The development and quality control of stone wall renovation mortar at Turku Castle

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- Short description of the castle and the structures of its outer wall
- The development of the stone wall renovation mortar
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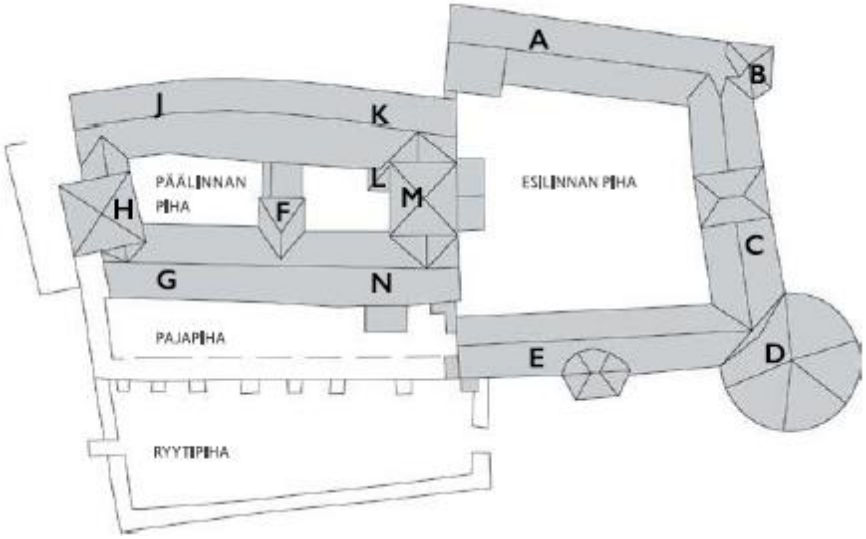
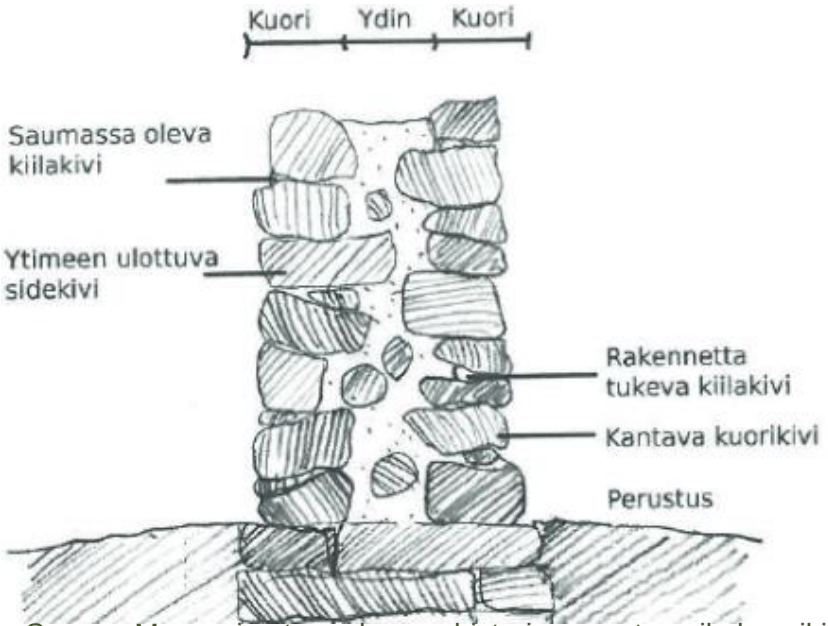


Source: Turun linnan piha ja ulkoalueiden rakennushistoriaselvitys, Merja Nieminen, 2019

Turku Castle

- Located in South-West Finland by the River Aura
- Is constructed of two buildings: the Main Castle (built 1280-) and the Bailey (built 1380-)
  - Multiple periods of construction and renovation
- Lower parts of the Main Castle's outer wall are granite and "cast walls". Upper parts are made of burnt tile and plastered
  - The condition of the outer walls varies from very poor to good (Condition investigation, 2015)
- Several types of mortars different in age and qualities can be found in the outer mortar joints of the granite wall
  - Lime-cement mortar, Parmu masonry cement, hydraulic lime mortar and lime mortar



Source: Museoviraston rakennushistorian osaston aikakausikirja3, Metsäranta P., Nordman J., 2010

The Development process

- Funding and leading the project: Senate Properties
- Research group: wide scale of expertises (architect, structural engineer, archeologist, contractor, conservator etc.)
- Starting points (at the year 2015):
  - Mortar close to original mortars
    - Known ingredients
  - Frost resistant
  - Repeatable and consistent in quality
  - Preservation of walls historical appearance
- Reference mortars (PhD Thorborg von Konow):
  - Olavinlinna LLh 15/85/525 (2009) and Suomenlinna LLh 15/85/505 (2006)
    - Industrial lime/Lime hydrate simmered in water
    - Natural hydraulic lime
    - Proportional/ratioed aggregate
- Verifying frost resistance
  - Measuring air-entainment, protective pore ratio, thin section analysis and freeze-thaw experiment SFS 5447

The Development process

- Research of the reference mortars (master's thesis, Joonas Lehtonen, 2016)
  -> frost resistance of the reference mortars partly insufficient
- Improving the structure of the protective pores
  - Optimizing the use of air-entrainment agents
  - Checking the distribution and ratio of aggregates
    -> problems in availability
- Minimizing the effect of aggregate distribution
  - Increasing the amount of binder
  - Effects on the shrinking and workability
    -> test renovations on the wall in 2016 and 2017

The Development process

- The Turku Castle wall renovation mortar LLh 15/85/440 (MSc Ari Leppäniemi)
  - Building lime/Lime hydrate simmered in water
  - Natural hydraulic lime (NHL 5)
  - Outlined/Proportional aggregate (mixture of three different aggregates)
  - Air-entrainment agent

The Olavinlinna reference mortar LLh 15/85/525

The Turku Castle renovation mortar LLh 15/85/525

- Added air-entrainment agent
- Changed aggregate mixture

The Turku Castle renovation mortar LLh 15/85/525

- Decreased amount of air-entrainment agent
- Changed aggregate mixture

The Turku Castle renovation mortar LLh 15/85/440

- Changed aggregate mixture
- Increased amount of binder

The Development process in test samples

The Olavinlinna reference mortar LLh 15/85/525, after 50 freezing cycles

Source: Development of repair mortars frost resistance for natural stonewalls, Joonas Lehtonen, 2016

The Turku Castle mortar LLh 15/85/525 + air-entrainment agent, after 25 freezing cycles

Source: Research RTEK/2497/2017, Tampere University, 2017

The Turku Castle mortar LLh 15/85/440 + air-entrainment agent, after 100 freezing cycles

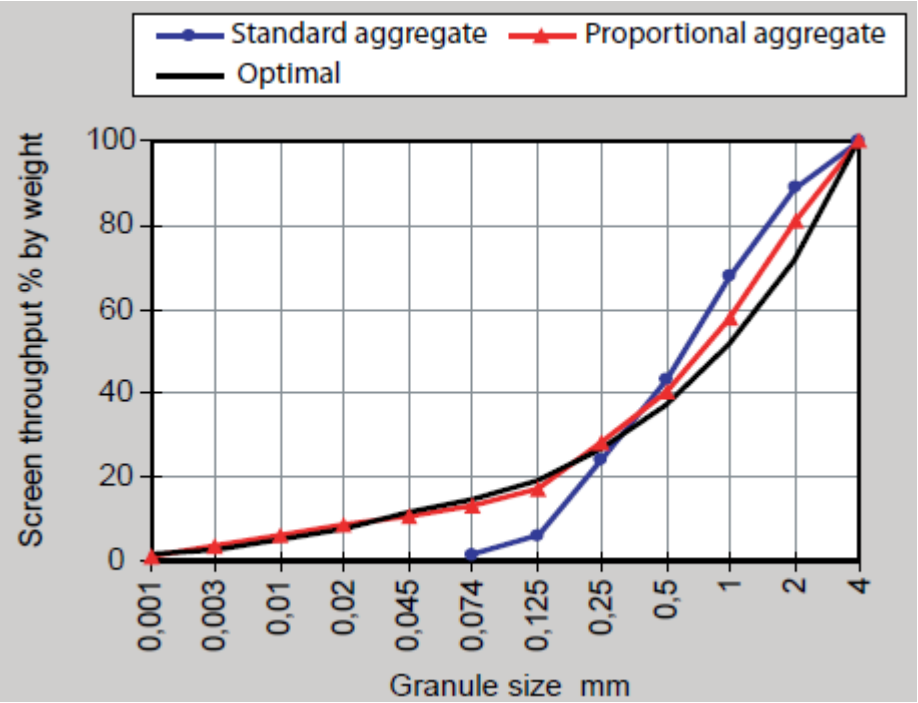
Source: Research RTEK/2557/2018, Tampere University, 2018

The Quality control

- Quality control tests performed in a laboratory
  - Sieving the aggregate's grain size distribution
  - Freeze-thaw tests of the mortar prisms (SFS 5447)
  - Protective pore ratio
- Quality control performed at the construction site
  - Tests on fresh mortar
  - Monitoring environment and circumstances
  - Inspecting the renovated mortar joints post after-care

Quality control performed in a laboratory

- Sieving the grain size distribution of the aggregate (Tampere University)
  - Every new batch of aggregate ordered
  - Comparing to aggregate distributions already proven to be functional and to the optimal distribution (von Konow)
  - Fine tuning the mixture ratios of the aggregate when necessary.

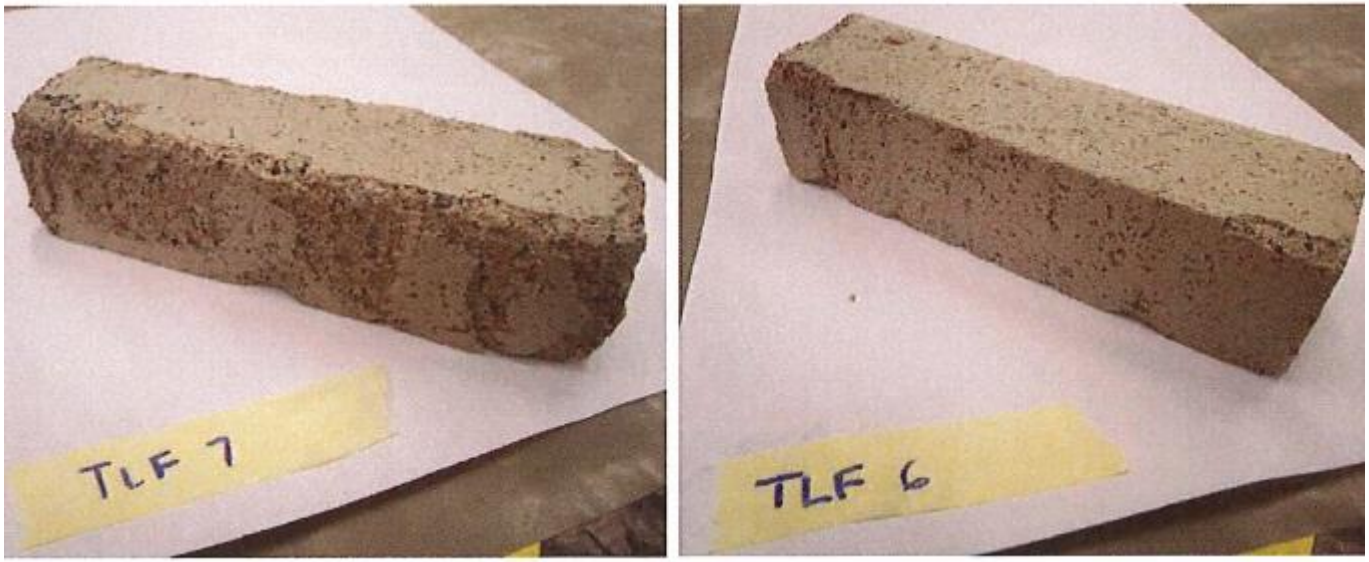


Source: Mortars in Old Structures, Thorborg von Konow, 2006

	%	0,001	0,003	0,01	0,02	0,045	0,074	0,125	0,25	0,5	1	2	4	6
Parikkala sand (fine) #4 mm	70,8	0,2	0,5	1,3	2,4	5,2	7,8	10,5	22,6	43,5	64,1	85	99,4	100
Parikkala sand (coarse) #6 mm	26,5	0,1	0,4	1,2	2,1	3,3	4,3	5,7	12,2	25,9	46,4	69,2	87,7	100
Quartzfiller	2,7	1	1,8	3,5	10	35,5	58	90	100	100	100	100	100	100
Proportional (new)	100	0,2	0,5	1,3	2,5	5,5	8,2	11,4	21,9	40,4	60,4	81,2	96,3	100
Proportional (old)	100	0,2	0,4	1,0	2,0	4,8	7,3	10,2	19,8	37,6	58,0	80,0	96,3	100
Optimal	100	**2**	**3**	**6**	**7,5**	**11**	**15**	**20**	**27**	**37**	**50**	**70**	**100**	
Proportional (von Konow)	100	**1**	**3**	**6**	**8**	**9**	**12**	**17**	**27**	**40**	**58**	**81**	**100**	

Quality control performed in a laboratory

- Freeze-thaw test of the mortar samples (SFS 5447)
  - For every new aggregate batch after grain size distribution check
  - Quick-carbonatizing (Tampere University)
  - Decrease on bending strength < 33 % after 100 cycles
  - Protective pore ratio > 0,20
- (Thin section analysis from hardened mortar from the stone wall if necessary)

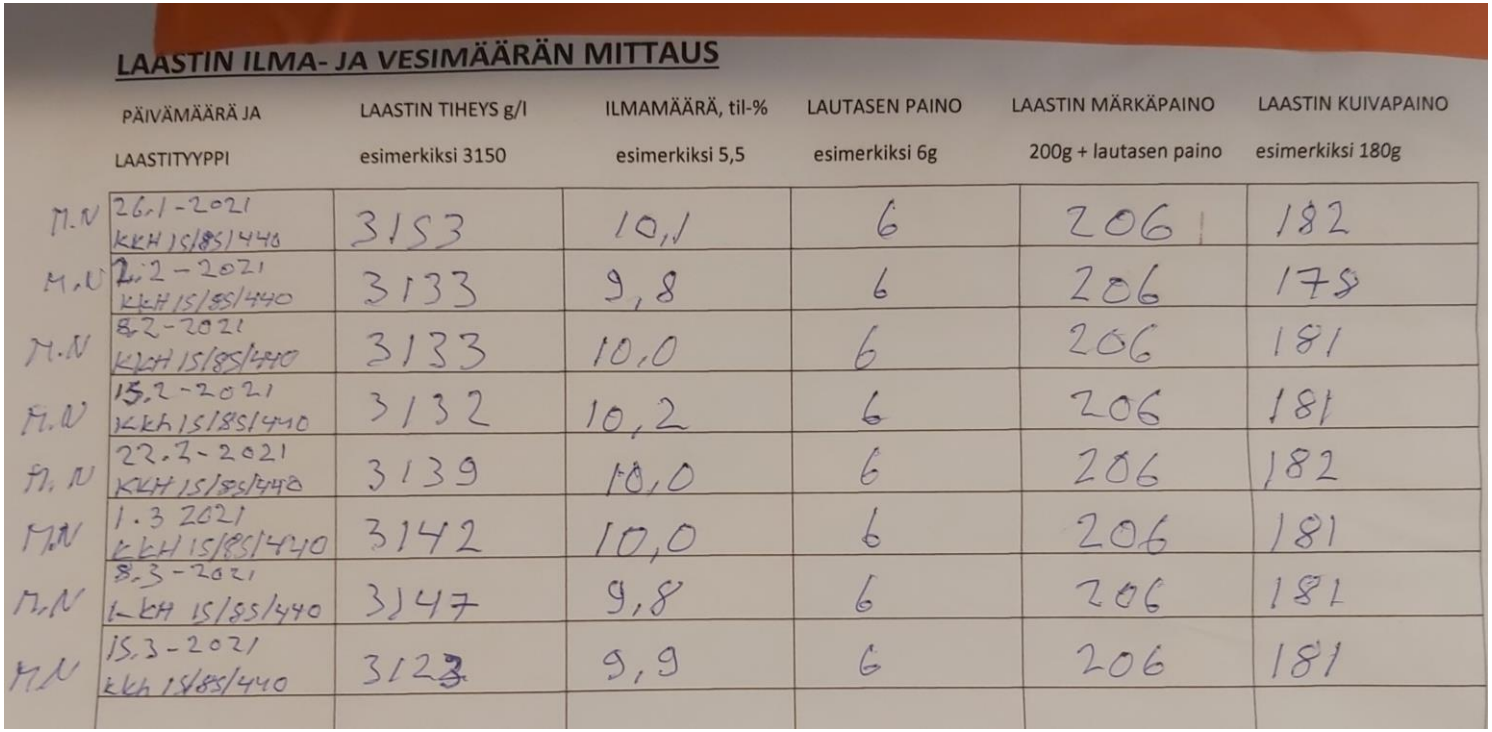


Source: Research RTEK/2557/2018, Tampere University, 2018

	Bending strength	Copression strength
Näyte nro	Taivutus-lujuus märkänä [MPa]	Puristus-lujuus märkänä [MPa]
TLF1	2.094	8.731
TLF2	2.545	10.920
TLF3	2.577	10.430
TLF4	2.240	10.150
TLF5	2.405	10.560
TLF6	2.402	11.020
Keskiarvo	**2.377**	**10.302**
TLF VRT 1	2.983	11.095
TLF VRT 2	2.558	10.970
TLF VRT 3	2.909	11.760
Keskiarvo	**2.817**	**11.275**
	15.6 %	**8.6 %**

Quality control performed on site

- Measurings of fresh mortar
  - Air-entrainment (10 %), water-entrainment (14 %), density -> indicators
  - Weekly from the first batch of mortar
- (”Home-made” freeze-thaw tests of the mortar samples)



LAASTIN ILMA- JA VESIMÄÄRÄN MITTAUS

	PÄIVÄMÄÄRÄ JA LAASTITYYPPI	LAASTIN TIHEYS g/l esimerkiksi 3150	ILMAMÄÄRÄ, til-% esimerkiksi 5,5	LAUTASEN PAINO esimerkiksi 6g	LAASTIN MÄRKÄPAINO 200g + lautasen paino	LAASTIN KUIVAPAINO esimerkiksi 180g
M.N	26.1-2021 KKH 15/85/440	3153	10,1	6	206	182
M.N	2.2-2021 KKH 15/85/440	3133	9,8	6	206	179
M.N	8.2-2021 KKH 15/85/440	3133	10,0	6	206	181
M.N	15.2-2021 KKH 15/85/440	3132	10,2	6	206	181
M.N	22.2-2021 KKH 15/85/440	3139	10,0	6	206	182
M.N	1.3 2021 KKH 15/85/440	3142	10,0	6	206	181
M.N	8.3-2021 KKH 15/85/440	3147	9,8	6	206	181
M.N	15.3-2021 KKH 15/85/440	3123	9,9	6	206	181

Turun linna muurikorjauksen laastien laadunvarmitusmittauksien keskiarvot syksy 2020 ja kevät 2021						
Laasti	**Ilmamäärä (til-%)**		**Vesimäärä kuivapainosta (p-**		**Laastin tiheys (g/l)**	
KKh 15/85/440 (muurin saumalaasti)	10,3	vaihteluväli 9,2-11,8	14,1	vaihteluväli 13,2-15,7	1999	vaihteluväli 1976-2019

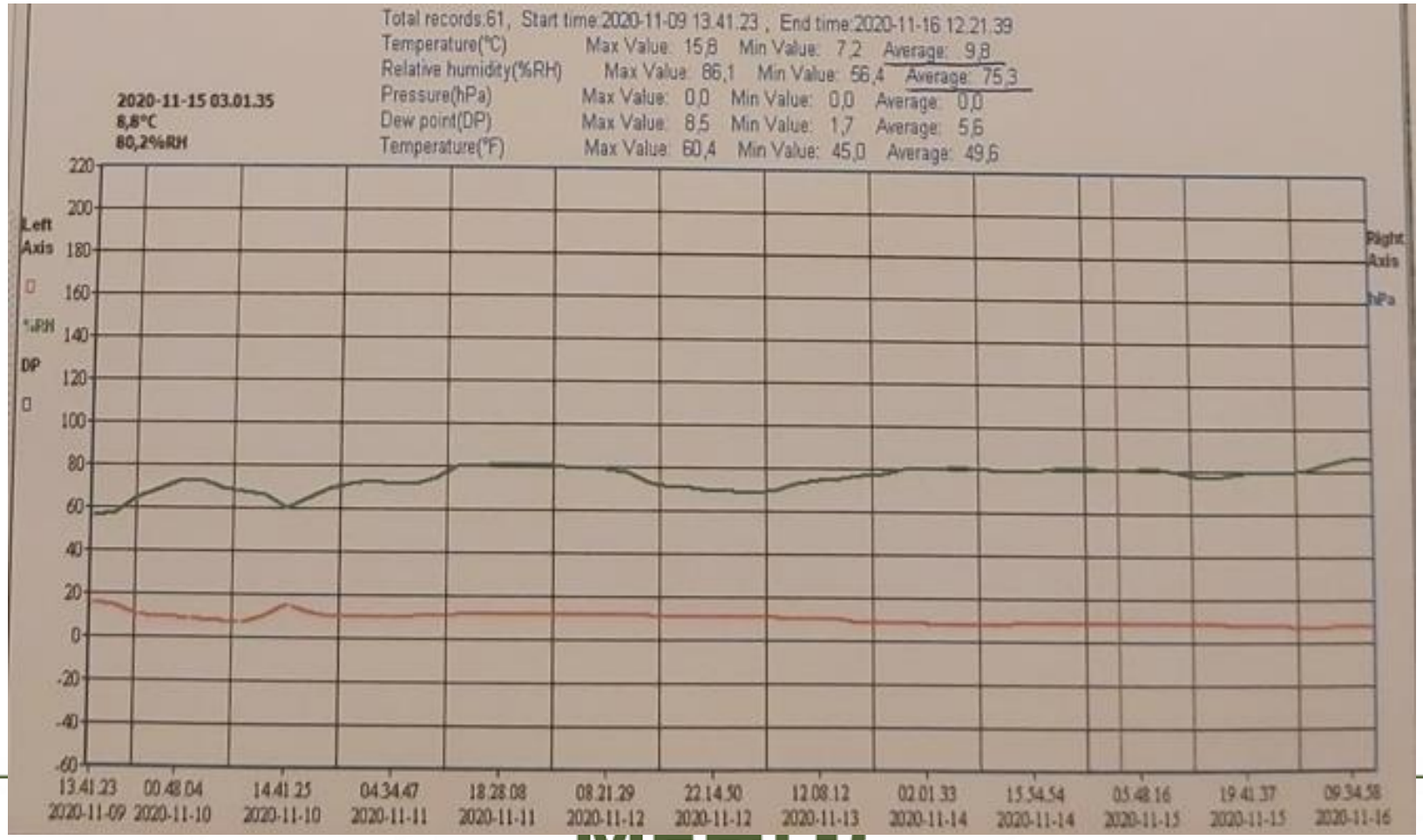
MEHTO


UNIT
3130
MAX:10000g d=1g
O/T


TESTING
Nr.
Lufporengehalt
in %
Inhalt 1L

Quality control performed on site

- Monitoring conditions
  - Constant monitoring of temperature and relative humidity
  - Working in winter -> stability on the conditions
- Visual inpection of the mortar joints and the wall surface post-aftercare



Source: Julkisivun muurikorjaus länsitornin pohjoissivu työraportti, Teemu Kajaste OSK Rotunda, 2021

THANK YOU!

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Members of the project:

Constructor: Senate Properties

Constructor consultant: Turkoosi Oy 2016-2018, Rakennuttajatoimisto HLC Oy 2018-

Conservation authority: Finnish Heritage Agency

Architect: Kari Järvinen ja Merja Nieminen Architects SAFA 2016-2019, Mustonen Architects Ltd 2019-

Structural engineer: Insinööritoimisto Lauri Mehto Oy

Archeologist: Muuritutkimus Oy

Contractor: Lainio & Laivoranta Oy