

Investigating the effects of anti-corrosive coatings on the bond between corrosion-damaged rebar and concrete repair materials

Moolla Muhammad Ameen^{1,*}, Nicholas Jarratt¹, and Hans Beushausen¹

¹Concrete Materials and Structural Integrity Research Unit, Department of Civil Engineering, University of Cape Town, South Africa

Abstract. Reinforcement corrosion causes destruction to the steel by a loss in cross section and rib height, which can affect the bond between steel and concrete. During repair of corrosion-damaged reinforced concrete members, a protective coating is usually applied to the cleaned corroded steel. There is, however, little information available on the bond performance of repair coatings. Furthermore, the effect of their coating thickness and other parameters like rebar diameter, corrosion degree and repair material properties are not well understood when considered in parallel with repair coatings. This paper seeks to contribute towards understanding the use of anti-corrosive coatings and the influence of their thickness on the bond between cleaned steel reinforcement and repair materials, when used in combination with different bar geometries at varying degrees of corrosion damage. In this investigation, two high tensile steel bars, Y12 and Y16, were considered. Rebar corrosion damage levels of 0%, 10% and 20% (of steel mass loss) were simulated by mechanical grinding of sound rebar samples to represent the condition of cleaned corroded rebar. A commercially available epoxy-modified, cementitious coating material was applied to the steel in one or two coats, with each coat being 0.6 mm thick. Three repair materials with CEM I 52.5N were considered in this study, which included one concrete with a w/b ratio of 0.45 and two mortars with w/b ratios of 0.47 and 0.65. Pull-out testing was conducted on 108 specimens, and the results analysed by means of the one-way ANOVA test to assess the effect of mainly coatings and other parameters on the bond. The results indicate applying coatings to 10% and 20% corroded steel does not significantly reduce the bond for the M65 and C45 mixes. Furthermore, the difference between one and two coats had little influence on the bond of corroded steel for all rebar geometries and repair mixes.

1 Introduction

The bond between rebar and concrete allows for load transfer and it affects the ultimate load-bearing capacity and stiffness of reinforced concrete members. Properties of both the steel and concrete can influence the bond strength, which is mainly the steel surface area; relative rib area on the steel surface between adjacent ribs [1], and the strength of the concrete. Bond strength in a reinforced concrete member under load can be characterized by forces from adhesion, which occurs prior to slip of the rebar, friction between the steel and surrounding concrete, and mechanical interlock [2]. The mechanical interlock component contributes to majority of the bond between deformed rebar and concrete, and occurs from the bearing pressure exerted by the rebar ribs on the concrete. It is well-known in literature that increasing the rebar diameter will result in a higher load to cause failure, and this is due to the larger steel surface

area in contact with the concrete [3]. As for the concrete, a low water-binder ratio is seen to increase the bond strength [4] due to stronger material substrate in contact with the steel.

Reinforcement corrosion is well-known to cause severe damage to the rebar, by loss of ribs and a reduction in cross-sectional diameter [5]. This affects the mechanical interlock of the bond as corrosion changes the surface profile of the bar, where these geometric alterations can have a significant effect on the bond. For corroding in-situ structures, the bond strength initially increases up to 5% steel mass loss due the presence of firm rust. As the corrosion degree increases, the build-up of more corrosion products creates a lubricated surface that destroys the bond [5]. One study found an ultimate bond strength reduction of 60%, when 10% of the steel mass was lost to corrosion; however, the corrosive products were not removed before pull-out testing [6]. In another study, it was observed that the bond strength reduction

* Corresponding author: mllmuh011@myuct.ac.za

of specimens with 20% steel mass loss were as high as 80% of uncorroded specimens [7]. Repair of in-situ corrosion-damaged RC structures should hence be conducted early to remove rust and avoid a major loss in bond strength. Furthermore, it should be noted that as the corrosion degree increases, the pull-out load reduces at a faster rate for larger bars [8].

When repairing corrosion-damaged reinforced concrete, a protective coating is usually applied to the corroded, and subsequently cleaned, steel. The function of anti-corrosive coatings is to prevent any further corrosion and reinstate the bond strength in repaired members. Most coatings available in the construction industry are manufactured for application to rebar in new construction, with however only a few coating types effectively proven suitable for repair application. Some rebar coatings are known to exhibit excellent corrosion resistance, such as epoxy-based coatings, but have a very smooth surface that significantly reduces the frictional forces on uncorroded rebar [9]. Other common rebar coatings like cement-based coatings offer good frictional resistance but reduces the relative rib area by accumulating between ribs, which reduces the mechanical interlock [10][9]. The above studies demonstrate the negative influence of coatings when used on uncorroded rebar.

During a repair scenario, either an anti-corrosive epoxy coating or zinc-rich primer can be applied to the corroded, and subsequently cleaned steel [11]. Commercial repair coatings widely used in the South African construction repair industry are commonly comprised of a cementitious base with additives, such as epoxies. There are, however, few publications that discuss the effects of epoxy-modified cementitious coatings on the bond between cleaned corroded steel and repair materials. Considering cleaned corroded steel at 12% steel mass loss, where some of the rib height and cross section is gone, the bond strength can be reduced by as much as 20% compared to uncorroded steel [9]. The study further showed the bond performance of epoxy-modified cementitious coatings was 70% of the uncorroded steel, when repaired after approximately 12% steel mass loss. The author notes the adhesion and friction from the cement-based coating provides a good bond [9]. It can be seen, therefore, that the bond is negatively affected by corrosion, and applying epoxy-modified cementitious coatings only has little influence on reducing the bond

There is, however, little insight into the influence of these coatings and how their thickness affects the bond of corroded steel. Furthermore, it is particularly important to also understand how the different influencing parameters, such as rebar diameter, corrosion degree, and repair material properties may affect the performance of these coatings when used in repair scenarios. Previous studies have been conducted to quantify the bond performance of epoxy-modified cementitious coatings when used on corroded cleaned steel at different corrosion degrees, up to approximately 13% steel mass loss [9]. However, there is no clear view

on how these coatings work at higher stages of corrosion damage, or when used on cleaned corroded bars of different size. Furthermore, the repair material influence on epoxy-modified cementitious coatings has not yet been investigated. These factors need to be addressed as there is difficulty for engineers in assessing the structural capacity of repaired concrete members. This paper seeks to contribute towards understanding the use of anti-corrosive coatings and the influence of their thickness on the bond between cleaned steel reinforcement and repair materials, when used in combination with different bar geometries at varying degrees of corrosion damage. This paper is divided into four sections. First, the introduction is presented, followed by the experimental methodology. The results and discussion follow, and the paper concluded with a view on the influence of repair coating thickness on the bond of corroded steel.

2 Experimental Methodology

This investigation involved conducting pull-out tests on 108 specimens at 7 days age. The parameters considered for this test includes rebar diameter, corrosion degree, coating thickness and repair material. The control specimens for this study are the uncorroded, untreated specimens. The variables chosen for the respective parameters in this study are shown in Table 1.

Table 1: Test variables

Parameter	Variable
Rebar diameter (mm)	12, 16
Corrosion degree (mass loss) and repair material in parenthesis	10% (M65) 20% (M65, M45, C45)
Coating thickness (mm)	0.6 mm (one coat) 1.2 mm (two coats)
Repair material	M65, M45, C45

Compressive strength tests were conducted on the repair materials at 7 days and 28 days age. The pull-out failure load (kN) recorded for each tested specimen was used as a basis for interpreting effects from the rebar diameter, repair material properties, corrosion degree and coating thickness on the bond. Most of these parameters greatly affect the rebar surface area, hence the decision to analyse pull-out failure loads (kN) as opposed to calculated bond strength (failure load divided by rebar surface area in MPa) was deemed more accurate to assess and quantify the influence for all the tested parameters used in this study.

It must be noted that Y12 rebar was tested among all parameters, whereas Y16 was limited to M65 repair material and corrosion damage level of 20% steel mass loss, but was tested at all coating thicknesses.

2.1 Corrosion-damage simulation

Corrosion damage was simulated using an angle grinder. This method of corrosion damage simulation was chosen due to time constraints and was considered to represent that of a corroded cleaned rebar. To achieve a desired corrosion degree equivalent to 10% mass loss, some of the ribs were removed and an uneven surface created. For 20% mass loss, all the ribs were removed. Figure 1 displays the uncorroded bars and those with 10% and 20% mass loss. Furthermore, when all the ribs were removed from bars in the 20% steel mass loss category, minor indentations were also created along the bar surface to represent chloride-induced corrosion damage. To accurately remove the correct amount of steel, the bars were grinded and weighed continuously until $\pm 1.5\%$ steel mass loss from the respective corrosion target levels.

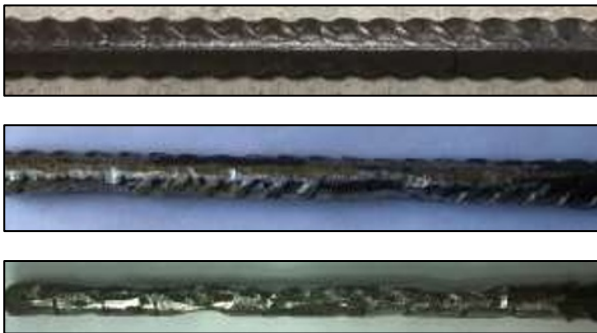


Fig. 1. Corroded 12 mm steel at 20% mass loss

2.2 Coating application

One commercially available epoxy-modified, cementitious coating material was considered for this study. The product datasheet specifies applying two coats of 1 mm each. Due to strength differences between the steel, coating and hardened repair material, a target coating thickness of 0.6 mm was chosen for each coat, in an attempt to reduce the potential of coating failure. The coating was applied using a paint brush, at an application rate of $1.5 - 2 \text{ kg/m}^2$. Figure 2 shows 12 mm uncorroded corroded steel with no coating, one coat, and two coats applied.

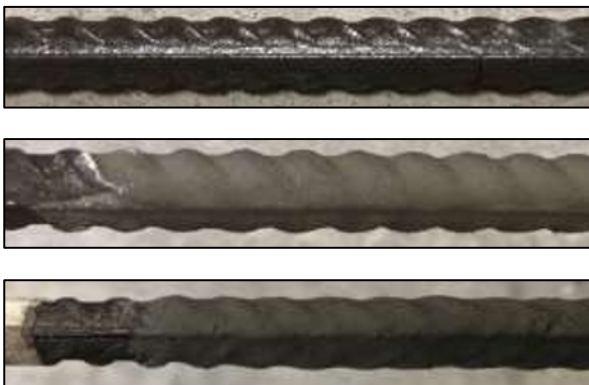


Fig. 2. Untreated (top), one coat (centre), two coats (bottom) 12 mm rebar

The time interval between applying the first and second coat was 2 hours, while the repair material was placed after 2 hours of drying of the coating. The average coating thickness of the bars was measured using an electronic Vernier Calliper. Readings were taken at 15 mm intervals along the length of the steel at the same location to ensure the desired coating thickness was attained. Figure 3 shows 12 mm 20% corroded steel with no coating, one coat, and two coats applied.

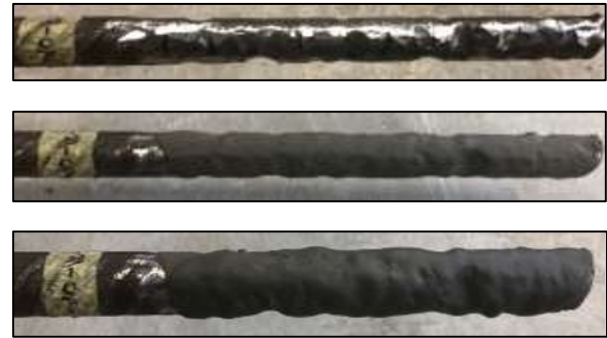


Fig. 3. 20% corroded - uncoated (top), one coat (centre), two coats (bottom)

2.3 Repair mix design and application

Table 2 displays the mix design along with the slump and flow for the concrete and mortars, respectively.

Table 2: Experimental mix design

Mix ID – kg/m ³	M65	M45	C45
w/b ratio	0.65	0.47	0.45
CEM I 52.5N	465	640	411
Water	300	300	185
Fine aggregate (dune sand)	738	650	426
Fine aggregate (crusher sand)	738	650	426
Coarse aggregate (19 mm Greywacke)	-	-	1040
Flow/Slump (mm)	600	540	85

The repair materials chosen for this study were mixed using the conventional CEM I 52.5. Before the fresh mixes were placed into moulds, their workability was assessed by means of the slump test for concrete, and the flow test for mortars, conducted in accordance with SANS 5862-1:2006 [12] and SANS 5862-2:2006 [13], respectively. Once the repair materials were placed, compacted, and demoulded after 24 hours, the specimens were cured in a moisture curing tank until seven days of age.

2.4 Test methods

The compressive strength of the different repair materials was tested for the purpose of mix characterization, and to monitor strength gain. The pull-out test involved measuring the pull-out force between a

cast-in reinforcing bar and the concrete, or mortar. A tensile load was applied to the steel manually at a constant load rate of 1 kN/s. The specimens were placed in a carbon steel chamber (16 mm plates) and positioned for loading, as shown in Figure 4.



Fig. 4. Cured specimens (left) and test set-up (right)

3 Results and discussions

3.1 Compressive strength

Figure 5 shows the average compressive strength for M65, M45 and C45 at 7 days and 28 days age. The strength at 7 days age as a percentage of the 28 days compressive strength was 81%, 85% and 91% for M65, M45 and C45 respectively.

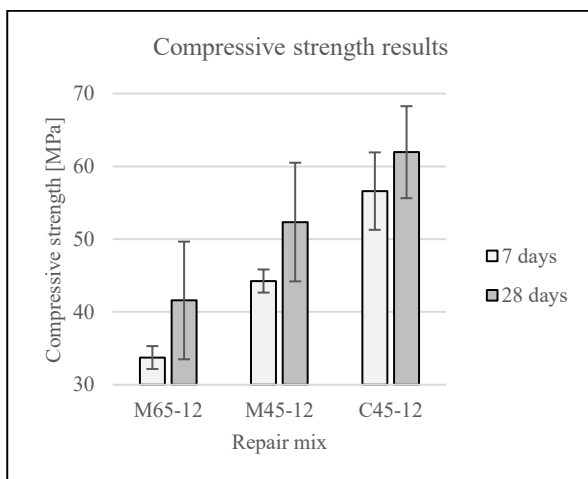


Fig 5. Average compressive strength for M65, M45 and C45

This shows the strength gain for concrete is quicker than for the mortars. The results show an increase in 10 MPa when the w/b ratio is lowered from 0.60 to 0.45 for the mortars. With the addition of stone and a slight increase in w/b ratio (to 0.47), the compressive strength increased by another 10 MPa, as seen for the concrete.

3.2 Pull-out force

Analysis of the pull-out test results was carried out by means of hypothesis testing, and included the one-way ANOVA test. This statistical test method was chosen to determine whether there was any significant difference between the mean pull-out force of the different tested parameters i.e., degree of corrosion (0%, 10%, 20% steel mass loss), coating thickness (untreated, 1 coat, 2 coats), rebar diameter (12 mm, 16 mm) and repair material

(M65, M45, C45). The null hypothesis for this study was that there is no significant difference in the mean pull-out force between untreated and coated specimens. The alternate hypothesis was that there is a statistically significant difference in the mean pull-out force between untreated and coated specimens. These hypotheses provided a basis to make observations and decisions concerning the effect of coatings on the bond strength of corroded repaired specimens.

3.2.1 Effect of repair material properties

Figure 6 displays the pull-out results for the uncorroded untreated specimens with different repair materials. Like the compressive strength, the pull-out force was affected due to the mortar's w/b ratio, when comparing M65 and M45. Since the compressive strength is directly related to the bond strength, the pull-out force increases with a lower w/b ratio.

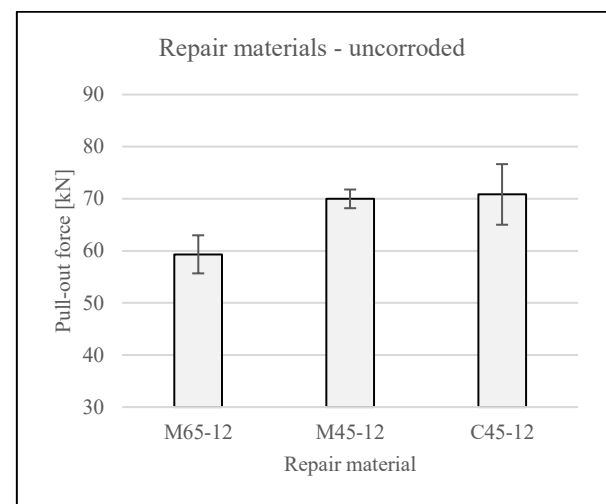


Fig. 6. Repair material properties on pull-out force

With the addition of stone to mix, no difference between the mortar (M45) and concrete (C45) was observed from the pull-out test results, despite the compressive strength of the concrete being higher.

3.2.2 Effect of rebar diameter

Figure 7 shows the pull-out results for the uncorroded 12 mm and 16 mm specimens. As the rebar diameter was increased from 12 mm to 16 mm, the pull-out force increased by 20%, although this difference was not significant, according to statistical analysis. The pull-out force on the 16 mm bars were higher than the 12 mm bars due to the larger ribs that contribute to greater bearing pressure, as well as the larger surface area which increases the frictional area. The forces present at the steel-concrete interface therefore increases. Despite these effects, when determining the bond strength as the pull-out force in relation to the steel surface area, there is a reduction.

The pull-out results in Figure 7 corresponds to a decrease in bond strength (MPa) as the rebar diameter

increases, which is in agreement with the findings from previous researchers [3].

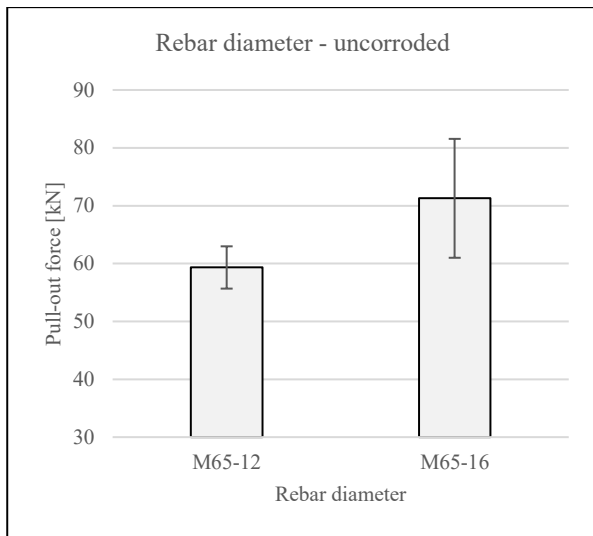


Fig. 7. Pull-out test results for various bar diameters of M65

This can however be a potential issue when doing research in this field as it can be easily assumed the bond strength decreases for larger bars, if the pull-out force is not considered separate from the steel area.

3.2.3 Effect of coatings on uncorroded rebar

Figure 8 displays the average pull-out force for uncorroded 12 mm bars with mixes M65, M45, and C45 that were untreated, coated once or coated twice. Coating of the uncorroded bars was seen to have a negative effect on the pull-out force. Considering specimens from M65, there was a 11% reduction of the pull-out force when one coat was applied and a further 7% reduction when two coats applied. These reductions were significantly different from the M65 control specimens, rejecting the null hypothesis. Furthermore, there is minimal influence from the coating thickness, as seen from the difference between one and two coats applied. For M45, the pull-out force reduced by 13% when one coat was applied, and only reduced by a further 3% with the second coat, compared to the untreated specimens. The large variation in results for M45 shows no significant difference between the untreated specimens and those with one coat. Specimens with C45 that were coated once, had 8% less pull-out force than the untreated specimens. When two coats were applied, the difference in pull-out force between the first and second coat was insignificantly small. The null hypothesis is hence confirmed as well for M45 and C45. Furthermore, like M65, the coating thickness is shown to have practically no influence on the pull-out force. The pull-out force of all three mixes was reduced when one coat was applied to uncorroded rebar, although this reduction was not significant. When two coats were applied to the two mortar mixes (M65-12 and M45-12), however, the pull-out force was shown to be significantly lower than the untreated specimens. This

result indicates that two coats have a negative effect on the bond performance.

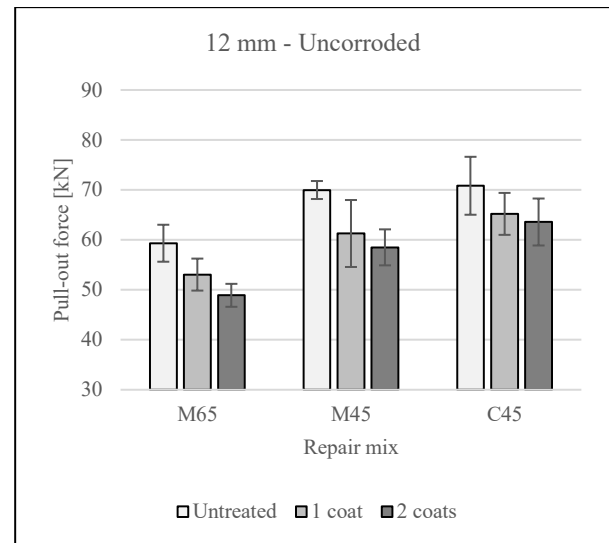


Fig. 8. Pull-out test results for uncorroded specimens with 12 mm bars

When coatings were applied to uncorroded deformed bars, the relative rib area was reduced due to the thickness of the cementitious coating, which tended to accumulate between the ribs of the steel surface. The bearing area between the ribs, which enables the mechanical interlock component and yields the majority of the bond, was hence reduced. Therefore, the pull-out force of uncorroded reinforcing bars was negatively affected by the coating, an outcome which was also found in [8][10]. Figure 9 shows the coating remnants between the ribs of the uncorroded steel after pull-out testing.



Fig. 9. Coating remnants between the ribs of the uncorroded, after failure.

3.2.4 Effect of previously corroded rebar

Figure 10 displays the pull-out results for the three mixes. M65 was tested at 0%, 10%, and 20% mass loss, whereas both M45 and C45 were only tested at 0% and 20% mass loss. Considering mix M65, there was a 15% reduction in pull-out force when 10% mass loss had occurred. For the specimens with 20% mass loss, there was a 21% reduction in pull-out force due to no ribs present on the steel surface. Specimens from both M45 and C45 experienced a 16% reduction in pull-out force when 20% corrosion occurred. The results from all mixes indicate that specimens with 20% mass loss are statistically different compared to the uncorroded specimens.

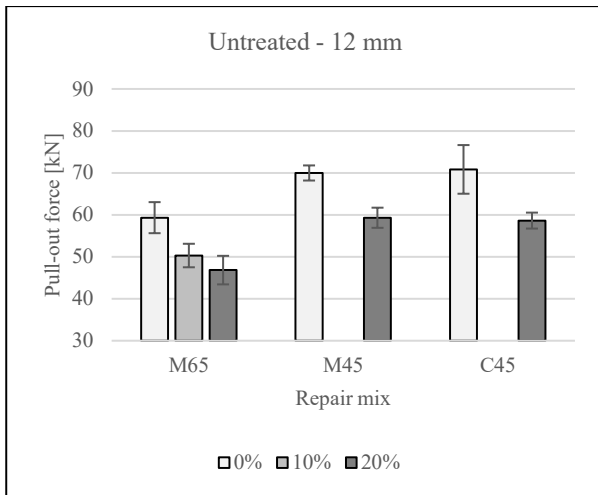


Fig. 10. Corrosion influence on pull-out force

Despite what the statistical analysis suggests, Figure 10 showed only a 10 – 20 kN reduction in pull-out force when compared to the uncorroded specimens. This shows the bond of the cleaned corroded steel at 20% mass loss for all mixes is not majorly different compared to the uncorroded steel. The results here highlight the importance of conducting repairs early with a thorough steel cleaning method to avoid the build-up of rust on corroding RC members with 20% mass loss, as this can be detrimental to the bond. This point has also been highlighted in previous studies [6][7].

For M65 at 10% mass loss, the rib height was reduced which lowered the mechanical interlock compared to the uncorroded specimens. For all mixes, it is believed that, while the mechanical interlock was reduced by the loss of all the rib height at 20% mass loss, the adhesion and frictional components of the bond increased after steel cleaning process.

3.2.5 Effect of coatings on previously corroded rebar

Figure 11 shows the pull-out results for the M65-12 specimens at 10% mass loss that were either untreated, coated once or twice.

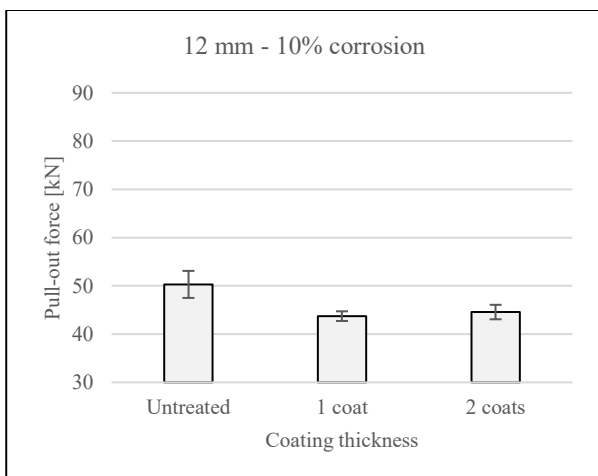


Fig. 11. Pull-out test results for 10% corroded M65-12

It is evident that applying one coat had a negative effect on the pull-out force of 10% corroded specimens compared to the untreated specimens, and applying a second coat showed no change in the pull-out force. This shows the coating thickness had minimal influence on the pull-out force when comparing specimens with one and two coats. The pull-out force was reduced by approximately 12% when applying one or two coats, which was not shown to be significant for the 10% mass loss case.

Figure 12 displays the pull-out force results for the 20% corroded specimens, for all coating treatments and mixes tested. Although there is a general trend where coating applications reduce the pull-out force for each of the mixes, this reduction was very small.

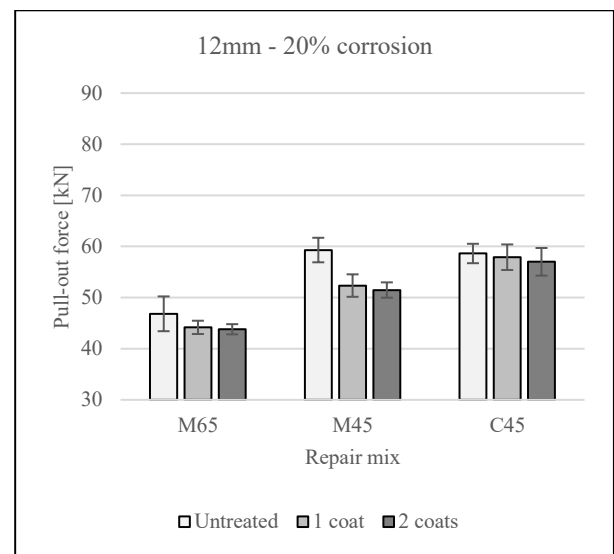


Fig. 12. Pull-out results for 20% corroded 12 mm specimens

For mix M65, the pull-out force reduced by 6% when one coat was applied, compared to untreated specimens. When two coats were applied, the pull-out force remained unaffected, similar to the 10% corroded specimens, making the null-hypothesis that there is no significant difference between untreated and coated corroded steel specimens of the mix M65 true. For mix M45, the pull-out force was reduced by 12% when one coating was applied. The statistical analysis suggests a significant difference in the pull-out force between untreated and treated specimens with one coat, rejecting the null hypothesis. When two coats were applied, however, there was no difference compared to the first coating. Poor performance from M45 was noticed and could be due to the average 28-day compressive strength of M45 (52 MPa) being higher than the coating (25 MPa). For mix C45, the pull-out force only decreased marginally for the first and second coat applied respectively, compared to untreated specimens. This accepts the null hypothesis and shows no effect of the coating on 20% corroded steel, for the concrete mix.

For the 20% corroded specimens, it can be noted that the addition of a second coating had little effect on the bond of cleaned corroded rebar, for all tested mixes. The mechanical interlock component of the bond no longer

existed due to the loss of ribs at 20% corrosion. Hence, the pull-out force was not as severely affected by the coating for 20% corroded specimens as the uncorroded specimens.

3.3 Coating performance

Figure 13 displays the effect of corrosion on pull-out strength, and the performance of coatings on 10% and 20% corroded specimens in relation to the uncorroded untreated specimens, denoted as the control.

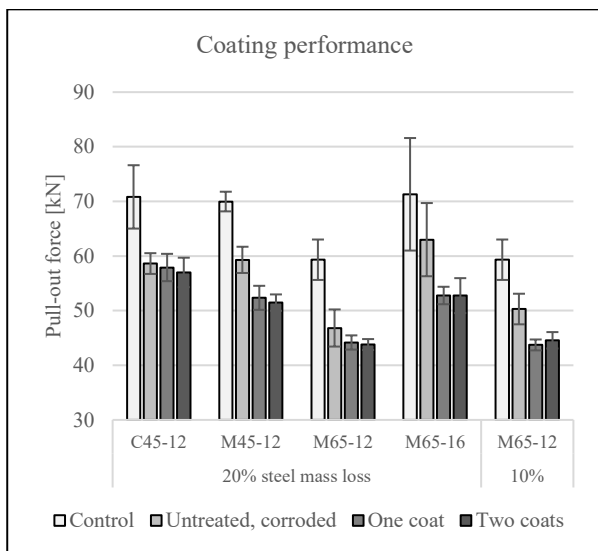


Fig. 13. Coating performance on corroded coated specimens

The results indicate a reduction in pull-out force for the untreated corroded specimens, when compared to the control. In general, for the C45-12 and M65-12 mixes, there was no significant difference in pull-out force between the untreated bars or the bars with one or two 0.6 mm thick coatings. Interestingly, the pull-out force from the corroded coated specimens of mix M65 was the same at 10% and 20% steel mass loss.

For mix M65 at 10% steel mass loss, the pull-out force for one and two coatings was 75% of the control, which is similar to what other researchers noticed [9]. For the 20% corroded specimens with two coats, the pull-out force of all mixes ranged from 73% to 80% of their respective controls. The results from all tested mixes, apart from M45, indicate no major effect from the coating thickness on the pull-out force and therefore the bond strength of corroded cleaned steel. Furthermore, the addition of the second coat had little effect on the bond performance for all mixes tested.

4 Conclusion

The main aim of this study was to investigate the influence of anti-corrosive coatings on the pull-out force of corrosion-damaged rebar. From the results of this study, it was observed:

- The w/b ratio of mortars with CEM I 52.5N showed a significant effect on the pull-out force. There was

no difference in pull-out force between the mortar and concrete of similar w/b ratios. As the rebar diameter was increased, the pull-out force increased which relates to a decrease in the bond strength. The results from this study display that the bond strength (MPa) should not be considered for corroded steel, or with coatings, as this is not a true measure and can potentially distort results. A new method i.e., assessing pull-out results, should be considered instead, to better evaluate the bond performance of corroded repaired steel.

- While a steel mass loss of 10% and 20% reduced the pull-out force for all mixes tested, when compared to uncorroded rebar, this reduction was only between 10 – 20 kN. Furthermore, the steel cleaning process should be prioritized early to remove rust, as the bond strength of cleaned corroded steel is much higher than for corroding steel with rust present.
- Epoxy-modified cementitious coatings applied to uncorroded steel will accumulate between ribs and reduce the relative rib area compromising the mechanical interlock that makes up the majority of the bond. The result of this was that the bond significantly reduced when two coats of 0.6 mm were applied, indicating these coatings should not be used in new construction.
- For M65 (10% and 20% mass loss) and C45 (20% mass loss), there was practically no difference between leaving the bars untreated or coating them, in terms of their pull-out strengths. For M45, there was a significant reduction in pull-out force when one coat of 0.6 mm was applied. Furthermore, the difference between one and two coats had little influence on the pull-out force of corroded specimens for all mixes.

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