# Supplementary material in addition to SR-Site modeling report TR-10-11 as requested by SSM

# 1.2. Water uptake in the CRT experiment

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# 2 Introduction

The Swedish Radiation Safety Authority (SSM) requests a comparison between measured and modeled water inflow to the Canister Retrieval Test (CRT) (SSM2011-2426-81). The CRT-experiment was used as a case study when “Buffer homogenisation” was considered in Åkesson et al. (2010), chapter 5. SSM motivates their request by the findings reported by Benbow et al. (2012).

The study carried out regarding this subject has been divided in two sections. First, an analytical investigation is performed regarding the water uptake, where estimates are calculated under different assumptions. Thereafter follows an estimate obtained from the thermo-hydro-mechanical (THM) numerical model of the entire CRT-experiment which was described in Åkesson et al (2010), chapter 5.

# 3 Analytical estimates of the water uptake

**Table 1. Average data for buffer blocks at installation, dimensions from Thorsager et al. (2002) and other from Johannesson (2007).**

| Type | Dimensions [mm] | Density [$kg/m^3$] | Water content | Dry density [$kg/m^3$] | Void ratio |
|---|---|---|---|---|---|
| Cylinders | H=504[1] | 1991 | 0.172 | 1699 | 0.636 |
| Rings | H=510[1] | 2087 | 0.171 | 1782 | 0.560 |
| Bricks[2] | H=123[3] | 1883 | 0.165 | 1616 | 0.720 |

[1]The average value and an additional 3 mm representing interface volumes between blocks.
[2]The total volume including bentonite bricks, pellets, and powder.
[3]This value is obtained from subtracting the canister height from the hight of 10 rings as descibed in the table.

**Table 2. Data for pellet filled gap at installation, from Johannesson (2007).**

| Type | Width [mm] | Density [$kg/m^3$] | Water content | Dry density [$kg/m^3$] | Void ratio |
|---|---|---|---|---|---|
| Pellet slot (dry) | 61 | 1101 | 0.1 | 1001 | 1.778 |
| Pellet slot (wet[1]) | 61 | 1574 | 0.572 | 1001 | 1.778 |

[1]The state when the pore volume between the pellets has been water filled.

From the data in Table 1 and Table 2 together with the specified geometry an estimate of the available pore volume at installation can be calculated as shown in Appendix A . The calculated total available pore volume, also accounting for the empty slot of 1 cm between canister and rings and a heave of the plug of 34 mm, motivated from measurements, becomes 2264 L

Figure 1 shows the accumulative measured volume of artificially supplied water to the CRT-experiment. During operation, the accumulated measured filter inflow was as given by Figure 1 when reading the left of the scales. Thus, according to measurements, a total of 670 L was added through the filters. At installation, water was being fed into the outer pellet filled slot through tubes, which were withdrawn after usage. According to Thorsager et al. (2002) the water volume added through the tubes at installation was 950 L. The right of the scales in Figure 1 gives the accumulated volume of total added water, i.e. the water volume of 950 L, added at installation, is included, which ends up about 1620 L at the end of the test. Thus, 72% of the available pore volume was filled according to the measured and reported water volumes.

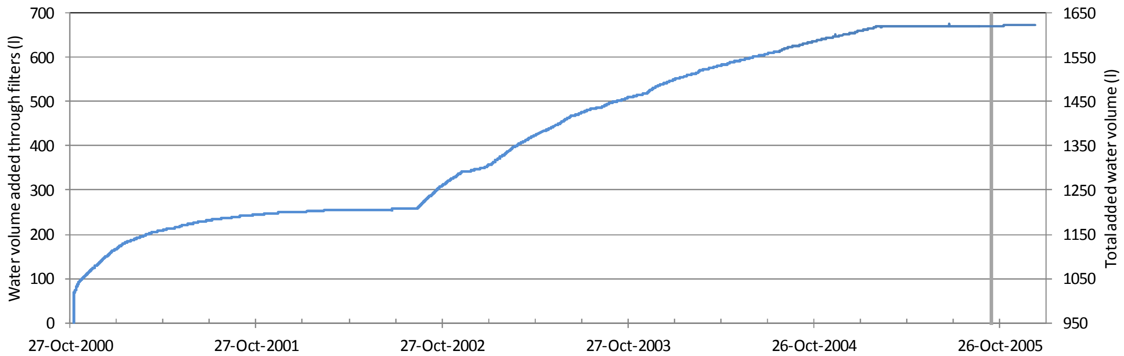


***Figure 1.*** *Accumulative volume of water added through filters (left scale) and reported accumulative volume of total added water (right scale).*

If using density and water content data at installation, given in Table 1 and Table 2, and excavation (reported in Johannesson, 2007) together with the specified geometry, an estimation of the added water volume may be calculated, see Appendix A for details. An estimate of 2036 L was obtained using the assumptions:

- the heights of the blocks at excavation are similar to the estimated average block height at installation,
- the lower ring-shaped buffer blocks, R1-R5, contain the same water volume as R6, and
- the bottom buffer block, C1, contain the same water volume as C2.

The difference between the estimate and measured value is significant, 2036 – 1620 = 416 L. According to the estimate 90% of the available pore volume was filled.

One potentially uncertain component in the total added water volume is the water volume of 950 L that was reported, (Thorsager et al. 2002), to be added when installing the pellet filled slot. If using the data in Table 2 together with the specified geometry, a value of 1096 L is obtained for the available volume between the pellets, see Appendix A for details. Also, sensor responses indicate that the open volume of 166 L between the canister and buffer rings was water filled at installation as well. If so, this gives a total volume of 1096 + 166 = 1261 L as compared to the reported 950 L. If calculating a new total added water volume based on the measured inflow from the filters and the estimated volume that was water filled (volume between pellets and the inner slot volume) we obtain 670 + 1261 = 1931 L which is more in line with that obtained from evaluating excavation data. According to this estimate 85% of the available pore volume was filled.

Table 3 and Figure 2 show compilations of the discussed volumes.

**Table 3. Compilation of the volumes discussed in the text.**

| Description | Volume [L] | Relative volume [%] |
|---|---|---|
| Estimation of available pore volume at installation | 2264 | 100 |
| Water volume: Reported at pellet filling + Measured filter inflow | 1620 | 72 |
| Water volume: Calculated from excavation data | 2036 | 90 |
| Water volume: Calculated available ”macro pore volume” in pellet filling and volume of inner slot + Measured filter inflow | 1931 | 85 |

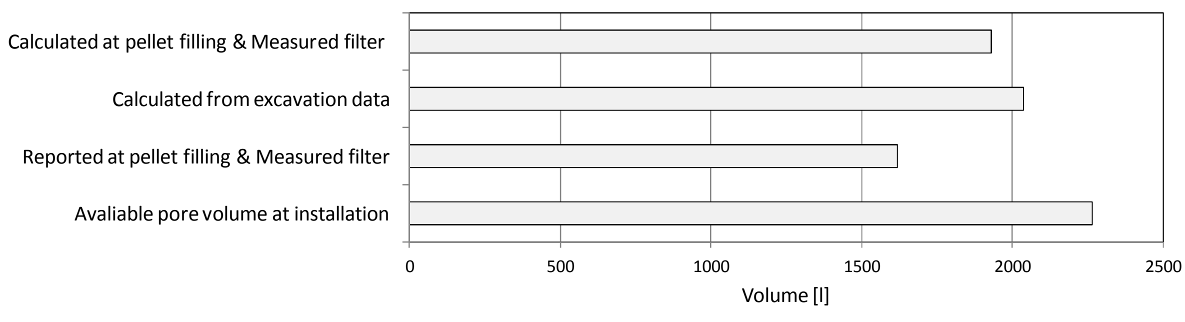


***Figure 2.*** *Graphical view of the volumes discussed in the text.*

# 4 Numerical estimate of the water uptake

The THM-evolution in the Canister Retrieval Test has been modelled with both Code Bright and Abaqus (Åkesson et al. 2010 and Börgesson et al. 2013). The entire test geometry was modelled with Abaqus. The modelling included the full test time, the temperature evolution, the mechanical evolution with swelling and homogenisation of the buffer and the water uptake by the bentonite. The modelling is in detail described by Börgesson et al. (2013). The results have been compared with measured results regarding suction in the bentonite, total pressure in the bentonite and forces and displacements of the plug. The comparison showed that the agreement was rather good. Figure 3 shows the element model.

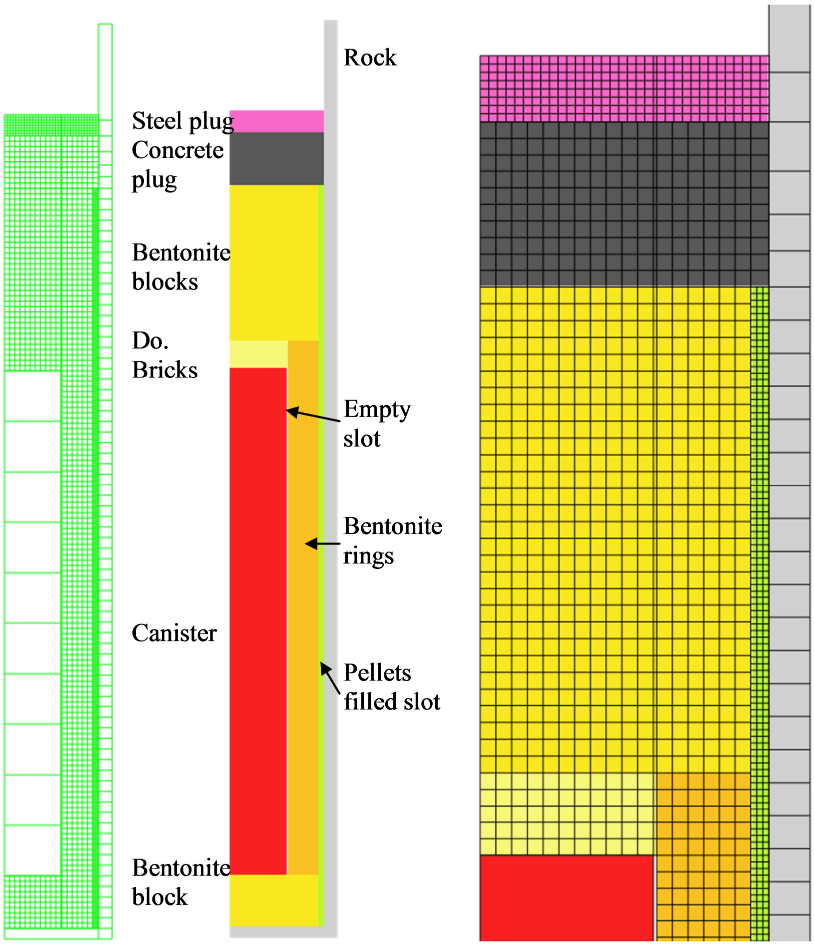


***Figure 3.*** *Element mesh and property areas of the 2D model. The model is axial symmetric around the left boundary.*

An interesting comparison is the water balance of the bentonite. Does the modelled water uptake agree with the measured? Such a comparison was not done in the referred reports.

Abaqus allows for evaluation of the water flow through nodes with settled water pressure. The total water inflow from the surrounding modelled filter mats was evaluated and plotted as function of time. Figure 4 shows a comparison between modelled and measured inflow into the filter mats.

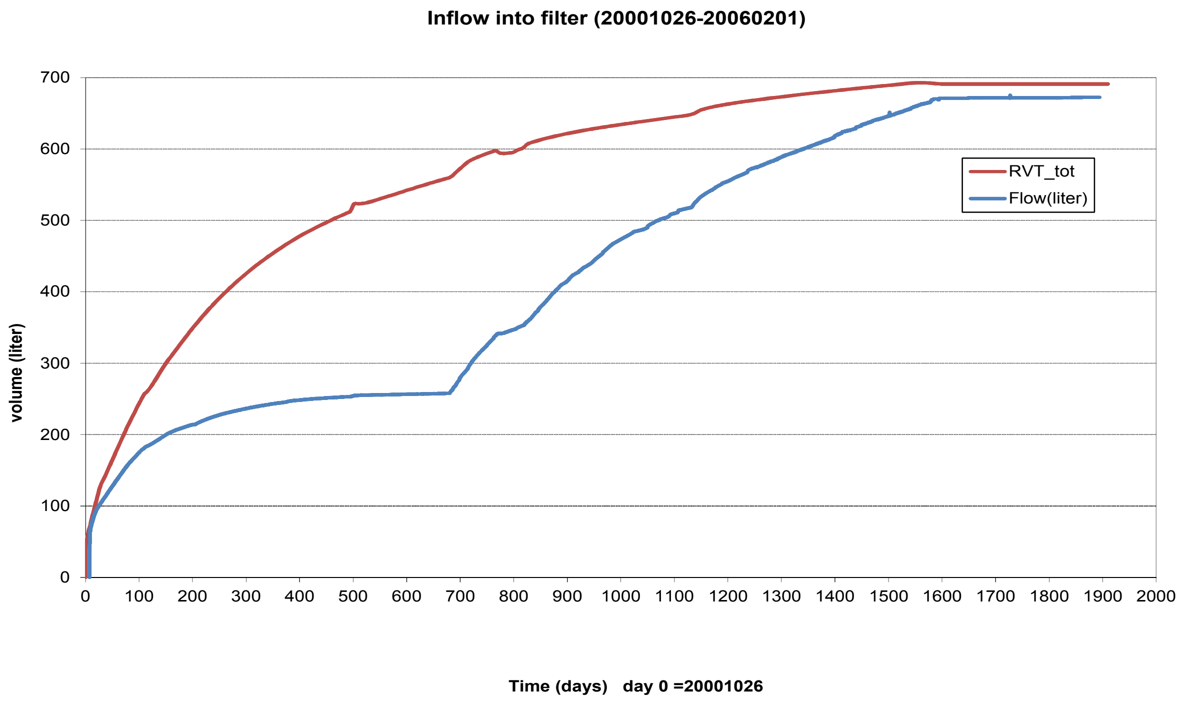


***Figure 4.*** *Modelled (red line) and measured (blue line) water inflow into the CRT test hole.*

As seen in Figure 4 the agreement at the end of the test is surprisingly good. However, the history paths do not have the same nice agreement. The measured inflow rate is much lower in the beginning of the test and after about 680 days the inflow has almost stopped. The water pressure applied to the filter was up to that day limited to one meter water head above the floor of the installation drift i.e. about 50 kPa in the centre of the test hole. After 680 days the water pressure was increased to 800 kPa and the result is seen in Figure 4 as a strong increase in measured water inflow rate. An interesting question is why the inflow almost stopped before increasing the water pressure. The most probable explanation is that the supply of water into the filter mats was not sufficient in order keep the filter mats water saturated. Flow tests in order to flush the filter mats showed that the connectivity was for some mats rather poor unless high water pressure was applied. When after 680 days the water pressure was increased to 800 kPa the supply of water was sufficient in order to keep the filter mats water saturated and thus meet the demand of the bentonite.

If the modelled inflow is adjusted so that the measured delay caused by insufficient water supply is taken into account we get the comparison shown in Figure 5.

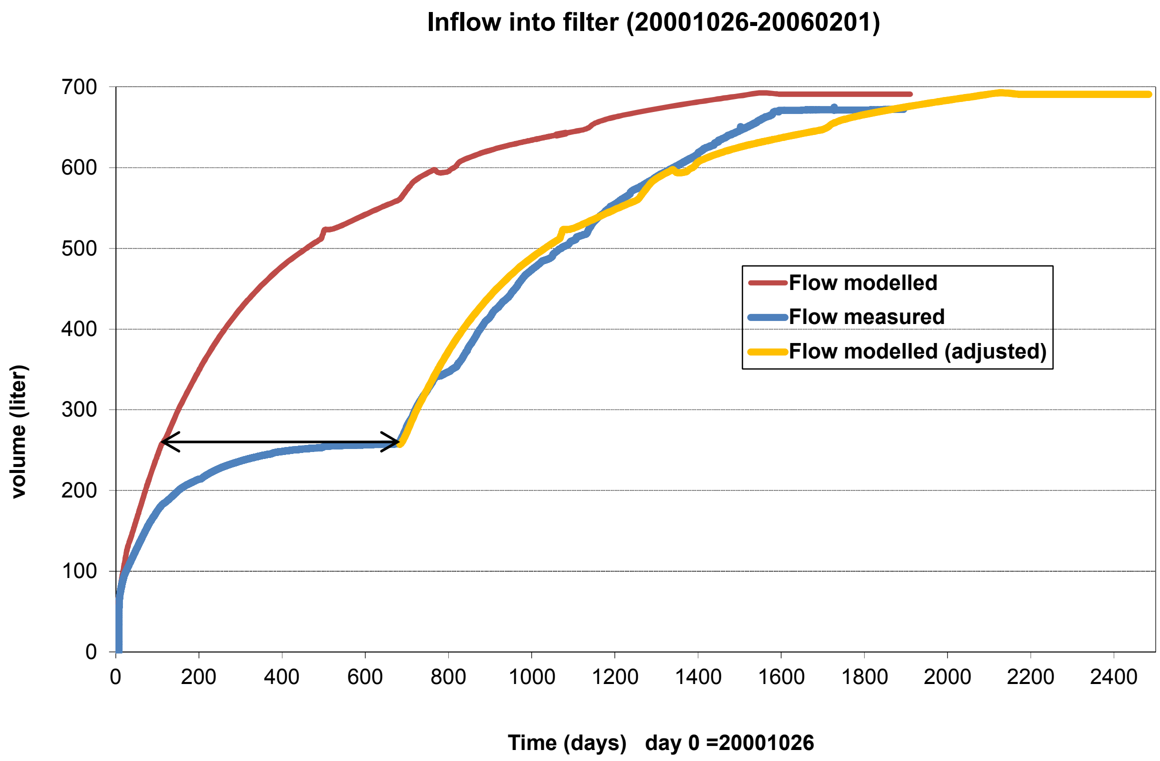


***Figure 5.*** *Modelled (red line) and measured (blue line) water inflow into the CRT test hole and the modelled inflow adjusted for the insufficient water supply (yellow).*

The adjustment is simply made by a parallel displacement of the modelled inflow at the total volume 260 L with about 590 days. In this way the modelled inflow restarts at the same inflow value as the measured when the filter was cleaned and the water pressure applied. This is of course not completely correct since the delay should lead to that the actual water distribution in the blocks have equalized more than in the model, which in turn should mean a slower  water uptake rate in the model. This is not seen until very late when the model underestimates the water uptake rate.

Another interesting question is if the measured water inflow corresponds to the actual supply of water to the filters or if any water has been lost to the rock or taken up from the rock. The volumes illustrated in Figure 2 show that the water taken up by the bentonite calculated from the excavation data is higher or in fair agreement with the estimates done from the inflow measurements depending on if the measured volume of water filling or the calculated volume available for water filling is used. This shows that it is not probable that any water has been lost to the rock in spite of the high water pressure applied in the mats. On the other hand, the lack of available water during the first 680 days before the water pressure increase shows that it is neither probable that there is any water inflow from the rock. The rock thus seems to be very tight which is confirmed by the inflow measurements into the test hole before installation when no inflow actually could be measured. In addition, the filter mats were fastened on cement levelling that was applied on the rock wall, which hindered water exchange between the rock and the filters.

Another fact that could influence the water uptake is that the filter strips only covered parts of the rock wall surface. 10 cm wide filter strips were attached vertically with 26 cm distance. The effect of this was investigated in a pre-study. The results showed that there is an influence on the water uptake rate of the buffer, but it is rather small in comparison with if the entire surface was covered with filter (Börgesson et al. 1999). A decrease in distance between the 10 cm wide strips from the actual 26 cm to 8 cm reduced the time to saturation with 5-10%. There is thus an overestimation in the modelled water uptake rate with about 15% due to the strip effect. In addition to this effect, the restricted water supply during the first 680 days was not included in the model. If this restriction had been included in the modelling the predicted water inflow would have been lower as shown in Figure 5. It is thus probable that the model underestimates the water uptake rate of the buffer. This conclusion is also supported by the measured inflow rate, which at the end of the water supply period (after 1600 days) is higher than the modelled since the inclination *dV/dt* is larger.

Summing up all the information given above the conclusion is that the water uptake models seem to slightly underestimate the water uptake rate of the buffer and that there is no indication of any buffer processes not taken into account by the models that delay the water saturation rate.

# 5 References

**Benbow S, Metcalfe R, Watson C, and Bond A, 2012.** SR-Site Independent Modelling of Engineered Barrier Evolution and Coupled THMC: Contribution to the Initial Review Phase. Swedish Radiation Safety Authority, Report no. 2012:18, ISSN 2000-0456.

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**Thorsager P., Börgesson L, Johannesson L-E, Sandén T, 2002.** Äspö Hard Rock Laboratory, Canister Retrieval Test, Report on installation. SKB IPR-02-30, Svensk Kärnbränslehantering AB.

**Åkesson M, Kristensson O, Börgesson L, Dueck A, Hernelind J, 2010.** THM modeling of buffer, backfill and other system components, Critical processes and scenarios. SKB TR-10-11, Svensk Kärnbränslehantering AB.

# Appendix A Volume calculations

**Location:** ”Administrativa dokument on”: \ Projekt\ SR-Site SSM-frågor\data\modeller\Task_1.2\Water_volume*

| MathCad-document |
|---|
| ‘Estimate of water in CRT 2.xmcd’ |

| Excel-documents | * in Location given above |
|---|---|
| ‘Sammanst C2.xls’ | \Block C2 |
| ‘Sammanst C3.xls’ | \Block C3 |
| ‘Sammanst C4.xls’ | \Block C4 |
| ‘Sammanst R6.xls’ | \Block C6 |
| ‘Sammanst C7.xls’ | \Block C7 |
| ‘Sammanst C8.xls’ | \Block C8 |
| ‘Sammanst C9.xls’ | \Block C9 |
| ‘Sammanst C10.xls’ | \Block C10 |

## Calculate initial water volume

$\rho_w := 1000$ $r_o := \frac{1.64}{2}$ $r_i := \frac{1.07}{2}$ $\Delta r := 0.061$

| | | | |
|---|---|---|---|
| Cylinders | $H_C := 0.504$ | $\rho_C := 1991$ | $w_C := 0.172$ |
| Rings | $H_R := 0.510$ | $\rho_R := 2087$ | $w_R := 0.171$ |
| Bricks | $H_B := 0.123$ | $\rho_B := 1883$ | $w_B := 0.165$ |
| Pellet slot | $H_P := 4 \cdot H_C + 10 \cdot H_R$ | $\rho_P := 1101$ | $w_P := 0.1$ |

$$V_{w\_init\_cylinders} := H_C \cdot r_o^2 \cdot \pi \cdot \frac{1}{1 + \frac{1}{w_C}} \cdot \frac{\rho_C}{\rho_w}$$

$$V_{w\_init\_rings} := H_R \cdot \left(r_o^2 - r_i^2\right) \cdot \pi \cdot \frac{1}{1 + \frac{1}{w_R}} \cdot \frac{\rho_R}{\rho_w}$$

$$V_{w\_init\_bricks} := H_B \cdot r_i^2 \cdot \pi \cdot \frac{1}{1 + \frac{1}{w_B}} \cdot \frac{\rho_B}{\rho_w}$$

$$V_{w\_init\_pellet} := H_P \cdot \left[\left(r_o + \Delta r\right)^2 - r_o^2\right] \cdot \pi \cdot \frac{1}{1 + \frac{1}{w_P}} \cdot \frac{\rho_P}{\rho_w}$$

$$V_{w\_init} := 4 \cdot V_{w\_init\_cylinders} + 10 \cdot V_{w\_init\_rings} + V_{w\_init\_bricks} + V_{w\_init\_pellet}$$

$V_{w\_init} = 3.392$

## Program calculating water volume from density and water content data

$$
\mathrm{vol}(DATA, \Delta r_{min}, H) := \left|
\begin{array}{l}
sum \leftarrow 0 \\
row \leftarrow 0 \\
j \leftarrow 0 \\
\text{while } row \le \mathrm{rows}(DATA) - 1 \\
\quad \left|
\begin{array}{l}
r_{start_j} \leftarrow DATA_{row,0} \\
r_{end_j} \leftarrow r_{start_j} \\
\rho_j \leftarrow 0 \\
w_j \leftarrow 0 \\
i \leftarrow 0 \\
\text{while } row \le \mathrm{rows}(DATA) - 1 \wedge DATA_{row,0} - r_{start_j} \le \Delta r_{min} \\
\quad \left|
\begin{array}{l}
r_{end_j} \leftarrow DATA_{row,0} \\
\rho_j \leftarrow \rho_j + DATA_{row,3} \\
w_j \leftarrow w_j + DATA_{row,2} \\
i \leftarrow i + 1 \\
row \leftarrow row + 1
\end{array}
\right. \\
\rho_j \leftarrow \dfrac{\rho_j}{i} \\
w_j \leftarrow \dfrac{w_j}{i} \\
sum \leftarrow sum + \dfrac{\rho_j}{1 + \dfrac{1}{w_j}} \cdot \left[ \left( \dfrac{r_{end_j}}{1000} \right)^2 - \left( \dfrac{r_{start_j}}{1000} \right)^2 \right] \\
j \leftarrow j + 1 \\
row \leftarrow row - 1 \quad \text{if } row \le \mathrm{rows}(DATA) - 1
\end{array}
\right. \\
volume \leftarrow \dfrac{sum \cdot H \cdot \pi}{\rho_w} \\
\begin{pmatrix} volume \\ r_{start} \\ r_{end} \\ \rho \\ w \end{pmatrix}
\end{array}
\right.
$$

## Calculate final water volume

$C4\_sol := vol(C4, 50, H_C)$ $\quad C4\_sol_0 = 0.502$

$C3\_sol := vol(C3, 60, H_C)$ $\quad C3\_sol_0 = 0.491$

$C2\_sol := vol(C2, 65, H_C)$ $\quad C2\_sol_0 = 0.512$

$R10\_sol := vol(R10, 50, H_R)$ $\quad R10\_sol_0 = 0.495$

$R9\_sol := vol(R9, 60, H_R)$ $\quad R9\_sol_0 = 0.322$

$R8\_sol := vol(R8, 60, H_R)$ $\quad R8\_sol_0 = 0.323$

$R7\_sol := vol(R7, 50, H_R)$ $\quad R7\_sol_0 = 0.324$

$R6\_sol := vol(R6, 55, H_R)$ $\quad R6\_sol_0 = 0.324$

$$V_{w\_final} := \left(C4\_sol_0 + C3\_sol_0 + 2 \cdot C2\_sol_0 + R10\_sol_0 + R9\_sol_0 + R8\_sol_0 + R7\_sol_0 + 6 \cdot R6\_sol_0\right)$$

$$V_{w\_final} = 5.428$$

## Calculate added water volume and compare with measurement

$\Delta V_{w\_calc} := \left(V_{w\_final} - V_{w\_init}\right)$ $\quad \Delta V_{w\_calc} = 2.036$

$\Delta V_{w\_measured} := 1.620$

$$\Delta V_{w\_calc} - \Delta V_{w\_measured} = 0.416$$

$$\frac{\Delta V_{w\_calc} - \Delta V_{w\_measured}}{\Delta V_{w\_measured}} = 0.257$$

## Calculate initial avaliable pore volume

| | | |
|---|---|---|
| Cylinders | $e_C := 0.636$ | $H_{swell} := 0.034$ |
| Rings | $e_R := 0.56$ | $\Delta r_{slot} := 0.01$ |
| Bricks | $e_B := 0.72$ | |
| Pellet slot | $e_P := 1.778$ | |

$$V_{av\_init\_cylinders} := H_C \cdot r_o^2 \cdot \pi \cdot \frac{e_C}{1 + e_C} \cdot \left(1 - \frac{\rho_s}{\rho_w} \cdot \frac{w_C}{e_C}\right)$$

$$V_{av\_init\_rings} := H_R \cdot \left(r_o^2 - r_i^2\right) \cdot \pi \cdot \frac{e_R}{1 + e_R} \cdot \left(1 - \frac{\rho_s}{\rho_w} \cdot \frac{w_R}{e_R}\right)$$

$$V_{av\_init\_bricks} := H_B \cdot r_i^2 \cdot \pi \cdot \frac{e_B}{1 + e_B} \cdot \left(1 - \frac{\rho_s}{\rho_w} \cdot \frac{w_B}{e_B}\right)$$

$$V_{av\_init\_pellet} := H_P \cdot \left[\left(r_o + \Delta r_{pellets}\right)^2 - r_o^2\right] \cdot \pi \cdot \frac{e_P}{1 + e_P} \cdot \left(1 - \frac{\rho_s}{\rho_w} \cdot \frac{w_P}{e_P}\right)$$

$$V_{av\_init\_slot} := \left(10 \cdot H_R - H_B\right) \cdot \left[r_i^2 - \left(r_i - \Delta r_{slot}\right)^2\right] \cdot \pi$$

$$V_{av\_init\_swell} := H_{swell} \cdot \left(r_o + \Delta r_{pellets}\right)^2 \cdot \pi$$

$$V_{av\_init} := 4 \cdot V_{av\_init\_cylinders} + 10 \cdot V_{av\_init\_rings} + V_{av\_init\_bricks} + V_{av\_init\_pellet}$$

$$V_{av\_init} := V_{av\_init} + V_{av\_init\_slot} + V_{av\_init\_swell}$$

$$V_{av\_init} = 2.264$$

## Calculate estimate of water volume added at installation

$w_{P\_wet} := 0.572$

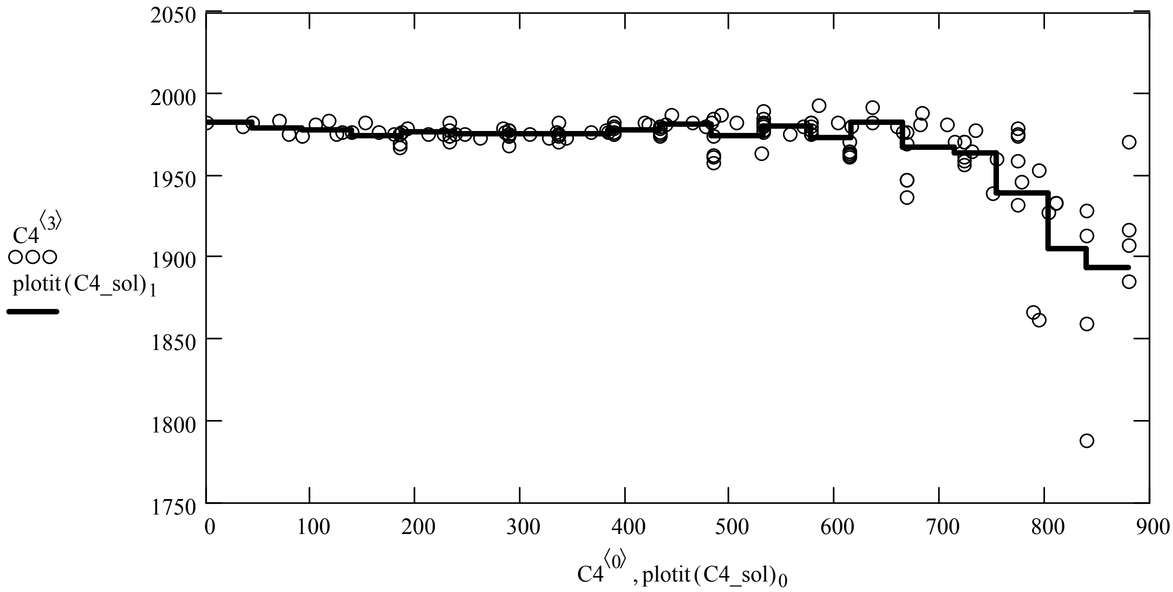
$$\Delta V_{init\_pellet\_wet} := H_P \cdot \left[ \left( r_o + \Delta r_{pellets} \right)^2 - r_o^2 \right] \cdot \pi \cdot \frac{e_P}{1 + e_P} \cdot \left( \frac{\rho_s}{\rho_w} \cdot \frac{w_{P\_wet}}{e_P} - \frac{\rho_s}{\rho_w} \cdot \frac{w_P}{e_P} \right)$$

$\Delta V_{init\_pellet\_wet} = 1.096$

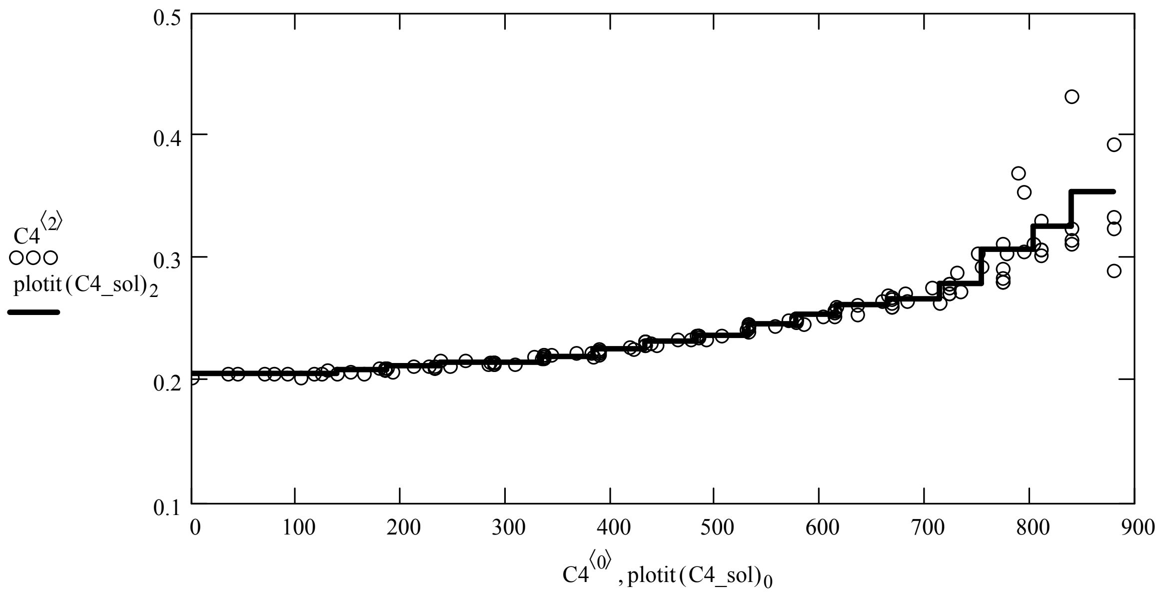
$V_{av\_init\_slot} = 0.166$

$\Delta V_{init\_pellet\_wet} + V_{av\_init\_slot} = 1.261$

Density - radius




Water content - radius



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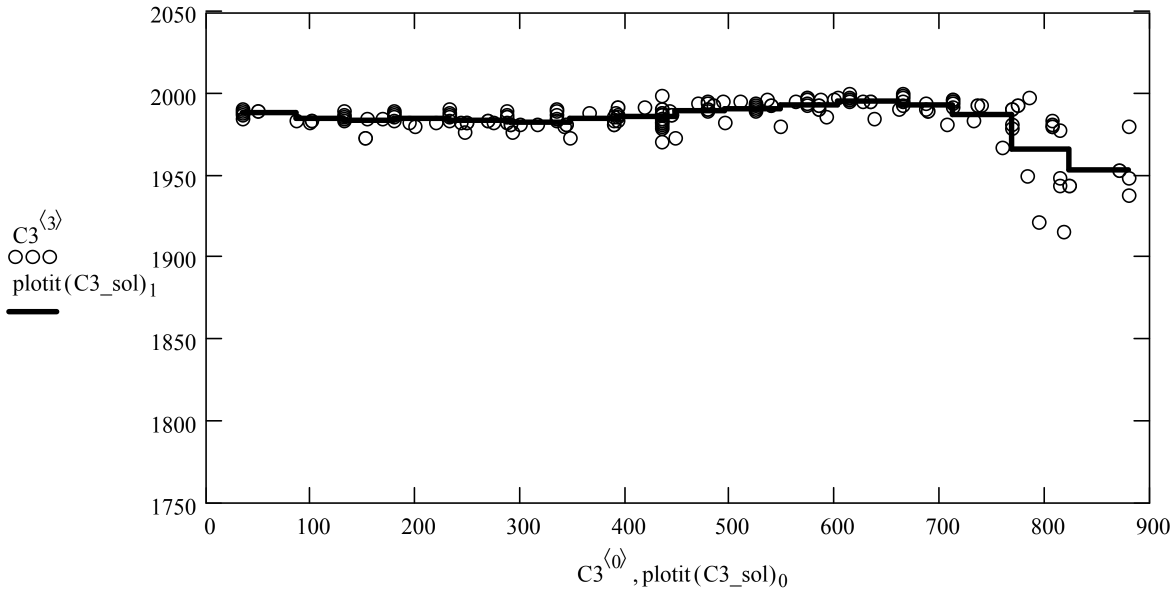


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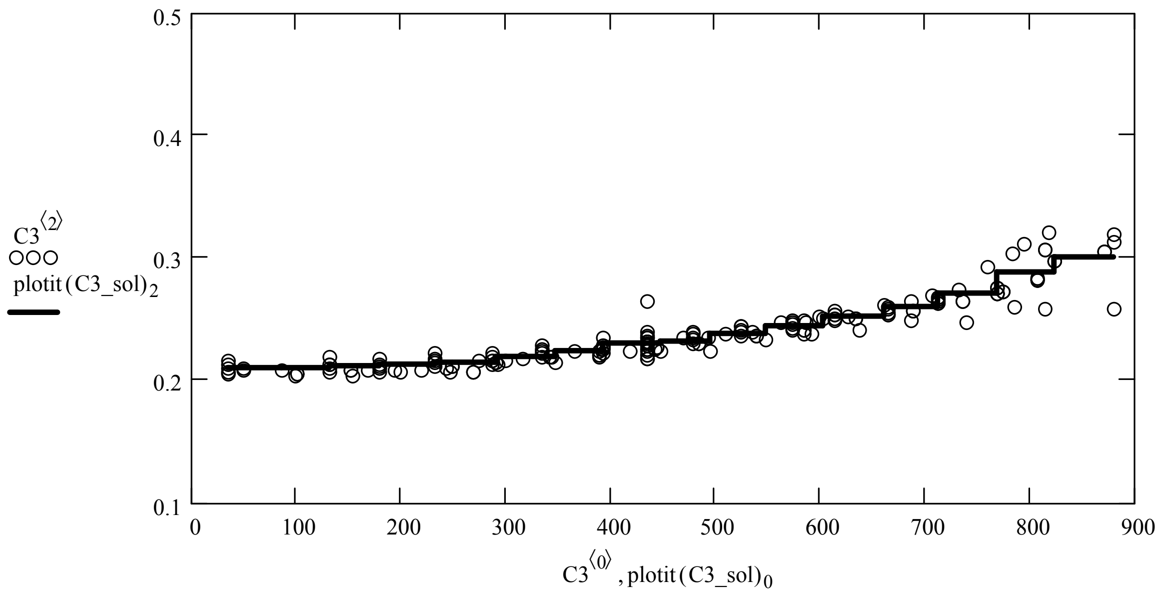

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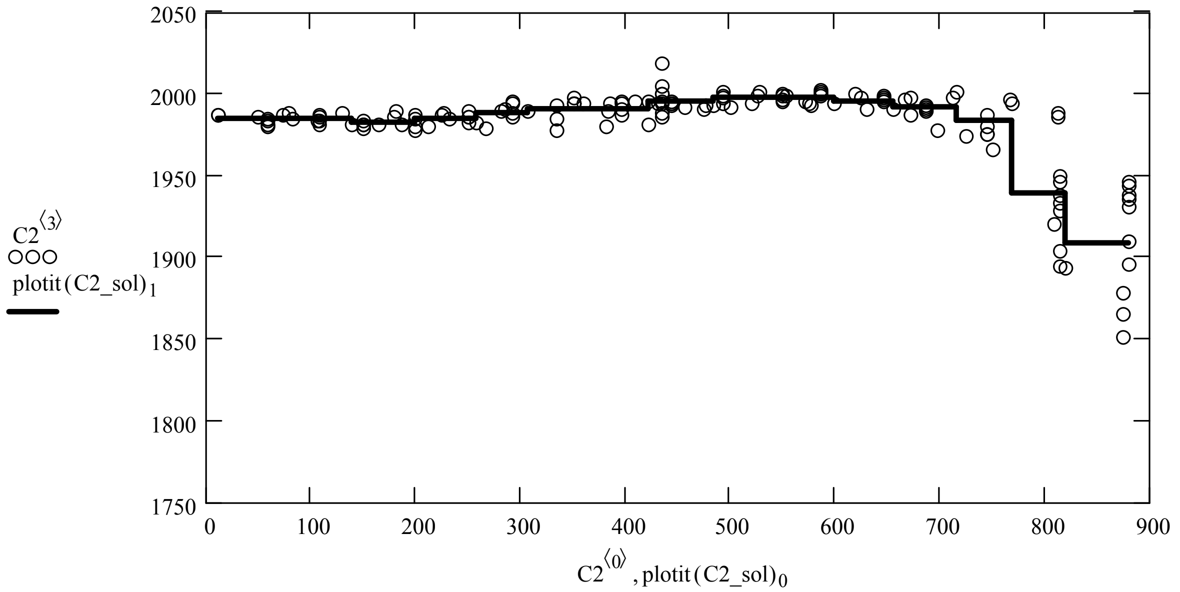


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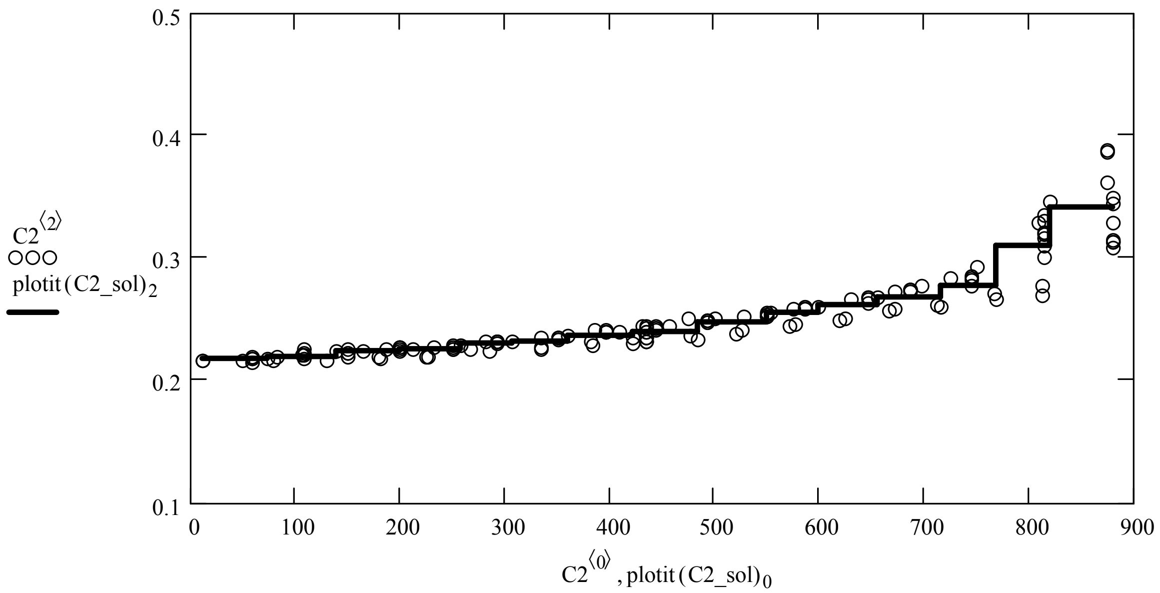

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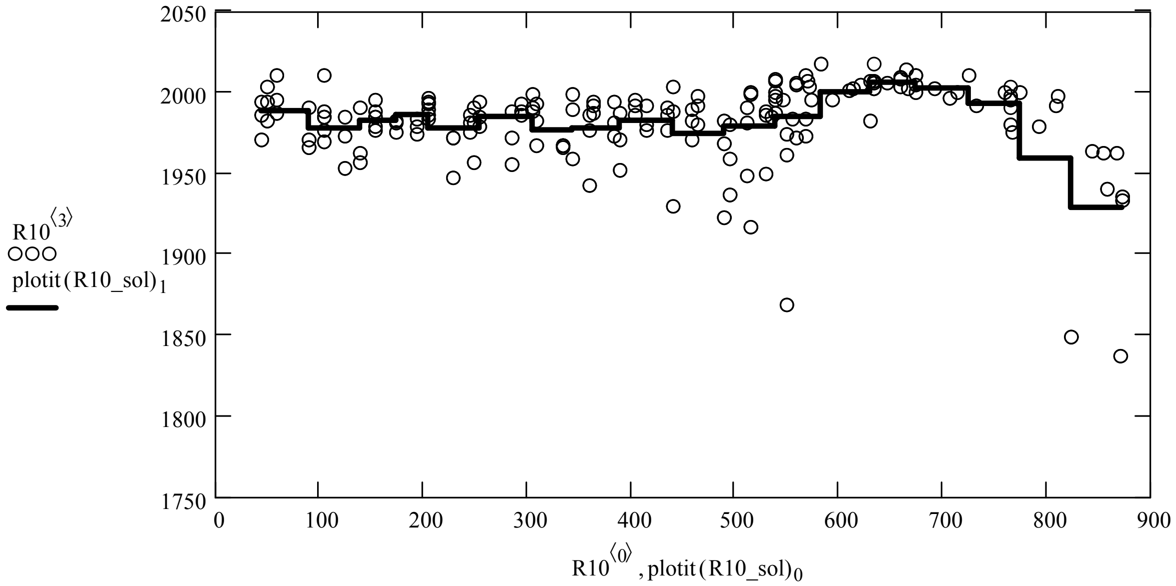


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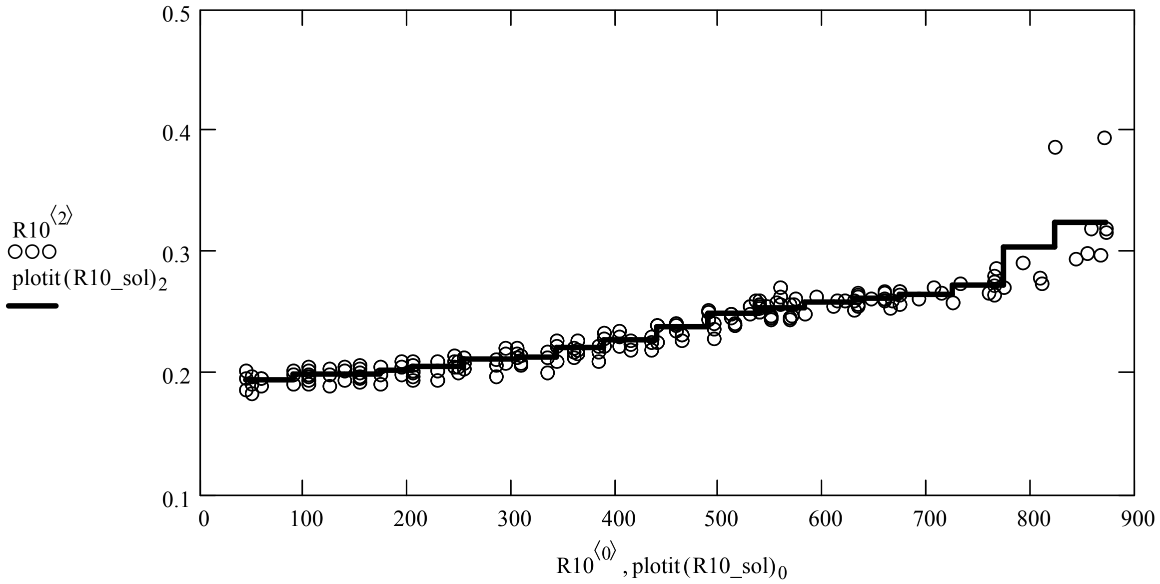

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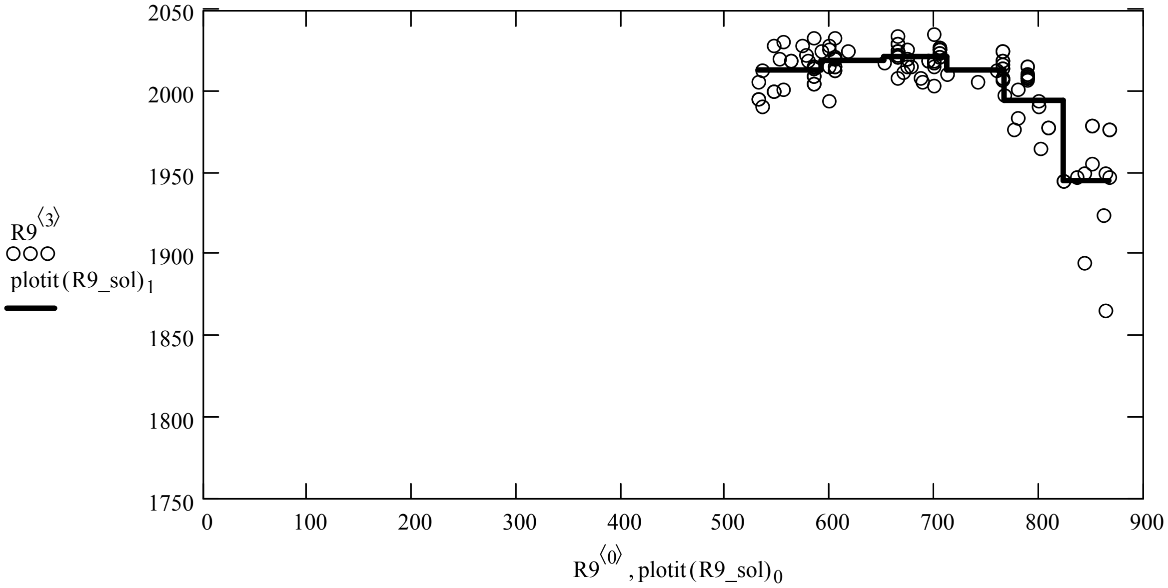


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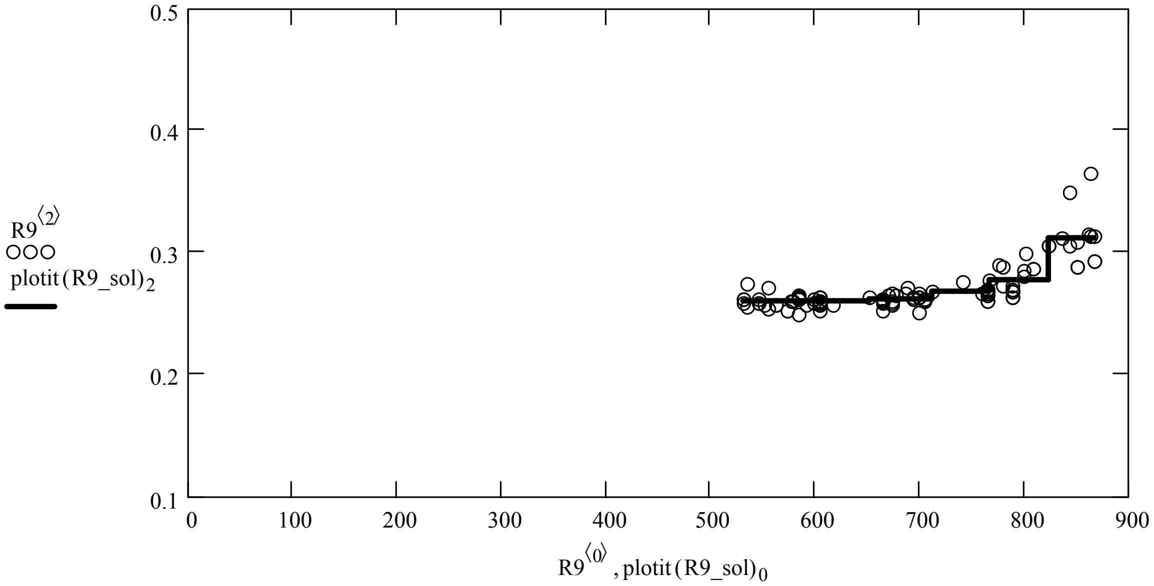

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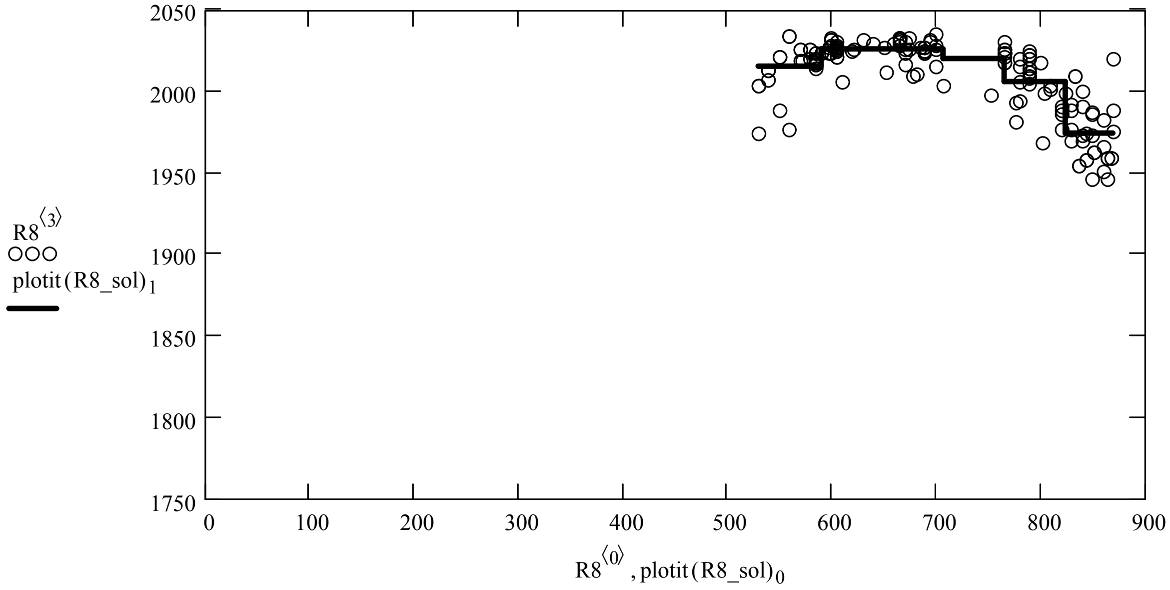


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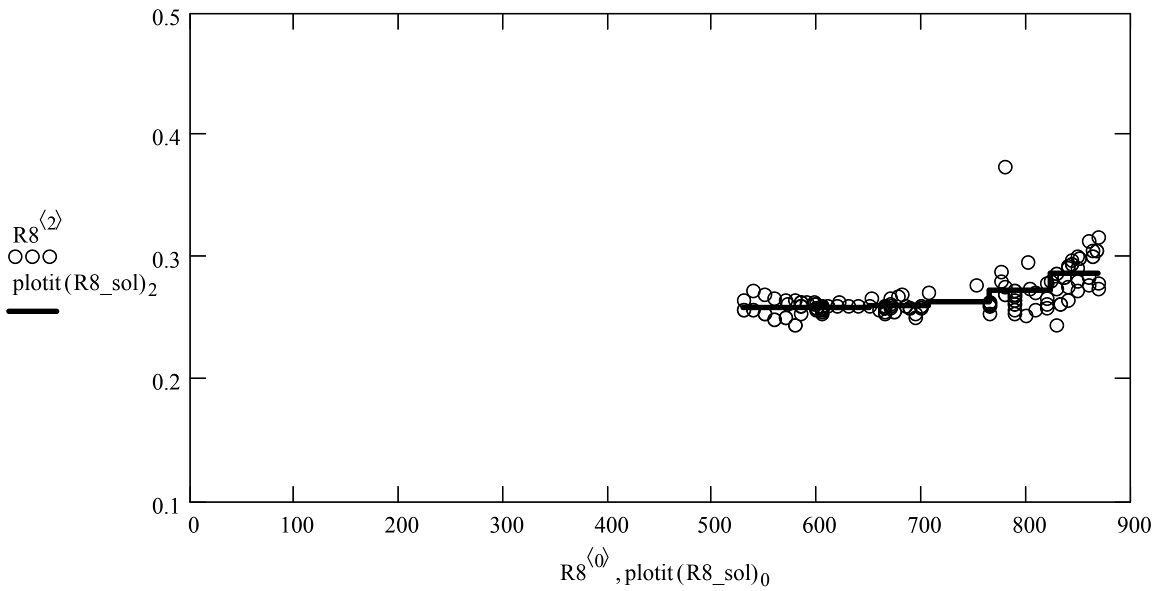

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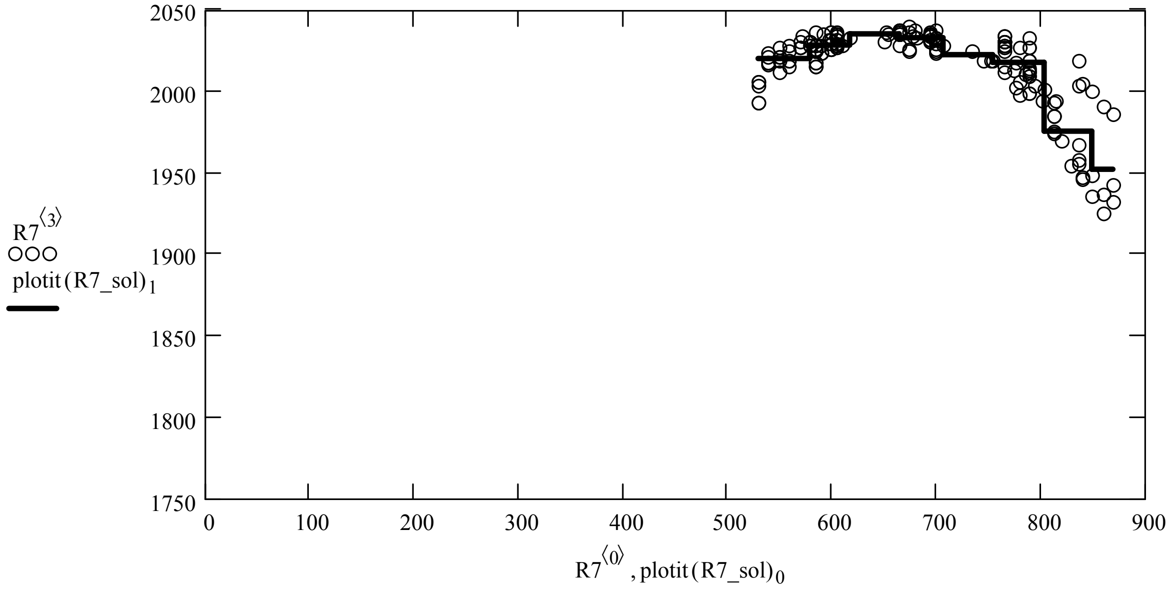


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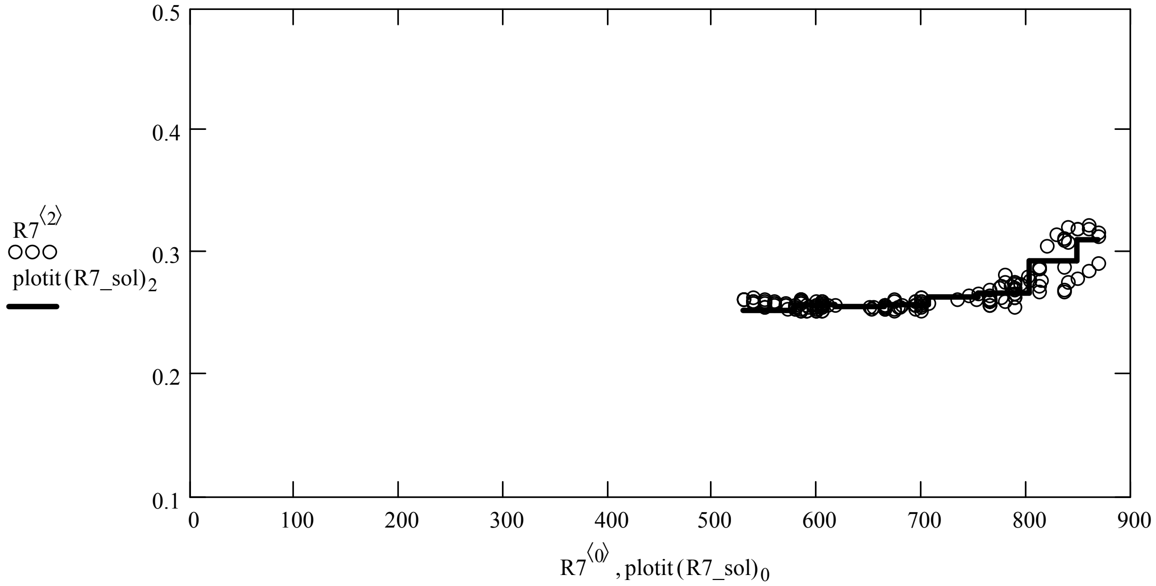
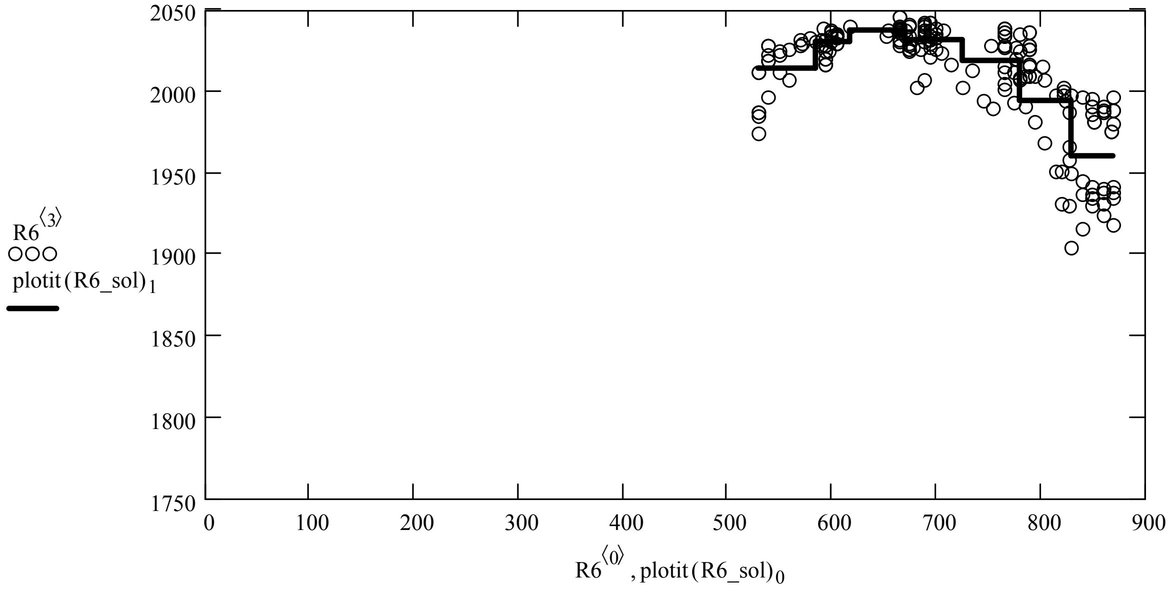


Density - radius




Water content - radius