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Annexes 2
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Test report – Masonry based on lime mortar

Determining the Secant Modulus of Elasticity of Masonry based on lime mortar and measuring the long-term compressive and flexural strength of hardened lime mortar

Specimens: 6 walls with the dimension 588x588x108 mm and 36 mortar prism with dimension the 160x40x40mm:

1 Wall type A
1 Wall type B
1 Wall type C
3 Walls type E
See annex 1 for details about the brick types A, B, C and E.

12 sets of 3 mortar prisms.
Applied mortar: K100/1200 mortar from *Vejle Kalk- & Mørtelværk*. (Lime Mortar 7.7%).

Start date: Wall type A, B and C were built 2013-09-05.
6 sets of mortar prisms were built 2013-11-21.
3 walls of type E and 6 mortar prism were cast 2014-01-08.

Method: The walls were tested according to EN 1052-1 Methods of test for masonry – Part 1: Determination of compressive strength.

The mortar samples were tested according to EN 1015-11 Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar.

Period: The experiments were conducted in the period from 2013-09-05 to 2015-03-13.

Results: See page 4-8 (table 1-4).

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Test setup

The deformation of the wall during the compression was measured with two *HBM 50 mm transducers*. The transducers were pushed downwards onto a steel rod, which was fixated to a lightweight aluminum frame. The mean deformation in the center of the wall was determined based on the mean value of the two measured deformations on each sides of the wall. The stiffness of the frame is assumed to be infinite in the vertical direction.

In order to determine the strains, the initial distance between the two aluminum frames was measured. The test was recorded with the data aquisition hardware *HBM Spider8* and the software *CatmanEasy*.

Picture 1: Test setup.

Above and below the wall a soft 10 mm layer of masonite was placed to reduce the irregularities on the surfaces. A steel profile was mounted above the masonite layer to distribute the load equally. The weight of the distribution profile was included in the calculations. The walls were tested in an Amsler 500 ton compression machine.

Determination of E_{0k} is based on the assumed characteristic compressive strength of the masonry equal to f_k = 3.15 MPa - in reality, the value is higher, but this is of lesser importance. This means that E_{0k} was determined in the range of $0{,}05f_k$ to $0{,}35f_k$.

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Picture 2: Placement of the deformation transducer on the steel rod.

Picture 3. Overall view of the test setup.

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Results

Secant Modulus of Elasticity

The results for the secant modulus of elasticity appear on table 1 and 2, while the strength values appear on table 3. The results for the hardened lime mortar prisms appear on table 4.

The values signed with an "a" were assumed to be wrong and omitted, because the deformation transducers were occasionally gushing out in sudden increase of speed, indicating that they could have been partially stuck. The deformation transducers underwent repairs and calibration before the following tests.

The tests signed with a "b" were performed until failure occurred.

The values signed with "c" are the mean of three tests repeated on the same test setup. The values for each single test can be seen in table 2 on the next page. The purpose was simply to see the difference in values between several tests which were done right after each other on the same wall and with the exact same setup. Notice that the last tests, which were performed at 429 and 554 days of curing were first tested three times in the elastic zone, before being tested to failure in the fourth test. The failure loads are shown in table 3 on the next page.

Table 1. Secant Modulus of Elasticity in MPa for wall A, B, C, E1, E2 and E3.

Built Date / Curing days / Wall	28 05-02-14	60 04-11-13	117 05-05-14	144 27-01-14	188 15-07-14	229 22-04-14	267 02-10-14	313 15-07-14	390 30-09-14	429 13-03-15	554 13-03-15
05-09-13	**A**		3365[a]		1736		3120		3310	2965[c]		3374[bc]
05-09-13	**B**		5533[a]		2317		4665		4507[c]	4574[c]		4306[bc]
05-09-13	**C**		3968[a]		2086		3184		3139[c]	2957[c]		3154[bc]
08-01-14	**E1**			1581		1649[c]		1472[c]			1443[bc]	
08-01-14	**E2**	345[b]										
08-01-14	**E3**	610[b]										

Date format: dd-mm-yy

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Table 2. Modulus of Elasticity in MPA for wall A, B, C and E1.

Wall A	**Days**		
	390	**554**	
Test 1	3098	3420	
Test 2	2707	3361	
Test 3	3089	3342	
Mean	**2965**	**3374**	
Wall B	**Days**		
	313	**390**	**554**
Test 1	4527	4541	4425
Test 2	4481	4587	4271
Test 3	4512	4595	4221
Mean	**4507**	**4574**	**4306**
Wall C	**Days**		
	313	**390**	**554**
Test 1	3082	3118	3090
Test 2	3162	2835	3194
Test 3	3173	2918	3178
Mean	**3139**	**2957**	**3154**
Wall E1	**Days**		
	188	**267**	**429**
Test 1	1681	1483	1365
Test 2	1661	1485	1493
Test 3	1606	1448	1472
Mean	1649	1472	1443

Table 3. Strength in MPa for wall A, B, C, E1, E2 and E3.

Wall	**Age at testing [days]**	**Failure load [kN]**	**Load area [mm^2]**	**Strength [MPa]**
A	554	663	54864	12.1
B	554	613	54864	11.2
C	554	338	54864	6.16
E1	429	337	54864	6.14
E2	28	267	54864	4.87
E3	28	282	54864	5.14

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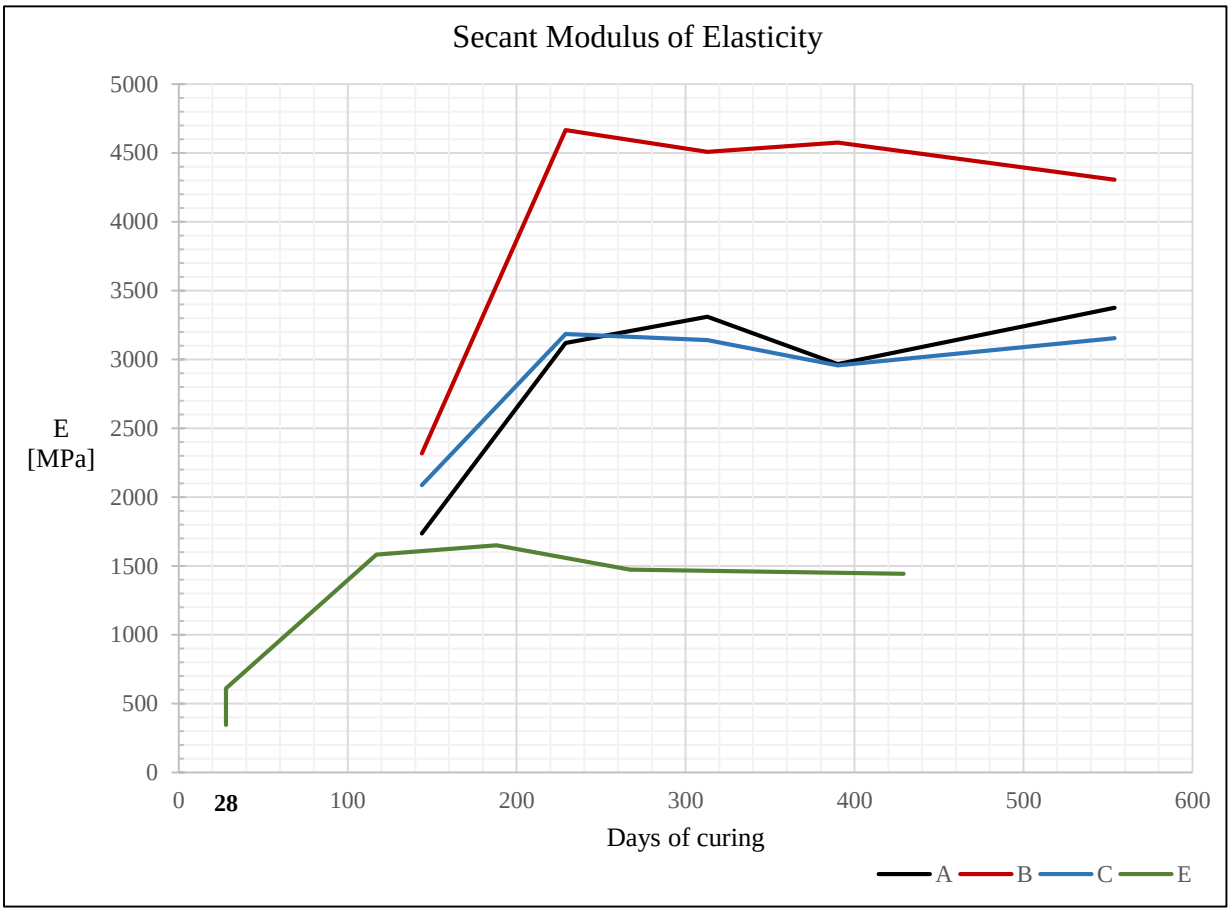
Results for the Secant Modulus of Elasticity – graphically depicted



Graph 1. The secant modulus of elasticity over time, for wall type A, B, C & E.

Stress-strain diagrams for each test are given in Annex 2.

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Mortar prisms

Initially 6 sets of prisms were cast 2013-11-21. Afterwards it was decided to add another 6 prisms to the test to gain more measurements. The last 6 sets of prisms were cast 2014-01-08. The values in table 4 are mean values[1].

Table 4: Mean compressive- and flexural strengths of lime mortar 7.7% during a period from 28 days to 421 days of curing.

Set no.	Cast date dd-mm-yyyy	Test date dd-mm-yyyy	Curing days	Mean compressive strength [MPa]	Mean flexural strength [MPa]
1	2014-01-08	2014-02-05	28	0.46	0.40
2	2013-11-21	2013-12-20	29	0.40	0.44
3	2013-11-21	2014-01-22	62	0.71	0.65
4	2014-01-08	2014-03-12	63	0.55	0.43
5	2014-01-08	2014-04-08	90	0.47	0.39
6	2014-01-08	2014-05-08	120	0.46	0.44
7	2013-11-21	2014-04-14	144	0.65	0.64
8	2014-01-08	2014-07-09	182	0.52	0.49
9	2014-01-08	2014-08-25	229	0.53	0.47
10	2013-11-21	2014-07-15	236	0.87	0.42
11	2013-11-21	2014-09-30	313	0.74	0.52
12	2013-11-21	2015-01-16	421	0.90	0.68
Standard deviation				0.17	0.10
Coefficient of Variation				27.6	20.7

The strength progressions are illustrated on graph 2 and 3 for the mean compressive- and flexural strength.

[1] The mean flexural strengths are based on results from three samples while the mean compressive strengths are based on results from six samples.

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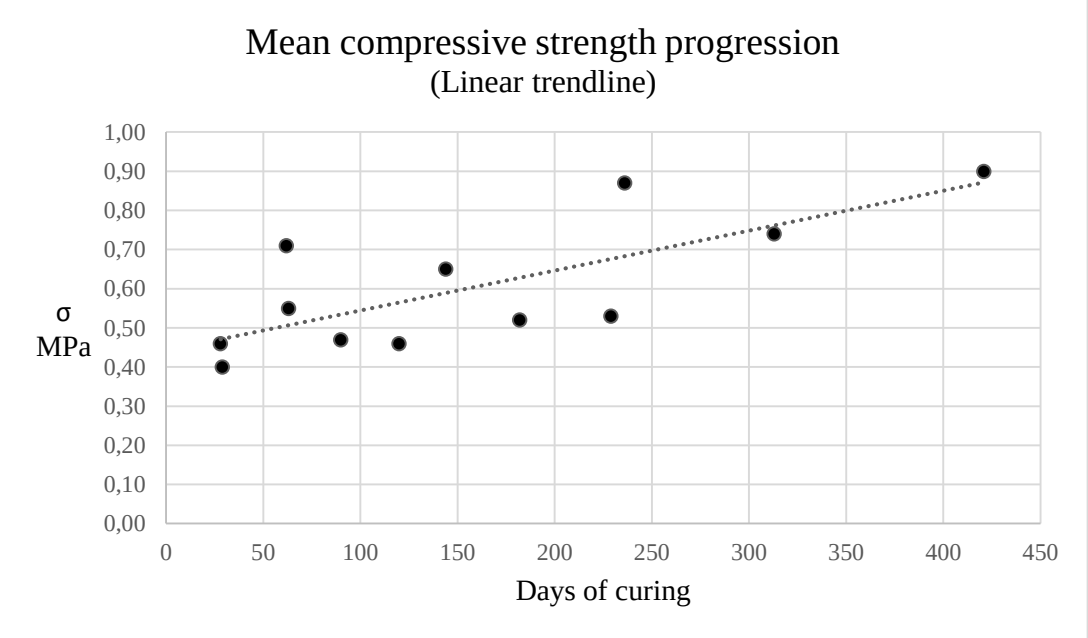
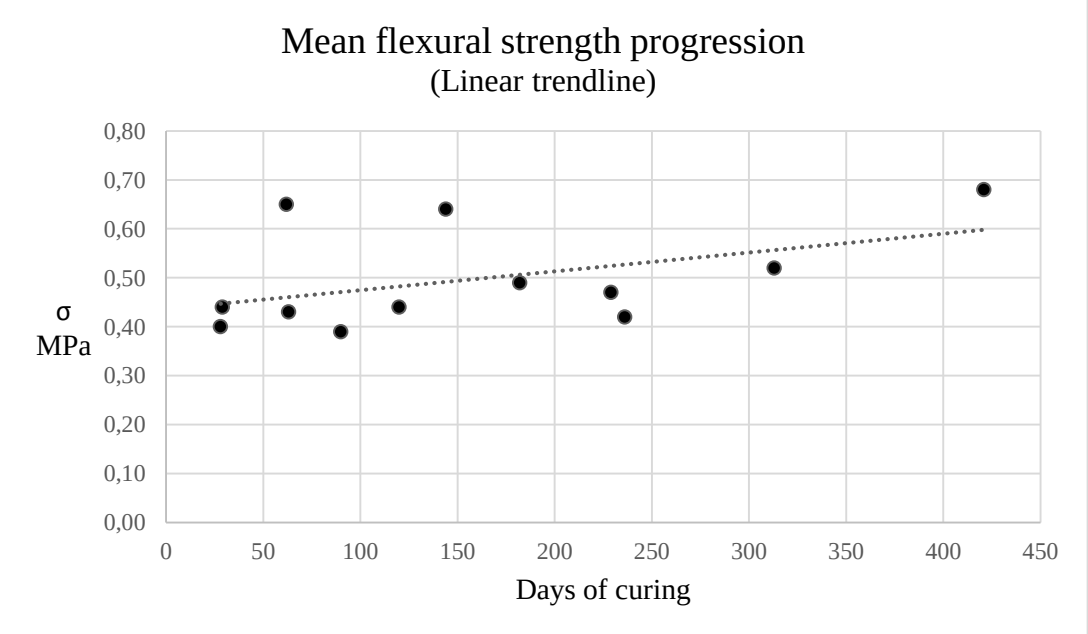
Graph 2: Mean compressive strengths of hardened lime mortar 7.7% during a period from 28 days to 421 days of curing.



Graph 3: Mean flexural strengths of hardened lime mortar 7.7% during a period from 28 days to 421 days of curing



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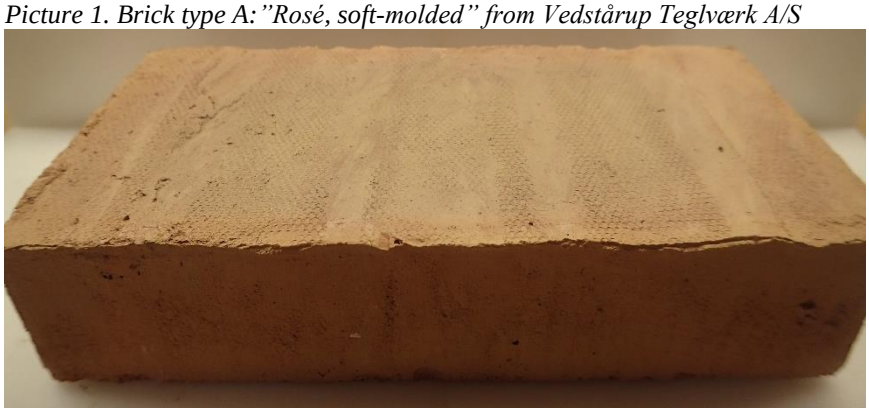
SELECTED BRICKTYPES

Annex 1

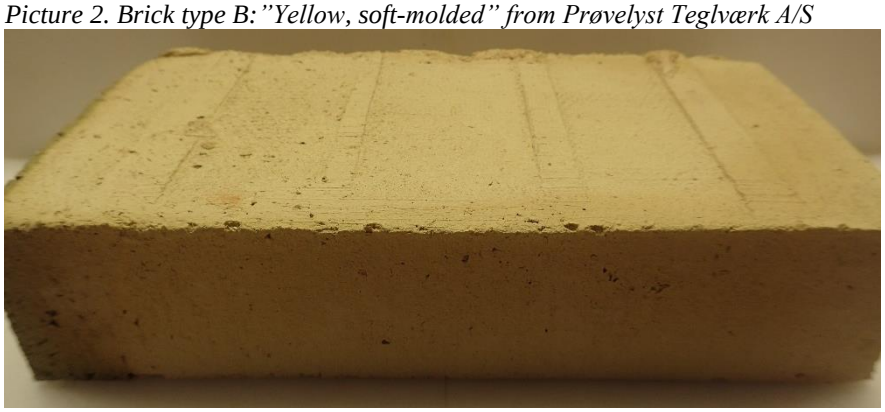
The bricks are selected and purchased by the Danish Technological Institute, Masonry department.

The bricks have the Danish standard format and their initial rate of water absorption is determined as described in DS / EN 772-11 for brick type A, B, C and E. The normalized compressive strength value for brick type E is from the DoP. The pictures below illustrates the applied brick types.

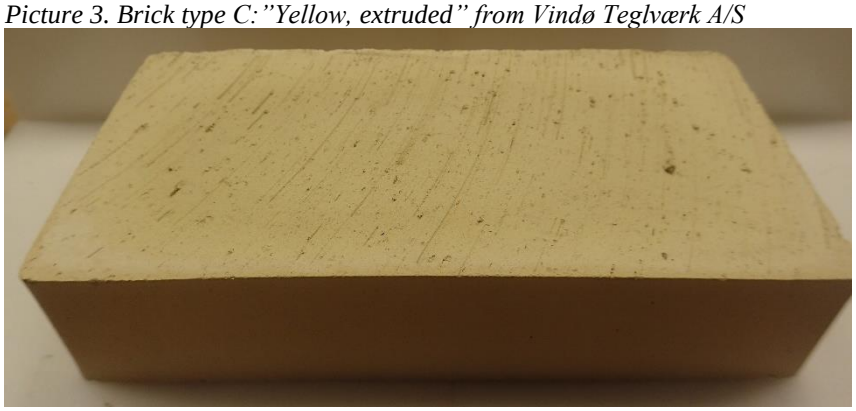
Picture 1. Brick type A:"Rosé, soft-molded" from Vedstårup Teglværk A/S



Picture 2. Brick type B:"Yellow, soft-molded" from Prøvelyst Teglværk A/S



Picture 3. Brick type C:"Yellow, extruded" from Vindø Teglværk A/S



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Picture 4. Brick type E:"Red, soft-molded – 2.2.07" from "Helligsø Teglværk A/S"

The values for the initial rate of water absorption and the normalized compression strength are given in the following two tables:

Table 1. Results for the initial rate of water absorption for brick type A, B, C and E.

Specimen	Initial rate of water absorption kg/m^2			
No.	A	B	C	E
1	1.4	2.4	3.8	1.7
2	1.3	2.5	3.0	1.7
3	1.5	2.4	3.7	1.8
4	1.2	2.2	3.1	1.9
5	1.4	2.6	3.8	1.7
6	1.3	2.3	3.2	1.7
7	1.2	2.3	3.4	1.7
8	1.4	2.3	3.1	1.7
9	1.3	2.5	3.4	1.8
10	1.1	2.4	3.7	1.7
Mean	1.3	2.4	3.4	1.7

Table 2. Results for the normalized compression strength for brick type A, B, C and E.

Specimen	Normalized compression strength MPa			
Type	A	B	C	E
Mean	27	32	42	16*

*Value from DoP – has not been tested by DTI.

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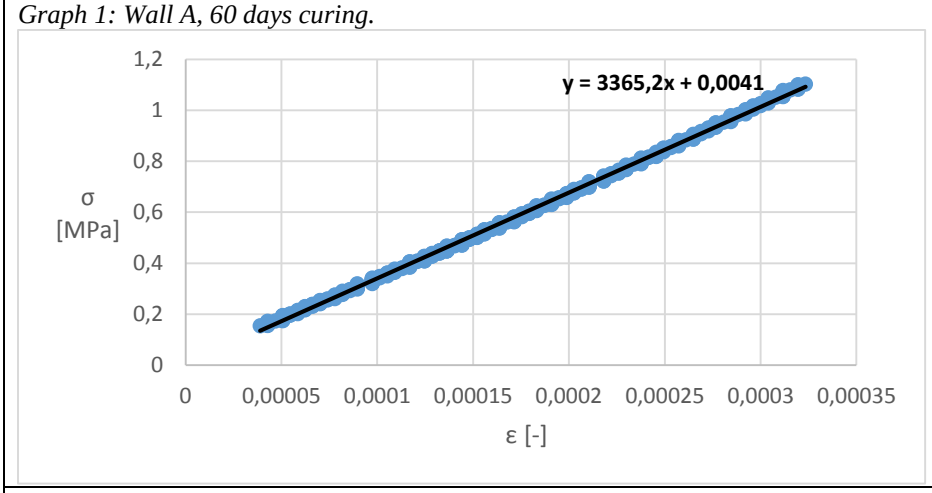
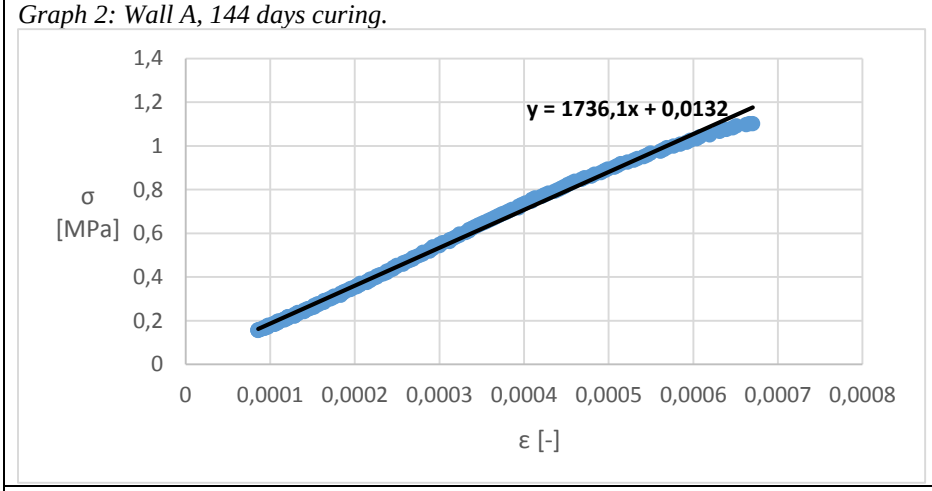
Annex 2

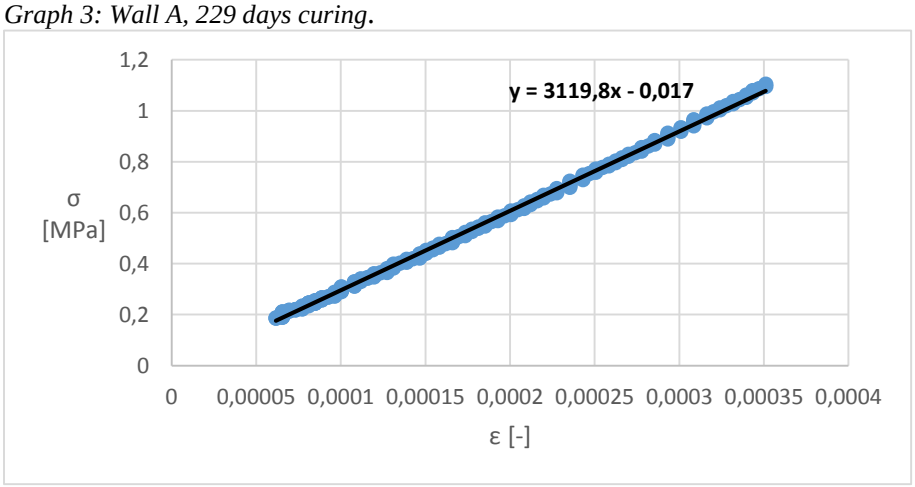
Graph 1: Wall A, 60 days curing.



Graph 2: Wall A, 144 days curing.



Graph 3: Wall A, 229 days curing.



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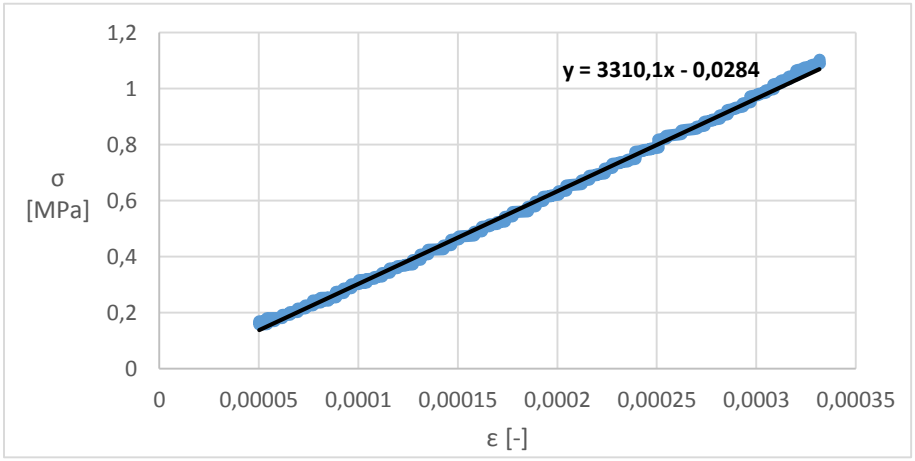
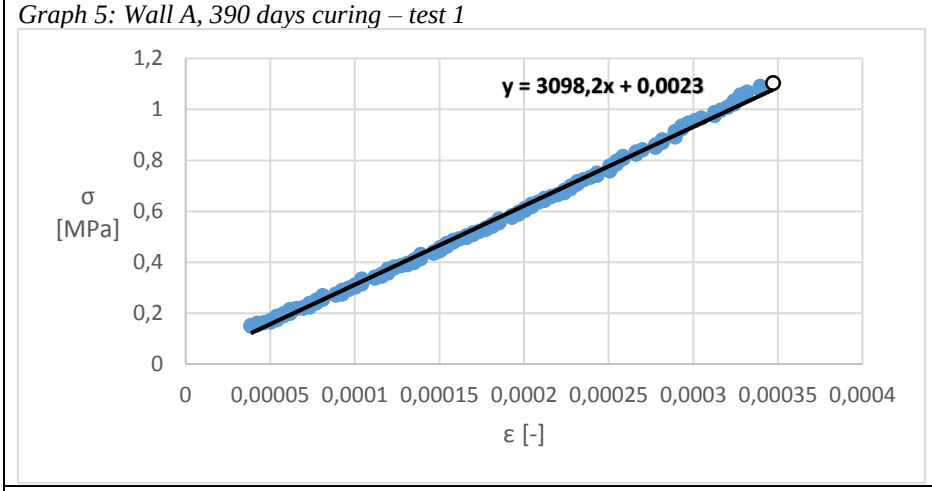
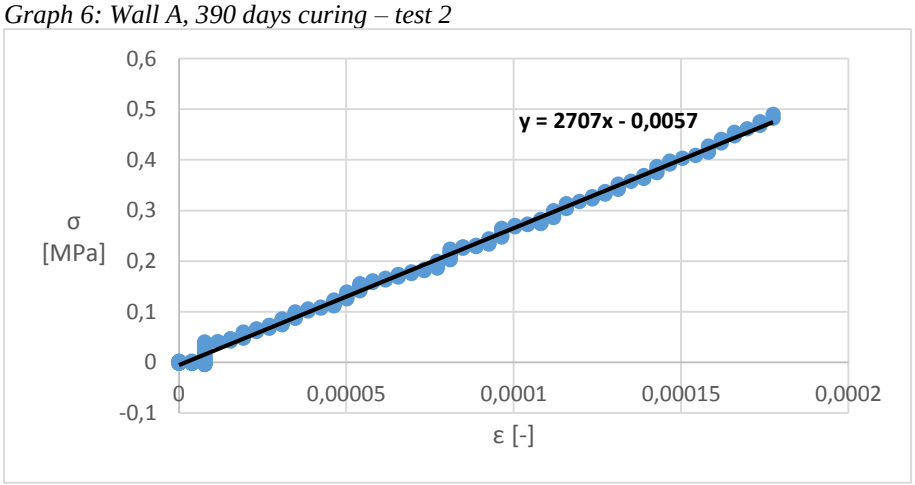
Graph 4: Wall A, 313 days curing



Graph 5: Wall A, 390 days curing – test 1



Graph 6: Wall A, 390 days curing – test 2



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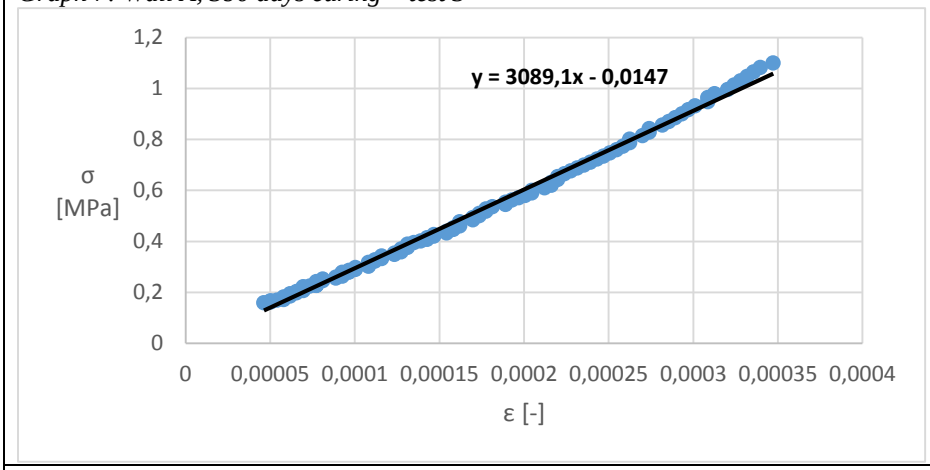
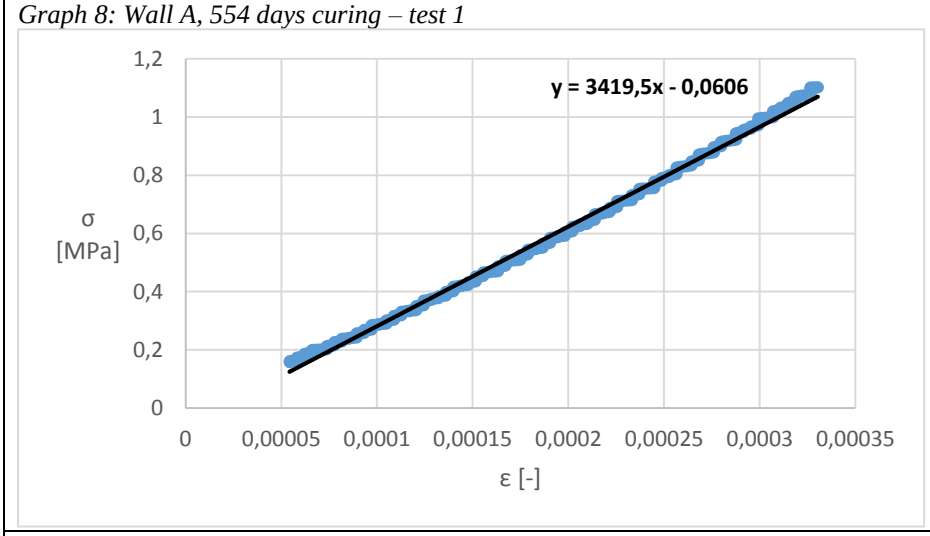
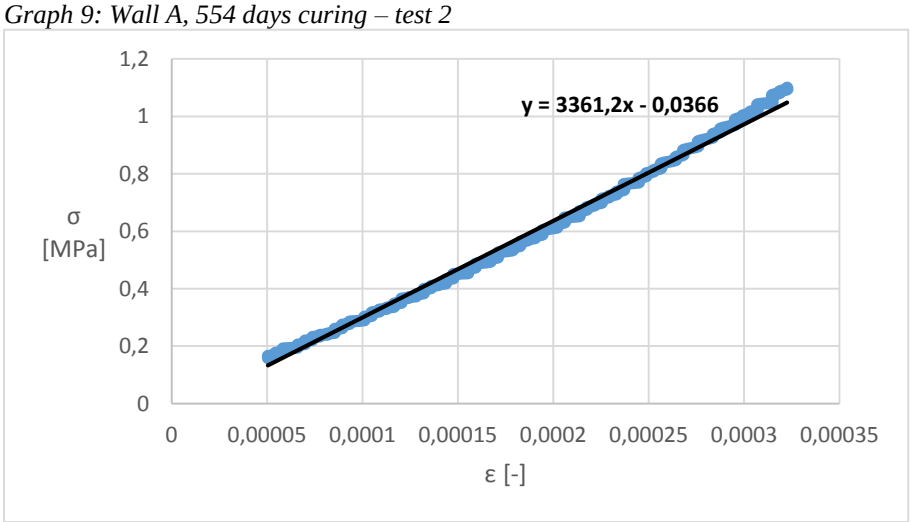
Graph 7: Wall A, 390 days curing – test 3



Graph 8: Wall A, 554 days curing – test 1



Graph 9: Wall A, 554 days curing – test 2



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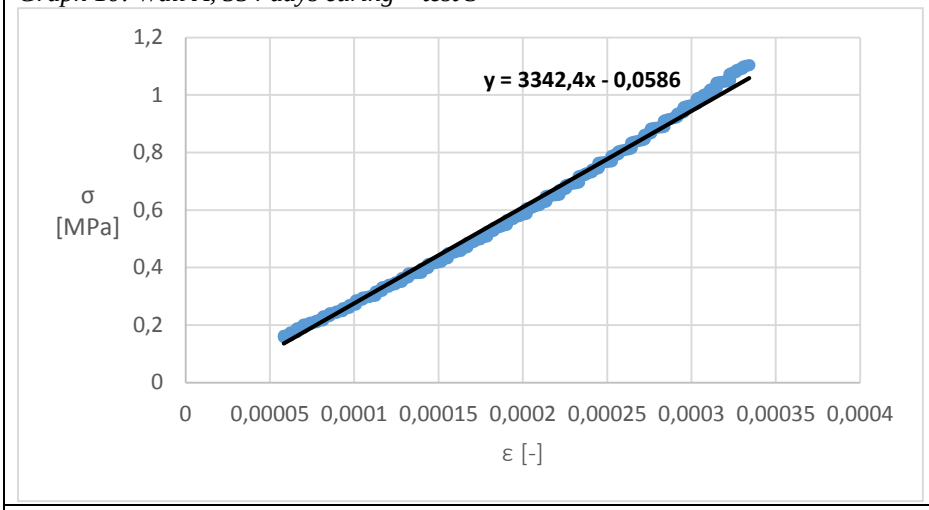
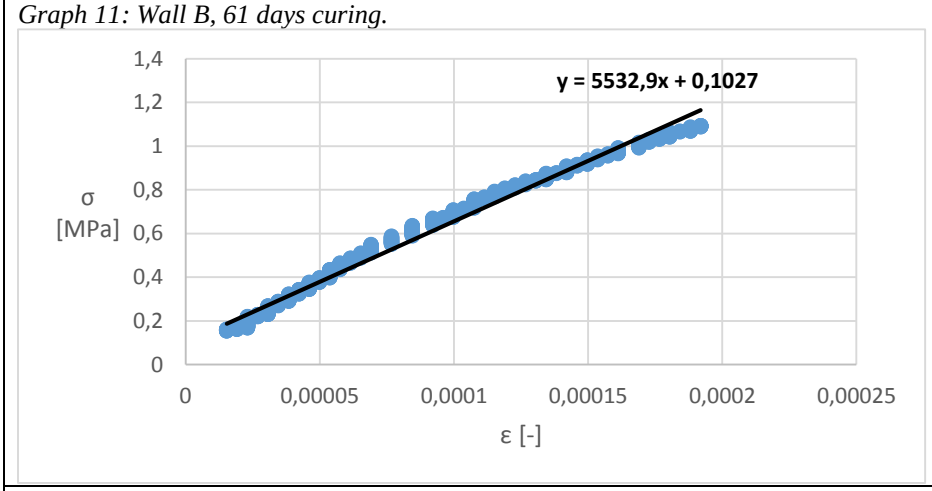
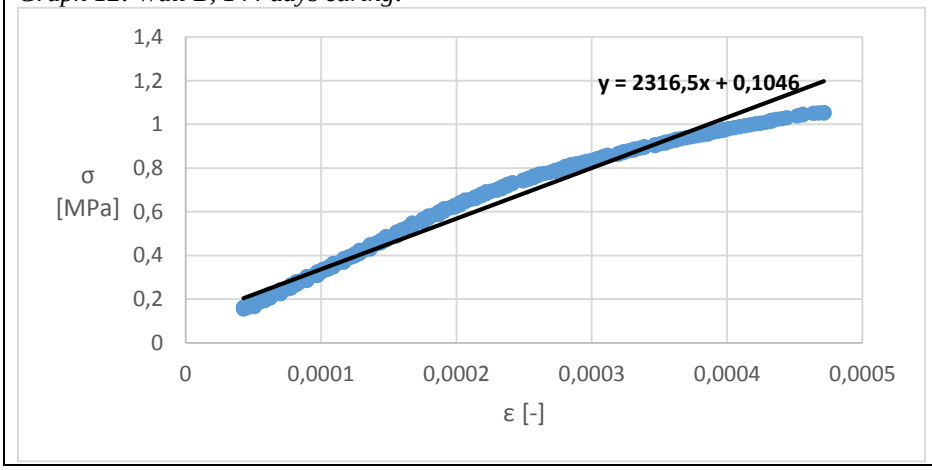
Graph 10: Wall A, 554 days curing – test 3



Graph 11: Wall B, 61 days curing.



Graph 12: Wall B, 144 days curing.



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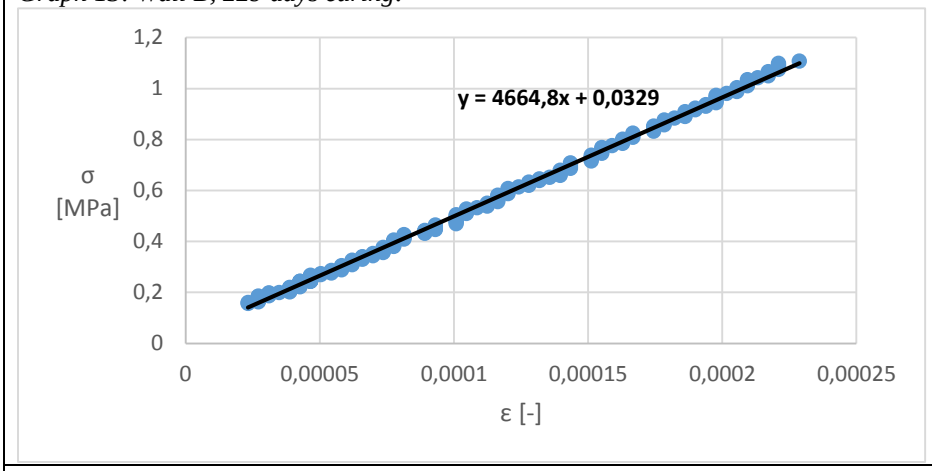
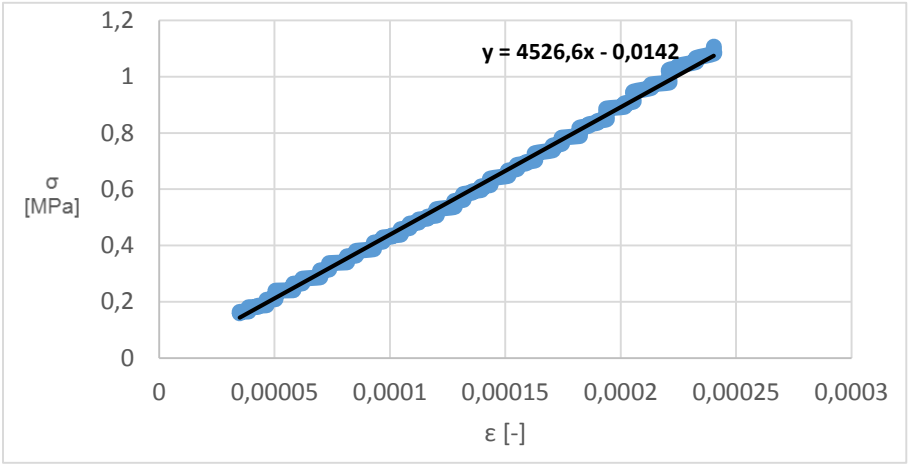
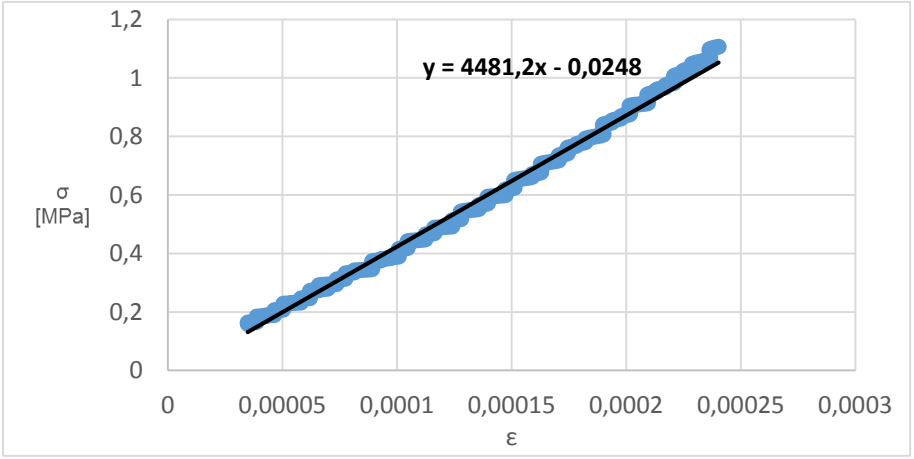
Graph 13: Wall B, 229 days curing.



Graph 14: Wall B, 313 days curing – test 1.



Graph 15: Wall B, 313 days curing – test 2.



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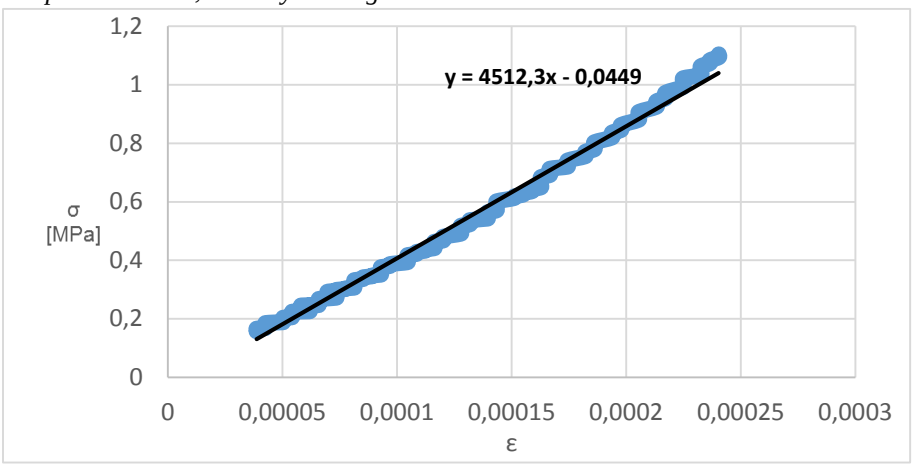
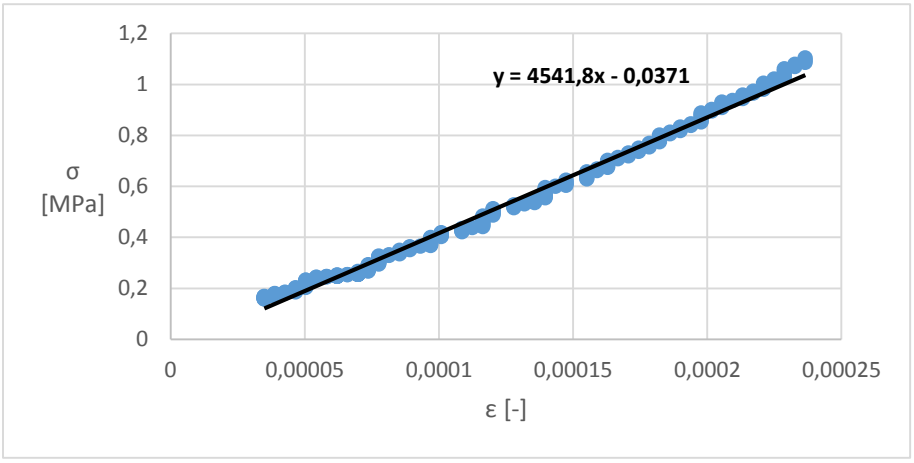
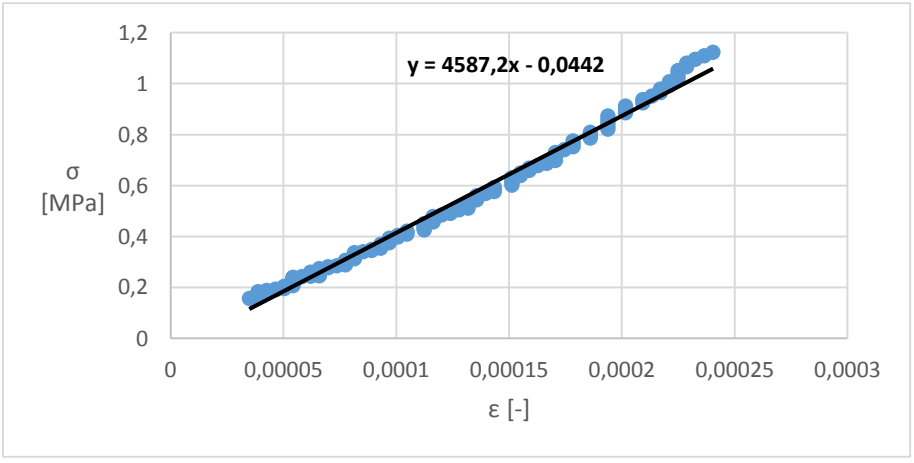
Graph 16: Wall B, 313 days curing – test 3.



Graph 17: Wall B, 390 days curing – test 1.



Graph 18: Wall B, 390 days curing – test 2.



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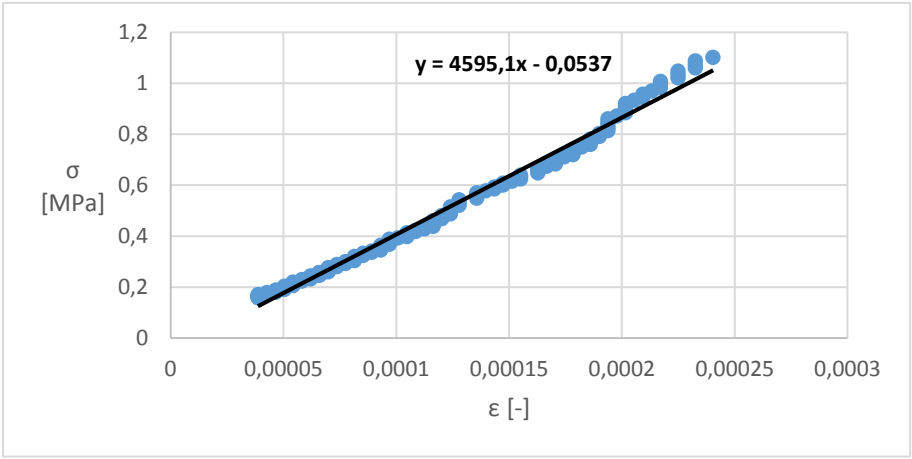
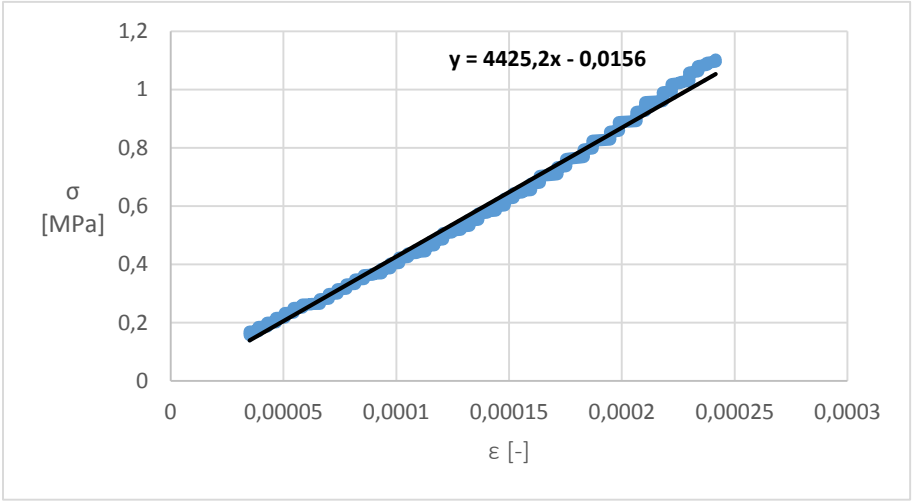
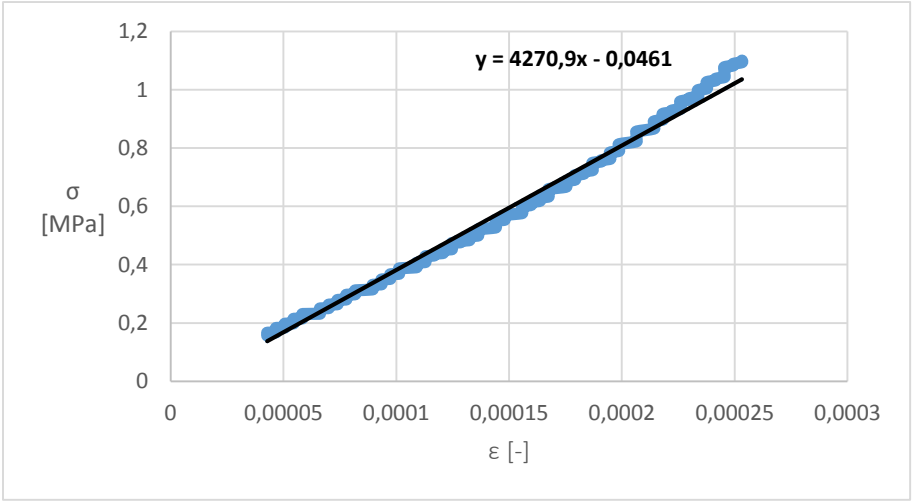
Graph 19: Wall B, 390 days curing – test 3.



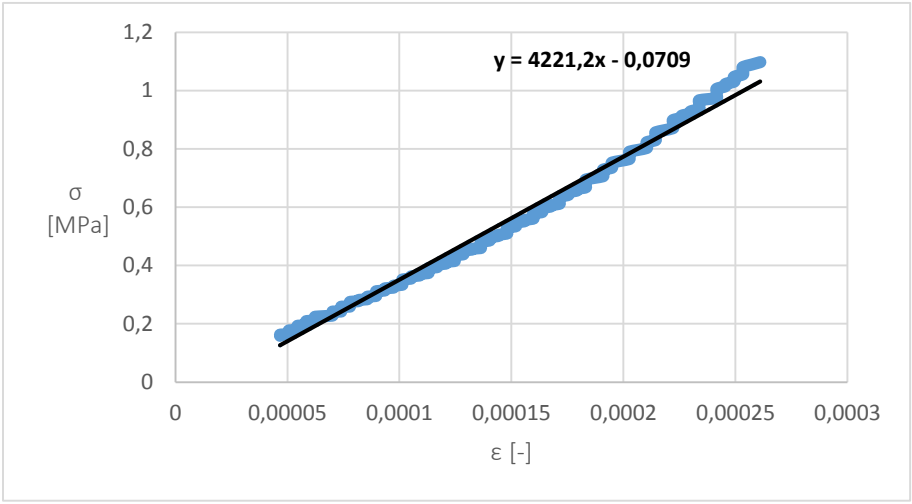
Graph 20: Wall B, 554 days curing – test 1.



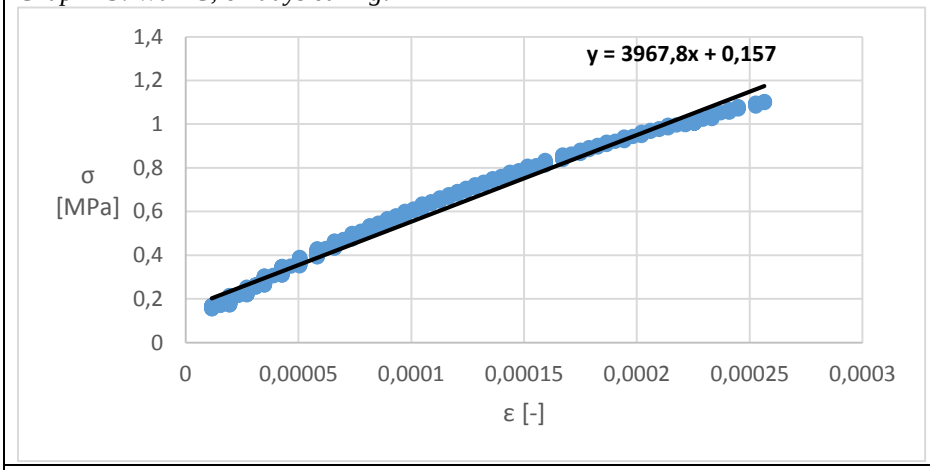
Graph 21: Wall B, 554 days curing – test 2.



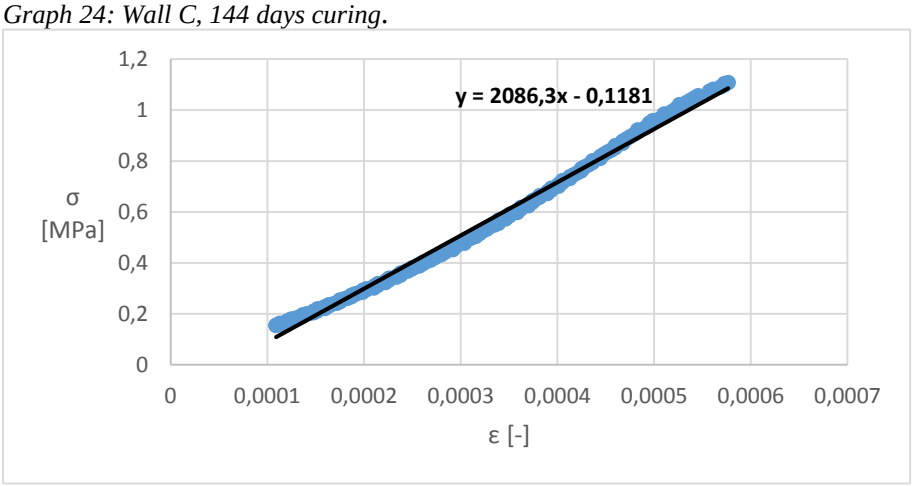
Graph 22: Wall B, 554 days curing – test 3.



Graph 23: Wall C, 61 days curing.



Graph 24: Wall C, 144 days curing.



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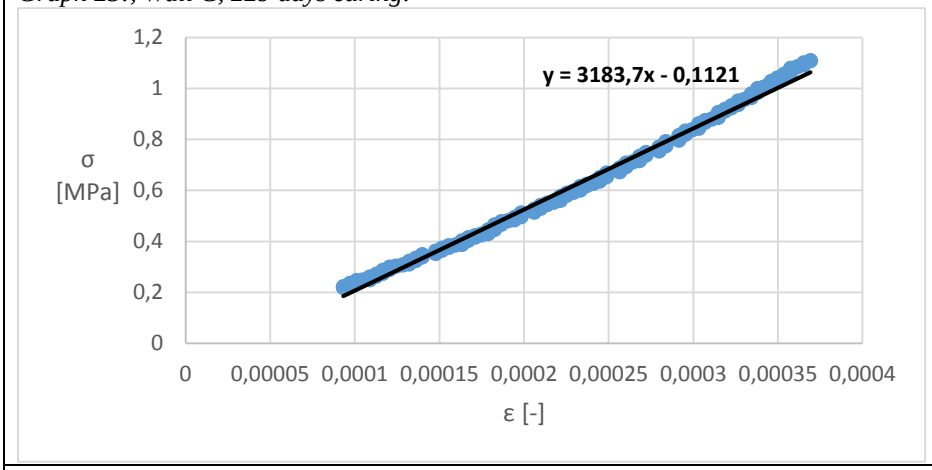
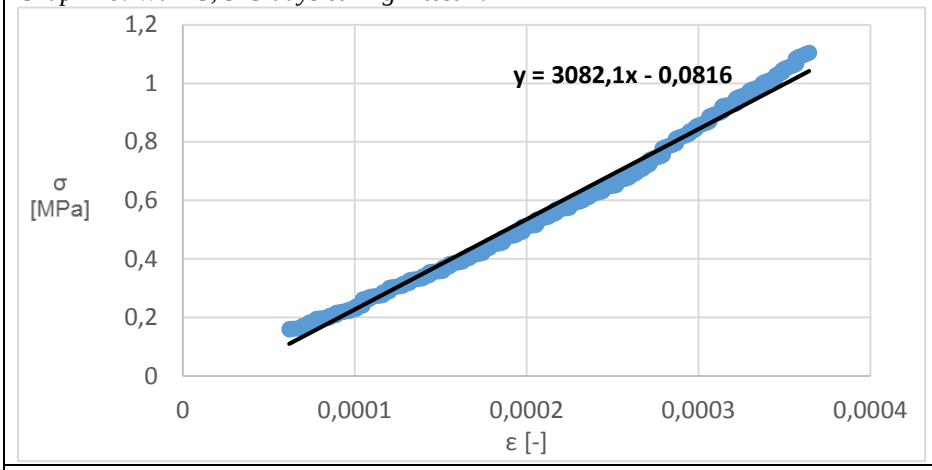
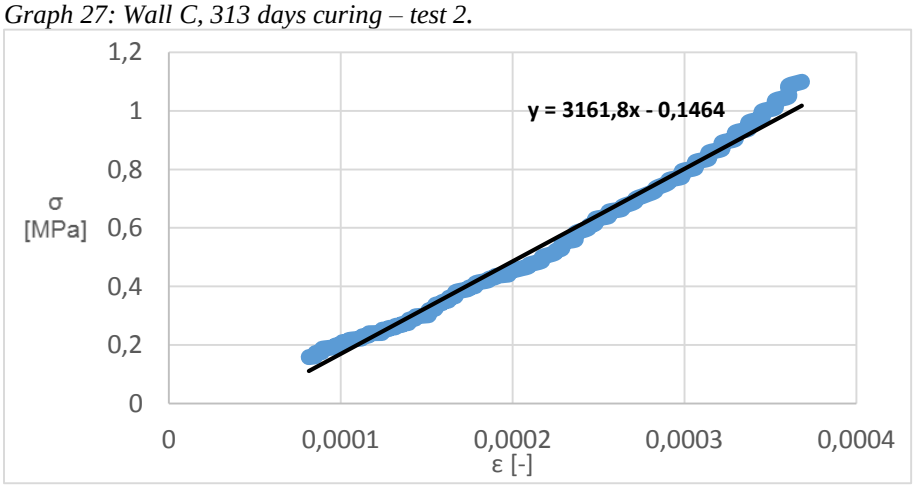
Graph 25:, Wall C, 229 days curing.



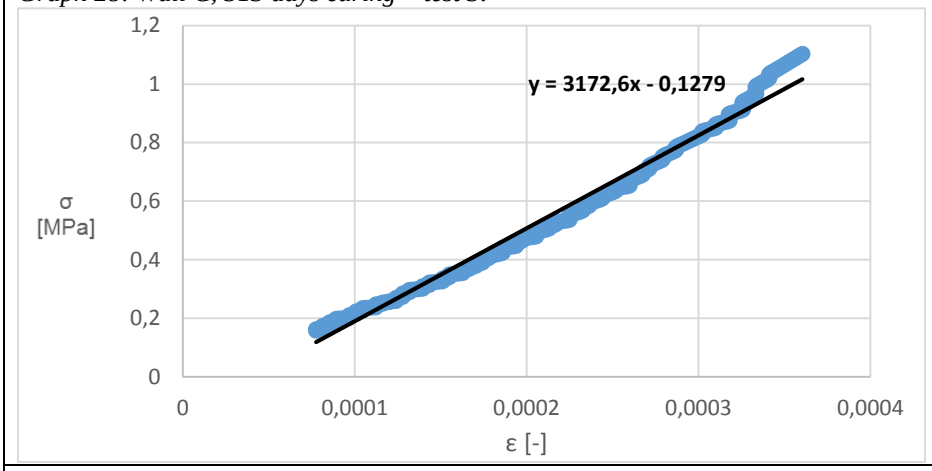
Graph 26: Wall C, 313 days curing – test 1.



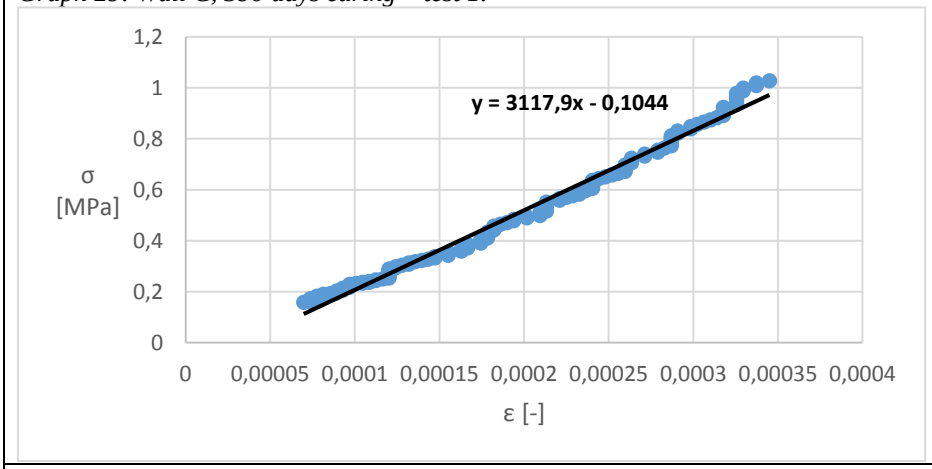
Graph 27: Wall C, 313 days curing – test 2.



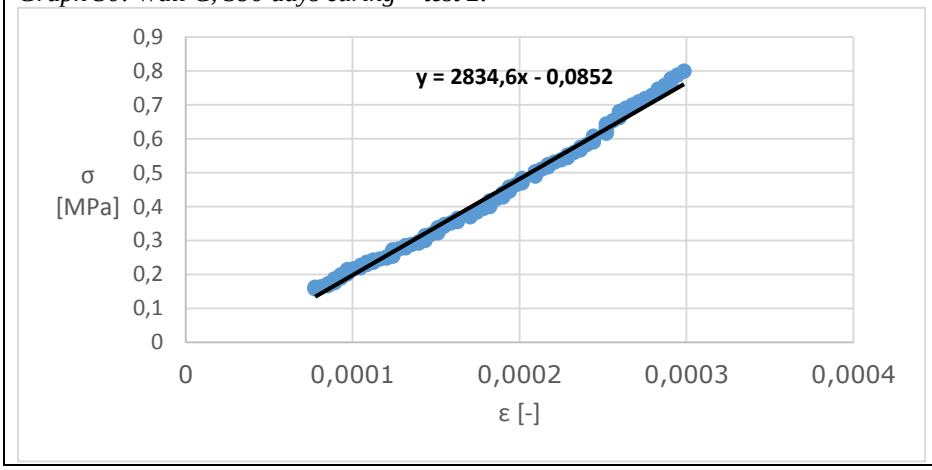
Graph 28: Wall C, 313 days curing – test 3.



Graph 29: Wall C, 390 days curing – test 1.



Graph 30: Wall C, 390 days curing – test 2.



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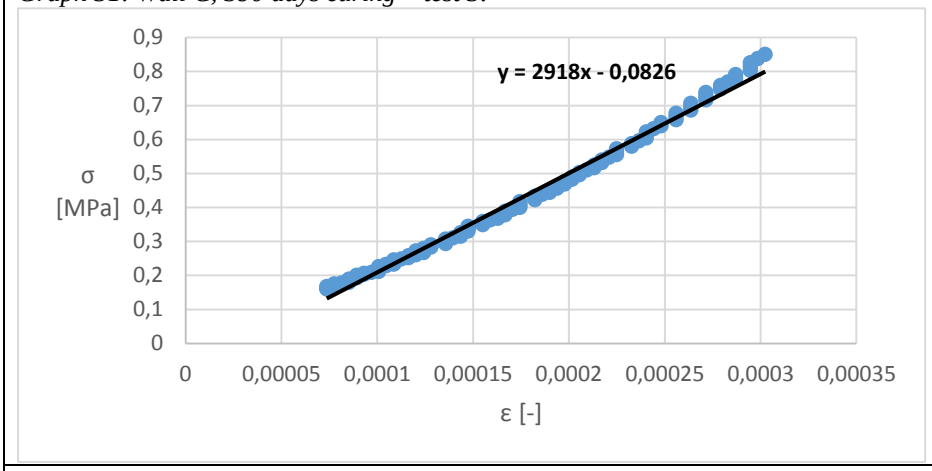
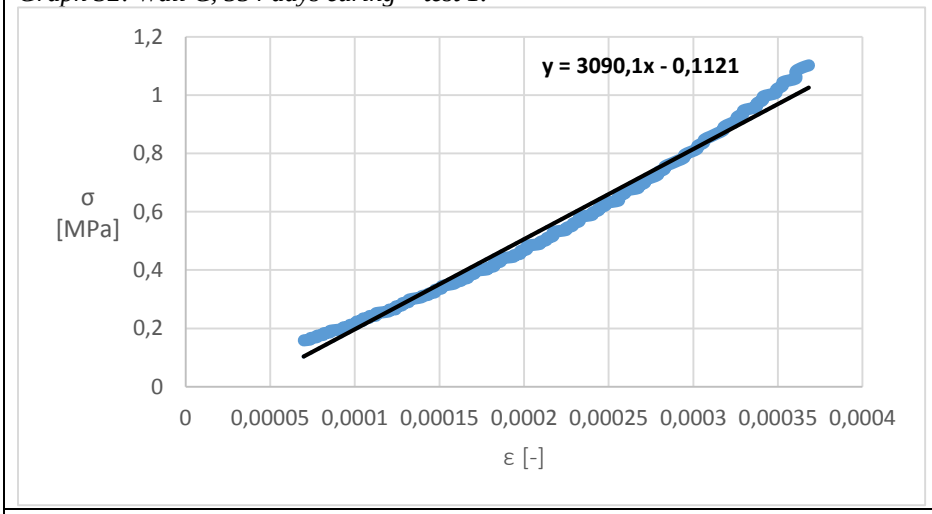
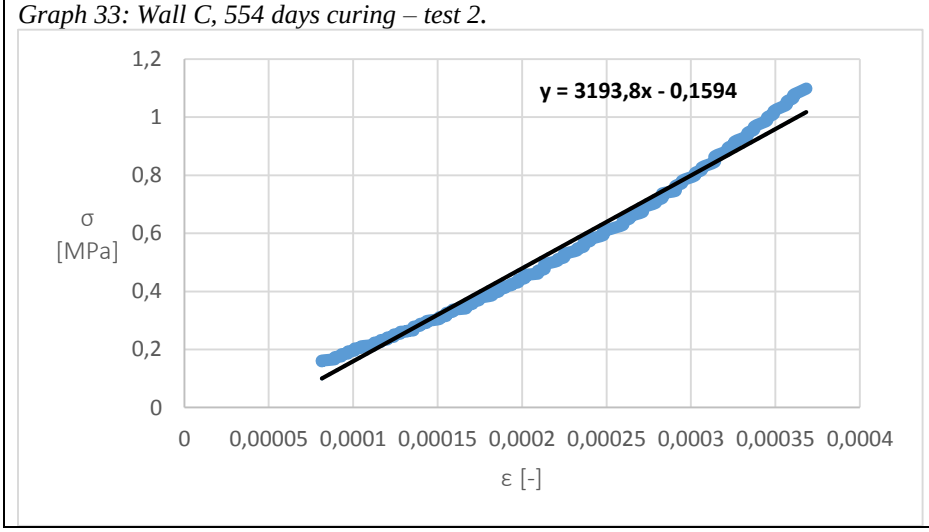
Graph 31: Wall C, 390 days curing – test 3.



Graph 32: Wall C, 554 days curing – test 1.



Graph 33: Wall C, 554 days curing – test 2.



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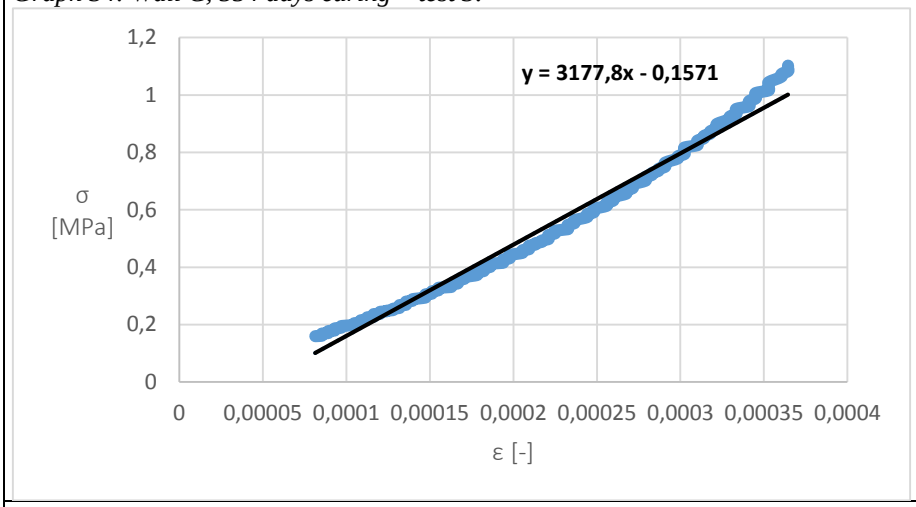
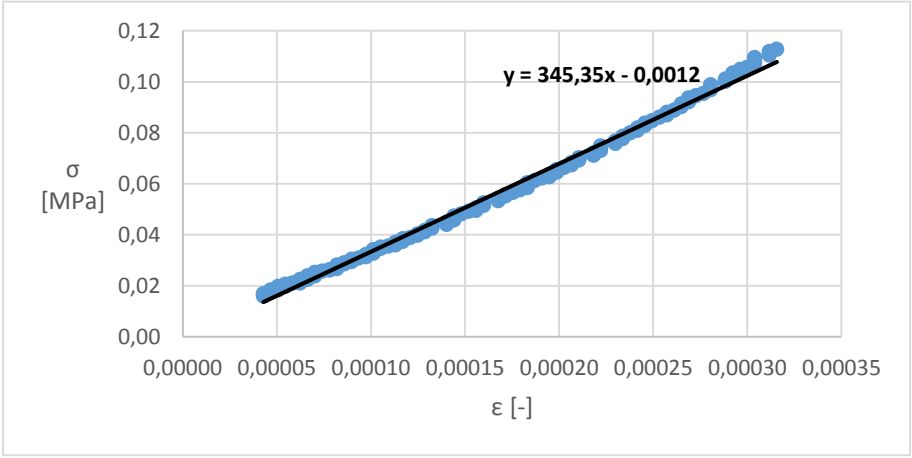
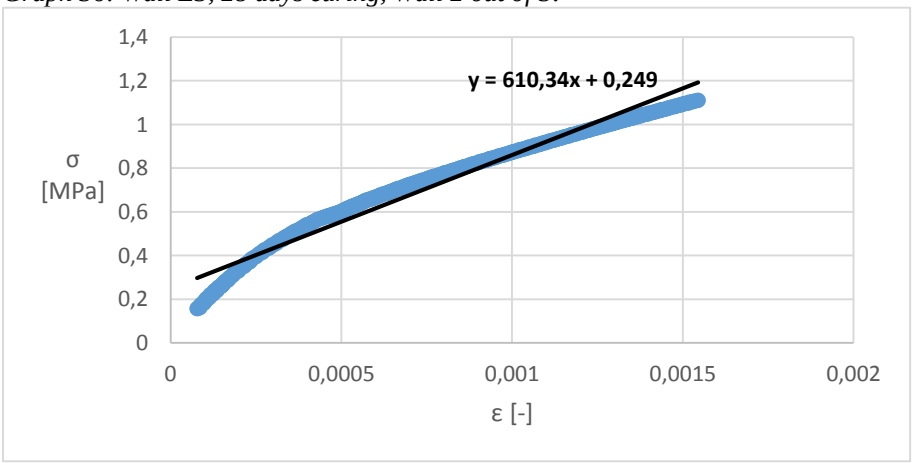
Graph 34: Wall C, 554 days curing – test 3.



Graph 35: Wall E2, 28 days curing, wall 1 out of 3.



Graph 36: Wall E3, 28 days curing, Wall 2 out of 3.



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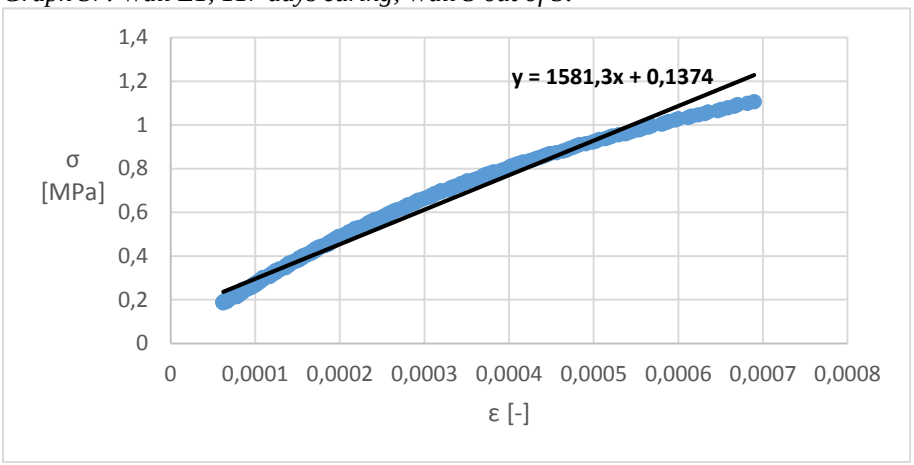
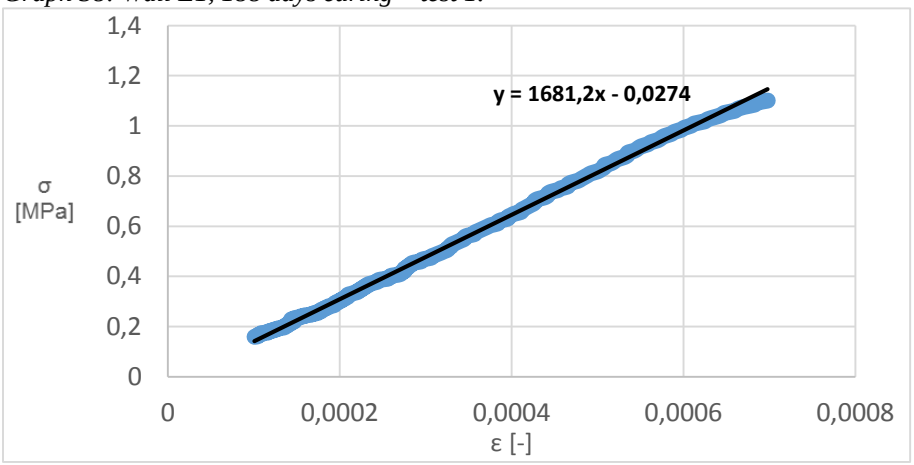
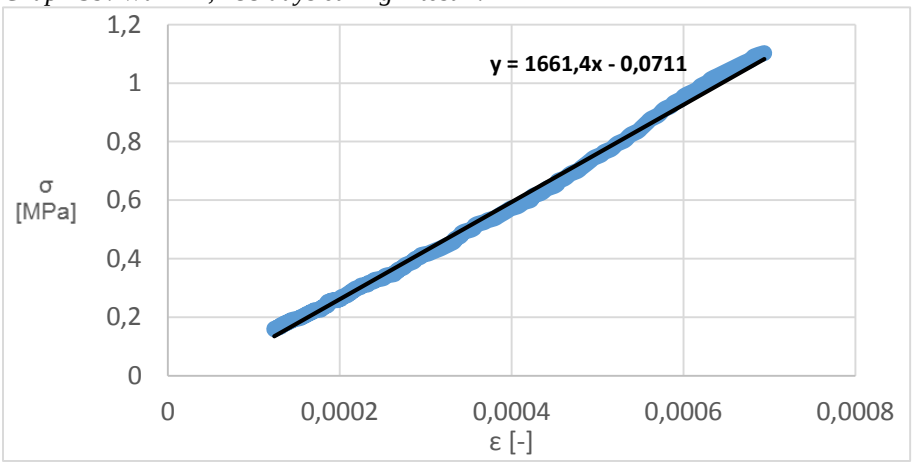
Graph 37: Wall E1, 117 days curing, Wall 3 out of 3.



Graph 38: Wall E1, 188 days curing – test 1.



Graph 39: Wall E1, 188 days curing – test 2.



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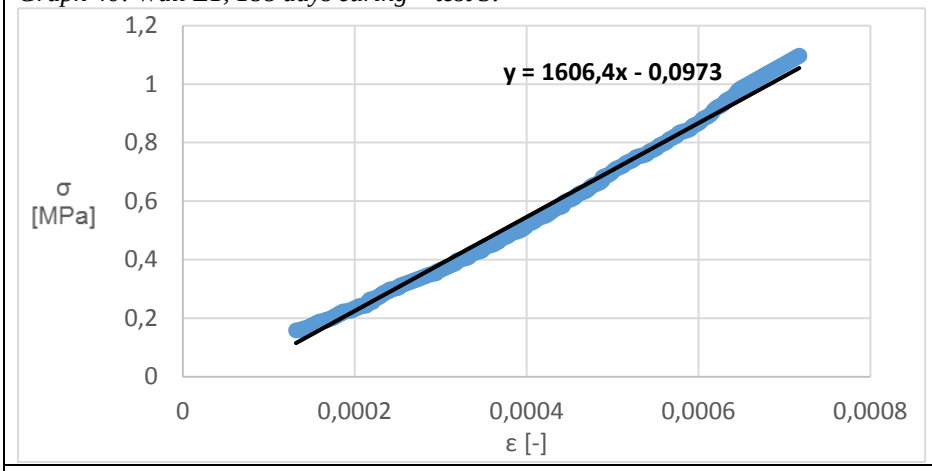
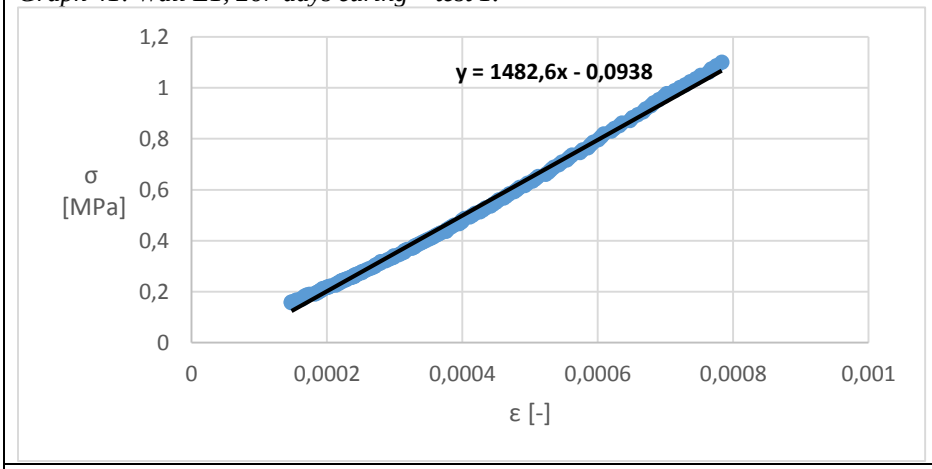
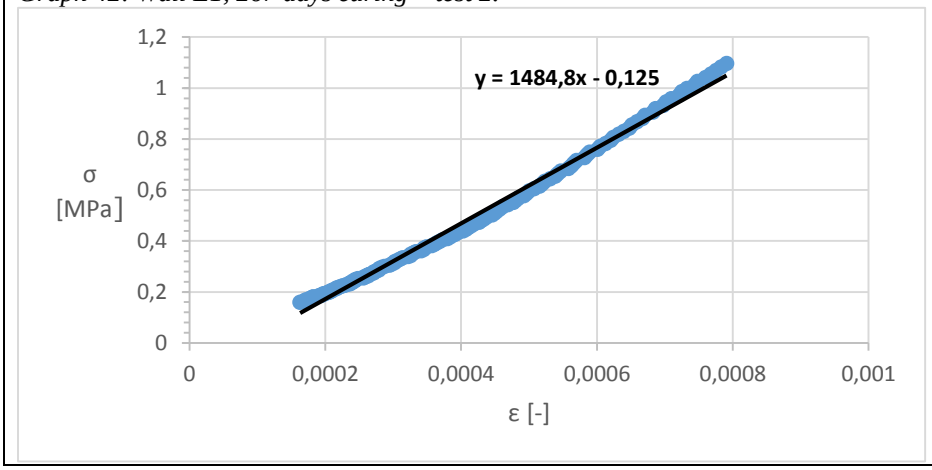
Graph 40: Wall E1, 188 days curing – test 3.



Graph 41: Wall E1, 267 days curing – test 1.



Graph 42: Wall E1, 267 days curing – test 2.



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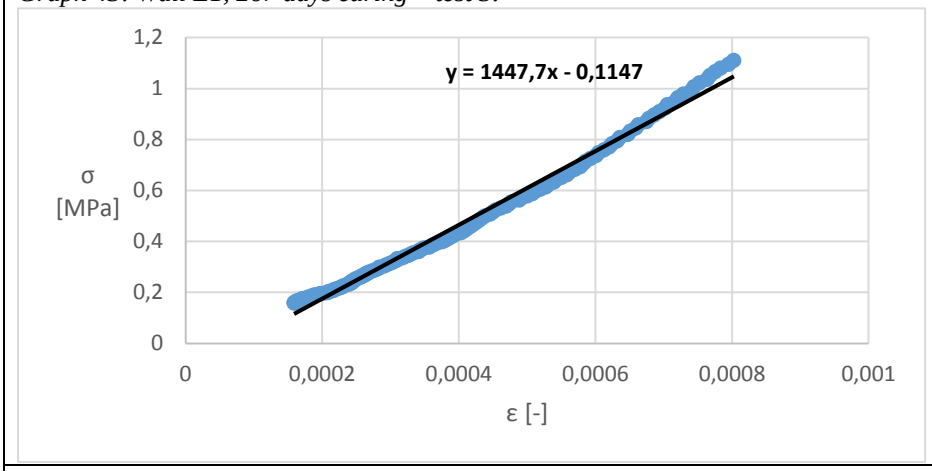
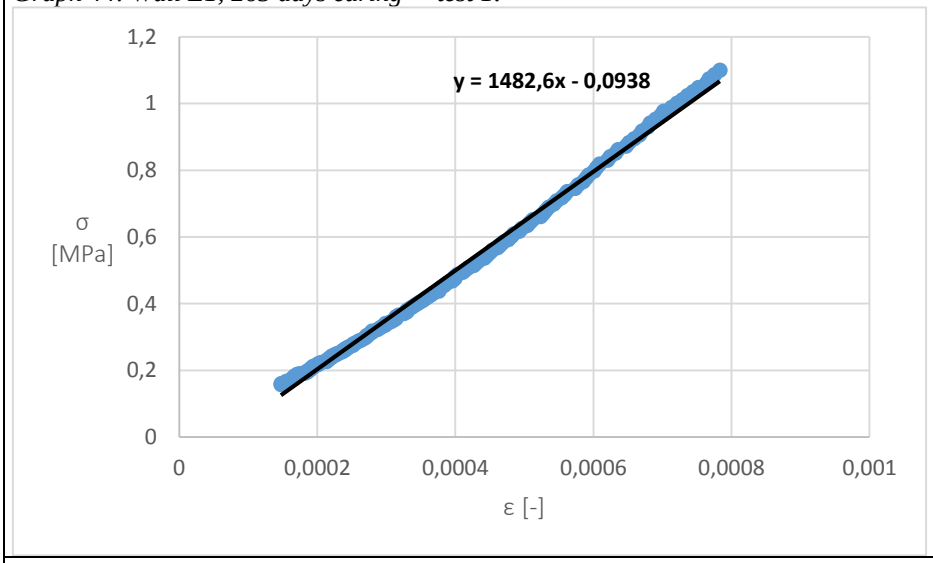
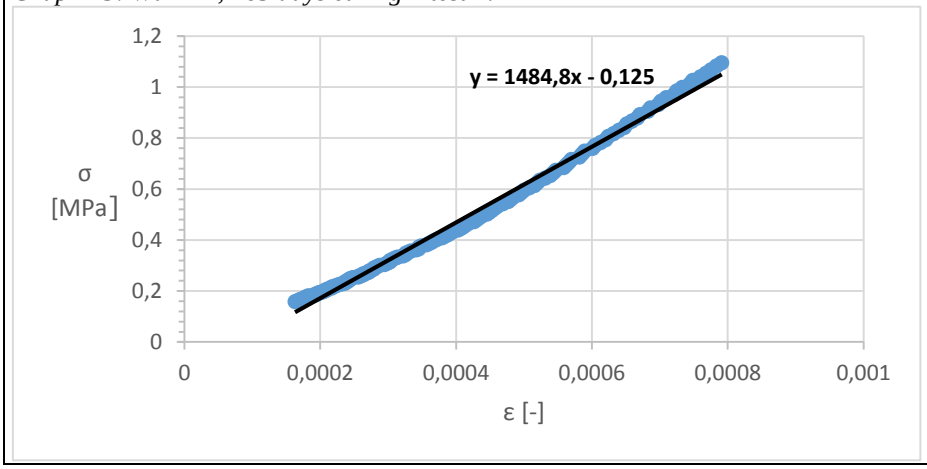
Graph 43: Wall E1, 267 days curing – test 3.



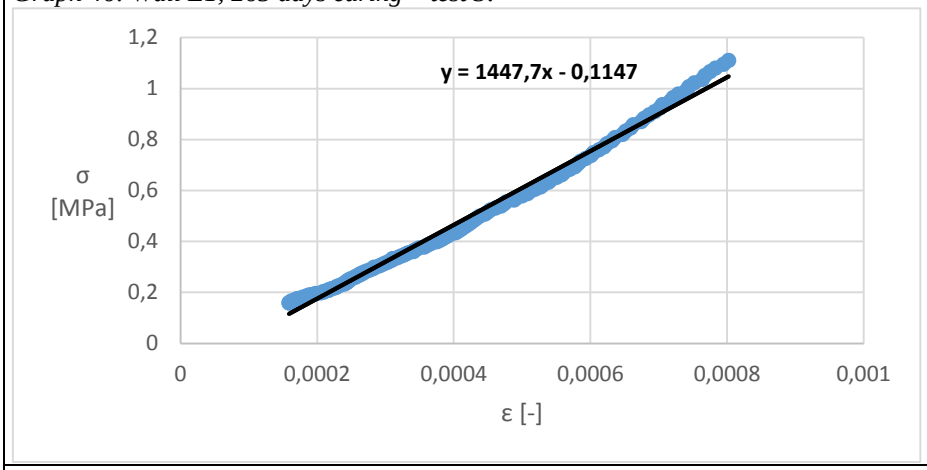
Graph 44: Wall E1, 265 days curing – test 1.



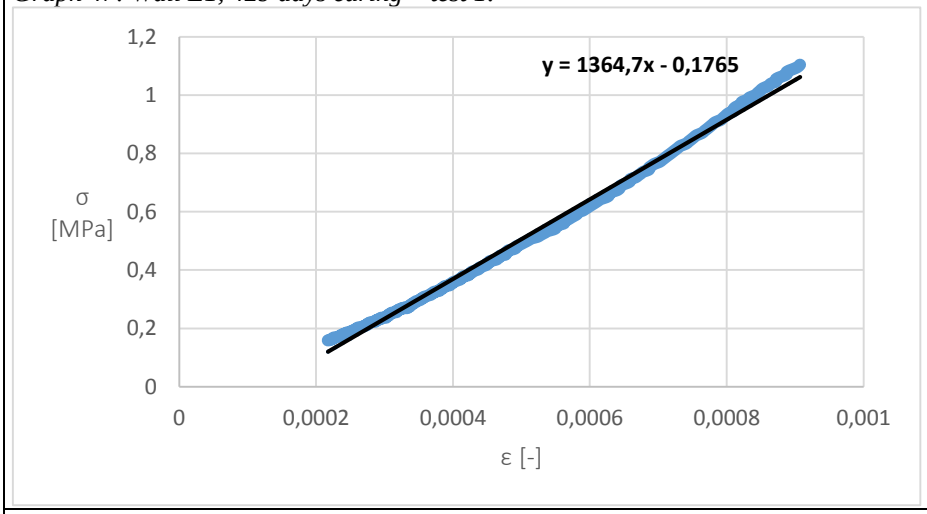
Graph 45: Wall E1, 265 days curing – test 2.



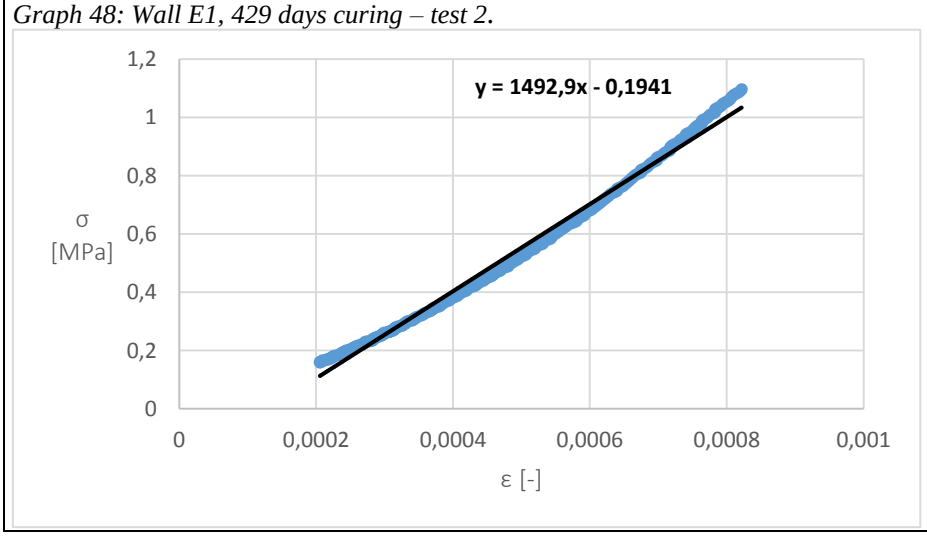
Graph 46: Wall E1, 265 days curing – test 3.



Graph 47: Wall E1, 429 days curing – test 1.



Graph 48: Wall E1, 429 days curing – test 2.



Graph 49: Wall E1, 429 days curing – test 3.