

LB/DON/31/09

# PERFORMANCE OF INSULATED ROOF SLABS ON BUILT ENVIRONMENTS IN TROPICAL CLIMATES

BY

R. U. HALWATURA,

LIBRARY  
UNIVERSITY OF MORATUWA, SRI LANKA  
MORATUWA

THESIS SUBMITTED TO THE DEPARTMENT OF CIVIL ENGINEERING IN THE FULFILLMENT OF THE REQUIREMENT FOR THE DOCTOR OF PHILOSOPHY IN ENGINEERING



Research supervised

By

PROF. M. T. R. JAYASINGHE

624 "08"  
-----  
624(043)

TH

DEPARTMENT OF CIVIL ENGINEERING  
UNIVERSITY OF MORATUWA  
SRI LANKA  
SEPTEMBER 2008

92927

University of Moratuwa



92927

92927

## ABSTRACT

The countries located close to the equator generally have tropical climatic conditions, where temperatures remain relatively high with humid conditions. Thus, the climatic conditions are usually identified as warm humid. With the rapid urbanization, two different solutions are adopted to meet the housing needs. One is the construction of medium to high rise apartment buildings which has become popular in many large cities located closed to the equator. Another option have been to pursue residential developments with a large number of detached houses located on small blocks of lands.

The energy consumption for buildings is becoming higher and high energy demand and the associated green house gas emission is another critical issue that needs attention in the long run. Global warming can also become a key factor in near future due to environment and climatic changes that are associated with it. This emphasise the need to develop and promote new passive techniques to achieve thermal comfort in built environment. The use of insulated roof slabs provide an alternative that may enable the creation of green cover at roof level. This can also become an alternative solution to the traditional roofs since insulation can be effective in creating desirable indoor conditions needed by free running spaces and the flat slab on top of the building can solve many environmental and social problems arising out of high density residential developments to a certain extent. In addition, this can be an ideal alternative to traditional roofs considering the better cyclone resistance that can be offered due to the self weight.

Considering all these facts, reinforce concrete solid slabs were considered as an alternative. With detailed experimental programmes on small scale models and prototypes, it is shown that a minimum insulation thickness of 25 mm with a material having a conductivity of about 0.03 W/mK can retard the heat flow significantly. In order to ensure that roof slabs have unrestricted access, an innovative solution was proposed and used as the insulation system for the experimental programme. Since it is practically difficult to predict the effect of insulated roof slabs on built environments such as houses using actual model based experiments, simulations have been used with computer software validated for tropical climatic conditions to predict the trends. Since there are strong indications of changing climatic patterns due to global warming, the performance of insulated roof slabs under such future scenarios have also been predicted using appropriately modified climatic files.

In order to emphasise the need to rely on carefully planned micro climate in future, thermal comfort models have been developed considering the climatic acclimatization that is expected from people gradually facing the global warming scenarios over a long period of time. With all these studies, it is highlighted the importance of adopting insulated roof slabs as a solution to combat the heat island effect in built up areas by creating roof top gardens. Since these slabs can be successfully adopted in air-conditioned commercial buildings, life cycle costing approach was used to predict the desirable insulation thickness for air conditioned spaces. With this multi-disciplinary approach, the usefulness of insulated roof slabs as an alternative to traditional roofs have been highlighted.

*Key words: Tropical climates, flat roof, heat island effect, global warming, thermal comfort, roof insulation, computer simulation, life cycle cost.*

## ACKNOWLEDGEMENT

The author is immensely grateful to the research supervisor, Professor M. T. R. Jayasinghe of the Department of Civil Engineering for his invaluable guidance and support throughout the research period.

Author wishes to extend his sincere gratitude to McBerton Polymer Ltd for funding the experimental programme for first two years of the research work.

Author wishes to thankfully acknowledge the excellent support given by Dr. A. A. D. A. J. Perera, Dr Mrs. C. Jayasinghe and Dr. L. L. Ekanayake of Department of Civil Engineering and Professor R. A. Attalage of Department of Mechanical Engineering.

Author would like to thanks Mr. R. M. J. S. B. Rathnayake and Mr. J. M. C. G. Jayasinghe, who have supported in numerous ways to complete the questionnaire surveys. Sincere gratitude is also due for all those who participated in the questionnaire survey.



University of Moratuwa, Sri Lanka.  
Electronic Thesis & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

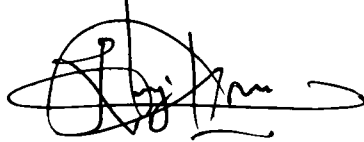
The support given by Prof. W. P. S. Dias (Head, Department of Civil Engineering), and Prof. S. A. S. Kulathilake (Research Coordinator, Department of Civil Engineering) is acknowledged gratefully. All the other lectures and research students are thanked for the positive attitude they adopted in promoting research at Civil Engineering Department.

The technical officers of the Department of Civil Engineering, Messrs S. P. Madanayake, S. L. Kapuruge, H. P. Nandaweera, G. V. Somarathna and laboratory assistants Mr. L. Perera and Mr. H. N. Fernando assisted the detailed experimental programme very much. Mr. J. M. Gunasekara helped in many ways with the apparatus manufactured.



Finally, the author wishes to thank all those who contributed to the completion of this project successfully.

## DECLARATION

I, Rangika Umesh Halwatura, hereby declare that the content of this thesis is the output of the original research work carried out over a period of 45 months at the Department of Civil Engineering , University of Moratuwa. Whenever any work by others is included in this thesis, it is appropriately indicated as a reference.



-----  
Eng. R U Halwatura  
Department of Civil Engineering  
University of Moratuwa  
Sri Lanka



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

-----  
Supervisor  
Prof. M T R J ayasinghe  
Department of Civil Engineering  
University of Moratuwa  
Sri Lanka

# Contents

|                 |      |
|-----------------|------|
| Abstract        | i    |
| Acknowledgement | ii   |
| Declaration     | iii  |
| Contents        | iv   |
| List of Figures | viii |
| List of Tables  | xii  |

|            |  |           |
|------------|--|-----------|
| <b>1</b>   | <b>INTRODUCTION</b> .....                                    | <b>1</b>  |
| <b>1.1</b> | <b>General</b> .....   | <b>1</b>  |
| <b>1.2</b> | <b>The objectives</b> .....                                  | <b>3</b>  |
| <b>1.3</b> | <b>The methodology</b> .....                                 | <b>4</b>  |
| <b>1.4</b> | <b>The main findings</b> .....                               | <b>5</b>  |
| <b>1.5</b> | <b>The arrangement of the report</b> .....                   | <b>5</b>  |
| <b>2</b>   | <b>LITERATURE REVIEW</b> .....                               | <b>7</b>  |
| <b>2.1</b> | <b>General</b> .....   | <b>7</b>  |
| <b>2.2</b> | <b>Thermal comfort in tropical climates</b> .....            | <b>7</b>  |
| 2.2.1      | Human body responses to environment conditions .....         | 8         |
| 2.2.2      | Thermal comfort .....  | 10        |
| 2.2.3      | The climate .....  | 11        |
| 2.2.4      | Tropical climatic conditions .....                           | 11        |
| 2.2.5      | Climate in Sri Lanka.....                                    | 13        |
| 2.2.6      | Psychrometric chart and comfort zone .....                   | 16        |
| <b>2.3</b> | <b>Energy crisis and global warming</b> .....                | <b>23</b> |
| 2.3.1      | High energy demand.....                                      | 23        |
| 2.3.2      | Energy demand in Sri Lanka .....                             | 28        |
| <b>2.4</b> | <b>Use of passive techniques</b> .....                       | <b>32</b> |
| 2.4.1      | Thermal comfort standard for passive buildings .....         | 32        |
| 2.4.2      | Thermal insulation .....                                     | 33        |
| 2.4.3      | Factors that affect the choice of insulating materials ..... | 35        |
| 2.4.4      | Natural ventilation .....                                    | 38        |
| <b>2.5</b> | <b>Use of roof top garden</b> .....                          | <b>40</b> |
| 2.5.1      | Solid slab as roofs.....                                     | 40        |
| 2.5.2      | Vegetation and their effects on micro-climate .....          | 43        |
| 2.5.3      | Roof top vegetation .....                                    | 46        |
| <b>2.6</b> | <b>Need for disaster resistance</b> .....                    | <b>50</b> |

|            |   |            |
|------------|---|------------|
| 2.6.1      | Tropical cyclones.....  | 50         |
| 2.6.2      | Earthquake .....  | 53         |
| <b>2.7</b> | <b>The effects of anticipated climate change.....</b>                   | <b>57</b>  |
| 2.7.1      | The reasons for climate change .....                                    | 58         |
| 2.7.2      | The activities responsible for greenhouse gases.....                    | 59         |
| 2.7.3      | The effects of climate change.....                                      | 59         |
| 2.7.4      | The global warming.....   | 60         |
| 2.7.5      | Heat Island effect.....   | 61         |
| 2.7.6      | Factors Contributing to the Heat Island Effect.....                     | 63         |
| <b>2.8</b> | <b>Life cycle cost .....</b>  | <b>64</b>  |
| 2.8.1      | Service life.....   | 66         |
| 2.8.2      | Inflation .....   | 66         |
| <b>2.9</b> | <b>Summary .....</b>  | <b>67</b>  |
| <b>3</b>   | <b>ROOF SLAB INSULATION SYSTEM.....</b>                                 | <b>70</b>  |
| <b>3.1</b> | <b>General .....</b>  | <b>70</b>  |
| <b>3.2</b> | <b>The insulation system .....</b>                                      | <b>71</b>  |
| 3.2.1      | The arrangement.....  | 71         |
| 3.2.2      | The reinforcement for the covering concrete .....                       | 73         |
| 3.2.3      | Concrete mix.....   | 74         |
| 3.2.4      | Effect of Silica fume on concrete .....                                 | 76         |
| 3.2.5      | Thickness of resistive insulation.....                                  | 77         |
| 3.2.6      | The experimental setup.....   | 77         |
| 3.2.7      | The load testing .....  | 78         |
| 3.2.8      | Durability of concrete.....   | 80         |
| 3.2.9      | Thermal characteristics.....  | 83         |
| <b>3.3</b> | <b>Results of experimental studies on models.....</b>                   | <b>86</b>  |
| <b>3.4</b> | <b>Summary .....</b>  | <b>90</b>  |
| <b>4</b>   | <b>PERFORMANCE OF LARGE BUILDINGS.....</b>                              | <b>91</b>  |
| <b>4.1</b> | <b>General .....</b>  | <b>91</b>  |
| <b>4.2</b> | <b>Large model.....</b>   | <b>91</b>  |
| <b>4.3</b> | <b>Thermal measurements.....</b>  | <b>94</b>  |
| <b>4.4</b> | <b>Possibility to use vegetation cover.....</b>                         | <b>97</b>  |
| <b>4.5</b> | <b>Computer simulation for predicting the performance.....</b>          | <b>100</b> |
| <b>4.6</b> | <b>Validation of simulation results.....</b>                            | <b>106</b> |
| <b>4.7</b> | <b>Temperature comparison with different insulation thickness .....</b> | <b>109</b> |
| <b>4.8</b> | <b>Insulated roof slabs with global warming effect.....</b>             | <b>110</b> |
| <b>4.9</b> | <b>Thermal performance with insulated roofs.....</b>                    | <b>115</b> |

|          |   |            |
|----------|---|------------|
| 4.10     | Summary .....   | 119        |
| <b>5</b> | <b>A COMPARISON WITH TRADITIONAL ROOFS .....</b>      | <b>121</b> |
| 5.1      | General .....   | 121        |
| 5.2      | Comparison with traditional roofs.....                | 121        |
| 5.2.1    | Different roofing types .....                         | 121        |
| 5.2.2    | Computer simulations.....                             | 122        |
| 5.2.3    | Data used for the simulations .....                   | 123        |
| 5.2.4    | The computer model .....                              | 126        |
| 5.2.5    | Effect of ceiling type .....                          | 128        |
| 5.2.6    | Effect of roofing material without insulation .....   | 129        |
| 5.2.7    | Effect of roofing material with insulation .....      | 132        |
| 5.2.8    | Findings of computer simulations .....                | 134        |
| 5.3      | Social acceptability .....                            | 135        |
| 5.3.1    | The details of the participants.....                  | 136        |
| 5.3.2    | The details related to thermal comfort.....           | 138        |
| 5.3.3    | Response to thermal discomfort .....                  | 141        |
| 5.3.4    | The preferred type of neighbourhood .....             | 144        |
| 5.3.5    | Findings from the questionnaire survey .....          | 144        |
| 5.4      | Summary .....   | 146        |
| <b>6</b> | <b>LIFE CYCLE COSTING .....</b>                       | <b>147</b> |
| 6.1      | General .....   | 147        |
| 6.2      | The need for life cycle costing.....                  | 148        |
| 6.3      | Life cycle cost with free running buildings .....     | 148        |
| 6.4      | Air conditioning load in multi storey buildings ..... | 149        |
| 6.4.1    | General information on questionnaire survey .....     | 150        |
| 6.4.2    | The details related to thermal comfort.....           | 151        |
| 6.4.3    | The details related to the air condition loads .....  | 154        |
| 6.4.4    | Findings from the questionnaire survey .....          | 157        |
| 6.5      | Life cycle with air conditioning .....                | 158        |
| 6.5.1    | Initial cost .....                                    | 158        |
| 6.5.2    | Service life.....                                     | 159        |
| 6.5.3    | Discount rate.....                                    | 159        |
| 6.5.4    | The model used.....                                   | 159        |
| 6.5.5    | Life cycle cost analysis.....                         | 160        |
| 6.6      | Life cycle cost comparison with global warming.....   | 166        |
| 6.7      | Disaster resistance .....                             | 173        |
| 6.7.1    | The possibility for uplifting of roof slabs .....     | 176        |
| 6.7.2    | Other advantages .....                                | 176        |
| 6.8      | Summary .....   | 177        |

|          |   |            |
|----------|---|------------|
| <b>7</b> | <b>CONCLUSIONS AND FUTURE WORK.....</b>   | <b>178</b> |
| 7.1      | The main conclusions .....  | 178        |
| 7.2      | Future work.....  | 180        |
|          | <b>REFERENCES .....</b>   | <b>182</b> |
|          | <b>Appendix .....</b>   | <b>193</b> |
|          | <b>Appendix A: The design calculation for the covering concrete .....</b>               | <b>193</b> |
|          | <b>Appendix B: About DEROB-LTH.....</b>   | <b>193</b> |
|          | <b>Appendix B: About DEROB-LTH.....</b>   | <b>194</b> |
|          | <b>Appendix C: Climatic Data Files.....</b>   | <b>195</b> |
|          | <b>Appendix D: Detail results on computer simulations with tree shadings.....</b>       | <b>198</b> |
|          | <b>Appendix E: Questionnaire survey format I.....</b>                                   | <b>207</b> |
|          | <b>Appendix F: Detail tables of computer simulation on free running buildings .....</b> | <b>210</b> |
|          | <b>Appendix G: Questionnaire Survey Format II .....</b>                                 | <b>219</b> |



University of Moratuwa, Sri Lanka.  
 Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)



## List of Figure

|  |    |
|--|----|
| Figure 1.1: The main climatic zone of the world .....  | 1  |
| Figure 2.1: Body heat loss and air temperature .....   | 8  |
| Figure 2.2: Heat exchange of the body (from Rosenlund, 2000) .....   | 9  |
| Figure 2.3: Map of world's climate.....  | 13 |
| Figure 2.4: Mean monthly temperatures in different parts of Sri Lanka for January to June .  | 14 |
| Figure 2.5: The Psychrometric chart .....  | 18 |
| Figure 2.6: Comfort Zone for low altitudes of Sri Lanka.....   | 20 |
| Figure 2.7: Comfort Zone for Colombo, Sri Lanka.....   | 22 |
| Figure 2.8: Population Living in Urban Areas .....   | 24 |
| Figure 2.9: Urban and Rural Populations, 1950-2030.....  | 25 |
| Figure 2.10: Predicted electricity demand for Sri Lanka.....   | 29 |
| Figure 2.11: Existing and Proposed power generation capacities .....   | 29 |
| Figure 2.12: Deferent categories of the end uses for electrical energy .....   | 30 |
| Figure 2.13: Energy consumption for different type of applications .....   | 31 |
| Figure 2.14: CEB load profile for small commercial and industry by end use .....   | 31 |
| Figure 2.15: Typical houses in Indonesia.....  | 39 |
| Figure 2.16: Sections of the different tested roofs.....   | 41 |
| Figure 2.17: Definitions of 'cold' and 'warm' materials.....   | 42 |
| Figure 2.18: Usefulness of trees .....   | 45 |
| Figure 2.19: Greenery on buildings in the forms of rooftop garden, podium garden, balcony<br>planting, fac-ade greenery. ( <a href="http://www.nparks.gov.sg/gardencity/skyrise.shtml">http:// www.nparks.gov.sg/gardencity/skyrise.shtml</a> )..... | 46 |
| Figure 2.20: Typical tropical cyclonic tracks .....  | 51 |
| Figure 2.21: The typical cyclonic belt and the usual cyclonic paths.....   | 52 |
| Figure 2.22: Three wind zones in Sri Lanka and its comparison with values recommended for<br>South India.....  | 52 |
| Figure 2.23: Typical anchor arrangement.....   | 53 |
| Figure 2.24: Typical roof bracing detail .....   | 53 |
| Figure 2.25: A world map showing the tectonic plates .....   | 54 |
| Figure 2.26: Reassembly of Sri Lanka in Gondwanaland and subdivisions in Madagascar and<br>South.....  | 56 |
| Figure 2.27: Global atmospheric concentration of CO <sub>2</sub> with changes occurred in recent times<br>.....  | 58 |
| Figure 2.28: Annual temperature trends for the period 1901 to 1996 .....   | 61 |
| Figure 2.29: Urban heat island effect .....  | 61 |
| Figure 2.30: Economic thickness of insulation .....  | 65 |
| Figure 2.31: Inflation rate in Singapore.....  | 67 |
| Figure 3.1: Detail arrangement of the insulation system proposed over reinforced concrete<br>slabs .....   | 72 |
| Figure 3.2: Arrangement of small scale models .....  | 78 |
| Figure 3.3: Sample panel for strength testing.....   | 79 |
| Figure 3.4: Loading arrangement of the sample panel .....  | 80 |
| Figure 3.5: The sorptivity testing specimen .....  | 82 |
| Figure 3.6: Plan view of the insulation arrangement.....   | 85 |

|  |     |
|--|-----|
| Figure 3.7: Soffit temperature distribution for different insulation thicknesses.....  | 87  |
| Figure 3.8: Heat flow values for different insulation thicknesses .....  | 88  |
| Figure 3.9: Surface temperatures for 25 mm insulation system .....   | 89  |
| Figure 4.1: Large scale model .....  | 92  |
| Figure 4.2: Laying of insulation panels.....   | 92  |
| Figure 4.3: Resistive insulation panels with reinforcement mesh placed on cover blocks .....   | 93  |
| Figure 4.4 : Proposed flashing arrangement.....  | 93  |
| Figure 4.5: Sample parapet wall.....   | 94  |
| Figure 4.6: Temperature distribution before installation.....  | 95  |
| Figure 4.7: Temperature distributions after installation .....   | 96  |
| Figure 4.8: Temperature comparison for before and after insulation.....  | 96  |
| Figure 4.9: Heat flow through the slab .....   | 97  |
| Figure 4.10: The model with an insulated roof slab provided with isolated plants.....  | 99  |
| Figure 4.11: The temperature measurements with and without the roof top garden.....  | 100 |
| Figure 4.12: Plan views of the model.....  | 103 |
| Figure 4.13: Simplified floor plans of the house used for the computer simulations.....  | 103 |
| Figure 4.14: Computer model of two storey houses with an insulated roof slab .....   | 105 |
| Figure 4.15: The indoor and slab soffit temperatures for April and December .....  | 105 |
| Figure 4.16: The outdoor and slab top temperatures with difference levels of transmittance<br>through shading screens as indicated in brackets ..... | 106 |
| Figure 4.17: Large scale models.....   | 107 |
| Figure 4.18: Three dimensional computer models for the selected buildings.....   | 107 |
| Figure 4.19: Temperature measurement for the model with flat slab.....   | 108 |
| Figure 4.20: Temperature measurement for the model with sloping roof.....  | 108 |
| Figure 4.21: Slab soffit temperatures for different insulation thicknesses .....   | 109 |
| Figure 4.22: Indoor temperature comparison for different insulation thickness .....  | 109 |
| Figure 4.23: Volume 4 indoor temperature variation with global warming.....  | 111 |
| Figure 4.24: Upper floor slab soffit temperature variation with global warming .....   | 111 |
| Figure 4.25: Upper floor volume temperature variation with global warming .....  | 112 |
| Figure 4.26: Slab soffit temperature variation with global warming .....   | 113 |
| Figure 4.27: Slab top temperature variation with global warming.....   | 113 |
| Figure 4.28: Upper floor volume temperature variation with global warming for 25 mm, 38<br>mm and 50 mm insulation thickness .....                   | 113 |
| Figure 4.29: Upper floor slab soffit temperature variation with global warming for 25 mm, 38<br>mm and 50 mm insulation thickness .....              | 114 |
| Figure 4.30: Upper floor slab top temperature variation with global warming for 25 mm, 38<br>mm and 50 mm insulation thickness .....                 | 114 |
| Figure 4.31: Modified comfort zone for tropical low lands .....  | 116 |
| Figure 4.32: Modified comfort zone when the outdoor temperature increase by 2 °C .....   | 117 |
| Figure 4.33: Modified comfort zone when the outdoor temperature increase by 4 °C .....   | 119 |
| Figure 5.1: Plan views of the model.....   | 127 |
| Figure 5.2: Simplified floor plans of the house used for the computer simulations.....   | 127 |
| Figure 5.3: Three dimensional view of computer models.....   | 128 |
| Figure 5.4: Ceiling soffit temperatures for different ceiling types .....  | 129 |
| Figure 5.5: Volume temperatures for different ceiling types .....  | 129 |
| Figure 5.6: Temperature variation in the upper floor room(Volume 4).....   | 130 |



|   |     |
|---|-----|
| Figure 5.7: Temperature variation in the ground floor room(Volume 1).....                 | 131 |
| Figure 5.8: Temperature variation in the ceiling soffit (Volume 4) .....                  | 131 |
| Figure 5.9: Temperature variation in the slab soffit (Volume 1).....                      | 132 |
| Figure 5.10: Temperature variation in the upper floor room (Volume 4) with insulations... | 133 |
| Figure 5.11: Temperature variation in the ground floor room (Volume 1) with insulations   | 133 |
| Figure 5.12: Temperature variation in the ceiling soffit (Volume 4) with insulation ..... | 134 |
| Figure 5.13: Temperature variation in the slab soffit (Volume 1) with insulation.....     | 134 |
| Figure 5.14: An indication of gender of those who participated .....                      | 136 |
| Figure 5.15: Percentages from seven districts selected .....                              | 136 |
| Figure 5.16: Age group of the participants.....   | 137 |
| Figure 5.17: Occupation of the participants .....   | 137 |
| Figure 5.18: Type of house that they occupy at present.....                               | 138 |
| Figure 5.19: Number of occupants in a house .....   | 138 |
| Figure 5.20: Material used for wall construction .....                                    | 139 |
| Figure 5.21: Colour of the external surfaces .....  | 139 |
| Figure 5.22: Colour of the interior walls .....   | 139 |
| Figure 5.23: Colour of the floor.....   | 140 |
| Figure 5.24: Type of roofing materials used .....   | 140 |
| Figure 5.25: Type of ceiling .....  | 141 |
| Figure 5.26: Colour of roof or ceiling facing the occupants .....                         | 141 |
| Figure 5.27: Colour of the roof facing sun .....  | 141 |
| Figure 5.28: Whether the house was considered too warm.....                               | 142 |
| Figure 5.29: The response to the thermal comfort.....                                     | 142 |
| Figure 5.30: Number of fans usually used.....   | 143 |
| Figure 5.31: Type of heat barriers used over the roof .....                               | 143 |
| Figure 5.32: Availability of a roof top garden.....                                       | 143 |
| Figure 5.33: Preferred type of neighborhood .....   | 144 |
| Figure 5.34: Preferred type of house .....  | 144 |
| Figure 6.1: The selected participants from different districts.....                       | 150 |
| Figure 6.2: Type of building.....   | 151 |
| Figure 6.3: Different roof types.....   | 151 |
| Figure 6.4: Different ceiling types.....  | 152 |
| Figure 6.5: External wall covering material .....   | 152 |
| Figure 6.6: External wall appearance .....  | 153 |
| Figure 6.7: Internal wall appearance .....  | 153 |
| Figure 6.8: Floor appearance .....  | 153 |
| Figure 6.9: Protection for windows .....  | 154 |
| Figure 6.10: Type of the air conditioning machine .....                                   | 154 |
| Figure 6.11: Availability of roof top garden.....   | 155 |
| Figure 6.12: View about the environmental pollution.....                                  | 155 |
| Figure 6.13: Dry bulb, wet bulb and A/C machine temperatures.....                         | 156 |
| Figure 6.14: Psychrometric chart with extended comfort zone.....                          | 156 |
| Figure 6.15: Computer models of three storey buildings .....                              | 160 |
| Figure 6.16: Life cycle cost with 50% land regaining for Rs. 100,000/= per perch .....    | 164 |
| Figure 6.17: Life cycle cost with 50% land regaining for Rs. 200,000/= per perch .....    | 164 |
| Figure 6.18: Life cycle cost with 100% land regaining for Rs. 100,000/= per perch .....   | 165 |

|   |     |
|---|-----|
| Figure 6.19: Life cycle cost with 100% land regaining for Rs. 200,000/= per perch .....                           | 165 |
| Figure 6.20: Life cycle cost without any land recovery factors for 2 °C increase (Case 1)..                       | 167 |
| Figure 6.21: Life cycle cost with 50% land regaining for Rs. 100,000/= per perch for 2 °C increase (Case 1).....  | 168 |
| Figure 6.22: Life cycle cost with 50% land regaining for Rs. 200,000/= per perch for 2 °C increase (Case 1).....  | 168 |
| Figure 6.23: Life cycle cost with 100% land regaining for Rs. 100,000/= per perch for 2 °C increase (Case 1)..... | 169 |
| Figure 6.24: Life cycle cost with 100% land regaining for Rs. 200,000/= per perch for 2 °C increase (Case 1)..... | 169 |
| Figure 6.25: Life cycle cost without any land recovery factors for 4 °C increase (Case 2)..                       | 170 |
| Figure 6.26: Life cycle cost with 50% land regaining for Rs. 100,000/= per perch for 4 °C increase (Case 2).....  | 171 |
| Figure 6.27: Life cycle cost with 50% land regaining for Rs. 200,000/= per perch for 4 °C increase (Case 2).....  | 171 |
| Figure 6.28: Life cycle cost with 100% land regaining for Rs. 100,000/= per perch for 4 °C increase (Case 2)..... | 172 |
| Figure 6.29: Life cycle cost with 100% land regaining for Rs. 200,000/= per perch for 4 °C increase (Case 2)..... | 172 |
| Figure 6.30: Three wind zones in Sri Lanka .....  | 174 |
| Figure 6.31: Typical single storey house.....   | 175 |



## List of Tables

|  |     |
|--|-----|
| Table 2.1: Annual mean temperature and neutrality temperature for various towns in Sri Lanka .....               | 21  |
| Table 2.2: The average occurrence of earthquakes of different magnitudes.....                                    | 55  |
| Table 2.3: Earthquakes in the vicinity of Colombo (Abayakoon 1998).....  | 57  |
| Table 3.1: Initial mix proportions used for initial investigations .....   | 75  |
| Table 3.2: The average compressive strength of concrete at 7 days and 28 days for defferent concrete mixes ..... | 75  |
| Table 3.3: Concrete mixes with 5% Silica fume .....  | 76  |
| Table 3.4: Average compressive strength of concrete with Silica fume .....                                       | 76  |
| Table 3.5: Different mixes considered for sorptivity test.....   | 81  |
| Table 3.6: Sorptivity test results of the mixes .....  | 83  |
| Table 3.7: Thermal conductivity of material used.....  | 84  |
| Table 3.8: Surface resistance values used for the calculation .....  | 85  |
| Table 3.9: Thermal expansion over 10 m length for 125 mm slab with the proposed insulation system .....          | 89  |
| Table 4.1: Material Properties used for the computer simulation .....  | 101 |
| Table 4.2: Absorptance and admittance of building elements used for the computer simulation .....                | 101 |
| Table 4.3: Building elements used for the computer simulation.....   | 102 |
| Table 4.4: Average climatic data applicable to Colombo, Sri Lanka.....   | 104 |
| Table 5.1: Roofing materials used in houses in Sri Lanka.....  | 122 |
| Table 5.2: Climatic data used for the computer simulation.....   | 123 |
| Table 5.3: Material Properties used for the computer simulation .....  | 124 |
| Table 5.4: Building elements used for the computer simulation.....   | 124 |
| Table 5.5: Absorptance and admittance of building elements used for the computer simulation .....                | 125 |
| Table 6.1: The individual cost component for different roofing arrangements.....                                 | 158 |
| Table 6.2: Air conditioning load for different options .....   | 162 |
| Table 6.3: Air conditioning cost for different options.....  | 162 |
| Table 6.4: Life Cycle Cost per square meter the simulations.....   | 163 |
| Table 6.5: Pay back time for all the cases expressed in years .....  | 166 |
| Table 6.6: Pay back time for all the cases expressed in years for 2 °C increase (Case 1).....                    | 170 |
| Table 6.7: Pay back time for all the cases expressed in years for 4 °C increase (Case 2).....                    | 173 |
| Table 6.8: Maximum uplift forces for a slopping roof (kN/m <sup>2</sup> ).....                                   | 175 |
| Table 6.9: Maximum uplift forces for a flat slab (kN/m <sup>2</sup> ).....                                       | 176 |