



NTNU – Trondheim
Norwegian University of
Science and Technology

Water Runoff Properties for Expanded Clay LWA in Green Roofs

Anders Olof Eriksson

Geotechnics and Geohazards

Submission date: June 2013

Supervisor: Arnfinn Emdal, BAT

Norwegian University of Science and Technology
Department of Civil and Transport Engineering



Report Title: Water Runoff Properties for Expanded Clay LWA in Green Roofs	Date: 07.06.2013		
	Number of pages (incl. appendices): 96		
	Master Thesis	X	Project Work
Name: Anders Eriksson			
Professor in charge/supervisor: Arnfinn Emdal			
Other external professional contacts/supervisors: Arnstein Watn and Jan Ove Busklein			

<p>Abstract: A lightweight aggregate (LWA) is a material that has a lower density than rock aggregates. There are many civil engineering application possibilities for LWA. A potential field of application for expanded clay LWA is as a storm water retaining layer in green roofs. In order to design reliable structures of green roofs, more knowledge about the characteristics of the material is needed. The purpose of this master thesis was to test if the software SEEP/W is an appropriate tool for simulation of water runoff from a green roof, designed with expanded clay LWA. The numerical modeling was not performed for all types of expanded clay LWA, but on crushed Leca[®] 4-10mm and round 10-20mm alone. To test if SEEP/W is advisable tool for simulating water flow in expanded clay LWA, a back calculation of a laboratory experiment was done. The purpose of back calculating the experiment is to calibrate a numerical model and then use it for a full scale ideal roof. Thereafter a sensitivity analysis of the SEEP/W input parameters was performed. It was possible to back calculate the laboratory experiment, meaning obtaining the same relation between water going in and water going out of the tested Leca[®] material. However, a lot of numerical problems occurred in the simulations. Unrealistic results were displayed, especially for Leca[®] 10-20mmR. In order to improve the performance of the material, and thereby obtain better water retaining characteristic, a suggestion is to increase the porosity and lower the saturated hydraulic conductivity for the expanded clay LWA materials in order to obtain a higher attenuation.</p>

Keywords:

1. Water Retention
2. SEEP/W
3. Green Roofs
4. Expanded Clay LWA

MASTER DEGREE THESIS

(TBA4900 GEOTEKNIKK, Master Thesis)

SPRING 2013

for

STUD.TECHN. ANDERS ERIKSSON

Water Runoff Properties for Expanded Clay LWA in Green Roofs

Vannavrenningsegenskaper for lettklinker i Grønne Tak

Background

NTNU Geotechnical Engineering and SINTEF Byggforsk have for a long time cooperated in research on expanded clay lightweight aggregates (expanded clay LWA). Low weight, good insulation properties and high permeability of the material makes it suitable for many civil engineering applications. Traditionally the material has been used for weight reduction, drainage and insulation. During the last years the material has also been successfully used as a draining and storm water retaining layer in green roofs.

The popularity of green roofs is increasing due to the capacity to ease the pressure on stormwater infrastructure. Although general guidelines for green roof construction exists (e.g. the FLL-guide) there exists no standard design method and the various climate conditions from one location to another result in different water runoff requirements. Obtaining more knowledge about what performance to expect from the material, for different roofs concepts and precipitation intensities, would facilitate the design procedure.

Large scale model test has been performed with expanded clay LWA for green roof applications. However a simulation tool is needed in order to gain better understanding of the water flow behavior inside expanded clay LWA and to be able to predict the water runoff from a specific green roof with expanded clay LWA. SINTEF Byggforsk has previously performed numerical modeling with a software, unsuccessfully, and now another software, SEEP/W, has been suggested for water flow simulation.

Contents of the Master Thesis

- 1) Literature review. The student shall get familiar with the topic by studying available literature with emphasis on performed research projects of water retention in green roofs.
- 2) SEEP/W, which will be used for the simulations, is a water flow calculation application created by GeoStudio[®]. Understand and gain knowledge about the program is of importance for the master thesis.
- 3) Back calculation, in SEEP/W, of water runoff experiment performed by SINTEF Byggforsk in Trondheim.
- 4) Perform numerical calculations on a full scale ideal green roof.
- 5) Evaluate if SEEP/W is an advisable tool for simulate water runoff in a draining layer.

Organization and Guidance

The master thesis is part of cooperation between NTNU and SINTEF Byggforsk in a research project for Saint-Gobain Weber. SINTEF Byggforsk will provide the software SEEP/W with an active Full License.

The main supervisor from SINTEF Byggforsk will be Vice President Research Arnstein Watn and guidance counselors Senior Engineer Jan-Ove Busklein and MSc researcher Elise Balmand. Assistant professor Arnfinn Emdal will be the supervisor from NTNU and R&D Director Oddvar Hyrve will represent Saint-Gobain Weber.

Results and Reporting

A report with a clear presentation of the results shall be submitted, organized with table of contents, objective of the master thesis, methodology used, obtained results, conclusions and enclosures.

Submission

The deadline for submission of the master thesis is on the 10th of June. An electronic version of the thesis shall be uploaded on DAIM and a CD containing a PDF version of the report must be submitted at the Department of Civil and Transport Engineering Front Office.

Language: English

Department of Civil and Transport Engineering, NTNU
Trondheim, January 2013

Arnfinn Emdal
Assistant professor
NTNU Geotechnical Engineering

Arnstein Watn
Vice President Research
SINTEF Byggforsk

Acknowledgement

The work of this master thesis has been carried out at the Division of Geotechnical Engineering at Norwegian University of Science and Technology and is a result of a cooperation between SINTEF Byggforsk and Saint-Gobain Weber.

First of all I would like to thank Arnstein Watn and Jan Ove Busklein who have provided me with valuable input and suggestions for of the thesis. Thank you Elise Balmand for the help with simulations and the software. I also appreciated the interest from the industry, which was represented by Oddvar Hyrve. Many thanks to Bridget Thodesen and Knut Noreng for providing me with reading material.

Finally I would like to express my gratitude for all the support and help from Camilla Bjäring. Without you the report would not have been completed.

Anders Eriksson
Trondheim, June 2013

Abstract

A lightweight aggregate (LWA) is a material that has a lower density than rock aggregates. There are many civil engineering application possibilities for LWA. A potential field of application for expanded clay LWA is as a storm water retaining layer in green roofs. In order to design reliable structures of green roofs, more knowledge about the characteristics of the material is needed. The purpose of this master thesis was to test if the software SEEP/W is an appropriate tool for simulation of water runoff from a green roof, designed with expanded clay LWA. The numerical modeling was not performed for all types of expanded clay LWA, but on crushed Leca® 4-10mm and round 10-20mm alone. To test if SEEP/W is advisable tool for simulating water flow in expanded clay LWA, a back calculation of a laboratory experiment was done. The purpose of back calculating the experiment is to calibrate a numerical model and then use it for a full scale ideal roof. Thereafter a sensitivity analysis of the SEEP/W input parameters was performed. It was possible to back calculate the laboratory experiment, meaning obtaining the same relation between water going in and water going out of the tested Leca® material. However, a lot of numerical problems occurred in the simulations. Unrealistic results were displayed, especially for Leca® 10-20mmR. In order to improve the performance of the material, and thereby obtain better water retaining characteristic, a suggestion is to increase the porosity and lower the saturated hydraulic conductivity for the expanded clay LWA materials in order to obtain a higher attenuation.

Summary

In natural habitats, the precipitation infiltrates naturally, since the vegetation and soil over many years have adapted to the climate. This balance of the ecosystem has been disturbed in urban areas by human development, such as impervious surfaces of roads, parking lots and house roofs. The amount of runoff water from these impervious surfaces fluctuates with the intensity and the duration of the rainfall and there is a risk that the capacity of the hydrological system will be exceeded. Overflow of water channels increases the probability of property damage, people getting hurt and environmental issues with stormwater. A solution to this problem can be roof top gardens, vegetative roofs or green roofs, which are growing in popularity. Experiments have shown that the water storage capabilities of green roofs can smoothen out the peak of the runoff. Green roof systems retain some of the rainwater and distribute the runoff over a longer period of time, compared to traditional roofs where runoff starts more or less immediately. The retention is possible thanks to the porous material that green roofs contain and this reduces the risk of overflow of drainage systems in cities.

A suggested material for use in green roofs is expanded clay lightweight aggregate, LWA. The characteristics of this material; its light weight and high porosity, make it suitable for green roof applications. Due to its low weight, none or limited structural reinforcement is needed and the high porosity enables water retention. SINTEF, a research institute in Norway, has studied the runoff-, retention- and water storage abilities of expanded clay LWA. Results from this study made it possible to perform numerical modeling of LWA material for green roof applications. The aim with the numerical modeling, performed by SINTEF, was to test if the water retention behavior of the expanded clay LWA could be simulated. However, the numerical modeling encountered problems, the software did not perform well and another program has been suggested, GeoStudio[®] SEEP/W.

The purpose of this master thesis was to test if the software SEEP/W is an appropriate tool for simulation of runoff from a green roof. In order to analyze this, it was necessary to first gain better understanding of the properties of expanded clay LWA, why this was a milestone. The results from the simulations were analyzed and suggestions for how the expanded clay LWA can be modified in order to improve the water retention performance are given. The numerical modeling was not performed for all types of expanded clay LWA, but on crushed Leca[®] 4-10mm and round 10-20mm alone.

In order to test if SEEP/W is advisable tool for simulating water flow in expanded clay LWA, a back calculation of a laboratory experiment was done. The purpose of back calculating the experiment is to calibrate a numerical model and then use it for a full scale ideal roof. Thereafter a sensitivity analysis of the SEEP/W input parameters was performed.

To perform a simulation of water flow, in SEEP/W, five input parameters are needed. These five parameters define the material properties and thereby explain how porous the material is, how the grain sizes are distributed, the hydraulic conductivity when the material is saturated and how much water that is left in the material after the free water has been drained away.

To back calculate the experiment performed by SINTEF, a simplified geometry of the equipment used in the experiment was created in SEEP/W. The necessary input parameters needed to define the Leca® materials were tested and the boundary conditions were defined for the model. When comparing the results from the back calculation and from the laboratory test, a good correlation for both materials could be seen. With the matching result, the calibrated model was scaled up to a reasonable ideal case roof and exposed for a rain event with another shape (different intensity and duration).

The ideal case roof simulations resulted in a 40 % reduction of the water runoff for Leca® 4-10mmC and 10 % for Leca® 10-20mmR. Compared with the back calculation of the laboratory experiment, the runoff reduction were 10 % for Leca® 10-20mmR and 20 % for Leca® 4-10mmC. In the Ideal roof simulation a similar ratio, between the two materials, was expected. It is difficult to say if it is the Leca® 10-20mmR that does not reduce the runoff enough or if it is the 4-10mmC that reduces too much. A reason why the water runoff ratio is not the same in the two simulations, could be that shape of the rain events are not that similar for the ideal case roof and the back calculation. In the back calculation rain is more intense and constant and in the ideal case it is less intense and fluctuates.

It was possible to back calculate the laboratory experiment, meaning obtaining the same relation between water going in and water going out of the tested Leca® material. However, a lot of numerical problems occurred in the simulations. Unrealistic results were displayed, especially for Leca® 10-20mmR. A reason could be the high saturated hydraulic conductivity value (from the laboratory permeability measurement) combined with the coarse grain size distribution is leading to a turbulent flow.

Another reason for the incomplete correlation could be that unsaturated flow dominates through Leca® and it is difficult to simulate the non-linear flow, even with the volumetric water content and hydraulic conductivity function.

In order to improve the performance of the material, and thereby obtain better water retaining characteristic, a suggestion is to increase the porosity and lower the saturated hydraulic conductivity for the expanded clay LWA materials in order to obtain a higher attenuation for the first runoff peak.

In the software SEEP/W it is possible to change the input parameters one by one and study the how the individual change of one input parameter affect the runoff from the ideal case roof. In reality are the five input parameters connected to each other, which means that altering one parameter will change all parameters, e.g. if the parameters defining the grain size distribution is changed, the saturated hydraulic conductivity will not stay the same. It is important to consider this when studying the sensitivity analysis for the input parameters.

Further work within this topic could be to change the geometry of the model and study how the inclination, layer thickness, rain intensity and the length of the drainage affect the water runoff. If enough time can be spent to run a large amount of simulations, a simple Excel-sheet could be created that estimates the runoff depending on the design of the green roof.

Table of Contents

Acknowledgement.....	i
Abstract	iii
Summary	v
List of Figures.....	ix
List of Tables.....	xi
1. Problem Description.....	13
1.1. Background.....	13
1.1.1 SINTEF – Green Roof Project	13
1.2 Objective.....	14
1.3 Limitations	14
2. Literature Review	15
2.1 History of Green Roofs	15
2.2 Positive Effects	16
2.3 How the Green Roof Retains Water	17
2.4 Green Roof Projects.....	20
2.4.1 SINTEF Field Test [7]	20
2.4.2 Green Roof in Oslo [8]	23
2.4.3 Green Roof Test in Mediterranean Climate [9].....	24
2.5 Material Production and Characteristics.....	26
2.5.1 Physical Properties	28
3. Theory.....	29
3.1 Method	29
3.2 Water Flow	29
3.3 Numerical Modeling	32
3.4 SEEP/W	33
3.4.1 Volumetric Water Content Function [18].....	34
3.4.2 Hydraulic Conductivity Function [18]	35
3.4.3 Water Flow Matrix [18]	37
4. Water Retaining Experiment [20].....	41
4.1 Laboratory Experiment of a Small Scale Green Roof	41
4.1.1 Leca® 10-20mmR.....	43
4.1.2 Leca® 4-10mmC.....	45
5. Back Calculation of the Laboratory Experiment.....	47

5.1 Material Properties	47
5.1.1 Saturated Water Content	47
5.1.2 Grain Size Distribution	48
5.1.3 The Saturated Hydraulic Conductivity	49
5.1.4 Residual Water Content	52
5.2 Geometry of the Model in SEEP/W	53
5.3 Results	57
5.3.1 Leca [®] 4-10mmC.....	57
5.3.2 Leca [®] 10-20mmR.....	60
5.3.3 Discussion	62
6. Modeling of Ideal Green Roof Drain Layer	65
6.1 The Model	65
6.1.1 Results	67
6.2.1 Discussion	68
6.2 Sensitivity Analysis of the Input Parameters.....	70
6.2.1 Discussion	73
6.3 SEEP/W	74
7. Conclusion	75
8. Recommendations.....	77
9. Bibliography.....	79
10. Appendices	81
Appendix A –Parameter Sensitivity for Leca [®] 10-20mmR	81
Appendix B – The Variation in Water Runoff, Displayed in Percentage	85

List of Figures

Figure 1. The various layers in a green roof.	16
Figure 2. Typical water runoff behavior from a green roof. [6] p. 47	18
Figure 3. Different water contents for a soil. a-wither point, b-saturated, c-fully soaked. [6] p. 46....	19
Figure 4. The wooden casket with the protective roof membrane.	20
Figure 5. To the left Sedum and to the right Nittedals Roofing Turf® with fully grown grass.	21
Figure 6. Runoff with both materials and water contents.	22
Figure 7. The roof with the three sections.	23
Figure 8. Results from the experiment.....	24
Figure 9. Flow chart of Leca® production at Weber factory in Rælingen, Norway.	27
Figure 10. Rotary kiln the length is usually between 30 to 60 meters depending on the composition of the raw material the different producers are using. [12]	27
Figure 11. A principle sketch over apparatus for testing permeability.....	29
Figure 12. Two different flow conditions.	30
Figure 13. The graph indicates where Darcy’s law is valid.....	31
Figure 14. Showing meshing of a soil and the nodal point for an element with corresponding degrees of freedom (directions for the displacements) and forces at the nodal points. [17] Ch.2 P. 8	32
Figure 15. Simplification of the solution approach.	33
Figure 16. To the left the volumetric water content function and to the right examples of volumetric water content function for different grain size distributions. [18] pp 63-64.....	34
Figure 17. To the left saturated soil with a short part for a water particle and to the right an unsaturated soil with longer flow paths for the water particles.	35
Figure 18. Pore water pressure, u_w , and pore air pressure u_a	38
Figure 19. One of the two wooden crates filled with Leca® 10-20mmR.....	41
Figure 20. The nozzles spreading water, simulating rain, over Leca® 10-20mmR.	42
Figure 21. The cumulative water runoff for Leca® 10-20mmR.	43
Figure 22. The runoff per time unit for Leca® 10-20mmR.	44
Figure 23. The cumulative water runoff for Leca® 4-10mmC.	45
Figure 24. The runoff per time unit for Leca® 4-10mmC.	45
Figure 25. The three different parts of which soil consist of.	48
Figure 26. The sieving of Leca® 4-10mmC (red line) and of Leca® 10-20mmR (orange line) with arrows indicating 10 % and 60 % passing with corresponding grain size. [20]	49
Figure 27. A test of the permeability being performed.	50
Figure 28. A sketch over the setup of the apparatus built for the experiment.	50
Figure 29. The plotted results from permeability test of Leca® 4-10mmC.....	51
Figure 30. The plotted results from permeability test of Leca® 10-20mmR.....	52
Figure 31. The geometry of SEEP/W model.	53
Figure 32. Steady state water runoff.....	54
Figure 33. Visual results for the first minute of rain water penetration.....	55
Figure 34. A example of element nodes displayed.	56
Figure 35. Presentation of the results from the numerical model at the top and the runoff data from laboratory experiment below for Leca® 4-10mmC.	57
Figure 36. The cumulative runoff for Leca® 4-10mmC.....	58

Figure 37. Presentation of the results from the numerical model at the top and the runoff data from laboratory experiment below for Leca® 10-20mmR.	60
Figure 38. The cumulative runoff for Leca® 10-20mmC.....	61
Figure 39. The numerical results (dotted) and laboratory results (solid lines) for Leca® 4-10mmC.....	63
Figure 40. The cumulative runoff results in the same graph (Leca® 4-10mmC).	63
Figure 41. The numerical results (dotted) and laboratory results (solid lines) for Leca® 10-20mmR. .	64
Figure 42. The cumulative runoff results for Leca® 10-20mmR in the same graph.....	64
Figure 43. An example of a roof showing the recommended minimal slope of a roof (1:40). [5] p.30	65
Figure 44. The 200mm thick drain layer in the profile A-A of Figure 43.	65
Figure 45. The results from the three simulations.	67
Figure 46. The figure show a simplification of the rain function, at the first peak, in SEEP/W.	68
Figure 47. Decrease and increase of the porosity.....	70
Figure 48. The result from variation of the D10 input parameter.	71
Figure 49. The result from variation of the D60 input parameter.	71
Figure 50. The result from variation of the saturated conductivity parameter.....	72
Figure 51. The result from variation of residual water content.....	72

List of Tables

Table 1. Shows the maximum water content for the materials.....	21
Table 2. A summary of runoff time and quantity.....	22
Table 3. The reduction of total runoff.....	23
Table 4. The data results from the test period.....	25
Table 5. Physical properties of Leca® produced at Rælingen. [13].....	28
Table 6. Variation in dry loose bulk density from different production sites. [14].....	28
Table 7. Values of the coefficient of permeability for various particles sizes.....	31
Table 8. The tested mean value of coefficient of discharge.	43
Table 9. A summary from Figure 22.	44
Table 10. The results for Leca® 4-10mmC from the same rain quantity.....	46
Table 11. The voids and the porosity for Leca. [20].....	48
Table 12. The best estimate values.	52
Table 13. A summary of the results for Leca® 4-10mmC.	59
Table 14. A summary of the results for Leca® 10-20mmC.	62
Table 15. A summary of the input parameters for the three materials.....	66
Table 16. A summary of the results.....	67

1. Problem Description

1.1. Background

In natural habitats, the precipitation infiltrates naturally, since the vegetation and soil over many years have adapted to the climate. This balance of the ecosystem has been disturbed in urban areas by human development, such as impervious surfaces of roads, parking lots and house roofs. In forests about 95 % of the rainfall is infiltrated compared to around 25 % in cities, where the remaining 75 % needs to be accommodated by the drainage system. The amount of runoff water fluctuates with the intensity and duration of the rainfall and there is a risk that the capacity of the hydrological system will be exceeded. Overflow of water channels increases the probability of property damage and people getting hurt and environmental issues with stormwater. When the maximum capacity of a combined sewer system is reached the system is releasing untreated water straight out into lakes and rivers. [1]

In order to even out the inflow into the drainage system, water retention systems, such as ponds and reservoirs, are needed. Areas without impermeable surfaces, where the water can infiltrate into the ground and later evaporate are also desired. However, the lack of space in urban areas restrains the construction of storage ponds and the important permeable surfaces. It is expensive to assign enough land for this purpose in the cities. [2]

An interesting alternative is a better employment of the, most commonly unused, impermeable roof surfaces. Roof top gardens, vegetative roofs or green roofs are solutions which are growing in popularity. Experiments have shown that the water storage capabilities of green roofs can smoothen out the peak of the runoff. Green roof system retain some of the rainwater and distribute the runoff over a longer period of time, compared to traditional roofs where runoff starts more or less immediately. The retention is possible thanks to the porous material that green roofs contain and this reduces the risk of overflow of drainage systems in cities. [1] [2]

1.1.1 SINTEF – Green Roof Project

A suggested material for usage in green roofs is expanded clay lightweight aggregate, LWA. The characteristics of this material; its light weight and high porosity, make it suitable for green roof applications. Due to its low weight none or limited structural reinforcement is needed and the high porosity enables water retention. [3]

SINTEF, a research institute in Norway, has studied the runoff-, retention- and water storage abilities of expanded clay LWA. Initially experiments were conducted in order to assess the material properties and hydraulic characteristics for a variety of expanded clay LWA, produced by different factories all over Europe. The most promising LWA samples were further tested in simple laboratory roofs to assess the water capabilities of the materials. Results from this study made it possible to perform numerical modeling of LWA material for green roof applications. The aim with the numerical modeling was to test if the water retention behavior of the expanded clay LWA could be simulated. However, the numerical modeling encountered problems. The result indicated an unlikely behavior of the tested material and Slide, the software used to perform the calculations, was not written for such simulations but rather for large scale slopes and embankments. Due to the inconvenience with using Slide another simulation program, GeoStudio[®] SEEP/W, has been suggested which is designed for water flow calculation. [3]

1.2 Objective

The purpose of this master thesis is to test if the software GeoStudio[®] SEEP/W is an appropriate tool for simulation of runoff from a green roof. In order to analyze this, it is necessary to first gain better understanding of the properties of expanded clay LWA, why this is a milestone. The results from the simulations will be analyzed and suggestions for how the expanded clay LWA can be modified in order to improve the water retention performance will be given.

1.3 Limitations

The numerical modeling will not be performed for all types of expanded clay LWA, but on crushed Leca[®] 4-10mm and round 10-20mm alone.

Only water retention and runoff will be studied. Other parameters affecting the amount of water flowing through a green roof, such as evaporation and plant uptake will not be studied.

2. Literature Review

The literature review started with reading relevant material about green roofs, provided by Bridget Thodesen who has experience with this topic from SINTEF. The NTNU library database was used to find reading material. Scientific articles, available on the Internet, have also been used.

This chapter starts with the history of green roofs and an explanation of the principle set up of a green roof, followed by a paragraph presenting the potential benefits of constructing green areas on top of houses. After that, the water retaining effect is illustrated and the final part of the literature review treats three different green roof field tests.

2.1 History of Green Roofs

The concept of building houses with vegetation on top is not a new phenomenon. However, the denomination of this green roofs, is less known, but as a matter of fact, one of the ancient wonders of the world, the hanging gardens of Babylon built around 500 BC, is more familiar. The purpose with green roofs is more or less the same today as back then, to reduce erosion caused by high stormwater flows and to create a better artistic appearance of the city, compared to gray concrete blocks. Other problems which did not exist in the ancient Mesopotamia, but can be found in the modern society can be improved by the use if green roofs. Examples of this are high energy consumption due to cooling in order to have a comfortable indoor climate and high levels of air pollution. [4]

In Norway, roofs covered with soil and grass have been used for many centuries. This technique gave and still gives, good insulation properties during cold winters. Modern green roofs were first built in Germany in the 1880s. During the industrialization, houses were built with tar, which is very flammable. A method was developed to reduce the fire hazards, where the tar roof was covered with sand and gravel. After some time, seed and plants rooted and spread over the roofs. [4]

Green roofs can be divided into two general classification systems, extensive or intensive. The extensive roof often contains one or two species of plants and it is designed for high hydrological and thermal performance. Minimum load is also considered in the design. This kind of roof requires a minimum of maintenance, and normally only personnel performing the upholding have access to the roof. [4]

The intensive green roof contains a variety of plants and looks more like a park. It is called intensive since it requires “intense” maintenance which is necessary to uphold the habitat of the roof. Sometimes structural reinforcement is needed to cope with the load from water ponds and trees. Intensive green roof areas are often accessible to the public. [4]

In a green roof the following different components are used, see Figure 1:

- Vegetation; nearly any plant can be placed on a roof top. Important factors controlling which plants to choose are the climate, the design of the structure and the maintenance budget. Sedum is a popular plant thanks to its’ drought-tolerance and capacity to grow in shallow soils.
- Planting medium; can consist of expanded clay LWA, which gives a light weight compared to natural soil and can it absorb more water. The expanded clay material will be described more detailed in chapter 2.5.

- Filter layer; typically consist of one or two layers of non-woven geotextile. The purpose of this layer is to allow water to flow and to prevent small particles from being flushed out of the planting medium, causing clogging of the drain layer. This layer also acts as a root barrier. Growing roots can damage the building if they penetrate joints in the structure.
- Drain layer; can be found under the filter layer and the function of this layer is to lead the water from the roof into the drain system of the building.
- Protective layer; the purpose of this layer is to inhibit damage of the roof membrane. During construction of the green roof there are risks that the membrane gets punctured and as mentioned before, roof penetration can cause leakage through the roof membrane.
- Roof membrane is necessary to use in order to prevent leakage of water into the structure.

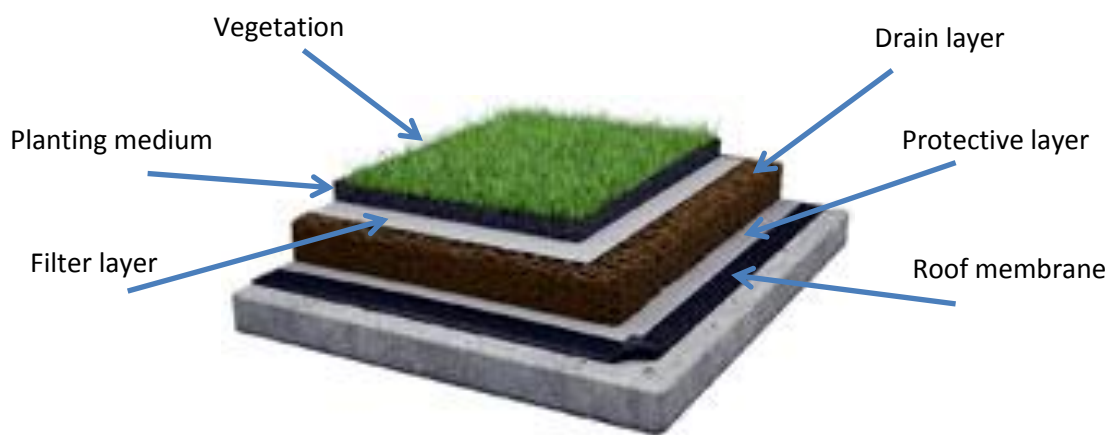


Figure 1. The various layers in a green roof.

2.2 Positive Effects

The shading and the insulation which comes with a green roof can reduce the energy consumption and the urban island heating effect in cities. Shades from plants and transpiration from a green roof can reduce the heating effect from solar energy with up to 90% compared to a building with a traditional roof. The plants chosen plays an important part for the shading, due to the leaf area more or less controls the magnitude of the shading effect. Green roof construction has in some cases resulted in a reduced indoor temperature between 3 to 4°C. Every 0,5°C decrease in indoor temperature may reduce up to 8% of the energy consumption due to less air-conditioning. [1]

Particles and pollutants can be filtered out by plants which will lead to better air quality. The particles will be washed away into the soil by the rain water and the pollutants will be absorbed by the plants. After installation of green roofs, reductions in sulfur dioxide and nitrous acids have been seen above the roof. Also air pollution from diesel engines can be reduced. [1]

In urban areas will hard surface reflect sound and studies have shown that the human effects of noise exposure can lead to sleep disturbance, heart disease and decreased performance in school etc. The vegetation and the properties of the material on a green roof can absorb noise. Some tests have shown a decrease with 5 dB and others have resulted in 40 dB reduction. [1]

Green roofs that are not accessible for the public can provide habitats for insects and birds. Studies of the biodiversity on green roofs have identified rare and endangered plant species. On the roof top of Ford Motor Company in Dearborn Michigan, numerous of insects and spider species but also two bird species have been identified. [1]

However, the most prominent environmental gain is the reduction of stormwater runoff. Instead of running straight to the sewage system, the precipitation is absorbed in the planting media or drain layer and will be released back into the atmosphere by evaporation or transpiration from the vegetation. How much water that is retained in the green roof system depends on how the system is designed e.g. selection of plants, material and layer thickness but also the climate plays an important role in terms of intensity and duration of a rain event. The temperature and humidity influence the water retention indirectly, since the water content of the water retaining layer at the start of a rainfall strongly affects the degree of storm water retention. A material that is initially dry results in a higher degree of storm water retention than a wet material. The rainwater retention capacity of green roofs can be used to increase a city's stormwater capacity without constructing expensive storage tunnels.

When the material inside the green roof becomes saturated water runoff will start. The delay of runoff is due to the time it takes for the material to become saturated which depends on the water conductivity and the porosity of the same material. This delay, compared to a regular roof, mitigates the pressure of the city's sewer system during an intense rainfall. If the runoff from a rainfall is spread over a longer period of time, it will result in a lower flow rate. Experiments have shown delay up to four hours, compared to the runoff from an "ordinary" roof.

2.3 How the Green Roof Retains Water

The retaining effect of water in green roofs can be subdivided into *amount of retained water*, *delay of runoff* and *reduced runoff intensity*. The amount of water that can be retained in a green roof is mainly controlled by the grain structure and the thickness of the growing medium. Due to the high permeability in the green roof layers, water cannot completely fill up the voids between the particles. This means that the retained water can be found on the surface of the grains and particles. The delay of runoff is defined as the time between the start of the precipitation and until the rainwater reaches the drainage system of the roof. The delay is controlled by the time it takes until the green roof medium is saturated, but also drainage path is important. The drainage path is governed by the slope of the roof, structure of the drain layer and distance to the outlet. [6]

Reduced runoff intensity means that the outflow is lower per unit of time compared to a traditionally roof. The difference between the highest value of the runoff from a green roof and the highest value from an ordinary roof is called attenuation, see Figure 2. Storage volume is the amount of water which can be retained. Lag is the difference in time between the peak value of the inflow and peak value of the outflow. [6]

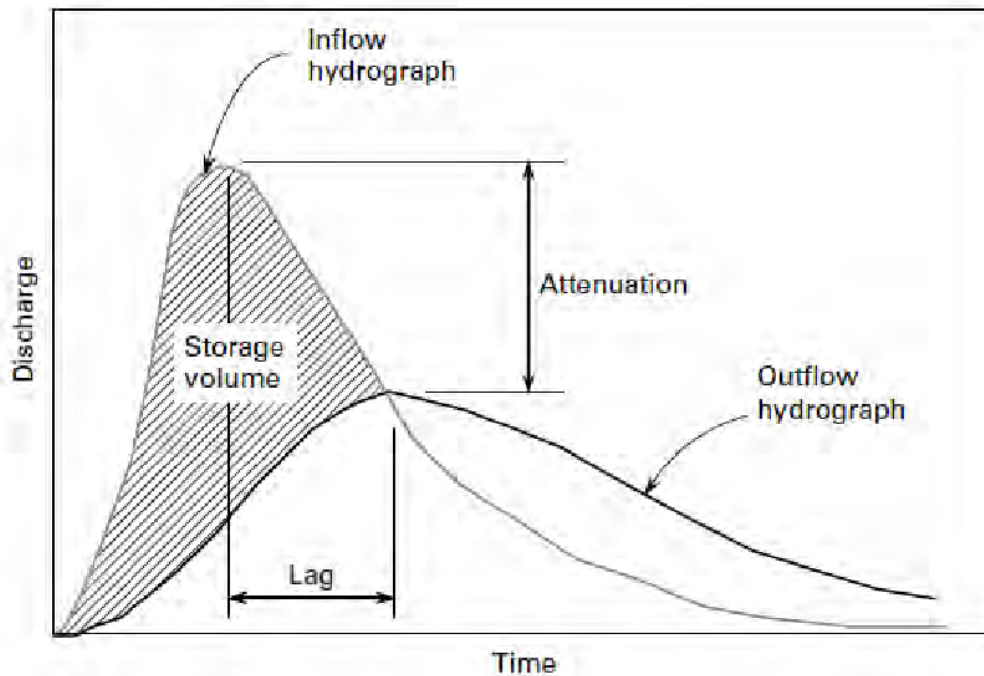


Figure 2. Typical water runoff behavior from a green roof. [6] p. 47

The precipitation will initially be absorbed in the vegetation, covering the green roof, and then will the rain water infiltrate down into the plating medium where the water will be retained until full saturation is reached for the plating medium. The excess water, from the plating medium, will drain to a water retaining layer before reaching the drain layer which leads the runoff water to the roof drainage pipes. The runoff will continue until the free water in the pores in the different layers (plating medium, water retaining layer and drainage layer) are fully drained. [6]

A green roofs primary capacity to retain water is defined as the difference between the amount of water stored in the pores and the water content at the moment in the pores. The primary capacity will vary depended on previously precipitation, the time since last rain event and evaporation rate. Figure 3 shows the a green roofs total primary capacity to retain water. The difference between point b which shows saturated soil and point a which demonstrate a soil where the plants cannot take up more water from the soil, known as the wither point.

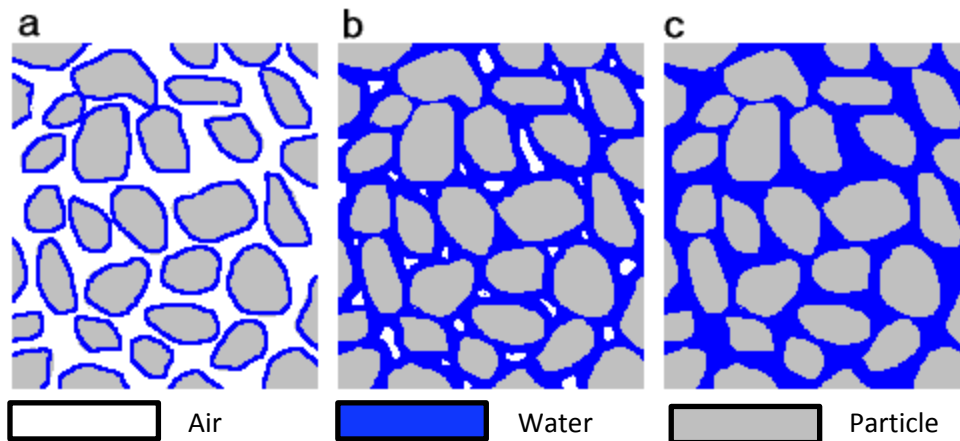


Figure 3. Different water contents for a soil. a-wether point, b-saturated, c-fully soaked. [6] p. 46

During intensive precipitation the ability to retain water will increase with escalating rain intensity. The capacity to retain water will be even higher then expected considering the amount which is required until the the point of saturation is reached. The amount of water that can be drained out is lower than the amount which is added during intensive raining. This retaining capacity is known as the green roof secondary retaining capacity. The secondary retaining capacity is momentarily and when the intensity of the precipitation decrease, will the free water in the pores drain out and reach a saturated situation. [5]

The secondary retaining capacity has a temporarily impact on the size of the runoff. The pores becomes filled with water which results in less runoff per time unit compared with a traditionally roof with the same precipitation intensity during the same time period. When more and more pores becomes water filled will the runoff intensity converge towards the intensity of the rain event. This is due to the weight from the free water inside the material. [5]

If the water content is low inside a green roof before a rainfall, the primarily retaining capacity will be great and the runoff will be reduced and delayed. While if the water content is close to the point of saturated material, will the runoff be of more or less the same magnitude as the precipitation but some delay will occur. [6]

In between two rain events, the amount of water that is absorbed in the plating medium will be taken up by the plants and some water will evaporate. This will lead to that the buffering capacity of the green roof can be restored. The time needed for this is depening on which plants that are used, time of the year and weather conditions.

2.4 Green Roof Projects

Three different green roof field tests with focus on the water retaining performance are presented in this chapter. The first two field tests were performed in Norway and the last one in Italy. All three projects showed stormwater retaining capability.

2.4.1 SINTEF Field Test [7]

SINTEF has performed a field test of green roofs in Trondheim, in order to study the runoff from sedum and Nittedals Roofing Turf^{®1} on a flat roof over time. Three test roofs with dimensions 2x2 m were constructed. A cornice of 200 mm height was built and a roof membrane was used to prevent uncontrolled leakage, see Figure 4. An opening of 20 mm was made at one side between the bottom of the roof and the cornice. The structure had a slope of 2 % towards the side with the opening. The reason for this is to drain the water off the roof, through the opening in the cornice and down into a gutter. The rainwater was then lead to a collecting barrel where the runoff could be measured.

The three roofs had different design. One roof was covered with Nittedals Roofing Turf[®], seeded with grass. Another roof, with sedum, consisted of a 70 mm drain layer of expanded clay lightweight aggregates and on top a 30 mm sandy soil layer covered with the sedum plants, Figure 5. The third and last roof had only the roof membrane in order to represent a traditional roof.



Figure 4. The wooden casket with the protective roof membrane.

¹ This product is communally used on cottages in Norway and is delivered in mesh bags with dimensions of 700x450mm and a thickness of 170mm. The material mainly consists of peat.



Figure 5. To the left Sedum and to the right Nittledals Roofing Turf® with fully grown grass.

The experiment started with two controlled tests, spreading a fixed amount of water during a specific time period. This produced a cumulative curve of the runoff for each of the three test roofs. To evaluate how the water content inside the materials affects the runoff, samples were taken before and after each initial test. Out of this sampling it was also possible to determine how much water that was absorbed during the tests. Before the field test, the maximum water content was measured in the laboratory. The samples were placed in small containers with grids at the ends of the pots, allowing free water movement. The containers were stored submerged in a water tank for four days. Thereafter the containers were taken out and the free water was drained out and the maximum water content could be measured, see Table 1.

Table 1. Shows the maximum water content for the materials.

Maximum water content [%]	
Nittledals Roofing Turf®	Sedum
978	302

The outdoor controlled experiments were performed during two days with similar weather conditions (sun and a little wind). Between these occasions there had been precipitation which resulted in higher initial water content of the materials in the green roofs during the second measurement. An amount of water corresponding to 52 [mm/m² h] was distributed over each of the three small scale roofs. After the one hour long rain event no more water was added. The measurement of the runoff water continued until the curve of the runoff had flattened out, reaching close to no runoff water, see Figure 6.

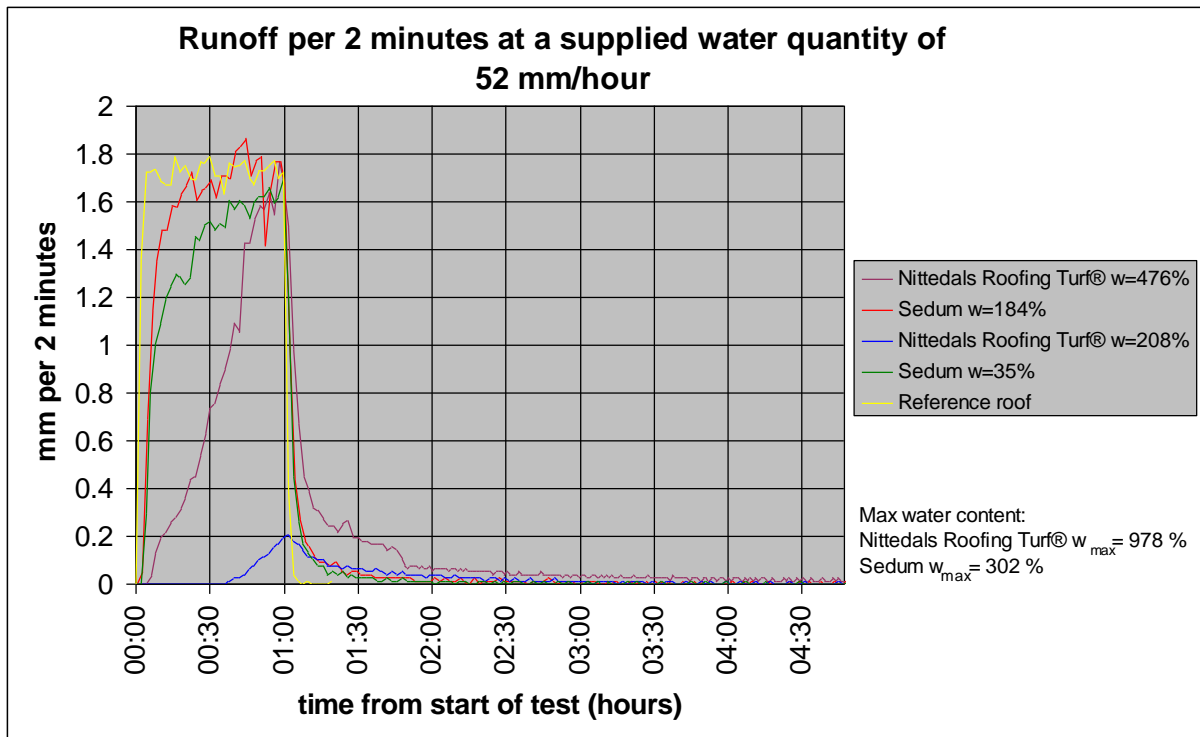


Figure 6. Runoff with both materials and water contents.

Table 2 and Table 3 summarize the findings from the water runoff test. From the tables it is possible to conclude that there exist a delay in runoff for the green roofs and a reduction of total runoff. The magnitudes of the runoff and the delay seem to correlate to the water content of the material at the point when the precipitation starts. From Table 3 conceivable to notice that the water content, at the start of a rain event, inside the material affects the total runoff.

Table 2. A summary of runoff time and quantity.

	Total runoff [mm]	Start of runoff [min:sec]	Equal runoff to reference roof [min]	Total runoff time [hours:min]
Nittedals Roofing Turf® (21% of w_{max})	4,4	36:30	-	5:20
Nittedals Roofing Turf® (48% of w_{max})	41	5:22	58	18:19
Sedum (11% of w_{max})	43,7	2:37	74 (calculated)	4:07
Sedum (61% of w_{max})	50,8	1:50	35	11:32
Reference roof	51,8	0:23	0	1:18

Table 3. The reduction of total runoff.

	After 1 hour	After 5 hours
Nittedals Roofing Turf® (21% of w_{max})	98%	92%
Nittedals Roofing Turf® (48% of w_{max})	53%	27%
Sedum (11% of w_{max})	22%	16%
Sedum (water 61% of w_{max})	10%	2%

2.4.2 Green Roof in Oslo [8]

In July 2009 a green roof experiment took place in Oslo. A roof, with a few degrees slope, of a garage was subdivided into three 8 m² parts, see Figure 7. The middle part was left without any change while the parts left and right were covered with 3 cm of soil and sedum on top. The part in the middle was used as a reference roof, simulating a traditional roof, while the two sedum covered parts reproduce the behavior from green roofs.

During the testing phase an intensive precipitation occurred corresponding to a 40-year rainfall. This rain event, 29 mm in 30 min, took place after a period of warm dry weather. The green roof absorbed the first 9 mm of precipitation and delayed the runoff with about five minutes. For the two hour measuring time, shown in Figure 8, an amount of 6 mm (22%) was retained in the green roof. Even though the green roof becomes wet after the 9 mm rain absorption, it still reduces the peak runoff.



Figure 7. The roof with the three sections.

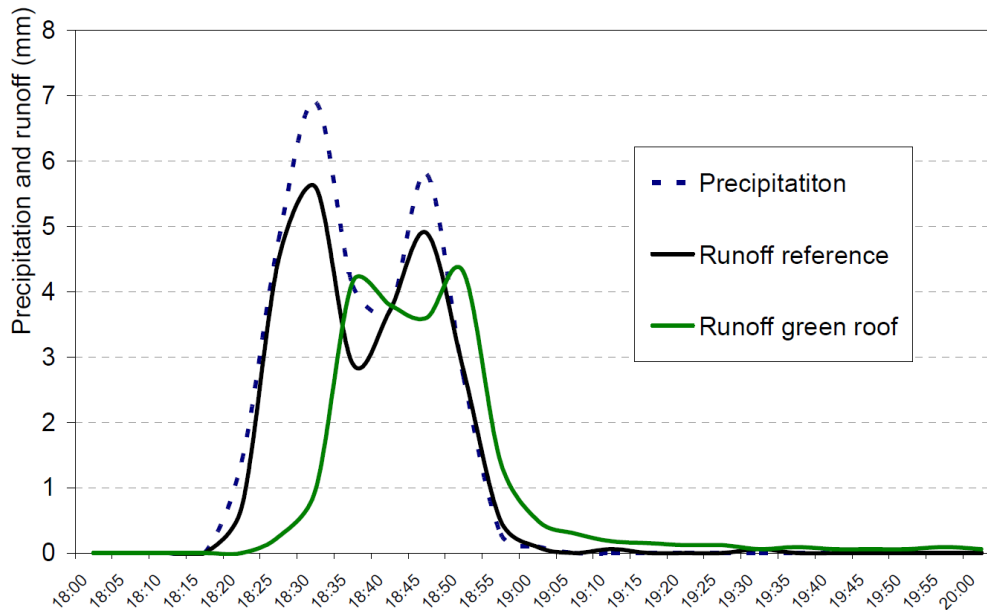


Figure 8. Results from the experiment.

2.4.3 Green Roof Test in Mediterranean Climate [9]

In May 2007, an experiment started on the rooftop of the Environmental Engineering laboratory building at the University of Genova, Italy. An area of 350 m² was used in the study. The green roof had, from the top and downwards, the following design:

- A 20 cm layer with growing medium consisting of mixed soil and peat.
- A filter layer constitute of a geotextile (100 g/m²).
- A drainage layer with a depth of 15 cm.
- Finally a protective layer consisting of a denser geotextile then the filter layer (300 g/m²).

A meteorological station which collects data with a 1 min resolution was placed on the roof and the roof was equipped with sensors measuring the runoff water in the outlet of the green roof. The rain events which occurred during the test period (May 2007 until August 2008) are shown in Table 4. The same table presents the peak values of the outflow, retained rain water volume, the peak reduction and the time delay. The retained rain water volume was calculated as the difference between the outflow and the rainfall magnitude. An example of this is the rain event on the 8th of august, 13,2 mm precipitation fell which lead to no out flow results in 100 % retained volume. In order to determent the peak flow reduction, the outlet flow from the green roof was compared to an impervious reference roof. The delay is the difference in time between the peak value of the rainfall event and when the flow peak occurs.

Table 4. The data results from the test period.

Rainfall event	Rain depth (mm)	Flow peak (L/s)	Retained Vol. (%)	Peak reduction (%)	Delay (min)
26 May 2007	9	No flow	100	100	–
28 May 2007	12.4	No flow	100	100	–
1 Jun 2007	42.4	0.02	99	99	345
5 Jun 2007	41.2	1.31	41	87	79
8 Aug 2007	13.2	No flow	100	100	–
9–10 Aug 2007	14	<0.01	95	98.7	793
20 Aug 2007	15.2	<0.01	95	99.9	89
21 Aug 2007	32.6	0.04	96	99	436
27 Aug 2007	28.6	0.02	99	99.6	150
21 Nov 2007	8	No flow	100	100	–
22–23 Nov 2007	138.2	1.27	9.5	79	148
4–5 Jan 2008	32.8	0.1	70	76	754
11–12 Jan 2008	41.4	0.6	15	87	427
16 Jan 2008	40.4	0.9	4.6	78	139
4 Feb 2008	30.4	0.8	51	70	197
9–10 Mar 2008	23.2	0.16	81	94	596
9–11 Apr 2008	55	0.1	93	96	1716
21 Apr 2008	25.4	0.62	23	46	145
17 Jun 2008	35.6	1.2	19	77	91
Mean	–	–	68	89	407
Standard Deviation	–	–	37	15	435

Palla (2011) observed that four out of nineteen rainfall events did not produce any runoff and three rainfall events resulted in a runoff greater than 1 litre/sec. During all the precipitation occasions the entire volume of rain water was infiltrated and no surface runoff occurred. Palla (2011) also highlights the lag or delay effect for the stormwater events (5th of June, 22nd and 23rd of November and 17th of June 2008). For these occasions a delay between 79 min and 148 min could be seen. These delays in time and the retained volume of water indicates that the green roof, built for the experiment, performed well.

2.5 Material Production and Characteristics

LWA can originate from natural resources or be produced in factories. The main natural resource is volcanic material. Boiling lava consists of air and gases, which during rapid cool down solidifies into a highly porous material. Due to the quick cool down of the molten mass, no crystallization occurs and the material obtains a glassy structure. This natural lightweight material is known as volcanic aggregates, scoria aggregates or pumice.

The raw materials used for the man-made production can be divided into three groups:

- Natural materials, e.g. clay, shale and slate.
- Manufactured products, e.g. glass.
- By-products from the industry, such as fly and bed ash.

Man-made lightweight aggregates can be produced in two different basic methods, either in a dry or wet process. The wet process resembles the method used to prepare clay for brick production, where clay is mixed with water and thereafter burned. While in the dry method shale or slate is crushed and milled into powder and pressed into lightweight pellets.

The characteristics of LWA vary depending on the method and the materials used in the production, either expansion or agglomeration. Expansion of the material occurs with high temperature, which causes generation of gas within the material. These conditions lead to an instant solidification of the material. Agglomeration on the other hand is a result of a process where some of the raw material melt and bind together. A result from the two different manufacturing processes can be that the shape and the texture will differ considerably from highly angular to completely round and the surfaces from rough and porous to smooth and dense. [10] [11]

A producer of expanded clay LWA is the Weber factory in Rælingen, Norway, where a wet process is used for manufacturing. Expanded clay LWA manufactured by Weber is called Leca®. The production phases at the factory in Rælingen can be simplified by Figure 9:

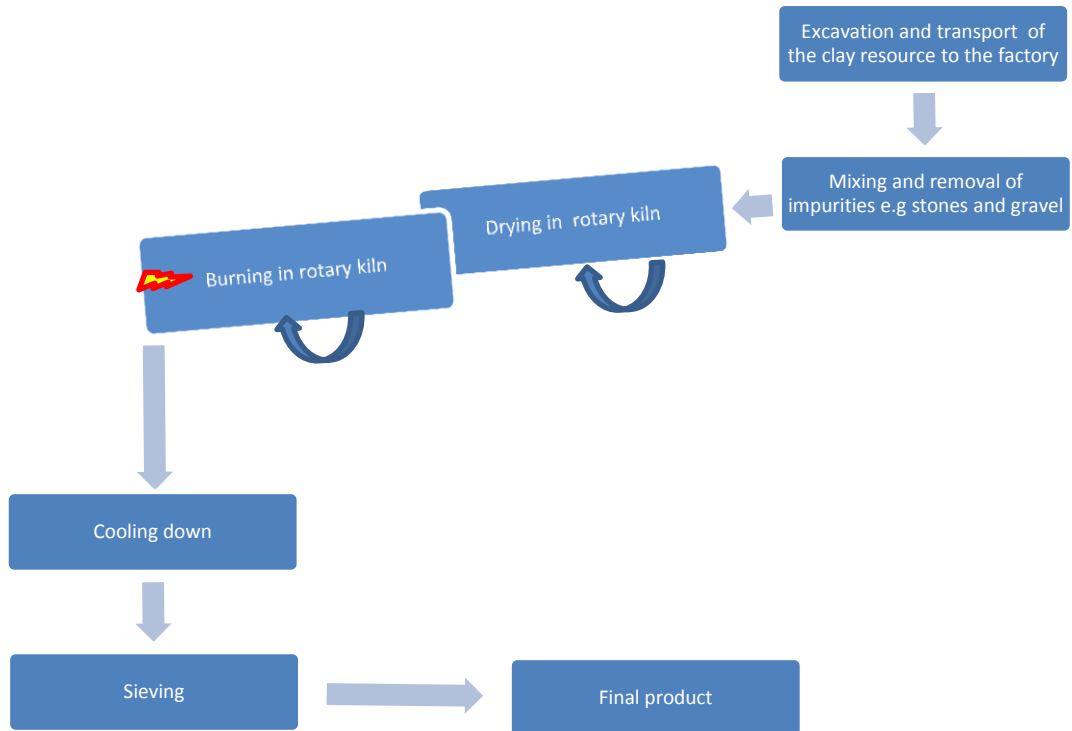


Figure 9. Flow chart of Leca® production at Weber factory in Rælingen, Norway.

First, clay and water is mixed into a paste that is fed in the top of a rotary kiln, see Figure 10. The rotary kiln is a long cylindrical “oven” which rotates along its longitudinal axle and is horizontally inclined. The kiln is divided into two different parts, a drying kiln where the temperature and the rotation velocity is lower and a burning zone with a higher temperature (around 1200°C) and a higher rotation speed. The clay paste is fed in the upper end of the kiln where it dries. By gravity and the rotation the material moves towards the burning zone in the lower end, where it expands. When the material reaches the end of the kiln, it drops out and is stored in piles where it cools down. After that, sieving is performed to obtain the requested particle size distribution. The expanded clay LWA that is produced in a rotary kiln has a round profile, particularly when a pre-shaping system is used before the drying and burning process. [10]



Figure 10. Rotary kiln the length is usually between 30 to 60 meters depending on the composition of the raw material the different producers are using. [12]

2.5.1 Physical Properties

The relation between the mass and the total volume that the loose material occupies is called the bulk density. Important factors that govern this parameter are the particle distribution and the water content, but also the shape and the surface conditions of the aggregates affect the result. Round and angular LWA with the same particle density can vary with almost 100 kg/m^3 in bulk density, depending on the proportions of voids. A general rule is that the bulk density of lightweight aggregates is higher for the fine particles and the lowest values can be found for the coarse-grained material.

Particle density, also referred to as unit weight, is the density of the whole grain, including pores. An important factor that influences this parameter is the porosity, since the specific density of the solid material is almost fixed (about 2700 kg/m^3). The density of LWA shows great variation depending on the origin. LWA from volcanic activities can have a bulk density between 280 and 1100 kg/m^3 . American plants produce expanded clay LWA with a bulk density from 500 to 700 kg/m^3 while European produced expanded clay LWA varies between $250\text{-}400 \text{ kg/m}^3$. [11]

The product specifications for expanded clay LWA produced at Rælingen are shown in Table 5.

Table 5. Physical properties of Leca® produced at Rælingen. [13]

Particle size range	4-10mm (crushed)	4-10mm	2-4mm	10-20mm
Bulk density, dry [kg/m^3]	250 (± 40)	320 (± 75)	360 (± 50)	260 (± 50)
Particle density, dry [kg/m^3]	540 (± 80)	600 (± 100)	650 (± 100)	450 (± 100)
Particle porosity [%]	80	78	45	83
Voids [%]	44	46	45	42

The data over loose bulk density from SINTEF's testing program of expanded clay LWA is shown in Table 6.

Table 6. Variation in dry loose bulk density from different production sites. [14]

Country and production location	Particle size range [mm]	Dry loose bulk density [kg/m^3]
Portugal, Avelar	10-20	275
Denmark, Hinge	10-20	215
Denmark, Ølst	10-20	260
Spain, Los Hueros	8-16	303
Sweden, Linköping	12-20	260
Finland, Kuusankoski	10-20	280

3. Theory

This chapter will start with illustrating the theory behind water flow and then continue with a short description of the Finite Element Method, followed by the explanation of the methodology used in the software in order to calculate water flow through a porous material.

3.1 Method

In order to test if SEEP/W is advisable tool for simulating water flow in expanded clay LWA, a back calculation of a laboratory experiment will be done. The approach used in order to collect data and evaluate the results will be explained in chapters 4 and 5.

The purpose of back calculating the experiment is to calibrate the numerical model and then use it for a full scale ideal roof and also evaluate the results. Thereafter a sensitivity analysis of the SEEP/W input parameters will be performed, see chapter 6.

3.2 Water Flow

In order for water to flow from one point to another in a porous material, there must exist a difference in energy (a potential) between the two points. Another condition is the existence of continuous pores in which the water can flow. A porous material's ability to allow fluids to flow through its pores is called the permeability. [15]

Figure 11 shows a principle set up of the equipment used to measure the permeability of a sample. To the left in the figure, water is added into the system and on the right side the water flows out and into a container with a known volume.

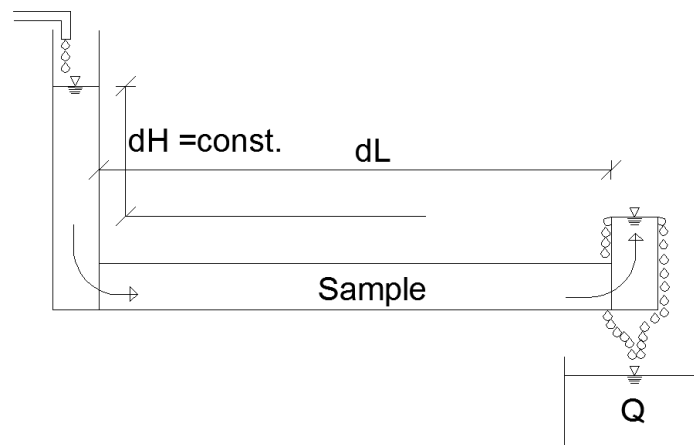


Figure 11. A principle sketch over apparatus for testing permeability.

The hydraulic gradient, i , is defined as the difference in potential over the length. It is the gradient that is the driving force of the water.

$$i = \frac{dH}{dL} \quad (3.1)$$

dH – hydraulic potential

dL – Length of the sample

The flow rate of water per unit area, v , is defined as the volume of water, Q , over the section area of the sample, A , and time.

$$v = \frac{Q}{A * t} \quad (3.2)$$

According to Darcy's law the coefficient of permeability can be calculated with the following equation:

$$k = \frac{v}{i} \quad (3.3)$$

The coefficient of permeability is only valid as long as the flow is laminar, which means that the flow occurs parallel with no disruption between the streamlines. Turbulent flow on the other hand is more chaotic and develops in higher flow rates, see Figure 12.

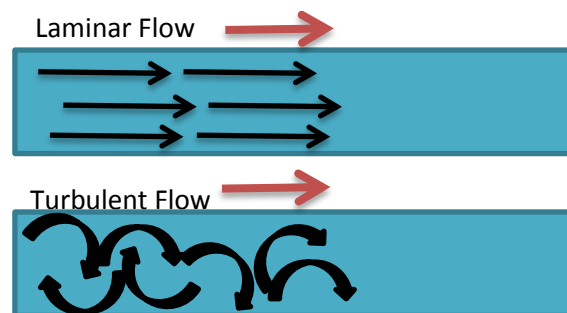


Figure 12. Two different flow conditions.

When the hydraulic gradient reaches a certain level the curve bends off, which means that the flow rate stops increasing linearly with the gradient, see Figure 13. The reason is that the flow in the pores no longer is laminar, but turbulent, which implies that Darcy's law is no longer valid.

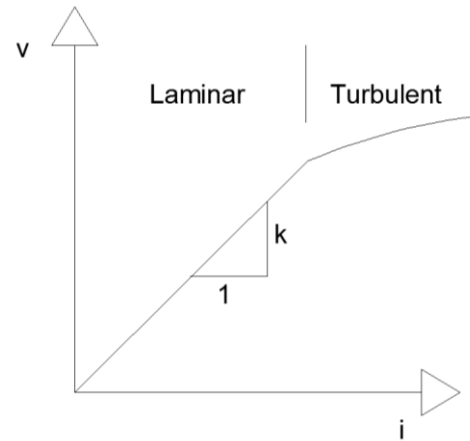


Figure 13. The graph indicates where Darcy's law is valid.

Typical values for permeability of different types of soil are given in Table 7. [16]

Table 7. Values of the coefficient of permeability for various particles sizes.

Type of soil	k [cm/s]
Gravel	>1
Sand	$1 - 10^{-3}$
Silt	$10^{-3} - 10^{-6}$
Moraine	$10^{-4} - 10^{-7}$
Clay	$10^{-6} - 10^{-9}$

3.3 Numerical Modeling

The Finite Element Method, FEM, is the numerical model used in GeoStudio® SEEP/W. The FEM is a powerful tool performing heavy calculations to solve a number of engineering problems. It was developed in the 1950's and is commonly used in geotechnical and structural engineering. The theoretical method used is called the displacement method. The reason for the name is that in the method forces and load are placed on a structure or element and the response in displacement and deformation is studied. The displacement method is suitable for static structural mechanics calculating deformations for beams, soil and rock. The method can also be used for flow applications; in that case the forces and loads are replaced by hydraulic head and fluid flux. Then the temperature and flux is analyzed instead of displacements. [17]

The main principle behind the FEM is to subdivide the structure into smaller elements which is called discretization or meshing. The behavior of an element is described approximately. Each and one of the elements will be puzzle parts of the main structure and the behavior of each and one for the elements will be calculated and then added together, see Figure 14.

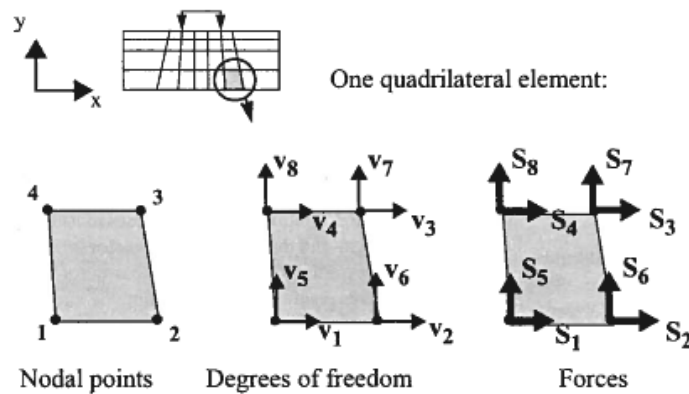


Figure 14. Showing meshing of a soil and the nodal point for an element with corresponding degrees of freedom (directions for the displacements) and forces at the nodal points. [17] Ch.2 P. 8

Like every modern FEM program, SEEP/W consist of a pre-processor where the user gives the input parameters e.g. geometry, material properties and boundary conditions etc. It is in the pre-processor that the meshing occurs. The pre-processor delivers the necessary information to the part of the program that performs the calculations and the results are displayed in the post-processor where the user can see the outcome of the problem.

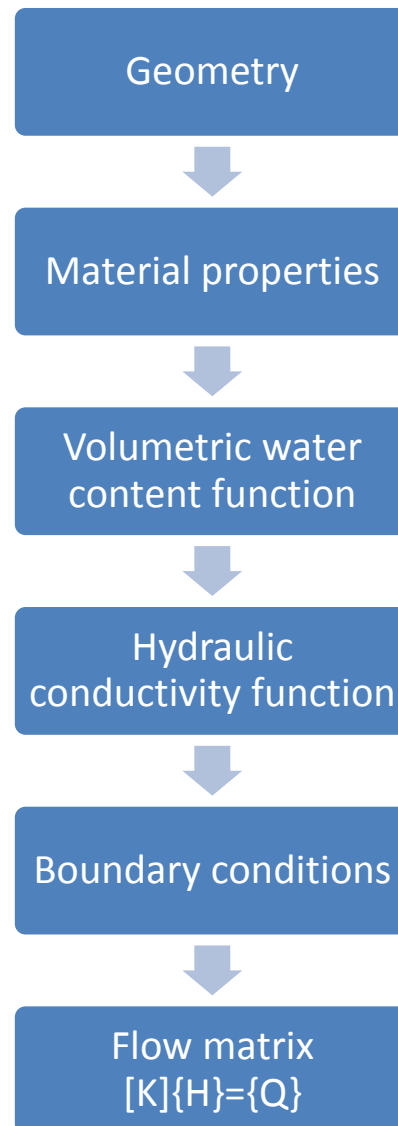
In order to succeed with numerical simulation it is important to choose adequate size of the elements. If too coarse elements are used the solution will not be accurate enough and if too small elements are used huge compute power will be needed. The same issues are valid for the time integration step, long time steps will give inaccurate values and small time steps will generate huge amount of data.

3.4 SEEP/W

SEEP/W is a FEM software designed for calculation of water flow in both saturated and unsaturated porous material. A mental picture of how the steps are connected in SEEP/W, can be helpful. Figure 15 shows a simplification of how the solution approach is designed.

Figure 15. Simplification of the solution approach.

- 1) First, a geometry is created by the user, where the soil layers, water ponds and interfaces are drawn and give a graphic definition of the model. The meshing is also performed in this step, the user chooses the shape and the size of the elements.
- 2) The next step is to define the properties of the soil or materials which will be used in the simulation. This is done by defining the input parameters of each of the materials, e.g. porosity and grain size distribution.
- 3) With the input from the previous step, the program creates a volumetric water content function, which defines how much water the material contains, depending on the pore water pressure.
- 4) After the water content function is defined, a hydraulic conductivity function can be generated. The hydraulic conductivity function defines the conductivity of an element based on the water content of the element. The function is given by defining the saturated water flow velocity and the shape of the water content function.
- 5) A last step before the calculations can be performed is to define the boundary conditions; the total hydraulic head or a water flow. These give the driving forces of the water flow in the model.
- 6) A flow matrix can be created and solved in SEEP/W when the points 1 to 5 have been determined. Point 1 to 4 gives the necessary input data to specify the $[K]$ -matrix, which is related to the geometry and material properties. A defined total hydraulic head boundary condition gives the $\{H\}$ -vector in order to calculate the flow or vice versa, when a flow boundary condition is defined, a $\{Q\}$ -vector is generated to calculate the total hydraulic head.



3.4.1 Volumetric Water Content Function [18]

Soil consists of a solid part and pores. The pores can be filled with air, water or both. In a saturated soil the pores are completely filled with water and no air exist in the voids. For a saturated soil the volumetric water content is equal to the porosity, n .

$$\theta_w = nS \quad (3.4)$$

θ_w = the volumetric water content

n = the porosity of the soil

S = the degree of saturation, (1.0 for a saturated soil)

For an unsaturated soil the water content within the pores will vary depending on the difference between the air pressure and water pressure ($U_a - U_w$). This difference is called the matric suction. In SEEP/W the volumetric water content function describes how the portion of the pores filled with water changes with the matric pressure. There are three characteristics for a soil that is pointed out on the graph: the air-entry-value, the slope of the curve both for the positive and negative pore-water pressures and the residual volumetric water content, see Figure 16.

- The air-entry value (AEV) corresponds to the value of the negative pore-water pressure when the largest voids in the soil start to drain. The AEV-value is given from the maximum pore size and the pore-size distribution within the soil.
- The slope of the curve describes how water is stored or drained out of the soil. On the left side where pore pressure is negative, water is drained from the AEV-value to the residual water content. The right side, where the pore pressure is positive, the slope of the volumetric function defines how more and more water is stored in the soil.
- Residual volumetric water content defines a point where no more water is drained out of the soil. It is possible to remove more water from the soil by evaporation but this is not considered in SEEP/W.

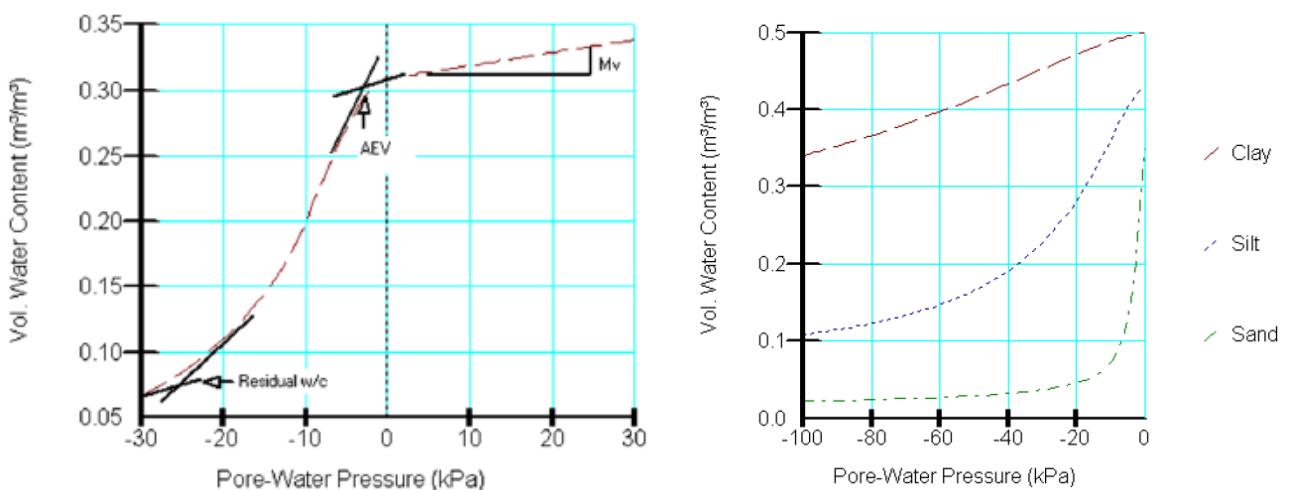


Figure 16. To the left the volumetric water content function and to the right examples of volumetric water content function for different grain size distributions. [18] pp 63-64

The shape of the volumetric water content function is highly influenced by the size of the particles and the distribution of the particle sizes, see Figure 16. The sand particles have more or less the same size and the particles are relatively large. This results in a steep inclination of the function, which means that most of the water can be released with a small negative pore-water pressure.

For the silt, which in this example consists of both sand and silt particles, the distribution of the pore size is broader. This is due to the fact that pores or voids between the sand particles are filled with smaller silt particles. With smaller pore sizes, the drain of the soil begins during larger negative pore-water pressure.

3.4.2 Hydraulic Conductivity Function [18]

It is within the pores of a soil that the transport of air and water takes place. For a complete saturated soil all the pores are filled with water, while for an unsaturated there is air in the pores. Air-filled pores cannot transport water and becomes non-conductive. This means that the water flow rate within a soil differs, from a higher flow rate in a fully saturated soil compared with a lower flow rate in an unsaturated soil. The reason for the lower flow rate is that the water flow path becomes longer in an unsaturated soil, whereas the flow path in a saturated soil is the shortest possible, see Figure 17.

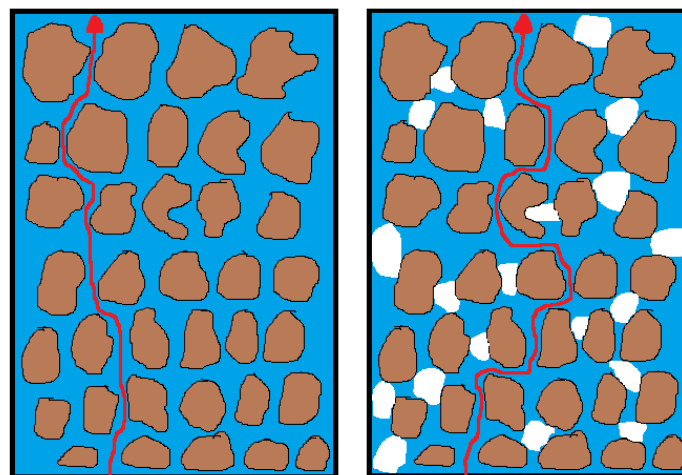


Figure 17. To the left saturated soil with a short part for a water particle and to the right an unsaturated soil with longer flow paths for the water particles.

When more and more air enters the pores the conductivity decreases further until the soil is drained and has reached the residual water content stage. The capability for water to flow through a soil is strongly connected with the amount of water in the soil and the volumetric water content function describes exactly this.

It is important to specify a hydraulic conductivity function for a material that has an unsaturated region. If the conductivity is set to be the same in the saturated and unsaturated regions, the results from a seepage analysis will indicate flow patterns which deviate from a “real” situation.

In SEEP/W there are three different estimation methods in order to establish the shape of the hydraulic conductivity function. The method used in the calculations for this analysis is the approach suggested by van Genuchten.

$$k_w = k_s \frac{[1 - (a\Psi^{(n-1)})(1 + (a\Psi^n)^{-m})]^2}{((1 + a\Psi^n)^{\frac{m}{2}})} \quad (3.5)$$

k_w = the calculated conductivity for a specified water content or negative pore-water pressure

k_s = saturated hydraulic conductivity

a, n, m = curve fitting parameters

$$n = \frac{1}{(1 - m)} \quad (3.6)$$

Ψ = required suction range

In the equation above for calculating the conductivity two curve fitting parameters are needed, a and m . van Genuchten stated that the best point for estimating the curve fitting parameters is the point halfway between the saturated water content and the residual water content. The slope of the function at this point is calculated by the following equation.

$$S_p = \frac{1}{(\theta_s - \theta_r)} \left| \frac{d\theta_p}{d(\log\Psi_p)} \right| \quad (3.7)$$

θ_s, θ_r = the saturated and residual volumetric water content

θ_p = the volumetric water content at the halfway point of the volumetric water content function

Ψ_p = the matric suction at the halfway point

a and m are estimated by the following equations:

$$m = 1 - \exp(-0.8S_p) \quad (3.8)$$

for $0 < S_p < 1$

$$m = 1 - \frac{0.5755}{S_p} + \frac{0.1}{S_p^2} + \frac{0.025}{S_p^3} \quad (3.9)$$

for $S_p > 1$

$$a = \frac{1}{\Psi} \left(2^{\frac{1}{m}} - 1 \right)^{(1-m)} \quad (3.10)$$

3.4.3 Water Flow Matrix [18]

How the functions in SEEP/W describes the water content and the hydraulic conductivity for a material have been illustrated earlier in this chapter. This section will present the equations which are governing the flow matrix, $[K]\{H\}=\{Q\}$.

Partial differential water flow equations, which the flow matrix consist of:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \quad (3.11)$$

H = the total head

k_x = the coefficient of permeability in the x-direction

k_y = the coefficient of permeability in the y-direction

Q = the applied boundary flux (rate of flow through a section of area)

θ = the volumetric water content

t = time

The equation above describes that the difference between the flow going in and the flow going out is equal to the change of the stored amount of water in the soil element over time $\frac{\partial \theta}{\partial t}$. Q is the flow going in and $\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right)$ and $\frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right)$ defines how much water that is leaving in the x- and y-direction.

During steady-state conditions, there is no water storage in the soil elements, this gives the following equation:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = 0 \quad (3.12)$$

Changes in the volumetric water content are controlled by the change in stress state and the characteristics of the soil. For saturated and unsaturated conditions the stress state are related to the difference between the total stress, σ and the pore-air pressure u_a ($\sigma - u_a$) and the difference between the pore-air and the pore water pressure u_w , ($u_a - u_w$), see Figure 18.

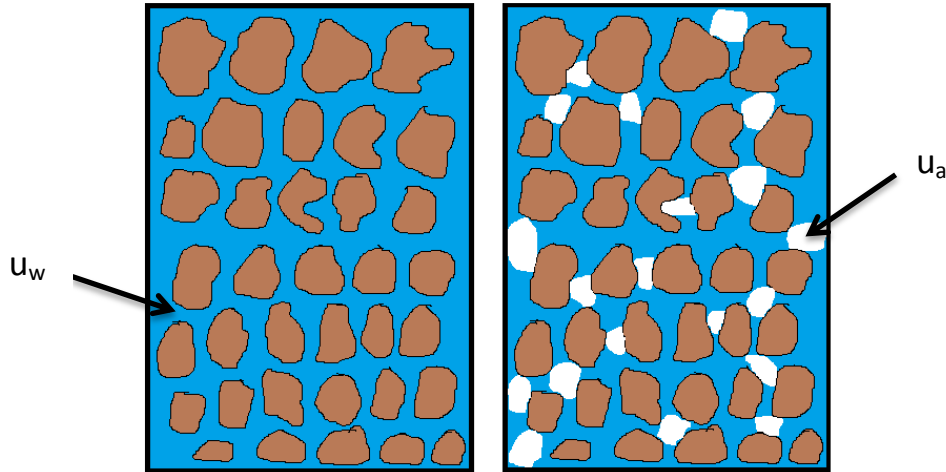


Figure 18. Pore water pressure, u_w , and pore air pressure u_a .

The program code in SEEP/W is written in a way that the total stress (σ) remains constant, i.e. no loading or unloading takes place for the soil elements. It is also assumed that the pore-air pressure is constant at atmospheric pressure. This means that the difference between the total stress and pore-air pressure is constant and causes no change of the volumetric water content. The volumetric water content is only dependent on the difference between pore air pressure (u_a) and pore water pressure (u_w). As mentioned before, the pore-air pressure is kept constant, which results in the change of volumetric water content being dependent on the pore water pressure change, according to:

$$\partial\theta = m_w \partial u_w \quad (3.13)$$

m_w = the slope of the water storage curve (see Figure 16)

The total hydraulic head, H , is a user input parameter and defined as:

$$H = \frac{u_w}{\gamma_w} + y \quad (3.14)$$

u_w = the pore water pressure

γ_w = the unit weight of water

y = the elevation

It is possible to rewrite the equation to:

$$u_w = \gamma_w(H - y) \quad (3.15)$$

Inserted into equation 3.13 gives:

$$\partial\theta = m_w \gamma_w \partial(H - y) \quad (3.16)$$

Then substituted into equation 3.11;

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) + Q = m_w \gamma_w \frac{\partial(H - y)}{\partial t} \quad (3.17)$$

For a soil element at an elevation, y , the elevation remains constant and the dependency disappears resulting in the following equation which is used in the SEEP/W FEM calculations.

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) + Q = m_w \gamma_w \frac{\partial H}{\partial t} \quad (3.18)$$

4. Water Retaining Experiment [20]

One of the ideas with green roofs is to ease the pressure on a city's drain or sewage system during heavy rain. Green roofs smoothen out the peak of the storm water runoff and store parts of the water in the porous material. Preliminary testing of 24 different expanded clay LWA materials were performed at Saint-Gobain Weber². The materials were produced at seven different factories in Europe and the objective was to find LWA materials that showed good potential, considering water storage and permeability. Two Danish produced Leca[®] products, round Leca[®] 10-20mmR (round) and Leca[®] 2-4mmC (crushed) and the Norwegian produced Leca[®] 4-10mmC (crushed), were selected and sent to SINTEF research institute in Trondheim for further testing. At SINTEF the permeability and maximum water capacity were measured.

The delay in water runoff and water storage ability for the two Leca[®] materials (4-10mmC and 10-20mmR) was tested and the procedure will be described in this chapter. It is the results from this experiment that will be back calculated in SEEP/W.

4.1 Laboratory Experiment of a Small Scale Green Roof

In order to perform the experiment, two wooden crates were constructed in the SINTEF laboratory, see Figure 19. The crates were two meter long and equally wide. A 200 mm high frame was built around the outer edge. A 200 mm high frame was built around the outer edge. The crates were built with a 2 % inclination towards one of the sides, allowing the water to flow out of the crates and into a gutter, which lead to a collecting barrel. To prevent water leakage and absorption of the wood, the inside of the small scale roofs were covered with an impermeable roofing membrane.



Figure 19. One of the two wooden crates filled with Leca[®] 10-20mmR.

² Competence Centre Exclay in Lillestrøm

In order to simulate rain, a system of nozzles spreading a controlled amount of water over the material was used, see Figure 20. The rig with the nozzles was installed about half a meter above the surface and a plastic membrane prevented drops from drifting away and from being absorbed by the material.



Figure 20. The nozzles spreading water, simulating rain, over Leca® 10-20mmR.

In this experiment, 144 L water was sprinkled over the four square meter surface during 15 minutes, corresponding to a 36 mm rain (per square meter). The water draining into the barrel was measured from the start of the simulated rain phase and until minimal water runoff could be observed. Two different layer thicknesses, 100 mm and 200 mm, were tested for both of the materials. From the experiment, it was possible to quantify the total runoff, the time delay in runoff and runoff per unit of time.

The total runoff reduction or coefficient of discharge, C , is defined as:

$$C = \frac{\text{Volume of outlet water in 15 minutes}}{\text{Volume of rain water in 15 minutes}} \quad (4.1)$$

In order to measure the coefficient of discharge, the test material should be irrigated until it is saturated and a constant outlet flow is reached during 10 minutes. Thereafter should a drain phase of 24 h follow, before a rain event of 27 L/m² is spread on the material and the amount of outlet water is measured. The 15 minutes rain should be repeated three times and the C-value, can be determined by taking an average of the three experiments.

The C-values found for the different Leca® materials can be seen in Table 8.

Table 8. The tested mean value of coefficient of discharge.

Leca® material	Layer of 100 mm	Layer of 200 mm
4-10mm (Crushed)	0,7	0,5
10-20mm (Round)	0,8	0,7

4.1.1 Leca® 10-20mmR

Figure 21, show the results of the cumulative water amount for Leca® 10-20mmR from three tests performed on a 100 mm layer and three test on a 200 mm layer. The red line labeled “Reference roof” shows the total amount water spread on the roof (36 mm). The difference between the reference roof curve and the curves bellow is the volume water that stays in the material and in a full scale green roof, this would be the volume water which never reaches the sewage system in a city.

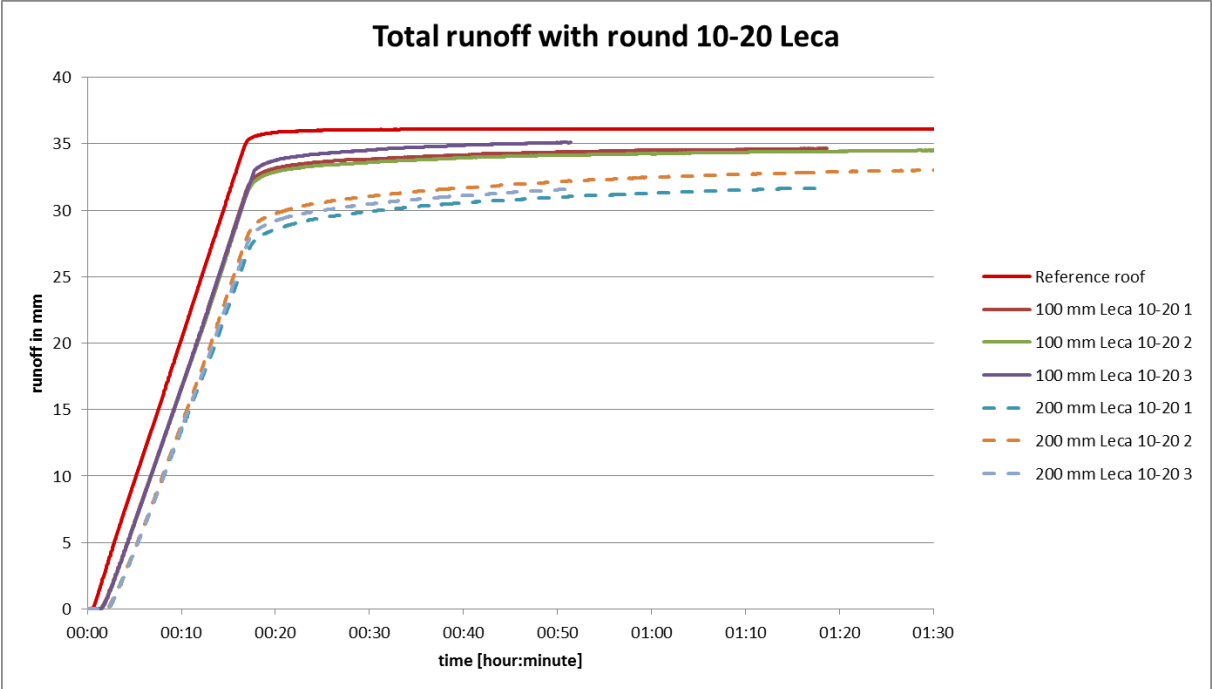


Figure 21. The cumulative water runoff for Leca® 10-20mmR.

Figure 22, shows the water runoff from Leca® 10-20mmR with two different layer thicknesses. It is possible to see delay and reduction of the runoff compared to the reference roof. The thicker 200 mm layer have more ability to delay and reduce the runoff thanks to the double water storing capacity compared to the layer with only the half depth.

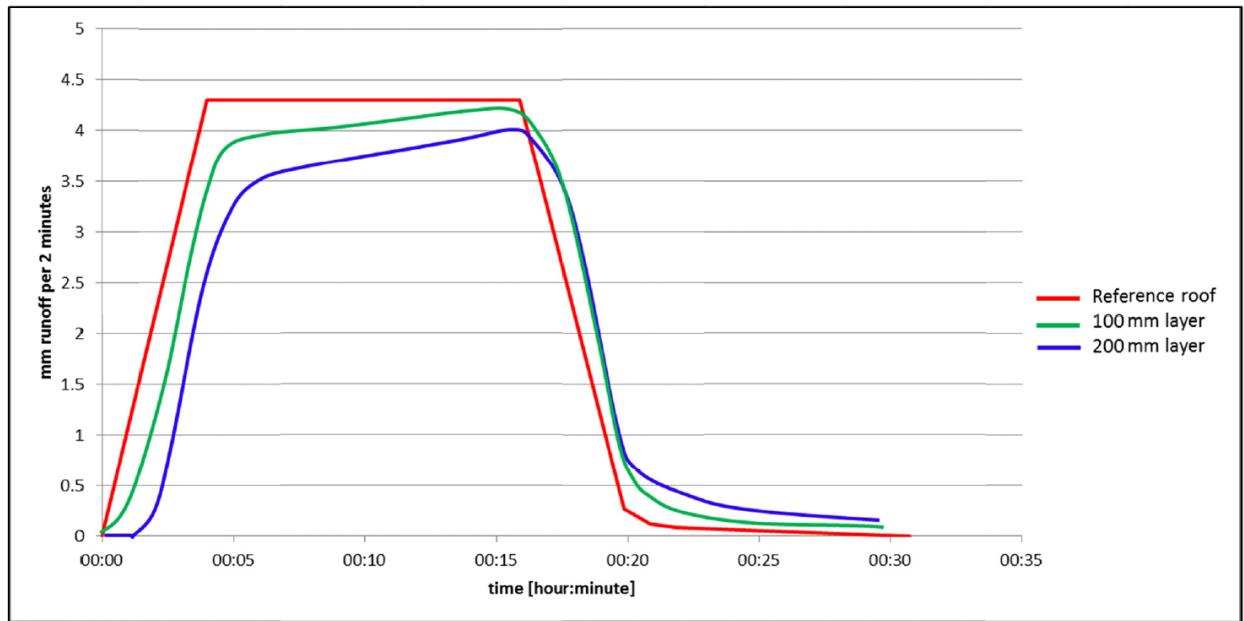


Figure 22. The runoff per time unit for Leca® 10-20mmR.

The result of the runoff experiment of the Leca® 10-20mmR, after the 36 mm rainfall, is shown in Table 9. The time values are compared with the reference roof test, which was performed by spreading the same amount of water during the same time in the wooden crates, without any material inside.

Table 9. A summary from Figure 22.

Property	100 mm layer	200 mm layer
Delayed start of runoff [min]	1	1,5
Extended runoff [min]	Ca 3,5	Ca 6
Maximum runoff per time unit [%]	100	92
Total runoff reduction after 1 hour [%]	3	11

4.1.2 Leca® 4-10mmC

In Figure 23 it is possible to see the cumulative water volume inside Leca® 4-10mmC. In the results from 4-10mmC and 10-20mmR, it is possible to notice that the curves are shifted down more for 4-10mmC compared to 10-20mmR, that means that a larger volume of water is stored in Leca® 4-10mmC.

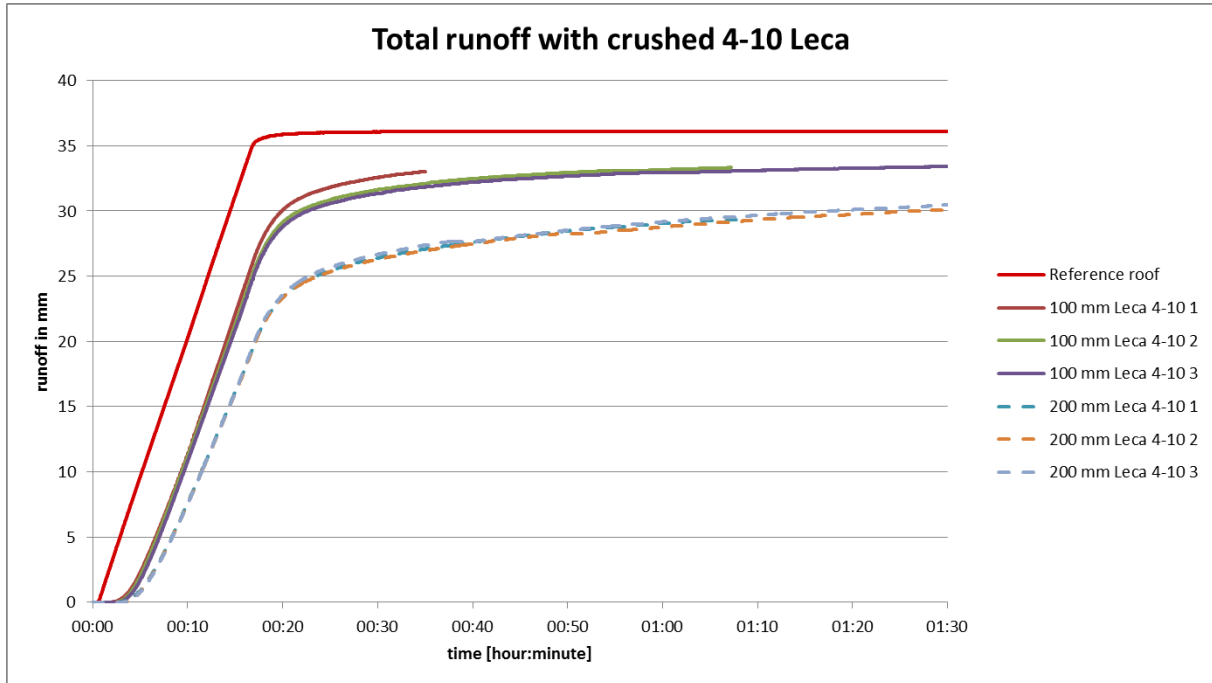


Figure 23. The cumulative water runoff for Leca® 4-10mmC.

In the water runoff curve, Figure 24, it is possible to observe the same behavior for this Leca® material compared to the 10-20mmR, considering delay in runoff and reduction of the runoff peak. The results display a significant reduction in runoff for the 200 mm layer.

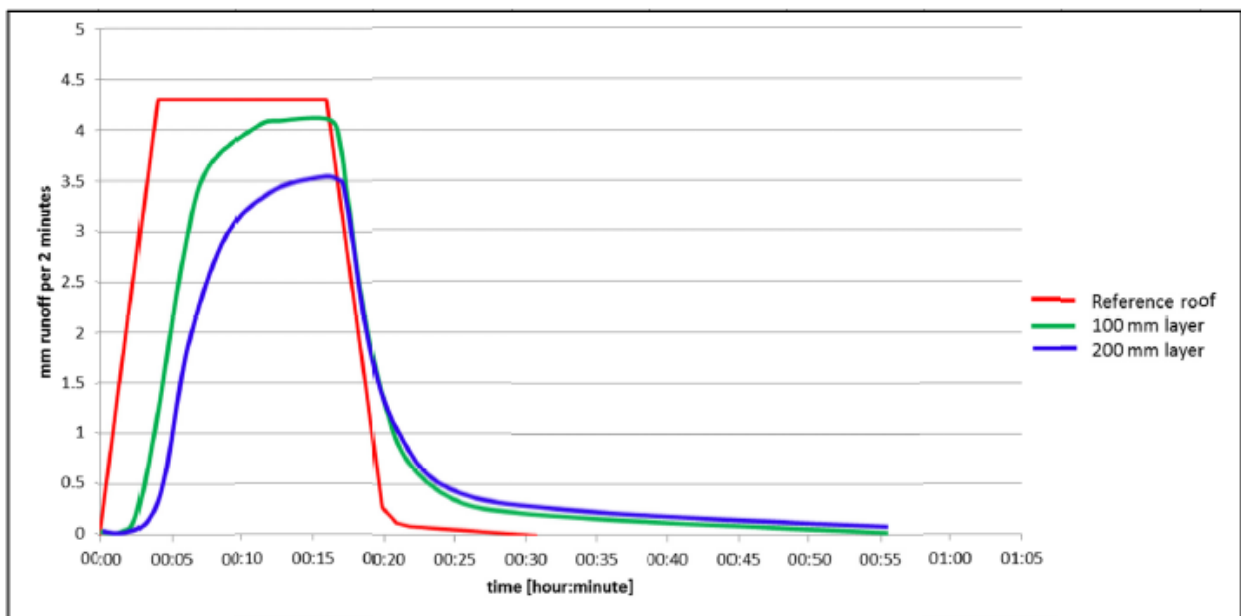


Figure 24. The runoff per time unit for Leca® 4-10mmC.

The key results for Leca® 4-10mmC can be seen in Table 10. Comparison of the results from the two tests indicates that Leca® 4-10mmC delays the runoff and reduces the runoff peak more than the 10-20mmR material.

Table 10. The results for Leca® 4-10mmC from the same rain quantity.

Property	100 mm layer	200 mm layer
Delayed start of runoff [min]	2	2,5
Extended runoff [min]	15	17
Maximum runoff per time unit [%]	96	79
Total runoff reduction after 1 hour [%]	8	20

5. Back Calculation of the Laboratory Experiment

In this thesis, an attempt to back calculate the runoff experiment executed by SINTEF (mentioned in chapter 4) was performed. The purpose of this task was to test if it is possible to receive the same result with SEEP/W as for the experiment. This chapter explains the procedure that was used, how the material input parameters were chosen. Thereafter the geometry of the model in SEEP/W and the assumptions made are illustrated. The last part of the chapter shows the results from the SINTEF laboratory experiment side by side with the result from the numerical calculations performed in SEEP/W.

5.1 Material Properties

In order for SEEP/W to perform a simulation of water flow, five input parameters are needed. These five parameters define the material properties and thereby explain how porous the material is, how the grain sizes are distributed, the hydraulic conductivity when the material is saturated and how much water that is left in the material after the free water has been drained away. The parameters are labeled in SEEP/W as:

- Saturated water content (the porosity)
- The Diameter (mm) at 10% passing (grain size distribution)
- The Diameter (mm) at 60% passing (grain size distribution)
- Coefficient of permeability - K (saturated conductivity)
- Residual water content

5.1.1 Saturated Water Content

In order to give a value for the saturated water content, it is important to know the porosity of the material. When all pores within a material are water filled, the volumes of the pores will be equal to the volume of water inside the material. The porosity of Leca[®] 4-10mmC and 10-20mmR was calculated from data of the voids, measured by Weber for 24 different Leca[®] materials, see Table 11. NO 10-20r corresponds to Leca[®] 10-20mmR and NO 4-10c corresponds to Leca[®] 4-10mmC. The label NO indicates that the material is produced in Norway.

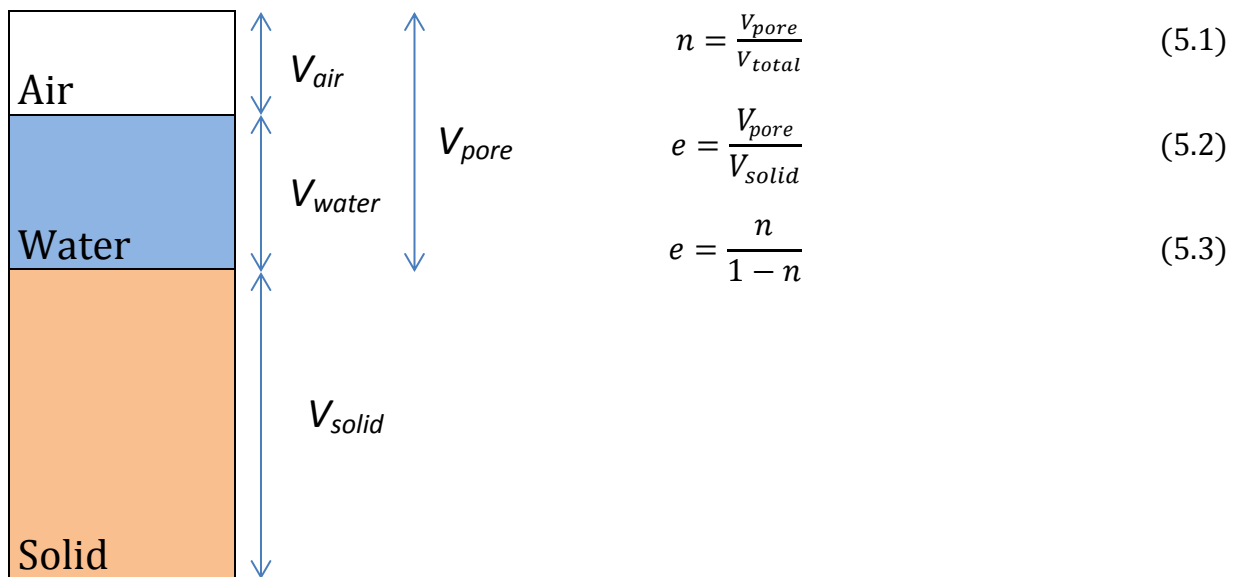


Figure 25. The three different parts of which soil consist of.

By the following equation, derived from Figure 25, the porosity can be calculated when the voids are known:

$$n = \frac{e}{1 + e} = \frac{0,44}{1,44} = 0,3 \quad (5.4)$$

The converted values, from voids to porosity, are inserted into Table 11 for each and one of the materials.

Table 11. The voids and the porosity for Leca. [20]

ID/Fraction	Voids (e)	Porosity - n (%)
NO 10-20r	0,43	0,3
NO 4-10c	0,44	0,3

5.1.2 Grain Size Distribution

In SEEP/W the grain size distribution is defined with two input parameters, the size of 10% of the material and the size of 60% of the material. These two values were taken from sieving measurements performed at NTNU for Leca® 4-10mmC and by Weber for the Leca® 10-20mmR, Figure 26. Out of the figure it is possible to deduce 6 mm and 9 mm (D10/D60) for Leca® 4-10mmC and 9 mm and 12,5 mm for Leca® 10-20mmR.

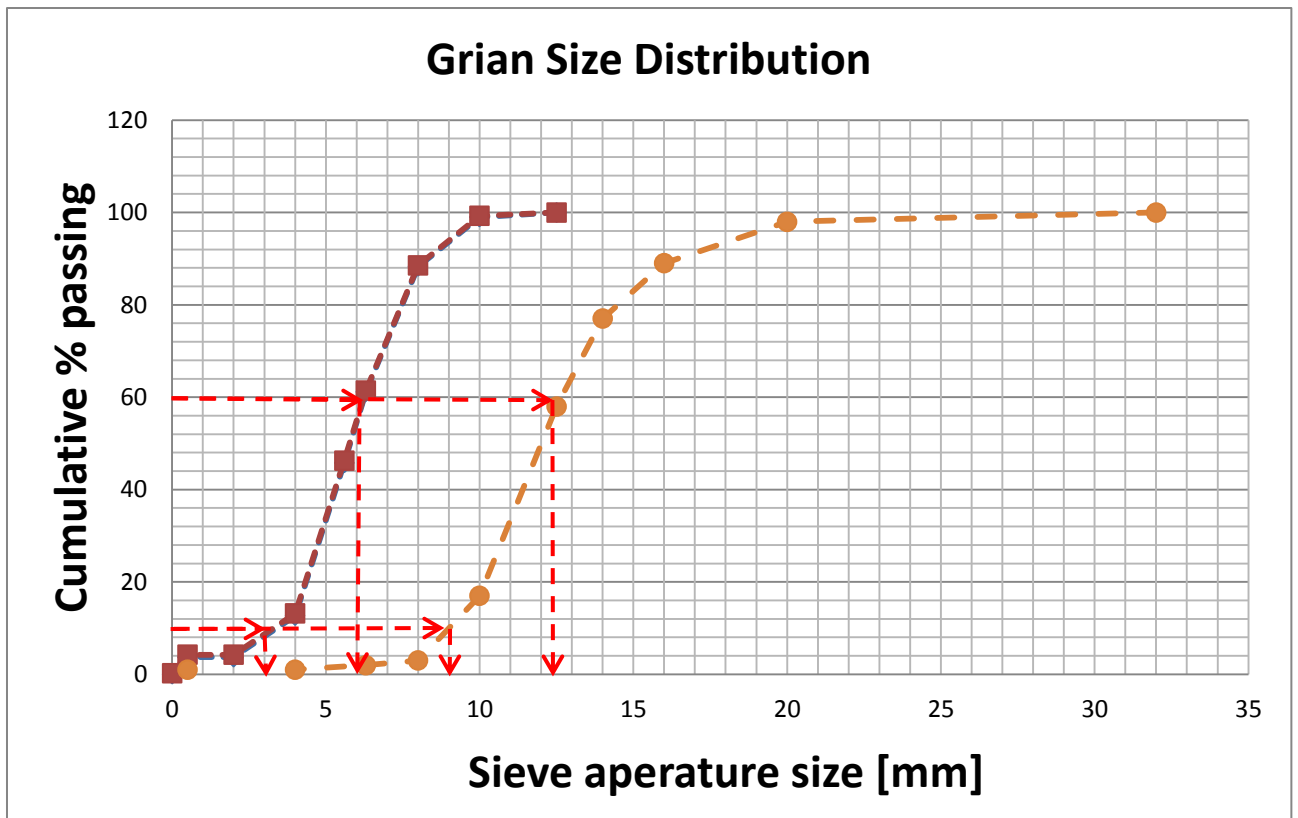


Figure 26. The sieving of Leca® 4-10mmC (red line) and of Leca® 10-20mmR (orange line) with arrows indicating 10 % and 60 % passing with corresponding grain size. [20]

5.1.3 The Saturated Hydraulic Conductivity

To determine a value for the saturated hydraulic conductivity it is necessary to measure the permeability of the material. Testing of the permeability of the two Leca® materials were performed according to the following procedure:

A 2 m long pipe with a diameter of 0,1 m was closed with a net in one end and then filled with a sample material. The other end of the pipe was thereafter also closed with a net and two 88° pipe bends were mounted, one on each end (see Figure 27). On one side a 1,3 m vertical pipe was attached.

Figure 28 shows an illustration of the experiment set up. Water was added on the left side where the vertical pipe was placed. The material in the horizontal pipe causes a resistance for the water flow and a potential, dH , is generated in the vertical pipe. When the water had passed through the material it flowed out into a bucket on the right side.



Figure 27. A test of the permeability being performed.

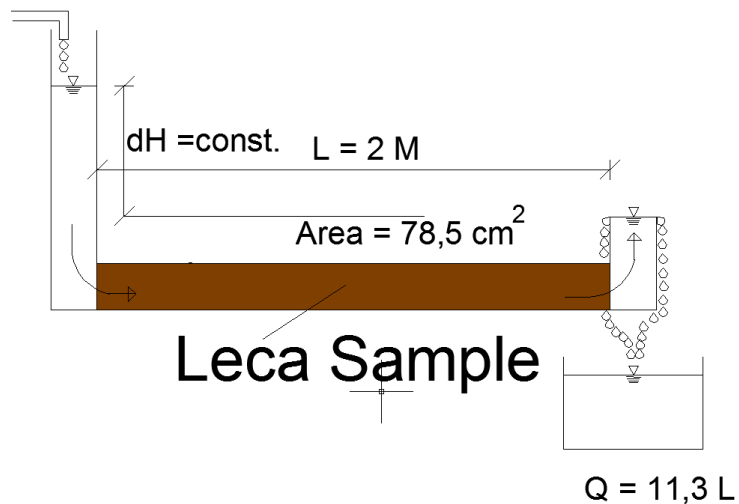


Figure 28. A sketch over the setup of the apparatus built for the experiment.

Before the measurements started, air bubbles formed on top of the sample in the horizontal pipe. Therefore water with a high potential was added in order to push out the air bubbles from the pipe. Not all air bubbles could be removed, some stayed inside the pipe.

The time to fill a bucket of a volume of 11,3 liter of water with different potentials, dH , was measured. The different potentials resulted in different time values. Thereafter the permeability was calculated according to the theory described in chapter 3.1.

The coefficient of permeability is the ratio between the flow rate, v , and the hydraulic gradient, i . The inclination of the dotted line in the figures are the assessed coefficient of permeability and is, as mentioned in earlier chapter, only valid for the linear laminar flow and not for the non-linear turbulent flow. Equation (3.3) is used to calculate the coefficient of permeability, k :

$$k = \frac{v}{i} \tag{3.3}$$

In Figure 29 the data bends off at the limit between the laminar flow and the turbulent flow for the two tests. The laminar flow section is assessed, for each and one of the tests, by the two dotted lines. On the right side, of the lines, the water flow is turbulent. The same methodology was used in Figure 30.

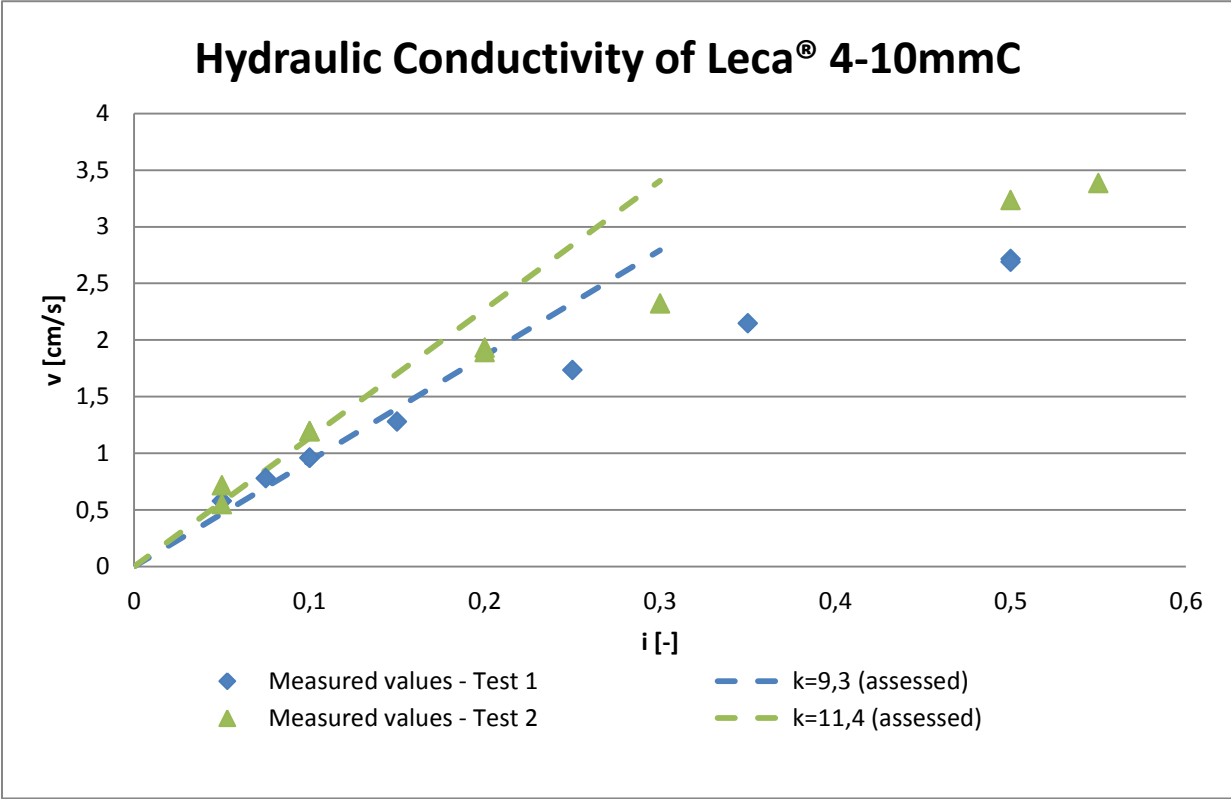


Figure 29. The plotted results from permeability test of Leca® 4-10mmC.

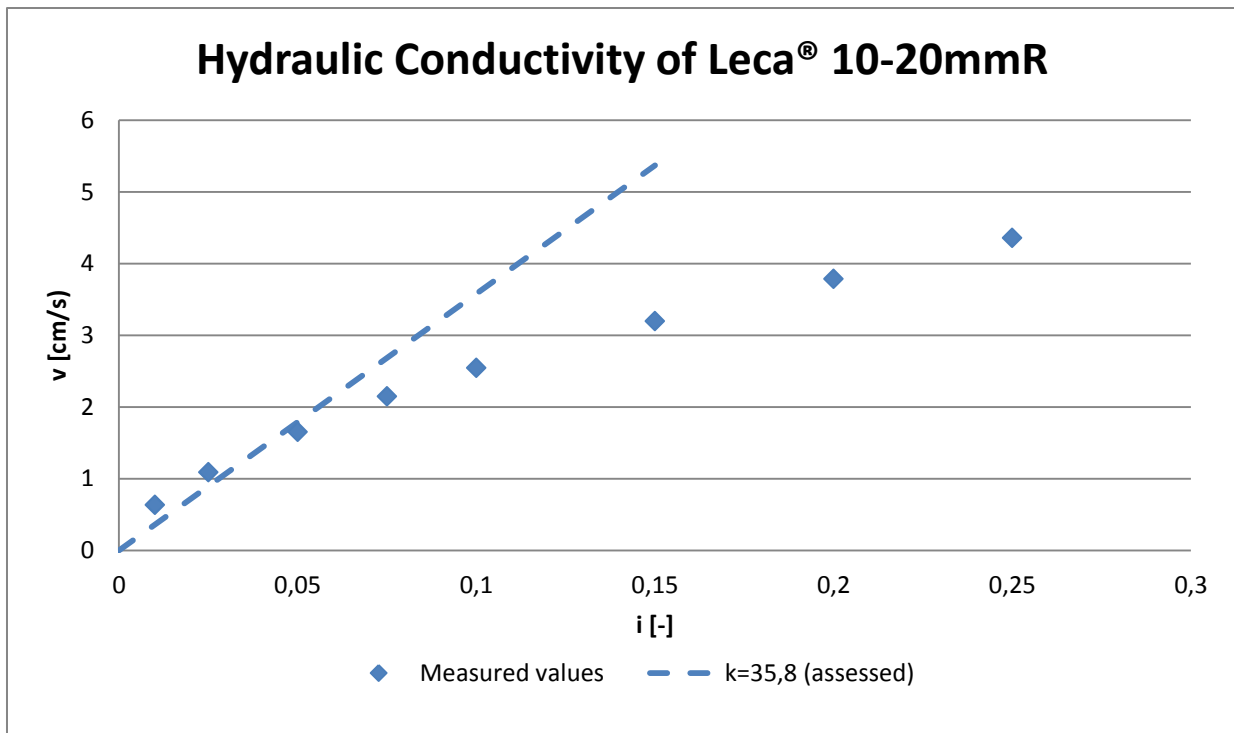


Figure 30. The plotted results from permeability test of Leca® 10-20mmR.

For the Leca®4-10mmC the coefficient of permeability was assessed to 11,4 cm/s and 9,3 cm/s. The results of the Leca®10-20mmR indicated a coefficient of permeability to 35,8 cm/s.

5.1.4 Residual Water Content

The residual water content has not been tested for neither of the two materials. In the user manual for SEEP/W a suggested value about 10-15 % of the materials porosity can be assumed, which was also actualized for both the Leca® materials.

The best estimate values for each and one of the parameters for the two Leca® materials is summarized in Table 12. The values presented in the table will be used as input data in the numerical model.

Table 12. The best estimate values.

	Leca® 4-10mmC	Leca® 10-20mmR
Saturated Water Content [m³/m³]	0,3	0,3
Diameter at 10% passing [mm]	3	9
Diameter at 60% passing [mm]	6	12,5
Saturated Conductivity [m/sec]	0,1	0,36
Residual Water Content [m³/m³]	0,05	0,06

5.2 Geometry of the Model in SEEP/W

The model geometry in SEEP/W was built up identical to the one used in the SINTEF laboratory experiment. Figure 31 shows how the material and equipment set up was drawn and simulated. The nozzles spreading the rain were reproduced as an inflow boundary condition, with a flux of 8×10^{-5} [m³/sec] over a length of 2 meters (corresponding to a rain event of 36 [L/m²] rain during 15 min). The sides and the bottom have impermeable boundaries and will be similar to the wooden crate, where no water is assumed to flow through. At the lower right corner there was a 10 mm opening between the black impermeable boundaries.

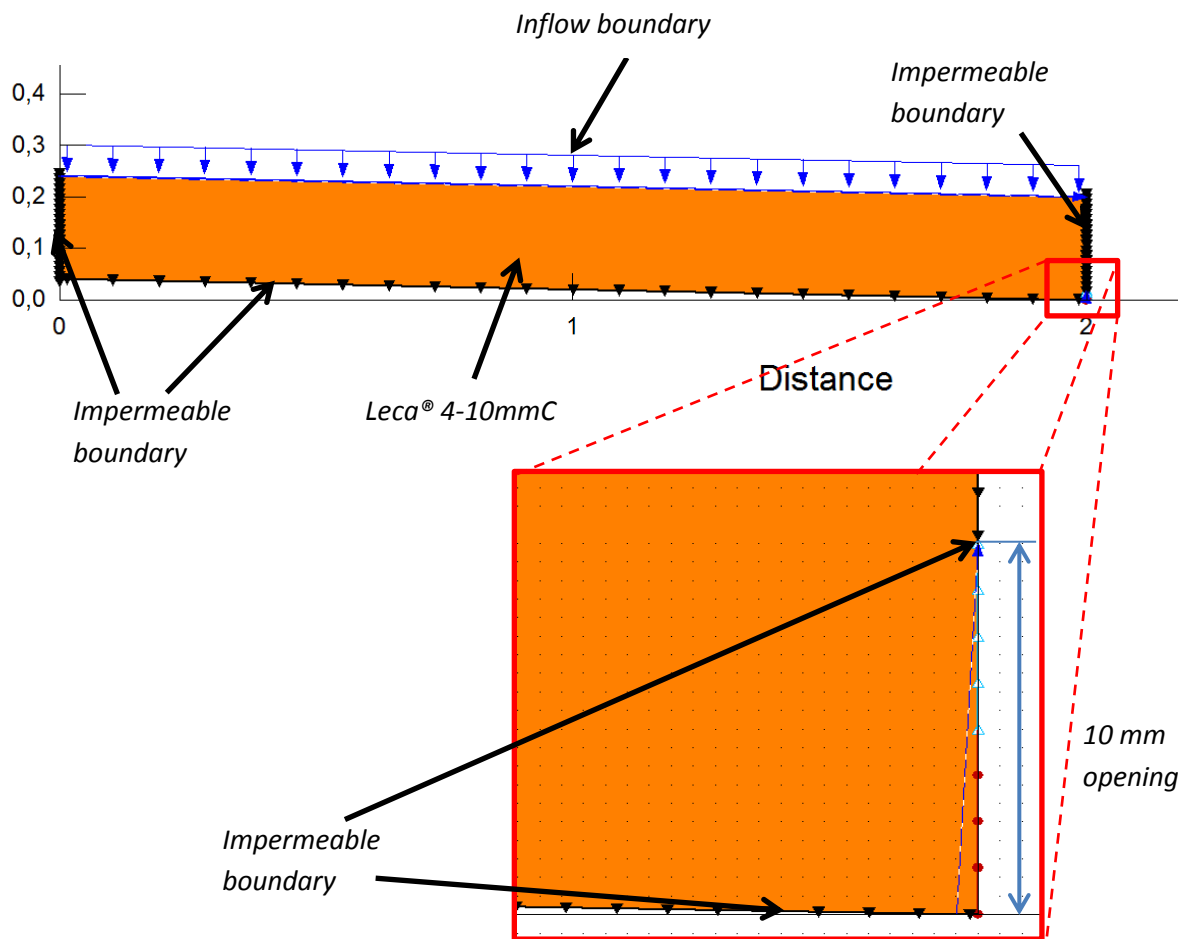


Figure 31. The geometry of SEEP/W model.

To simulate a scenario of a long period of precipitation followed by a stormwater event, an initial steady state phase of the water flow was created. In the steady state phase, the water runoff ($7,95 \times 10^{-5} \text{ [m}^3/\text{sec]}$) is equal to the inflow $8,03 \times 10^{-5} \text{ [m}^3/\text{sec]}$, see Figure 32, a condition which can be expected for a green roof drain layer exposed long lasting rainfall. The water flow behavior can be seen in the same figure. The vertical green lines are the flow paths through the material. They are vertical until few centimeters above the impermeable bottom boundary, where the flow paths bend and become more horizontal.

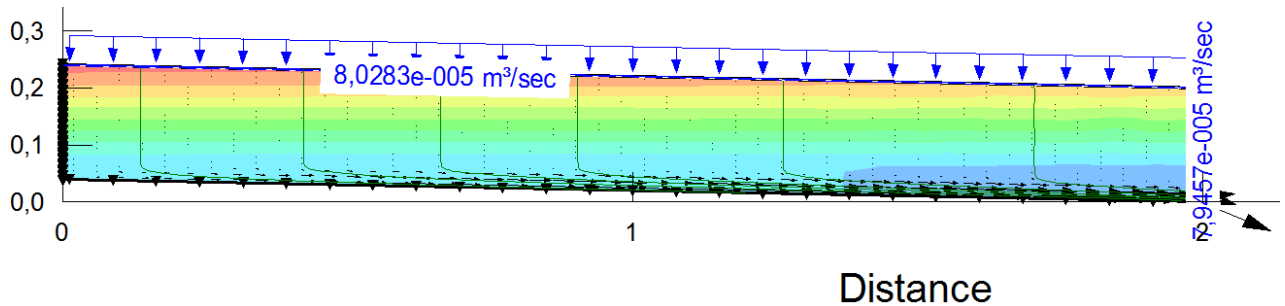


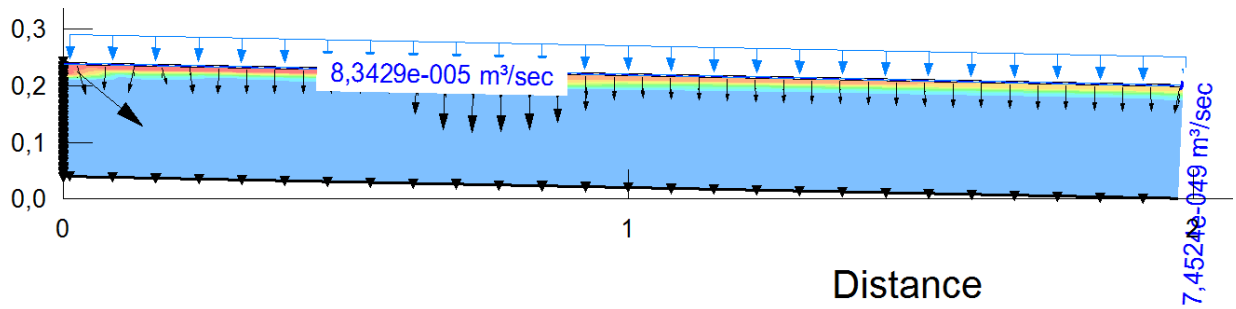
Figure 32. Steady state water runoff.

In the runoff experiment executed by SINTEF the material was left to drain until no more water runoff could be seen and thereafter a 15 minutes stormwater event was initiated. This procedure was reproduced by a second phase in the model, namely a transient phase. The difference between the transient phase and the steady state phase is that the user can define the duration in time for the transient phase. The user can also define when a boundary condition shall be initiated.

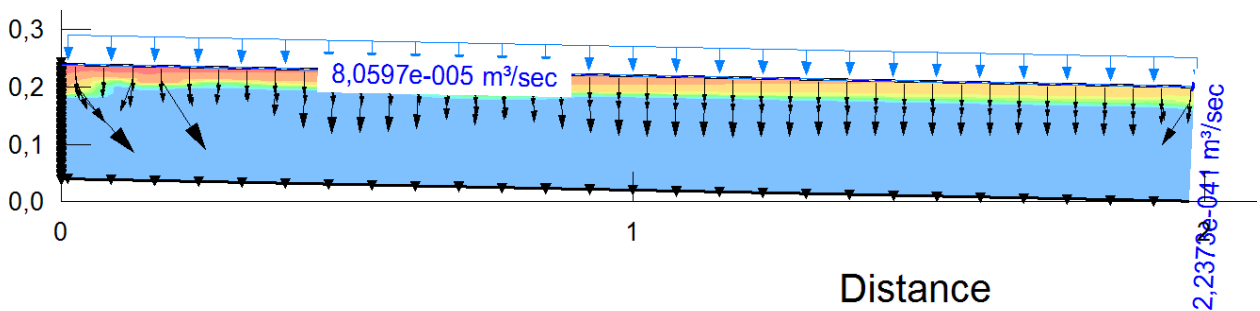
In the transient phase, for this back calculation, the rain (inflow boundary) was set to zero until a negligible runoff was reached. At that point the inflow boundary was turned on for 15 minutes and then followed by a drain period, where the inflow equal to zero. The flow vectors (black arrows) in Figure 33, visualize how the water penetrates down into the material during the first minute in the transient flow phase. The outflow is negligible for this time period (10^{-49} to 10^{-11}) [m^3/sec].

Figure 33. Visual results for the first minute of rain water penetration.

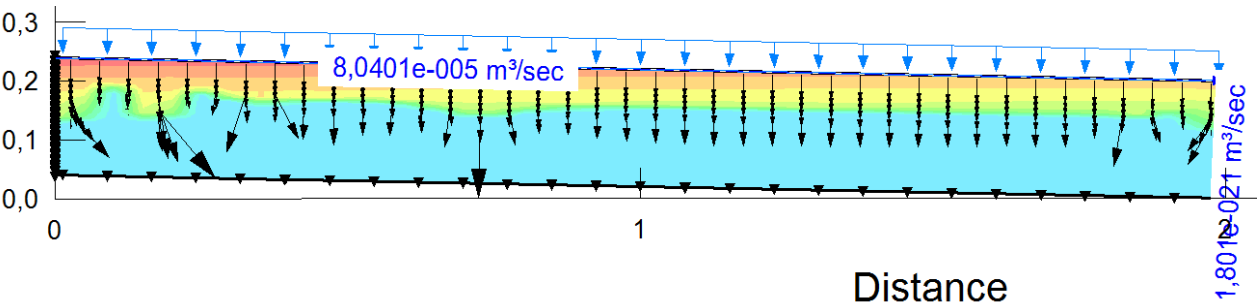
10 sec



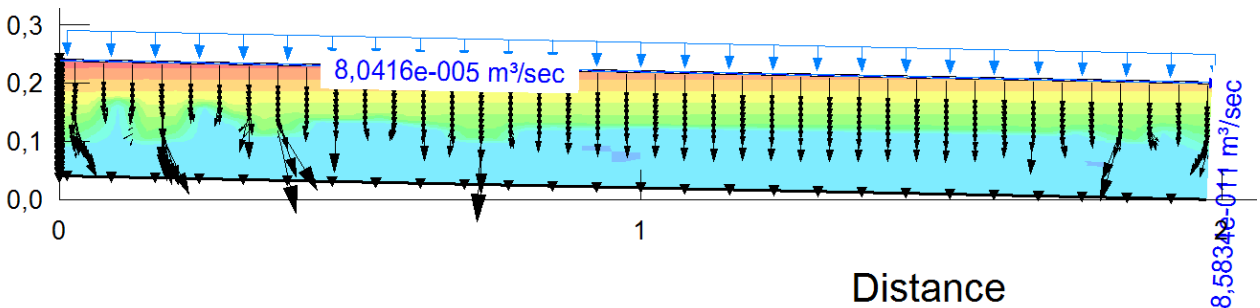
20 sec



40 sec



60 sec



The total water flow at all the nodes, see Figure 34, for the inflow boundary could be plotted versus time and presented in graphs. The same procedure was done of the nodes at the outflow boundary (the 10 mm opening). In SEEP/W it is also possible to plot cumulative water flow for the two boundaries. Two simulations were performed on each one and one of the Leca® materials, one with the layer thickness of 100 mm and the other with a 200 mm layer thickness.

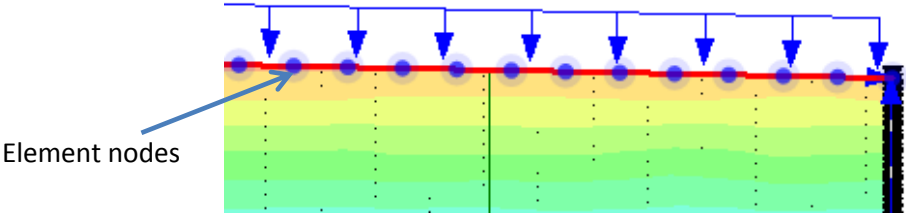


Figure 34. A example of element nodes displayed.

5.3 Results

The results from the numerical calculations by SEEP/W, Figure 35 to Figure 36, are placed on top of the results from the SINTEF laboratory experiment (same figures as in chapters 4.1.1 - 4.1.2).

5.3.1 Leca® 4-10mmC

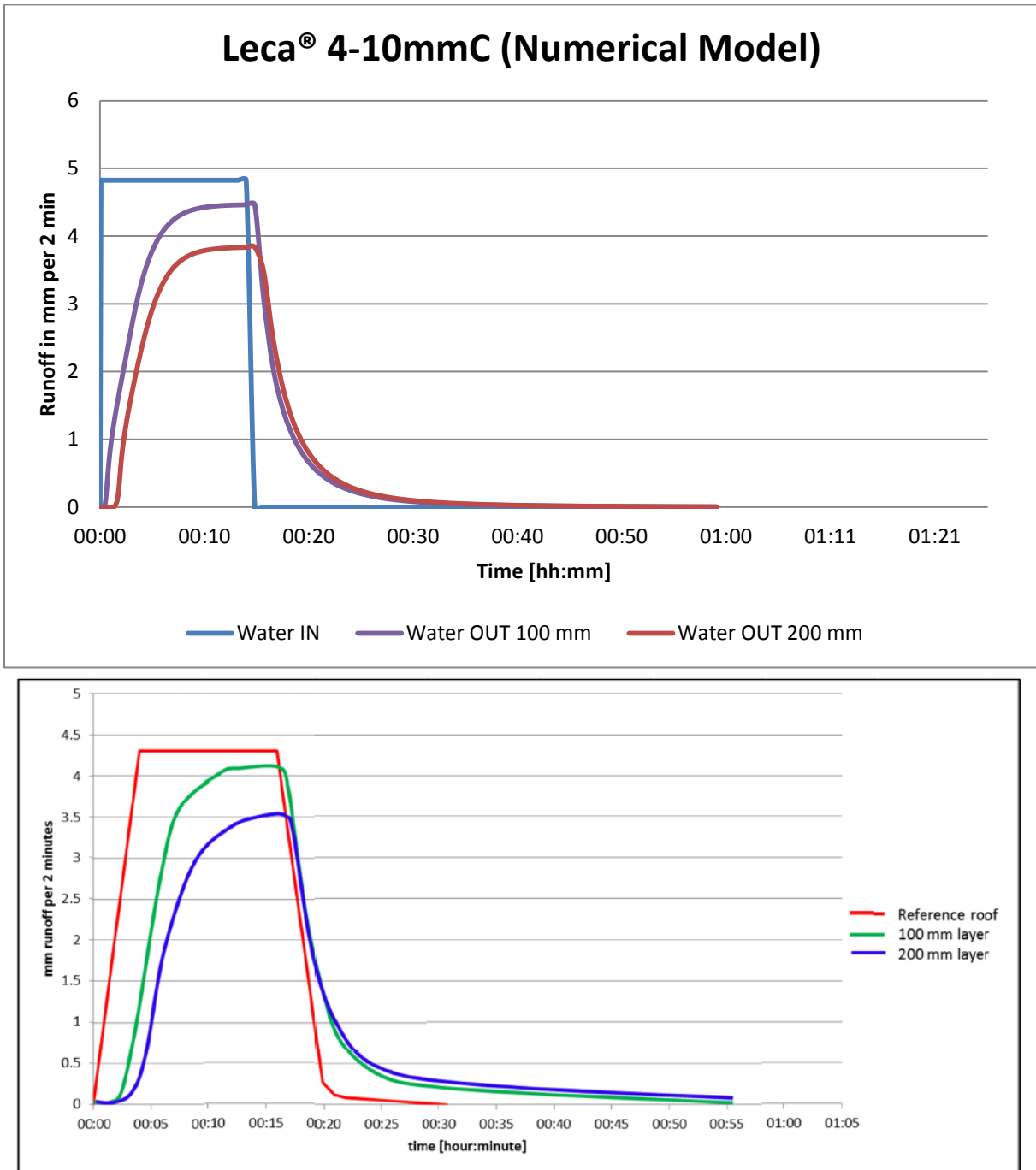


Figure 35. Presentation of the results from the numerical model at the top and the runoff data from laboratory experiment below for Leca® 4-10mmC.

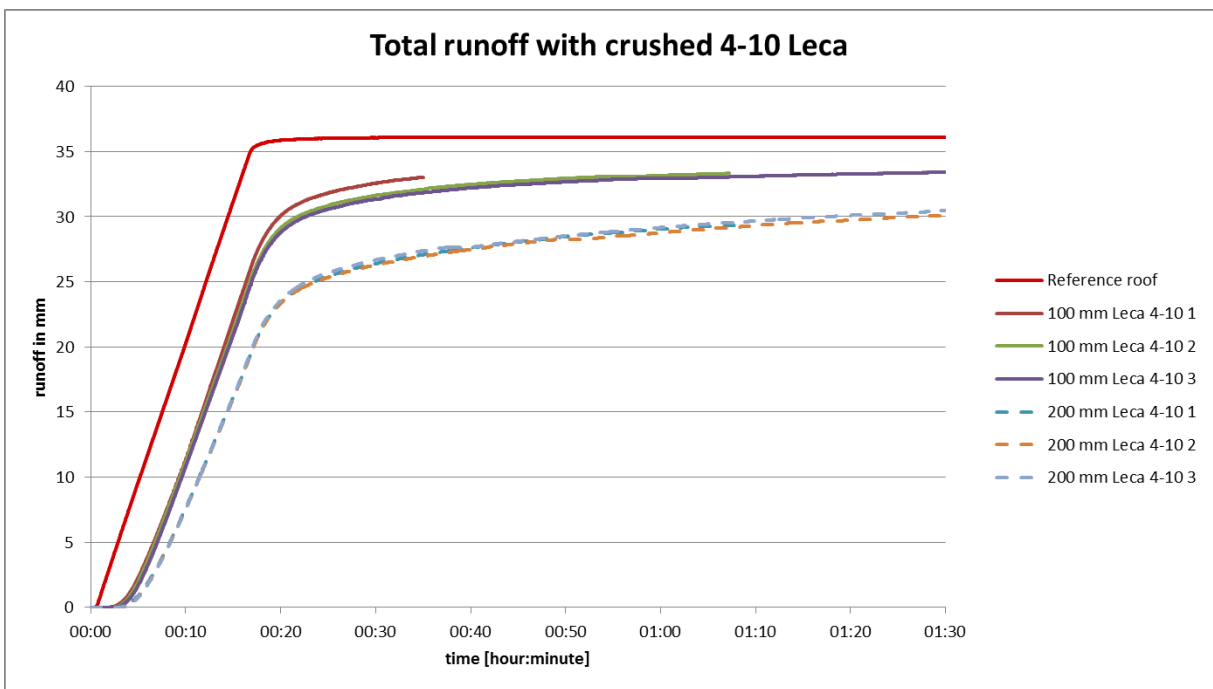
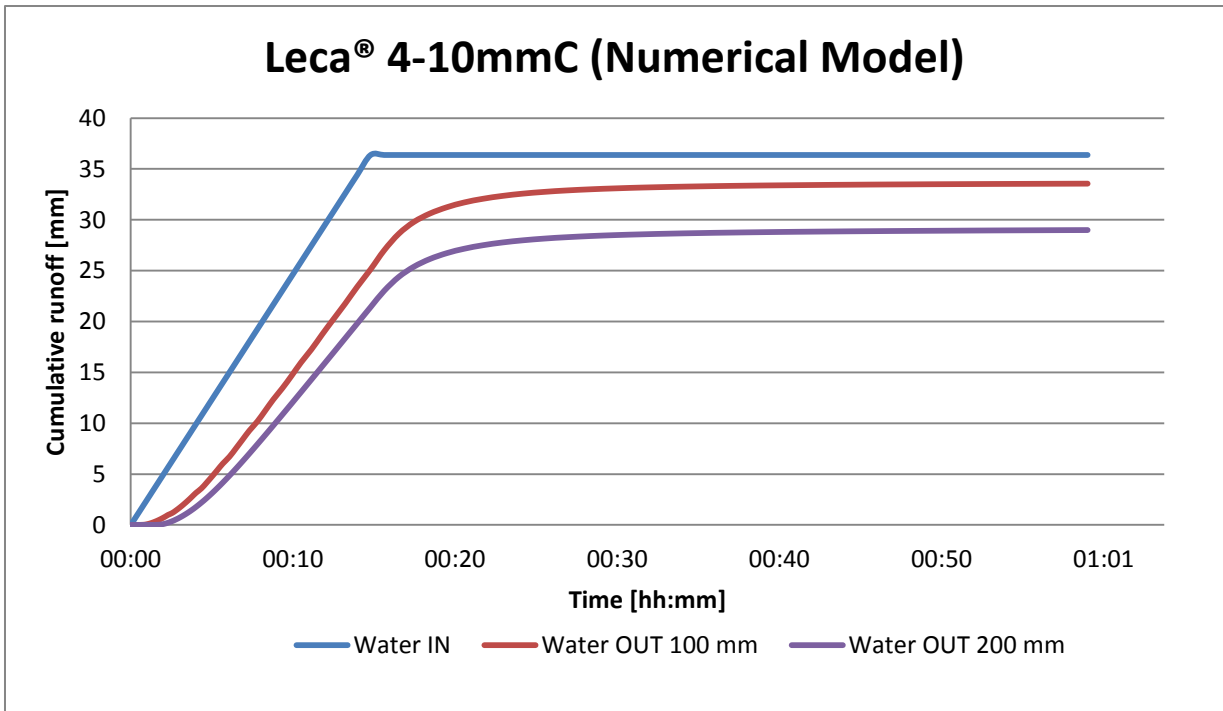


Figure 36. The cumulative runoff for Leca® 4-10mmC.

Four different characteristics have been compared between the numerical model and the laboratory test (Table 13). The four points are:

- Delayed start of runoff – The delay in time between the water runoff start from a reference roof without any material and the start of runoff from a Leca® material.
- Prolonged “main” runoff time – Extended runoff time compared to the reference roof.
- Runoff per time unit at 15 minutes – The water runoff per time unit at the end of the rain event, relative to the reference roof.
- Total runoff reduction – The difference in the cumulative runoff between the reference roof and the cumulative runoff from a Leca® material.

The definition of start of runoff has been set to a runoff of about 0.5 mm per 2 min (10^{-5} m³ per sec) and the stop of runoff (prolonged runoff) has been set to about 0.05 mm per 2 min (10^{-6} m³ per sec), the reason behind the definitions will be discussed later in this chapter.

Table 13. A summary of the results for Leca® 4-10mmC.

Leca® 4-10mmC	Numerical Model	Laboratory test	Numerical Model	Laboratory test
Layer thickness	100 mm	100 mm	200 mm	200 mm
Delayed start of runoff	~1 min	2 min	~2 min	2.5 min
Prolonged "main" runoff time	17 min	15 min	~17 min	17 min
Runoff per time unit at 15 minutes	92%	96%	79,5%	79%
Total runoff reduction	7,7 %	8 %	19,9 %	20 %

5.3.2 Leca® 10-20mmR

The results for the simulations and laboratory test of Leca® 10-20mmR, see Figure 37, Figure 38 and Table 14 are presented in the same way as for Leca® 4-10mmC.

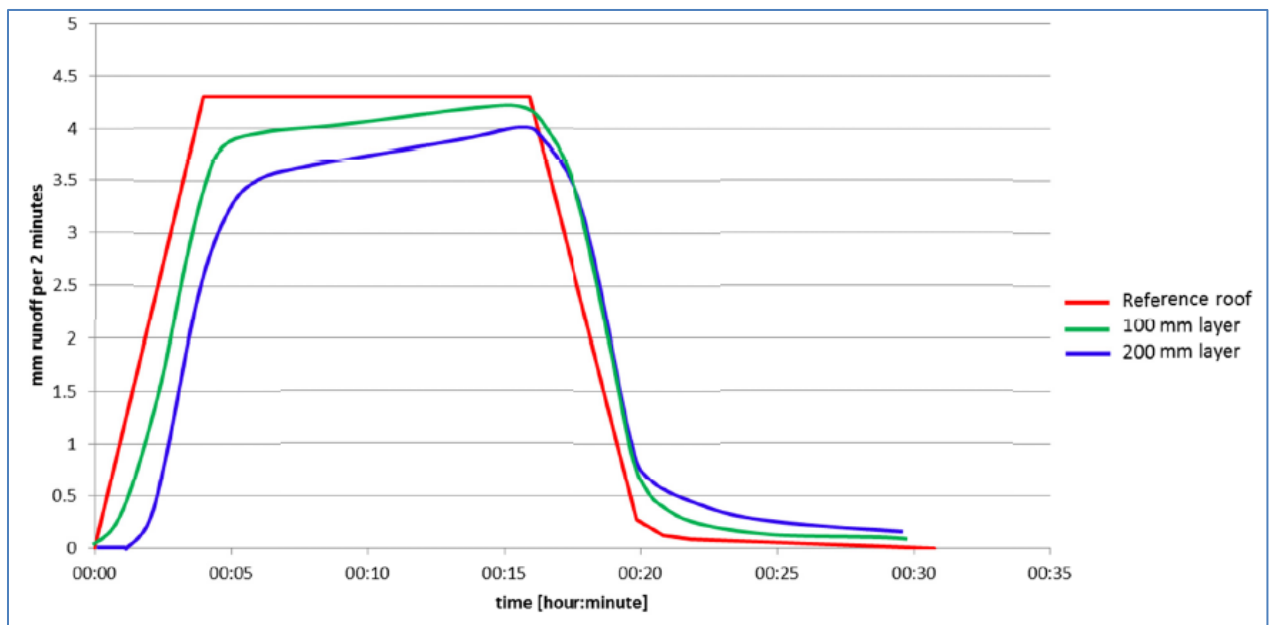
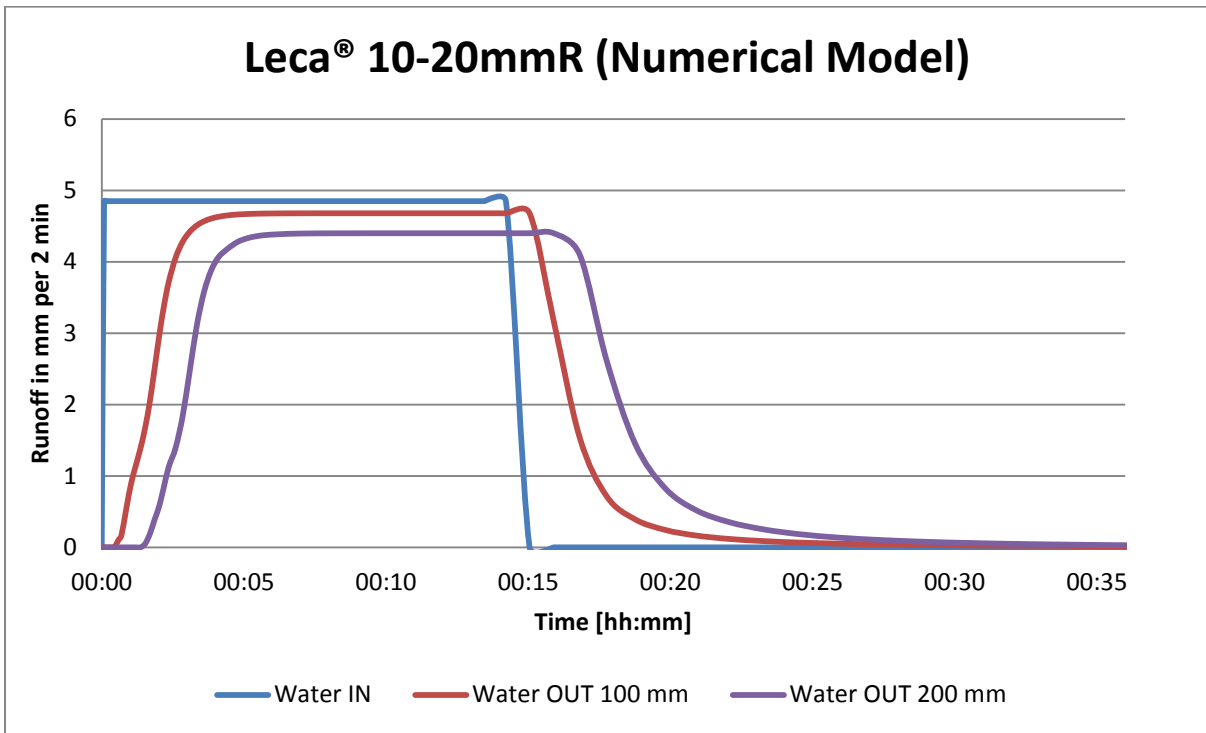


Figure 37. Presentation of the results from the numerical model at the top and the runoff data from laboratory experiment below for Leca® 10-20mmR.

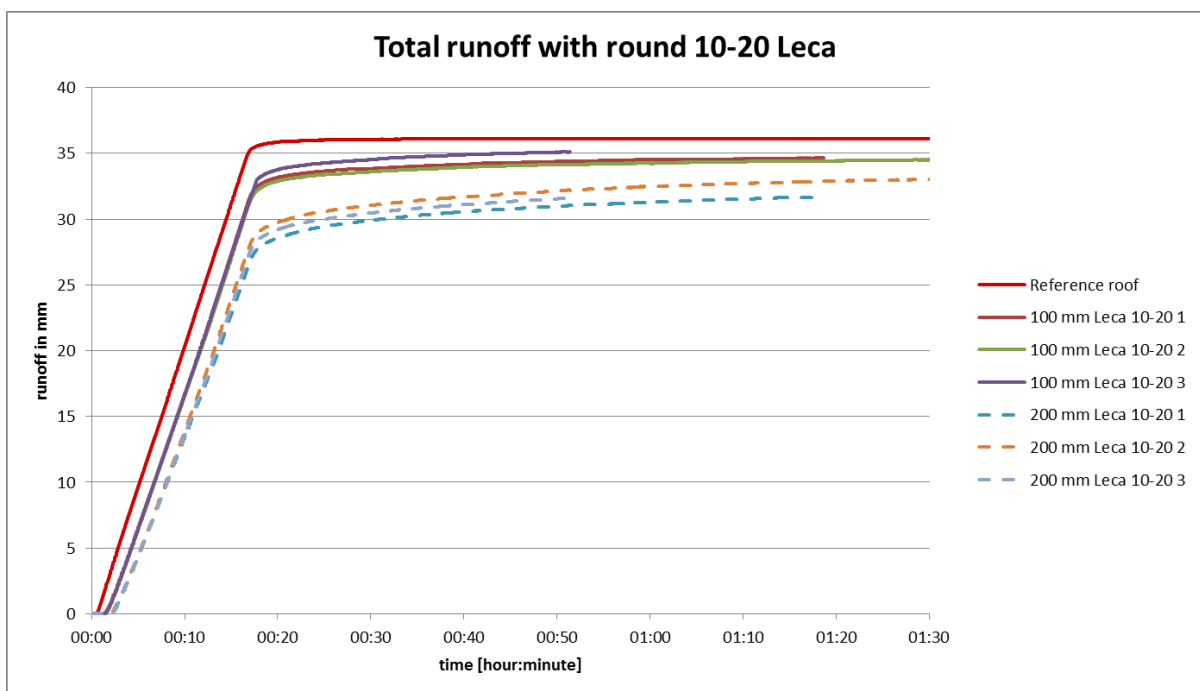
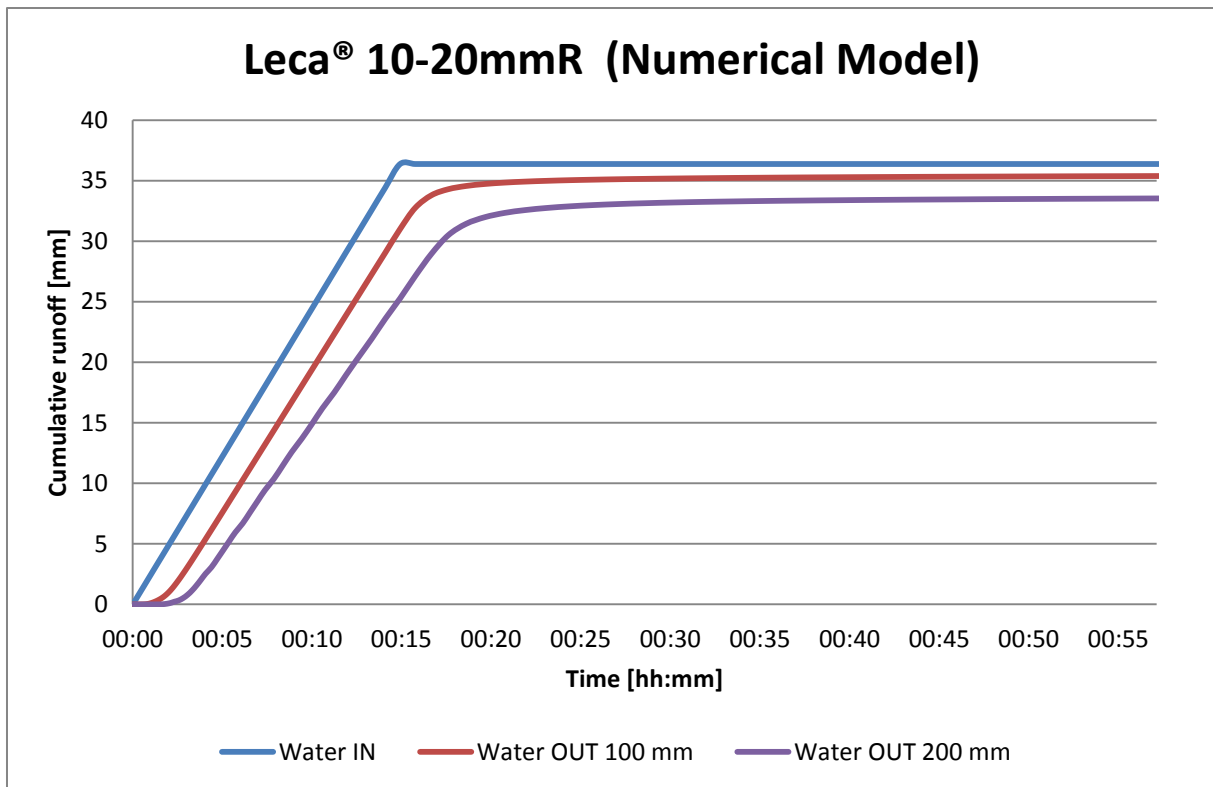


Figure 38. The cumulative runoff for Leca® 10-20mmC.

Table 14. A summary of the results for Leca® 10-20mmC.

Leca® 10-20mmR	Numerical model	Laboratory test	Numerical model	Laboratory test
Layer thickness	100 mm	100 mm	200 mm	200 mm
Delayed start of runoff	~1 min	1 min	~2min	1.5 min
Prolonged "main" runoff time	~4 min	Ca 3.5 min	~4 min	Ca 6 min
Runoff per time unit at 15 minutes	96,5 %	98 %	91,2 %	92%
Total runoff reduction	2,7 %	3 %	7,3 %	11 %

5.3.3 Discussion

Comparing the results (Table 13 and Table 14) from the numerical model and from the laboratory test, a good correlation can be seen for both materials but how to define start and stop of runoff is not very clearly. The reason is due to numerical issues and that zero values of water runoff, which would be good definitions of start and stop of runoff, are never given in SEEP/W. At the same moment a rain event has been applied over of the Leca® material, a runoff of the size $10^{-50} \text{ m}^3/\text{sec}$ will be given at the outflow section. No water flow is expected at this point due to the fact that the water particles require some time before reaching the outlet; nevertheless a water flow is given. The reason is that zero values are not wanted in the equations performed in the numerical calculations. When division is performed in the equations, if the numerator or the denominator is equal to zero, parts of an equation can become equal to zero or a singularity can arise which can cause a progressing error in the iterations.

The same size of the values (10^{-50}) will be found at the final part of the runoff graphs and the runoff acts as an asymptote towards zero. That is why a definition of start and stop of runoff is needed.

In Figure 39 and Figure 41 the results from the laboratory experiment and numerical modeling are placed in the same graph. When comparing the runoff results in these figures, the results seem to deviate more than in Table 13 and Table 14. In these tables the runoff has been related to the reference roof in the laboratory test and Water IN flow for the numerical model.

A cause for the shift in time and size between Water IN and the reference roof, is the fact that in the laboratory experiment it was the runoff *from* a roof that was measured not the amount of water added *on* the roof, which is the case for the numerical model. The runoff cannot be turned on and off like a simulated rain event. This is the reason for having some lag and more distributed runoff for the reference roof.

By studying the cumulative runoff, see Figure 40 and Figure 42, it can be observed that the water volumes are the same, 36 mm going in, for the laboratory test and the numerical model. The dotted lines (results from the numerical model) and the solid lines (results from the laboratory experiment) converge good on a straight line at 36 mm. This means that the area under the reference curve is equal to the area under the Water IN curve in Figure 39 and Figure 41.

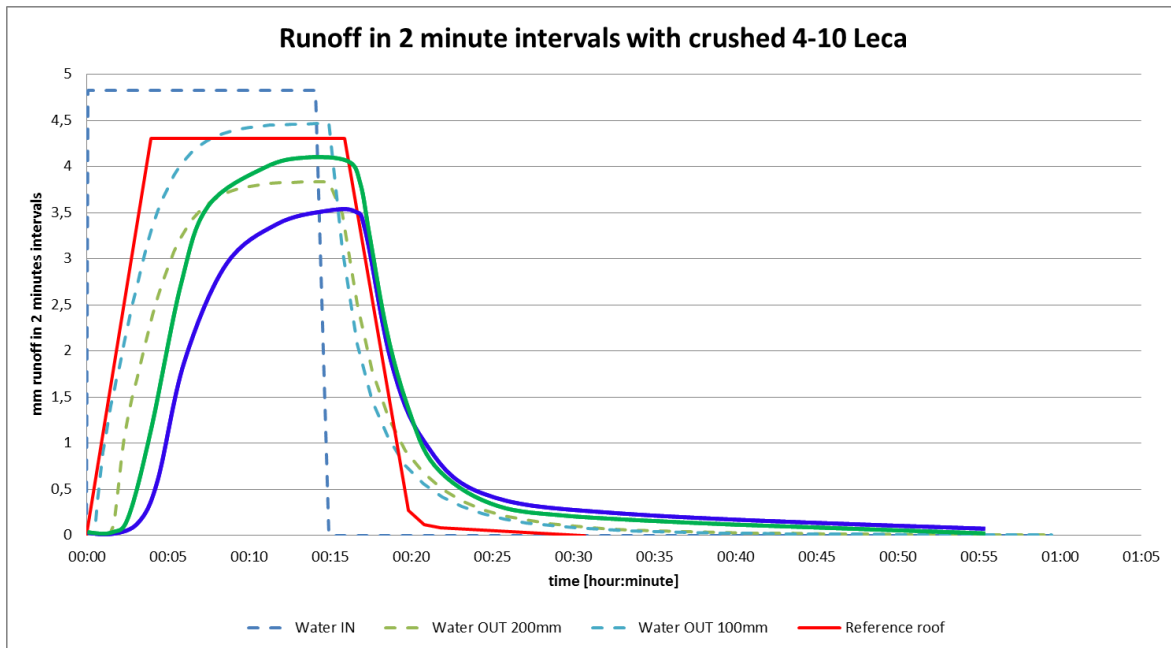


Figure 39. The numerical results (dotted) and laboratory results (solid lines) for Leca® 4-10mmC.

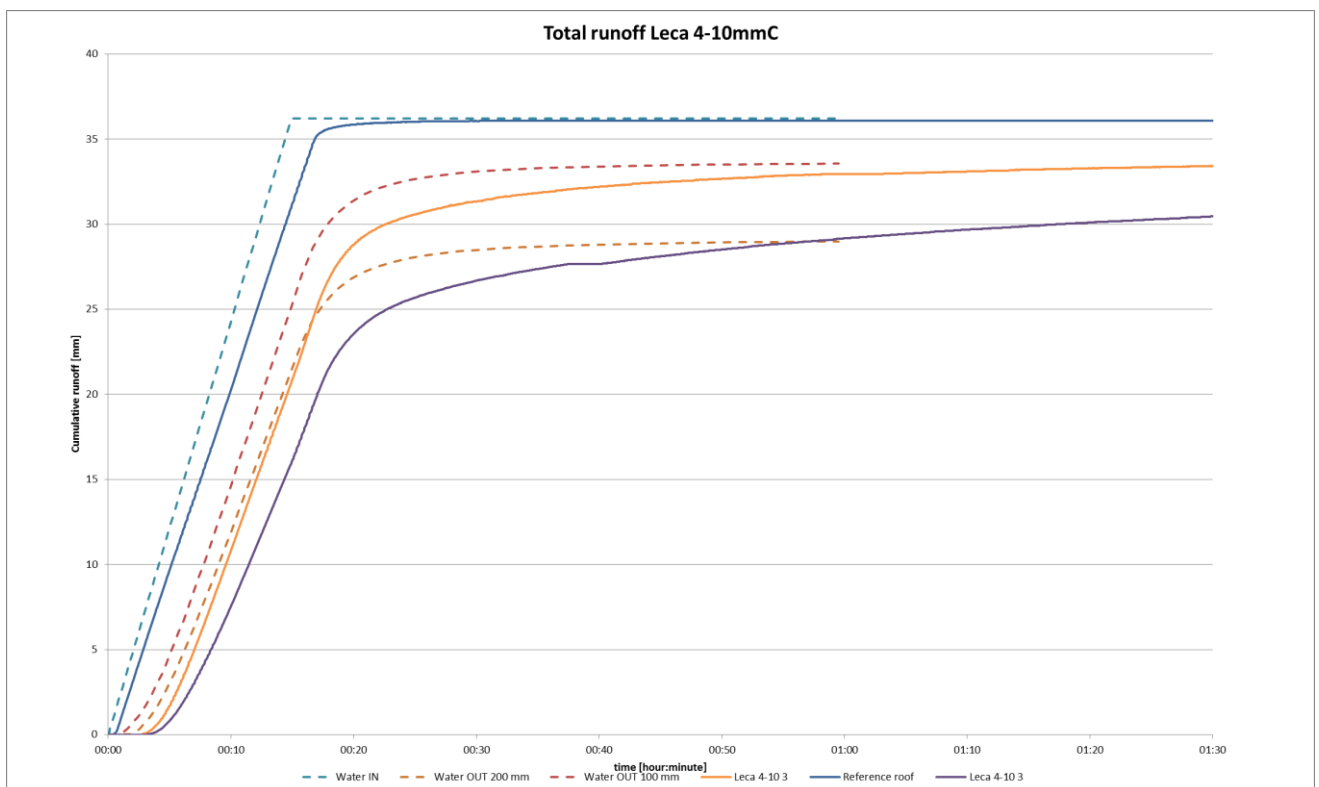


Figure 40. The cumulative runoff results in the same graph (Leca® 4-10mmC).

It seems as if the different phases (start of runoff ect) occurs earlier in the numerical model in comparison with the laboratory model. This could have something to do with the surface area. The rather large surface area for the Leca® material is not considered in SEEP/W. Surface area is not an input parameter but should affect the results. If water particles need to get around a particle with a large area, that will require more time than if the water particles need to pass a perfect round particle with a rather small surface area.

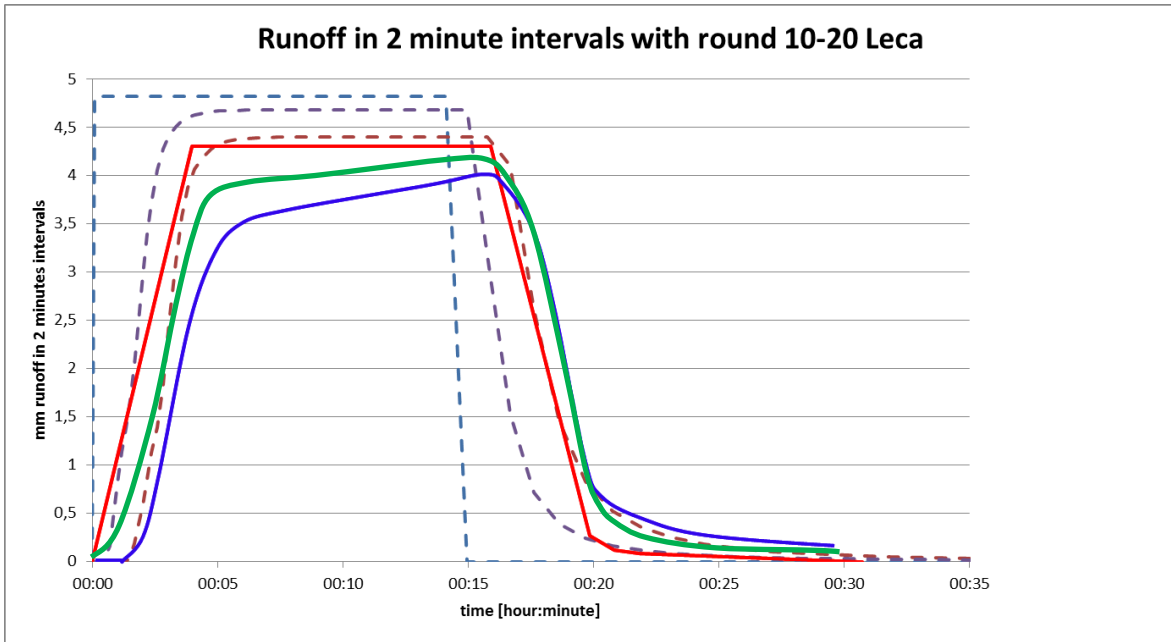


Figure 41. The numerical results (dotted) and laboratory results (solid lines) for Leca® 10-20mmR.

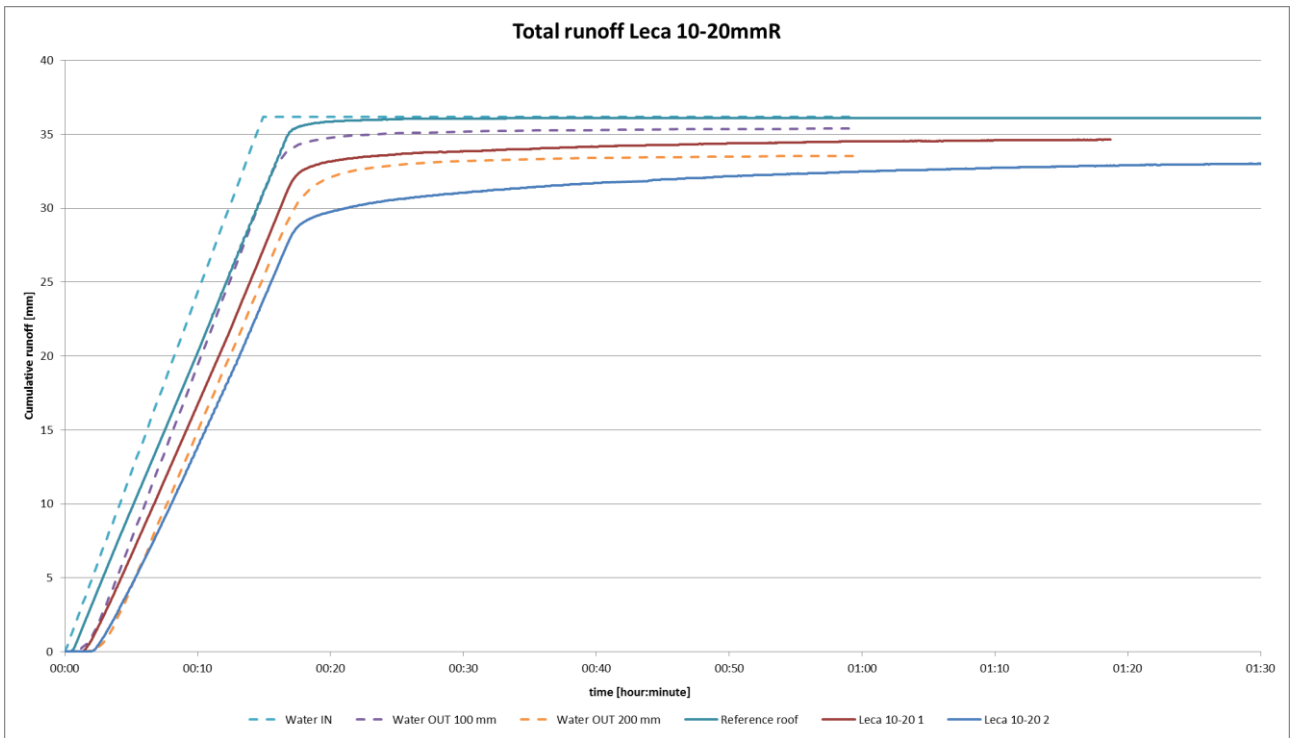


Figure 42. The cumulative runoff results for Leca® 10-20mmR in the same graph.

It should also be remembered that it is an unsaturated water flow that is attempted to be back calculated and to simulate a highly non-linear water flow, which unsaturated flow is, can be very complicated and this is a reason that the results do not match perfectly (Figure 39 and Figure 41).

6. Modeling of Ideal Green Roof Drain Layer

After the back calculation operation in SEEP/W, the model was scaled up to a reasonable ideal case roof and exposed for a rain event with another shape (different intensity and duration). This section will describe the simulation of an "ideal roof", assumptions made, results and finish with a input parameter sensitivity analysis.

6.1 The Model

The geometry of the ideal drain layer is similar to the geometry of the model created for the back calculation of the SINTEF water retaining experiment. The distance was changed from 2 m to 10 m and the inclination was altered from 2 % to 2.5 %. The geometry to the right of the model was also adjusted. In the back calculation model, the drain outlet was design as a 10 mm gap between the bottom of the roof and the cornice around the 2x2 m wooden casket. In the ideal case roof the geometry and drain outlet was assumed from Figure 43. The recommended minimal slope is 1:40, which corresponds to 2.5 % inclination and the longest drain path was set to be 10 m, see Figure 44.

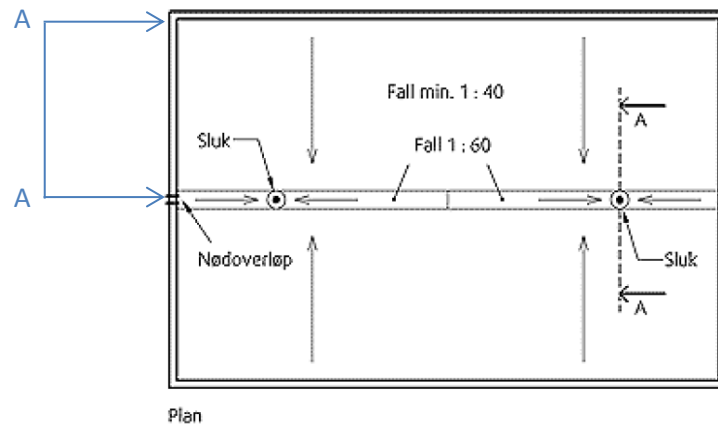


Figure 43. An example of a roof showing the recommended minimal slope of a roof (1:40). [5] p.30

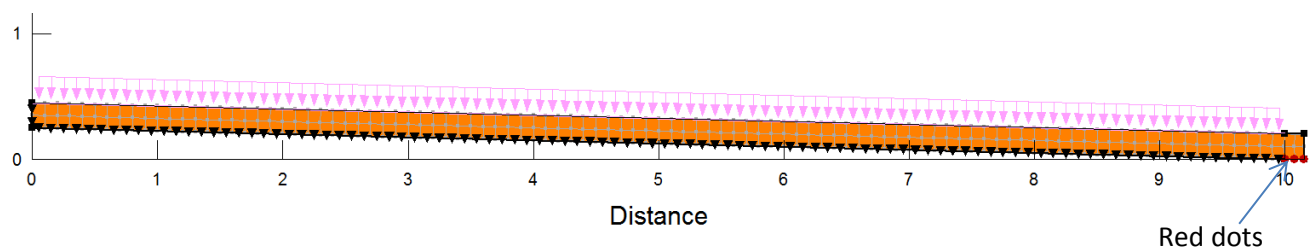


Figure 44. The 200mm thick drain layer in the profile A-A of Figure 43.

The boundary conditions are similar to the back calculation model with impermeable boundaries (black triangles) to the left and at the bottom of the orange Leca® 4-10mmC material. The red dots to the right are the drain boundary condition where the total hydraulic head is set to 0 m. The pink connected arrows pointing downward on top the Leca® material is the boundary representing the chosen rain event. The shape and intensity of the rain event is the same as the precipitation which occurred in the experiment performed by B.C.Braskerud (chapter 2.4.2, dotted line Figure 7).

The material properties used in the calculations was the best estimate values given from the back calculations. Two different Leca® materials were used in the back calculations but in the model of the ideal drain layer a third “material” was added in order to represent the response from a reference roof, similar to the reference roofs described in projects in the chapters 2.4.1 and 2.4.2, which simply consist of a roofing membrane. The two Leca® materials were simulated with 200 mm thickness and the “membrane material” with a 1 cm thickness. The input parameters for each and one of the materials are shown in Table 15.

Table 15. A summary of the input parameters for the three materials.

Parameter	Leca® 4-10mmC	Leca® 10-20mmR	Membrane (Ref. Roof)
Saturated water content (porosity) [m3/m3]	0,3	0,3	0,2
Diameter at 10% passing [mm]	3	9	1
Diameter at 60% passing [mm]	6	12,5	6
Saturated conductivity [mm]	0,1	0,36	0,5
Residual water content [m3/m3]	0,05	0,06	0,03

The calculations were divided into an initial steady state phase followed by a transient phase, analogous with the methodology in the back calculation, in order to perform simulations of a storm water event on a saturated material. The duration of the rainfall was set to about 40 minutes, with two peak values. The reason of choosing a rain event with dual peaks is to study the response for each and one of the peaks and especially the second peak when the material has high water content. The result of the water runoff for each and one of the three simulations is plotted in Figure 45, together with the rain event.

6.1.1 Results

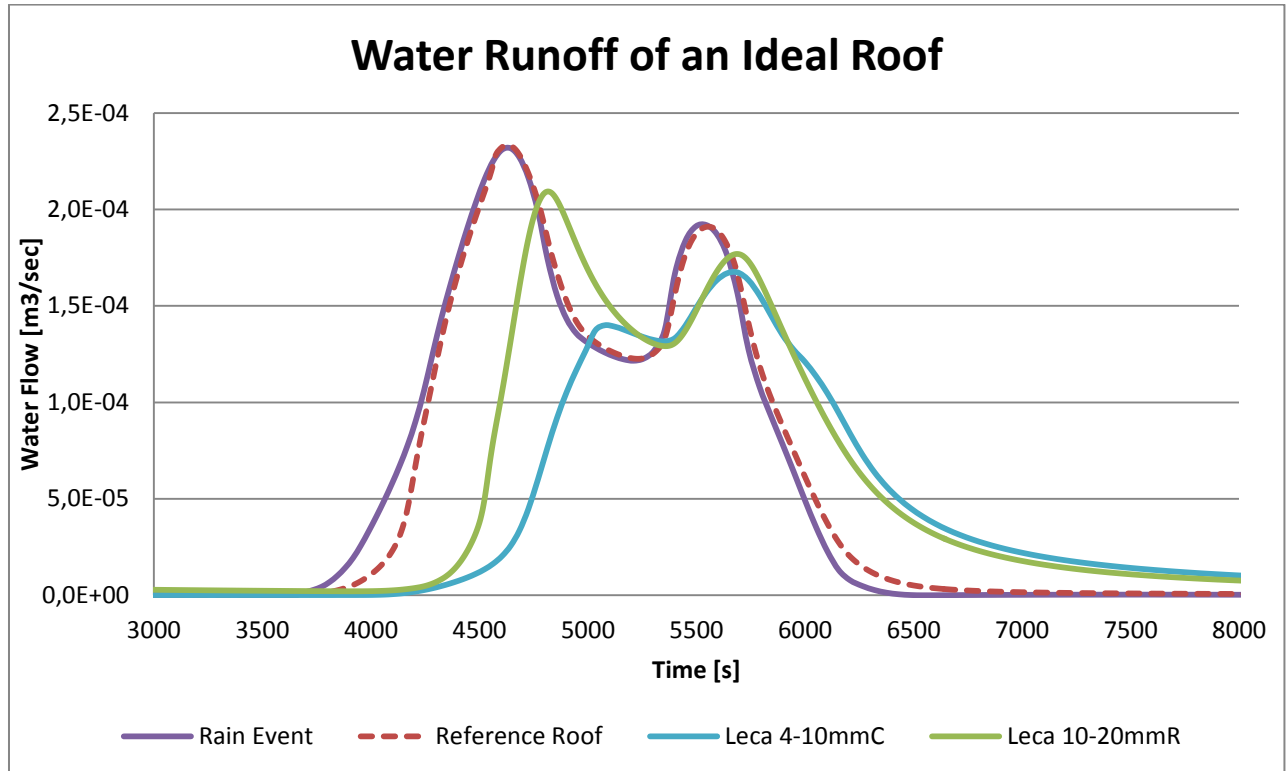


Figure 45. The results from the three simulations.

Three sections in Figure 45 have been compared for the three simulations and can be seen in Table 16. The sections are labeled as:

- Start of runoff – The first point in time where the runoff increases.
- First peak – The first maximum point in time.
- Second peak – The second maximum point in time.

The start of runoff has been defined as the point in time when the water flow at moment of time, X_n , is greater than the water flow in the time step before, X_m , [$X_m < X_n$].

Table 16. A summary of the results.

	Leca® 4-10mmC	Leca® 10-20mmR	Reference Roof
<u>Start of runoff</u>			
Time Lag [Sec]	71,6	320	50
<u>First Peak</u>			
Peak Rain/Peak Runoff	60,06 %	89,82 %	100,15 %
Reduction	39,94 %	10,18 %	-0,15 %
Time Lag [Sec]	457,8	200	10
<u>Second Peak</u>			
Peak Rain/Peak Runoff	86,71 %	91,66 %	98,98 %
Reduction	13,29 %	8,34 %	1,02 %
Time Lag [Sec]	149,6	150	10

6.2.1 Discussion

The studied rainfall is not an extreme rain event but has occurred and it is interesting to study the water runoff response. In Table 16, the start of runoff has been set to 72 sec for Leca® 4-10mmC and 320 sec for Leca® 10-20mmR. When studying Figure 45 the start of runoff seems to occur more or less at the same point in time. However, the definition of start of runoff seems to be reasonable, and the reason could be numerical problems in the model that leads to that the runoff goes up and down. The start of runoff appears reasonable for reference roof and for Leca® 4-10mmC but not for 10-20mmR. A visual inspection of Figure 45 for finding the wanted point for the start of runoff maybe better for Leca® 10-20mmR but less precise.

The ideal case roof simulations resulted in a 40 % reduction of the water runoff for Leca® 4-10mmC and 10 % for Leca® 10-20mmR. Compared with the back calculation of the laboratory experiment, the runoff reduction were 10 % for Leca® 10-20mmR and 20 % for Leca® 4-10mmC. In the Ideal roof simulation a similar ratio, between the two materials, was expected. It is difficult to say if it is the Leca® 10-20mmR that does not reduce the runoff enough or if it is the 4-10mmC that reduces too much. A reason why the water runoff ratio is not the same in the two simulations, could be that shape of the rain events are not that similar for the ideal case roof and the back calculation. In the back calculation rain is more intense and constant and in the ideal case it is less intense and fluctuates.

Another issue is the water runoff from the reference roof (100,15% runoff), see Table 16, which is higher than the maximum input value for the rain. A reason could be that the rain values (Water IN) in the rain function is given as point values and that SEEP/W smoothen out the values, see Figure 46.

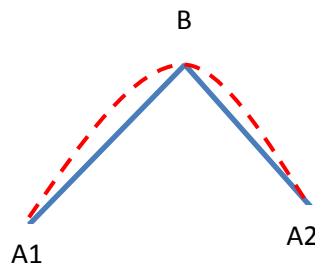


Figure 46. The figure show a simplification of the rain function, at the first peak, in SEEP/W.

A1, A2 and B are input values in SEEP/W for the rain intensity. A1 and A2 have the same water flow value but at different point in time and point B is in the middle and is the given peak value of the rain fall. A function in SEEP/W smoothen out the curve (red dotted line) resulting in slightly higher peak value then the given input data point value and the reduction of water runoff is related to the given input value of the rain fall. However this is not an issue which needs to be considered, 100,15% is about 100%.

SEEP/W is created to simulate water flow in a porous material and not surface water flow on top of a material, this causes issues when attempting simulating a reference roof. For simulating the surface water flow on a reference roof, a porous material was needed in order to perform the calculations. The membrane material input values, see Table 15, is assumed values. In order to establish the assumed values the response were studied for different input data values for the reference roof and compared with Baskerud project (chapter 2.4.2). About the same time lag for the start of runoff and prolonged runoff was successfully acquired but not the same runoff reduction. Braskerud got a considerable water runoff reduction from his reference roof which was not obtained from the numerical reference roof. A roof membrane can absorb little water, so the water runoff reduction of the reference roof, in Baskerud project, can be questioned.

In the second runoff peak less difference between the two materials can be observed. At this point the water content is high and the saturated hydraulic conductivity influence the water flow, which can be seen in sensitivity analysis.

6.2 Sensitivity Analysis of the Input Parameters

The analysis was conducted by changing the best estimate parameters, individually, with +/-10% and +/-20% (both increase and decrease the parameters) and run a simulation each time a parameter was altered. By changing the input parameters one by one it was possible to study which parameter that influence the water runoff the most. The results can be seen in Figure 47 to Figure 51. The same parameter study were performed on Leca® 10-20mmR and the results can be seen in the Appendix A.

The point or sections that will be studied is the first peak, second peak and water runoff about 30 minutes after the rain has stopped (8000 seconds). After the rain fall has stopped the different runoff curves coverage more and more and the point 8000 seconds seem to be suitable point for evaluation.

Figure 47. Decrease and increase of the porosity.

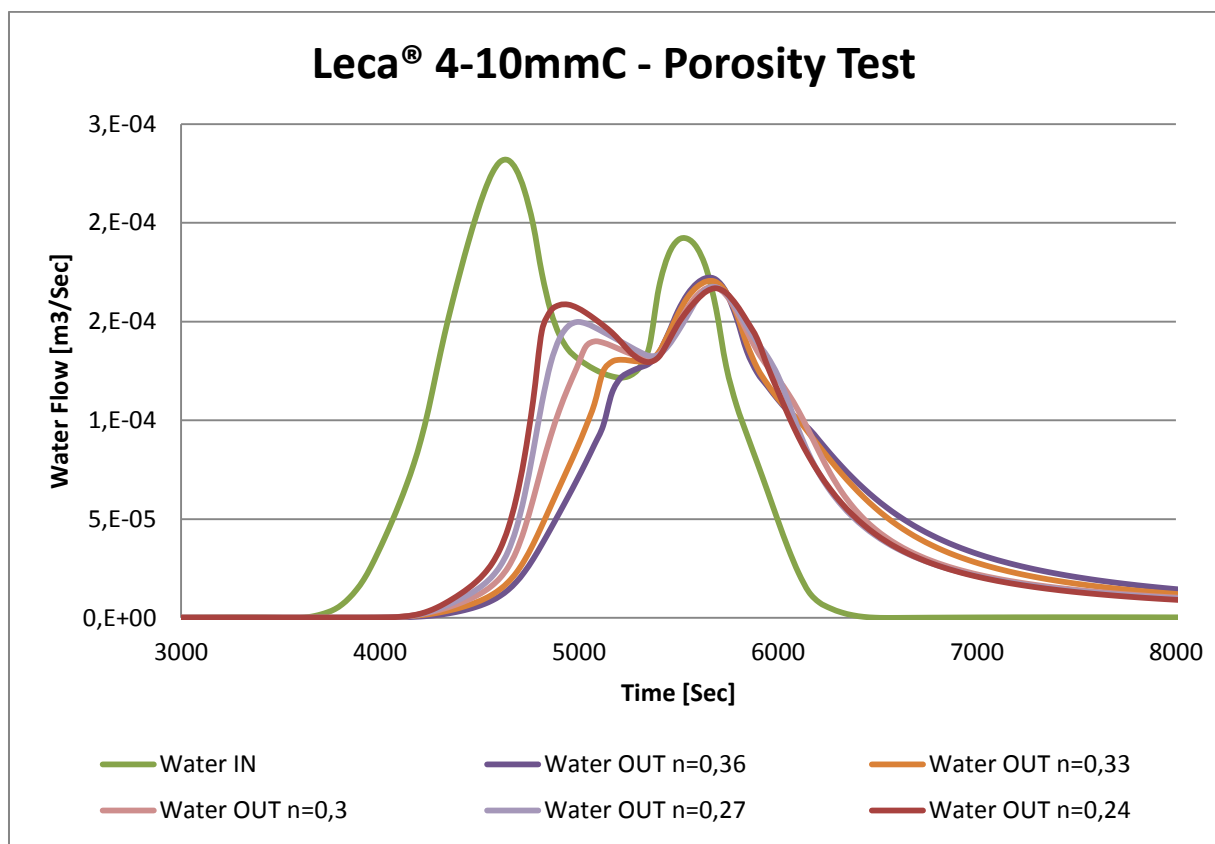


Figure 48. The result from variation of the D10 input parameter.

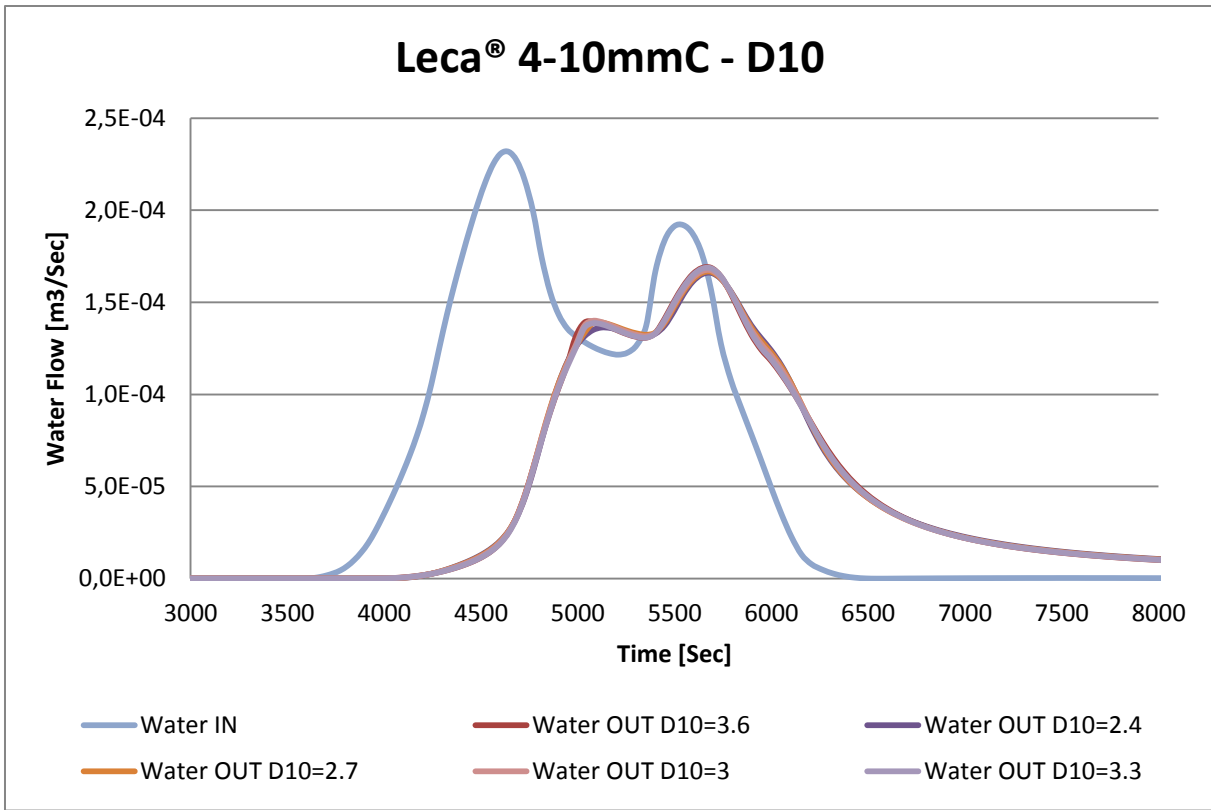


Figure 49. The result from variation of the D60 input parameter.

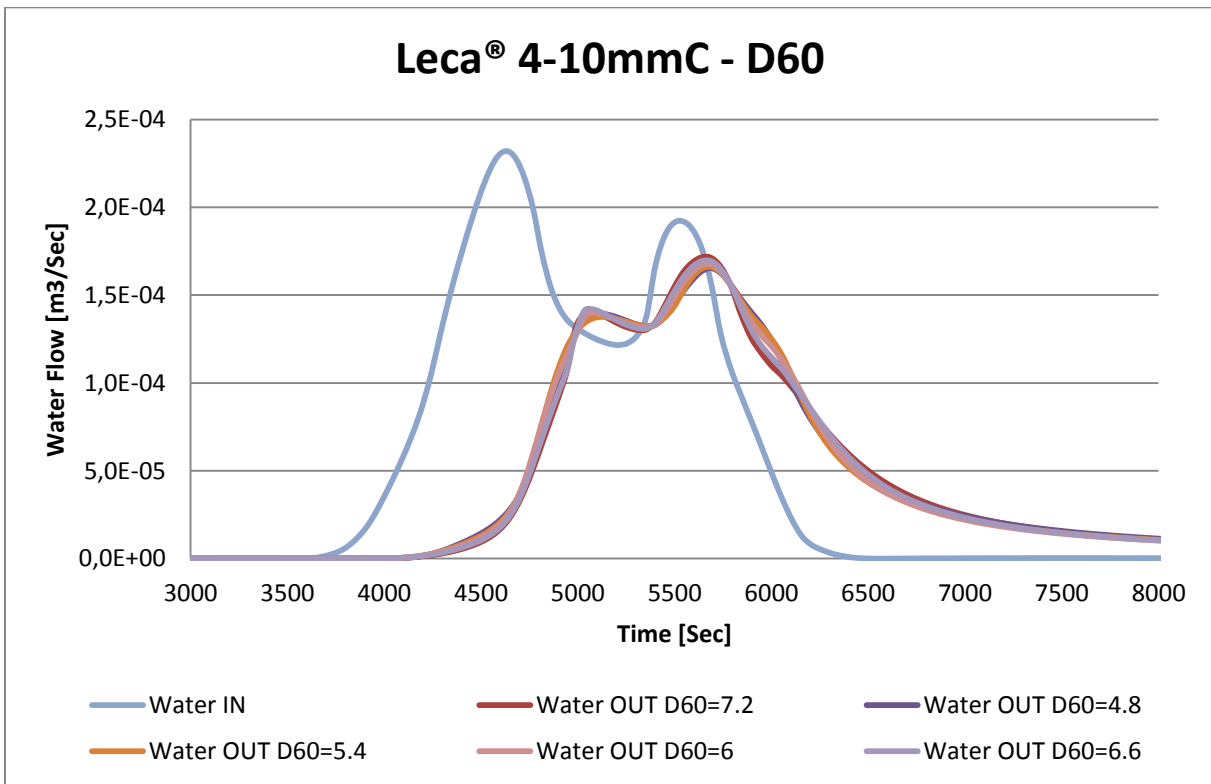


Figure 50. The result from variation of the saturated conductivity parameter.

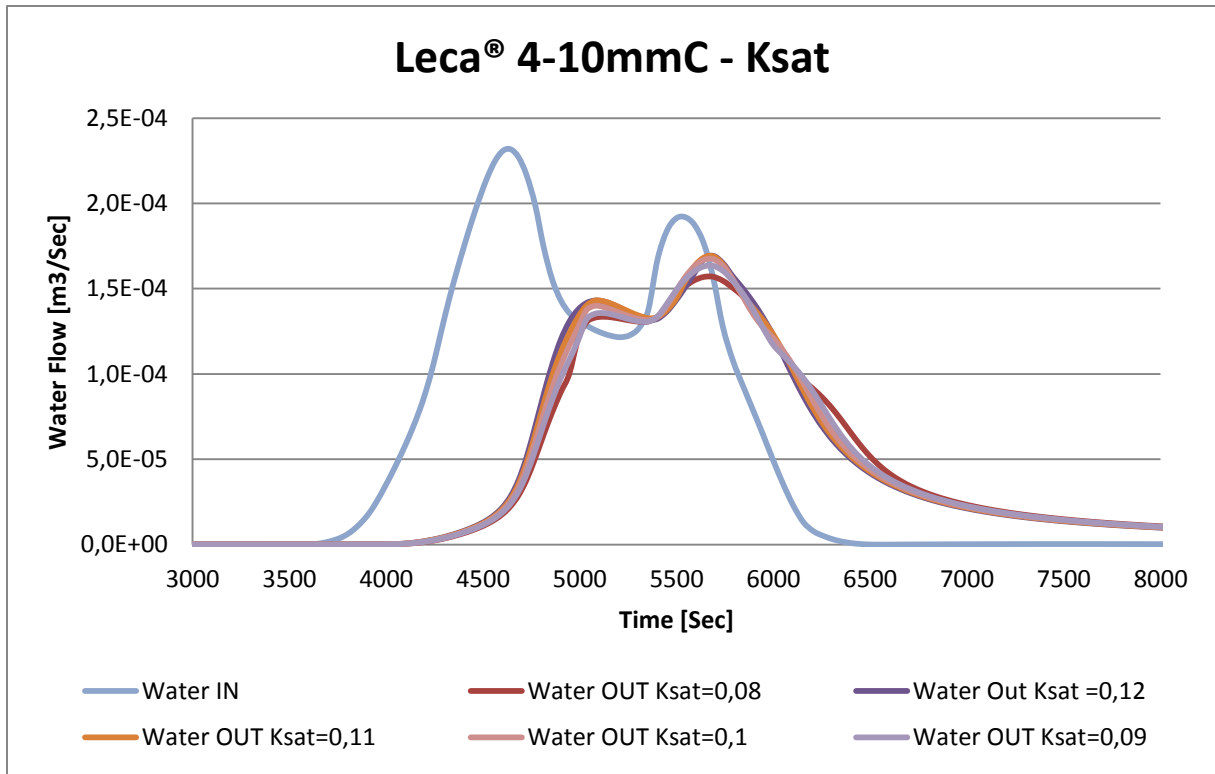
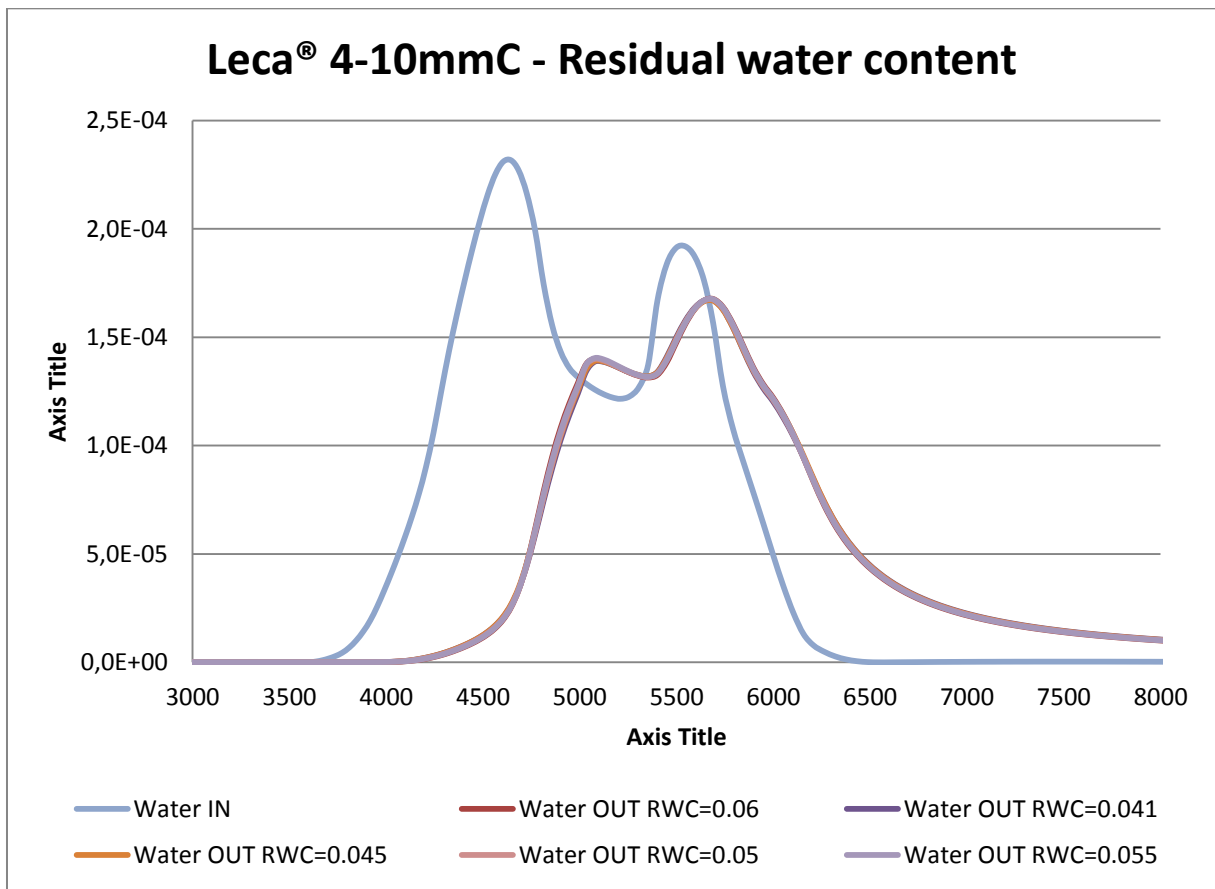


Figure 51. The result from variation of residual water content.



6.2.1 Discussion

Figure 47 to Figure 51, Appendix A and the column figures in Appendix B have mainly been used for the following analysis.

Some trends in the figures have been seen; lowering the porosity, a higher water flow is reached for both materials for the first peak and vice versa (higher porosity, lower runoff for both materials for the first peak). Also when decreasing the porosity, the first peak shifts to the left in the figures which means that the peak value is reached earlier for both materials and higher porosity delays the first peak (shifts it to the right).

The other trend that can be observed is when reducing the saturated conductivity, the runoff is reduced for both material at the first peak and when increasing the saturated conductivity, the water flow is increased.

The D60 parameter seems to affect the water runoff more than the D10 parameter. The residual water content parameter has no or little effect of the results.

For the second peak there are generally less difference between all of the five parameters and the trends gives counteracting results, e.g. increase in porosity for 4-10mmC increases the runoff and the opposite for 10-20mmR. A decrease in porosity results in increased flow for 10-20mmR and decreased (small) for 4-10mmC.

At 8000 seconds the tendency is that reduced porosity gives less runoff and increased porosity results in a higher runoff. This depends on the volume of water, for higher porosity more volume of water can be held in the material and opposite for a lower porosity. Another tendency is that a decrease of the saturated conductivity increases the runoff and an increase of the saturated conductivity decreases the runoff.

In order to improve the performance of the material, and thereby obtain better water retaining characteristic, a suggestion is to increase the porosity and lower the saturated hydraulic conductivity for the expanded clay LWA materials in order to obtain a higher attenuation for the first runoff peak.

In the software SEEP/W it is possible to change the input parameters one by one and study the how the individual change of one input parameter affect the runoff from the ideal case roof. In reality are the five input parameters connected to each other, which means that altering one parameter will alter the parameters, e.g. if the parameters defining the grain size distribution is changed, the saturated hydraulic conductivity will not stay the same. It is important to consider this when studying the sensitivity analysis for the input parameters.

6.3 SEEP/W

Is the software SEEP/W an advisable tool for simulating the water runoff in drain layer of a green roof? The simulations give matching results with the laboratory experiments but also realistic behavior for the ideal case roof. However, many simulations were run until satisfying result was obtained and during the work with the software a trial and error methodology was used. The biggest issue was all the numerical problems that occurred, especially for calculating water flow in Leca® 10-20mmR. For Leca® 4-10mmC the simulations have been conducted relatively well with not too much numerical problems.

The solutions for dealing with the numerical problems (highly unstable water flow for the boundary conditions) were to change the mesh size and change the length of the time integration steps. For the simulations with Leca® 10-20mmR changing and turning of these parameters have taken a lot of time. The cause of the problems with one material but not with the other is unknown. The porosity and residual water content is more or less the same for the both materials but D10, D60 and the saturated hydraulic conductivity differ a bit. It could be that the input parameters for Leca® 10-20mmR and particularly the high saturated hydraulic conductivity leads to turbulent water flow, which the software is not written for.

The software works but a lot of practices is needed to gain more experience about how to perform the simulations in SEEP/W in an efficient manner. It is difficult to learn a program by studying the user manual and not be able to consultate with an experienced person about issues with the software.

7. Conclusion

It was possible to back calculate the laboratory experiment, meaning obtaining the same relation between water going in and water going out of the tested Leca® material. However, a lot of numerical problems occurred in the simulations. Unrealistic results were displayed, especially for Leca® 10-20mmR. A reason could be the high saturated hydraulic conductivity value (from the laboratory permeability measurement) combined with the coarse grain size distribution is leading to a turbulent flow.

Another reason for the incomplete correlation could be that unsaturated flow dominates through Leca® and it is difficult to simulate the non-linear flow, even with the volumetric water content and hydraulic conductivity function.

More input parameters are necessary. It is too general to define a material with only five input parameters. Add more points for the grain size distribution and a parameter for the particle surface area could be useful.

Residual water content has not been tested but a suggested value has been assumed, this can be a source of error but the sensitivity analysis of the parameters indicated small dependency of this parameter for the results.

In order to improve the performance of the material, and thereby obtain better water retaining characteristic, a suggestion is to increase the porosity and lower the saturated hydraulic conductivity for the expanded clay LWA materials in order to obtain a higher attenuation for the first runoff peak.

In the software SEEP/W it is possible to change the input parameters one by one and study how the individual change of one input parameter affects the runoff from the ideal case roof. In reality the five input parameters are connected to each other, which means that altering one parameter will change all parameters, e.g. if the parameters defining the grain size distribution are changed, the saturated hydraulic conductivity will not stay the same. It is important to consider this when studying the sensitivity analysis for the input parameters.

8. Recommendations

Further work within this topic could be to change the geometry of the model and study how the inclination, layer thickness, rain intensity and the length of the drainage affect the water runoff. If enough time can be spend to run a large amount of simulations, a simple Excel-sheet could be created that estimates the runoff depending on the design of the green roof.

Another option of using the experience from multiple analyses would be to create figures (similar to what exists for slope stability) out of which it is possible to “read out” or give a thumb rule of what of runoff and delay to expect for a certain design and rain intensity.

To move on with the project a full scale test on a roof with 10 m drain length to confirm the results and more laboratory testing could be conducted but also test other Leca® products with higher porosity and other grain size distribution.

A further progress might also be to spend more time in understanding SEEP/W as well to evaluate usage of another software that have more input parameters, e.g. surface area of the particles.

Other interesting facts for expanded clay LWA would be how much rain is needed for the phreatic level, in the material, to reach the bottom of the planting media. If this could happen, up lift of the plant layer could occur and the Leca® particle could flush out of the roof.

A deeper study of the drain time and evaporation could be a supplementary project. The time which is required between two rain events is interesting. Depending on the water content and the time which it takes to reach a “good” or desired water content, estimations could be done of when the green roof is “ready” for a another intensive precipitation, if more knowledge would be obtained about this topic.

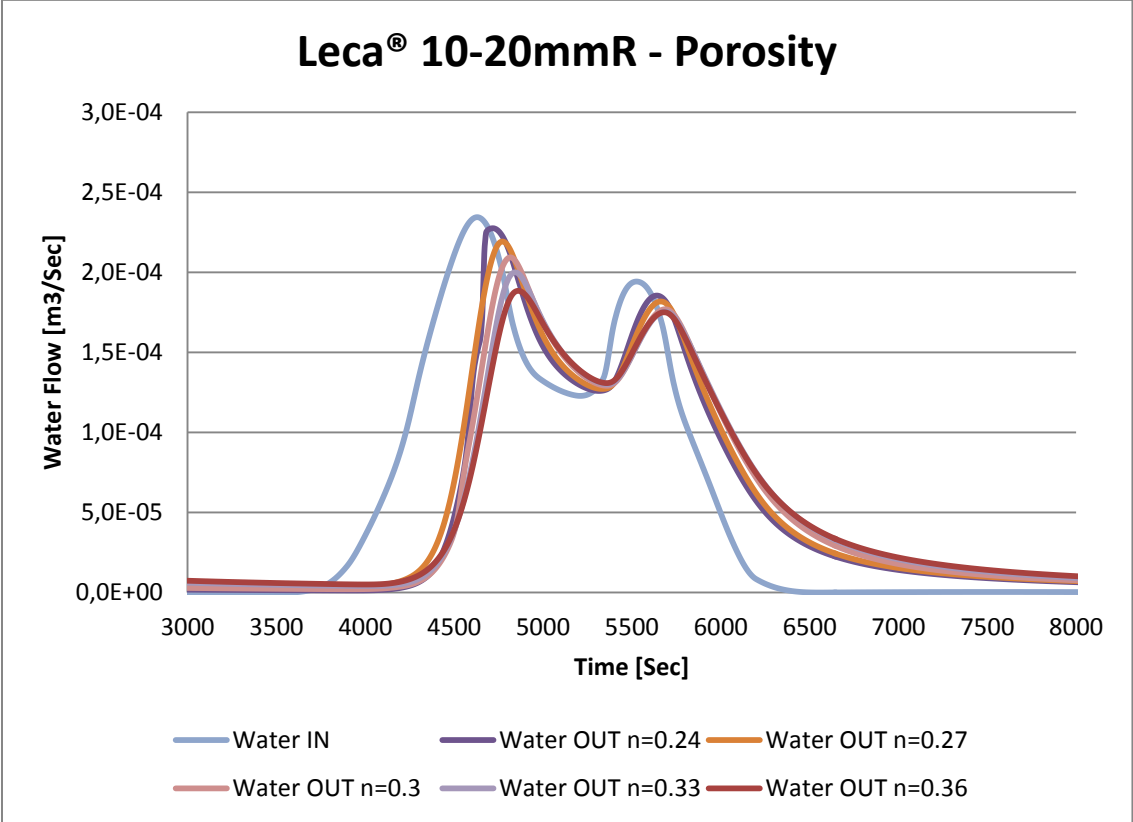
9. Bibliography

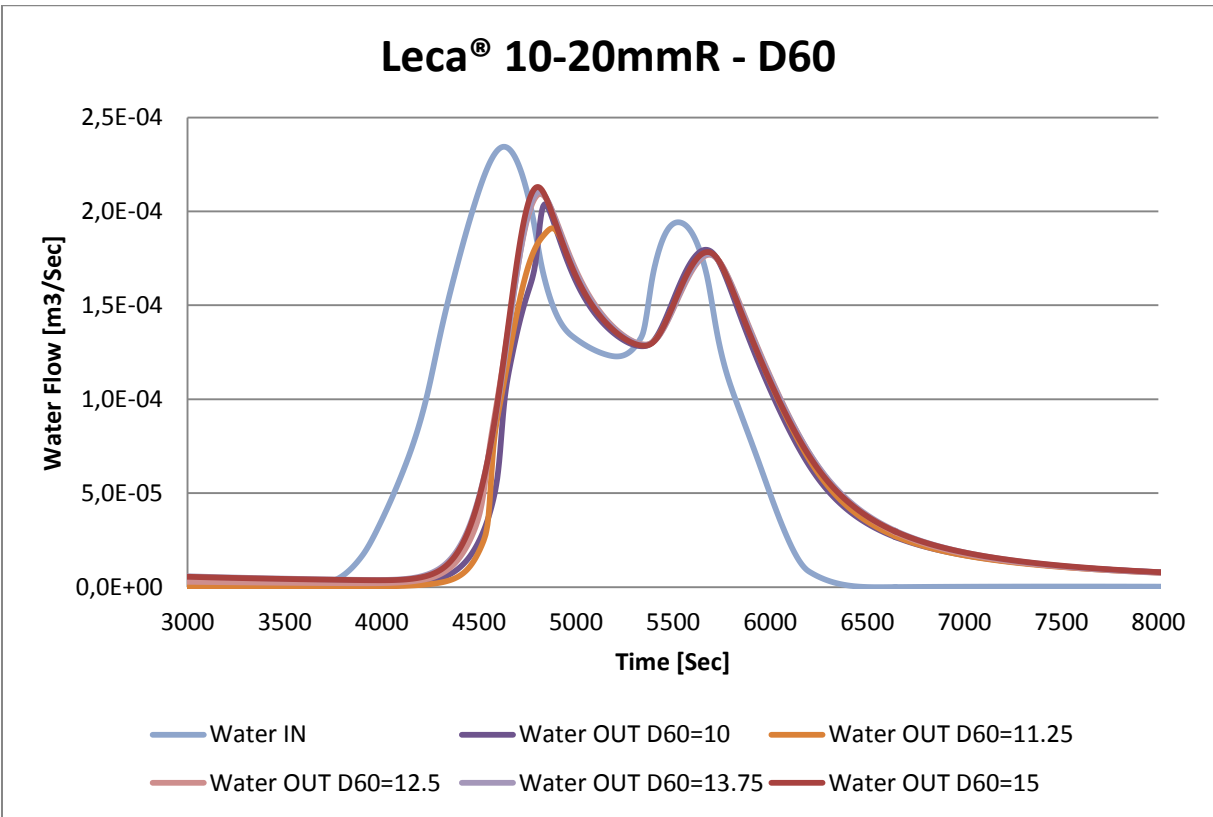
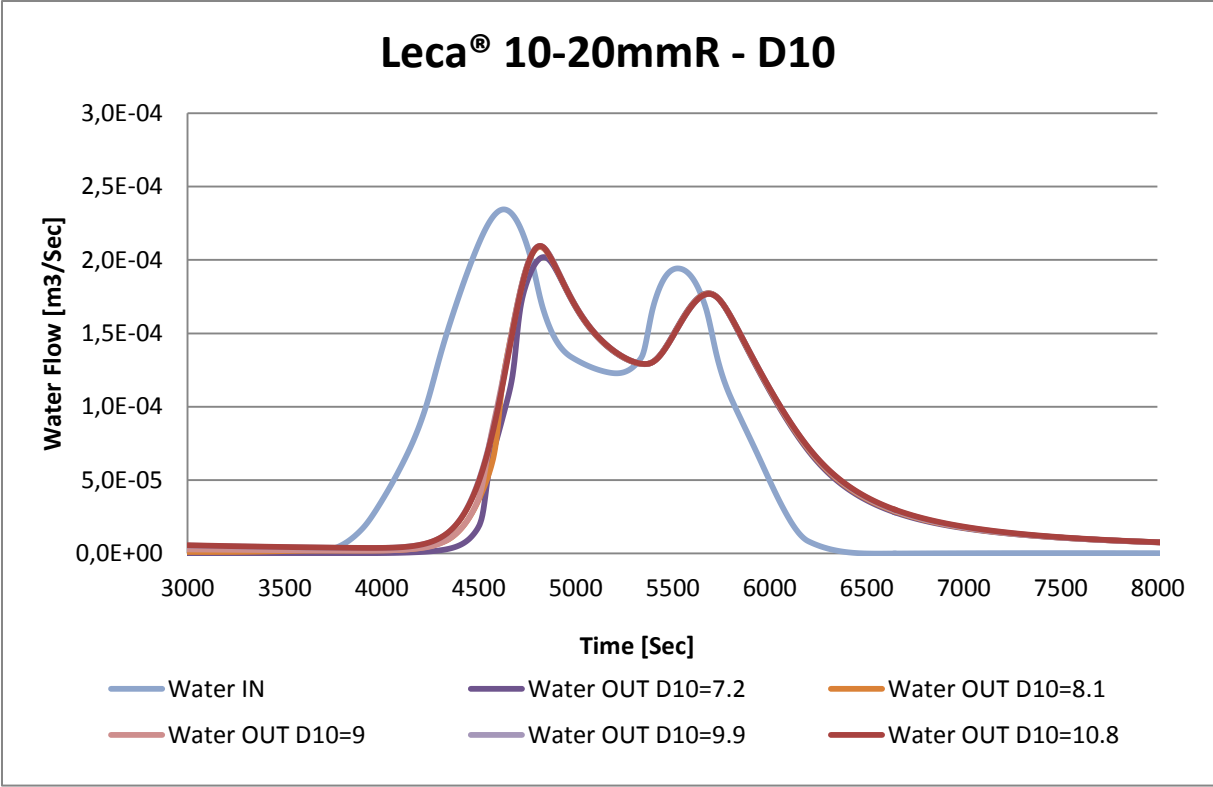
- [1] Kristin L. Getter; D. Bradley Rowe (2006). *The Role of Extensive Green Roofs in Sustainable Development [Online]*. Available 2013-01-20.
- [2] Jeroen Mentens; Dirk Raes; Marin Hermy (2005). *Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? [Online]*. Available 2013-01-20.
- [3] Bridget Thodesen; Jan Ove Busklein; Elise Balmand; Kati Alakoski; Tone Storbråten (2012). *Numerical modelling of the runoff and storm water storage capabilities of green roofs using lightweight expanded clay aggregate*. Article Copenhagen Green Roof Congress 2012.
- [4] Christopher G. Wark; Wendy W. Wark (2003). *Green Roof Specifications and Standards*. The Construction Specifier, August 2003 Vol.56, No.8.
- [5] Knut Noreng; Marius Kvalvik; Jan Ove Busklein; Ingrid Merete Ødegård, Corinna Susanne Clewing; Helen Kristine French (2012). *Grønne tak – Resultater fra et kunnskapsinnhentingsprosjekt*. Prosjektrapport 104 – SINTEF.
- [6] Bengtsson L.,(2005). *Peak flows from thin sedum-moss roof*. Nordic Hydrology Vol 36, No 3 pp 269–280.
- [7] Jan Ove Busklein (2010). *Urbanization – Green roofs in urban areas. Field experiments runoff water*. SINTEF Report
- [8] B.C. Braskerud (2010). *Detention of Heavy Rain on an Extensive Norwegian Sedum Roof*. Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway.
- [9] A. Palla; J.J. Sansalone; I. Gnecco; L.G. Lanza (2011). *Storm water infiltration in a monitored green roof for hydrologic restoration*. Water Science & Technology – IWA Publishing.
- [10] Berntsson Leif; Chandra Satish (2003). *Lightweight aggregate concrete [Online]*. Available 2012-11-05.
- [11] EuroLightCon (1998). *LWAC Material Properties State-of-the-Art [Online]*. Available 2012-11-05.
- [12] Picture, available online 2011-11-29. http://www.patfab.com/rotary_kiln.htm
- [13] Product specifications, available online 2012-11-09. Weber Saint-Gobain webpage; www.weber-norge.no
- [14] Høva Endre Magnus (2009). *Documentation of material properties for Leca® LWA aggregates and evaluated characteristics geotechnical parameters*. SINTEF Report, Trondheim.
- [15] Skulbørstad Roar (2002). *Mechanical and hydraulic properties of light weight clay aggregate*. Master Thesis, Spring 2002. Department of Geotechnical Engineering, NTNU, Trondheim.
- [16] Janbu Nilmar (1989). *Grunnlag i geoteknikk*. Tapir, NTH, Trondheim.

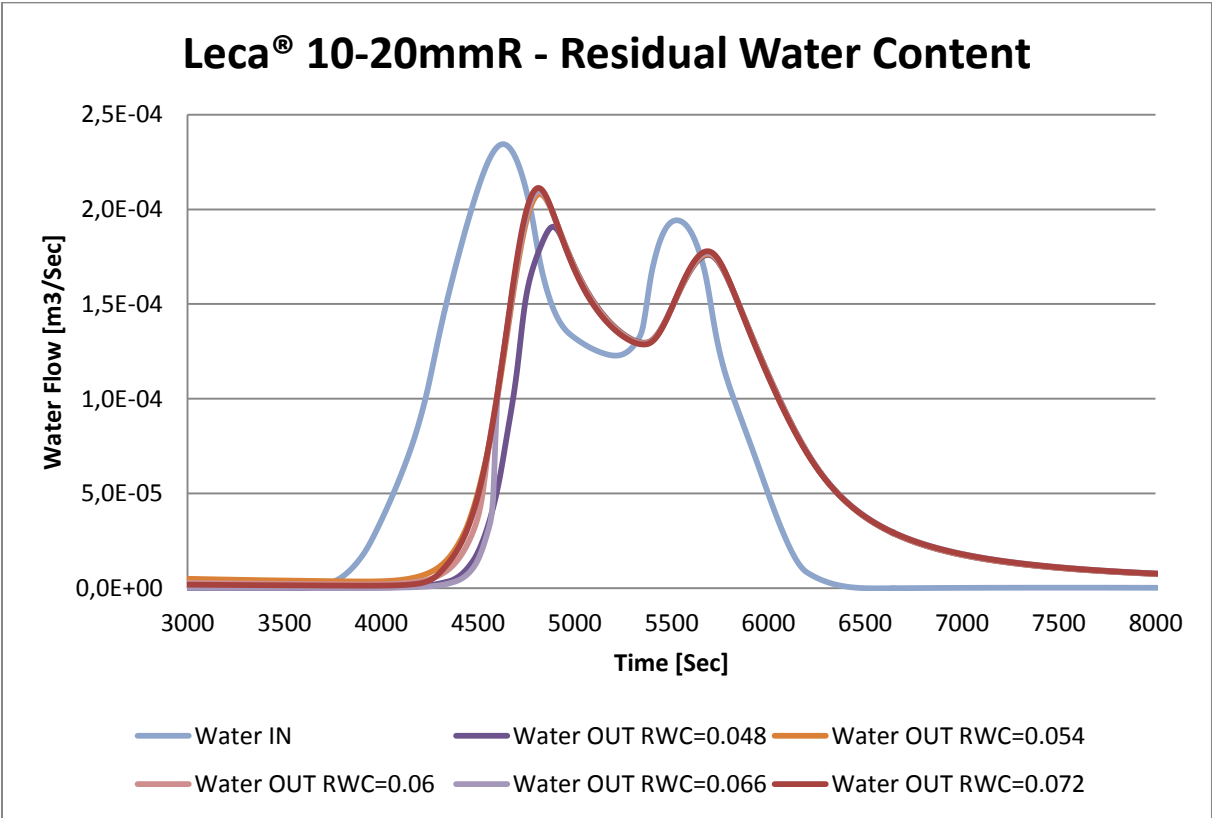
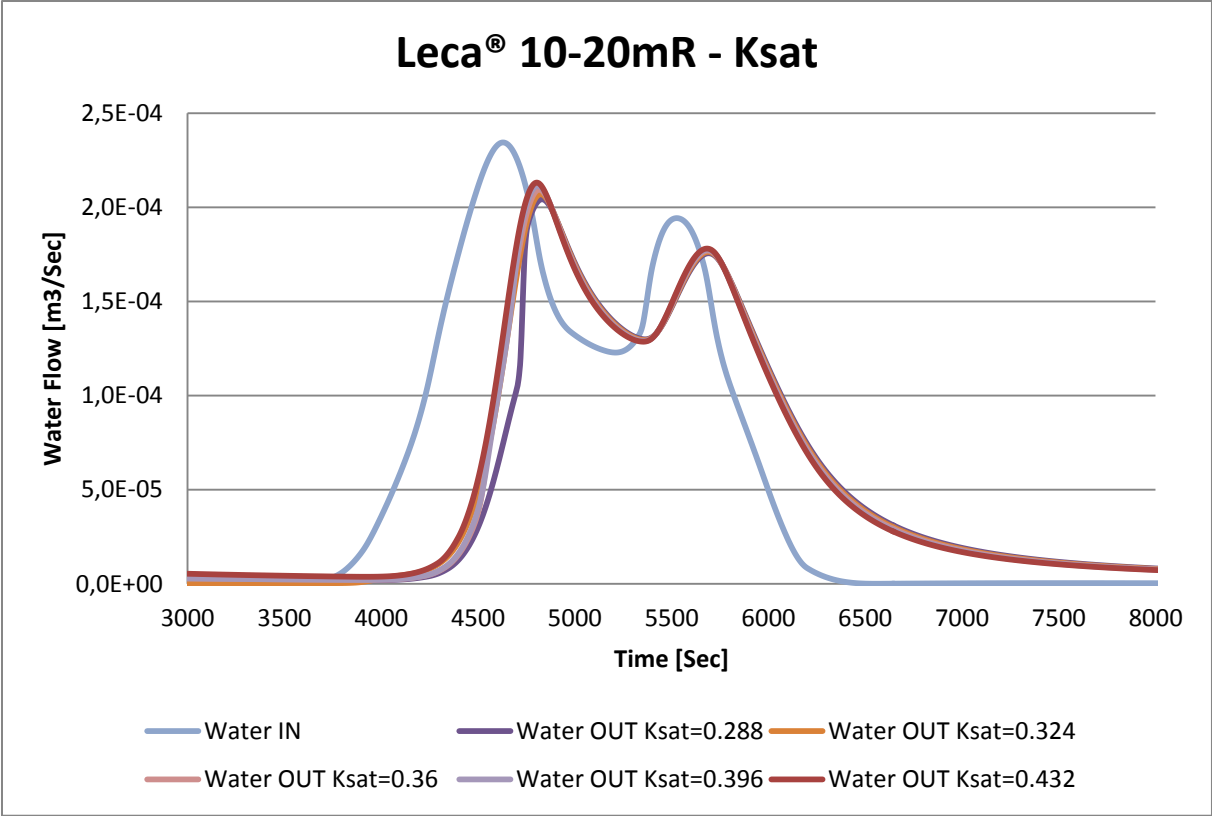
- [17] Nordal Steinar (2012). *Geotechnical Engineering Advanced Course – Lecture Notes and Background Material*. Norwegian University of Science and Technology, Geotechnical Division. Tapir, Trondheim.
- [18] GEO-SLOPE International Ltd. *Seepage Modeling with SEEP/W – An Engineering Methodology. November 2012 Edition [Online]*. Available 2013-01-30.
- [19] Jan Ove Busklein, Bridget O’Brien Thodesen, Elise Balmand (2012). *Testing of Leca’s® Attributes and Use in Green Roofs Solutions. – Water Retention*. SINTEF – Report
- [20] Storbråten T. (2012). Green Roof – Phase 1 – Laboratory test. Saint-Gobain Weber, Competence Centre Exclay, Lillestrøm.
- [22] Picture, available 2013-03-07. <http://www.e-weber.com/en/activities/expanded-clay.html>

10. Appendices

Appendix A -Parameter Sensitivity for Leca® 10-20mmR



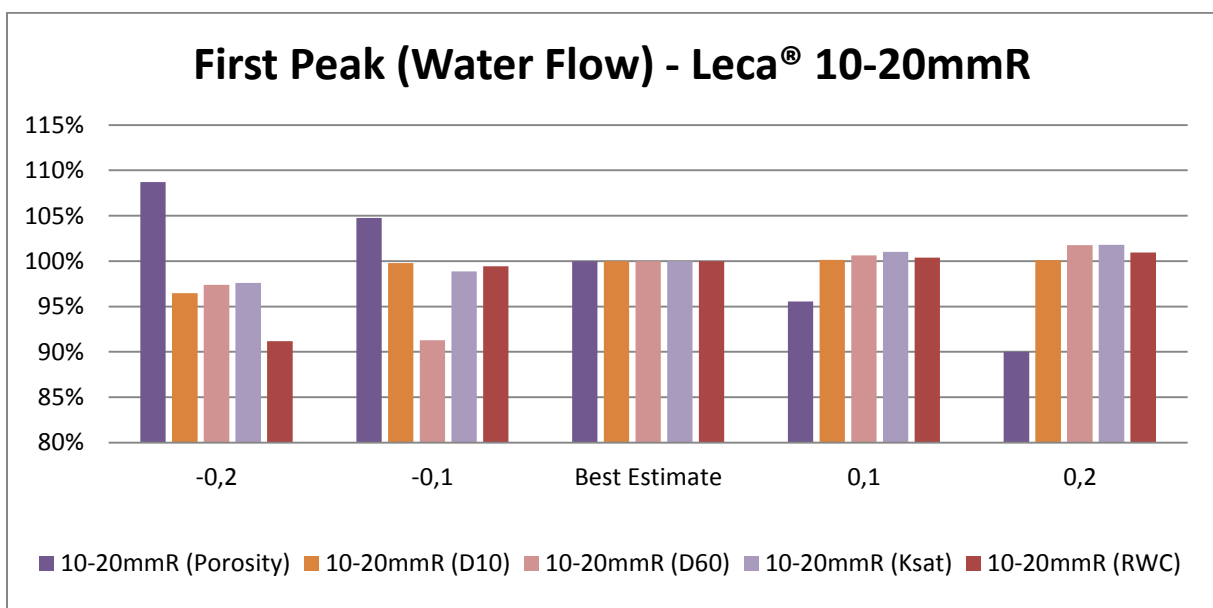
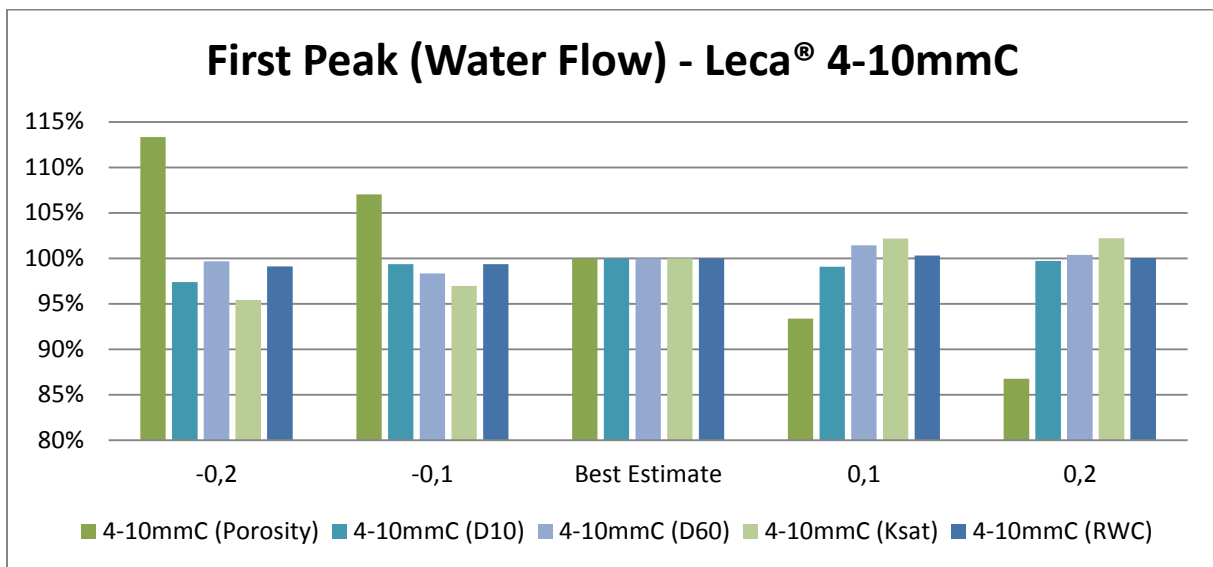


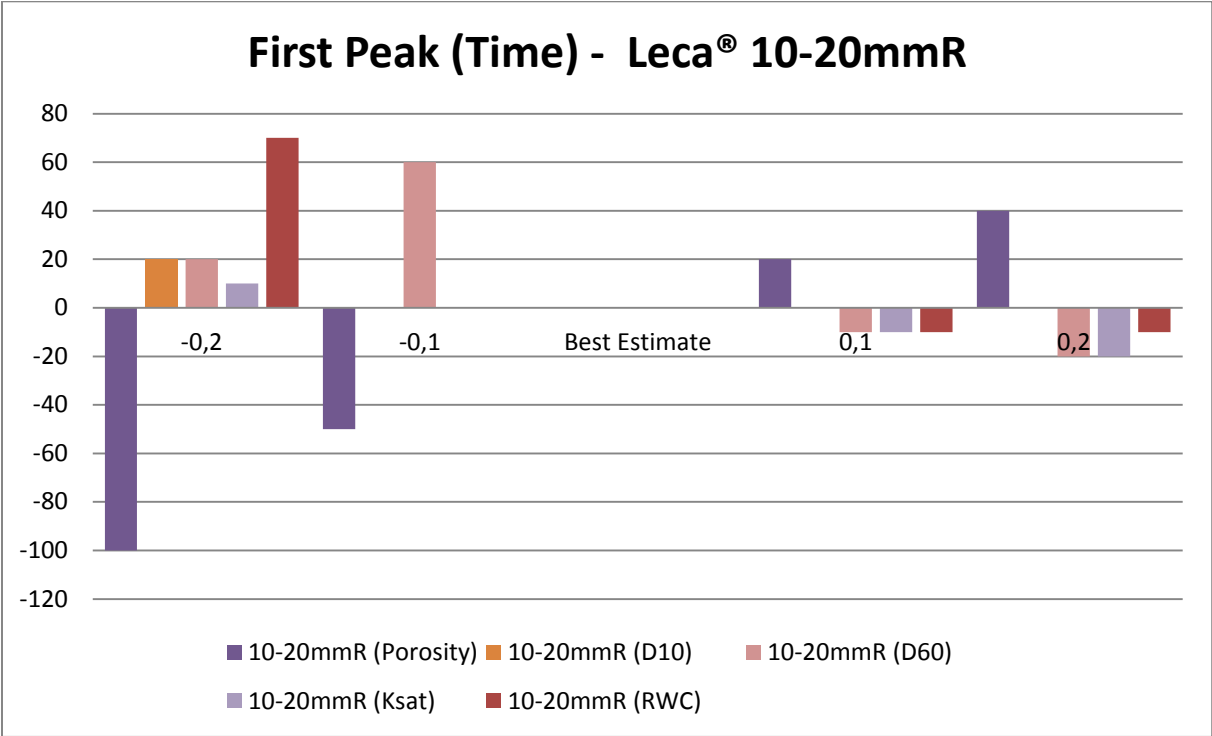
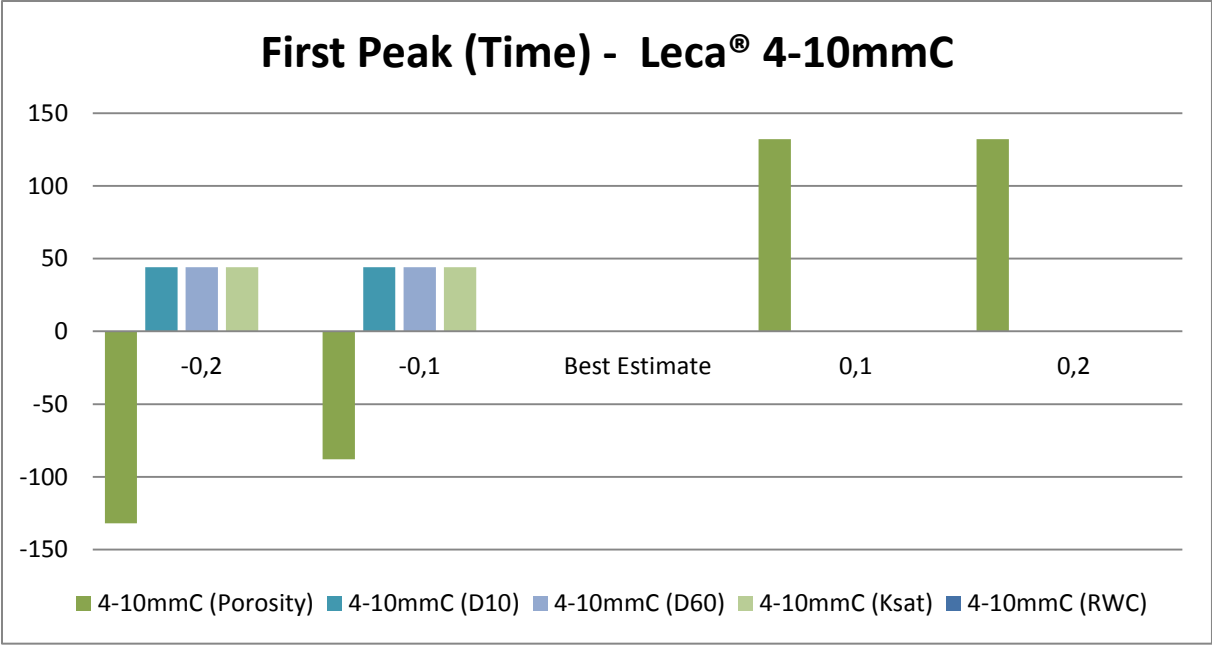


Appendix B – The Variation in Water Runoff, Displayed in Percentage

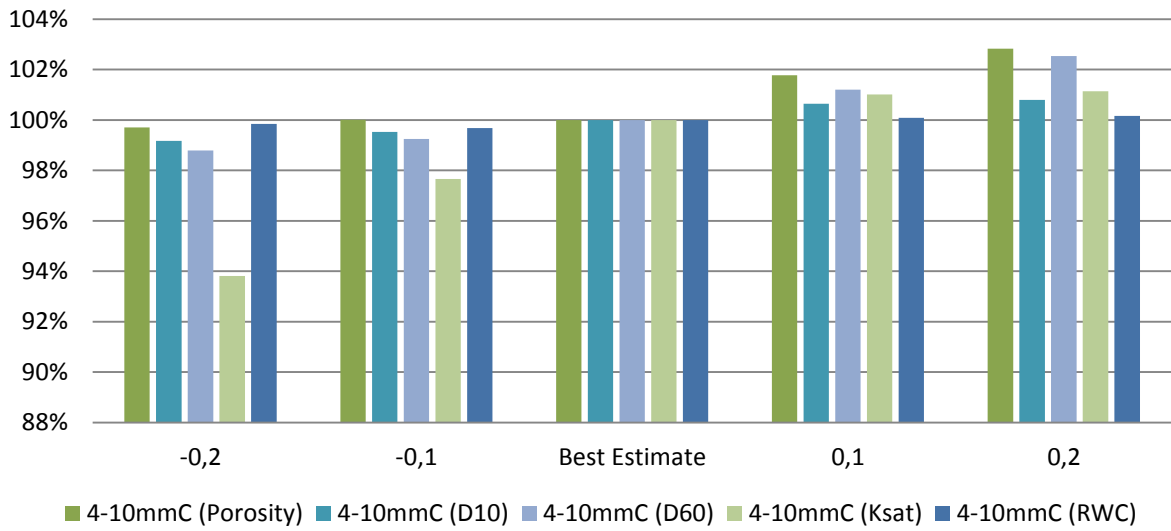
Five simulations have been performed. The one in the middle is the best estimate values chosen for Leca® 4-10mmC and 10-20mmR. To the left the values have been reduced with 10 % and 20 % and to the right of the middle values, there is an increase of the best estimate values with 10 % and 20 %.

So, the column figures shown below is a comparison of the values of the first peak, second peak and runoff at 8000 seconds. At the left, in the two following, figures the porosity have been decreased with 20 %, which results in a 13 % higher runoff for Leca® 4-10mmC and 9 % for Leca® 10-20mmR (green and purple columns). While a 20 % increase of the porosity gives 14 % and 10 % reduction of the runoff for the first peak.

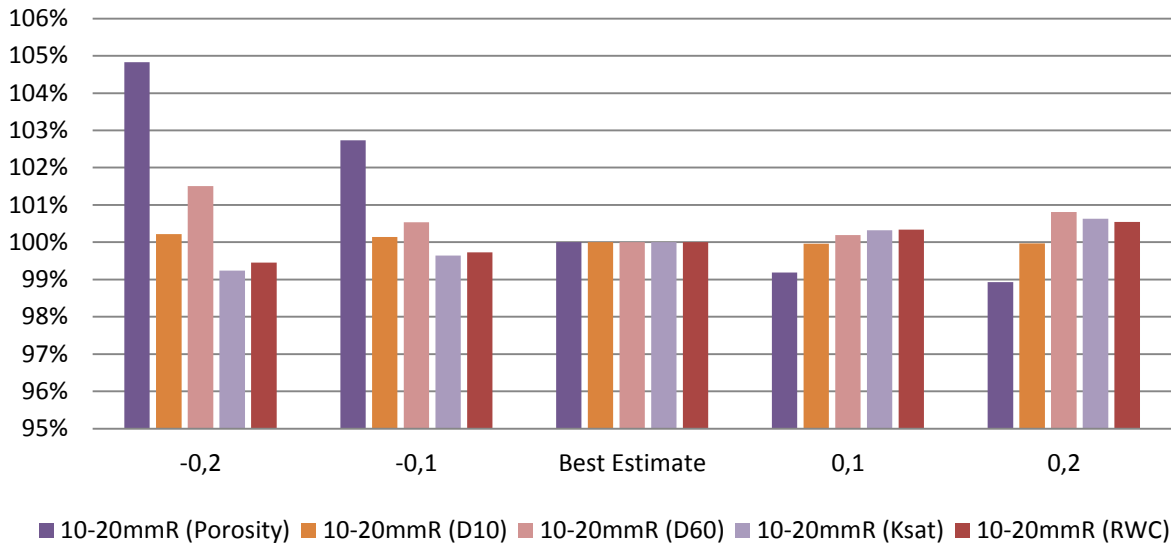




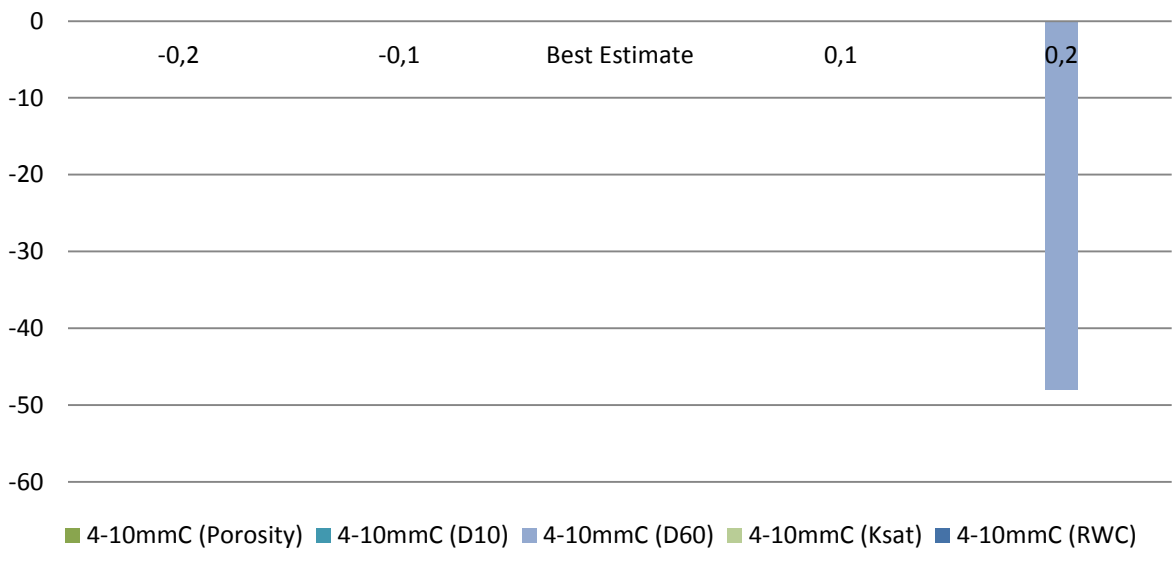
Second Peak (Water Flow) - Leca® 4-10mmC



Second Peak (Water Flow) - Leca® 10-20mmR



Second Peak (Time) - Comparison



Second Peak (Time) - Leca® 10-20mmR

