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1 WORK PERFORMED BEFORE START-UP OF THE HERØY FOU PROJECT^{1-2,4}

This report contains a summery of the work performed in WP2.A4. More details are given in the reports¹⁻⁵.





EARLIER INSPECTIONS 18-1069 HERØYSUND BRU Muliticonsult 2017 Concrete coverage in areas where chloride content and potential measurements were done – 76 inspection points Chloride (CI-) content 0.40-1.56 wt% (sement) Statens Vegvesen October 2019 During concrete repair, corrosion and voids were discovered inside cable ducts. No more details reported. 0 🕥 SINTE Prøvingsrappor **SINTEF 2020** Analysis of injection mass from SSV – delivered in October 2019 Laboratorieun innsiden av ki 0 Chloride (CI-) content 0.03-0.04% of dry mass KINTEDLIRINET Betong <u>Dekra 2020</u> REPORT Detecting voids inside tendon ducts (due to observations by SVV in October 2019) 0 Herøysund bridge Documented a lot of missing grout 0 Documented brakage in 3 wires (3SC) through drilling holes 0 ting voids in grouted tendon ducts with NDT REPORT: Ref. 7204-R-584522-Ver.1 7

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EARLIER INSPECTIONS, cont.

SVV and NTNU August 2020

- Drilled holes in three different locations selected from the Decra results with indication of missing grout.
- \circ $\;$ Several holes in the concrete drilled to expose the cable duct and wires
- Injection mass (SINTEF analysis), part of broken wire from two positions collected and photos taken.

SINTEF 2020

- Analysis of injection mass
- \circ $\;$ Low chloride content in solid 0.035% and pH 13 $\;$



NTNU/MTP RAPPORT

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| 2020/Loca Image: state st | ation | 2, Kabelbane 2, but North side of the bridge Image: State of the bridge Image: State of the bridge Proversion Image: State of the bridge Serious corrosion on wires, more in the top Image: State of the bridge Sroius corrosion of the duct Image: Image: Image: State of the bridge Sroius corrosion of the duct Image: Image: Image: Image: Image: State of the bridge State of the bridge Image: Im | d | |
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| FRACTUR From inspecti | ED W on Aug | IRES Just 2020 – Inspection point 3 | | |

• Fracture in wire no. 2 from top

- \circ $\,$ Corrosion on the wire on both side of the fracture
- \circ $\,$ Min. wire diameter close to the fracture 2.9 mm $\,$
- Only part of the wire diameter exposed to corrosion
- At fracture: 30-35% of the cross section intact



Deep corrosion attack

FRACTURED WIRES From inspection August 2020 – Inspection point 1



Deep corrosion attack No corrosion Corrosion attack No corrosion

Corrosion observations

• No fracture had occured in this wire

- Deep corrosion grooves in the wire oval form with length 5-15 mm, depth 1.5 mm snd width 3-4 mm
- All grooves were on the same side of the wire, while the rest of the wire surface was without and serious attacks.

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| MÅLØY B Image: State of the sta | BRIDC | SE Solution | Corrosion observations • Serious corrosion attacks on wires • Fracture occured in several wires • Lack of injection mass • Investigation of 3 fractured wires documented • Areas with and without corrosion • Deep corrosion attacks close to the fractures • Fracture region showed cup and cone with remaining wall thickness 1 mm and depth 6 mm (see photo) • Internal and external corrosion on the duct • SEM: Indication of high local content (3-13 wt%) Analysis of injection mass: • C1: ~ 0.18% • Sulphate (SO ₃): 1.19-1.44 wt% (inj.mass) • pH: ? | | |

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2 SUMMERY OF OUTCOME FROM MSc PROJECTS

2.1 MSc student Bettina Horn Myhre³

| Or | ojective | | |
|---------------------|--|--|---|
| Exa | amine how pH, chloi | ride (Cl⁻), sulphur and | d oxygen affect the stability of the |
| oxi | de/passive layer and | d corrosion properties | s on prestressed tendons in injection mass |
| | | | |
| | | | |
| Pa | arameters | | |
| <u>Ра</u> о | pH: | 12 – 14 | Based on values from SINTEE analysis of |
| <u>Ра</u> ∘ ∘ | <mark>arameters</mark> pH: Chloride: | 12 – 14 0.01 – 0.6 wt% | Based on values from SINTEF analysis of samples from the bridge |
| <u>Ра</u> о о | a <u>rameters</u> pH: Chloride: Sulfat: | 12 – 14 0.01 – 0.6 wt% 0 – 20.000 ppm (0 | Based on values from SINTEF analysis of samples from the bridge |
| ● ○ ○ ○ | a <u>rameters</u> pH: Chloride: Sulfat: Temperature: | 12 – 14 0.01 – 0.6 wt% 0 – 20.000 ppm (0 Room temperature | Based on values from SINTEF analysis of samples from the bridge |

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| gin University from and Through Master's thesis convolutioners | Bettina Horn Myhre Effects of chloride, sulfate and pH on the corrosion of tensile wires in grouted tendon ducts in Herøysundet bridge Master's thesis in Materials Science and Engineering Supervisor: Roy Johnsen Co-supervisor: Andreas Erbe, Mette Geiker June 2022 | |
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CONCLUSIONS Bettina H. Myhre

- 1. The chloride content is most important for initiation of corrosion, however, in combination with pH is also important.
- pH 12.5 combined with 0.36 g/l chloride result in corrosion. However, at 0.036 g/l chloride and pH 12.5 corrosion is not initiated.
- 3. Addition of sulphate (Na₂SO₄ eller MgSO₄) did not effect initiation of corrosion (with the tested comcentrations).

15

- 4. Effect of oxygen not documented through the test program.
- lacksquare NTNU Kunnskap for en bedre verden

2.2 MSc Student Christopher Andresen Bjerk⁵



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2.2.1 Results from inspection on Herøysund Bridge^{3, 5}







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| 2SA-3 cr=c | 0.07%, moist | ture = 10.2%, injection mass: * | 1 Image: state stat | | |
| | or en bedre ver | den | |] | |
| COA-4 pH=1 | 2.44 (PW), C | fr = 0.039%, moisture = 45.1% | , injection mass: 2 Image: Corrosion observations «Wet» injection mass covering the wires and the volume between wires Light surface corrosion on wires, but production marks could be seen Slight corrosion on the inside of the duct | | |
| 3SA-1 | | fen | Corrosion observations • No injection mass • Some shallow surface corrosion (production marks could be seen) • Indication of local corrosion attacks on wire(s) in the bottom of the duct • Internal corrosion of the duct | | |



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| Post-tensioned Visual components Observations af removal of concrete | Visual | Р | rior Ir | spectio | ns, App | endix B, | C,D | Recent Inspections, Appendix A | | | | | | | | | |
|---|--|----------------|--------------|-------------|--------------|--------------|--------------|--------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|----|
| | observations after removal of concrete | 2017 Jan 20 | | uary 020 | August 2020 | | | August 2023 | | | | | | | | | |
| | | NA | NA | NA | TL-1 | TL-2 | TL-3 | 1SA | 2SA- 1 | 2SA- 2 | 2SA- 3 | 2SA- 4 | 3SA- 1 | 3SA- 2 | 3SA- 16 | 1NA | 2N |
| Wire | Wires adhered to filler material | | | ~ | ~ | ~ | | | ~ | | | | | ~ | | ~ | V |
| | Surface corrosion | | | | \checkmark | | ~ | \checkmark | \checkmark | | \checkmark | \checkmark | \checkmark | | \checkmark | | |
| | Non-uniform and pitting corrosion | | ~ | | ~ | \checkmark | | | | ~ | | | ~ | | | | |
| | Wire breakage | | \checkmark | | | | \checkmark | | | \checkmark | | | | | | | |
| | Presence of loose wires | | | | | ~ | | | \checkmark | | | | | | | | |
| Duct | No corrosion | | | ~ | | \checkmark | | | | | | | | | | \checkmark | V |
| | Internal corrosion | | | | ~ | | ~ | \checkmark | \checkmark | | \checkmark | \checkmark | ~ | | | | |
| | External corrosion | | | | | | | | | | | | | | | | |
| | Both internal and external corrosion | | ~ | | | ~ | | | | ~ | | | | ~ | | | |
| Filler Material | Fully grouted | | | ~ | | | | \checkmark | | | | \checkmark | | \checkmark | | \checkmark | v |
| | Presence of voids | | \checkmark | | ~ | ~ | ~ | | \checkmark | | \checkmark | | \checkmark | | \checkmark | | |
| | Moist grout | | | | | | \checkmark | | | \checkmark | | \checkmark | | | | | |
| | Frost damaged | | | | ~ | | \checkmark | | | | | | | | | | |
| | White injection mass | | | | | | | | ~ | ~ | ~ | ~ | | | | | |
| Mild steel | Corrosion | | | NA | NA | ~ | | NA | NA | NA | NA | NA | NA | NA | NA | NA | N |
| | No signs of | | | | | | ~ | | | | | | | | | | |

OBSERVATIONS – FOR DISCUSSION

From the litterature

The following elements are important for initiation of corrosion o pH, chloride content, sulphide, oxygen, temperature, humidity

Observations from Herøysund Bridge

○ **2SA-4**, pH= 12.44 (PW), CI⁻ = 0.039%, moisture = 45.1%, injection mass: $2 \rightarrow minor \ corrosion$

- **2SA-3**, Cl⁻ = 0.07%, moisture = 10.2%, injection mass: $1 \rightarrow minor \ corrosion$ 0
- **3SA-2**, pH= 13.76 (PW), moisture = 10.8%, injection mass: $2 \rightarrow minor \ corrosion$ 0
- **2NA**, pH=14.1 (PW), Cl⁻ = 0.061%, moisture = 10.2%, injection mass: $1 \rightarrow no \ corrosion$ 0
- Location 3 (2020), pH=13, Cl⁻ = 0.037%, moisture = 44% (wet) \rightarrow serious corrosion + wire fracture 0
- Location 1 (2020), pH=13, Cl⁻ = 0.035%, moisture = 21% (dry) \rightarrow serious corrosion 0

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2.2.2 Results from experimental work⁵

MSc Student Christopher – 2023/24

OBJECTIVES

- a) How do different pH, chloride, and sulfate concentrations affect the corrosion of tensile wires?
- b) How does oxygen affect the corrosion behavior of tensile wires?
- c) How does the carbonation of a solution affect the corrosion behavior of tensile wires?
- d) Are the corrosion properties of steel embedded in concrete different from steel that is not in concrete in a given solution?
- e) If a steel sample and a steel sample embedded in concrete were connected and placed in the same solution, would it be possible to observe a galvanic effect?
- f) Can the corrosion observed in the tension wires on the Herøysund bridge be explained by the findings from the executed test program?





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3 CONCLUSIONS

- 1. At a lower pH (12.5) the solution became more corrosive compared to at a higher pH (13).
- At a pH of 12.5 and no sulfate, corrosion initiated with a chloride concentration of 0.005 M. In solutions with a pH of 13 and no sulfate, a threshold between 0.02 and 0.005 M chloride was observed, where corrosion did not occur and where it did occur. It was also observed that with increasing chloride concentration at both pH levels, the corrosiveness increased.
- 3. At a pH of 12.5 and a chloride concentration of 0.005 M, the addition of a small amount of sulfate had a significant impact, making the solution more corrosive. At a pH of 13 with the same chloride concentration, a much larger amount of sulfate was required to achieve the same increase in corrosivity. At both pH levels, it was observed that the corrosion properties did not change significantly beyond a certain concentration of sulfate.
- 4. With a *combination of chloride and sulfate in the solution*, it was observed that the corrosivity increased further compared to when only chloride was present.
- 5. For most of the samples where corrosion was seen, it primarily occurred at the interface between the coating and the exposed steel.
- The effect of using sealed and open containers was significant. Open containers led to carbonation of the solution (decrease of the pH) and oxygen supply. Both factors led to a more corrosive solution.

4 FURTHER WORK

There are still uncertainties related to give a clear explanation of the reason(s) for the corrosion failures on the wires. Based on the executed work in the two MSc thesis projects, the follow proposal for further work is given:

- 1. From the long-term exposure experiments, it was seen that corrosion was initiated at the interface between the coating and the exposed steel. This might be because of crevice corrosion and needs further investigation.
- To gain a better understanding of the galvanic experiments conducted, it is recommended to measure OCP and take LPR of freely exposed samples equivalent to those tested in the galvanic experiments and in the same solutions. This will help assess the effect of the measured galvanic current.
- 3. For a better understanding of the condition of the samples from the galvanic experiments, it is recommended to measure the anodic and cathodic polarization curves at the end of the tests on the same samples and solutions as in this project. This will give more insight into whether the samples are in a passive or active state.

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4. Another suggestion for future research is to thoroughly explore the existing literature on galvanic coupling in prestressed reinforcement, given the limited information available. Based on these findings, it should be determined if the galvanic experiments should be modified and conducted over different time periods to produce more field-relevant results for galvanic couplings.

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