THE EFFECTS OF CONSTRUCTION MATERIALS ON THERMAL COMFORT IN RESIDENTIAL BUILDINGS; AN ANALYSIS USING ECOTECT 5.0.

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
THE MIDDLE EAST TECHNICAL UNIVERSITY

BY

NEVİN AYDIN GEZER

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
THE DEPARTMENT OF ARCHITECTURE

JULY 2003

Approval of the Graduate School of Natural and Applied Sciences of the Middle East Technical University

Prof. Dr. Tayfur Öztürk
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Selahattin Önür
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Asst. Prof. Dr. Soofia Tahira Elias-Özkan
Supervisor

Examining Committee Members:

Assoc. Prof. Dr. Arda Düzgüneş

Assoc. Prof. Dr. Demet Irklı

Asst. Prof. Dr. Soofia Tahira Elias-Özkan

Inst. Dr. Sema Onurlu

Inst. Françoise Summers

ABSTRACT

THE EFFECTS OF CONSTRUCTION MATERIALS ON THERMAL COMFORT IN RESIDENTIAL BUILDINGS; AN ANALYSIS USING ECOTECT 5.0.

Aydın Gezer, Nevin
M. Sc., Department of Architecture
Supervisor: Asst. Prof. Dr. Soofia Tahira Elias Özkan

July 2003, 99 pages

The aim of this study was to provide information about the effects of construction materials on thermal comfort in residential buildings using Ecotect 5.0. Three residential buildings, each of different construction in the province of Yozgat, Turkey were used as study material to this end. At the end of this study, the effects of materials on thermal comfort have been explained by graphical and statistical analysis.

Pertinent literature reports that the thermal responses of occupants depend to some extent on the outdoor climate in naturally ventilated buildings with operable windows. Furthermore, an adaptation occurs in these buildings regarding the occupants' previous thermal experiences, the availability of control, and shifts in expectations. The study therefore focused on collecting data on both indoor and outdoor air temperature and humidity to show the comfort level in such buildings.

By collecting data on 3 houses constructed of different materials the author aimed to show the effects of materials on thermal comfort. The analyses were further extended with computer simulations, which enabled restriction of the parameters on construction materials.

The study has shown that in naturally ventilated residential buildings, construction materials affect both thermal comfort and thermal performance of the buildings. Buildings with traditional construction material showed a better performance in achieving the preferred thermal comfort while decreasing energy costs.

Keywords: Construction Materials, Thermal Comfort, Ecotect 5.0, Residential Buildings, Naturally Ventilated Buildings.

ÖZ

MESKENLERDE BİNA MALZEMELERİNİN ISIL KONFORA ETKİSİ; ECOTECT 5.0. İLE BİR ANALİZ

Aydın Gezer, Nevin
Yüksek Lisans, Mimarlık Bölümü
Tez Yöneticisi: Y. Doç. Dr. Soofia Tahira Elias Özkan

Temmuz 2003, 99 sayfa

Bu çalışmada meskenlerde kullanılan yapı malzemelerinin ısıl konfora etkisinin Ecotect 5.0 yardımıyla araştırılması amaçlanmıştır. Bu çalışmada her biri farklı malzemeden yapılmış Yozgat ilindeki üç ev örnek olarak kullanılmıştır. Çalışma sonucunda malzemenin ısıl konfora etkisi analizler ve grafiklerle açıklanmıştır.

Araştırma ile ilgili olarak yazılmış eserler gösteriyor ki, ev ahalisinin ısıl tepkileri, pencereleri kontrol edilebilen, böylece doğal olarak havalandırılan binalarda dış iklime bağlıdır. Ayrıca, bu binalarda ev ahalisinin geçmiş ısıl deneyimleri, kontrol edebilme, ve tercihlerdeki değişmeler sayesinde adaptasyon görülmektedir. Bu sebeple, bu çalışma doğal olarak havalandırılan binalarda ısıl konfor düzeyini göstermek amacıyla iç ve dış sıcaklık ve nem verilerini toplamaya yoğunlaşmıştır. Farklı malzemeden yapılmış 3 farklı evden data toplanarak malzemenin ısıl konfora etkisini göstermek amaçlanmıştır. Analizler bilgisayar modellemeleriyle devam edilip parametrenin yapı malzemesiyle sınırlanması sağlanmıştır.

Çalışma sonuçları yapı malzemesinin bina performansı ve doğal olarak havalandırılan binalarda ısıl konforu etkilediğini gösteriyor. Geleneksel yapı malzemesiyle yapılmış ev, tercih edilen ısıl konforu sağlamada daha az enerji harcayarak daha iyi bir performans göstermiştir.

Anahtar Kelimeler: Yapı Malzemeleri, Isıl Konfor, Ecotect 5.0, Meskenler, Doğal Olarak Havalandırılan Meskenler.

Anneme

ACKNOWLEDGEMENTS

I would like to first express my sincere appreciation to Asst. Prof. Dr. Soofia Tahira Elias-Özkan, my advisor for her guidance, patience and support throughout the study. My special thanks go to Françoise Summers for her great contribution in this project. Without her initiation and guidance, this study would not have been possible. Thanks are also due to the Kerkenes Team and particularly to Tuğrul Karagüzel for the completion of graphs and drawings.

I would like to thank the British Council for enabling the realization of a Partnership programme between the Architectural Association, London and METU, which was the starting point of this research. Thanks are due Prof. Dr. Simos Yannas of AAEE and Yasemin Somuncu for their briefings and guidance on software and instruments.

Most of all I would like to thank my life partner, Muzaffer, for his support and encouragement during the most difficult days of the study and for his help in the statistical analysis of my data.

My baby boy, Bahadır, who is the sunshine of my life, for behaving well and allowing me to work on my thesis.

…and finally to my mother. Without her help, I would never have finished this study.

TABLE OF CONTENTS

CHAPTER

APPENDIX

LIST OF TABLES

TABLE

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

ANOVA	Analysis of Variance
ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineering
^0C	Centigrade Degree Celsius
C_o	Heat Loss by Convection
df	Degrees of Freedom
DDHRS	Discomfort Degree Hours
E_e	Heat Loss by Evaporation
Er	Heat Loss by Respiration
ET*	Effective Temperature
exp	Exponential
^0F	Degree Fahrenheit
IAQ	Indoor Air Quality
i.r.	Infra Red
K	Heat Loss by Conduction
^0K	Degree Kelvin
kWh	Kilowatt Hours
M	Rate of Metabolic Heat Production
met	Unit of Metabolic Rate

MS	Mean Squares
PPD	Predicted Percentage Dissatisfied
PMV	Predicted Mean Vote
R_a	Heat Loss through Radiation
rh	Relative Humidity
S	Heat Stored in the Body
SS	Sum of Squares
t-test	Tukey' s Procedure
U-Value	Thermal Transmittance
u.v.	Ultra-violet
W	Energy Used

LIST OF SYMBOLS

SYMBOLS	
H_o	Null Hypothesis
k	Number of Treatments
m	Degree of Freedom
n	Sample size, group count
$Q_{\alpha, n, v}$	Studentized Range Distribution
T_c	Comfort Temperature
Tm	Monthly Mean Temperature
Tn	Thermal neutrality
ν	Degree of Freedom
w	Width
X	Sample Mean
z	Standard normal variable
μ	Population Mean
$\sum$	N-Ary Summation
α	Level of significance
σ	Standard Deviation

0

COPYRIGHT NOTICES

Ecotect 5.0.	is licensed to Nevin Aydın Gezer.
Weather Tool 1.1	is licensed to Nevin Aydın Gezer.
M.S. Office	is licensed to Muzaffer Gezer.
Data Loggers	are provided by the British Council Partnership Programme.
Thermohygrometers	are provided by the British Council Partnership Programme.
Aerial	is licensed to Kerkenes Project, Middle East Technical University

CHAPTER 1

INTRODUCTION

In this chapter are presented the argument and objectives of the study, together with a brief overview of the general methodology. It concludes with a disposition of subject matter that follows in the remaining chapters.

1.1 Argument

The thermal dynamics of the human body is one of the main aspects that affect its health. As buildings are made to accommodate human beings, these properties must be taken into consideration in their design. The thermal comfort of occupants is their well-being in a particular environment for a particular climate with respect to their capacity to adapt to the thermal equilibrium, physiological, psychological and behavioural changes. The human body needs to be shielded from the external environment in order to maintain its heat balance. This shield is the 'environmental envelope'[1] of the building where the heat exchange is conducted. Moreover, it is the thermophysical properties of the construction materials that determines the rate of this heat exchange and provides one of the aspects of thermal comfort within any building.

According to the ASHRAE Handbook of Fundamentals (1989), the environmental factors that affect the quality of indoor environment are the *thermal climate* (which is determined by wet- and dry-bulb temperatures, relative humidity or

---

[1] Foster, Jack Stroud. *Mitchell's Building Series, Structure and Fabric, Part1*. (The Mitchell Publishing Company Limited: London, 1983).

water vapour pressure, and air movement), *atmospheric components* (that include gases and vapours) and *air distribution or mixing pattern of ventilation air*. The thermal climate is vitally important to prevent seasonal increase in mortality, and in dehydration and discomfort caused by reduced relative humidity (rh). Moreover, reduced relative humidity can cause damage to the skin, eyes, nose, throat and mucous membranes (pp. 8.27).

Achieving comfort in a building starts with the knowledge of the climate in question and passive strategies to control this climate in order to provide the right design approaches for maintaining comfort. The selections of site, the orientation of the building, vegetation, choice of thermal mass or thermal insulation for the particular climate, as well as the selection of building materials are the major and prime controls in maintaining the thermal comfort of occupants.

Recent studies (de Dear and Brager 1998; ANSI/ASHRAE Standard 55-2000R) have shown that the thermal responses of occupants depend to some extent on the outdoor climate in naturally ventilated buildings with operable windows. Furthermore, an adaptation occurs in these buildings regarding the occupants' previous thermal experiences, the availability of control, and shifts in expectations. Buildings in Central Anatolia are for the most part naturally ventilated. While earlier ones were made of traditional materials such as adobe, recent ones are more commonly of frame structure with brick infill walls. Knowing that materials affect regarding thermal comfort and indoor air quality (IAQ) of the building, their thermal performance needs to be investigated because they are of vital importance for human life.

As technology advanced, in the second half of the 20th century, a high degree of comfort in buildings using mechanical devices and systems was achieved regardless of climate. The modern building began to be designed alike around the world. The main concern was keeping a microclimate providing comfort inside regardless of the one outside. Mainly air conditioning and heating systems were relied upon for solving the problem of comfort. As time passed, the disadvantages of this design aspect were observed and energy-efficient design became important while a balanced climatic design in regard to local climatic elements became a major issue.

It is once again believed that a house in a desert should be different than one in a cool region, and studies have been conducted to achieve human comfort naturally, relying especially on material and design.

Richard Hyde (2000) states that it is appropriate to consider, in particular, the nature of traditional buildings and their environments. These buildings encapsulate thousands of years' naive research into the relationship between building and climate and represent more holistic models for the development of a climate-responsive architecture. These traditional models can be examined as precedents which may shape architecture, rather than provide a set of ready-made solutions. Analytical studies of traditional buildings offer an understanding of the relationship between culture, climate and building form. Indeed, the historical aspects of traditional architecture are dependent on the concerns for climate-responsive architecture. Hyde (2000) further insists that analytical studies of traditional buildings regarding traditional materials may lead to comfort prediction. (pp. 7-8)

Many studies have shown that the most important consideration for the occupants is thermal comfort in the building.[2] The primary concern for an architect should therefore be providing comfort in the buildings they design. The designer needs to possess adequate information about the aspects that make up the thermal environment and thermal comfort in order to maintain the satisfaction of the occupants. As the building materials are one of the important layers in the transfer of heat between outside and inside, it is one of the tangible objects that affect the IAQ and thermal comfort. In this respect, traditional construction techniques and materials are open to investigation in order to uncover their effects on thermal comfort. Achieving thermal comfort by using better building materials would further reduce energy consumption due to heating and/or cooling loads.

---

[2] J. Fergus Nicol, *Mulcom, Thermal Comfort*, (London Metropolitan University), 17 Dec. 2002, <http://www.unl.ac.uk/LEARN/port/1998/mulcom/web/comfort/thermal/itc/content/ cont1.html>.

1.2 Objectives

The objective of the study was to determine whether or not traditional materials are more conducive to providing thermal comfort to occupants in a building than contemporary ones. The thermal environment encompasses those characteristics of the environment which affect the heat exchange of the human body. The question was "How can we ensure that buildings will be thermally comfortable for their occupants?"[3] and, "Do construction materials have a role in achieving thermal comfort or not?"

This study was based on both field work that was conducted in Yozgat, a province of the Central Anatolia climatic region, and on computer simulations. The field study includes data collection on three village houses that were constructed of three different materials. This study aimed at questioning materials and the main objective was to establish 'whether they make a difference on thermal comfort or not'. The field of traditional materials and contemporary materials was explored. A major point to be investigated was to determine if materials make a change in comfort, and, if so, which ones play a better role in increasing comfort while decreasing the cost of the building proper.

1.3 Procedure

Looking back at traditional building techniques and materials and comparing them with new ones is one of the ways of questioning how to achieve thermal comfort; this study has dealt with building materials from the human comfort point of view. The first phase of the study was to survey individual houses in order to simulate them and produce orthographic drawings. Digital photos were used to rectify images into elevations. The rectification was done using the software, Aerial. The second phase was collecting data. First, the indoor and outdoor climatic data (air

---

[3] J. Fergus Nicol, *Mulcom, Thermal Comfort*, (London Metropolitan University), 17 Dec. 2002, <http://www.unl.ac.uk/LEARN/port/1998/mulcom/web/comfort/thermal/itc/content/ cont1.html>.

temperature and relative humidity) were compiled for each of the houses. Graphs comparing rh and temperature of indoor and outdoor were then produced from these. Finally, the houses were compared among themselves.

In the third phase of the study, simulation models of the houses using the environmental design software, Ecotect 5.0 were run and alternative materials were specified. By this method, alternative graphs of thermal performance of the houses were obtained to see whether using different materials in the same houses made a difference in thermal comfort or not. Calibration was modelled to handle the differences between the results produced by simulation and actual data. The materials and their effects on thermal comfort were assessed and the costs of the buildings were compared in order to show thermal comfort capacity.

1.4. Disposition

The study is presented in five chapters, including this first Introduction where is presented its argument and objectives of the study, together with a brief overview of the general methodology. It concludes with this disposition of subject matter that follows in the remaining chapters.

In the second chapter is given a summary of literature surveyed on the general characteristics and criteria of climatic elements and thermal comfort, and on several properties of materials.

In Chapter 3 is described the study material and method used to conduct the research. Statistical methods are described to identify the sample size.

In Chapter 4 are presented the results of the analysis and data collection, together with a discussion of these in terms of achieving thermal comfort.

Chapter 5 concludes the study by summarizing its findings.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a survey of literature about thermal comfort including the climatic elements and their effect on comfort; strategies of climate control; comfort zones; and current debates on thermal comfort and thermal comfort models are presented.

2.1. Climatic Elements

The "climate" of a given region is determined by the pattern of variations of several elements and their combinations. The principal climatic elements, when human comfort and building design are being considered, are solar radiation, longwave radiation to the sky, air temperature, humidity, wind and precipitation such as rain, snow, etc. (Givoni, 1976, pp. 1).

> Climate, as it affects human comfort, is the result of the air temperature, humidity, radiation-including light- air movement, and precipitation. To achieve comfort, these factors need to be handled in such a way as to establish some form of balance between the environmental stimuli so that body is neither losing nor gaining too much heat, nor is subject to excessive stresses from other variables. In climatic terms, therefore, a building needs to respond to heat, cold, ground and sky radiation, wind and other stresses (Rapoport, 1969, pp. 88-89). These factors will be described in more detail in the following section.

2.1.1. Solar Radiation

Solar radiation is an electromagnetic radiation emitted from the sun which has different wavelengths. These wavelengths are broadly divided into three regions: ultra-violet (u.v.), visible and infra-red (i.r.). Only the small section of this range is light visible to the eye. Although the peak intensity of solar radiation is in the visible range, over one-half of the energy is emitted as i.r. radiation (Givoni, 1976, pp 1-2).

Olgyay (1963), reports that radiation effect of inside surfaces can be used to balance higher or lower air temperatures. This means that we can be comfortable at low temperatures if the heat loss of the body can be counteracted with the sun's radiation. At temperatures under 70^0F a drop of 1^0F in air temperature can be neutralized by elevating the mean radiant temperature by 0.8^0 F. However this possibility of neutralization has its limitations cause in practice we shall not find more than 4^0 or 5^0 F differences between air and wall temperatures.

The four main channels of radiant heat transfer affecting building are, in the order of importance: direct shortwave radiation from the sun; diffused shortwave radiation from the sky-vault; short-wave radiation reflected from the surrounding terrain; and long-wave radiation from the heated ground and nearby objects. These affect buildings in two ways: First it affects by entering through windows and being absorbed by internal surfaces which causes a heating effect. Secondly it affects through being absorbed by the outside surfaces of the building which creates a heat input. A large proportion of this heat input is conducted through the structure and eventually emitted to the interior. Another major form of heat transfer affecting buildings is the outgoing long-wave radiation exchange from building to sky. This is an effect which is reduced when the sky is clouded and is strongest when the atmosphere is clear and dry as in hot arid zones where it can be utilized as a source of energy for cooling buildings (Konya, 1980, pp. 11-12).

2.1.2. Air Temperature

Givoni (1976), reports that the rate of heating and cooling of the surface of the earth is the main factor determining the temperature of the air above it. As the air is transparent to almost all solar radiation, it has only an indirect effect on air temperature.

Givoni further states that the annual and diurnal patterns of air temperature depend on the variations in surface temperature. Wide differences in temperature exist between land and water surfaces. Great bodies of water are affected more slowly than land masses under the same conditions of solar radiation. Therefore land surfaces are warmer in summer and colder in winter than sea surfaces on the same latitude. The air masses originating over these surfaces differ accordingly. The average temperature of air is higher in summer and lower in winter over land than over the sea. Also temperatures are generally lowest just before sunshine, as diffused radiation from sky causes temperatures to rise even before sunrise, and highest over land about two hours after noon, when the effects of the direct solar radiation and the high air temperatures already existing are combined.

A change in altitude also changes the temperature of the air. The air masses in the mountains have lower pressure than in low height regions. So when the air mass rises up, it expands and is cooled. Conversely, when an air mass descends it is compressed and heated. These are known as adiabatic cooling and heating. The rate of temperature change is about 1^0C/100 m. in altitude (Givoni, 1976, pp. 6-7).

2.1.3. Humidity

Givoni reports that the moisture content of the atmosphere can be expressed in several terms, such as the absolute humidity, specific humidity, vapour pressure and relative humidity. Absolute humidity is defined as the weight of water vapour per unit volume of air (g/m^3) and the specific humidity as the weight of water vapour per unit weight of air (g/kg). The vapour pressure of the air is the part of the whole atmospheric pressure that is due to the water vapour and is measured in mm Hg. The relative humidity at any temperature is the ratio of the actual absolute humidity to the maximum moisture capacity of the air at that temperature which can be defined as the percentage of the absolute saturation humidity.

Givoni adds that the term atmospheric humidity refers to the water vapour content of the atmosphere. Water vapour enters the air by evaporation, principally from the surfaces of the oceans and also from moist surfaces, vegetation and small water bodies. The vapour is carried and distributed over the earth's surface by the winds. He further insists that the air's capacity for water vapour increases gradually with its temperature. For this reason the vapour distribution over the earth is not uniform. It is highest in the equatorial zones and decreases towards the poles, varying parallel with the pattern of annual solar radiation and temperature averages (Givoni, 1976, pp. 13-14).

Konya (1980) reports that although the absolute humidity of a given body of air does not change unless water vapour is added to or taken from it, the relative humidity of the air concerned will vary with any change in temperature. If the air actually contains all water it can hold, it is said to be saturated and its relative humidity is then 100 percent, but if the actual vapour content is less than the potential content at the same temperature, the relative humidity is then less than 100 percent. Relative humidity, therefore, is the ratio of the actual humidity in a given volume of air to the maximum moisture capacity at that particular temperature.

Konya (1980) further reports that relative humidity affects the behaviour of many building materials and their rate of deterioration, and vapour pressure affects the rate of evaporation from the human body. Whereas the diurnal differences in vapour pressure levels are small, they are subject to wide seasonal variations and are usually higher in summer than in winter. Relative humidity on the other hand may undergo wide variations, as the result of diurnal and annual changes in air temperature which determine the potential moisture capacity, even when the vapour pressure remains almost constant. Moreover, according to the Healthy Building

2000 Workshop 10 humidity affects the perception of IAQ, thermal comfort, occupant health, building durability, material emissions, and energy consumption.

> Relative humidity is important for human comfort mostly for its effect on the evaporation of sweat. In order to evaporate, there needs to be a source of high temperature from which the latent heat of vaporisation can be drawn, and sufficient vapour pressure to allow vaporisation. In hot dry climates sweat is readily evaporated. In humid or tropical environments there is abundant heat, but very low vapour pressure as the air is already almost at saturation point, so sweating is much less effective. At relative humidities above 80%, sweat is produced but most of it cannot evaporate as the air immediately surrounding the body quickly becomes saturated. Humidities less than 20% result in large amounts of evaporation or both sweat and other bodily fluids, drying out the eyes and mucous membranes which can greatly increase susceptibility to infection. [4]

2.1.4. Wind

According to Givoni (1976), the distribution and characteristics of the winds over a region are determined by several global and local factors. The main determinants are the seasonal global distribution of air pressure, the rotation of the earth, the daily variations in heating and cooling of land and sea and topography of the given region and its surroundings (pp. 8).

Olgyay (1963) asserts that desirable air movements should be utilized for cooling in hot periods, and as a relief from vapour pressure during times of high absolute humidity. Conversely air movements should be blocked and avoided during the cold season. He further adds that air movement affects body cooling. It does not decrease temperature but causes a cooling sensation due to heat loss by convection and due to increased evaporation from the body. As velocity of air movement increases, the upper comfort limit is raised. However, this rise slows as higher temperatures are reached.

2.1.5. Condensation and Precipitation

Givoni (1976) reports that if air containing water vapour is cooled, its moisture holding capacity is reduced so that the relative humidity is increased. This continues until it becomes saturated. The temperature at which this air becomes saturated is known as the dew point. The dew point at a given atmospheric pressure depends only on the vapour pressure of the air. Any cooling below the dew point causes the condensation of the vapour in excess of the air's capacity. Givoni further adds that cooling of the air may be effected by three processes: contact with cooler surfaces, mixing with cooler air and expansion associated with rising air currents (adiabatic cooling). The first two processes result in dew and fog formation; the third is the one that can cause large-scale precipitation (pp. 15).

Condensation can damage building materials. It is often more serious problem in "well-sealed" but under insulated buildings. Humidity within a space can be removed from the building in two ways: by additional heating which raises the temperature so that relative humidity is reduced and by ventilation which removes the humidified air.[5]

---

[4] *Relative Humidity,* (Cardiff University, The Welsh School of Architecture), 14 Apr. 2003, <http://www.squ1. com>.

[5] *Thermal Analysis*, (Cardiff University, The Welsh School of Architecture), 14 Apr. 2003, <http://www.squ1.com>.

2.2. Strategies of Climate Control

According to Donald Watson (1983) the building envelope is a device through which heat exchange between the interior and exterior environments is controlled. It intercedes with the external climate, creating a new interior microclimate zone. The fundamental control options consist of admitting or excluding heat gain from external energy sources, and containing or rejecting heat energy present in the interior. Most of these controls are static or fixed in place such as insulation placed in wall and ceiling cavities, and the area and orientation of glazing in the building shell. However some of the most important controls are dynamic such as operable window sash, movable window insulation, and a variety of adjustable sun-shading devices.

Watson adds that the strategies of climate control can be divided into eight solutions which can be separated into those appropriate to under heated (winter) conditions and those appropriate to overheated (summer) conditions. These are:

- Promote solar gain,
- Minimize conductive heat flow,
- Minimise infiltration,
- Minimise solar gain,
- Promote ventilation,
- Promote radiant cooling,
- Promote evaporative cooling,
- Promote conductive cooling (pp. 33).

2.3. Thermal Comfort

According to ANSI/ASHRAE 55 Standard-2000R (2001), thermal comfort can be defined as that condition of mind, which expresses satisfaction with the thermal environment. The main criteria for thermal comfort for the human body as a whole can be divided into environmental variables: air temperature, mean radiant temperature, humidity, air velocity and personal variables: clothing and metabolic rate (activity). In addition there are other environmental parameters that can cause local thermal discomfort such as draught, a high vertical temperature difference between head and feet, radiant temperature asymmetry and warm or cold floors (pp. 9-24).

According to the ASHRAE Handbook of Fundamentals (1989) some of the factors which influence indoor environmental effects on humans are psychology and physiology. Similarly, Victor Olgyay (1963) in his work *Design with Climate* mentions that man's energy, heath and comfort mainly depends on the effects of his environment. It is shown in his work that in certain season man's physical strength and mental activities are at their best within a given range of climatic conditions, and outside this range efficiency lessens, while stresses and the possibility of disease increase (pp. 14).

He further points out that the measurement of climatic effects has been investigated in many ways of which two will be mentioned here. The first method describes the negative effects of climate on man, expressed as stress, pain, disease, and death. The second defines the conditions in which man's productivity, health, and mental and physical energy are at their highest efficiency. Both approaches may be combined, to show overlapping and opposite relationships, in defining desirable or unpleasant atmospheric and thermal conditions. The experiments done by Huntington, as reported by Olgyay related to man's physical strength and mental activity are at their best within a given range of climatic conditions, and that outside this range efficiency lessens, while stresses and the possibility of disease increase (Olgyay, 1963, pp. 14).

Again, according to the ASHRAE Handbook of Fundamentals (1989) human beings spend 95% of their time indoors and it is a controlled environment. It is also mentioned that certain aspects of heath , such as mortality and heat stress in heat waves, and the effects of hot and cold extremes on specific diseases has strong physiological basis linked to outdoor temperature. These show that outdoor climate should be considered in terms of human heath and comfort (pp. 8.26).

De Dear and Brager (1998) state that persons in developed countries spend their 80 % time indoors. This suggests that the quality of indoor environment may have a significant effect on comfort, heath and overall sense of well-being (pp. 1). In this respect studies regarding the traditional methods of maintaining comfort and the adaptation through behaviour in the Central Anatolia need to be conducted.

To know about the thermal climate, we need to know about the heat exchange between human and their environment. The human body continuously generates heat with an output varying from about 100W for a sedentary person to 1000W for a person exercising actively. To avoid discomfort, the body temperature must be within a narrow range, and within a wider range to avoid danger from heat or cold stress (ASHRAE Hand., 1989, pp. 8.1).

2.3.1. Comfort Zone

The range of conditions in which thermal comfort is experienced is called comfort zone which differs according to individuals preferences and is affected by the clothing worn, geographical location, age, and sex. Although the comfort zone is defined as a subjective assessment of the environmental conditions, the limits of the zone do have a physiological basis; the range of conditions under which the thermo-regulatory mechanisms of the body are in a state of minimal activity. Comfort, is dependent on several aspects and cannot be expressed in terms of any one of these aspects as they affect the body simultaneously and influence of any aspect depends on the levels of the other factors. Several attempts have been made to evaluate the combined effects of these factors on the physiological and sensory response of the body and to express any combination of them in terms of a single parameter or "thermal index" which can be set out on a monogram (Konya, 1980, pp. 27-28).

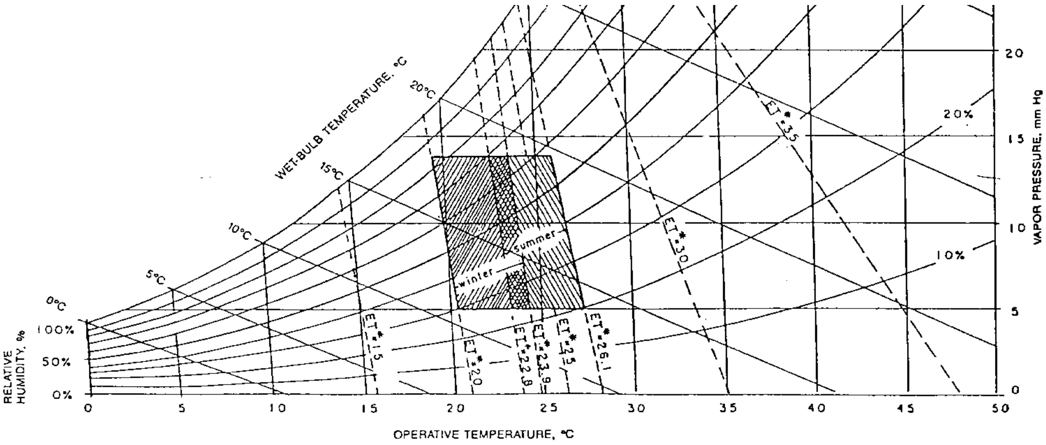


Figure 2.1. Standard Effective Temperature and ASHRAE Comfort Zones

(Source: ASHRAE Handbook of Fundamentals 1989)

The comfort zones are intended to provide acceptable thermal environment for occupants wearing typical indoor clothing and at a near sedentary activity. Acceptable thermal environment is an environment that at least 80% of the occupants would find thermally acceptable.[6] Figure 2.1 shows the Standard Effective Temperature lines on a psychometric chart and the ASHRAE comfort zones.

Konya (1980) points out that a systematic procedure for adapting the design of a building to human requirements and climatic conditions is proposed by Olgyay (1963). His method is based on a Bioclimatic Chart on which comfort zones for summer and for winter can be determined for the climatic region to which it is to be applied. Once the chart is produced, any climatic condition can then be plotted on the chart to evaluate comfort requirements and deviations from the comfort zone. Whether these deviations can be eliminated by natural means, is ascertained. A version of Bioclimatic chart is shown in Figure 2.2.

---

[6] *Comfort Zones*, (City University of Hong Kong), 17 Dec. 2002, < http://personal.cityu.edu.hk/~bsapplec/thermal.htm >

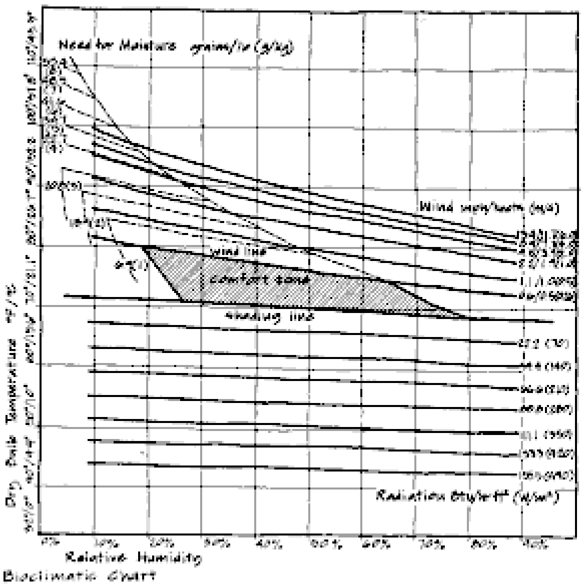


Figure 2.2. Olgyay's Bioclimatic Chart
(Source: G. Z, Brown, *Sun, wind, and light*, (New York: Wiley), 1985.)

Psychometric chart that bioclimatic chart is founded on represents the psychometric processes by the movement of the state point which is represented in Figure 2.3. Common processes include:

Sensible cooling/sensible heating, cooling and dehumidification/heating and humidification, humidification/dehumidification, evaporative cooling/chemical dehydration.[7]

---

[7] *Climatic Design of Buildings - An Overview, Psychrometric Chart, (*Hong Kong University), 31 May 2003, <http://arch.hku.hk/~cmhui/teach/65156-7e.htm>.

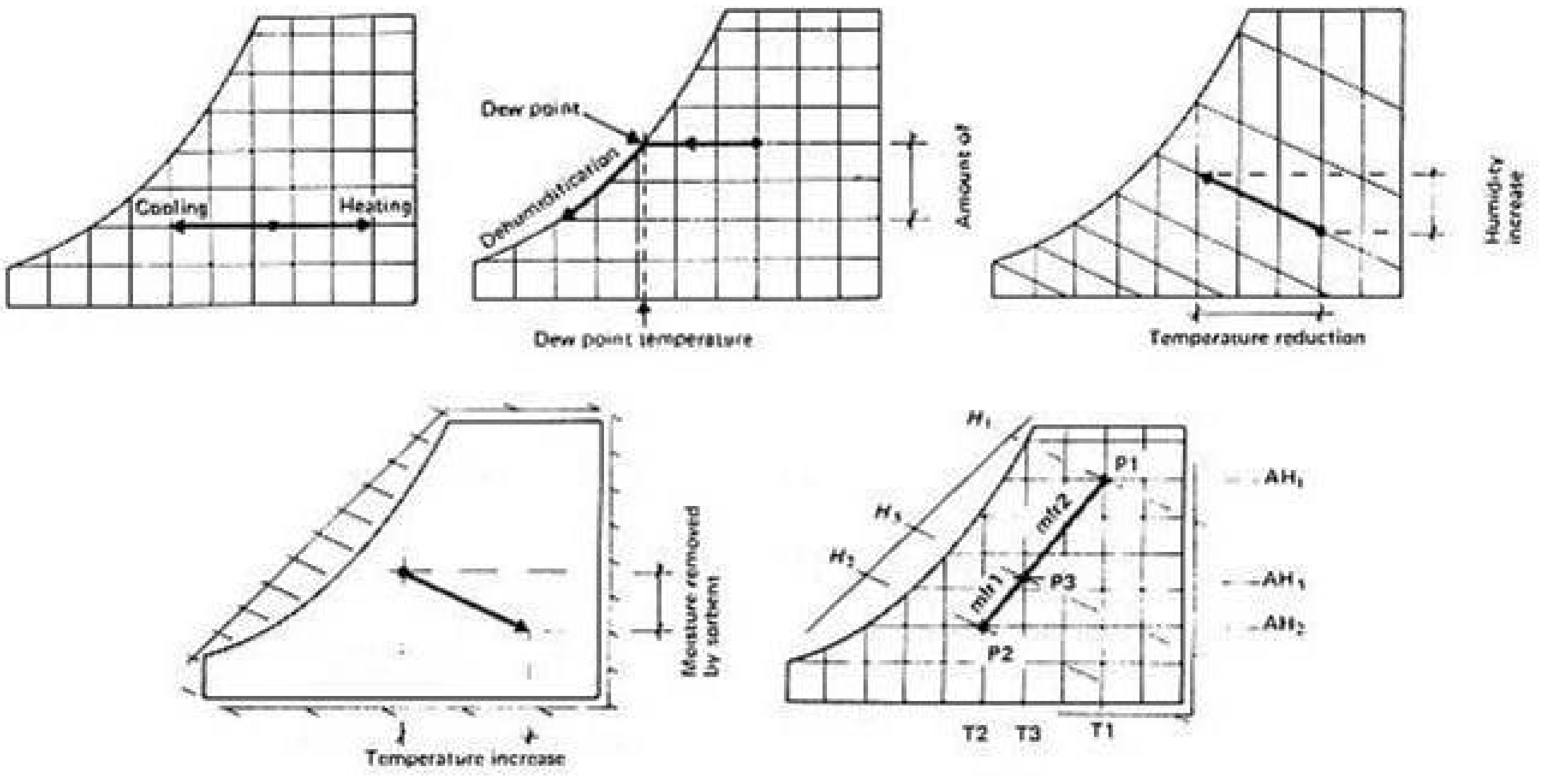


Figure 2.3. Psychrometric processes

(Hong Kong University, 31 May 2003, <http://arch.hku.hk/~cmhui/teach/65156-7e.htm>)

2.3.2. Comfort Prediction

Before the technology advanced and controllable heating and cooling devices has been invented, the knowledge of thermal and environmental design was down to the designer's experience. Examples of the design aspects that the designer should consider were how many and where to put fireplaces, stoves; the shading and ventilating elements; creating micro climate within the building complex and which material to built with. The air conditioning system brought the question of thermal comfort.[8] Because of the variation in climatic factors and the differences between people, mathematical models have been derived to predict the average acceptability of an indoor climate. The main aim of comfort models is to provide a single index that encompasses all the relevant conditions. There are two types of approaches to predict thermal comfort. One approach is based on heat balance of the human body. The second approach assumes an adaptation to the thermal environment is possible regarding the physiological, behavioural and psychological adaptation. The former approach uses climate data to support its theory and experiments are done in climate chamber. The latter uses the data collected from subjects in real buildings. Nick Baker quotes the study by Oseland [9] (1994) that the behavioural difference is the reason that the two approaches come up with different solutions. It is therefore no surprise that the people in workspaces respond differently than the ones in their homes. According to Baker, Oseland concluded that the same group of subjects when tested in three contexts-climate chamber, workspace and their home became progressively more tolerant- accepting winter comfort temperatures 3 ^{0}K lower than in the climate chamber, with an intermediate value in the workspace. [10]

---

[8] J. Fergus Nicol, *Thermal Comfort*, (Learn, School of Architecture, University of North London), 31 May 2003, <http://www.unl.ac.uk/LEARN/student/info/notes/comfort/comfort.html>

[9] N. A. Oseland, *A Within Groups Comparison of Predicted and Reported Thermal Sensation Votes on Climate Chambers, Offices and Homes*, (Proceedings of Healthy Buildings 94), Budapest, 1994.

[10] Nick Baker, *Designing for Comfort, Recognising the Adaptive Urge*, (The Martin Center for Architectural and Urban Studies, University of Cambridge), 30 Apr. 2003, <www.caed.asu.edu/msenergy/Neeraj/Baker.pdf>

2.3.3. Models for Thermal Comfort

The relation between the thermal environment and the comfort of the people has brought two distinguishable concepts which are as follows:

a) *the heat balance approach*; a model of human thermal response based on the assumption that a necessary condition for thermal comfort is a balance between the metabolic heat production and the heat loss from the body.

b) *the adaptive approach*; an approach to the study thermal comfort starting from the observation that there are a range of actions which occupants can take to achieve thermal comfort, and that discomfort is caused by constraints imposed on the range of actions by social, physical or other factors. Over time this means that people are comfortable at the 'usual' or 'average' temperature which they experience.[11]

a) Heat Balance Approach: In order to stay healthy, the internal body temperature must be kept at 37^0C and heat produced must be balanced by the heat lost from the body. The mathematical expression for this balance is one of the ways of calculating the thermal conditions to provide in a building. It is also known as analytical or climate chamber approach and the best known one is Fanger's (1970) model which forms the basis for the international ISO Standard 7730. The ANSI/ASHRAE Standard 55 is also based on the heat balance approach. The basic for heat balance equation is

$M — W = E_e + R_a + K + C_o + E_r + S$ *(by convention, all units watts/*m^2 *of body surface area)*

Where *M is the rate of metabolic heat production, W energy used in doing mechanical work,* E_e *heat loss by evaporation,* R_a *heat loss through radiation, K heat*

---

[11] J. Fergus Nicol, *Mulcom, Glossary*, (London Metropolitan University), 17 Dec. 2002, <http://www.unl.ac.uk/LEARN/port/1998/mulcom/web/gloss.html>.

loss by conduction (generally negligable0), C_o *heat loss by convection,* E_r *heat loss by respiration, and S heat stored in the body.*[12]

Fanger (1970) also developed a practical application of the heat balance equation called *Predicted Mean Vote* (PMV) and Predicted *Percentage Dissatisfied* (PPD). These depend on the prediction of the thermal sensation of group of persons in an arbitrary, but stationary, climate. The basis of the former equation was obtained from the thermal sensation vote indicated the personally experienced deviations to the heat balance (seven point scale; from +3 [hot] to -3 [cold], 0=neutral). By this equation he was able to determine the function of the activity, clothing, air temperature, mean radiant temperature, relative humidity and air velocity.

Nicol[13] points out that when Fanger (1970) realized that the vote predicted was only the mean value to be expected from a group of people, he extended the PMV to predict the proportion of any population who will be dissatisfied with the environment. So PMV is defined by Fanger in terms of PPD. As PMV moves away from neutral (PMV = 0) in either direction, PPD increases. The maximum number of people dissatisfied with their comfort conditions is 100% and, as you can never please all of the people all of the time, the minimum number even in what would be considered perfectly comfortable conditions is 5%.[14] Figure 2.4 shows the PMV scale and PPD.

---

[12] J. Fergus Nicol, *Mulcom, Thermal Comfort*, (London Metropolitan University), 17 Dec. 2002, <http://www.unl.ac.uk/LEARN/port/1998/mulcom/web/comfort/thermal/itc/content/ cont1.html>.

[13] J. Fergus Nicol, *Thermal Comfort*, (Learn, School of Architecture, University of North London), 31 May 2003, <http://www.unl.ac.uk/LEARN/student/info/notes/comfort/comfort.html>

[14] *Comfort Factors*, (Cardiff University, The Welsh School of Architecture), 14 Apr. 2003, <http://www.squ1.com>.

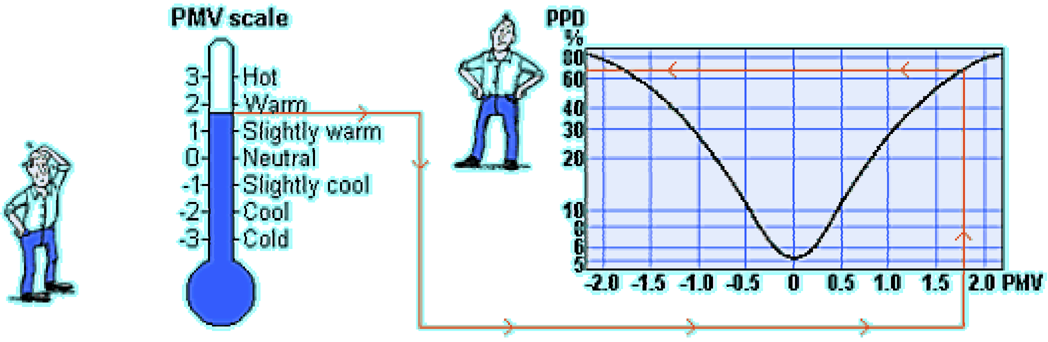


Figure 2.4. PMV and PPD
(Source: *Thermal Comfort,* Innova AirTech Instruments, 12 Apr. 2003, <http://www.innova.dk/books/ thermal/thermal.htm>)

b) Adaptive Approach: The Adaptive comfort models add human behaviour to climate variables. They assume that, if changes occur in the thermal environment to produce discomfort, then people react in ways which tend to restore their comfort. Such actions could include taking off clothing, reducing activity levels or even opening a window. The main effect of such models is to increase the range of conditions that designers can consider as comfortable, especially in naturally ventilated buildings where the occupants have a greater degree of control over their thermal environment. Nicol mentions the early works of Humphreys (1976, 1978) and de Dear and Brager (1998) to build the adaptive model through meta-analysis.[15]

As adaptive models depend on human behaviour so much, they are usually based on extensive surveys of thermal comfort and indoor/outdoor conditions. Humphreys & Nicol (1998) give equations for calculating the indoor comfort temperature from outdoor monthly mean temperature (average of the mean minimum and maximum air temperatures for a given month) as follows.[16]

---

[15] J. Fergus Nicol, *Mulcom, Thermal Comfort*, (London Metropolitan University), 17 Dec. 2002, <http://www.unl.ac.uk/LEARN/port/1998/mulcom/web/comfort/thermal/itc/content/ cont1.html>.

[16] *Comfort Factors*, (Cardiff University, The Welsh School of Architecture), 14 Apr. 2003, <http://www.squ1.com>.

Free Running Building (buildings which had neither centralized heating nor cooling plant (naturally ventilated) :

$T_c = 11.9 + 0.534\ T_m$ ……………..…………………..(2.1)

Heated or Cooled Building (Climate controlled [centralized HVAC]):

$T_c = 23.9 + 0.295(T_m\text{-}22)\ \exp([-(T_m\text{-}22)/33.941]^2)$ ……………..(2.2)

Unknown system (free running and climate controlled buildings together):

$T_c = 24.2 + 0.43(T_m\text{-}22)\ \exp(-[(T_m\text{-}22)/28.284]^2)$ …..…………(2.3)

(where T_c is comfort temperature, T_m the monthly mean and exp meaning exponential).

The adaptive model that De Dear and Brager originally developed in 1998 and revised as a standard for naturally ventilated buildings in 2000, suggest that thermal expectations of building occupants, and their subsequent expectations for indoor comfort, will depend on outdoor temperature. This comfort standard could be applicable to buildings in which occupants control operable windows, and where activity levels are <1.2 met[17]. In this standard the comfort temperature for buildings with natural ventilation is calculated from the equation (2.4) and shown in Figures 2.5 and 2.6

$T_n = 18.9 + 0.255ET^*$ ………………………..(2.4)

with $5<ET^*<33^0C$. The 90% acceptability range is between T_n - 2.5^0C and $Tn + 2.5^0C$

where T_n is the thermal neutrality and ET* is the Effective temperature.[18]

---

[17] ***Methobolic rate*** is the rate of energy production of the body by metabolism, which varies with activity and expressed in met units. ANSI/ASHRAE, Standard *5-2000R-Thermal Environmental Conditions for Human Occupancy,* (Atlanta: ASHRAE Inc), 2001.

[18] ***Effective Temperature*** (ET*) is the operative temperature (to) of an enclosure at 50% relative humidity which would cause the same sensible plus latent heat exchange from a person as would the actual environment. ***Operative Temperature*** is the uniform temperature of an imaginary black

Originally ET* was used in the formula, but according to the revised standard in 2000, mean monthly outdoor air temperature can be used instead of ET*.

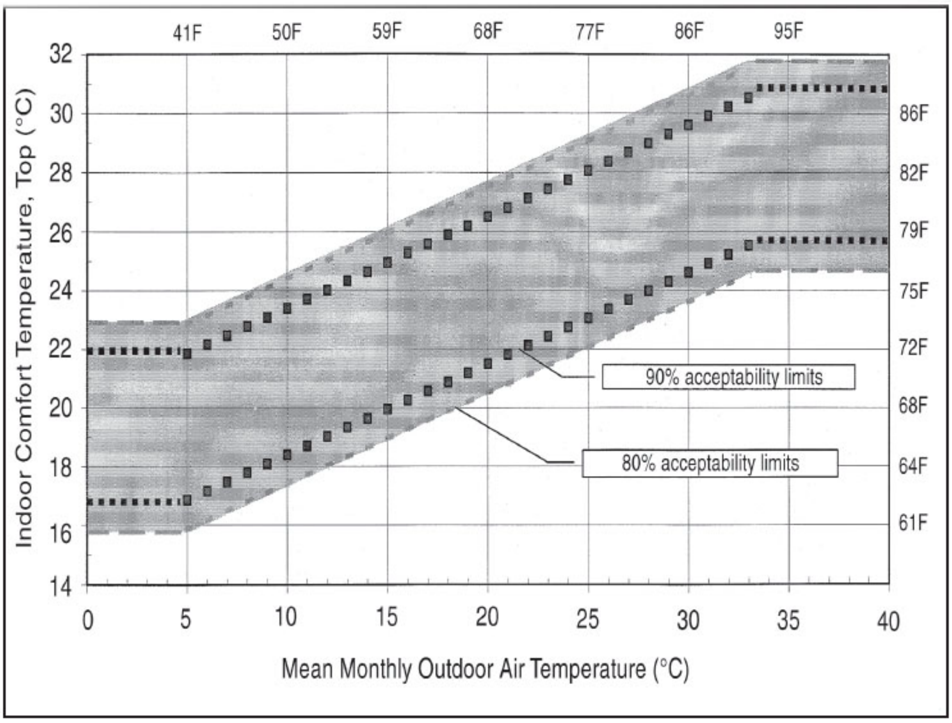


Figure 2.5. Adaptive Standard for Naturally Ventilated Buildings

(Source: Schiller Brager & de Dear, "A standard for natural ventilation." *ASHRAE Journal.* V.42(10), pp. 21-27, 2000)

---

enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. Operative temperature is numerically the average of the air temperature (ta) and mean radiant temperature (tr), weighted by their respective heat transfer coefficients (hc and hr). De Dear R. and G.Schiller Brager, "Developing an Adaptive Model of Thermal Comfort and Preference", ASHRAE Transactions, V.104, part 1, pp. 145-167, 1998.

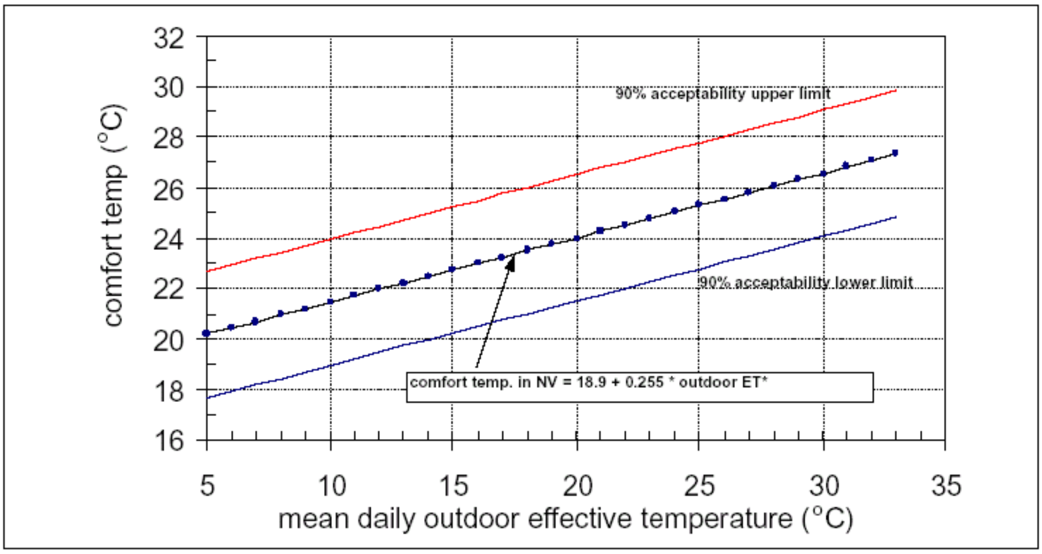


Figure 2.6. The optimum and limits of the adaptive comfort zone for a 90% acceptability level in naturally ventilated buildings

(Source: de Dear & G.Schiller Brager, "Developing an Adaptive Model of Thermal Comfort and Preference", ASHRAE Transactions, V.104, part 1, pp. 145-167, 1998)

2.4 Thermophysical Properties of Building Materials

Conduction, convection, radiation and evaporation / condensation are the four ways of the heat transfer in buildings. Givoni (1976) reports that during the process of heat entry through the building, the mode of heat transfer may change. For example; solar energy reaches the wall surface in the form of radiation, absorbed at the external surfaces and flows across the wall material by conduction. If the wall contains an air space then convection and radiation occurs. Continues by conduction and finishes by convection and radiation through inside air and other surfaces.

The properties of materials that affect the rate of heat transfer through building, and as a result the indoor thermal conductions and comfort of the occupants are: thermal conductivity, resistance and transmittance; surface characteristics; surface convective coefficient; heat capacity and transparency to radiation of different wavelength (Givoni, 1976, pp. 103).

2.5 Thermal Effects of Building Materials

Givoni (1976) points out that the envelope of a building is not only a separator from the external environment but also is a prevention for climatic elements to affect the building directly. Three types of building materials can be used to build this envelop which are: opaque, transparent and translucent.

He further points out that heat may enter the buildings firstly, through transparent and translucent materials and open windows secondly, through the modifying influence of the rest of the building materials. The internal thermal comfort conditions than may be affected both directly and dependent on the properties of the materials by the external temperature and humidity (pp. 120).

> When the indoor thermal conditions are not controlled by mechanical means, the materials affect the temperatures of both the indoor air and surfaces and thus have a very pronounced effect on the occupant’ comfort. Even when control is used, in the form of heating or air-conditioning for instance, the thermophysical properties of the materials used determine the amount of heating or cooling which is provided and also the temperature of the internal surfaces (radiant temperature). Therefore, even in these circumstances, the materials have an effect on the comfort of the occupants, as well as on the economical efficiency of the control systems (Givoni, 1976, pp. 120).

Olgyay (1963) reports materials which reflect rather than absorb radiation and which more readily release the absorbed quantity as thermal radiation will cause lower temperature within the structure. He further adds that white materials may reflect 90 % or more, black material 15 % or less, of radiation received (pp. 113-114).

Givoni (1976) mentions that thermophysical properties have to be considered while choosing a building material and decrement factor should be taken into account. He emphasizes the combined effect of material properties and colour. The thermal resistances of the materials play an important role in heat flow. Increasing the thermal resistance of a wall or a roof reduces the heat flow through the building.

Givoni (1976) further explains that the temperatures within ventilated buildings are determined by combination of the effect of two factors: heat flow across the walls, and outdoor air entering the space. When the external colour is light, the effect of ventilation is dominant and marks the influence of wall thickness. On the other hand, when the exterior is dark, the possible heat flow across the walls is increased greatly, so that the effect of thickness on temperatures is much more noticeable (pp. 137). He also mentions the effect of materials on internal heating. The experiments they have done in Haifa Building Research Station shows that when there is a significant internal heating the response depends on the thermophysical properties of the materials. The effect of thermal resistance is in the opposite direction from its effect when the heat load operates on the external walls (pp. 144).

In another experiment they have done, for a same roofing material of different colours, the external colour was the main determining factor for the ceiling temperature and consequently for the occupants' comfort in unconditioned buildings. The effect of external colour on ceiling temperature is reduced when the thermal resistance and the heat capacity of the roof is increased. In solid flat roofs the indoor climate are affected by the external colour and depend on the diurnal variations in outdoor air temperature. The thickness, thermal resistance and insulation of roof have particular interrelated effects on the indoor climate (pp. 145-149).

Simos Yannas (1994) states that "the general principles to be followed in the specification and construction of external building materials are as follows:

- Specify appropriate levels of thermal insulation
- Specify materials with low environmental impact
- Ensure the conductivity and integrity of insulation materials through detailing and on site
- Provide adequate thermal capacity for heat storage in the building structure (pp. 95). "

2.6 Materials

This section describes the common materials that are used in building constructions as being considered traditional or contemporary. Their properties and applications are mentioned.

2.6.2. Traditional Materials

Traditional material is considered in this study as being used from the earliest building on and being as a raw material that can be produced by local means as a building material.

a) Stone: Stulz and Mukerji (1993) reports that stone is a natural resource which is one of the oldest, durable and abundant. When located near the building site, it is an inexpensive building material. By processing, some other building materials can be produced. The stone types mainly used in building are divided into three geological categories: (i) Igneous rocks such as granite and volcanic stones; (ii) Sedimentary rocks such as sandstones and limestones; and (iii) metamorphic rocks such as slates, quartzites and marble. For extraction, from a simple cutting tool to more sophisticated mechanized equipment are used according to the level of preciseness wanted.

They further add that it is used as rubble for foundations, ashlar for regular course masonry, impermeable stone as damp proof courses and external cladding of walls, slate for roofing, gravel and stone chippings as aggregate for concrete and terrazzo, granules for surfacing bituminous felts, powders for extending paint, limestone for lime and cement production.

Some of the advantages are: abundantly availability, easily accessibility in hilly regions, low investment cost for extraction, strength and durability, impermeability to provide rain protection, and appropriateness to arid zones as it has high thermal capacity. Some of the problems are: deterioration from atmospheric pollution, efflorescence caused by certain salts and sea spray, damage due to thermal movement of some stones, surface damage due to water, low resistance to earthquake forces (Stulz and Mukerji, 1993, pp. 3-6).

b) Earth: Stulz and Mukerji (1993) reports that earth is a natural resource which is one of the oldest and versatile that is commonly used through out the world as building material. It is cheap, has excellent heat insulation capacity and strong in compression. Building can consist of entirely or partially of soil and can be monolithic or made of various components such as bricks, renders, and infills. Earth can be used in the foundations, walls, floors and roofs as base course, direct moulding, rammed earth, straw clay construction, renders, and soil blocks.

Earth construction methods according to Stulz and Mukerji are: dug out, earth sheltered space, sod, wattle and daub, cob on posts, direct shaping, poured earth, rammed earth, lumps of ill-formed clay, cut blocks, tamped blocks, pressed blocks, machine moulded adobe, extruded earth, sun-dried bricks.

They add that soil can be stabilised so as to increase compressive strength, reduce shrinking and swelling, reduce or exclude water absorption, reduce cracking, reduce expansion and contraction using fibres. Soil can be stabilised with: sand and clay, lime and pozzolanas, portland cement, gypsum, bitumen, sodium silicate, cow dung or horse urine, plant juices, resins, molasses, whey, animal products such as hair, termite hills.

Some of the advantages of constructing with earth are: availability in large quantities in most regions, low cost, easy workability, suitability as construction material for most parts of the building, fire resistance, high thermal capacity, low thermal conductivity and porosity, low energy input in processing, unlimited reusability of unstabilized soil and environmental appropriateness. Some of the problems of constructing with earth are: excessive water absorption of unstabilized soil, causing cracks and deterioration by frequent wetting and drying; low resistance to abrasion and impact; low tensile strength; lack of intuitional acceptability in most countries because building and performance standards often do not exist (Stulz and Mukerji, 1993, pp. 7-13).

c) Fired Clay Products: Stulz and Mukerji (1993) reports that the technique of firing clay is more than 4000 years old. When firings between 850-1000°C, an irreversible reaction occur that give the particles the property of glassy ceramic. A large variety of soils are suitable for this process. The essential property for this process is plasticity to facilitate moulding.

Some of the advantages are: high compressive strengths, porosity to enable the construction to breathe, high thermal capacity, fire resistance, weather resistance and cost saving in surface protection, reusability of poor quality and broken bricks. Some of the problems are: relatively high fuel consumption of the firing process, the high cost to small scale producers and by this way less quality brick production, a weakening or breaking of bricks called ‘lime blowing’ which is caused by the hydration of quicklime particles, derived from limestone in brick making clays, efflorescence (Stulz and Mukerji, 1993, pp. 37-45).

d) Lime: Stulz and Mukerji (1993) report that the history of lime production begins more than 2000 years ago. Temperatures above 900°C required to produce quicklime which can then be slaked to produce hydrated lime. Being one of the most known versatile, it is used for numerous industrial and agricultural processes, environmental protection and building construction. The areas of application of lime are as a stabilizer in soil constructions with clayey soil; as hydraulic binder with a pozzolanas; hydraulic lime without pozzolanas; non-hydraulic lime to use as a binder in renders; mixture in the cement mortar and plasters; limewash.

Some of the advantages are: less energy input than cement for production, superior to portland cement as mortars and plasterwork, providing gentle surfaces which can deform rather than crack and help to control moisture movement and condensation; cheaper and structurally more suitable substitutes as lime-pozzolanas than portland cement; cheap as paint and also mild germicide. Some of the problems are: the extra time needed for soils stabilized with lime than cement; the hydration of stored quicklime in moist conditions, even with humid air; the possibility of reacting with CO_2 thus becoming useless; lime bursting that may cause blisters, cracks and unsightly surfaces and the uneven production of lime in traditional kilns (Stulz and Mukerji, 1993, pp. 51-60).

e) Pozzolanas: Stulz and Mukerji (1993) reports that pozzolanas is natural or artificial materials containing silica and/or alumina. They are not cementitious but can be added to lime to harden at ordinary temperatures in presence of water. Pozzolanas can replace 15 to 40 % of portland cement without reducing the long term strength of the concrete significantly.

They further add that there are two types of pozzolanas: natural and artificial. Natural pozzolanas are basically volcanic ashes from geologically recent volcanic activity. Artificial pozzolanas result from various industrial and agricultural processes, usually as by products and if not been used, they will cause a waste problem. Compared with cement these materials contribute to cost and energy savings. Furthermore, they help to reduce environmental pollution and improve the quality of the end product.

The first natural pozzolanas that is used in building construction is said to be the volcanic ashes. The natural pozzolanas that is suitable for construction is limited to a few regions of the world. Pozzolanas can be found as fine grained ashes or as solid form, but it had to be ground to use as a pozzolanas. The most important artificial pozzolanas are burnt clay, pulverized-fuel ash, ground granulated blast furnace slag and rice husk ash. When clay soils are burnt, the water molecules are driven off to form a quasi-amorphous material that is reactive with lime and is called burnt clay. This was discovered in ancient times and the first pozzolanas were made from crushed pottery fragments. This is a traditional technology that is still being widely practised in India, Indonesia and Egypt. Pulverized fuel ash is preferable to Portland cement when we compare the production processes. Rice husk ash is produced by the combustion of agricultural residues and removing the organic matter and produces. It yields the largest quantity of ash and has the highest silica content (Stulz and Mukerji, 1993, pp. 65-69).

f) Timber: According to Stulz and Mukerji (1993) timber is not only one of the oldest building materials but also one of the versatile ones. It is acceptable in terms of indoor comfort and health aspects. Timber is a complex material that is found in several species and forms and it is suitable for all kinds of applications. Because of the depletion of the forests and the environmental, climatic and economic disasters that follow deforestation, alternative building materials should be considered. Timber is used as complete or partial building and roof frame structures, using pole timber, sawn timber beams, or glue laminated elements. It is used as structural or non-structural floors, walls, and ceilings or roofs, made of pole timber, sawn timber boards, or large panels from plywood, particle board, fibre board or wood-wool slabs. Also wood-wool slabs are used as insulating layers. Furthermore it is used as facings and door or window frames.

Some of the advantages of timber are as follows: It is suitable for construction in all climatic zones. It is versatile, and provides comfortable and healthy living environments. It is a renewable in the sense of re-afforestation. Most species has very high strength regarding earthquake and hurricane resistance. Timber is a traditional material and rarely needs sophisticated skills. The production and processing of timber is requires less energy than many other building materials. Timber provides good thermal insulation and sound absorption. It is better than steel in the sense that the building frame do not collapse after fire. Some of the problems of timber are as follows: High costs and diminishing of species due to uncontrolled cutting. Thermal and moisture movement causes distortions, shrinkages and splitting. Some species are weak to fungal decay and insect attack. It has significant fire risk. The toxic chemical preservatives are unhealthy in long term. Failure of joists between timber members due to shrinkage or corrosion of metal connectors may occur. It may loose its colour and be brittle due to exposure to sunlight, wind-borne abrasives or chemicals (Stulz and Mukerji, 1993, pp. 101-109).

As it is mentioned by Carey Simonson (2000) indoor climate and indoor air quality is important in order to provide comfort, health, productivity for the occupants. For this fact, regulating the indoor temperature and humidity is important but energy consuming. The need for passive and less energy intensive methods for moderating indoor environment brought the idea of moisture storage of the building materials. According to the Healthy Building Workshop 2000 wood and wood based products in the building envelope and furnishings control the indoor climate by moderating the diurnal changes in indoor humidity. And furthermore the following wood based materials have shown particular suitability for moisture storage applications: medium density fibre board, parquet tile, chip board, organic insulation, and perforated and non-perforated wood (pp. 1).

2.6.1. Contemporary Materials

Contemporary building materials in this study are considered as being mostly manufactured and the common usage of the material dates only a few centuries back.

a) Factory Produced Brick: BS 3921 Specification for clay bricks and blocks describes a brick as a walling unit designed to be laid in mortar and not more than 337.5 mm long, 225.0 mm wide and 112.5 mm high, as distinct from block which is defined as a unit having one or more of these dimensions larger than those quoted. The conductivity varies with density. Diatomaceous earth bricks which are very light, have a thermal conductivity of about 0.14 W/mK (Everett, 1994, pp 92).

b) Concrete: As Alan Everett (1994) declares concrete is generally understood to be a mixture of cement, water and aggregate which takes the shape and texture of its mould, formwork, on site. When cured at a suitable temperature and humidity it hardens (pp. 119).

> ‘Some of the applications of concrete are as plain mass concrete, no-fines concrete, lightweight aggregate concrete, aerated concrete, reinforced concrete, and prestressed concrete. Within these applications no-fines concrete is a lightweight concrete with only single size coarse aggregate leaving voids between them, suitable for loadbearing and non-loadbearing walls in framed structures or base coarse for floor slabs. No-fines concrete provides an excellent key for rendering, good thermal insulation due to air gaps, and low drying shrinkage. The large voids also prevent capillary action.’[19]

The thermal conductivity (k) of no-fines gravel aggregate concrete is comparable to that of typical brickwork. To have a quick understanding in thermal conductivity, thermal transmittances (U-Value) for walls are as follows:

279 mm brick cavity wall, plastered inside	U = 1.7 W/m^{2}K
305 mm no-fines dense aggregate concrete rendered and plastered	
203 mm no-fines clinker aggregate concrete rendered and plastered	

---

[19] R. Stulz and K Mukerji, *Appropriate Building Materials,* 3rd ed., (London: SKAT Publications and IT Publications, 1993), 74.

305 mm no-fines clinker aggregate concrete rendered and plastered } $U = 1.3 W/m^2K$

(Everett, 1994, pp 119, 145)

Stulz and Mukerji (1993) reports that concrete has various advantages. Some of them are as follows: Concrete has high compressive strength and can take any shape. When reinforced it combines compressive strengths with high tensile strengths, so that it can be used in any building design and all structural requirements. It is suitable for prefabrication of components and for constructions in dangerous conditions such as earthquake and expansive soils. The energy requirement to produce 1 kg of plain concrete is the lowest of the manufactured building materials.[20] It has high thermal capacity and high reflectivity which is an important feature in hot dry or tropical highland climates. Properly executed concrete is highly durable, free of maintenance, resistant to moisture penetration, chemical action, fire, insects, and fungal attack.

They further add that concrete has some problems such as high cost of cement, steel and formwork. It is difficult to control the quality of concrete regarding the risk of cracking and gradual deterioration on building sites. Corrosion of reinforcement that leads to expansion cracks in moist climates is another problem. Reinforced concrete begins to fail in high temperature due to steel that it contains. The negative electromagnetic effects of reinforced concrete create an unhealthy environment (Stulz and Mukerji, 1993, pp. 75-76).

c) Ferrocement: According to Stulz and Mukerji (1993) ferrocement is principally the same as reinforced concrete having following differences:

---

[20] The energy requirement to produce 1kg of plain concrete is 1 MJ/kg while reinforced concrete (with 1 % by volume of steel) is 8 MJ/kg. R. Stulz and K Mukerji, *Appropriate Building Materials,* 3rd ed., (London: SKAT Publications and IT Publications, 1993), 75.

- Its thickness rarely exceeds 25 mm, while reinforced concrete (RC) components are seldom less than 100mm.

- A rich portland cement mortar is used, without any coarse aggregate as in RC.

- Compared with RC, ferrocement has a greater percentage of reinforcement, comprising closely spaced small diameter wires and wire mesh, distributed uniformly throughout the cross-section.

- Its tensile strength to weight ratio is higher than RC, and its cracking behaviour is superior.

- Ferrocement can be constructed without formwork for almost any shape.

They add that ferrocement is used in boat construction; embankment protection, irrigation canals, drainage systems; water storage tanks; sanitary appliances; walls, roofs and other building components, or complete building, either in situ or in the form of precast elements.

Some of the advantages of ferrocement are as follows: The materials required to produce ferrocement are readily available in most countries. It can take almost any shape and it is adaptable to almost any traditional design. It is a useful substitute in the absence of timber. As a roofing material, ferrocement is a climatically and environmentally more appropriate and cheaper than galvanized iron and asbestos cement sheeting. The manufacture of ferrocement components requires no special equipment, is labour intensive and easily learnt by unskilled workers. Compared with reinforced concrete, ferrocement is cheaper, requires no formwork, is lighter, and has ten times greater specific surface of reinforcement, achieving much higher crack resistance. Ferrocement is not attacked by biological agents, such as insects, vermin and fungus. Some of the problems of ferrocement are as follows: Ferrocement is still a relatively new material, therefore its long term performance is not sufficiently known. Structural design and calculation requires considerable knowledge and experience. Galvanized meshes can cause gas formation on the wires and thus reduce bond strength. The excessive use of ferrocement for buildings can create unhealthy living conditions, as the high percentage of reinforcement has harmful electromagnetic effects (Stulz and Mukerji, 1993, pp. 77-82).

d) Cement: Stulz and Mukerji (1993) reports that most common type is ordinary portland cement. Fine grey powder, mixed with sand, gravel and water produces a longlasting concrete and mortar. It is usually produced in large centralized plants, whereas small-scale cement production is a common practice in China. The areas of application of cement are as a binder for several inorganic and organic materials; in concrete production together with sand and gravel; in ferrocement production together with sand and chicken-wire mesh; mortar and binders; screeding and as paint mixed with excess water.

Some of the advantages are: high strength to remain unaffected by water; resistance to fire and biological hazards. In small-scale cement production, the advantages are; low capital investment, use of cheaper quality coke or coal; lower transportation costs; lower technical sophistication; adaptability to market demands; capability of using different raw materials and producing a variety of cementitious products; increase of supporting industries around the plant. Some of the problems are: too expensive for the majority of the population, storage problems to avoid premature setting, cracks in hot dry conditions due to temperature fluctuations, rapid deterioration due to sulphates and salts, over-strong or mortars that cause brittleness or lack of durability due to the high reputation of cement (Stulz and Mukerji, 1993, pp. 61-64).

e) Glass: Everett (1994) reports that glass was commonly used in Egypt five hundred years B.C. but, history of contemporary use dates back to 19th century. Glass consists of sand, soda ash, limestone and dolomite, a small amount of alumina, a few residual materials and broken glass. Glass is used in building mainly as flat glass, and for products such as lenses, glass fibres and foamed (cellular) glass. The types of glass are translucent, transparent, foamed glasses and special products such as toughened or tempered glass and one way glasses; and glass fibre products. Glass can also be found as plate glass, prismatic glass, glass block, structural glass, spandrel glass.

Everett (1994) adds the density of glass is 2560 kg/m^3 (for comparison: Perplex (ICI) 807, Aluminium 7850 kg/m^3), its melting point is approximately 1500^{0}C (Aluminium 660, steel 1900^{0}C). Although ordinary glass is relatively transparent, solar heat rejecting glasses are available. Ordinary glass transmits a very small amount of suns ultra violet rays and none in the health band. It is extremely durable in normal conditions and restricted by the standard BS 952. Glass must resist to wind loads, impact by persons and animals, and sometimes thermal and other stresses. As the coefficient of thermal movement for glass is lower than the materials in which it is normally fixed, allowance should be made for movement. Dark heat absorbing frames should be preferred to white or polished aluminium frames. A ventilated cavity behind glass helps in cooling it, and consequently removes condensation. Although glass is dense and is a good conductor of heat (k= 1.05 W/mK), its surface resistances are high which causes for example a 3 percent increase in thermal resistance by doubling the thickness of a 6mm glass pane (pp.190-199).

f) Aluminium: Arthur R. Lyons (1997) report that aluminium has only been available as a construction material for about a hundred years. It is extracted from the ore bauxite, an impure form of aluminium oxide or alumina which is then dissolved in caustic soda, filtered, impurities are removed and dried. And several other processes are made to produce the pure aluminium. Typically the production of 1 tonne of aluminium requires 14000 kWh of electrical energy, although recycling waste aluminium requires only one twentieth of this energy.

Lyons (1997) further adds that aluminium is one of the lightest metals with a density of 2700 kg/m^3, compared to steel 7900 kg/m^3. Its duration is linked to the protection of the natural oxide film, which is always present on the metal surface. The strength of aluminium is halved from its ambient value at a temperature of 200 ^{0}C, and for many of the alloys is minimal by 300 ^{0}C. Several finishes are applied to aluminium such as anodising, surface texturing, plastic coating, and paint. For long-term durability all external aluminium finishes should be washed regularly with a mild detergent solution, at intervals less than three months.

Applications of aluminium in buildings include roofing and cladding, curtain wall and structural glazing systems, flashings, rainwater goods, vapour barriers and, internally, ceilings, panelling, luminaries, ducting, architectural hardware and walkways. The probable thermal bridging effects where aluminium extrusions are used for double-glazing systems, thermal breaks are inserted between the aluminium in contact with the interior and exterior spaces (Lyons, 1997, pp. 125-127).

CHAPTER 3

MATERIAL AND METHOD

This chapter involves two subsections, namely, the material and the method. Material consists of data collected during the field surveys, software and instruments that are used to conduct the study, and the buildings the research is based on. Identifying the right sample size, data collection and data evaluation are included in Method.

3.1. Material

The study was carried out on three residential buildings in Yozgat, Central Anatolia. Materials were temperature and humidity data collected; the software and instruments to conduct the survey and the buildings in question.

3.1.1. Data

Relative humidity and temperature data was collected from three residential buildings in Yozgat. The sample size is determined by statistical equations that are mentioned in the next section. The data is checked to show if the houses really have significant difference or not by using analysis of variance (ANOVA).

The data (relative humidity and air temperature) was collected several times during the cold and hot seasons of the years 2002-3 to show the need for thermal comfort in severe climatic conditions. The air temperature and relative humidity is collected with a sampling time of 15 minutes over periods of 3 days to 15 days during

August, September, October, March and May.[21] Sampling day and sampling period is also supported by a similar study done by Eduardo L. Krüger (2001) in which relative humidity values were estimated from absolute humidity and outdoor air temperature.

3.1.2. Software and Instruments

In this study data loggers and thermohygrometers were used to collect the data. To evaluate this data and thermal comfort of the building, the software "Ecotect" was used as an environmental design tool. These instruments are discussed in the following sections.

a) Ecotect 5.0: "ECOTECT is a conceptual design analysis tool designed by Dr. Andrew Marsh of Square One research that features overshadowing, shading design, lighting, acoustic and wind analysis functions as well as thermal. It uses CIBSE Admittance Method to calculate heating and cooling loads for any number of zones within a model. These load factors are direct and indirect solar gains, internal gains, inter-zonal gains, inter-zonal heat flow and pull-down loads due to intermittent usage."[22] It can display hourly internal temperatures and load breakdowns as well as annual temperature distributions and the effects of thermal mass.

> According to the software authors, the strength of ECOTECT lies in allowing the user to "play" with design ideas at the conceptual stages, providing essential analysis feedback from even the simplest sketch model. ECOTECT progressively guides the user as more detailed design information becomes available.
>
> Again according to the software authors, weaknesses of the software are as follows: As the program can perform many different

---

[21] Some of the data is collected in lesser periods than 15 days because of the shortage of data loggers.

[22] *Thermal Analysis*, (The Web Site of Welsh School of Cardiff), 14 Apr. 2003, <http://www.squ1.com>.

> types of analysis, the user needs to be aware of the different modelling and data requirements before diving in and modelling/importing geometry. For example; for thermal analysis, weather data and modelling geometry in an appropriate manner is important; and appropriate/comprehensive material data is required for almost all other types of analysis.[23]

In this study Ecotect 5.0 was used to run models and to specify alternating materials to the houses. By this method, the alternative graphs of hourly temperatures, discomfort period and monthly heating and cooling loads of the houses in respect to thermal neutrality comfort band were obtained and the effects of different materials on thermal comfort in the same houses were observed. The results produced by simulation and collected in real life differed so that calibration was modelled to handle the difference. The materials and its effects on thermal comfort were assessed. The outcomes will be discussed in the related chapter.

b) Data Logger: The data logger which is shown in Figure 3.1 is used to record temperature and humidity data at predetermined intervals over set periods of time. This particular type of instrument can be used both inside and outside the building since it has been designed to withstand extreme environments. Since the loggers are sensitive instruments , they could not be placed in direct sunlight, near heat producing apparatus or exposed to precipitation. Placement in a discrete location ensures that they do not get moved or lost. It must be noted that short wave radiations can interfere with the data collection. The interior data logger has to be placed in a location where there is control over openings, such as windows, and activities such as cooking[24].

---

[23] Building *Energy Software Tool Directory*, 05 Sept. 2002, (U.S. Department of Energy), 17 Dec. 2002, <http://www.eren.doe.gov/buildings/tools_directory/software /ecotect.html>.

[24] Tinytag Data logger User's Guide.

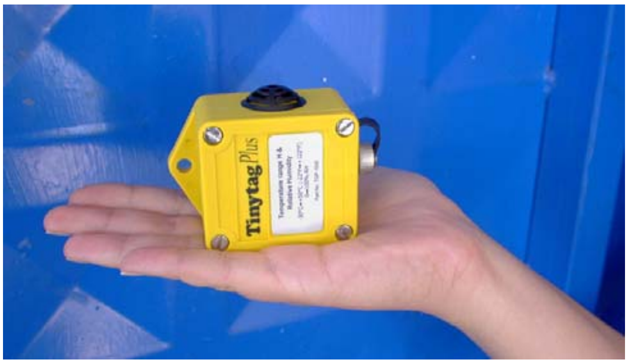


Figure 3.1. Tinytag data logger
(Source: Photo by Françoise Summers)

In this project two or three loggers were used; two were placed inside the buildings and the third one placed outside. Two weeks data of temperature and relative humidity was collected. Data loggers were launched and downloaded by the software called Gemini Data logger Manager which allows setting the duration and interval readings for the measurements as desired. Then the tabular data was exported to Spread Sheet Documents to produce and develop the comparison graphs by superimposing the interior and exterior data of relative humidity and temperature. The interior temperature and humidity graphs were used in order to calibrate the simulation runs.

c) Thermohygrometer: The 'thermohygrometer' is used to read simultaneously temperature in °C or °F and relative humidity in %. This instrument is used to study environmental changes at different places.[25] In studies where data loggers are used, thermohygrometer is advisable for initial spot readings to calibrate them against each other. Figure 3.2 shows the initial spot readings done in Yozgat by the author. While taking initial spot readings of temperature and humidity, the researcher has to be careful because the humidity and temperature of the human may

---

[25] Thermohygrometer User's Guide

affect the data taken. Researcher should not breath towards the instrument, should handle it properly and give time to the instrument for stabilizing.[26]

Figure 3.2. Initial Spot reading taken by the author in order to calibrate the instruments. (Source: Photo by Françoise Summers)

---

[26] Architectural Association Graduate School 2001-02 Course Handouts

3.1.3. Buildings

Three, single-storey, detached dwellings were selected for the study in the village of Şahmuratlı in Yozgat, Turkey. Survey of the houses and the first set of measurements started in late August 2002 and the last set of data was collected in May 2003. Surveying the houses allowed the study to be performed in the 3-D model form as well as in computer simulations. Figures 3.4, 3.6, 3.8 are diagramatic drawings of the houses which show the location of the data logger for each set of readings.

a) Babayiğit House: The Babayiğit house is a traditional single-storey village house built in a composite structural system of load-bearing sandstone external walls and mud brick internal walls. Floors are of compacted earth. Roof construction is of twigs over wooden beams and rafters covered with a thick layer of mud. At the time of data collection, the house was occupied by a single occupant who was in the building throughout the whole day. The occupant used a typical indigenous stove called *soba* to heat the house in winter. The room where the data logger was placed was unheated. Figure 3.3 shows the front façade of the building, and Figure 3.4 is the orthographic drawings done after the survey.

Figure 3.3. Photo Showing the Front (South) Elevation of the Babayiğit House. (Source: Photo by Françoise Summers)

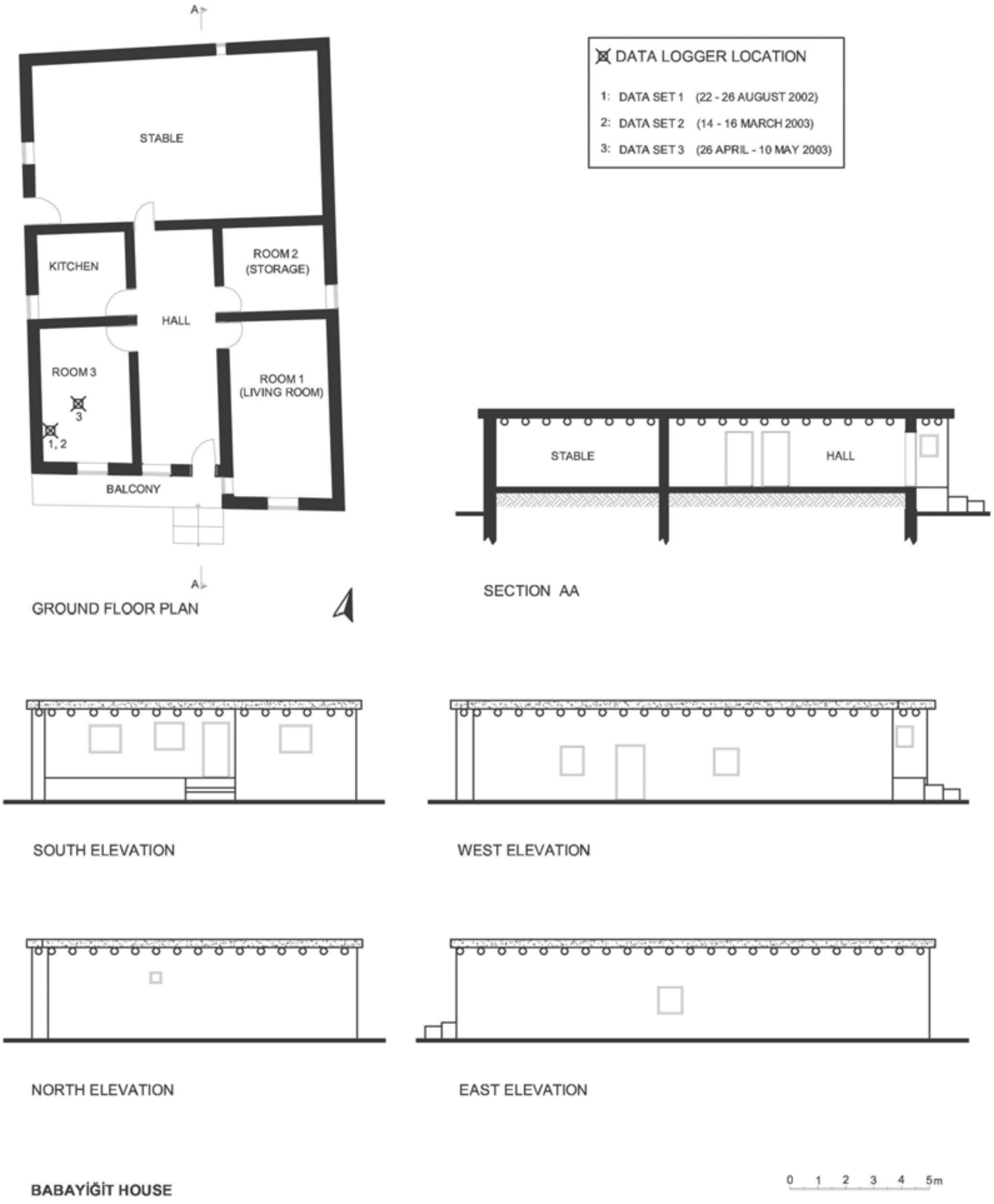


Figure 3.4. Orthographic Drawings of the Babayiğit House

(Source: Plan and elevations by the author, section and the final layout by Tuğrul Karagüzel)

b) Blue House: The Blue House which is presented in Figure 3.5 is of recent construction with uninsulated, load bearing single-leaf external brick walls, reinforced concrete floors and uninsulated, pitched clay tile roof. During readings the building was occupied by a family of seven. The data logger was placed in an unused and unheated room with closed windows. In Figure 3.6 the orthographic drawings of the building are presented.

Figure 3.5. A perspective view of Blue House
(Source: Photo by Françoise Summers)

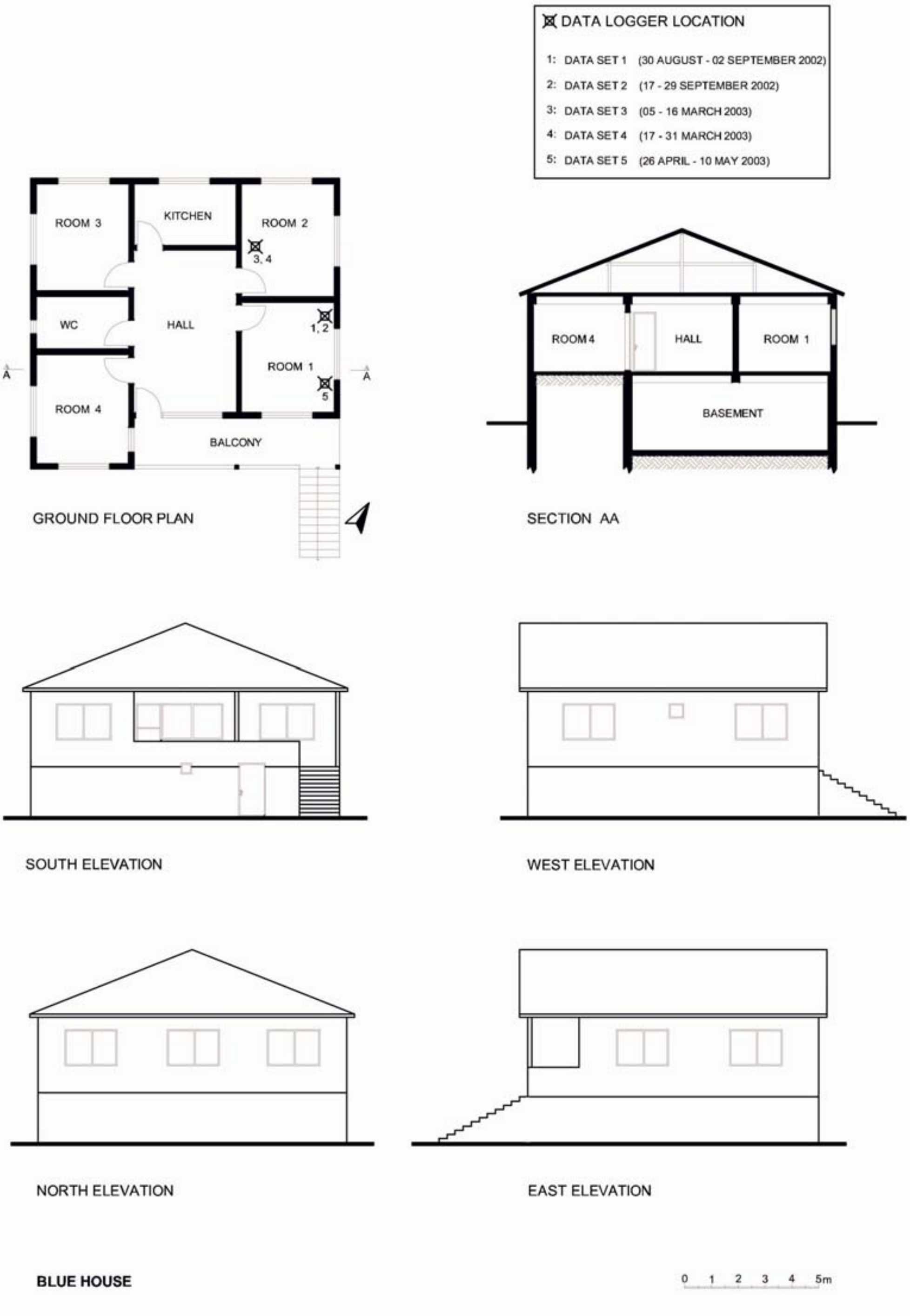


Figure 3.6. Orthographic Drawings of the Blue House

(Source: Plan by the author, section, elevations and final layout by Tuğrul Karagüzel)

c) Kerkenes Depot: The Kerkenes Depot House which is shown in Figure 3.7 has a reinforced concrete structure with insulated cavity brick external walls and single leaf brick internal walls, pitched roof, and 150mm concrete floor slab with mosaic covering. The building was usually occupied by a single person working between 06:00 and 18:00 hours every day. For Data Set 1, the data logger was placed in an unoccupied room with closed shutters. For Data Set 2, it was placed in the working room. Figure 3.8 shows the orthographic drawings of the Kerkenes Depot.

Figure 3.7. Kerkenes Depot House
(Source: Photo by Françoise Summers)

Although designed as a typical house, the building is used by the Kerkenes Archeology Project for conservation and storage of archeological material.

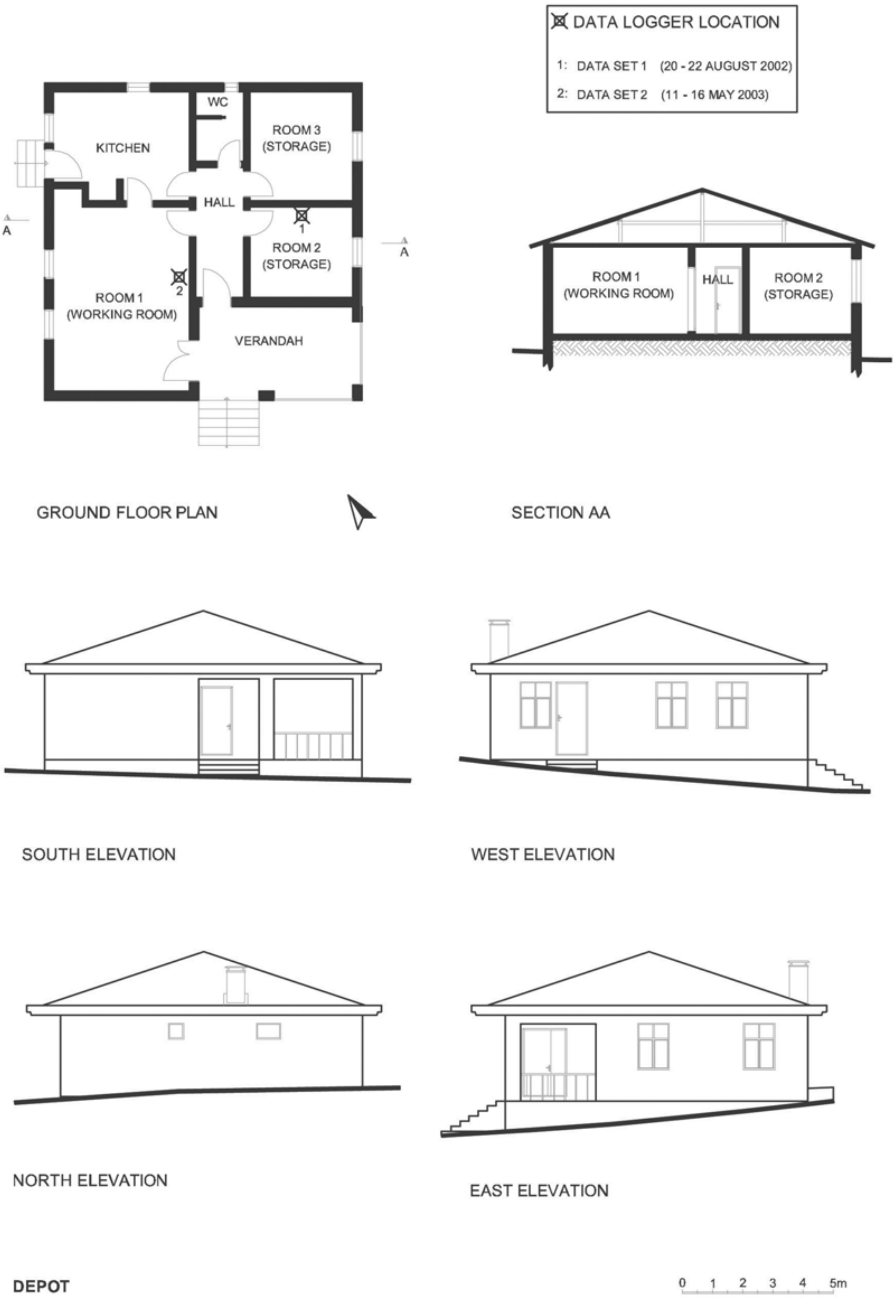


Figure 3.8. Orthographic Drawings of the Kerkenes Depot House

(Source: Drawings by Abdul Warfa, final layout by Tuğrul Karagüzel)

3.2. Method

To perform the study, several steps of statistical and computer analysis were conducted. First the sample size was determined, second the data was collected, third the data was evaluated by analyses of variance (ANOVA), and last Ecotect analyses were done.

3.2.1. Identifying the Right Sample Size

Determining the right sample size is extremely important in order to make educated inferences from the study. Finding the right sample size is possible from the following formula: (Devore, 2000, pp. 283)

$$\mathbf{n = (2z_{\alpha/2}\cdot\sigma / w)^2 \qquad \ldots\ldots\ldots\ldots\ldots(3.1)}$$

where n is sample size, z is variable of standard normal, **α** is level of significance, **σ** standard deviation and w is the width.

A smaller confidence interval would give a better solution on the result but in that case one has to collect a larger sample size. The assumption that an **α** of 0.10 would be adequate for this research is made at this point. In a research that has been carried out in 17-29 September 2002 in the Blue House, a data set of 1137 samples was collected at the site of the study for both interior and exterior temperatures, and humidity. For standard deviation (**σ**), the available samples on interior and exterior temperatures, and humidity were used. Deriving a plausible width (**w**) was the next step. Working out a width for the combination of interior and exterior temperature, and humidity helped gradually in making an educated guess on what kind of width is in the scope of our interest. All the results for the calculations are listed on Table 1. The calculation of width is possible from Formula 3.2 derived from Formula (3.1): (Devore, 2000, 283)

$$\mathbf{w = 2 \cdot z_{\alpha/2} \cdot \sigma / \sqrt{n}} \qquad \ldots\ldots\ldots\ldots\ldots(3.2)$$

As the daily variations in temperature and humidity at the inner surface of the building element are smaller in magnitude than those at is outer surface, the data on interior temperatures and humidity provided a smaller width dominating over the required sample size for 90% Confidence Interval ($\alpha = 0.10$) by requiring more samples than those for exterior. These figures are presented in Table 3.1 below. According to the given formula a smaller width is required for a larger sample size, therefore, the smaller width as given in row 3, taken into consideration for the calculation of the sample size, instead of the calculated widths as shown in row 2. As a last step, a comparison between a minimum numbers of observation required for an interior-temperature and interior-humidity was carried out. Maximum of minimums were selected in order to satisfy the worst case. The study showed that interior-humidity dominates over the others, requiring 1376 samplings, which may be rounded off to 1400. Consequently, it turned out that a two-week data-collecting period of 15-minute intervals between readings would be adequate for the research.

Table 3.1. Chart showing standard deviation, width, and number of observations required for external-internal temperature and humidity

	Ext. Temp. of Blue	**Int. Temp. of Blue**	**Ext. Hum. of Blue**	**Int. Hum. of Blue**
Standard Deviation for a set of data of 1137 samplings	5.27	2.45	15.22	3.95
Width for a set of data of 1137 samplings	0.5144	0.2392	1.4855	0.3849
Width taken for our research	0.5	0.22	1.4	0.35
Minimum **number of observations** required	1204	1345	1281	**1376**

3.2.2. Data Collection

Data was collected several times since August 2002. Due to the shortage of data loggers, to collect data concurrently for the three houses was impossible. For this reason data collection were carried out consecutively in the houses. The Data Sets that were measured in the years 2002 and 2003 are presented in Table 3.2 for the houses:

Table 3.2. Data Sets for Each House

	Babayiğit House	Blue House	Depot
Data Set 1	22-26 Aug. 2002	30 Aug.-2 Sept. 2002	20-22 Aug. 2002
Data Set 2	14-16 March 2003	17-29 Sept. 2002	11-16 May 2003
Data Set 3	26-10 May 2003	5-16 March 2003	
Data Set 4		17-31 March 2003	
Data Set 5		25 April-10 May 2003	

3.2.2. Data Evaluation

Data collected was analyzed and evaluated in order to show if there is a significant difference between the houses of 3 different building materials. As data was collected for one week only in the month of May for the depot, data from the other two buildings for the same number of days in May was considered for the statistical analysis (ANOVA). For the Depot 11-16 May, for the Babayiğit and Blue Houses 5-10 May is the data collection period that is used in ANOVA.

The ANOVA at a 5% level of significance was applied and when significant difference was found amongst the groups (three houses with three different building materials), multiple comparisons procedure called Tukey's Procedure (*t – test)* was conducted to determine the source of difference according to the following formulas:

$$\mathbf{s_x = \pm (\sigma^2 / n)^{1/2}} \qquad \textbf{……(3.3)}$$

where s_x is the standard error, $\boldsymbol{\sigma}$ is the variance of the group, and n is the group count.

Tukey's procedure involves the use of Studentized range distribution - $Q_{\alpha, m, v}$ that the value was obtained from the tables. $Q_{\alpha, k, k(n-1)}$ is used to obtain simultaneous confidence intervals for all pair wise differences $\mu_i - \mu_j$.

$$\mathbf{X_{i.} - X_{j.} - Q_{\alpha, k, k(n-1)} (s_x) \leq \mu_i - \mu_j \leq X_{i.} - X_{j.} + Q_{\alpha, k, k(n-1)} (s_x)} \qquad \textbf{...(3.4)}$$

($X_{i,\ j}$ is the sample means, μ the population mean, m and ν are the degrees of freedom, k is the number of treatments and n is the group count) (Devore, 2000, pp. 414-15).

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter results obtained from the analysis of variance and the *t* - test according to the houses with different building materials were presented. The graphs of temperature and humidity data were added and concluded with computer analysis followed by the discussion of results.

4.1. Results for ANOVA

The analysis of variance tables constructed with respect to different houses with three different building materials are as follows.

Analysis of Variance for 3 buildings with different building materials constructed. Our null hypothesis *Ho* is that there is no difference amongst the houses with respect to their building materials.

Table 4.1. Analysis of Variance for Internal Temperatures of Three Buildings with Different Building Materials

Source of Variation	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Squares (MS)	Calculated F-Value (MS_{AG} / MS_{WG})	F $_{expected}$ (α=0.05, 2, ∞)
Among Groups, (AG)	2	4756.0372	2378.019	975.2292	2.9957
Within Groups, (WG)	1482	3613.7389	2.43842	---	---
Total	1484	8369.7761	---	---	---
Conclusion: Ho is rejected with 95% confidence.					

The means and associated standard errors for the 3 houses shown in Table A.1 in Appendix A are; 15.13010101 ± 0.0701862, 17.32768 ± 0.0701862, and 19.51374 ± 0.0701862 respectively; giving a mean square among groups of 2378.019 and a mean square within groups of 2.43842. According to single factor ANOVA, the calculated F value, 975.2292, is larger than the expected F value (α=0.05, 2, ∞) of 2.9957 as obtained from statistical tables, so that the null hypothesis is rejected at a 5% level of significance.

The ANOVA had shown that houses differed significantly according to the building materials. A *Tukey's* procedure (*t*-test) was conducted in order to determine the source of the difference.

The MS within groups is the best unbiased estimate of the variance and that mean of each group therefore have the same standard error which is calculated according to the formula (3.3) as:

$$s_x = \pm\, (2.43842/495)^{1/2} = \pm\, 0.0701862$$

The expected Q-value at a 5% significance level for degrees of freedom of 3 and ∞ is given as 4.12, and the difference in the means was calculated according to the formula (3.4) as:

$$X_{i.} - X_{j.} - (Q_{0.05,3,\infty})(0.0701862) \le \mu_i - \mu_j \le X_{i.} - X_{j.} + (Q_{0.05,3,\infty})(0.0701862)$$

$$X_{i.} - X_{j.} - 0.289167 \le \mu_i - \mu_j \le X_{i.} - X_{j.} + 0.289167$$

In order to find the mean(s) that was(were) differing significantly, the 3 sample means needed to be arranged in increasing order which is shown in Table 4.2, and every pair differing by less than 0.289167 was underscored, but for our case none was underscored. The groups all differed by more than 0.289167. Therefore we can interpret that each of the three houses with different building materials were significantly different and considered as not belonging to the same population.

Table 4.2. Sample Means Arranged in Increasing Order

X_1 (Babayiğit)	X_2 (Blue)	X_3 (Depot)
15.13010101	17.32768	19.51374

4.2. Data and Charts

Several data of temperature and humidity were collected from 2002 August to May 2003. In the summer and autumn of 2002, we were able to measure interior and exterior data of temperature and humidity of one house at a time with the two data loggers. In 2003, three data loggers were available which enabled us to measure 2 houses at a time in March and May.

The data of interior and exterior temperature and humidity are superimposed on spread sheets which are demonstrated in the following section in order to produce graphs of interior and exterior data on one chart. In humidity graphs, the apsis shows the date and time of the reading period with 15 minute intervals. Ordinate shows the relative humidity as percentage. In temperature graphs the apsis shows the date and time of the reading period with 15 minute intervals and the ordinate shows the temperature as ^{0}C.

In the following section the data sets are presented from Figure 4.1 to 4.20 according to chronological order for each house. For Babayiğit House, the indoor air temperature and humidity are outstandingly stable. For Data Set 1, in August, air temperature is at around 21^{0}C despite outdoor air temperature between 18 and 30^{0}C; humidity is at around 58-62 % despite the outdoor humidity between19 and 70%. For Data Set 2, in March, air temperature is at around 18^{0}C despite outdoor air temperature between minus 10 and 11^{0}C; humidity is at around 85-90 % despite the outdoor humidity between 40 and 100%. The higher temperature of the house than outdoors shows the use of stove and the convective coupling between rooms in the house. For Data Set 3, in April and May, air temperature is at around 9-16^{0}C despite

4.2.1. Babayiğit House

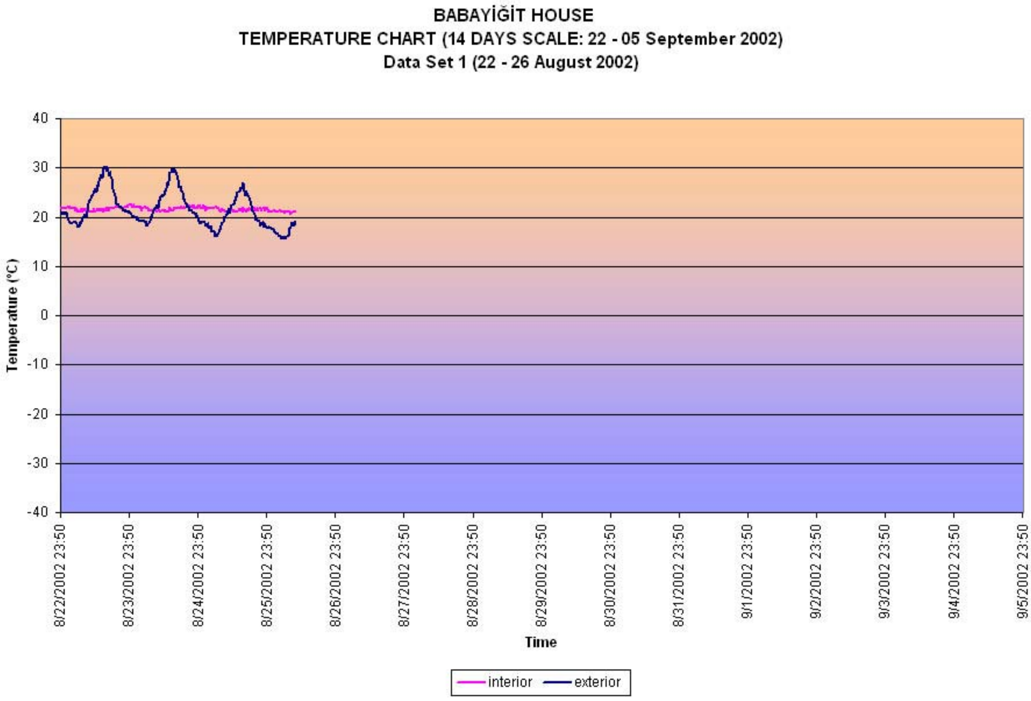


Figure 4.1. Babayiğit House Temperature, Data Set 1

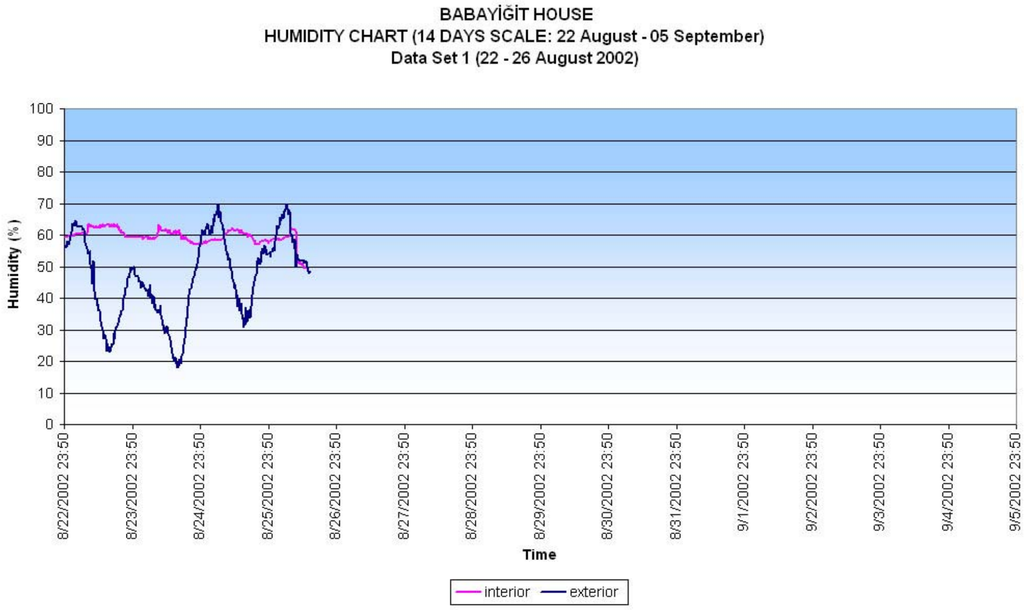


Figure 4.2. Babayiğit House Humidity, Data Set 1

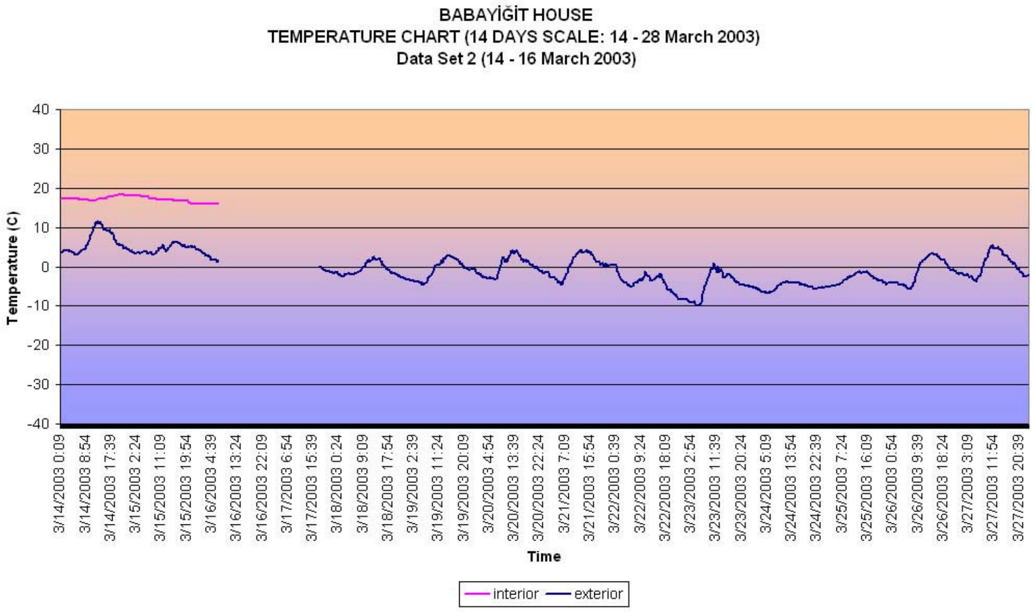


Figure 4.3. Babayiğit House Temperature, Data Set 2

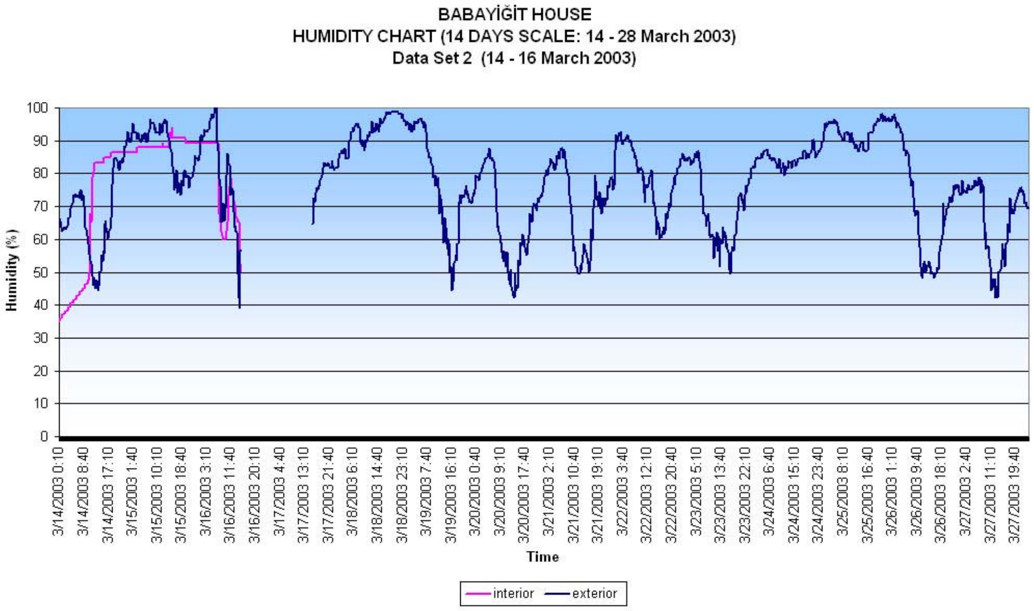


Figure 4.4. Babayiğit House Humidity, Data Set 2

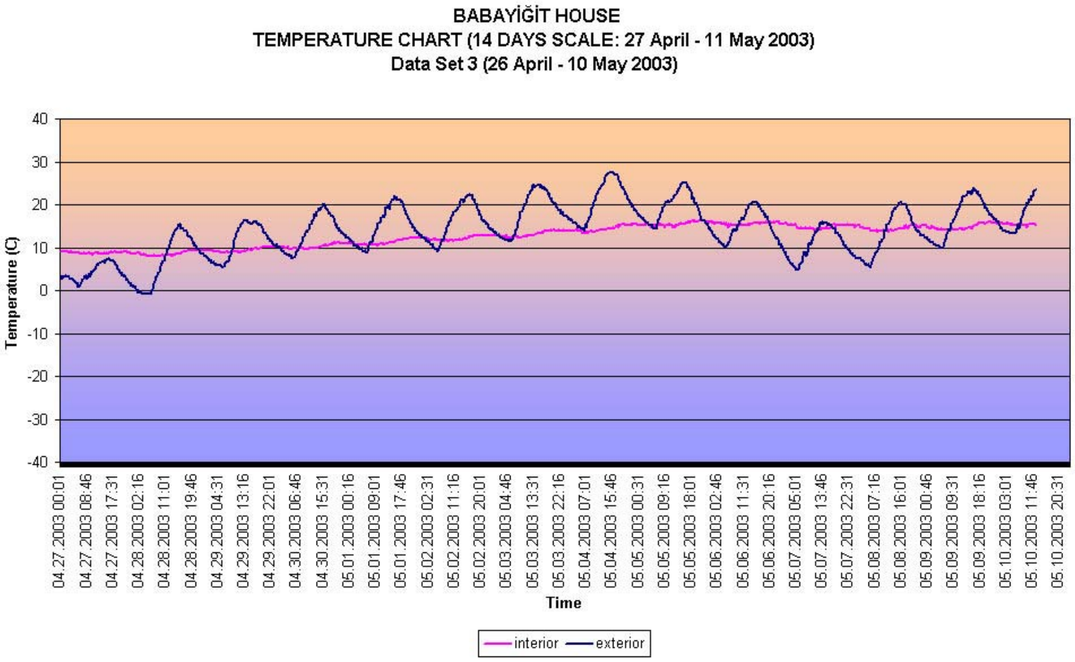


Figure 4.5. Babayiğit House Temperature, Data Set 3

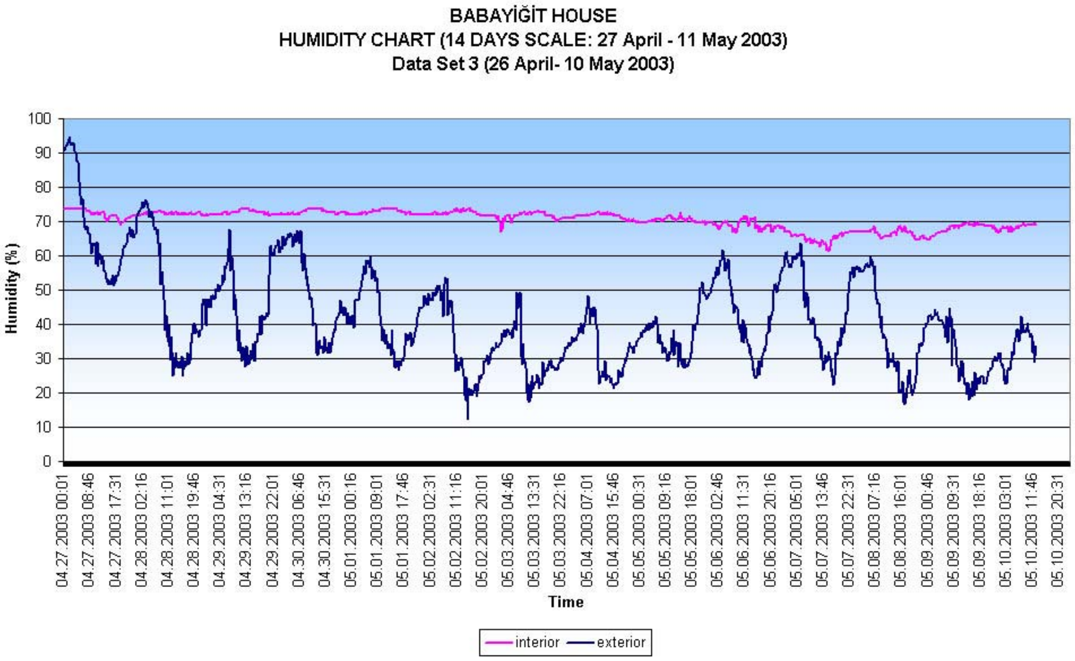


Figure 4.6. Babayiğit House Humidity, Data Set 3

4.2.2. Blue House

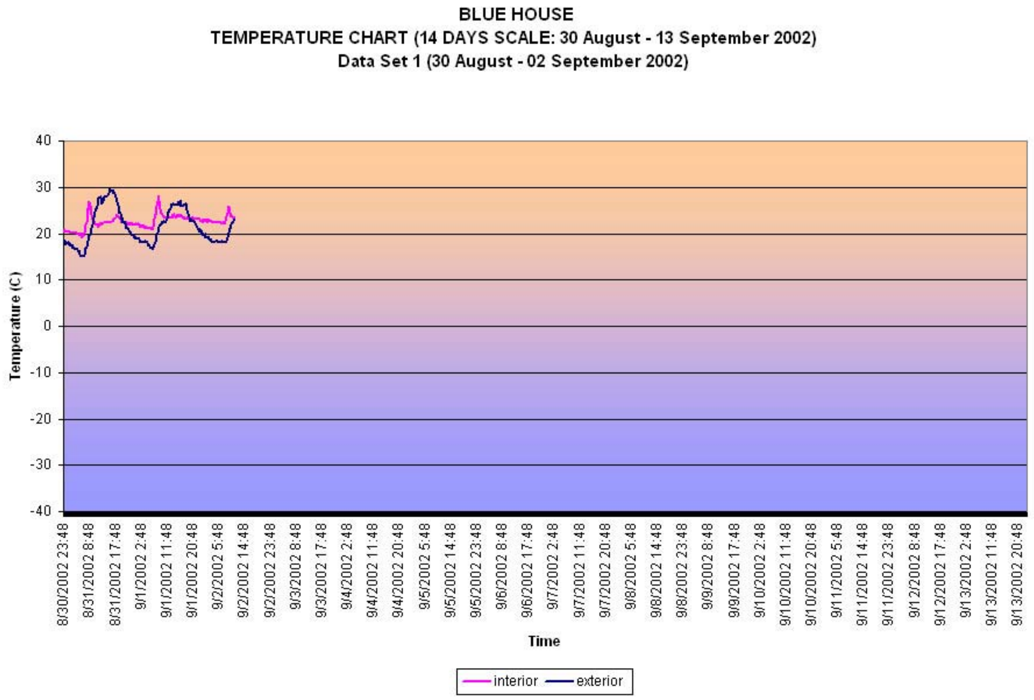

BLUE HOUSE
TEMPERATURE CHART (14 DAYS SCALE: 30 August - 13 September 2002)
Data Set 1 (30 August - 02 September 2002)

Figure 4.7. Blue House Temperature, Data Set 1

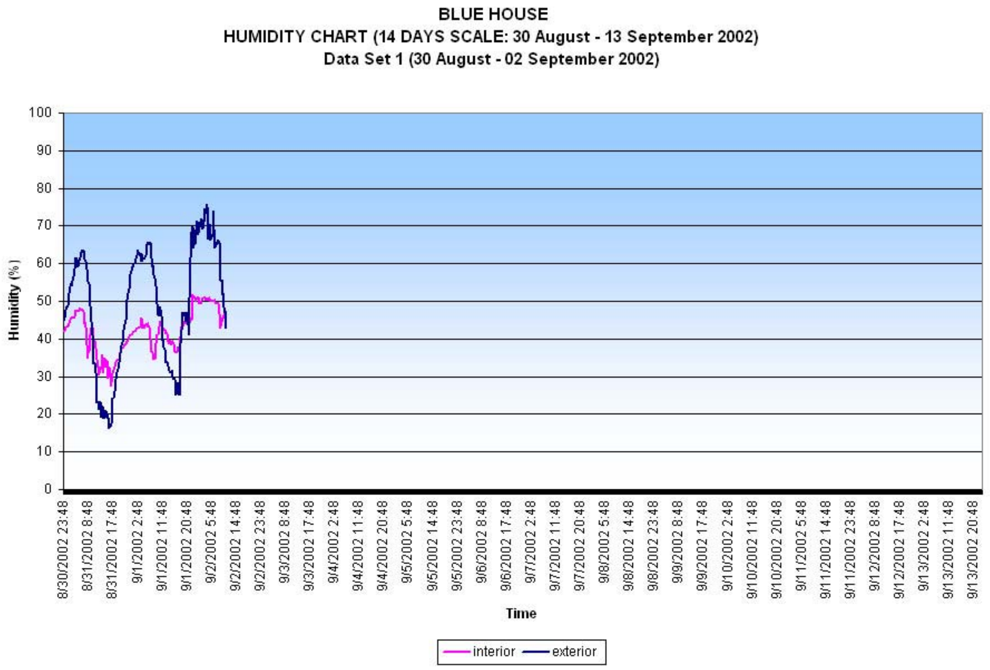

BLUE HOUSE
HUMIDITY CHART (14 DAYS SCALE: 30 August - 13 September 2002)
Data Set 1 (30 August - 02 September 2002)

Figure 4.8. Blue House Humidity, Data Set 1

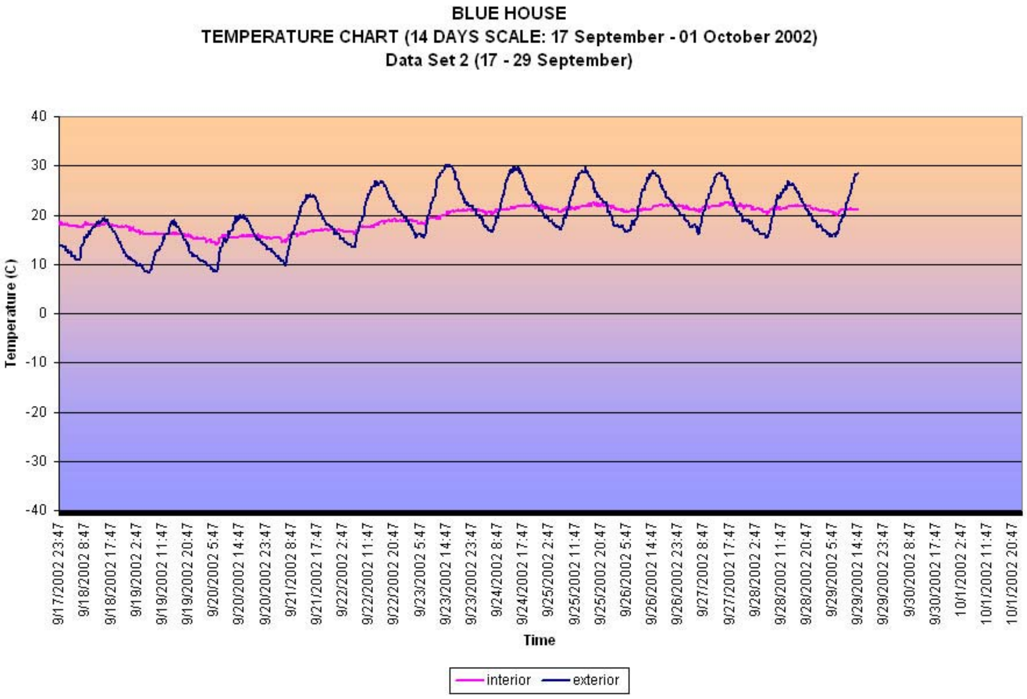


Figure 4.9. Blue House Temperature, Data Set 2

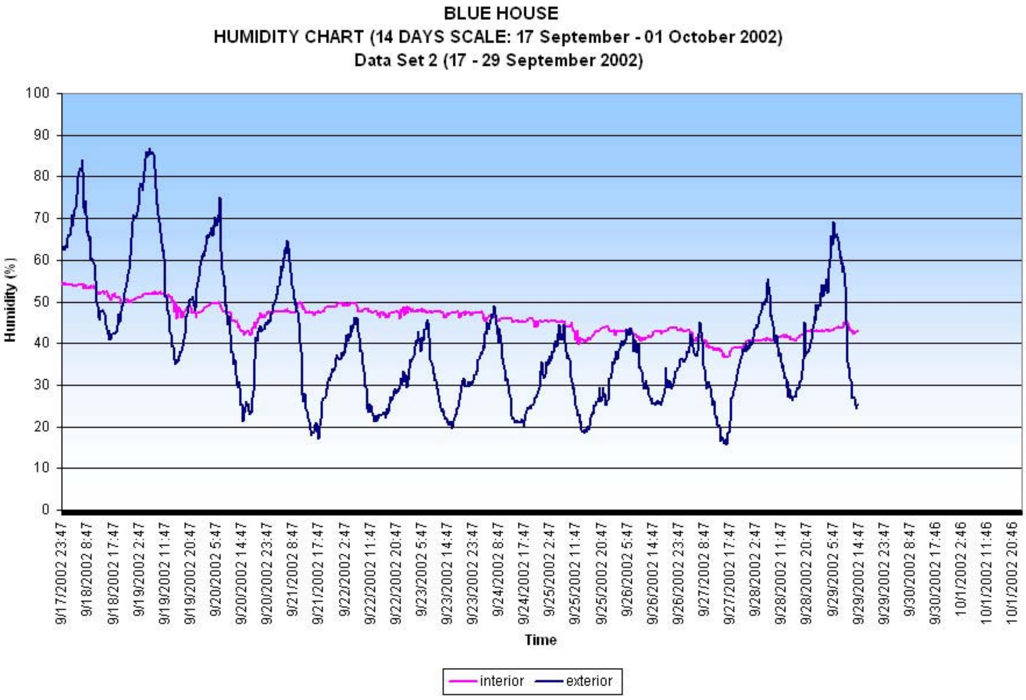


Figure 4.10. Blue House Humidity, Data Set 2

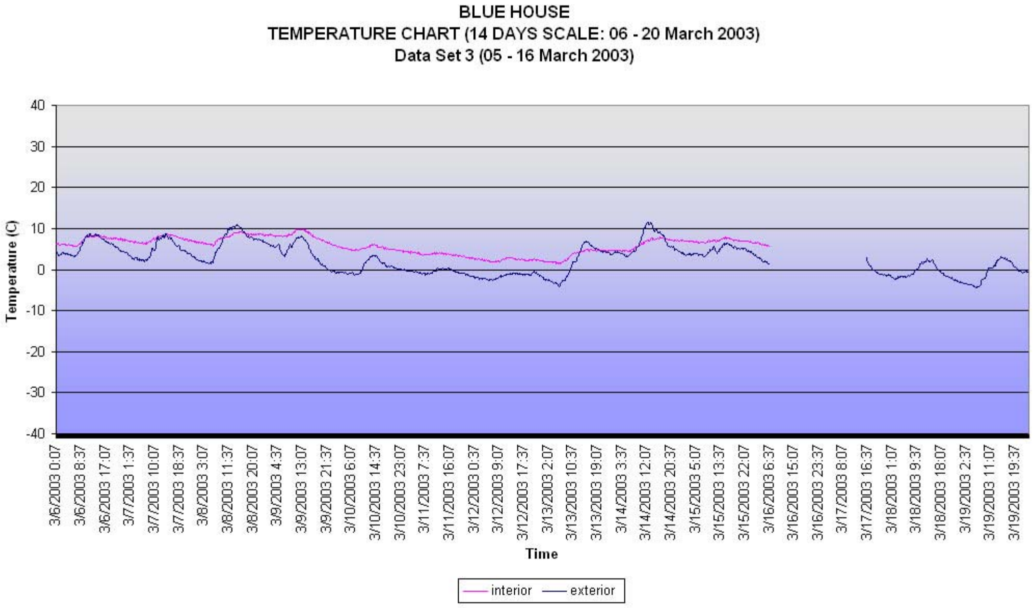


Figure 4.11. Blue House Temperature, Data Set 3

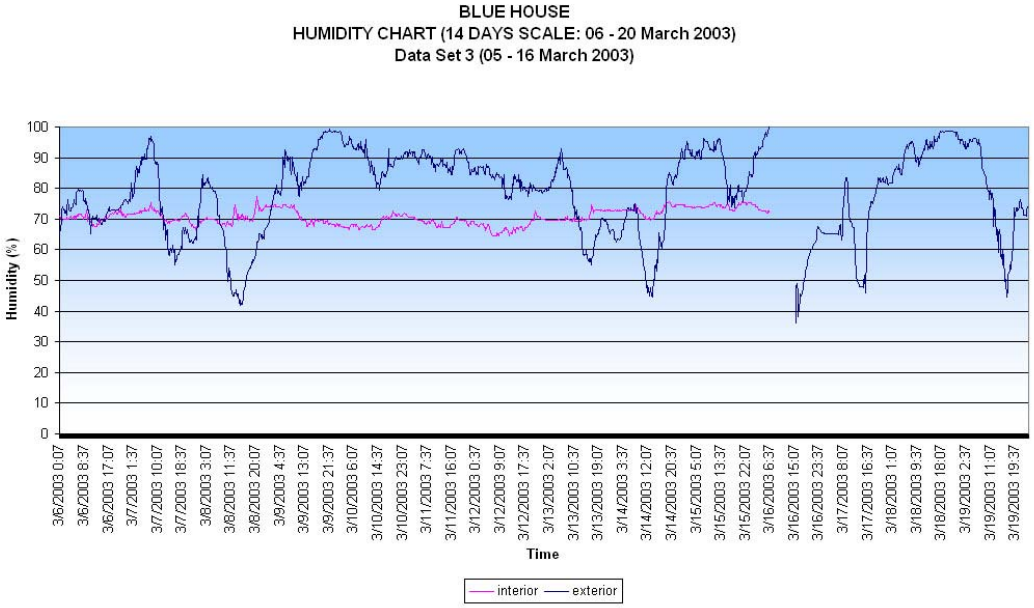


Figure 4.12. Blue House Humidity, Data Set 3

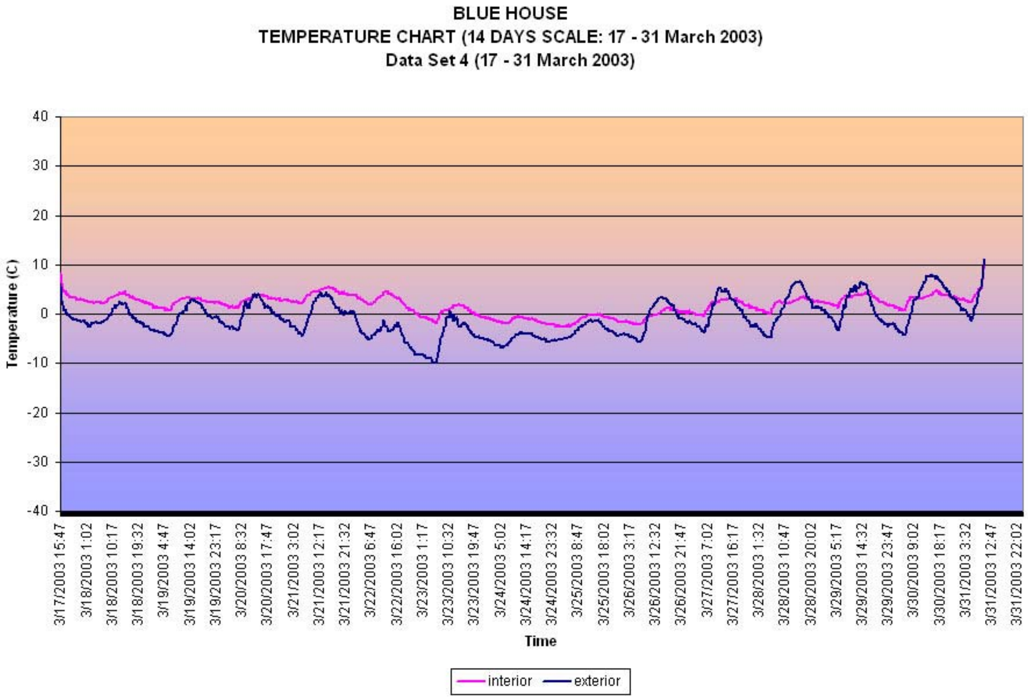


Figure 4.13. Blue House Temperature, Data Set 4

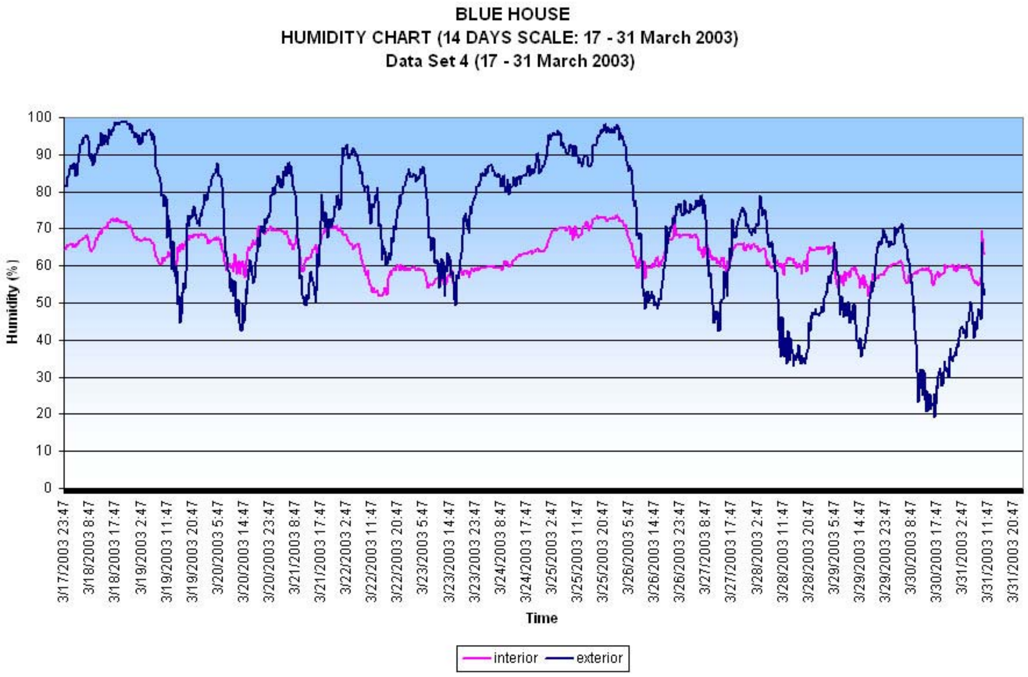


Figure 4.14. Blue House Humidity, Data Set 4

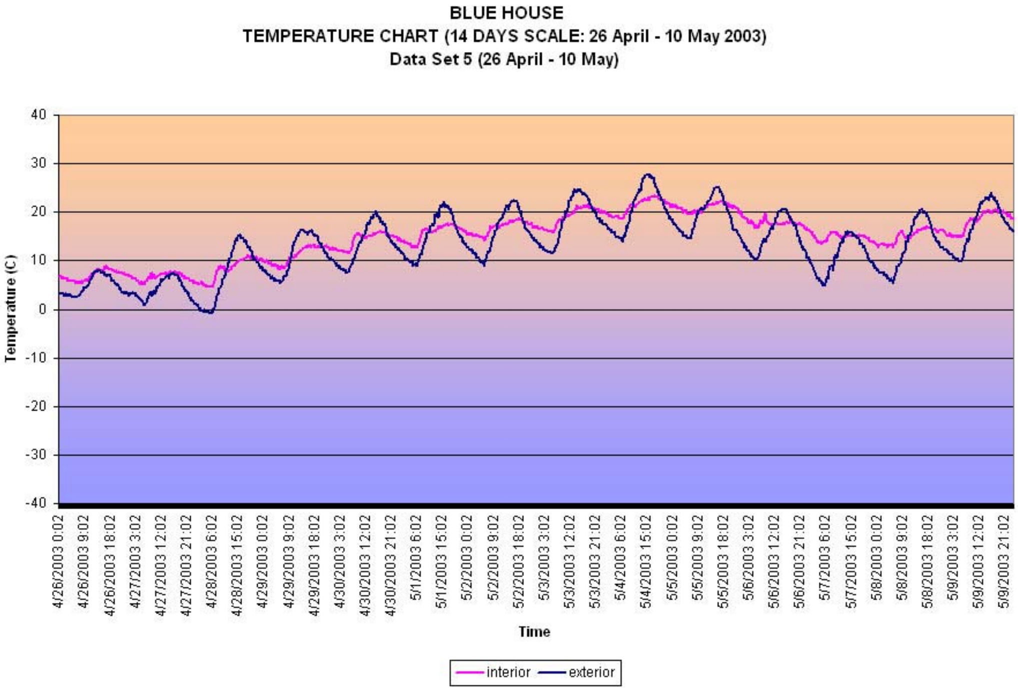


Figure 4.15. Blue House Temperature, Data Set 5

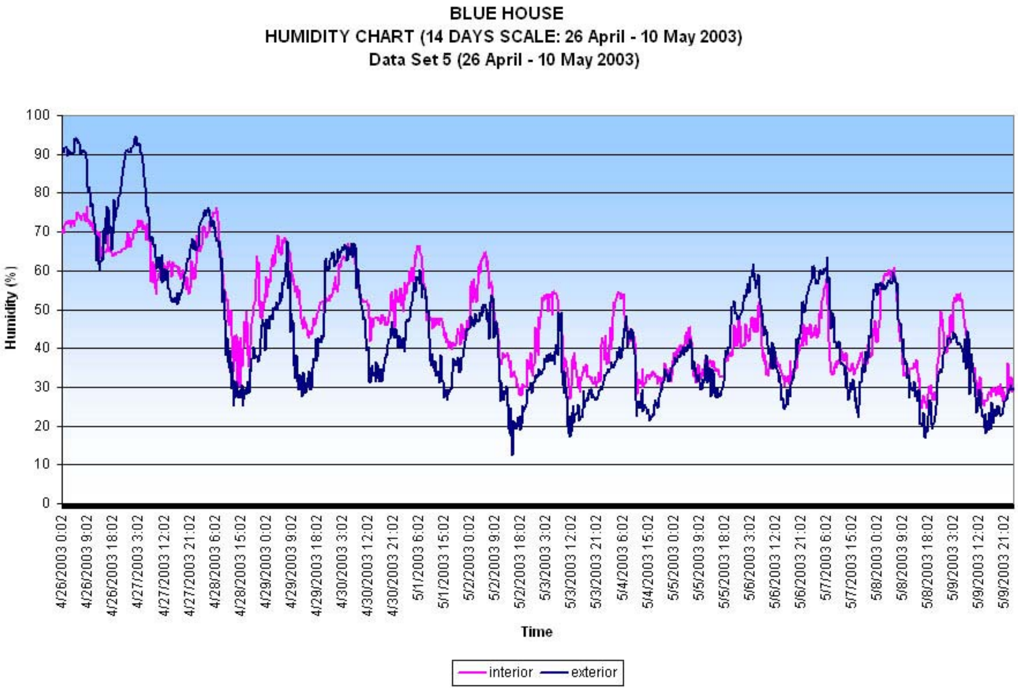


Figure 4.16. Blue House Humidity, Data Set 5

4.2.3. Depot

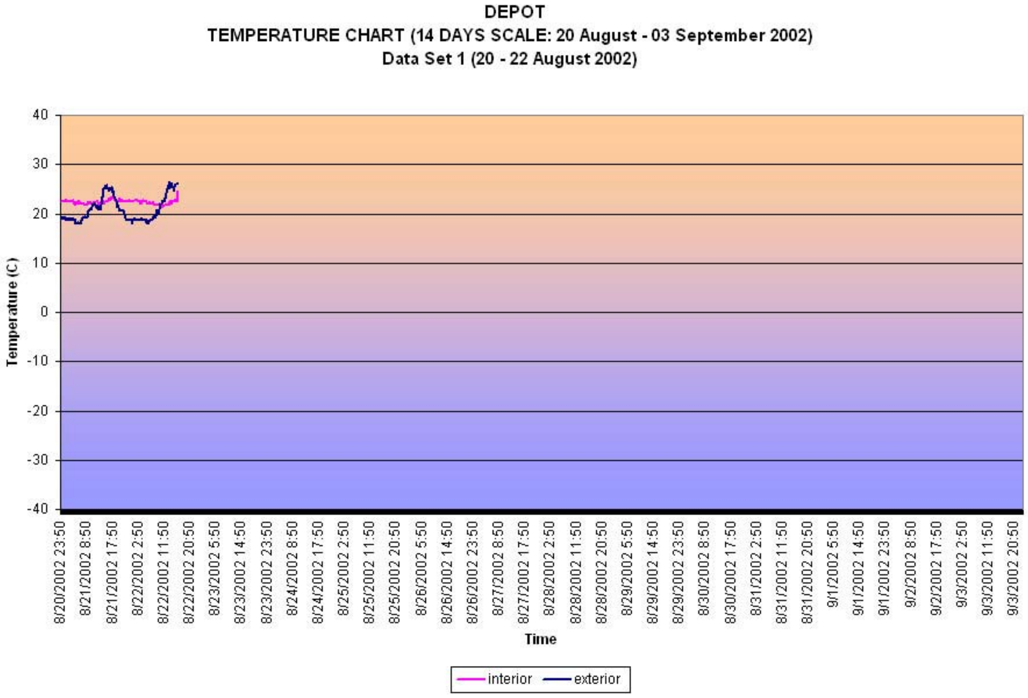


Figure 4.17. Depot Temperature, Data Set 1

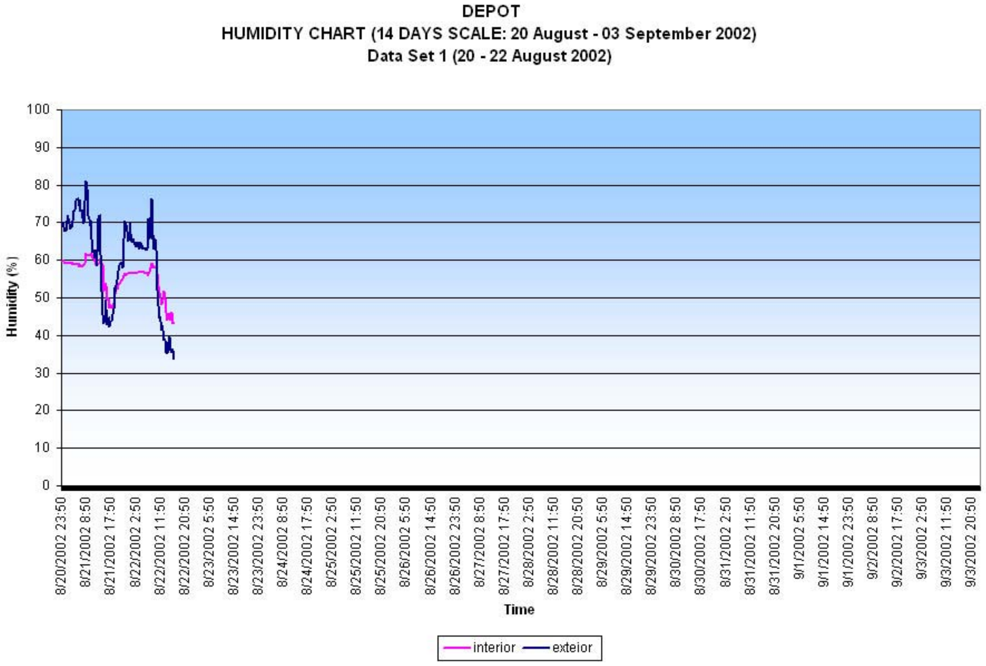


Figure 4.18. Depot Humidity, Data Set 1

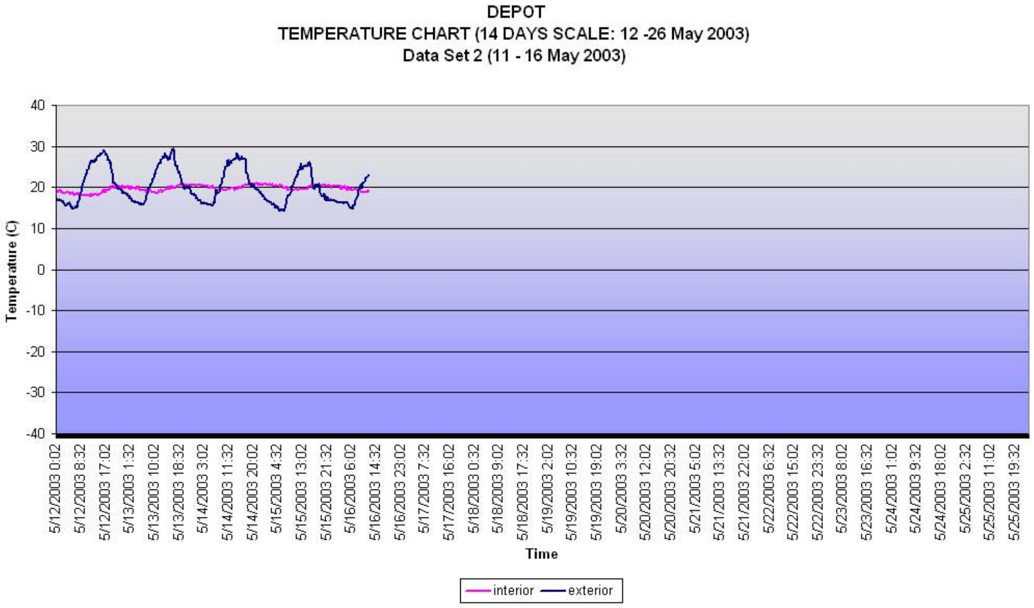


Figure 4.19. Depot Temperature, Data Set 2

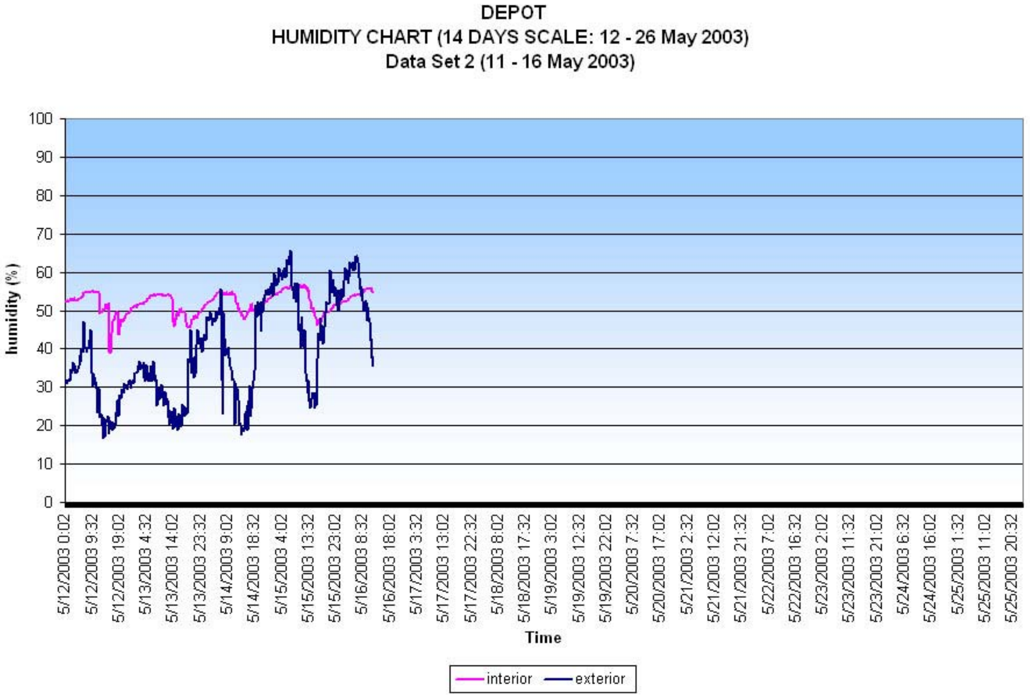


Figure 4.20. Depot Humidity, Data Set 2

outdoor air temperature between 0 and 28^{0}C; humidity is at around 60-75 % despite the outdoor humidity between 12 and 75%. This measurement clearly illustrates the thermal capacity of the Babayiğit House as it responds very slowly to a 28^{0}C rising of the outdoor air temperature. The humidity stands very stable, that is most probably because the house was not ventilated.

For Blue House, the indoor air temperature and humidity responds to the outdoor climate faster than the Babayiğit House, the indoor values follow the profile of the outdoor ones. For Data Set 1, in August and September, air temperature varied from 19 to 27 ^{0}C while outdoor air temperature varied from 15 to 30^{0}C; humidity varied from 29 to 48 % while the outdoor humidity varied from 18 to 75%. For Data Set 2, in September, air temperature varied from 15 to 22 ^{0}C while outdoor air temperature varied from 9 to 30^{0}C; humidity varied from 37 to 55 % while the outdoor humidity varied from 16 to 85%. For Data Set 3, in March, air temperature varied from 2 to 10 ^{0}C while outdoor air temperature varied from minus 5 to 11^{0}C; humidity varied from 65 to 75 % while the outdoor humidity varied from 40 to 100%. For Data Set 4, in March, air temperature varied from minus 10 to 10 ^{0}C while outdoor air temperature varied from minus 2 to 5^{0}C; humidity varied from 51 to 72 % while the outdoor humidity varied from 20 to 100%. For Data Set 5, in April and May, air temperature varied from 5 to 23 ^{0}C while outdoor air temperature varied from 0 to 27^{0}C; humidity varied from 25 to 75 % while the outdoor humidity varied from 15 to 95%. The fluctuation of interior humidity in Data Set 5 is more than the others which may be because of the unreported ventilation of the house by the occupants. The fast respond to the outdoor climate of the Blue House and larger fluctuations suggest that it has a lower thermal capacity.

For the Kerkenes Depot, the indoor air temperature and humidity values were more or less stable showing similar performances as Babayiğit House. For Data Set 1, in August, the air temperature varied little around 22^{0}C despite the outdoor varying between 19 and 26^{0}C; humidity varied between 45 and 62% while outdoor ranging between 35 and 80%. Data Set 2, in May, the air temperature varied little around 20^{0}C despite the outdoor varying between 15 and 30^{0}C; humidity varied between 40 and 57% while outdoor ranging between 20 and 65%. The stability of indoor air temperatures demonstrates the effect of thermal insulation.

4.3. Ecotect Analysis

The ANOVA test has shown significant differences in the interior temperatures of the Babayiğit, Blue Houses and the Depot Building. They were made out of different building materials, but as they have several other differences such as the orientation of site, floor area, window/floor area ratio, and the placement of the data loggers. These differences prevent us from inferring that the differences in the interior temperatures were because of the building materials only.

Ecotect Analysis enabled us to restrict the parameters to building materials. Babayiğit House was chosen as a case study for the analysis and Ecotect model was produced, which is shown in Figure 4.21 to estimate their effect on thermal comfort. The Ecotect Analyses conducted which will be presented in the following section are as follows: Monthly Discomfort Degree Hours, Temperature Distribution and Monthly Heating/Cooling Loads.

Yozgat weather data - which was obtained from Turkish Meteorology Department for year 2002 and reformatted for Ecotect and which is shown in Figure 4.22 was used for the thermal analyses. The Figure not only gives information about daily maximum and minimum values of outdoor air temperatures for each month against thermal comfort bands derived from thermal neutrality temperatures but also gives information about direct and diffuse solar radiation; relative humidity and wind speed of the year 2002 for Yozgat. The material properties that were used in the analyses of the 5 different models of the Babayiğit House are presented in Table 4.3.

Table 4.3. The Material Properties Used in the Ecotect Analyses.

Material Properties	**U-Value (W/m^2K)**	**Admittance (W/m^2K)**
Mud brick wall (400mm mud-brick)	1.33	4.51
Stone wall (500mm low density sand stone)	2.84	6.44
Hollow brick wall (190mm hollow brick with 10mm plaster on either)	1.63	4.54
Insulated cavity hollow brick wall (190mm and 90mm hollow bricks with 100mm thermal insulation inside and 10mm plaster on either side)	0.30	3.52

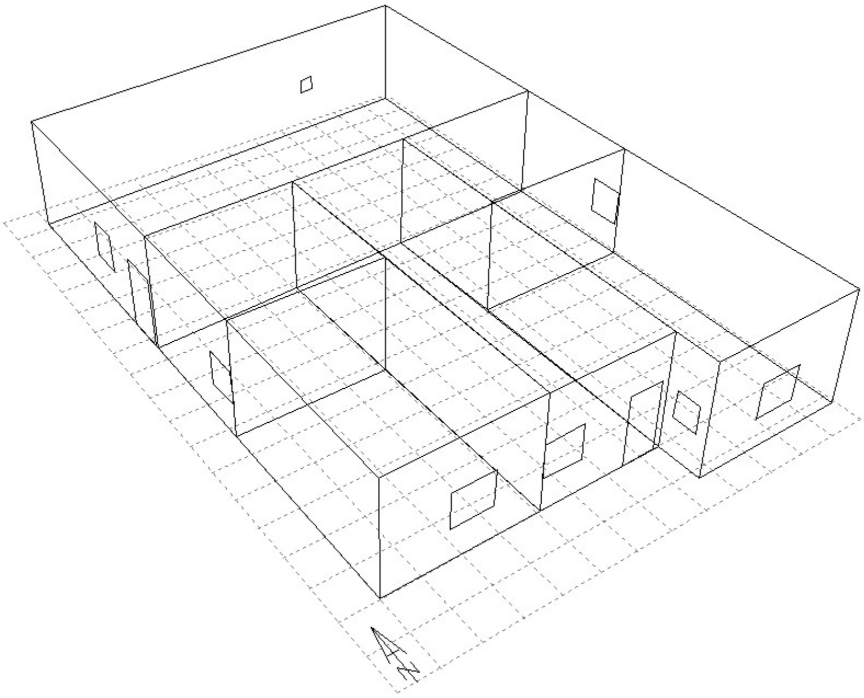


Figure 4.21. Ecotect Model of Babayiğit House

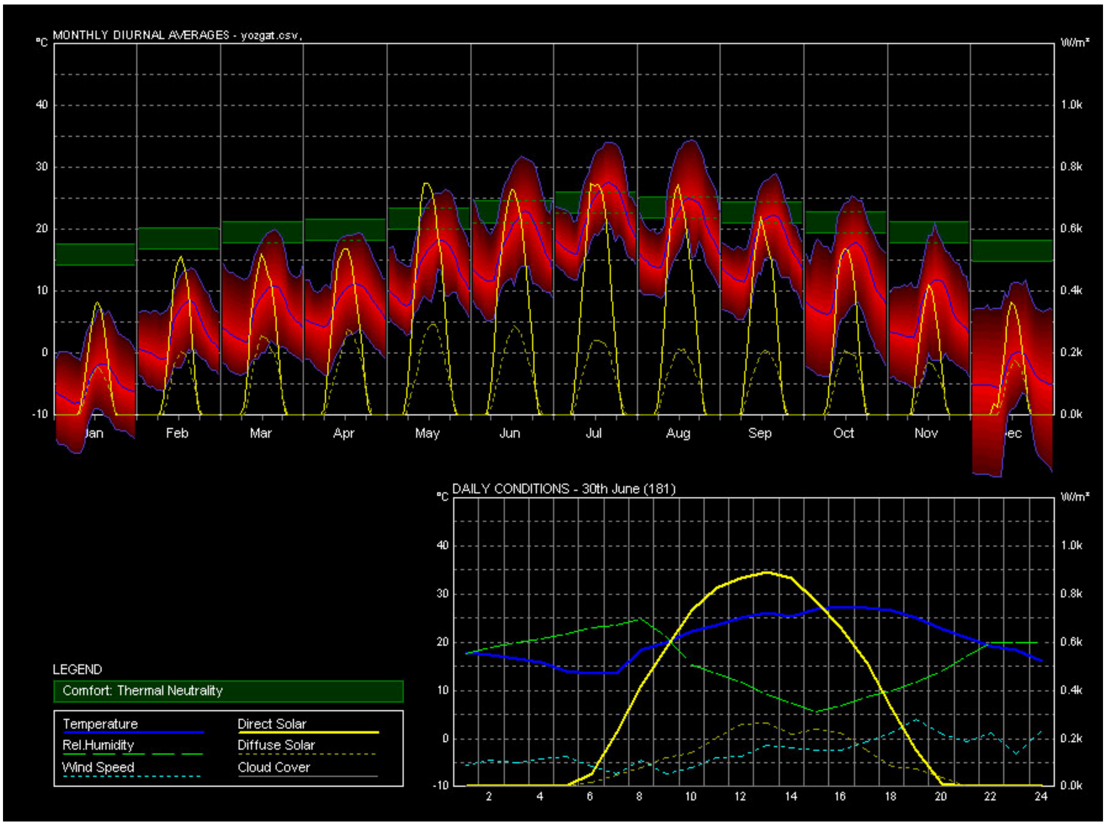


Figure 4.22. Yozgat Weather Data
(Source: Weather Tool 1.1)

4.3.1. Monthly Discomfort Degree Hours

According to adaptive (free run) and static comfort theory Babayiğit House has shown different discomfort levels according to different building materials in natural ventilation conditions. Table 4.4 shows the discomfort degree hours of Babayiğit House. In the Table the most and the least comfortable conditions are highlighted to demonstrate the differences easily. It is seen from the Table that Babayiğit House would be thermally more comfortable according to adaptive rather than static comfort model. It is also seen that hollow brick cavity wall with thermal insulation stays within the comfort zone for the longest period and stone exterior wall with mud brick interior wall has the least comfort period amongst the group of wall combinations studied.

Table 4.4. Discomfort Degree Hours of Babayiğit House According to Different Building Materials With Respect to Adaptive (Free Run) and Static Comfort Models
(Source: Analysis Values from Ecotect 5.0)

	Too Hot (DHrs)		Too Cool (DHrs)		Total (DHrs)	
	Adapt.	Static	Adapt.	Static	Adapt.	Static
Mud Int. & Stone Ext. Walls (Actual Condition)	1666	169	42996	71218	**44662**	71387
Stone Walls	**1653**	**166**	**43001**	**71225**	44654	**71391**
Mud Brick Walls	2122	261	40065	68099	42187	68360
Hollow Brick Walls	2111	260	40590	68635	42702	68895
Hollow Brick Cavity Walls with Thermal Insulation	**3658**	**546**	**33602**	**61097**	**37261**	**61644**

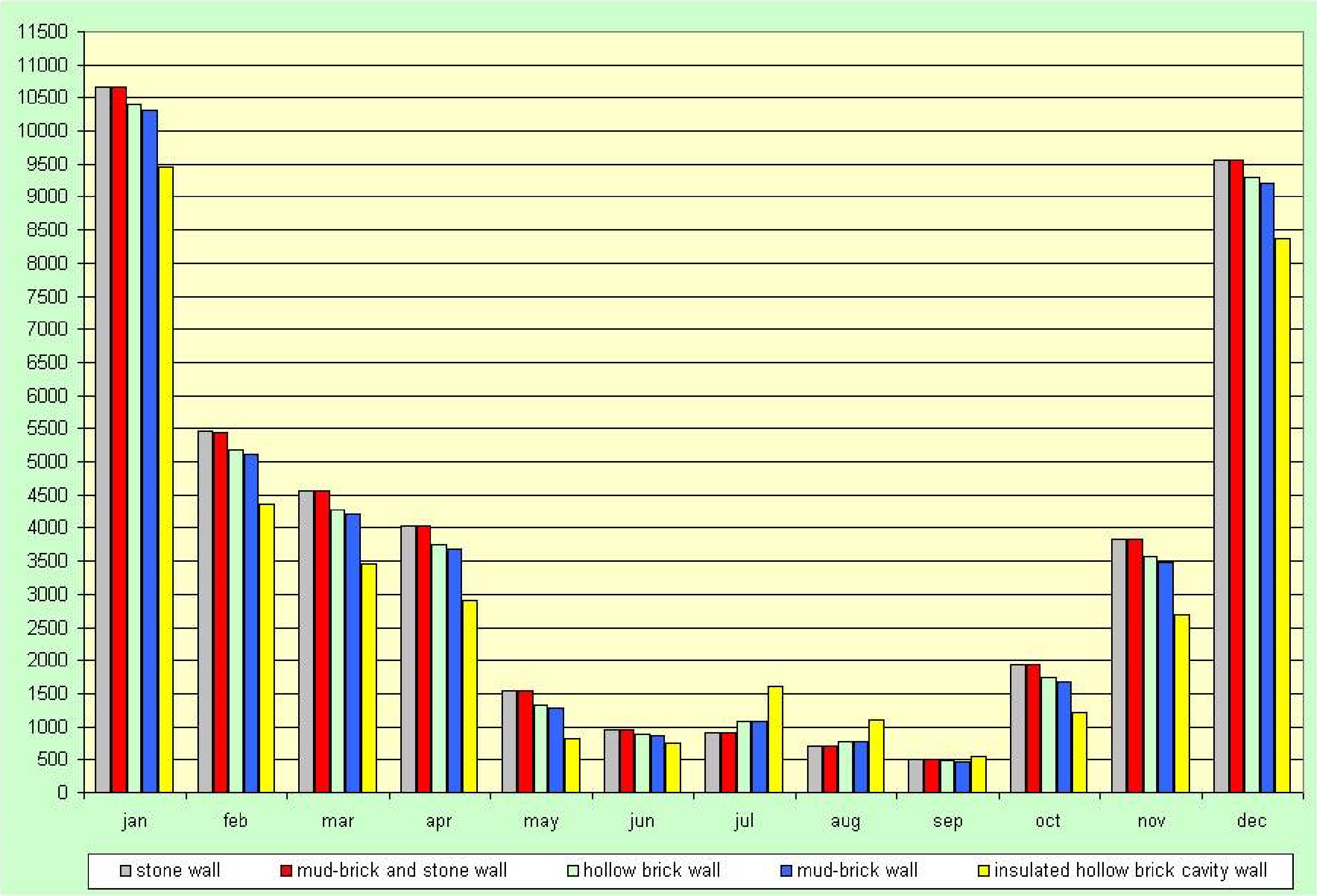
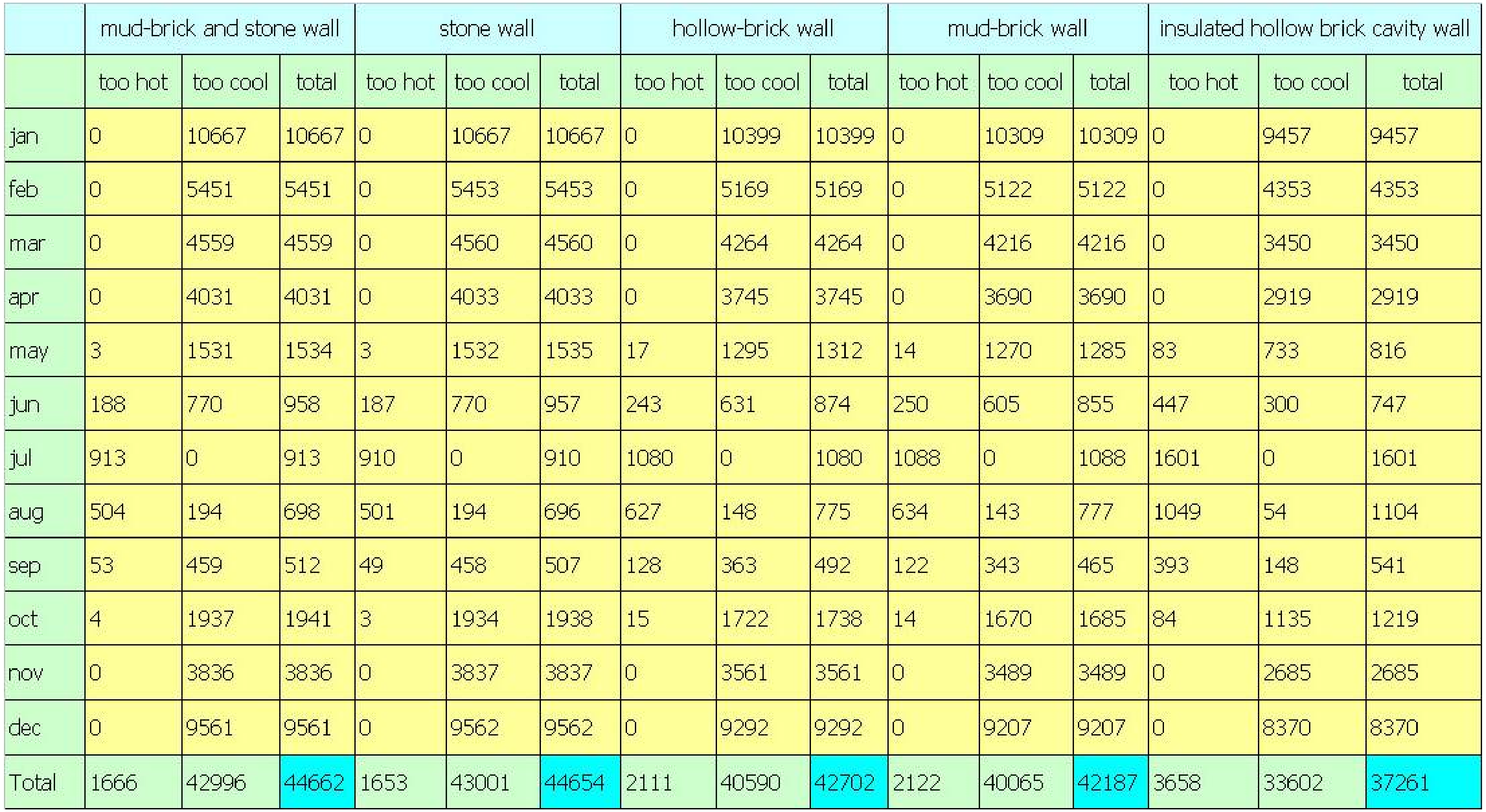


Figure 4.23. Discomfort Degree Hours of Babayiğit House According to Different Building Materials (Source: M.S. Excel

Monthly Discomfort Graphs of Babayiğit House with different building materials were imported to a spread sheet to show the effect of different building materials month by month according to adaptive (free run) comfort model which is shown in Figure 4.23. As the analysis shows the discomfort, the shortest bars represent the most comfortable situation amongst the group. The general monthly trend does not change significantly. It can be understood from the figure that hollow brick cavity wall with thermal insulation has shown better comfort conditions in cool season, but worse comfort conditions in warm season - July August and September. The stone wall and mud-brick and stone wall were acting similarly throughout the year whereas hollow brick wall showed similar properties as mud-brick wall. The whole data of discomfort degree hours of Ecotect analysis can be found in Table 4.5. From the Table 4.5 and Figure 4.23 it can be inferred that stone wall is the most comfortable whereas insulated hollow brick cavity wall is the least comfortable for warm period. For cool period it is the opposite.

Table 4.5. **Discomfort Degree Hours of Babayiğit House According to Different Building Materials (Adaptive Free Run Comfort Theory)**
Source: Value from Ecotect, Table from M.S. Excel



	mud-brick and stone wall			stone wall			hollow-brick wall			mud-brick wall			insulated hollow brick cavity wall		
	too hot	too cool	total	too hot	too cool	total	too hot	too cool	total	too hot	too cool	total	too hot	too cool	total
jan	0	10667	10667	0	10667	10667	0	10399	10399	0	10309	10309	0	9457	9457
feb	0	5451	5451	0	5453	5453	0	5169	5169	0	5122	5122	0	4353	4353
mar	0	4559	4559	0	4560	4560	0	4264	4264	0	4216	4216	0	3450	3450
apr	0	4031	4031	0	4033	4033	0	3745	3745	0	3690	3690	0	2919	2919
may	3	1531	1534	3	1532	1535	17	1295	1312	14	1270	1285	83	733	816
jun	188	770	958	187	770	957	243	631	874	250	605	855	447	300	747
jul	913	0	913	910	0	910	1080	0	1080	1088	0	1088	1601	0	1601
aug	504	194	698	501	194	696	627	148	775	634	143	777	1049	54	1104
sep	53	459	512	49	458	507	128	363	492	122	343	465	393	148	541
oct	4	1937	1941	3	1934	1938	15	1722	1738	14	1670	1685	84	1135	1219
nov	0	3836	3836	0	3837	3837	0	3561	3561	0	3489	3489	0	2685	2685
dec	0	9561	9561	0	9562	9562	0	9292	9292	0	9207	9207	0	8370	8370
Total	1666	42996	44662	1653	43001	44654	2111	40590	42702	2122	40065	42187	3658	33602	37261

4.3.2. Temperature Distribution

Annual internal temperature distribution graphs of Babayiğit House according to different building materials show the number of hours a particular internal temperature was encountered over the entire year. The vertical axis shows the hour count while the horizontal axis shows the temperature. These graphs clearly show whether a building is consistently warmer or cooler than outside air conditions and the hour count that the building stayed in comfort. From Figure 4.24 to 4.28 shows the Ecotect analysis graphs according to hollow brick cavity wall with thermal insulation; hollow brick wall; mud brick wall, stone wall, stone (exterior) and mud brick (interior) wall respectively. Each line on the graphs shows the temperature distribution within each zone into which the building is divided for the sake of analysis.

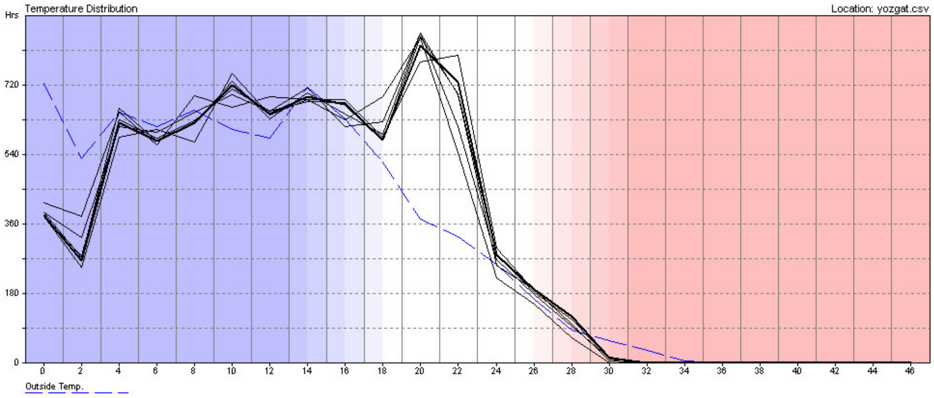


Figure 4.24. Annual Temperature Distribution of Babayiğit House

Specified Material is Hollow Brick Cavity Wall with Thermal Insulation

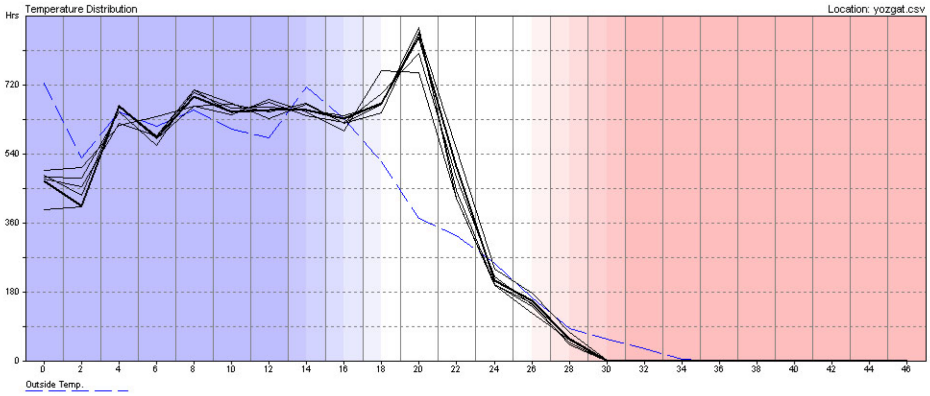


Figure 4.25. Annual Temperature Distribution of Babayiğit House

Specified Material is Hollow Brick

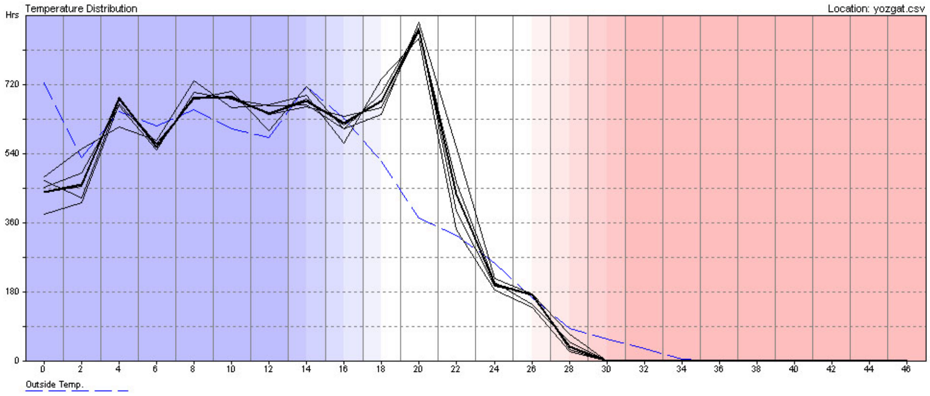


Figure 4.26. Annual Temperature Distribution of Babayiğit House

Specified Material is Mud Brick

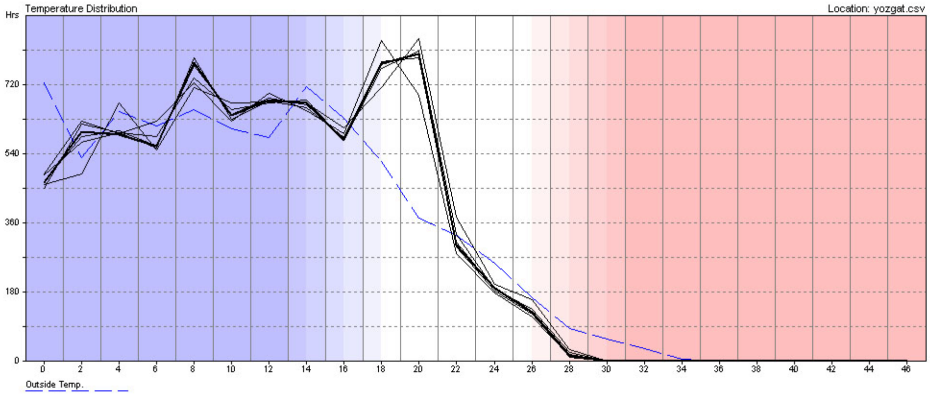


Figure 4.27. Annual Temperature Distribution of Babayiğit House

Specified Material is Stone

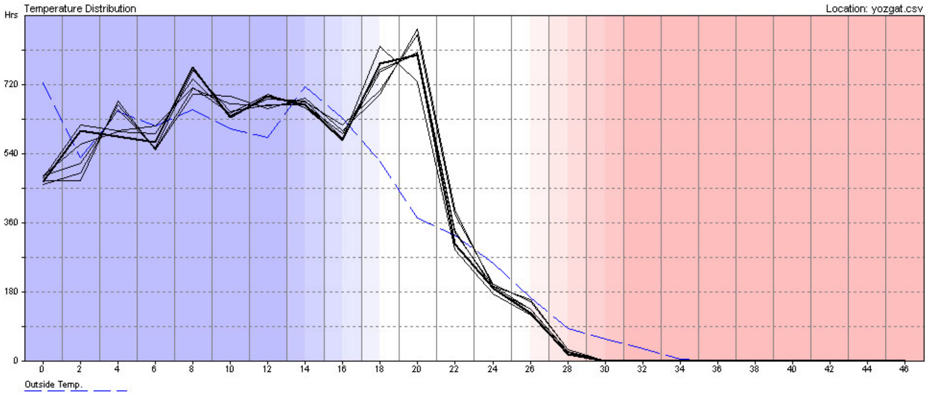


Figure 4.28. Annual Temperature Distribution of Babayiğit House

Specified Material is Stone (exterior) and Mud Brick (interior)

Figure 4.29 shows the superimposition of annual temperature distribution of Babayiğit House according to different building materials.

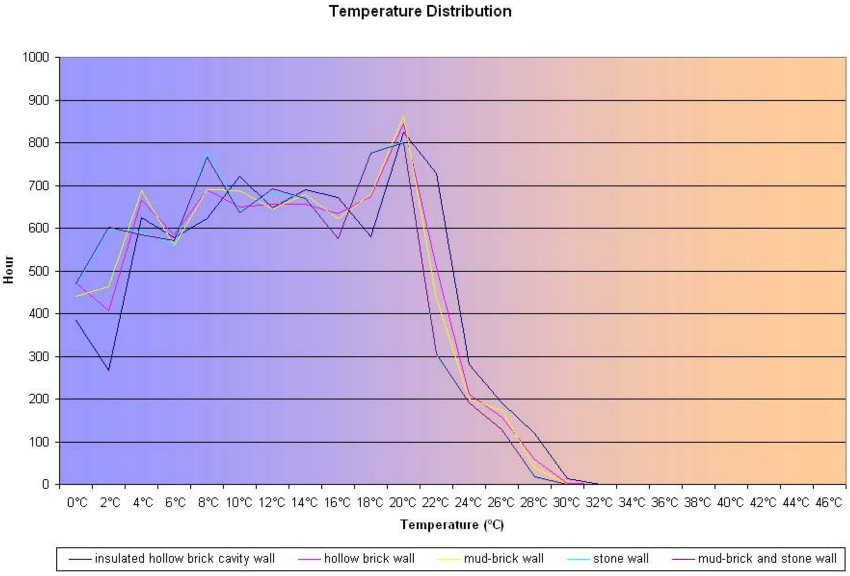


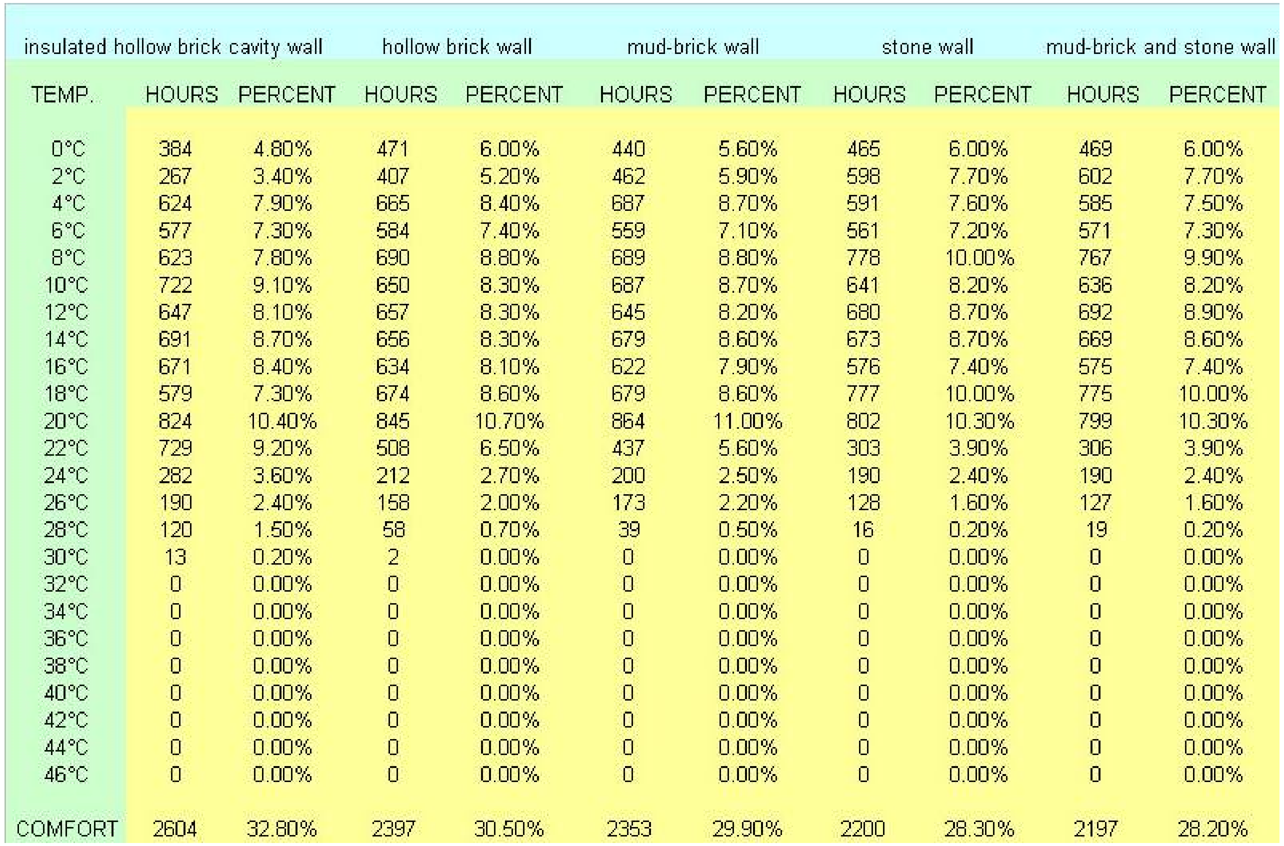
Figure 4.29. Annual Temperature Distribution of Babayiğit House

(Souce: Values from Ecotect, graph from M.S. Excel)

As can be seen from Table 4.6, hollow brick cavity wall with thermal insulation stays comfortable (32.80%) for the longest period and mud-brick whereas stone wall stays comfortable (28.20%) the shortest period amongst the group. The stone wall and mud-brick and stone wall were in comfort for approximately same percentage as 28.30 and 28.20 % respectively which indicates that the indoor temperatures mostly depend on the properties of the exterior wall. The mud-brick wall and hollow brick wall stays in comfort for the same percentage as 8.60% at 18^0C.

Table 4.6. Annual Temperature Distribution of Babayiğit House According to Different Building Materials

Source: Values from Ecotect, Table from M.S. Excel



	insulated hollow brick cavity wall		hollow brick wall		mud-brick wall		stone wall		mud-brick and stone wall	
TEMP.	HOURS	PERCENT	HOURS	PERCENT	HOURS	PERCENT	HOURS	PERCENT	HOURS	PERCENT
0°C	384	4.80%	471	6.00%	440	5.60%	465	6.00%	469	6.00%
2°C	267	3.40%	407	5.20%	462	5.90%	598	7.70%	602	7.70%
4°C	624	7.90%	665	8.40%	687	8.70%	591	7.60%	585	7.50%
6°C	577	7.30%	584	7.40%	559	7.10%	561	7.20%	571	7.30%
8°C	623	7.80%	690	8.80%	689	8.80%	778	10.00%	767	9.90%
10°C	722	9.10%	650	8.30%	687	8.70%	641	8.20%	636	8.20%
12°C	647	8.10%	657	8.30%	645	8.20%	680	8.70%	692	8.90%
14°C	691	8.70%	656	8.30%	679	8.60%	673	8.70%	669	8.60%
16°C	671	8.40%	634	8.10%	622	7.90%	576	7.40%	575	7.40%
18°C	579	7.30%	674	8.60%	679	8.60%	777	10.00%	775	10.00%
20°C	824	10.40%	845	10.70%	864	11.00%	802	10.30%	799	10.30%
22°C	729	9.20%	508	6.50%	437	5.60%	303	3.90%	306	3.90%
24°C	282	3.60%	212	2.70%	200	2.50%	190	2.40%	190	2.40%
26°C	190	2.40%	158	2.00%	173	2.20%	128	1.60%	127	1.60%
28°C	120	1.50%	58	0.70%	39	0.50%	16	0.20%	19	0.20%
30°C	13	0.20%	2	0.00%	0	0.00%	0	0.00%	0	0.00%
32°C	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%
34°C	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%
36°C	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%
38°C	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%
40°C	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%
42°C	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%
44°C	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%
46°C	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%
COMFORT	2604	32.80%	2397	30.50%	2353	29.90%	2200	28.30%	2197	28.20%

4.3.3. Monthly Heating Cooling Loads

According to the analysis of comfort (Table 4.6) insulated hollow brick cavity wall pretends to be most comfortable and mud brick and stone wall pretends to be least comfortable throughout the year. If so, how much would the heating cooling loads cost to maintain the favourable thermal comfort indoors?

Heating Cooling loads of air conditioning system working with 95% efficiency and 1 occupant is considered for the calculations. The thermal comfort zone is chosen as 18-26 ^{0}C for the temperature band that the calculation would take place according to the standards (Schiller Brager & de Dear. (2000); ANSI/ASHRAE (2001) Standard 55-2000R) applied to the Yozgat weather data, 2002.

As can be seen from Figure 4.31 hollow brick wall requires the most and mud-brick wall requires the least heating/cooling load for a year. Total values obtained from Ecotect analysis can be referred from Table 4.7. To show the effect of insulation hollow brick wall and hollow brick cavity wall with insulation is superimposed on Figure 4.30. Heating loads were displayed in red and projected above the centre line of the graph whereas cooling loads were blue and projected below. The vertical scale is in kWh (kilowatt-hours), and the horizontal axis is in months of the year.

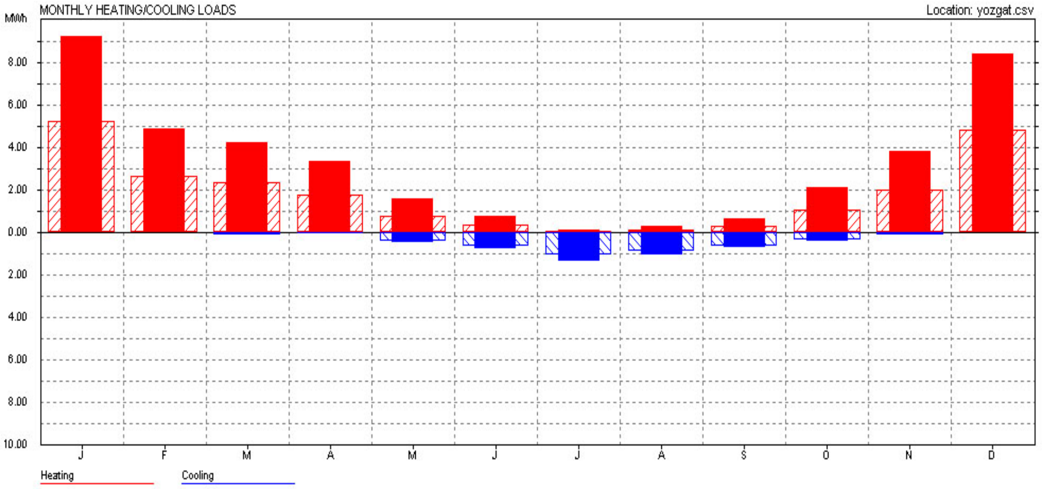


Figure 4.30. Comparison graph of monthly heating/cooling loads of hollow brick wall and hollow brick cavity wall with thermal insulation. Hatched bars are hollow brick cavity wall with thermal insulation; solid bars are hollow brick wall.

(Source: Ecotect)

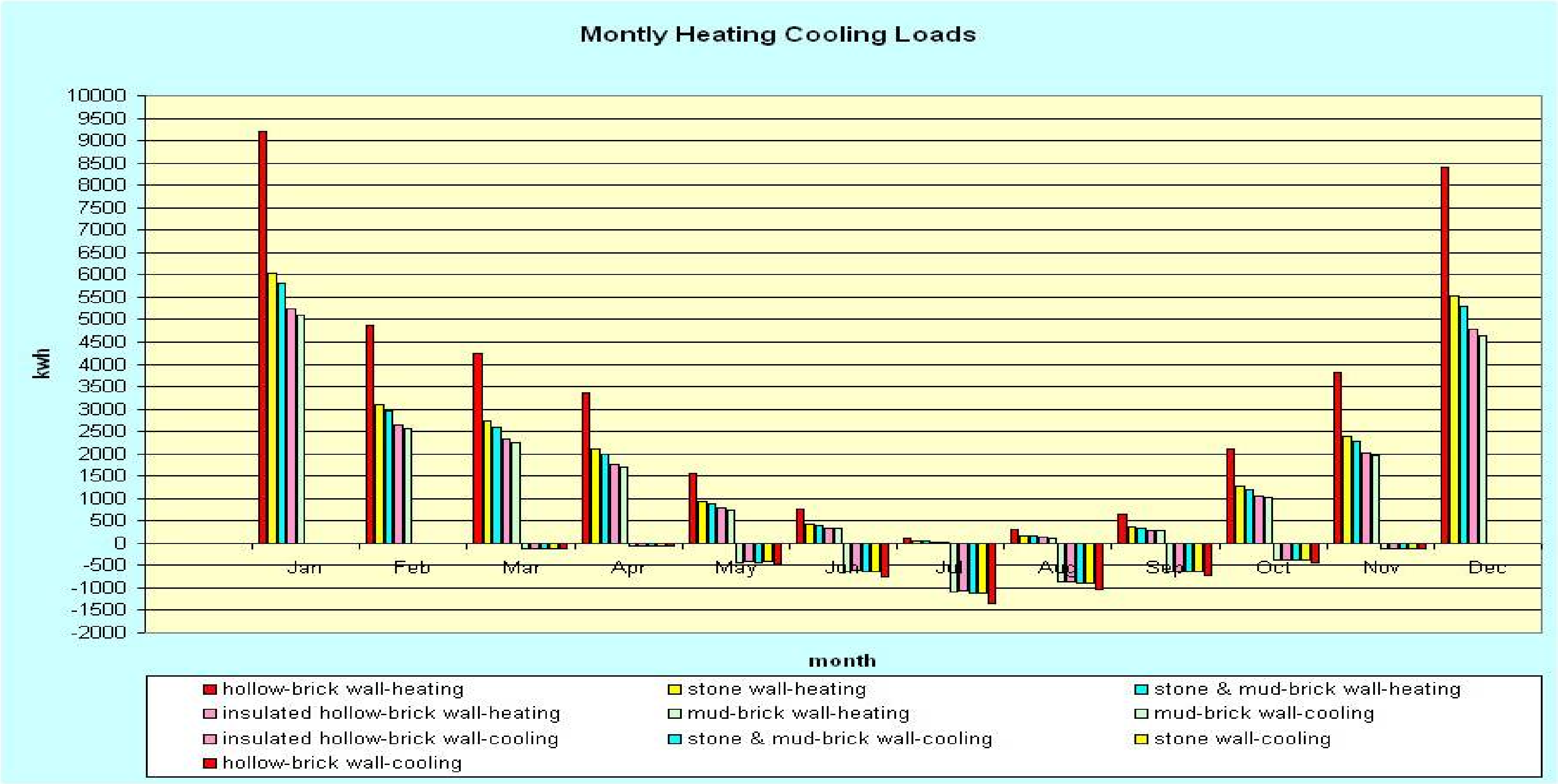
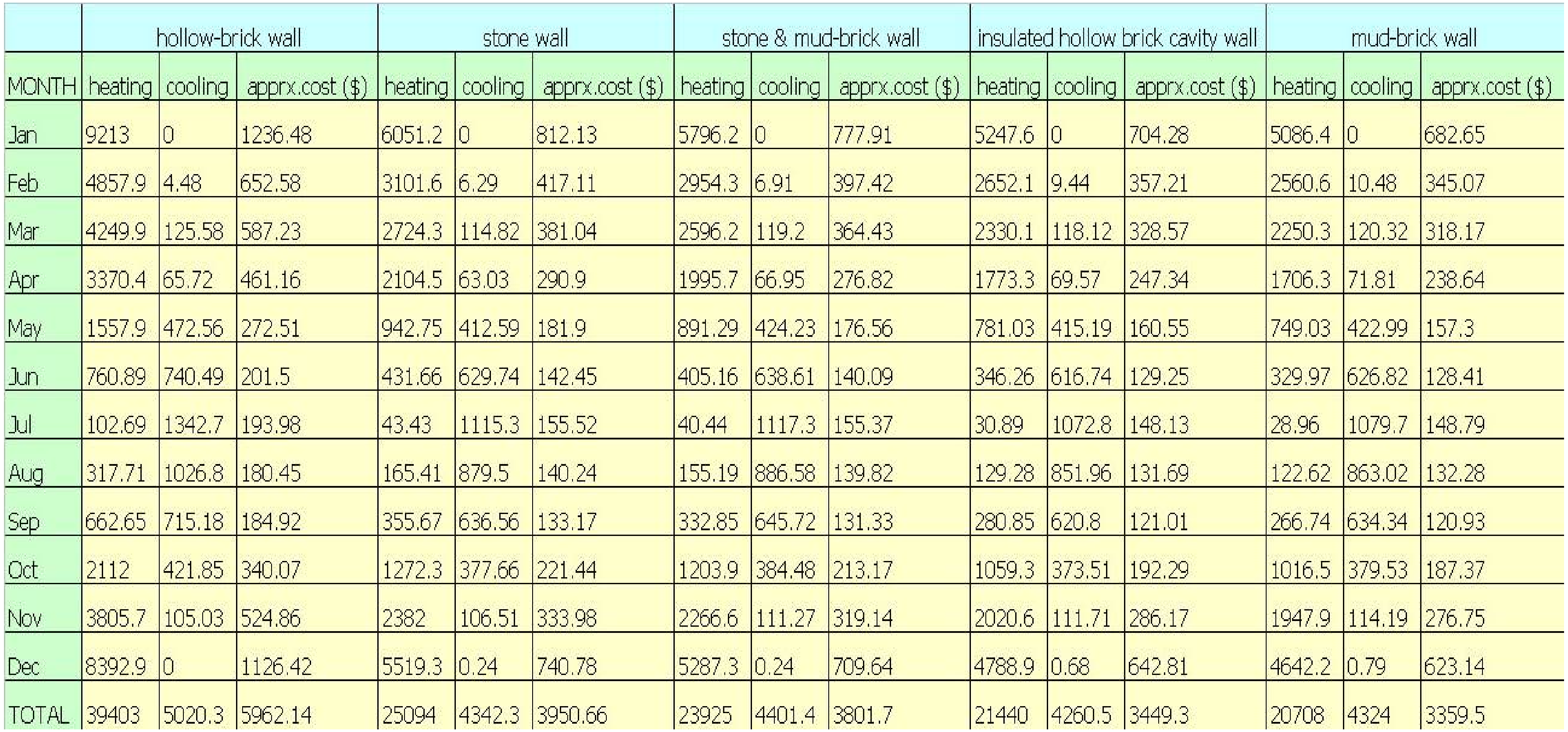


Figure 4.31. Comparison Graph of Monthly Heating/Cooling Loads of Babayiğit House According to Different Building Materials

Source: Value from Ecotect, graph from M.S. Excell

Table 4.7. Monthly Heating / Cooling Loads (kWh) of Babayiğit House According to Different Building Materials

Source: Value from Ecotect, Table from M.S. Excell



	hollow-brick wall			stone wall			stone & mud-brick wall			insulated hollow brick cavity wall			mud-brick wall		
MONTH	heating	cooling	apprx.cost ($)	heating	cooling	apprx.cost ($)	heating	cooling	apprx.cost ($)	heating	cooling	apprx.cost ($)	heating	cooling	apprx.cost ($)
Jan	9213	0	1236.48	6051.2	0	812.13	5796.2	0	777.91	5247.6	0	704.28	5086.4	0	682.65
Feb	4857.9	4.48	652.58	3101.6	6.29	417.11	2954.3	6.91	397.42	2652.1	9.44	357.21	2560.6	10.48	345.07
Mar	4249.9	125.58	587.23	2724.3	114.82	381.04	2596.2	119.2	364.43	2330.1	118.12	328.57	2250.3	120.32	318.17
Apr	3370.4	65.72	461.16	2104.5	63.03	290.9	1995.7	66.95	276.82	1773.3	69.57	247.34	1706.3	71.81	238.64
May	1557.9	472.56	272.51	942.75	412.59	181.9	891.29	424.23	176.56	781.03	415.19	160.55	749.03	422.99	157.3
Jun	760.89	740.49	201.5	431.66	629.74	142.45	405.16	638.61	140.09	346.26	616.74	129.25	329.97	626.82	128.41
Jul	102.69	1342.7	193.98	43.43	1115.3	155.52	40.44	1117.3	155.37	30.89	1072.8	148.13	28.96	1079.7	148.79
Aug	317.71	1026.8	180.45	165.41	879.5	140.24	155.19	886.58	139.82	129.28	851.96	131.69	122.62	863.02	132.28
Sep	662.65	715.18	184.92	355.67	636.56	133.17	332.85	645.72	131.33	280.85	620.8	121.01	266.74	634.34	120.93
Oct	2112	421.85	340.07	1272.3	377.66	221.44	1203.9	384.48	213.17	1059.3	373.51	192.29	1016.5	379.53	187.37
Nov	3805.7	105.03	524.86	2382	106.51	333.98	2266.6	111.27	319.14	2020.6	111.71	286.17	1947.9	114.19	276.75
Dec	8392.9	0	1126.42	5519.3	0.24	740.78	5287.3	0.24	709.64	4788.9	0.68	642.81	4642.2	0.79	623.14
TOTAL	39403	5020.3	5962.14	25094	4342.3	3950.66	23925	4401.4	3801.7	21440	4260.5	3449.3	20708	4324	3359.5

4.4. Discussion

Yannas (1994) has mentioned several properties of construction materials which have been supported by this research. Following conclusions may be revealed from the study to guide the designers to maintain comfort (pp. 95-99).

- The choice of materials has a bearing on occupant comfort.
- Thermal insulation has a considerable effect on thermal comfort.
- The heat storage capacity of construction materials has an important role on thermal comfort and heating / cooling loads.
- Thermal capacity of heavyweight constructions (mud-brick wall and stone wall) moderates the fluctuations in indoor temperature caused because of high daily diurnal change.

As lightweight structures warm up faster and to a higher peak temperature than a heavyweight structure, and also cool down faster and reach a lower overnight temperature, the hollow brick wall which is considered as lightweight amongst the analysed group, has required a higher heating load together with a moderate thermal comfort condition. It is also easily understood from the temperature and humidity graphs of Blue House from Figure 4.7 to 4.16 that it follows fluctuations of the outdoor climate.

The analysis of Monthly Discomfort Degree Hours (Figure 4.23, Table 4.4 and Table 4.5) has shown that the traditional materials such as mud-brick and stone have advantages on the control of summer overheating. It is also easily understood from the temperature and humidity graphs of Babayiğit House from Figure 4.1 to 4.6 that traditional building materials with high thermal capacity have moderated the indoor climate.

According to the analysis, the external stone with internal mud-brick wall has shown the least comfort both for the analysis of 'discomfort degree hours' and 'temperature distribution'. Following that, comes the stone wall and mud-brick wall. Regarding 'discomfort degree hour' (Table 4.5) hollow brick goes in between them. From the result can be inferred that mud-brick has decreased by 0.10 % (Table 4.6) the property of stone to provide comfort. However it is most probably because of mud-brick's lower U-value and admittance which disabled the heat transmittance and lowered the heat absorbed by the material.

From Table 4.5 can be seen that traditional building materials with high thermal capacity (stone, mud-brick) has been too hot for a lesser period than hollow brick and insulated hollow brick and too cool for more than insulated hollow brick and approximately equal to hollow brick. As thermal capacity would allow keeping the heated air inside more, and the summer period is pretty comfortable, the choice of traditional materials would decrease the heating cooling loads whereas provide the same thermal comfort and having the least 'environment impact'[27] (Table 4.7).

Thermal insulation is further needed if a relatively lightweight material such as hollow brick will be chosen for the climate of Central Anatolia. As from the analysis hollow brick required the most amount of heating / cooling cost whereas insulated hollow brick is the 2nd best. The problem of overheating would easily be overcome by night ventilation to maintain the comfort in summer if insulated hollow brick is preferred to use.

The traditional techniques and skills to build a house are almost abandoned while increasing the cost of workmanship, so that to build a traditional village house may cost more than the contemporary ones. However the energy inputs to maintain the required thermal comfort as revealed from the study is quite lower than the contemporary buildings without thermal insulation (Randall, 1999, pp. 64-79). The designer has to decide on the thermal properties of the materials in order to maintain

---

[27] Yannas, Simos. *Solar Energy and Housing Design*. (London: Architectural Association, 1994).

comfort. Optimising the initial cost besides decreasing the maintenance cost should be the benchmark to select a construction material.

Conceptual design period is the perfect timing of deciding on the building form, environmental factors and the choice of materials. This study has shown that we can easily grasp the future thermal performance of the building in question and make relevant adaptations in order to maintain the occupant comfort.

CHAPTER 4

CONCLUSION

This study focused on the effects of construction materials on thermal comfort in residential buildings in the village of Şahmuratlı in Yozgat, Turkey. It concentrated on traditional and contemporary building materials with respect to increasing the thermal comfort of the occupants while decreasing the heating/cooling loads of the building. To do that, field survey of three houses in Yozgat was conducted and interior and exterior temperature and humidity were measured.

According to the statistical analysis three houses with three different building materials had provided different comfort conditions inside. It was found that hollow brick cavity wall with thermal insulation provided the most comfort whereas mud-brick and stone wall provided the least comfort. However the building materials showed opposite properties for the heating / cooling loads of the Babayiğit House. Hollow brick wall required the most heating / cooling loads whereas mud-brick wall required the least in the same comfort band.

This study has revealed that the performance of a house could easily be predicted in the conceptual design period with some kind of an environmental design tool. Its being a demonstration of the evaluation of thermal performance, further analysis could be done to predict the effects of traditional passive design elements on thermal comfort and their means of effectiveness. The completion of this study would be constructing unit building of selected different materials and measure the environmental parameters to provide a comparison of conceptual design with the realised ones.

LITERATURE CITED

Books

ASHRAE. (1989). *Handbook: Fundamentals*. SI (Metric) Edition. Atlanta: ASHRAE Inc., pp.8.1-8.27.

ANSI/ASHRAE. (2001). Standard *5-2000R-Thermal Environmental Conditions for Human Occupancy.* Atlanta: ASHRAE Inc.

de Dear, R. J. and G. Schiller Brager. (1998). “Developing an Adaptive Model of Thermal Comfort and Preference.” ASHRAE Transactions, V.104, part 1, pp. 145-167.

Devore, Jay L. (2000). *Probability and Statistics for Engineering and the Sciences*, 5th ed. Duxbury: Thomson Learning, pp. 283-415.

Everett, Alan. (1994) *Materials*, 5th ed. London: Longman, pp. 92-199.

Fanger, P.O. (1970). *Thermal comfort. Analysis and Applications in Environmental Engineering.* Copenhagen: Danish Technical Press.

Foster, Jack Stroud. (1983). *Mitchell’s Building Series, Structure and Fabric, Part 1*. London: The Mitchell Publishing Company Limited, pp. 1.

Givoni, Baruch. (1976). *Man, Climate and Architecture*. 2nd ed. London: Applied Science Publishers, pp. 1-144.

Hensen, J. L. M. and L. Centnerova. (2001). *"Energy Simulation of Traditional vs. Adaptive Thermal Comfort for Two Moderate Climate Regions."* in Proc. Int. Conf. "Moving Thermal Comfort Standards into the 21st Century" held in Windsor, Oxford Brookes University

Humphreys, Michael A. (1976) *Field studies of thermal comfort compared and applied*. Building Services Engineer 44.

Humphreys, Michael A. (1978). *Outdoor temperatures and comfort indoors.* Building Research and Practice Vol. 6 (2).

Humphreys, Michael A. and J. Fergus Nicol. (1998). *Understanding the Adaptive Approach to Thermal Comfort*. ASHRAE Transactions, 104, Part 1.

Hyde, Richard. (2000). *Climate Responsive Design: a Study of Buildings in Moderate and Hot Humid Climates*. London; New York: E & FN, pp. 7-8.

Konya, Allan. (1980). *Design Primer for Hot Climates.* London: The Architectural Press, pp. 11-28.

Krüger, Eduardo L. (2001). "*Estimation of Relative Humidity for Thermal Comfort Assessment*". 7th International IBPSA Conference, Rio de Janeiro, Brazil, August 13-15.

Lyons, Arthur R. (1997). *Materials for Architects and Builders, an Introduction*. London: Arnold a member of the Hodder Headline Group, pp. 125-127.

Olgyay, Victor. (1963). *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. New Jersey: Princeton University Press, pp. 14-114

Oseland N. A. (1994) *A Within Groups Comparison of Predicted and Reported Thermal Sensation Votes on Climate Chambers, Offices and Homes*. Proceedings of Healthy Buildings 94, Budapest.

Raimes, Ann. (1999). *Keys for Writers*. 2nd ed. Boston: Houghton.

Randall Thomas, ed. (1999). *Environmental Design: an Introduction for Architects and Engineers.* London; New York: E & FN Spon, pp. 64-79.

Rapoport, Amos. (1969). *House Form and Culture*. New Jersey: Prentice Hall, Inc., pp. 88-89.

Schiller Brager, Gail and Richard de Dear. (2000). "A standard for natural ventilation." ASHRAE Journal. V.42 (10), pp. 21-27.

Simonson, Carey, ed. (2000). *The Effect of Wood Based Materials on Indoor Air Quality and Climate.* Healthy Building 2000-Workshop 10.

Stulz, R. and K Mukerji. (1993). *Appropriate Building Materials.* 3rd ed. London: SKAT Publications and IT Publications, pp. 3-109.

Thermohygrometer User's Guide.

Tinytag Data logger User's Guide.

Turabian, K.L. (1996). *A Manual for Writers of Term Papers, Theses and Dissertations.* Chicago: University of Chicago Press.

Watson, Donald. (1983). *Climatic Design: Energy-Efficient Building Principles and Practices*. New York: McGraw-Hill, pp. 33.

Yannas, Simos. (1994). *Solar Energy and Housing Design*. London: Architectural Association, pp. 95.

Web Sites

The Adaptive Model of Thermal Comfort: Macquarie University's ASHRAE RP-884 Project. 9 Feb. 2001. Macquarie University. 17 Dec. 2002. <http://atmos. es.mq.edu.au/~rdedear/ashrae_rp884_home.html>.

Baker, Nick. *Designing for Comfort, Recognising the Adaptive Urge*. The Martin Center for Architectural and Urban Studies, University of Cambridge. 30 Apr. 2003. <www.caed.asu.edu/msenergy/ Neeraj/Baker.pdf>

Climatic Design of Buildings-An Overview, Psychrometric Chart. Hong Kong University. 31 May 2003. <http://arch.hku.hk/~cmhui/teach/ 65156-7e.htm>.

Comfort Zones. City University of Hong Kong. 17 Dec. 2002. <http://personal.cityu. edu.hk/ ~bsapplec/thermal.htm >.

Ecotect. Building Energy Software Tool Directory. 05 Sept. 2002. U.S. Department of Energy. 17 Dec. 2002. <http://www.eren.doe.gov/buildings/tools_ directory/software/ecotect. html>.

Nicol, J. Fergus. *Mulcom, Thermal Comfort.* London Metropolitan University. 17 Dec. 2002. <http://www.unl.ac.uk/LEARN/port/1998/mulcom/web/ comfort/thermal/itc/content/ cont1.html>.

Nicol, J. Fergus. *Mulcom, Glossary*. London Metropolitan University. 17 Dec. 2002. <http://www.unl.ac.uk/LEARN/port/1998/ mulcom/web/ gloss.html>.

Nicol, J. Fergus. *Thermal Comfort.* Learn, School of Architecture, University of North London, UK. 31 May 2003. <http://www.unl.ac.uk/LEARN/student/ info/notes/comfort/comfort.html >

Relative Humidity. Cardiff University, the Welsh School of Architecture. 14 Apr. 2003. <http://www.sq1.com>.

Roset, Jaume, I. Marincic, J.M. Ochoa and R. Serra. *Learning about Humidity in Thermal Comfort.* Departament de Pisica Aplicada. 10 Dec. 2002. http://www. fa.upc.es/personals/jroset/esun-058.html

Thermal Analysis. Cardiff University, the Welsh School of Architecture. 14 Apr. 2003. <http://www.sq1.com>.

Thermal Comfort. Innova AirTech Instruments. 12 Ap. 2003. <http://www. innova.dk/books/thermal/thermal.htm>

Yerba Buena Gardens, Arch. 249x: Microclimates. 11 Sep. 2002. University of California, Berkeley. 31 May 2003. <http://arch.ced.berkeley.edu/cources/ Arch249x/Fall_2002/exercises/yerba/249xmicroexercise2.htm>

APPENDIX A

DATA GROUPED FOR ANOVA

Table A.1. Interior Temperatures of the Babayiğit, Blue House (5-10 May) and the Depot (11-16 May) with 15 Minutes intervals

	Groups (Interior Temperatures of Houses)		
	Babayiğit House (Group 1)	Blue House (Group 2)	Kerkenes Depot (Group 3)
	14,8	20,2	20,5
	15,1	19,9	18
	15,1	20,2	17,1
	15,4	20,2	16,8
	15,4	19,9	17,1
	15,4	20,2	17,1
	15,4	20,5	17,1
	15,1	21,1	16,8
	15,1	21,1	16,8
	15,4	21,1	17,1
	15,4	21,1	17,1
	14,8	21,4	16,8
	15,1	21,1	17,1
	15,1	21,4	16,8
	14,8	21,8	17,1
	15,4	21,4	16,8
	15,1	21,8	16,8
	15,4	21,4	17,1
	15,4	21,8	17,1
	15,1	21,8	16,8
	15,7	21,8	16,8
	15,7	21,4	17,7
	15,4	21,8	17,4
	15,4	21,8	17,7
	15,4	21,8	17,1
	15,7	22,1	17,1
	15,4	22,1	17,4
	15,7	21,8	17,4
	15,4	22,1	17,4
	16	22,1	18,3

	Table A.1. (continued)		
	15,7	22,1	18,3
	16	22,1	18
	16,2	22,1	18
	16	22,1	18
	15,7	22,1	18,3
	16,2	21,8	18,9
	16,2	21,8	18,3
	16,2	22,1	18,6
	16,2	21,8	18,6
	16,2	22,1	18,9
	16	21,8	18,9
	16	21,8	19,2
	16	21,1	18,9
	16	21,8	19,2
	16,2	21,4	18,9
	16,2	21,1	18,6
	16,2	21,4	18,6
	16,2	21,1	18,6
	16,2	20,8	18,6
	16,2	21,1	18,6
	16,2	21,4	18,6
	16,2	21,1	19,2
	16,2	21,1	18,9
	16,2	20,8	18,9
	16	20,8	18,9
	16	20,8	19,2
	16	20,5	19,2
	16,2	19,9	18,9
	16	19,9	18,9
	15,7	20,2	19,2
	16,2	19,5	19,2
	16	19,5	19,2
	16	19,2	18,9
	16	18,9	18,9
	15,7	18,9	18,9
	15,7	18,9	19,2
	15,7	18,6	19,2
	15,4	18,9	19,2
	16	18,9	18,9
	15,7	18	19,2
	15,7	18,3	18,9
	15,7	17,7	18,6
	16	18	18,9
	15,7	18	18,6
	15,7	18	18,9
	15,7	18,3	18,9
	15,4	17,7	18,9
	15,7	17,7	18,9
	15,7	17,4	18,9
	15,4	17,1	18,9
	15,7	16,8	18,6
	15,7	17,4	18,6
	15,1	16,8	18,3
	15,4	16,8	18,9

	Table A.1. (continued)		
	15,4	16,8	18,9
	14,8	17,7	18,9
	15,4	17,7	18,3
	15,4	18	18
	15,4	18,3	18
	15,1	18	18,6
	15,1	17,7	18,6
	15,1	18	18,6
	15,1	18,3	18,3
	15,1	19,2	18,3
	15,1	19,9	18,3
	15,1	18,9	18,3
	15,4	18,3	18,3
	14,8	18	18
	15,1	17,7	18
	15,1	17,7	18
	15,4	17,4	18
	15,4	17,4	18
	15,1	17,4	18,3
	15,4	17,7	18
	15,1	17,4	18,3
	15,4	17,4	18,3
	15,4	17,7	18
	15,1	17,7	18
	15,4	17,7	18
	15,4	17,7	17,7
	15,4	17,7	17,7
	15,1	17,4	18,6
	15,1	17,4	18
	15,4	17,4	18,3
	15,7	17,4	18,3
	15,4	17,4	18,6
	15,4	17,4	18,3
	15,7	17,7	18,3
	15,7	17,7	18,3
	16	17,7	18
	15,7	17,4	18,3
	15,7	17,7	18,3
	16	18	18,6
	15,7	18	18,6
	15,7	18	18,6
	15,7	18	18,9
	15,7	17,7	19,2
	15,4	17,7	18,9
	16	17,7	19,5
	15,7	18,3	19,2
	15,7	18	18,9
	15,7	18	19,2
	15,7	18	19,5
	16	17,7	19,2
	16	18	19,5
	16	17,7	19,2
	15,7	17,7	20,2
	16	17,4	19,9

	Table A.1. (continued)		
	15,7	17,7	20,2
	16	17,4	20,2
	16	17,7	20,2
	15,7	17,7	20,2
	16	17,7	19,9
	15,7	17,4	20,2
	16	17,4	19,9
	16	17,4	20,2
	15,7	17,1	20,2
	16	17,1	20,2
	16	17,4	19,9
	16	16,8	19,9
	16	16,5	19,9
	16	16,8	20,2
	16	16,8	20,2
	15,7	16,2	20,2
	15,4	16,2	19,9
	15,4	16,5	20,2
	15,7	16,2	19,9
	15,4	16	20,2
	15,7	16	19,9
	15,7	15,7	20,2
	15,7	15,7	20,2
	15,7	15,4	20,2
	15,7	15,1	19,9
	15,4	15,1	20,2
	15,1	14,5	19,5
	15,1	14,5	19,9
	15,4	14,5	20,2
	15,4	14	19,9
	15,4	14	19,9
	15,1	13,7	19,9
	15,1	13,7	19,9
	15,1	14	19,9
	15,4	14	19,5
	15,4	13,7	20,2
	15,1	13,4	20,2
	15,1	14	19,9
	14,8	14	20,2
	14,8	14,2	19,5
	14,5	14,2	19,2
	14,8	14,2	19,5
	14,8	14	19,5
	14,8	14,5	19,2
	14,5	14,8	19,5
	14,5	15,4	19,2
	14,8	15,4	19,2
	14,5	15,4	19,5
	14,8	16	19,2
	14,8	15,7	18,9
	14,5	15,7	19,2
	14,8	16	19,2
	14,5	15,7	19,2
	14,5	15,7	19,2

	Table A.1. (continued)		
	14,8	15,7	19,2
	14,8	15,7	18,9
	14,5	15,7	18,9
	14,8	15,4	18,9
	14,5	15,7	18,9
	14,8	15,4	18,9
	14,5	15,1	18,9
	14,2	15,1	18,6
	14,2	14,8	18,6
	14,5	14,5	18,6
	14,5	15,1	18,6
	14,5	14,8	18,6
	14,5	15,1	19,2
	14,5	15,1	19,2
	14,5	15,4	19,2
	14,2	14,8	19,2
	14,5	15,1	18,9
	14,8	15,1	19,2
	14,8	15,1	19,2
	14,5	15,1	19,2
	14,8	15,4	19,2
	14,8	15,4	19,5
	14,8	15,1	19,5
	14,8	15,4	19,9
	14,5	15,1	20,2
	14,5	15,1	19,5
	14,5	15,1	19,5
	14,8	15,1	19,9
	14,5	15,4	20,2
	15,1	15,1	20,2
	15,1	15,1	19,9
	15,4	15,1	19,9
	15,4	15,4	20,2
	15,4	15,4	19,9
	15,4	15,1	19,9
	14,8	15,4	19,9
	15,1	15,1	20,2
	15,4	15,1	20,5
	15,1	15,1	20,5
	15,1	15,1	20,5
	15,1	15,4	20,8
	15,1	15,1	20,5
	15,1	14,8	20,5
	15,4	14,8	20,5
	15,4	14,8	20,8
	15,1	14,5	20,8
	15,1	14,5	20,5
	15,1	14,5	20,5
	15,1	14,5	20,5
	15,1	14,2	20,8
	15,4	14	20,5
	15,4	14	20,8
	15,1	14,2	20,2
	15,1	14	20,5

	Table A.1. (continued)		
	15,1	14	20,5
	15,1	13,7	20,8
	15,1	14	20,5
	15,1	14	20,2
	15,1	13,4	20,8
	15,1	13,1	20,5
	15,1	13,1	20,8
	15,1	12,8	20,5
	14,8	13,1	20,8
	15,1	13,4	20,2
	15,1	13,4	20,5
	15,1	13,4	20,5
	15,1	13,4	20,5
	15,1	13,4	20,5
	15,1	13,7	20,5
	14,8	13,4	20,5
	14,8	13,1	20,2
	14,8	13,4	20,5
	14,8	13,1	20,5
	14,5	13,1	20,2
	14,5	13,1	20,2
	14,5	12,8	20,2
	14,5	13,1	20,5
	14,5	13,4	20,5
	14,8	13,1	20,2
	14,5	13,4	20,2
	14,5	13,4	20,2
	14,5	13,1	19,9
	14	12,8	19,9
	14	13,4	20,2
	14,2	13,4	20,2
	14	13,7	20,2
	14,2	14	20,2
	14	14	19,9
	14,2	14,8	19,9
	14,2	15,4	19,9
	14,2	15,4	19,9
	13,7	15,7	19,2
	14,2	15,7	19,5
	14	16	19,2
	14	16,2	19,5
	14	16	19,2
	14	15,7	19,5
	14	15,4	19,9
	14,2	14,8	19,5
	14,2	15,1	19,5
	14	14,8	19,5
	14	14,5	19,2
	14	14,8	19,5
	14	14,5	19,5
	14,2	14,8	19,2
	14,2	14,5	19,5
	13,7	14,8	19,5
	14,2	15,1	19,5

	Table A.1. (continued)		
	14,2	15,4	19,5
	14,2	15,4	19,5
	14,2	15,4	19,9
	14	15,4	19,9
	14,2	15,7	19,9
	14,2	15,7	19,9
	14,2	15,7	19,9
	14,2	15,7	19,9
	14,2	16	19,2
	14,5	16,5	19,5
	14,5	16,2	19,9
	14,5	16,5	19,9
	14,5	16,5	19,5
	14,5	16,5	19,9
	14,5	16,2	20,2
	14,5	16,8	20,2
	14,5	16,8	19,9
	14,8	16,8	19,9
	14,5	16,8	19,9
	14,8	16,5	20,2
	15,1	16,8	20,5
	15,1	16,8	20,5
	14,8	17,1	20,5
	14,8	16,8	20,5
	14,5	16,8	20,5
	15,1	16,8	20,8
	15,1	16,8	20,5
	15,1	16,8	20,8
	15,1	16,5	20,5
	15,1	16,2	20,5
	15,1	16,5	20,8
	15,1	16,5	20,8
	15,4	16,5	20,8
	15,1	16,5	20,8
	15,1	16,2	20,8
	14,8	16,2	20,8
	15,1	15,7	20,8
	14,8	15,7	21,1
	14,8	16,2	21,1
	14,8	16,2	21,1
	14,8	16,2	20,8
	15,1	16,2	20,5
	15,1	16,5	20,8
	15,1	16,2	21,1
	15,1	16,5	20,5
	15,1	16,2	20,8
	15,1	16	20,8
	15,1	15,7	20,5
	15,1	15,7	20,8
	14,8	15,4	20,8
	14,8	15,1	20,8
	14,8	15,1	20,8
	14,5	15,1	20,8
	14,5	15,1	20,5

	Table A.1. (continued)		
	14,8	15,7	20,8
	15,1	15,1	20,8
	14,8	15,4	20,8
	14,8	15,1	20,5
	14,8	14,8	20,5
	14,8	15,1	20,8
	14,5	15,4	20,8
	14,8	15,4	20,5
	14,5	15,1	20,2
	14,5	15,4	20,5
	14,2	14,8	20,5
	14,2	15,4	20,5
	14,5	15,1	20,2
	14,5	14,8	20,2
	14,5	15,4	20,2
	14,2	15,1	20,5
	14,2	14,8	20,5
	14,5	14,8	20,5
	14,2	15,4	20,5
	14,5	15,1	20,2
	14,2	15,7	20,2
	14,5	16,5	20,2
	14,5	16,8	19,9
	14,2	17,4	19,9
	14,5	17,7	19,9
	14	18	19,9
	14,2	18	19,9
	14,5	18,3	20,2
	14,5	18,3	19,2
	14,5	18,9	19,5
	14,2	18,3	19,5
	14,5	18,6	19,5
	14,2	18,3	19,5
	14,2	18,6	19,9
	14,5	18,9	19,5
	14,2	18,9	19,2
	14,5	18,6	19,5
	14,5	18,3	19,5
	14,5	18	19,5
	14,5	18,6	19,5
	14,5	18,3	19,5
	14,5	18,6	19,5
	14,5	18,6	19,2
	14,2	19,2	19,5
	14,2	19,2	19,5
	14,5	19,5	19,5
	14,2	19,5	19,5
	14,8	20,2	19,5
	14,5	19,9	19,5
	14,8	20,2	19,5
	14,8	19,9	19,5
	14,8	20,2	19,5
	14,8	20,2	19,5
	14,8	20,2	19,9

	Table A.1. (continued)		
	14,8	20,2	19,5
	14,5	20,5	19,9
	14,8	20,5	19,9
	15,1	19,9	20,2
	15,1	20,2	20,2
	15,1	19,9	20,2
	15,1	19,9	20,2
	15,1	20,2	20,2
	15,4	20,5	19,9
	15,4	20,5	20,2
	15,7	20,2	20,2
	16	20,5	20,2
	15,7	20,2	19,9
	15,7	20,2	20,2
	15,7	20,2	20,5
	15,7	19,9	20,2
	15,7	19,9	20,8
	15,7	20,2	20,2
	15,4	19,9	20,2
	15,7	20,2	20,5
	15,7	20,2	20,5
	16	20,2	20,2
	16	19,9	20,5
	16	19,9	20,5
	16	19,9	20,5
	16	19,5	20,5
	16	19,5	20,2
	15,7	19,5	20,5
	15,7	19,2	20,2
	15,7	19,5	20,5
	15,7	19,5	20,5
	15,7	19,2	20,2
	15,7	18,9	20,2
	15,7	18,6	20,2
	15,7	18,9	19,9
	15,4	18,6	20,2
	15,7	18,9	20,2
	15,7	18,6	20,2
	15,7	18,9	20,2
	15,7	18,9	20,2
	15,7	18,6	20,5
	15,7	18,3	20,2
	15,4	18,3	20,2
	15,7	18,3	20,2
	15,4	18	20,2
	15,7	17,7	20,2
	15,7	17,4	20,2
	15,7	17,7	19,5
	15,7	17,4	19,9
	15,4	17,7	20,2
	15,7	17,1	19,9
	15,4	16,8	19,9
	15,4	17,1	20,2
	15,1	16,8	20,2

	Table A.1. (continued)		
	15,7	17,1	19,9
	15,1	17,1	19,9
	15,1	17,1	19,2
	15,1	16,8	19,5
	15,4	16,8	20,2
	15,1	16,8	19,5
	15,1	17,4	19,9
	15,4	17,4	19,5
	15,4	17,4	19,2
	15,1	18,3	19,2
	15,4	18,9	19,5
	15,4	18,6	19,5
	15,4	18,9	19,5
	15,1	19,2	19,5
	15,4	19,9	19,5
	15,1	20,2	19,5
	15,4	20,5	19,2
	15,1	20,5	19,2
	15,4	20,2	19,2
	15,1	20,8	19,2
	14,8	21,4	19,2
	14,8	20,8	19,2
	15,4	20,5	18,9
	15,4	20,5	18,9
	15,4	20,5	18,9
	15,4	20,5	18,9
	15,4	20,8	18,9
	15,4	21,1	18,9
	15,4	21,1	18,9
	15,4	21,1	18,9
	15,4	21,1	19,2
	15,4	21,4	18,9
	15,1	21,4	19,2
$\sum X_i$	7489.4	8577.2	9659.3
X	15.13010101	17.32768	19.51374
n_i	495	495	495
$N(Xn_i)$	1485	1485	1485