP - Cooling - Bottom]

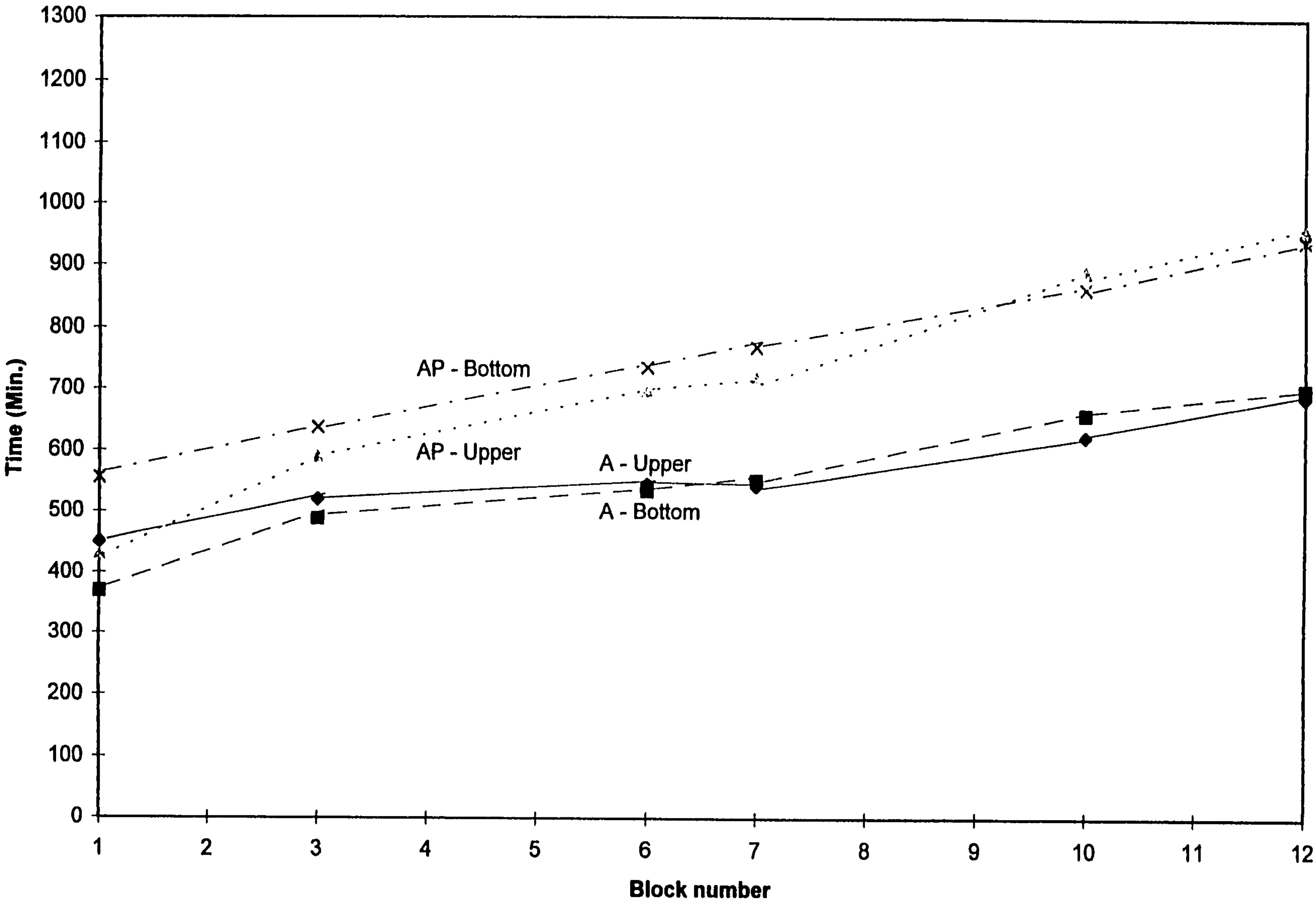


Figure 5.47 Comparison between the time required for cooling unimpregnated (A) and Paraffin impregnated (AP) autoclaved blocks from 60°C to 22°C at 2 m/s air flow velocity

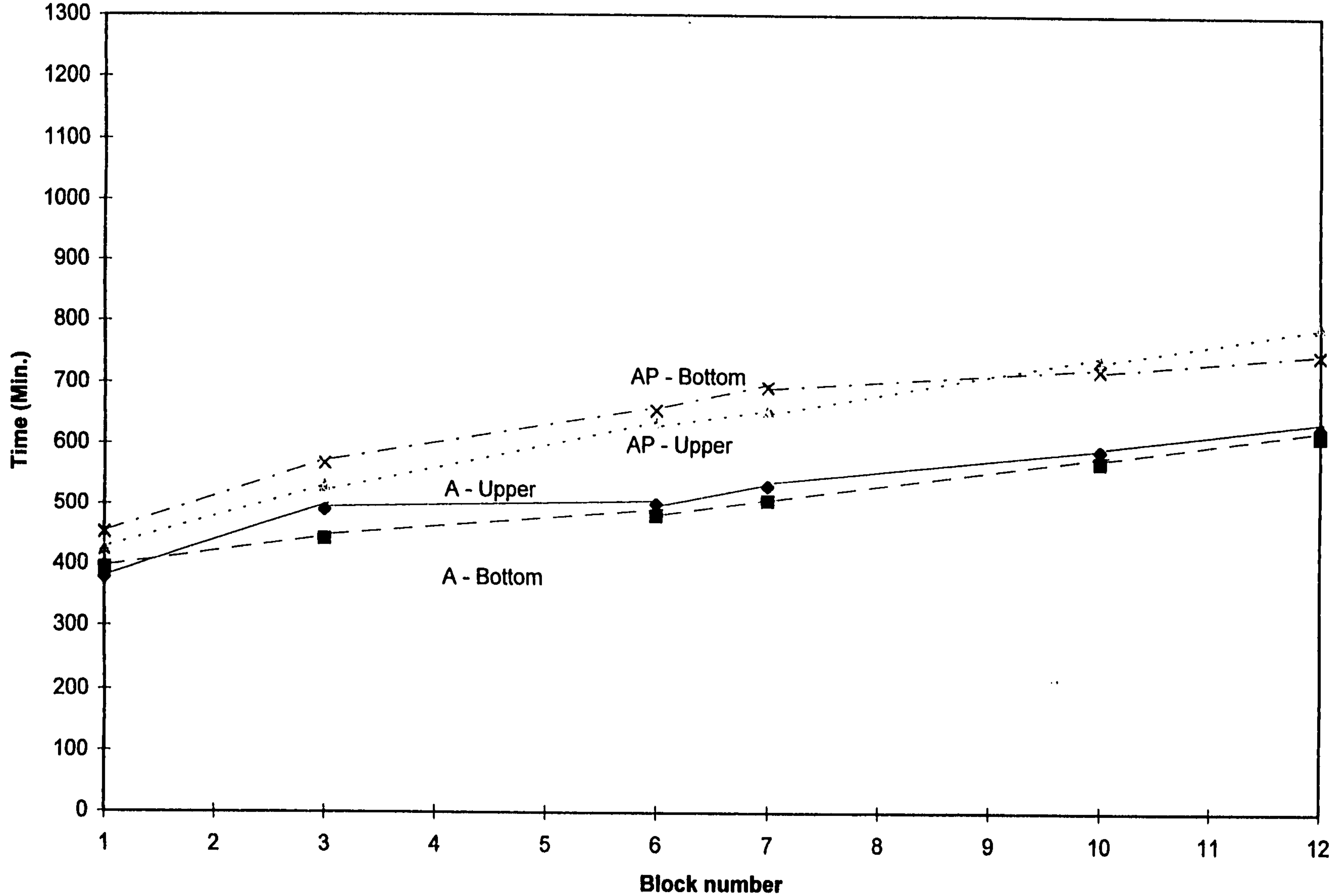


Figure 5.48 Comparison between the time required for cooling unimpregnated (A) and Paraffin impregnated (AP) autoclaved blocks from 60°C to 22°C at 2.5 m/s air flow velocity

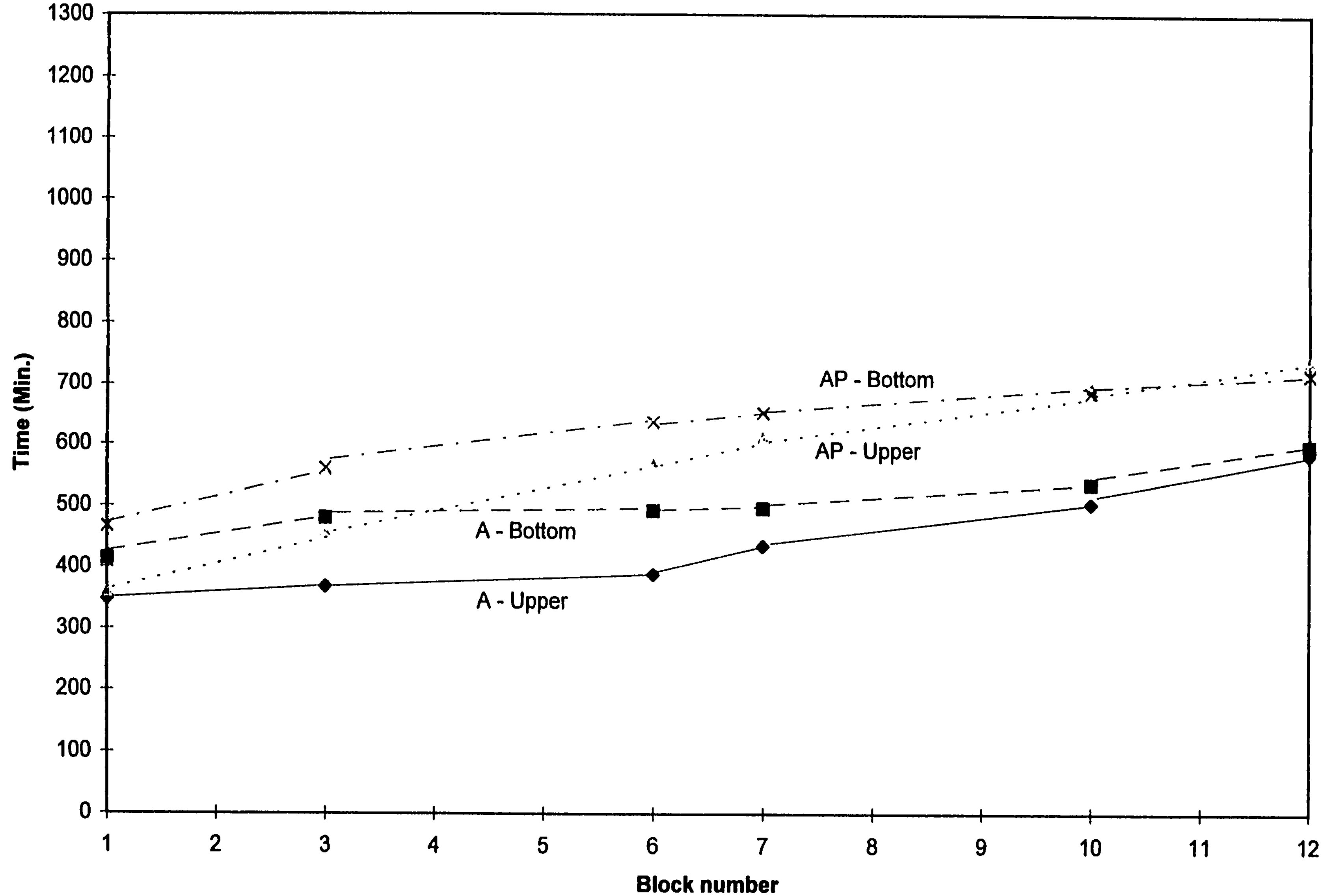


Figure 5.49 Comparison between the time required for cooling unimpregnated (A) and Paraffin impregnated (AP) autoclaved blocks from 60°C to 22°C at 3 m/s air flow velocity

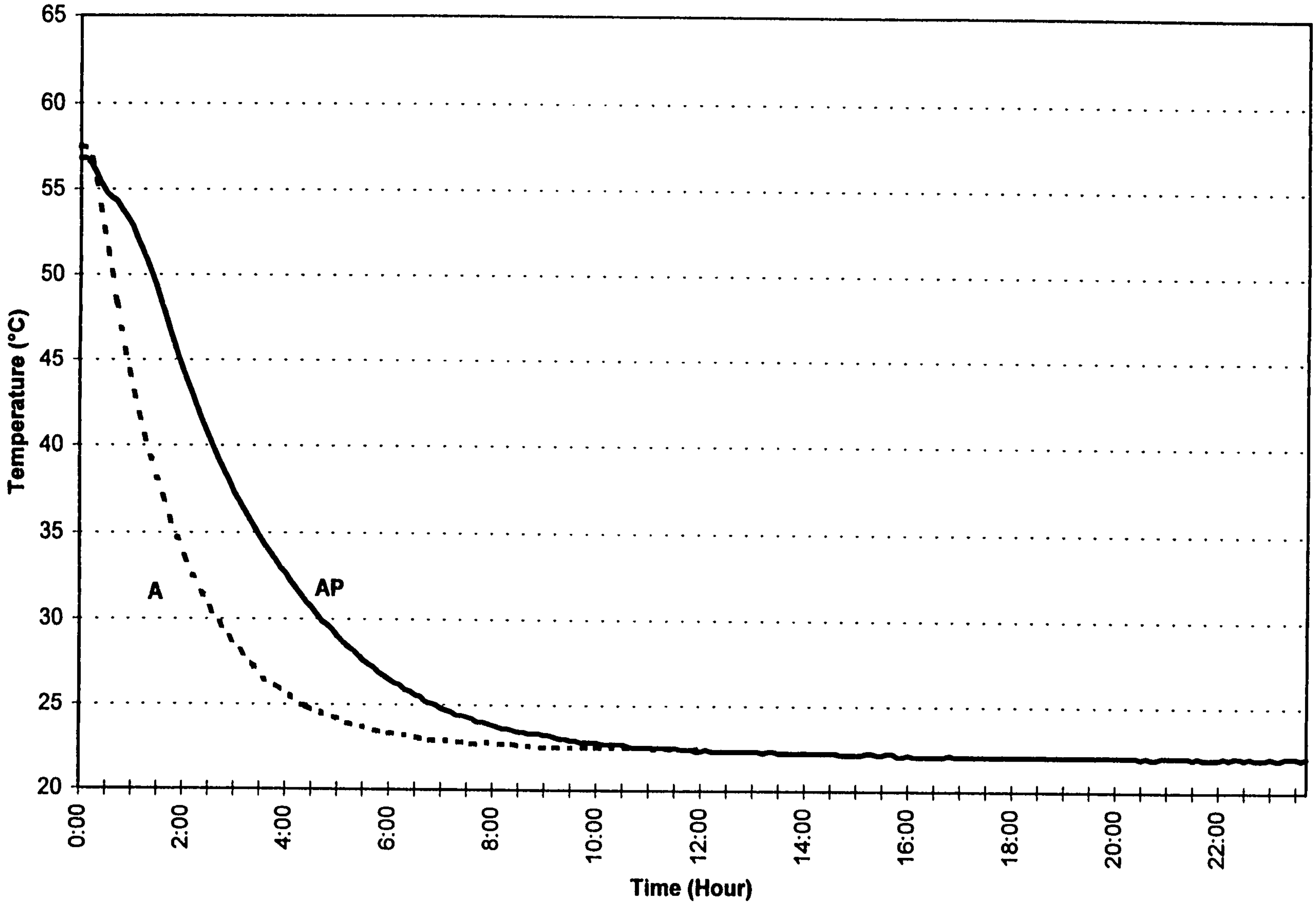


Figure 5.50 Time-temperature curves for unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 7 at 2 m/s air flow velocity

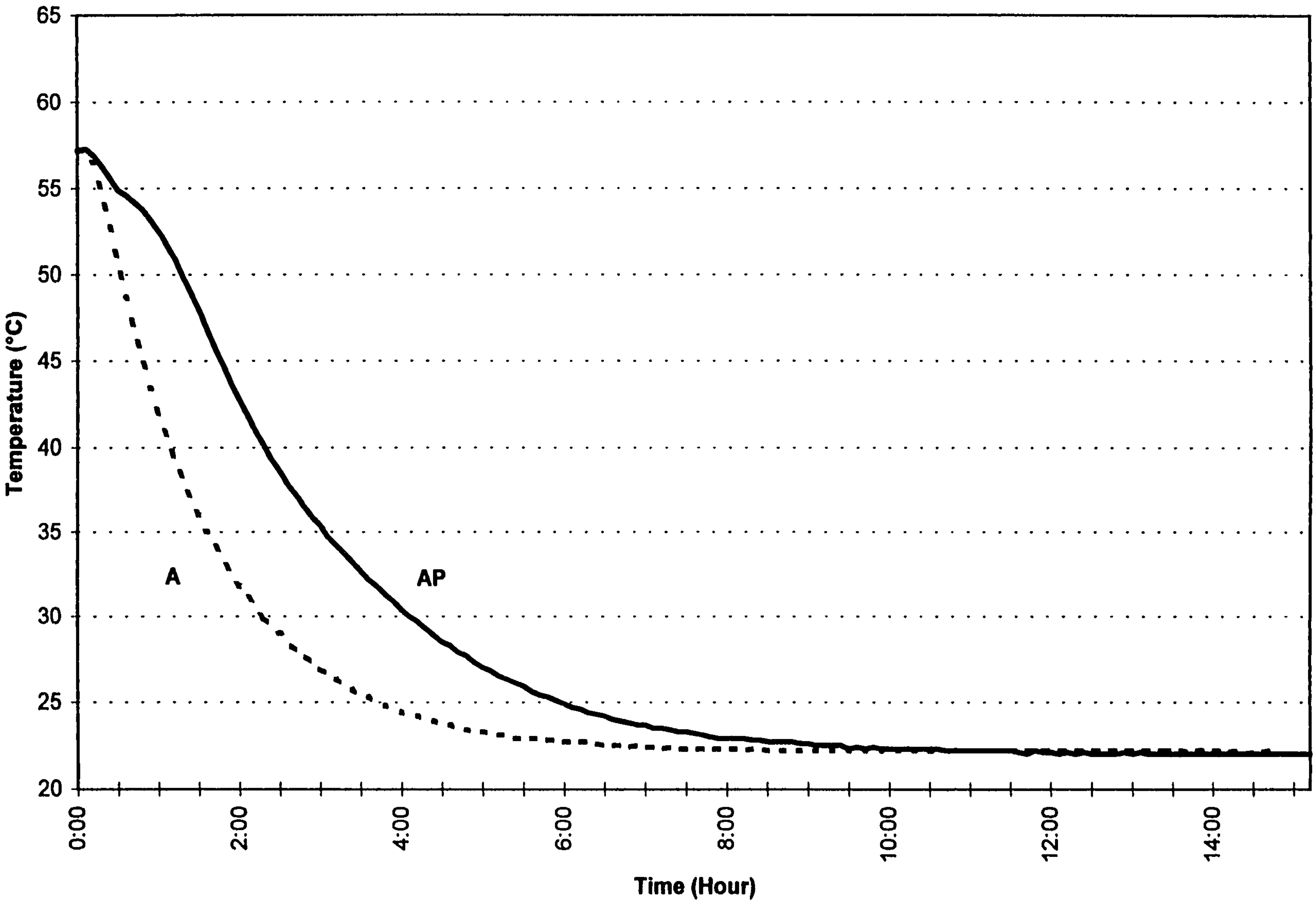


Figure 5.51 Time-temperature curves for unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 7 at 2.5 m/s air flow velocity

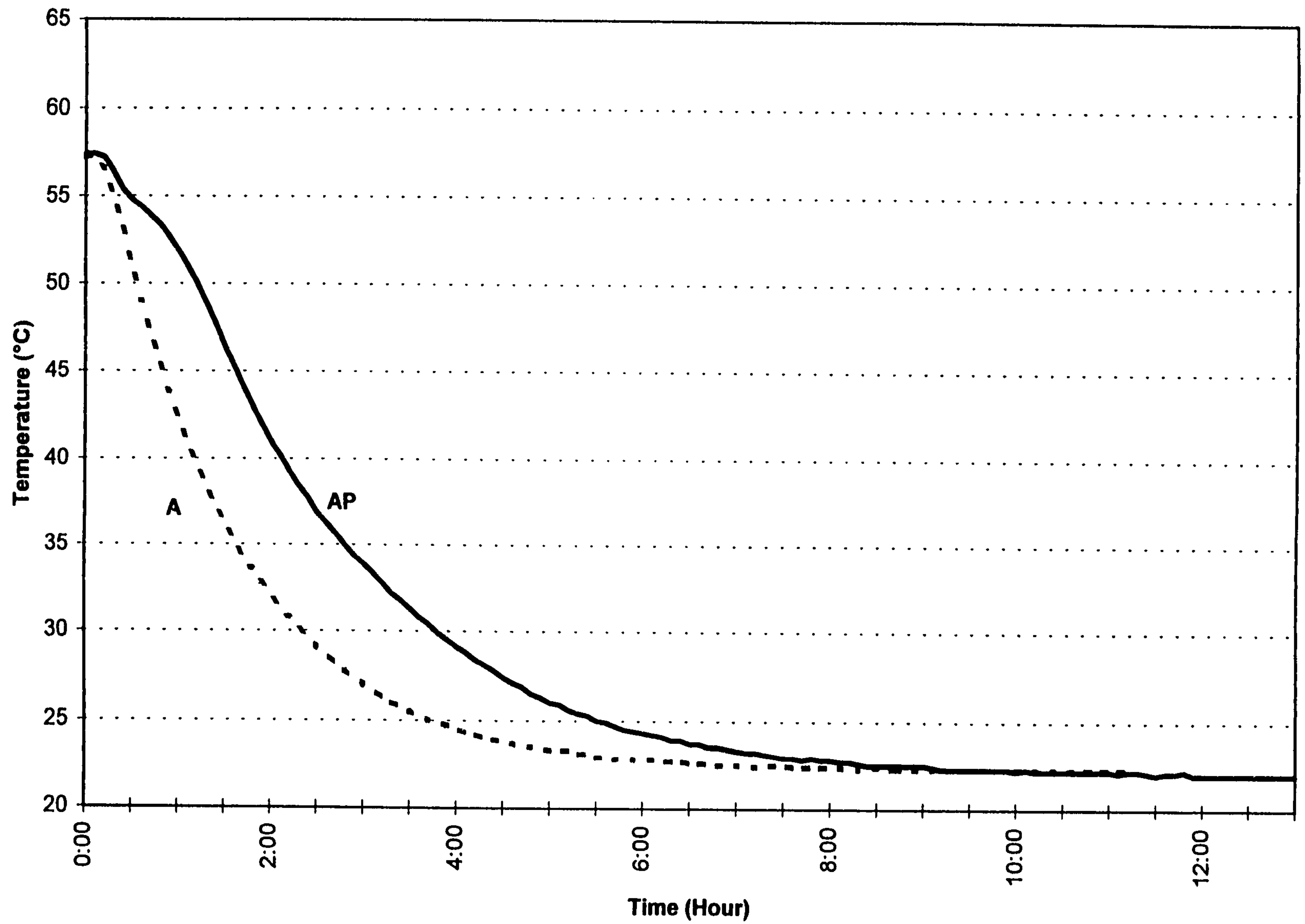


Figure 5.52 Time-temperature curves for unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 7 at 3 m/s air flow velocity

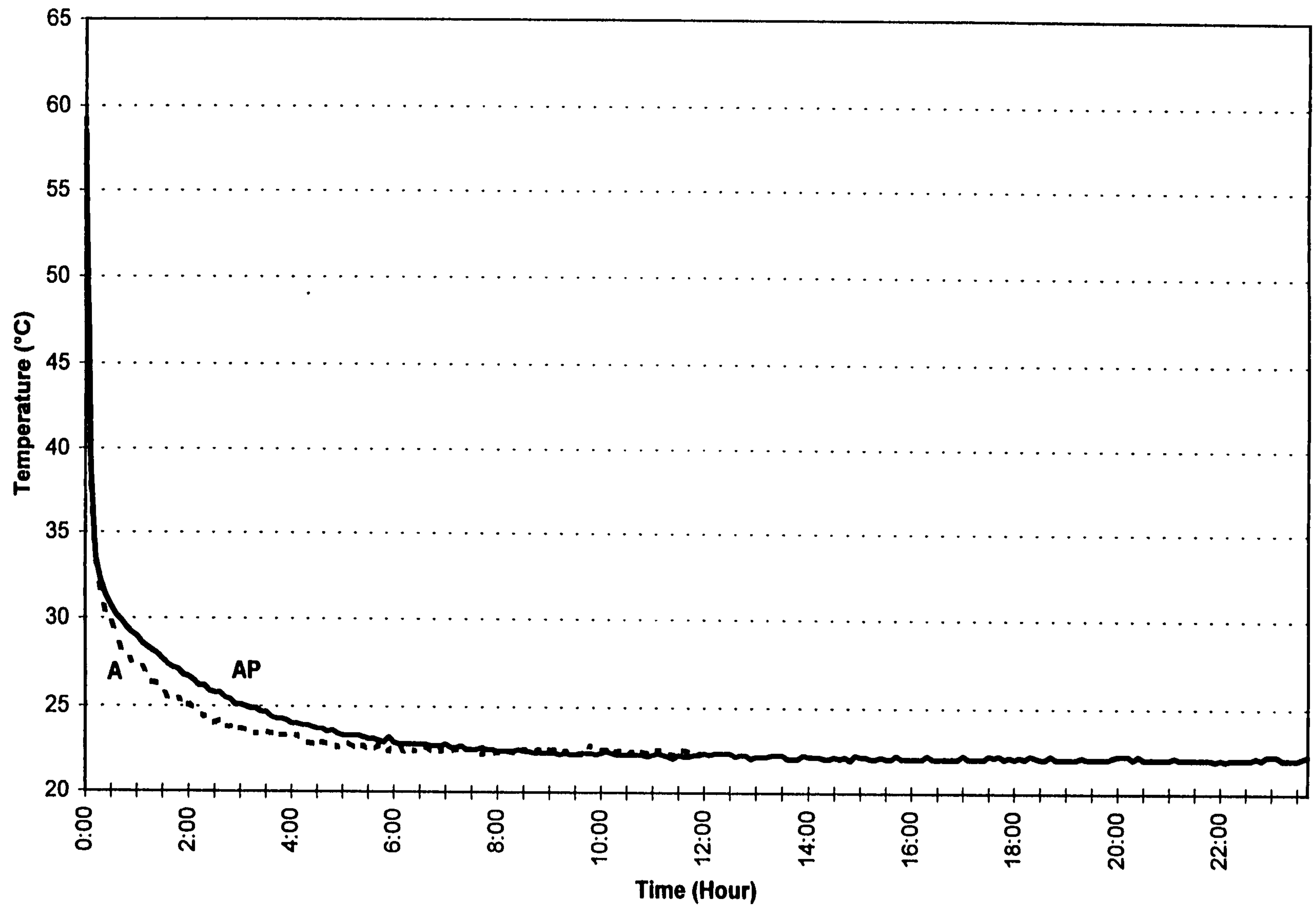


Figure 5.53 Time-temperature curves for the outgoing air from unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 12 at 2 m/s air flow velocity

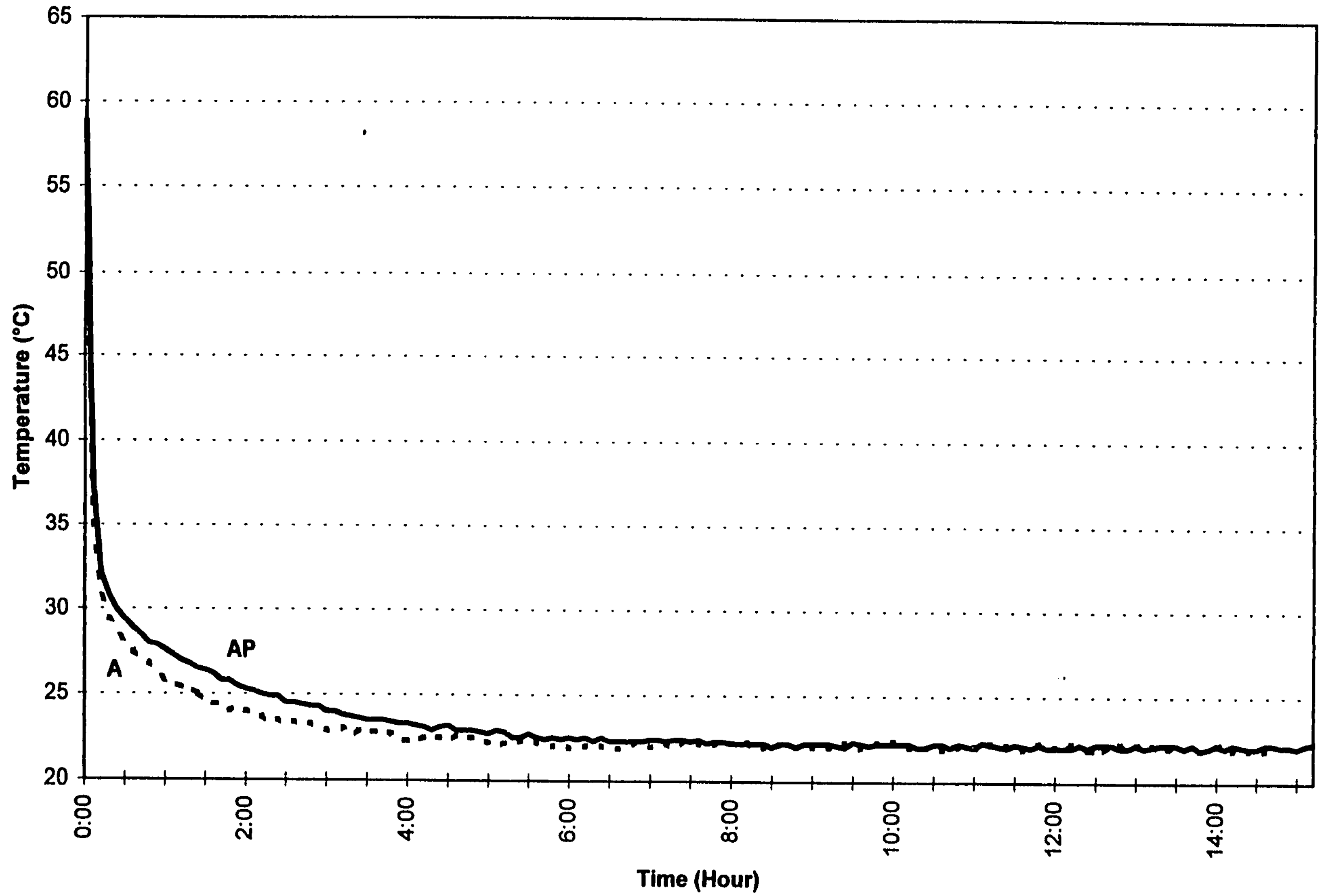


Figure 5.54 Time-temperature curves for the outgoing air from unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 12 at 2.5 m/s air flow velocity

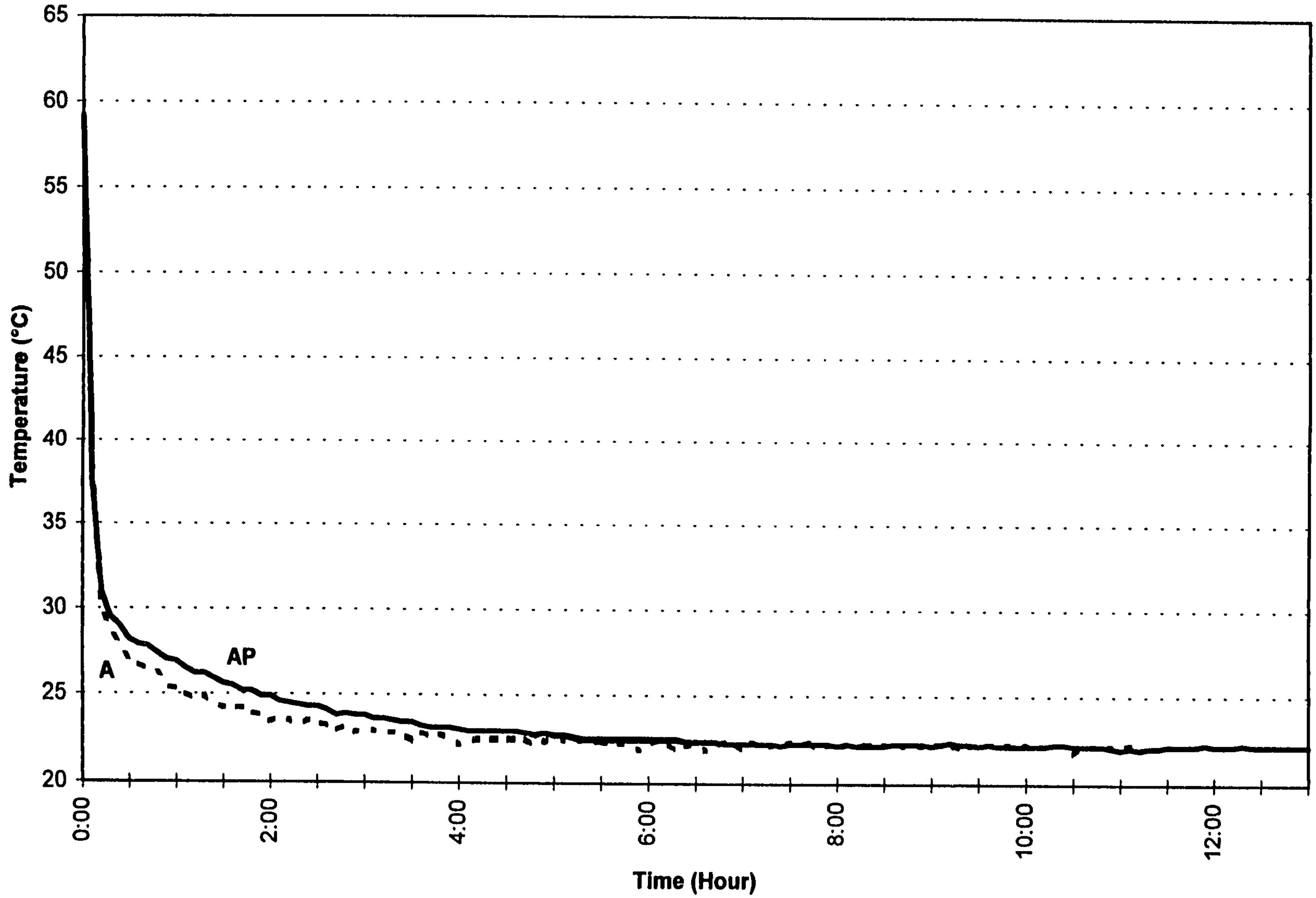


Figure 5.55 Time-temperature curves for the outgoing air from unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 12 at 3 m/s air flow velocity

5.2.3 Regular concrete blocks unimpregnated (R) and impregnated with Paraffin (RP)

The average percentage of Paraffin impregnated in regular concrete blocks was about 3.9 and the operating air temperature was 45°C to cool down concrete blocks with 60°C.

a). Figures 5.56 and 5.57 clearly demonstrate that faster air flow results in shorter cooling cycles. Since 1.5 times more energy was stored in the Paraffin impregnated regular blocks (4510 KJ) than in unimpregnated blocks (2941 KJ) it will also be noticed that the time required to complete the cooling mode (846 min. to 663 min.) in the former was about 1.3 greater than for the latter at the same air velocity.

b). Comparison between upper and bottom parts (block number 1, 3, 6, 7, 10 and 12):
One can see from Figures 5.58, 5.59 and 5.60 that the heat stored in PAR impregnated blocks will maintain a comfortable room temperature for about 4 hours longer than in unimpregnated blocks at the same air flow velocity in each respective case. Small variations between upper and lower portions of the blocks are also noted as before.

c). Based on data from Figures 5.61, 5.62 and 5.63, one can establish that Paraffin impregnated regular blocks took 15, 14 and 13 hours at 2, 2.5 and 3 m/s air flow velocity respectively to exhaust the heat stored previously. For unimpregnated blocks, it only took 11, 10 and 9 hours. From the diagrams, we can see that PAR impregnated regular blocks maintained significantly higher temperature for about 6 hours compared with unimpregnated regular blocks. The PCM transition temperature in the RP concrete blocks is clearly indicated at about 54°C which is identical with the value obtained from the DSC analysis of PAR.

d). Outgoing air temperature profiles (block number 12):

The air temperatures at various air flow velocities do not exhibit any significant differences in this case. However, lower air flow velocities also tend to maintain higher outgoing air temperatures for a longer period of time and the Paraffin impregnated blocks retained a slightly higher temperature for almost 4 hours longer than the unimpregnated blocks, as shown in Figures 5.64, 5.65 and 5.66. If there is more latent heat stored in the concrete blocks and greater interior surface areas for increased heat transfer rate, higher outgoing air temperature can be achieved.

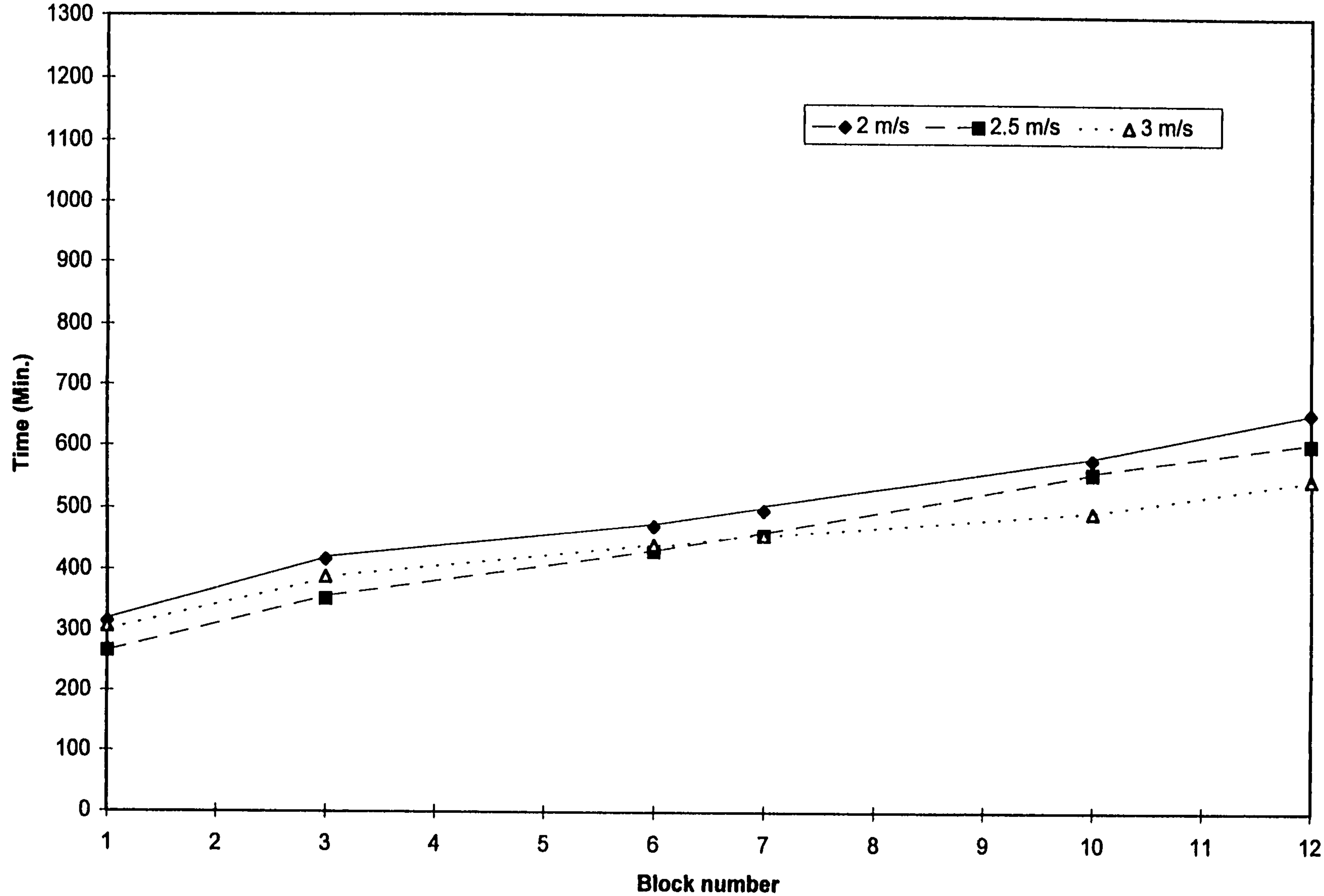


Figure 5.56 Time required for cooling unimpregnated regular blocks (R) from 60°C to 45°C at different air flow velocities [R - Cooling - Bottom]

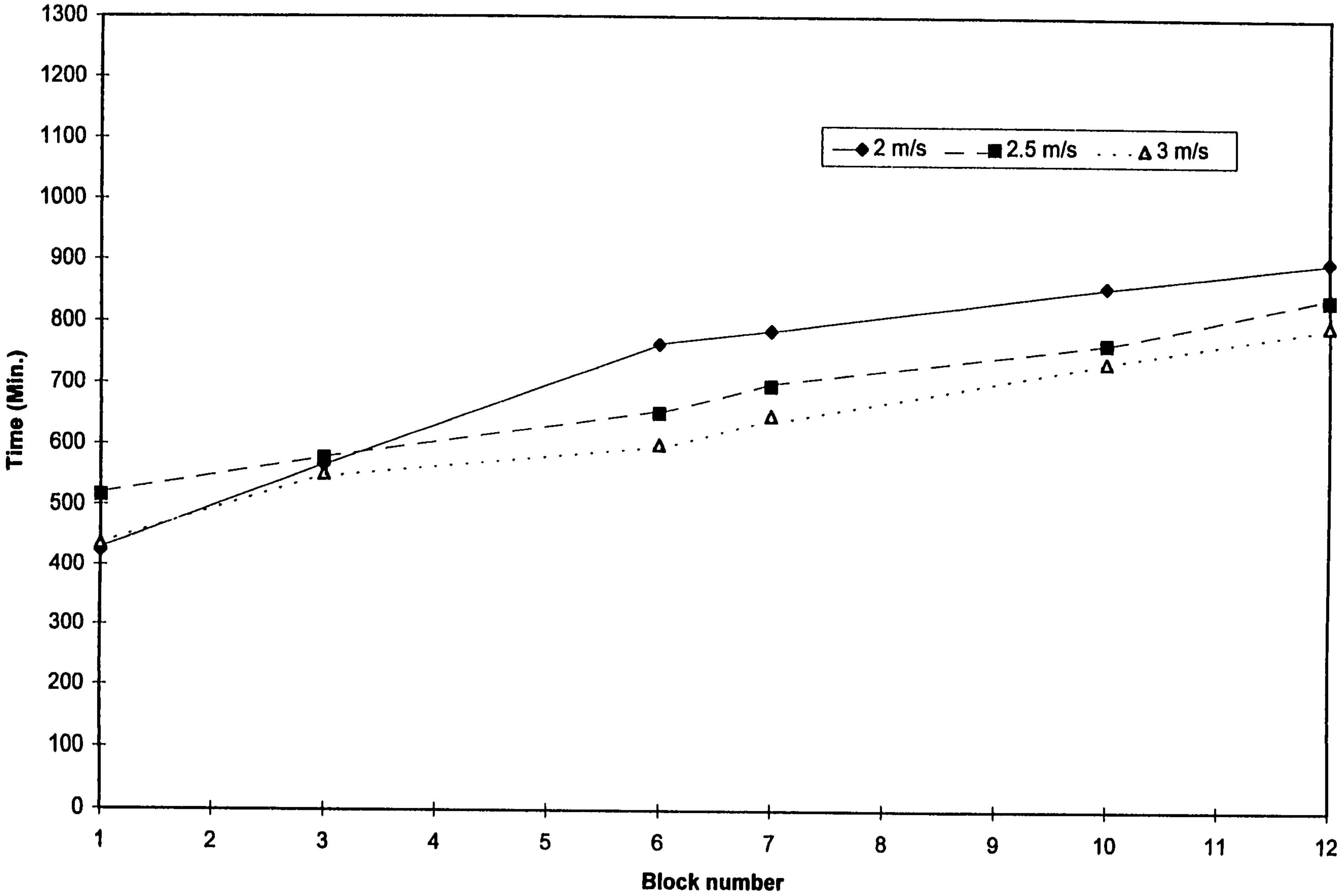


Figure 5.57 Time required for cooling PAR impregnated regular blocks (RP) from 60°C to 45°C at different air flow velocities [RP - Cooling - Bottom]

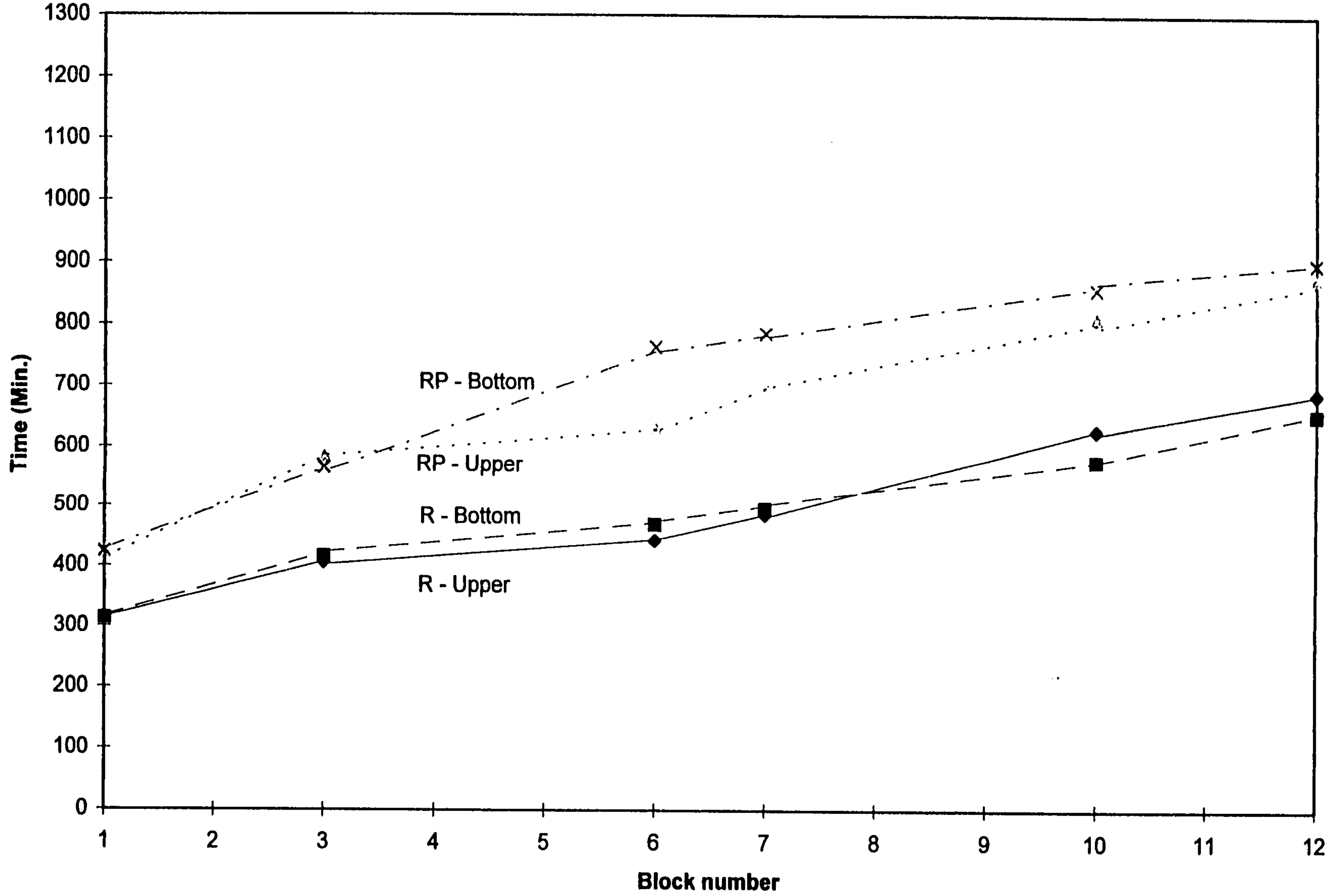


Figure 5.58 Comparison between the time required for cooling unimpregnated (R) and Paraffin impregnated (RP) regular blocks from 60°C to 45°C at 2 m/s air flow velocity

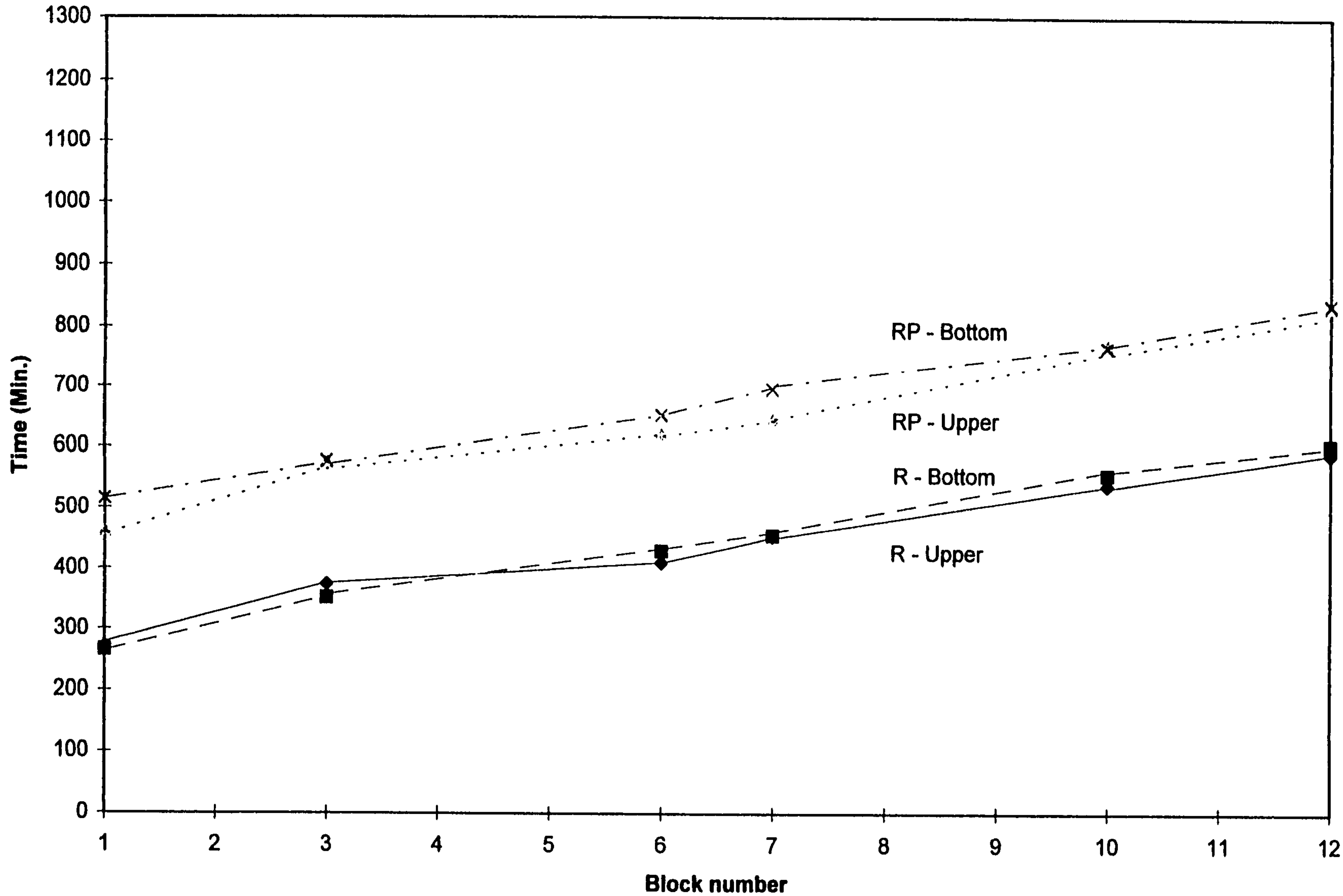


Figure 5.59 Comparison between the time required for cooling unimpregnated (R) and Paraffin impregnated (RP) regular blocks from 60°C to 45°C at 2.5 m/s air flow velocity

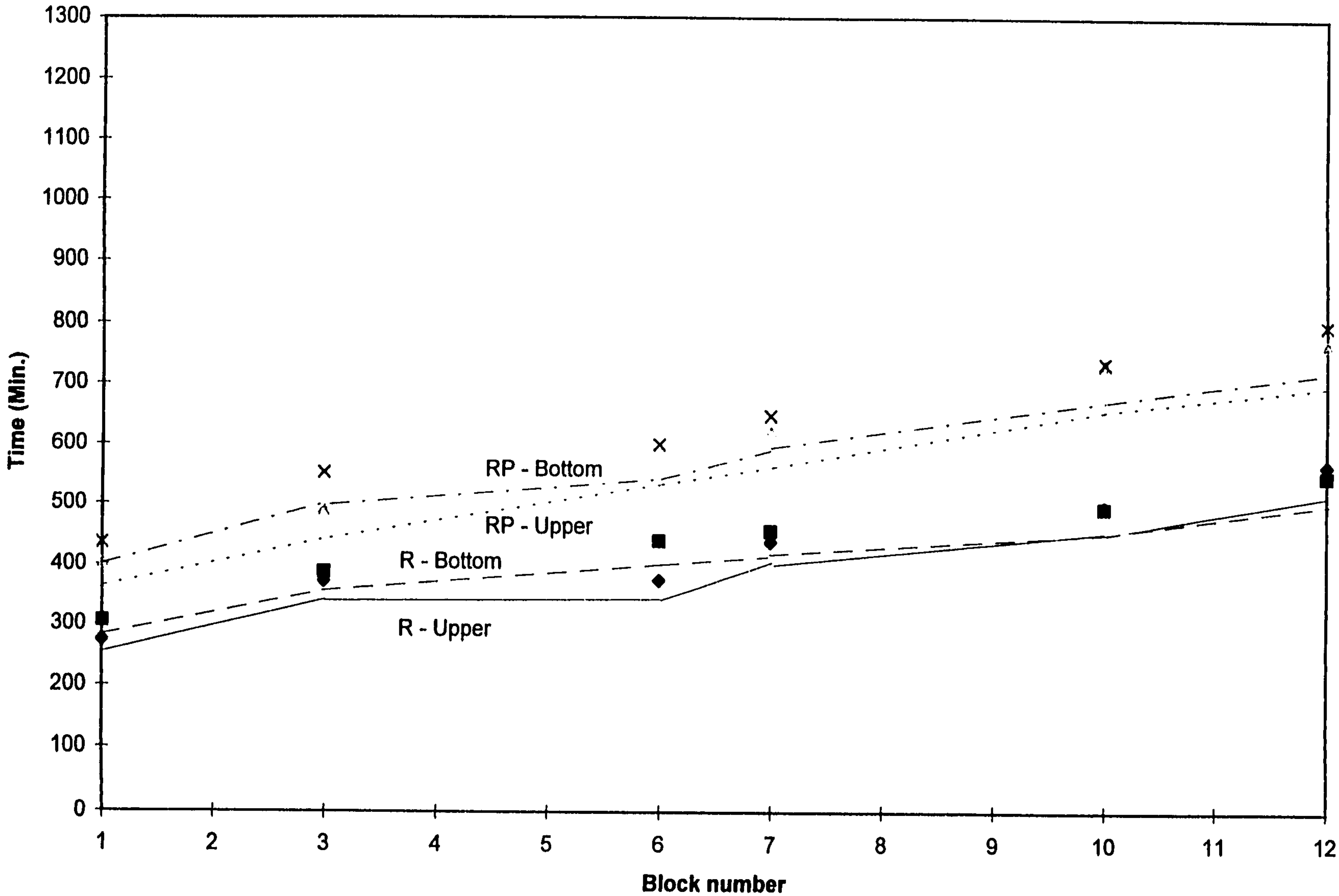


Figure 5.60 Comparison between the time required for cooling unimpregnated (R) and Paraffin impregnated (RP) regular blocks from 60°C to 45°C at 3 m/s air flow velocity

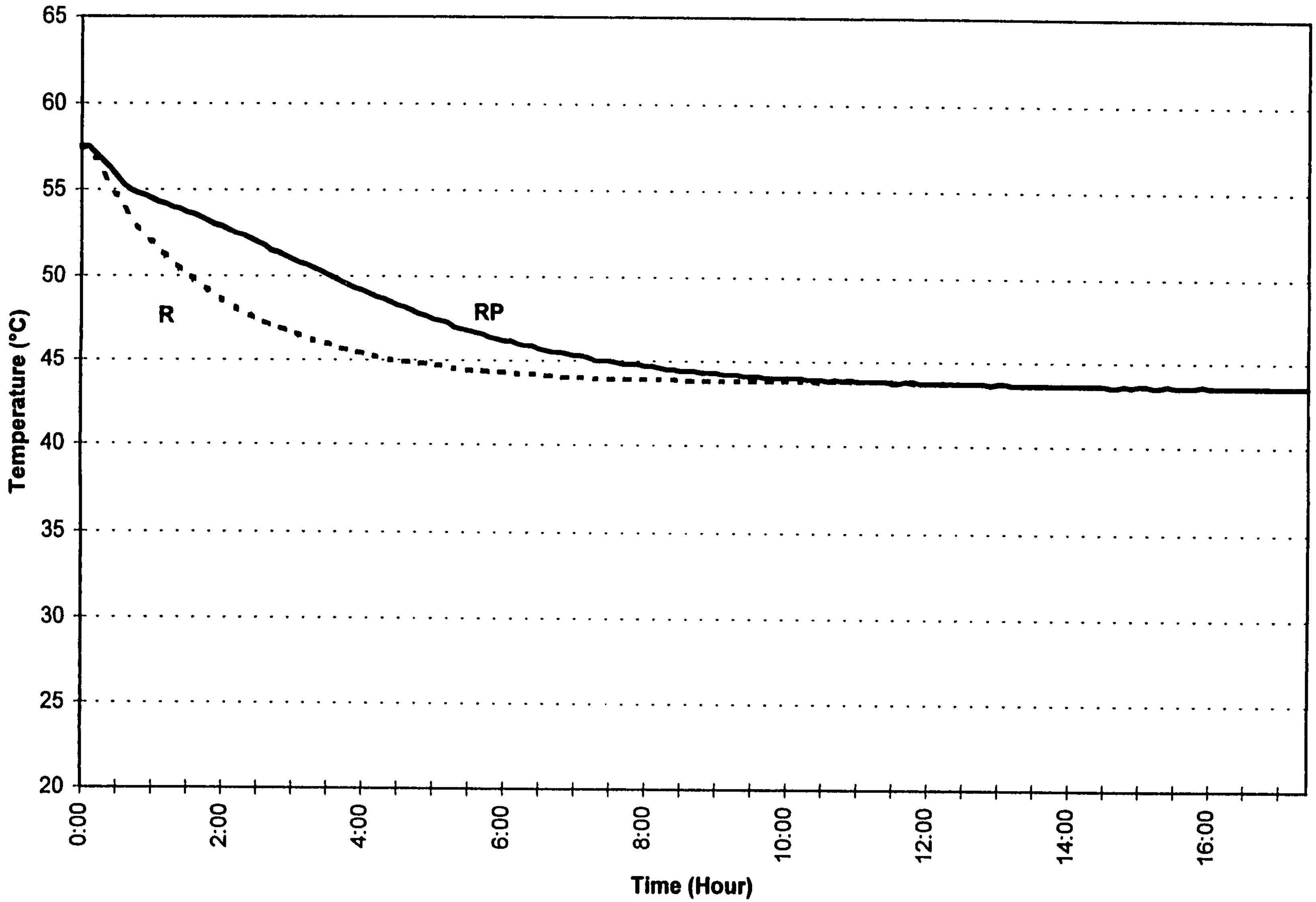


Figure 5.61 Time-temperature curves for unimpregnated (R) and Paraffin impregnated (RP) regular block number 7 at 2 m/s air flow velocity

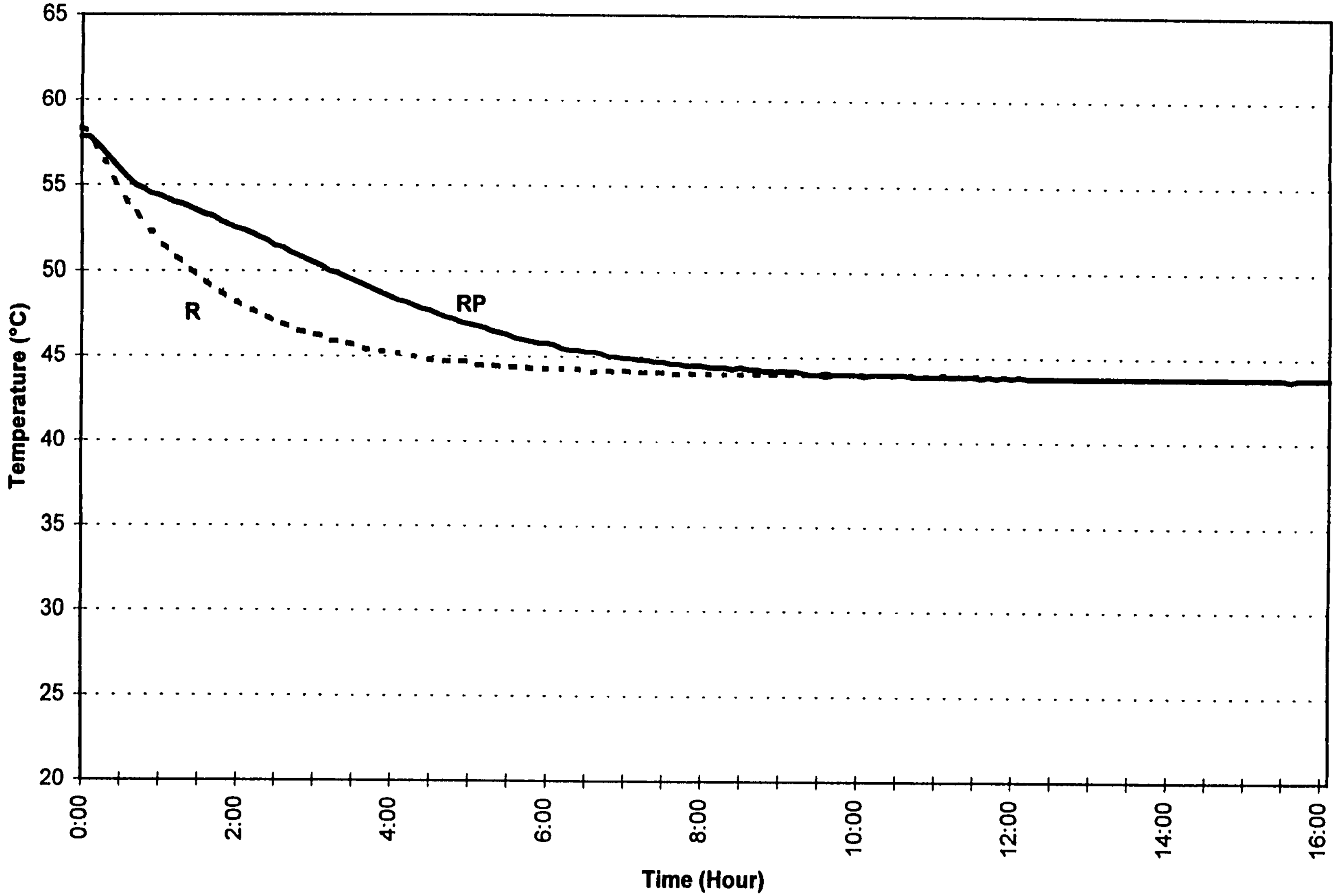


Figure 5.62 Time-temperature curves for unimpregnated (R) and Paraffin impregnated (RP) regular block number 7 at 2.5 m/s air flow velocity

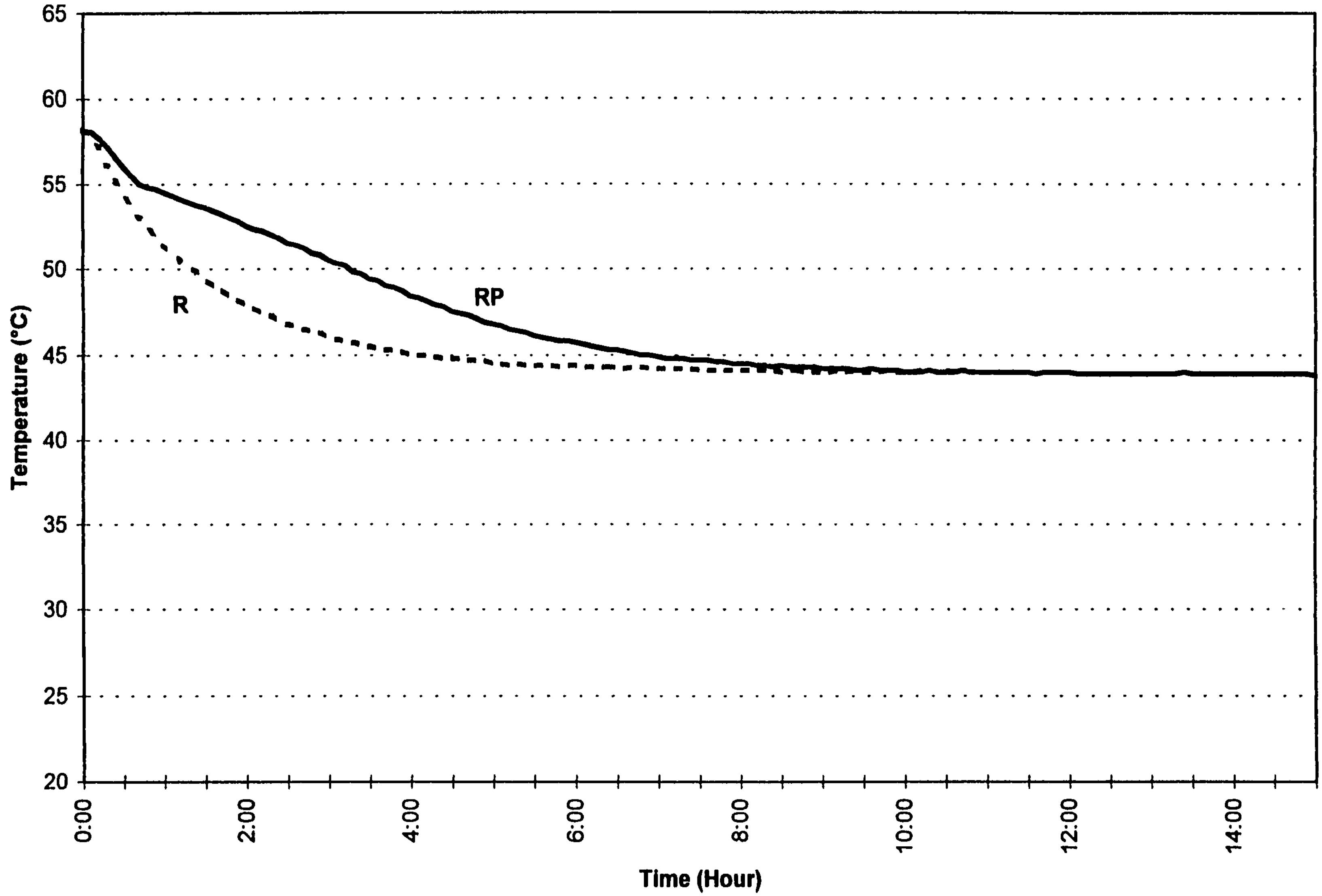


Figure 5.63 Time-temperature curves for unimpregnated (R) and Paraffin impregnated (RP) regular block number 7 at 3 m/s air flow velocity

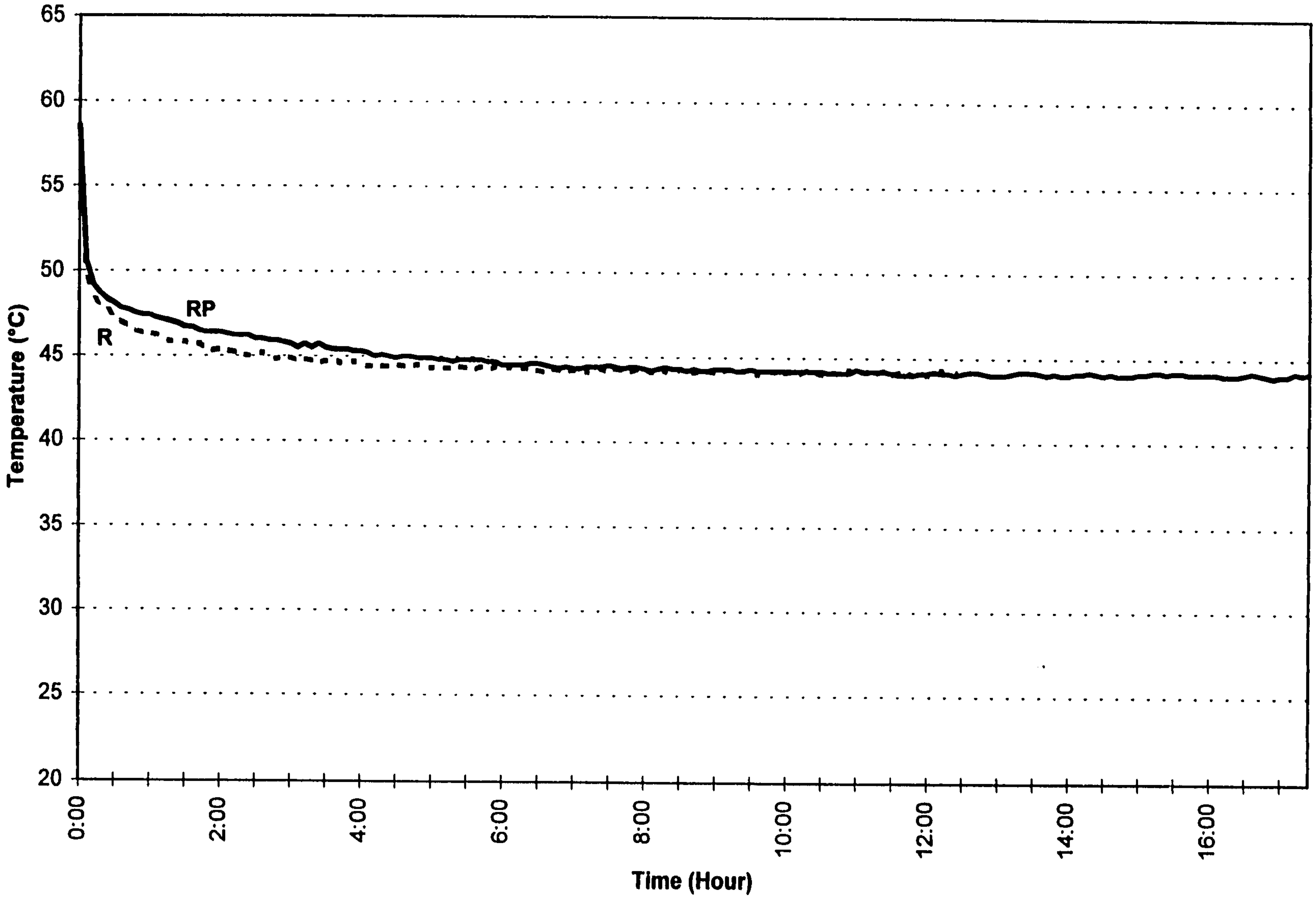


Figure 5.64 Time-temperature curves for the outgoing air from unimpregnated (R) and Paraffin impregnated (RP) regular block number 12 at 2 m/s air flow velocity

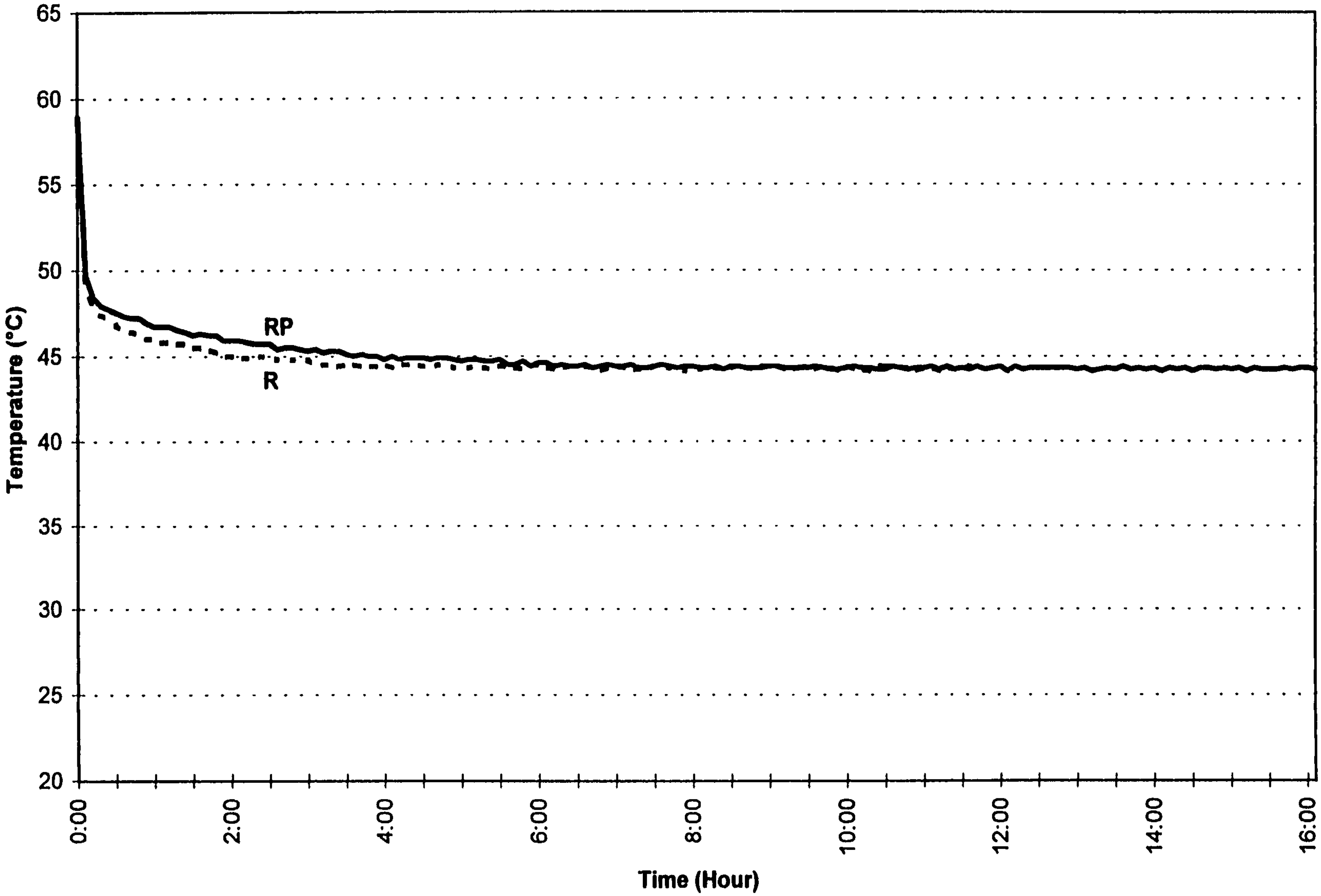


Figure 5.65 Time-temperature curves for the outgoing air from unimpregnated (R) and Paraffin impregnated (RP) regular block number 12 at 2.5 m/s air flow velocity

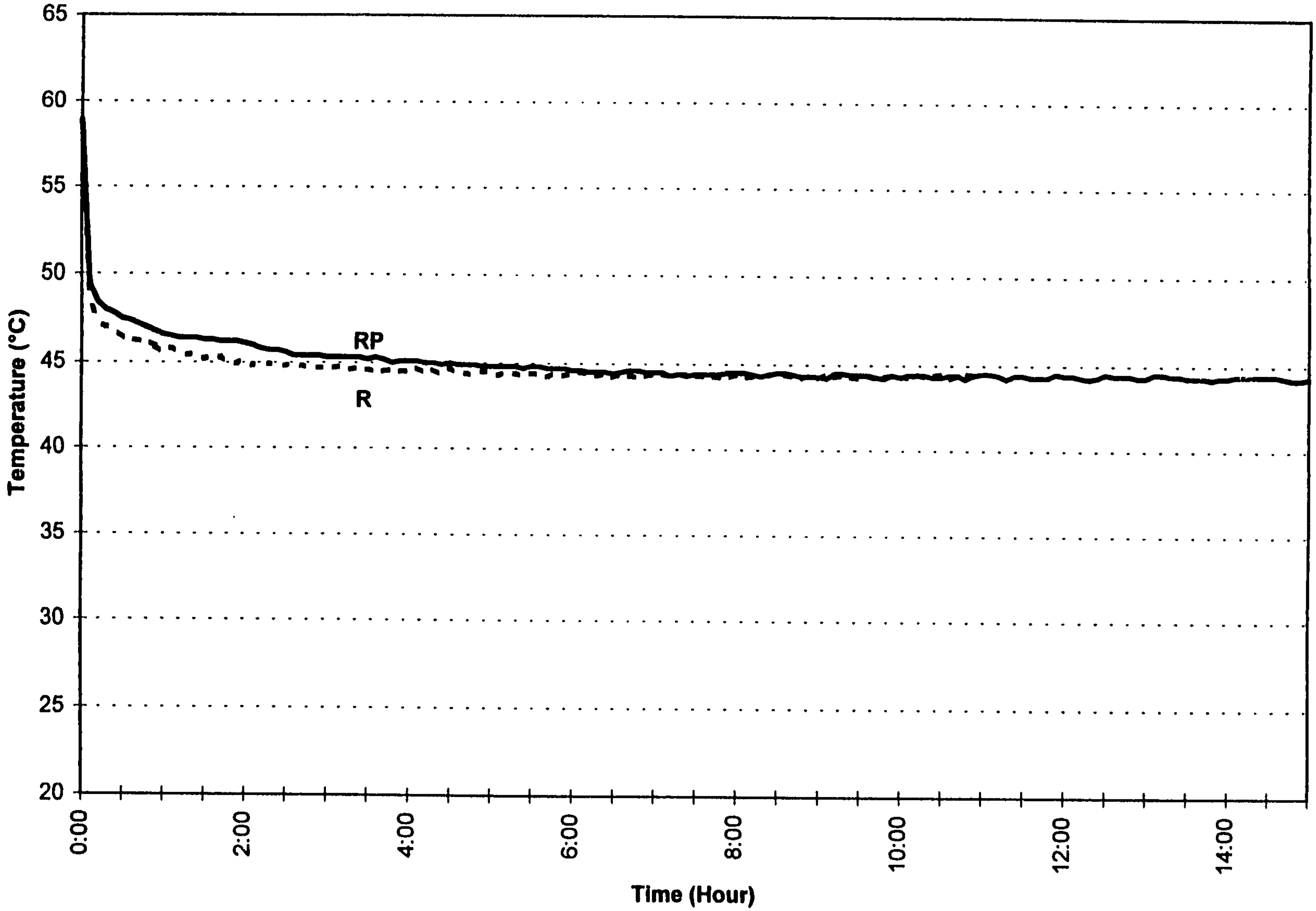


Figure 5.66 Time-temperature curves for the outgoing air from unimpregnated (R) and Paraffin impregnated (RP) regular block number 12 at 3 m/s air flow velocity

5.3 Natural cooling mode

The concrete block tunnel insulated by a wooden box and several plies of insulation was heated up to 60°C and cooling was achieved by using the surrounding room air. In all following discussions, block number 7 was used as comparison. We called this technique, natural cooling.

This form of heat storage would not normally be used in this manner but it does indicate a possible application such as an emergency condition where a long term heat supply could be useful or where the heat supply, although adequate, is intermittent or erratic.

5.3.1 Autoclaved concrete blocks unimpregnated (A) and impregnated with Paraffin (AP)

Cooled by surrounding room temperature, PAR impregnated autoclaved block number 7 needs 150 hours (6 days and 6 hours) to complete the natural cooling. We can see from this (Figure 5.67) that during the experiment the temperature of PAR impregnated block number 7 is 8°C higher and the cooling needs longer time due to the latent heat.

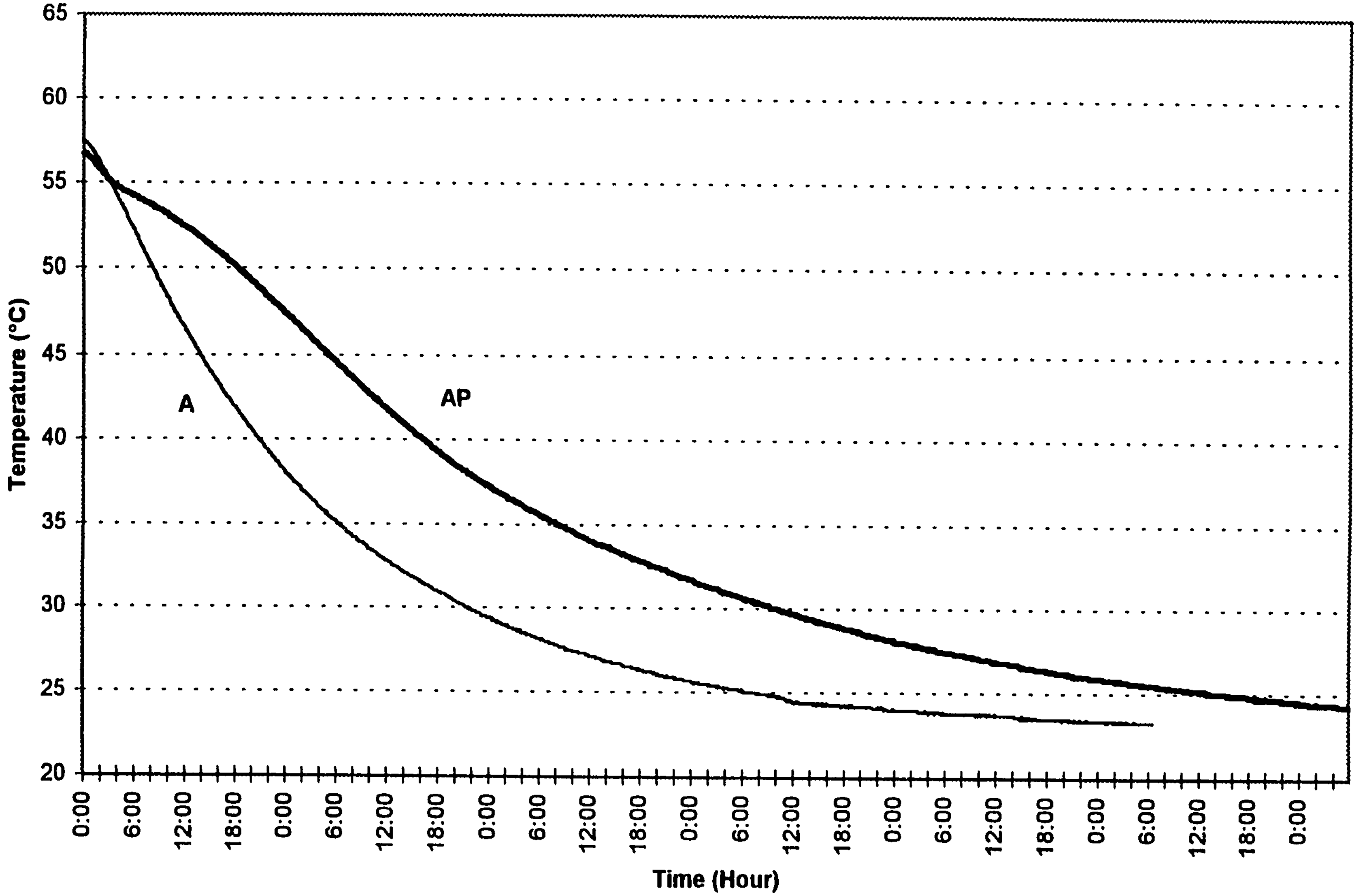


Figure 5.67 Time-temperaure curves of unimpregnated (A) and Paraffin impregnated (AP) autoclaved block number 7 in natural cooling mode [from 60°C to room temperature]

5.3.2 Regular concrete blocks unimpregnated (R) and impregnated with Paraffin (RP)

For PAR impregnated regular block number 7, the natural cooling mode needs 174 hours (7 days and 6 hours) to release the stored energy. The temperature differences between unimpregnated and PAR impregnated are up to 6°C, as shown in Figure 5.68. Compared with previous case having 150 hours, this is due to greater amount of heat (both sensible and latent heats) stored in regular blocks than in autoclaved blocks.

As shown in Figure 5.68, the recorded temperature is 39.7°C at the end of second day in central part of PAR impregnated regular block number 7. At the bottom of block number 12 (Figure 5.69), where the temperature was measured at the end of the second day, it was 35.4°C. Whereas the cycle time for these test were extraordinarily long, the difference in the two temperatures does indicate the importance of ascertaining the effects of insulation, air leakage and position of the block when determining the exact thermal storage potential.

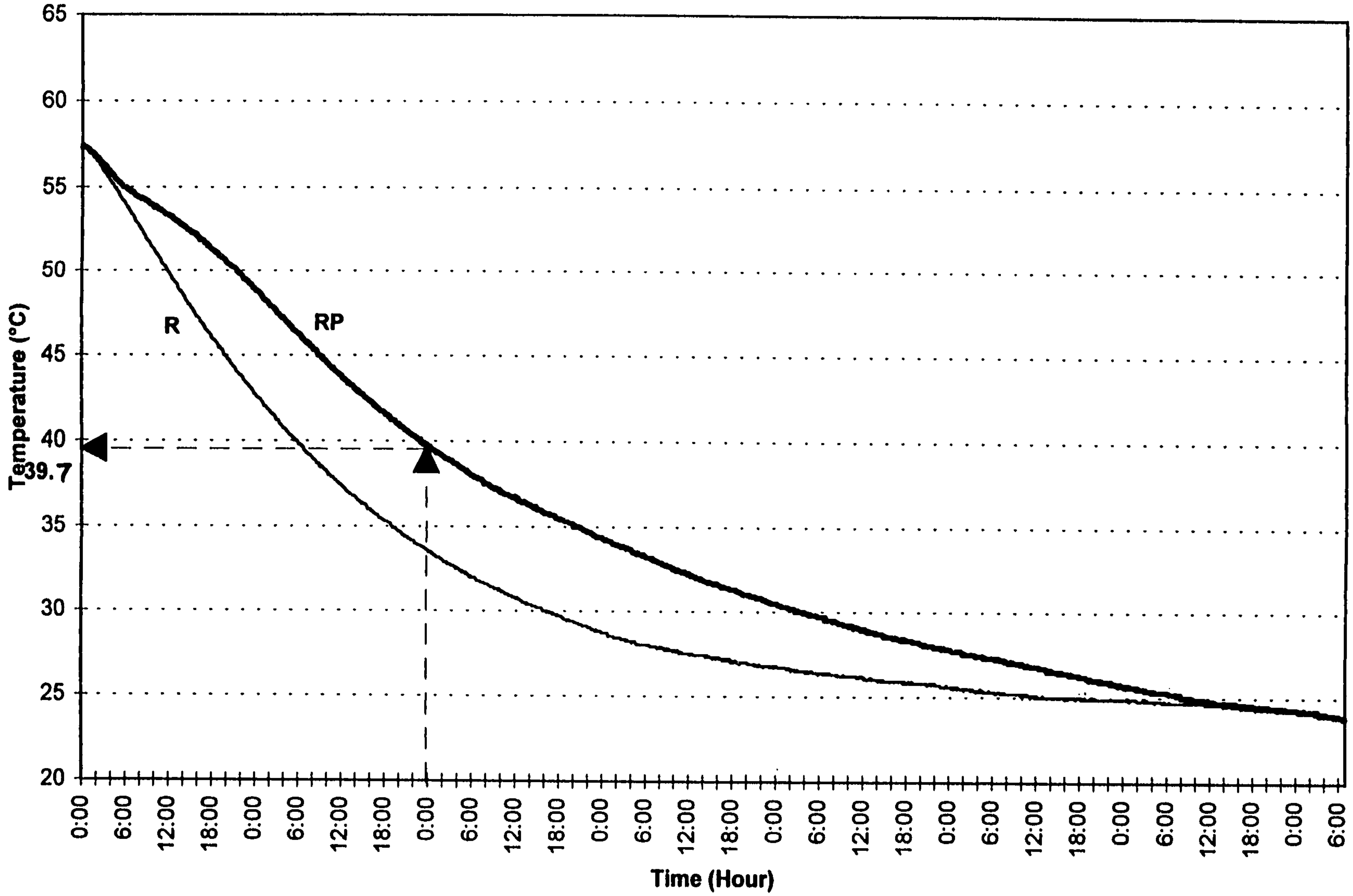


Figure 5.68 Time-temperaure curves of unimpregnated (R) and Paraffin impregnated (RP) regular block number 7 in natural cooling mode [from 60°C to room temperature]

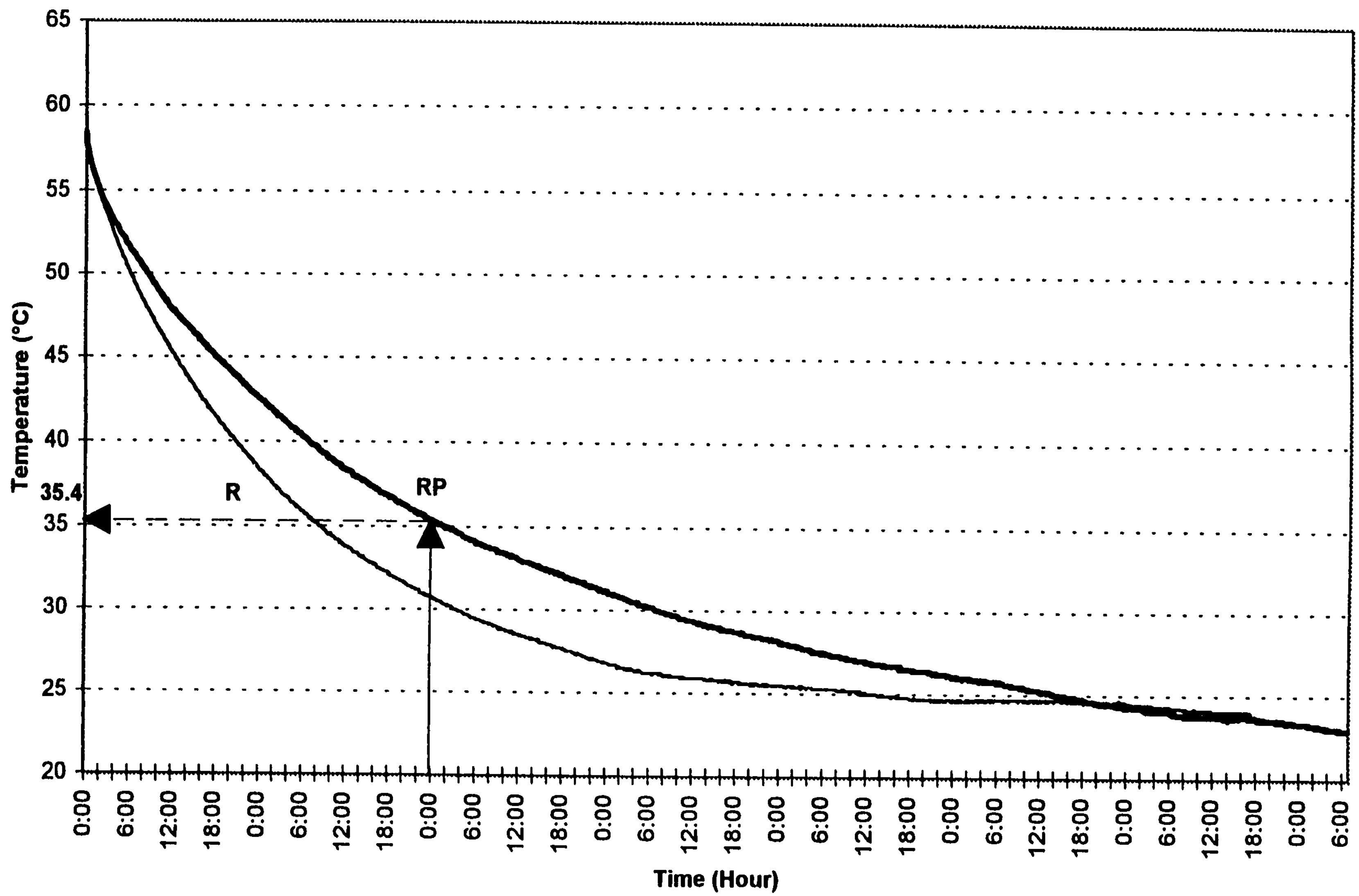


Figure 5.69 Time-temperaure curves for the air temperature of unimpregnated (R) and Paraffin impregnated (RP) regular block number 12 in natural cooling mode [from 60°C to room temperature]

5.4 Utilizing PCM latent heat storage

Previously, two temperature ranges in PAR impregnated autoclaved blocks were used, 22°C to 60°C and 45°C to 60°C. The purpose of this was to evaluate the heating and cooling performance by comparing latent-sensible heat storage and latent heat storage only.

Firstly, from Figures 5.70 and 5.71, one can see that utilizing only the latent heat storage range, 45°C to 60°C, this one provides better performance. During the heating mode, utilizing only the latent heat storage range results in a faster charging time and in the cooling mode, it shows a longer discharging period. Secondly, it also releases a higher air temperature (Figure 5.72). Thirdly, it will be seen that the ratio of sensible and latent heat storage to sensible heat storage is high (table 5.1) of considerable interest is the close correlation between the heating and cooling curves over virtually the same period of time at the same air flow velocity thus indicating the possibility of a very satisfactory heat recovery performance in practice.

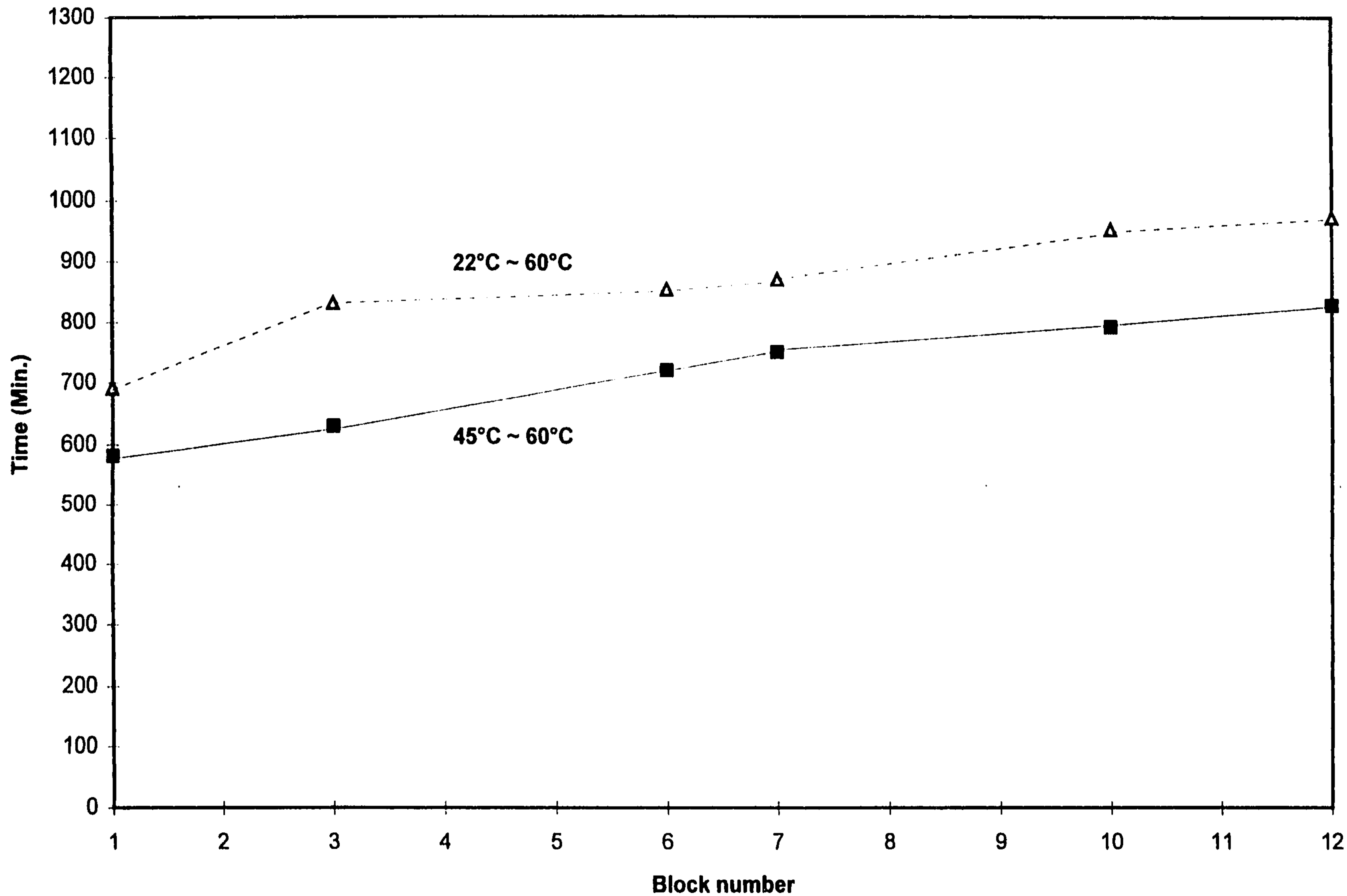


Figure 5.70 Time required for Paraffin impregnated autoclaved blocks (AP) from 22°C and 45°C to 60°C at 3 m/s air flow velocity [AP - Heating - Bottom]

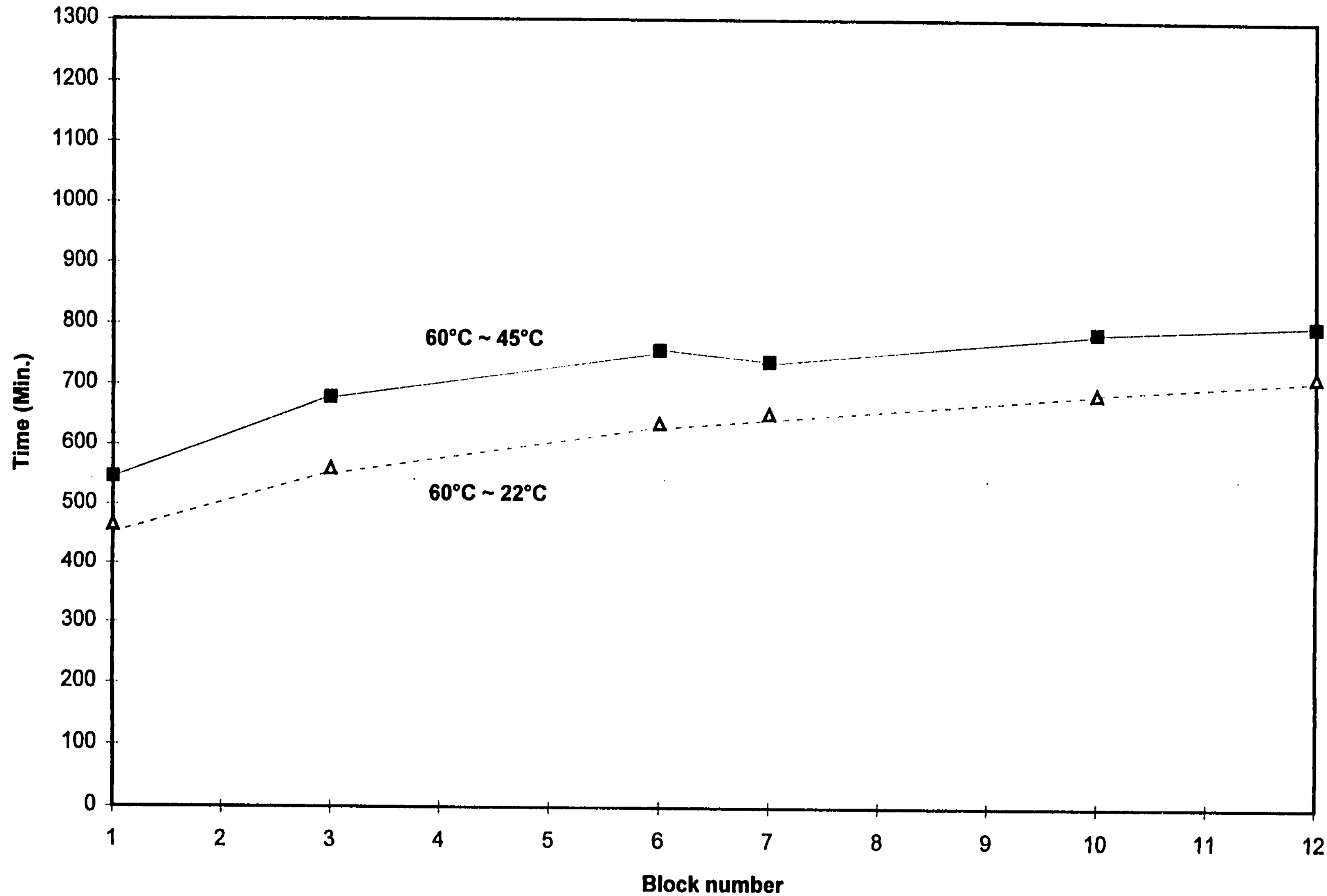


Figure 5.71 Time required for Paraffin impregnated autoclaved blocks (AP) from 60°C to 22°C and 45°C at 3 m/s air flow velocity [AP - Cooling - Bottom]

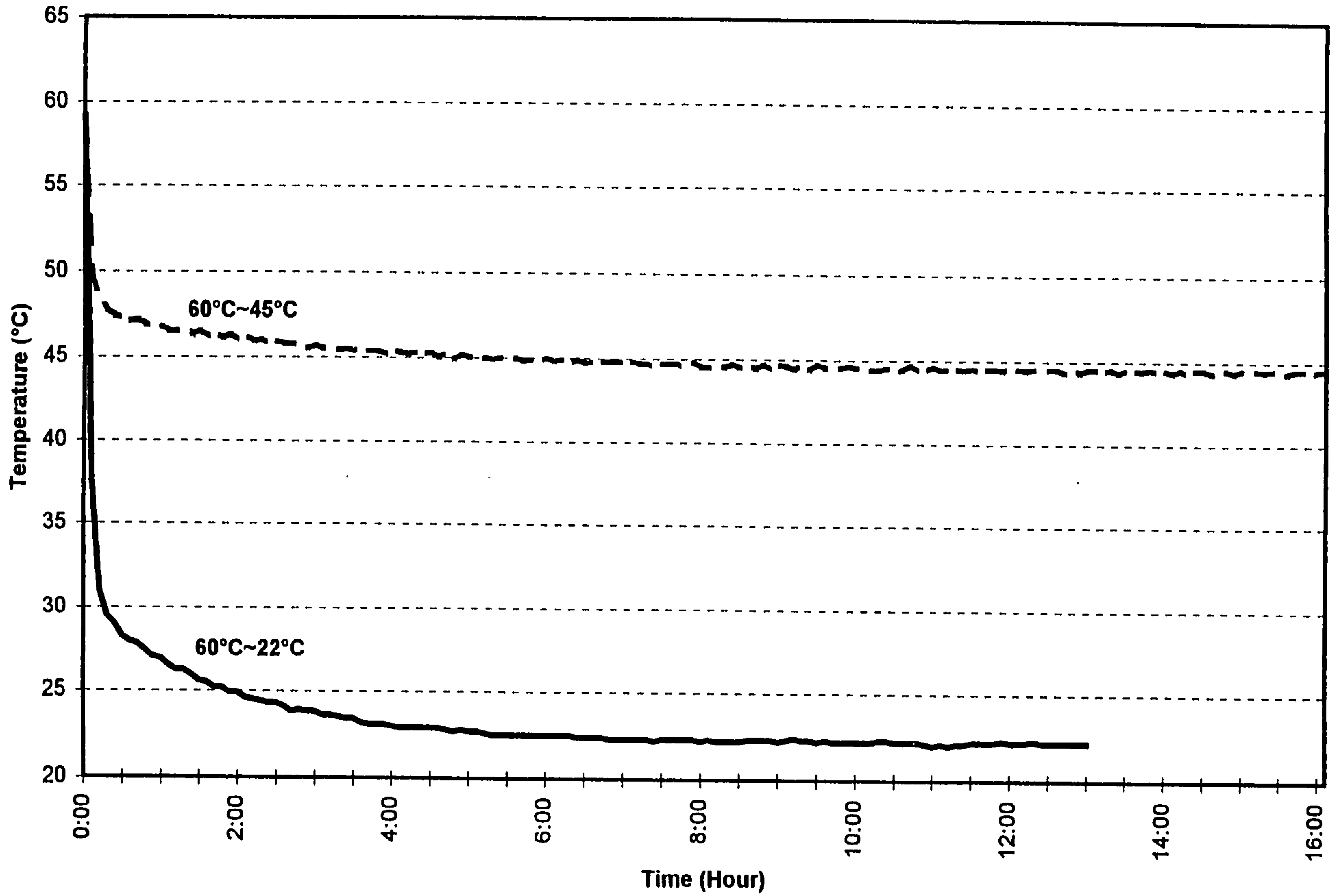


Figure 5.72 Time-temperature curves for the outgoing air from Paraffin impregnated autoclaved (AP) block number 12 at 3 m/s air flow velocity

5.5 PCM stability in concrete blocks

All unimpregnated and PCM impregnated concrete blocks were weighed before and after testing. Furthermore, the PCM impregnated blocks were also cut (along their thickness) to investigate the distribution of PCMs by visual and DSC analysis. It was observed that the BS and PAR were evenly distributed in autoclaved and regular block.

A slight decrease in the weight of the autoclaved and regular blocks impregnated with PAR was found after 20 cycles of heating and cooling. This was probably due to some PAR leakage during the heating cycles. Most likely, this leakage is caused by the very thin film of impregnated PAR which remains on the exterior surfaces of the blocks. Due to its high chemical stability, Paraffin does not have any potential reaction with the hydration products of cement or the aggregates or with materials in contact with the impregnated blocks.

For the autoclaved blocks impregnated with PAR, the total weight loss is around 0.42% after 20 heating and cooling cycles which represents about 5% of total PCM used for impregnation.

For the regular blocks impregnated with PAR, the total weight loss is 1.2% which represent about 31% of total PCM weight. The higher amount of PCM leakage occurring in regular concrete blocks is due to the block's denser structure. Absorption of PCMs is more difficult in such a structure which comprises denser aggregates. Therefore, the appropriate PCM amount that could be impregnated in these blocks without loss should be determined to achieve reliable and long term performance.

Figures 5.73 and 5.74 present the DSC diagrams of PAR impregnated in autoclaved and regular blocks after 20 heating and cooling cycles. The DSC analyses of samples taken from different parts of an AP block show that the PAR is evenly absorbed by the dendritic structure and chemically stable.

The weight of autoclaved blocks impregnated with BS did not change after 20 heating and cooling cycles. The data in Figure 5.75 were obtained from testing four samples collected from different BS impregnated blocks. Based on the results of DSC analyses performed at 2 °C/min, we can say that the thermal characteristics have not changed. The latent heats in both melting and freezing is due to the presence of BS.

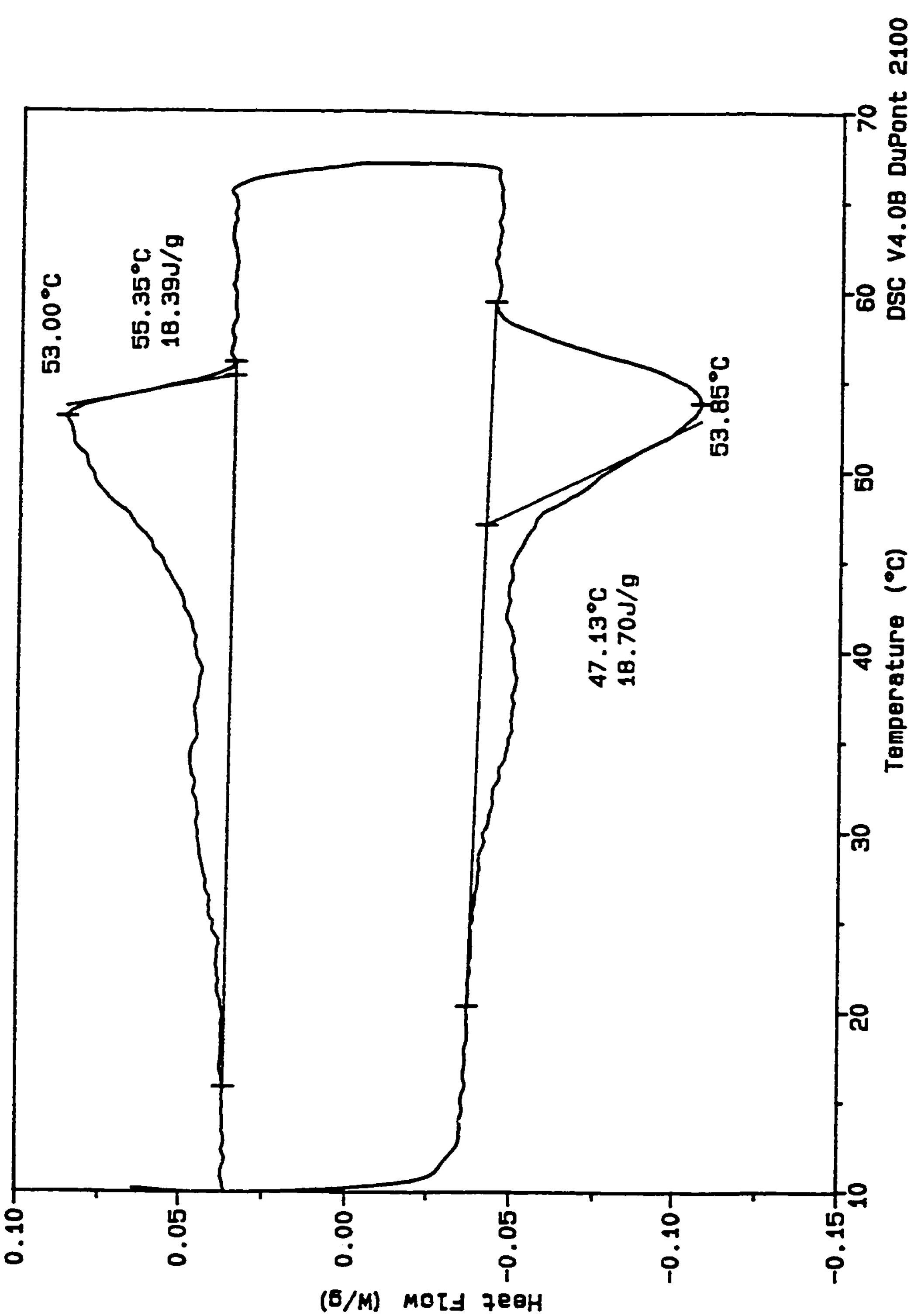


Figure 5.73 DSC analysis of Paraffin impregnated autoclaved blocks (AP) number 12

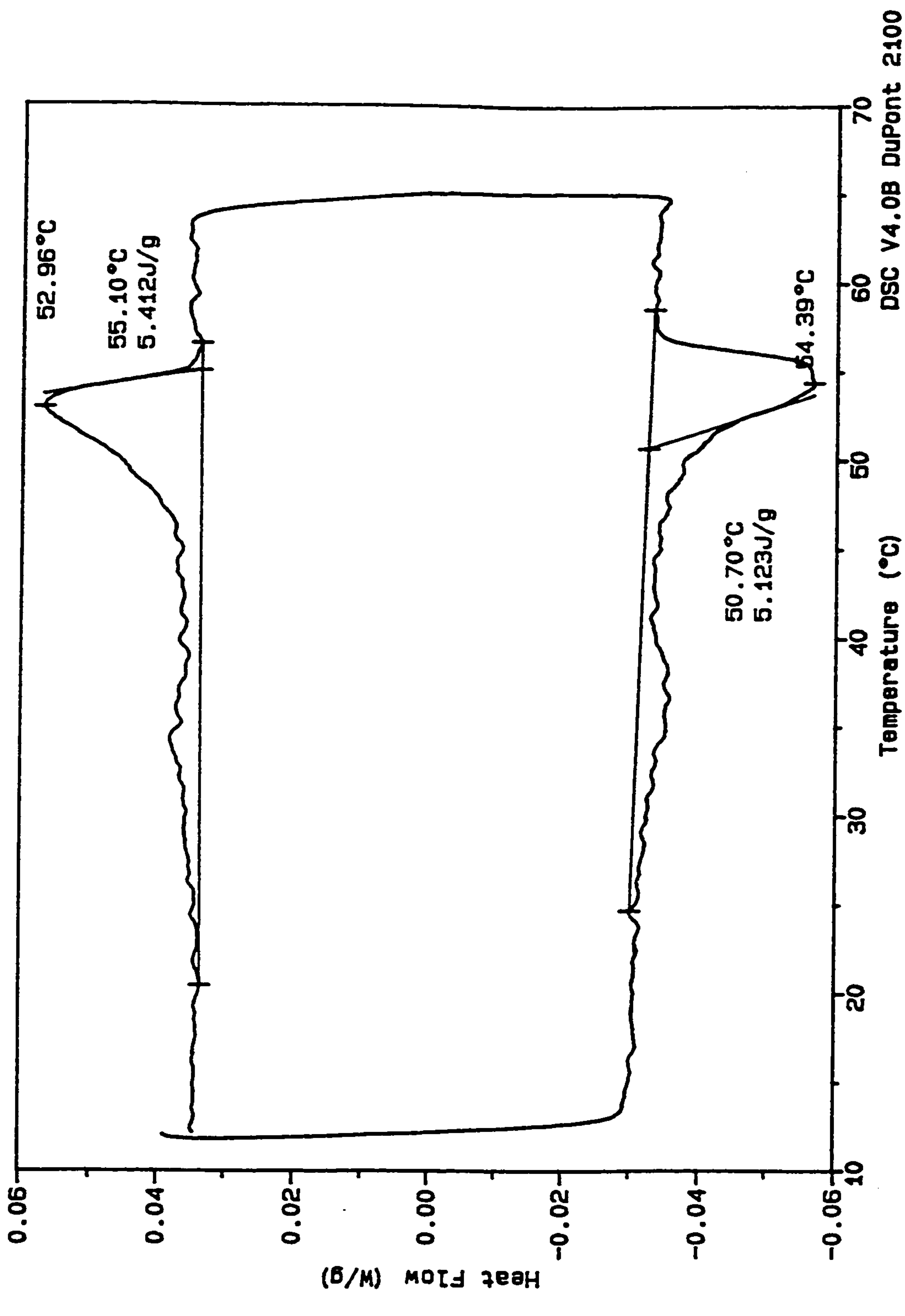


Figure 5.74 DSC analysis of Paraffin impregnated regular blocks (RP) number 12

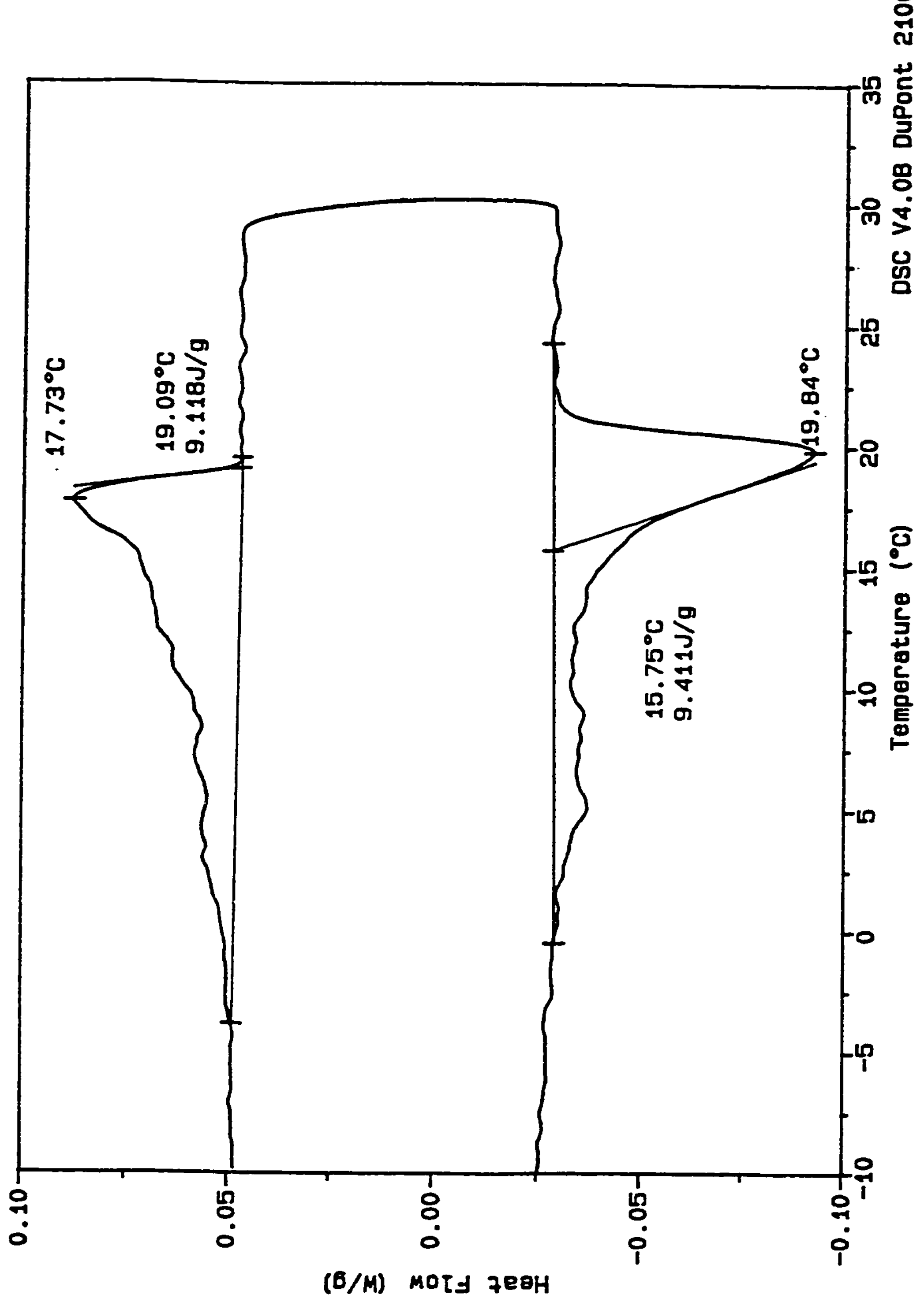


Figure 5.75 DSC analysis of Butyl Stearate impregnated autoclaved blocks (ABS) number 10

5.6 Prediction of required air flow velocity to complete the charging and discharging in a designated time

As shown in table 5.1, AP concrete blocks have the highest PCM percentage and heat storage ratio (up to 2.2 times). Moreover, autoclaved concrete blocks are lighter and widely used in industry and PAR is a more stable PCM. The following is an advanced step to verify the predicted trend in using autoclaved blocks impregnated with PAR.

Type of block	A	A	A	R	R
PCM	BS	PAR	**PAR**	PAR	PAR
% of PCM in block	5.6	8.4	**8.4**	3.9	3.9
Temperature range	15°C~25°C	22°C~60°C	**45°C~60°C**	22°C~60°C	45°C~60°C
Storable sensible heat in blocks (KJ)	1428	5337	**2107**	7451	2941
Storable sensible heat in PCM (KJ)	233	1136	**449**	705	278
Storable latent heat in PCM (KJ)	977	2771	**2082**	1718	1291
Total storable heat (KJ)	2638	9244	**4638**	9874	4510
Total storable heat / storable sensible heat in block	1.9	1.7	**2.2**	1.3	1.5

Specific heat of block: 0.88 KJ/Kg*°K [18]
Specific heat of BS: 2.41 KJ/Kg*°K [18]
Specific heat of PAR: 2.04 KJ/Kg*°K [18]
Latent heat of BS: 101 KJ/Kg (15°C ~ 25°C)
Latent heat of PAR: 189 KJ/Kg (22°C ~ 60°C), 142 KJ/Kg (45°C ~ 60°C)

Table 5.1 Calculated storable heats in various PCM blocks

As stated, 2, 2.5 and 3 m/s air flow velocities were tested both in heating and cooling. In addition, a higher velocity of 3.9 m/s was also tested to verify its effect on the duration of the process. The time for heating and cooling was calculated by averaging the time required by the upper and bottom parts of block number 12. By establishing air flow velocity versus time relations, we can extrapolate to get the appropriate air flow velocity necessary to charge and discharge energy within a designated time. For example, considering an office building which has to be heated during the day time (16 to 18 hours), we assume the necessary time for charging heat during night time into AP blocks is 6 to 8 hours. So, we put in Figure 5.76 the time-air velocity data already obtained and through extrapolation on X-axis, velocities of 4.7 m/s to 5.2 m/s were obtained. Considering these data, approximately 5 m/s is the appropriate air flow velocity recommended to achieve the expected goals. For discharging heat to office space, we consider 16 to 18 hours heat supply, so, 1.1 m/s to 1.8 m/s air flow velocity is the appropriate air flow range (Figure 5.77).

Plotted in the same way, Figures 5.78 and 5.79 can be used for the predictions for ABS blocks. For the heating mode, 3.6 m/s to 4.2 m/s is the appropriate air flow range and for the cooling mode, 1.1 m/s to 1.7 m/s is the desired air flow range. Figures 5.80 and 5.81 represent the diagrams for RP blocks in charging and discharging processes respectively. We can see that for the heating mode, the range is from 4.8 m/s to 5.6 m/s and for cooling mode, the range is 1.2 m/s to 1.9 m/s. The AP blocks exhibit greater storable latent-sensible heat ratio (see table 5.1) at an average air flow velocity of 5 m/s.

There are some other factors to consider in practice which would render charts such as Figures from 5.76 to 5.81 more accurate. These would include relevant conditions, such as local power supply policies, the operation of the facility, actual vertical multi-row construction and HVAC dispatch systems.

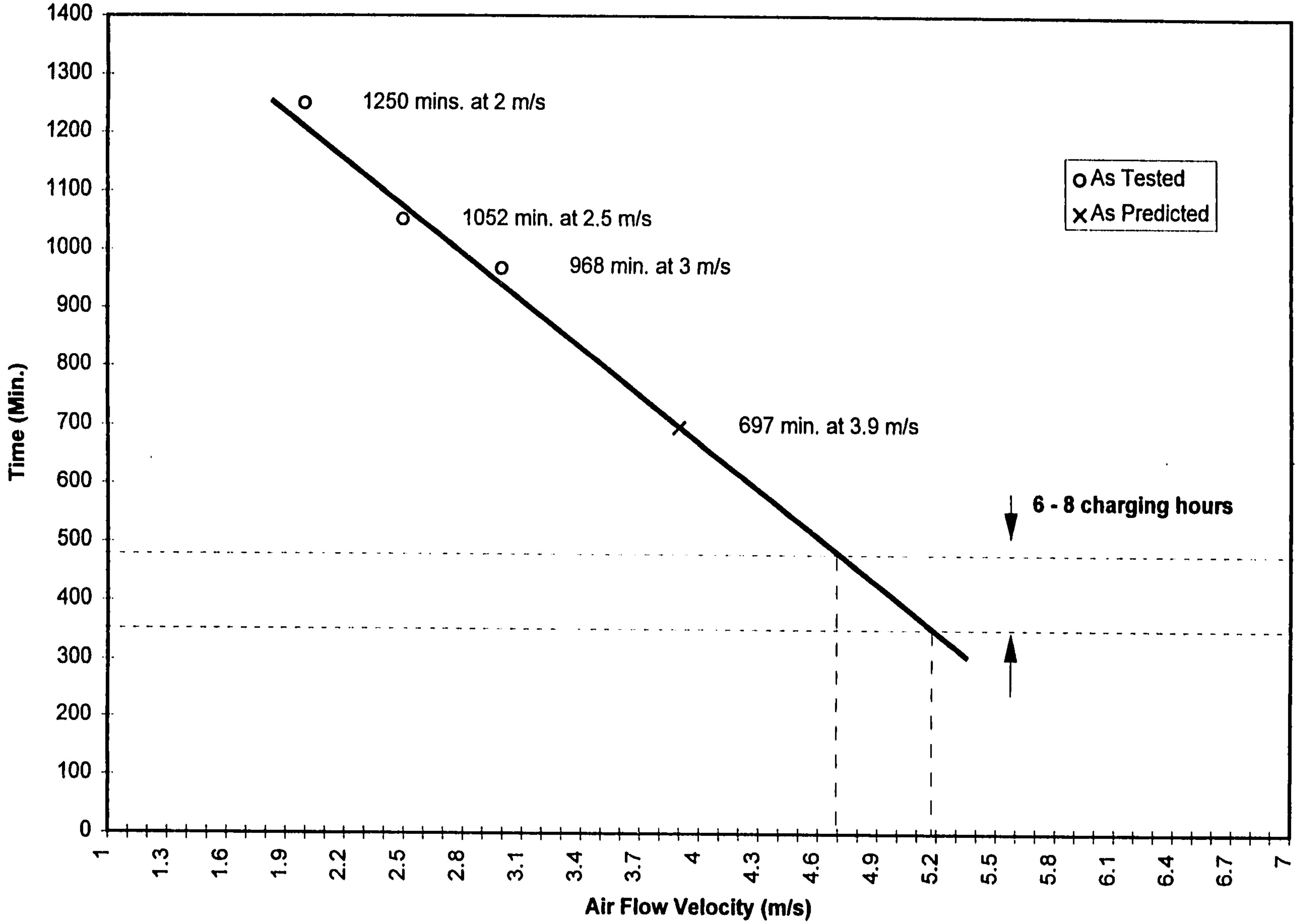


Figure 5.76 Prediction in heating mode of AP

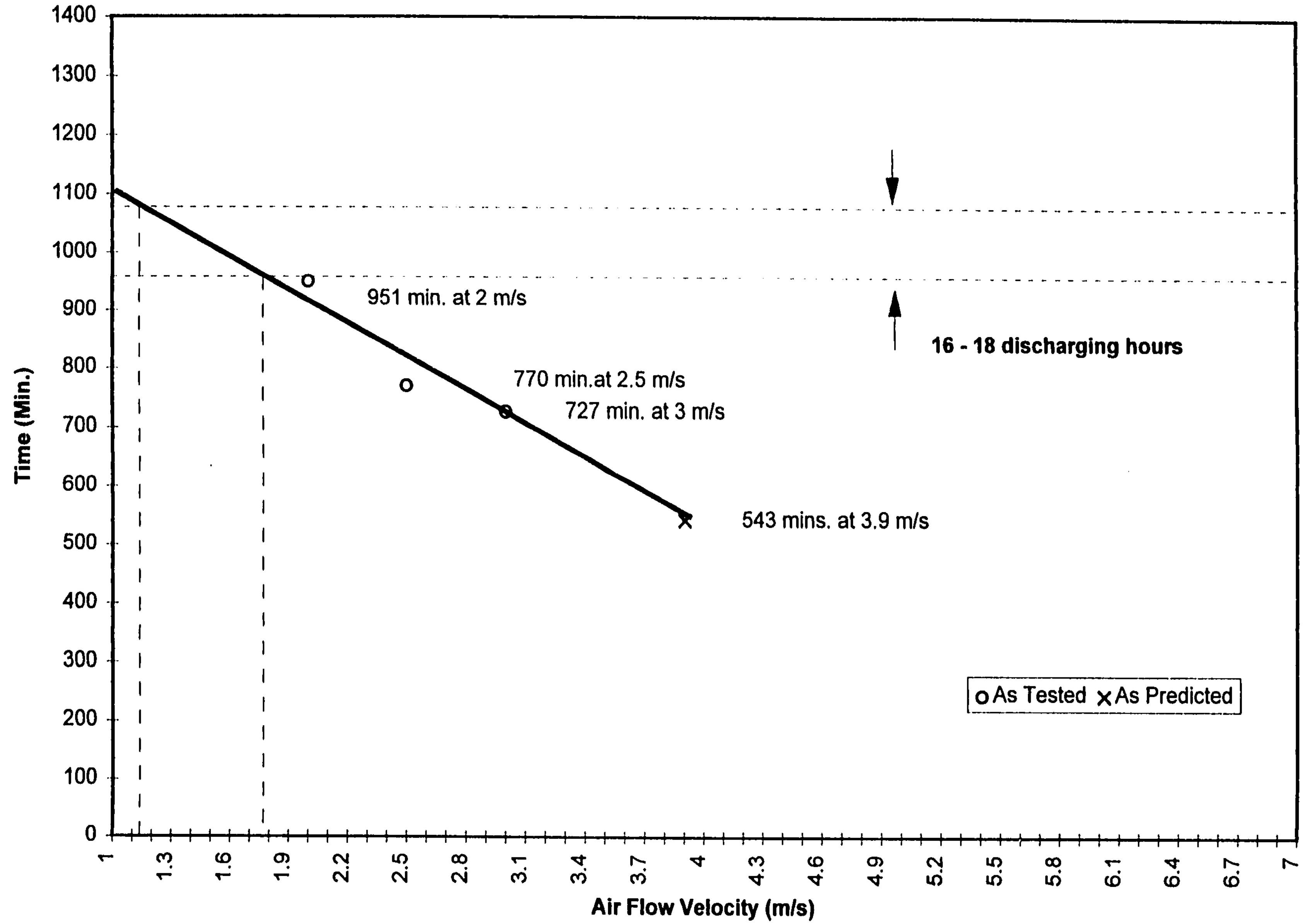


Figure 5.77 Prediction in cooling mode of AP

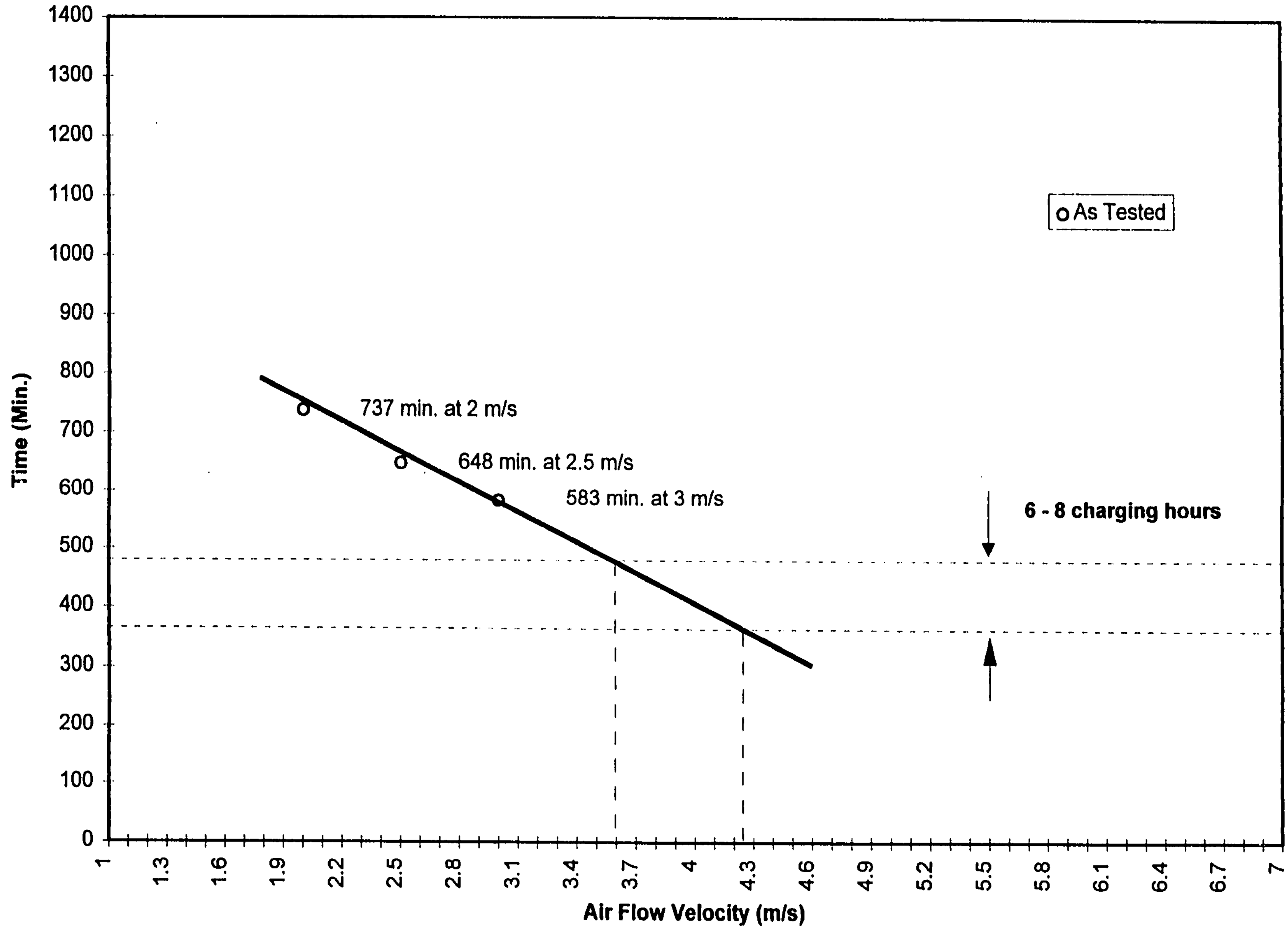


Figure 5.78 Prediction in heating mode of ABS

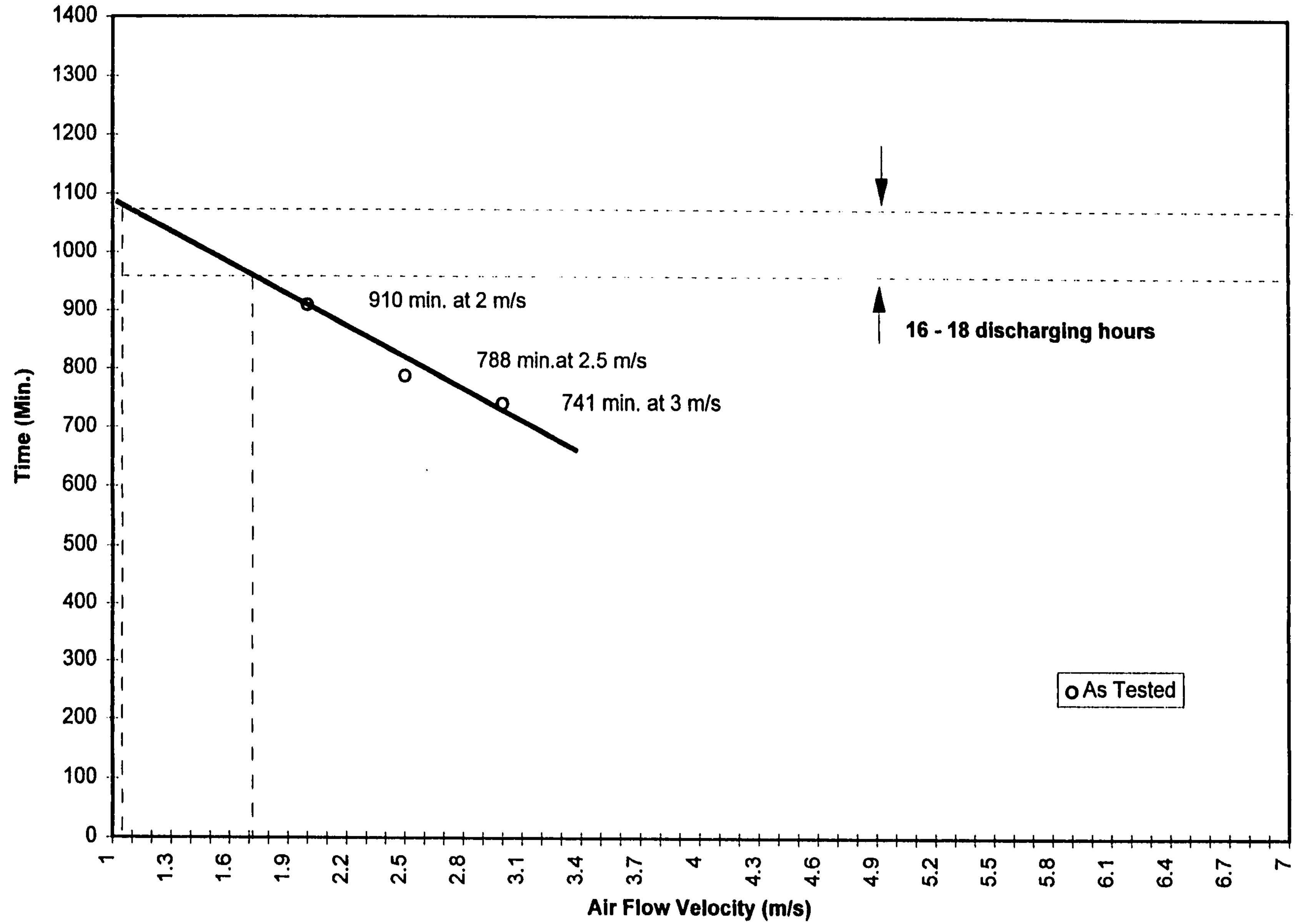


Figure 5.79 Prediction in cooling mode of ABS

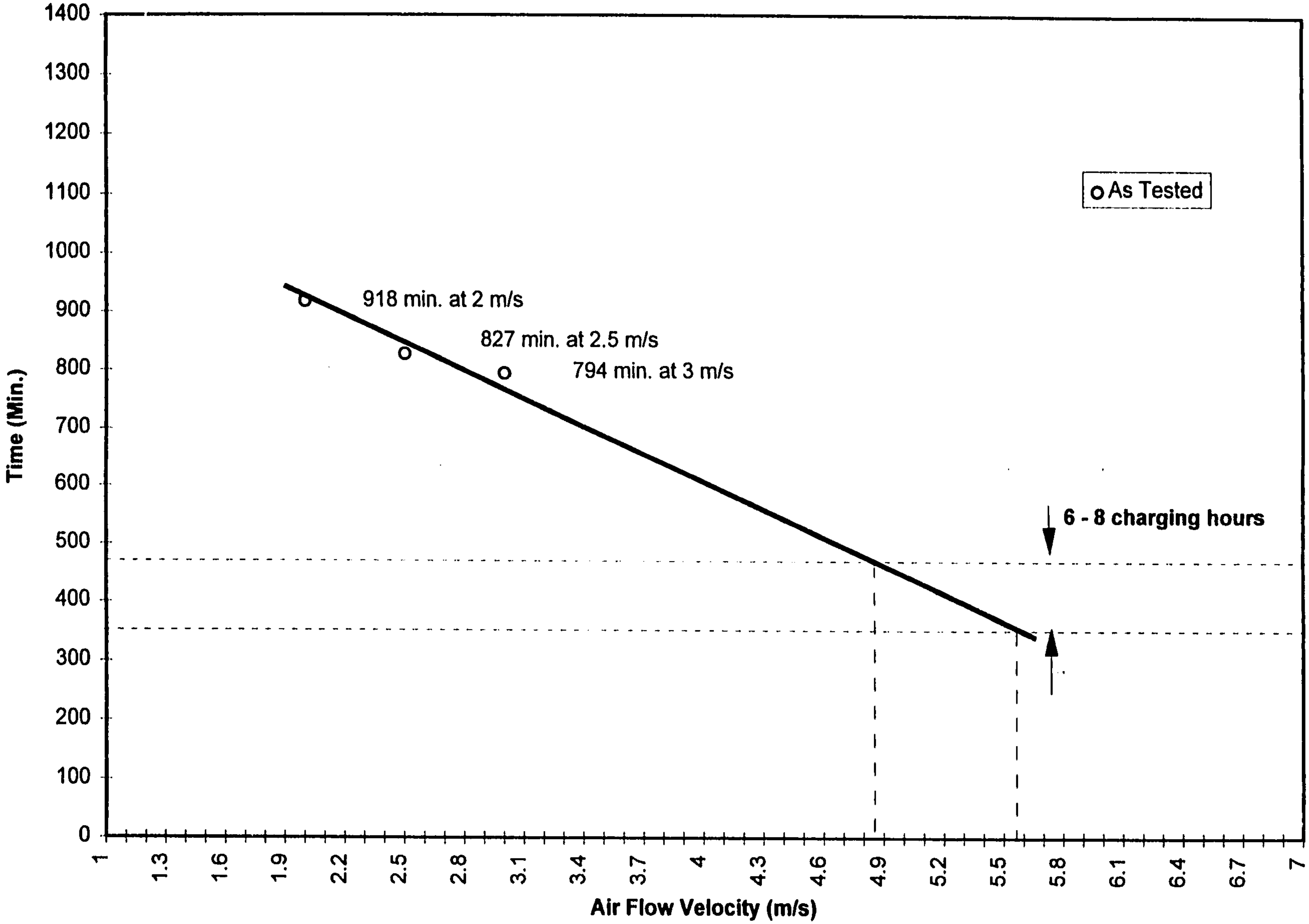


Figure 5.80 Prediction in heating mode of RP

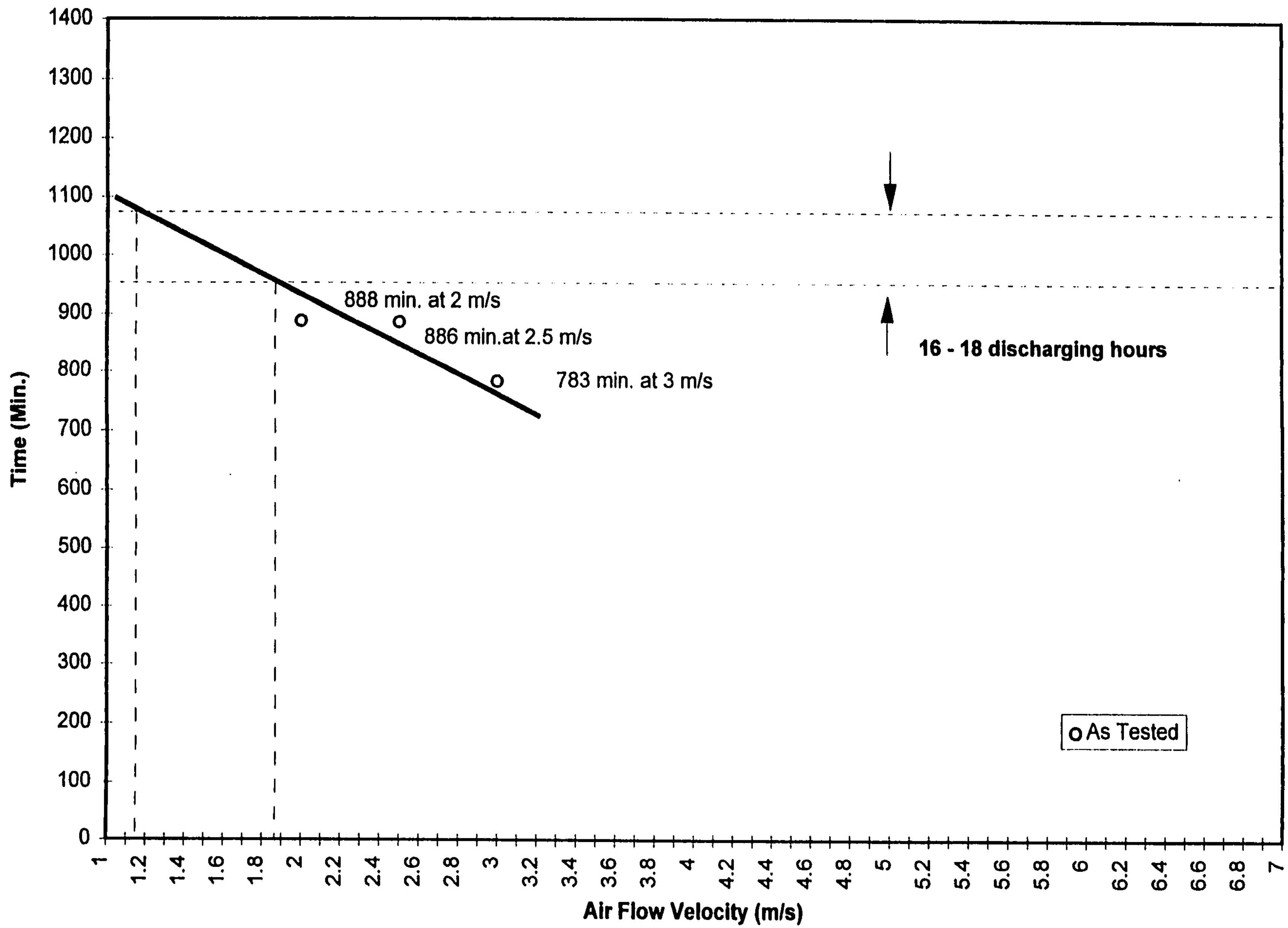


Figure 5.81 Prediction in cooling mode of RP

CHAPTER 6. CONCLUSIONS

6.1 Outcome of the research

The thermal storage performance difference between unimpregnated and PCM impregnated block was evaluated by building a thermally insulated concrete block tunnel through which air was passed at certain range of temperature and flow velocities.

The tested tunnel was monitored by a computerized data acquisition system and an HVAC system was controlled by a microprocessor based digital controller.

The PCMs selected in this experiment were Butyl Stearate and Paraffin due to their favorable latent heat storage capacity, melting and freezing temperature ranges and chemical stability.

The BS and PAR were incorporated into blocks by immersing blocks in melted PCMs.

The three different PCM-block combinations used in these experiments were:

-BS impregnated autoclaved blocks (ABS);

-PAR impregnated autoclaved blocks (AP);

-PAR impregnated regular blocks (RP).

They were heated from 15°C to 25°C, 22°C to 60°C and 45°C to 60°C operating temperature ranges respectively and cooled from 25°C to 15°C, 60°C to 22°C and 60°C to 45°C under air flow velocities of 2, 2.5 and 3 m/s. For Paraffin impregnated autoclaved blocks (AP), the 45°C to 60°C temperature range was tested to evaluate the thermal storage performance by using only the latent heat and the air flow velocity 3.9 m/s was also tested.

Among the various PCM blocks, Paraffin impregnated autoclaved blocks (AP) operated at PCM temperature transition range (45°C ~ 60°C) exhibit the highest total storable heat / storable sensible heat in block ratio which means that more heat can be stored at the same mass volume.

6.2 Conclusions

1. The study shows the possibility of obtaining PCM concrete blocks using different kind of phase change materials having different thermal characteristics.
2. The experimental results showed that PCM impregnated concrete block can function as thermal storage device; Paraffin (UNICERE 55) can be impregnated in both regular and autoclaved blocks without any chemical interactions with concrete components, but BS (EMEREST 2326) can only be impregnated in autoclaved blocks and not in the regular ones due to its reaction with the alkaline components.
3. It was proved that thermal storage capacity of autoclaved block can be enhanced by impregnating it with Butyl Stearate or Paraffin.

4. Both Butyl Stearate and Paraffin can be incorporated in both regular and autoclaved blocks by immersion where the PCMs were evenly absorbed by whole concrete structure.
5. The autoclaved block possesses a more porous structure than regular block. Therefore, more PCMs can be impregnated in autoclaved block and result in greater storable latent heat.
6. The experimental results show that the Butyl Stearate and Paraffin in block transition points are close to those obtained from DSC analyses.
7. Taking in account the ratio between total stored heat and sensible heat, high values can be obtained using the transition temperature ranges of PCMs; among the systems studied in this research, AP blocks with a certain amount of PAR (8.4 %) exhibit the greatest ratio.
8. The higher the air flow velocity, the shorter the charging or discharging process so that time limits can be controlled as desired.
9. The heat can be charged (or discharged) to (or from) the PCM impregnated block at a designated time schedule which can result in using various energies or electricity during an off-peak demand period. In addition, it can effect a reduction in the size and energy consumption of the HVAC system.
10. The outgoing air temperature of PCM impregnated block maintains a temperature which is higher for 3 to 4 hours longer when discharging previously stored heat as compared to the unimpregnated block. This means that the PCM impregnated block can provide a more comfortable room temperature. In practice, of course the difference maintained would be more than 1°C.

This research has realized its objectives and demonstrated that PCM concrete block shows considerable promise as a cost effective and practical means of thermal storage in buildings. While it is now ready for use, it is still in an early stage of development and further work is expected to extent its range of application.

Although suitable in Canada under appropriate circumstance, the principal application of latent heat storage in concrete block at present will be found in those climate with significant diurnal temperature swing such as that found in large areas of the U.S. However, when fossil fuel prices rise significantly, as they inevitably must or when the use of high grade energy is restricted, then, as a practical means of thermal storage, PCM concrete block will find a wide range of application in Canada as well.

6.3 Recommendations

By utilizing different air flow velocity combinations in heating and cooling processes, we can design a system for operation in a range of situations. For example, in office environments, we can quickly charge heat into the blocks during evening and operate at slower air flow velocities to discharge the stored heat during daytime.

Recommended further studies:

1. Vertical arrangement and multiple rows at different heights of concrete blocks: to simulate the practical construction techniques.

2. Evaluate the mechanical properties of PCM impregnated concrete blocks: compressive strength test and others.
3. Different transition points: using PCMs with several consecutive narrow melting temperatures in whole arrangement could improve latent heat storage performance.
4. Appropriate PCM impregnation amount: PCM percentages should be established for optimum performance and to prevent leakage.
5. Fire and fume test: to reduce the flammability of PCM concrete block and meet the NBCC or ASTM flammability standards.
6. Incorporating PCM into other concrete products, such as concrete wall, hollow panel, tiles, etc.
7. PCM concrete applications in solar energy conservation.
8. Knowing better the cause of the PCM losses and how to avoid them.

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