

This item was submitted to Loughborough's Institutional Repository (<https://dspace.lboro.ac.uk/>) by the author and is made available under the following Creative Commons Licence conditions.



CC creative commons
COMMONS DEED

Attribution-NonCommercial-NoDerivs 2.5

You are free:

- to copy, distribute, display, and perform the work

Under the following conditions:

BY: **Attribution.** You must attribute the work in the manner specified by the author or licensor.

Noncommercial. You may not use this work for commercial purposes.

No Derivative Works. You may not alter, transform, or build upon this work.

- For any reuse or distribution, you must make clear to others the license terms of this work.
- Any of these conditions can be waived if you get permission from the copyright holder.

Your fair use and other rights are in no way affected by the above.

This is a human-readable summary of the [Legal Code \(the full license\)](#).

[Disclaimer](#) 

For the full text of this licence, please go to:
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

Diagnosing the Cause of Incipient Anodes in Repaired Reinforced Concrete Structures

C Christodoulou¹, C Goodier², S Austin², J Webb¹, G K Glass³

1: AECOM Europe, Colmore Plaza, 20 Colmore Circus Queensway, Birmingham, B4 6AT,
U.K.

2: Loughborough University, School of Civil and Building Engineering, Loughborough, U.K.

3: Concrete Preservation Technologies, University of Nottingham Innovation Lab,
Nottingham, UK, NG7 2TU

e-mail to: christian.christodoulou@aecom.com

ABSTRACT

The incipient anode (or halo) effect often occurs on repaired reinforced concrete structures. The diagnosis of this problem is widely reported to be macrocell activity. This diagnosis is based on very limited data. Indeed potential measurements on field structures repaired with proprietary materials have provided data that suggest that macrocell activity is not a cause of incipient anode formation. Alternative mechanisms that may cause incipient anode activity include repair/parent material interface effects, residual chloride contamination within the parent concrete, and/or vibration damage to the steel/parent concrete interface during repair area preparation.

Keywords: Concrete (A), steel reinforced concrete (A), corrosion (C).

1. INTRODUCTION

Corrosion of steel reinforcement affects many concrete structures. Patching is a common repair technique that involves the removal of physically deteriorated concrete (by hydro-demolition or jack hammer), cleaning the steel reinforcement within the patch and finally restoring the concrete profile with a proprietary repair mortar [1, 2]. This process renders the steel within the repair area passive [3]. In many cases corrosion-induced deterioration has subsequently been observed in the parent concrete in the immediate area around the patch repairs, sometimes within a few months following completion of the repair process [4]. This phenomenon is known as incipient or ring anode formation or the halo effect [3, 5].

The concept that macrocell activity (the formation of spatially separated anodes and cathodes) causes the incipient anode effect was first introduced by Page and Treadaway [6] in 1982. They suggested that the redistribution of anodic and cathodic sites following concrete repair affects future corrosion risk. Since that time the macrocell diagnosis developed to the extent that it is almost exclusively considered as the cause of incipient anode formation in the corrosion literature. Some quotes taken from prominent literature in this field include:

- i. Unless *“stringent measures are taken to remove all significantly chloride-contaminated material from around the corroding areas, the likelihood of corrosion reappearing and cracking the concrete adjacent to the repairs is high. This is because replacement of the most intensely anodic regions of the reinforcement with passive steel in the repaired zones effectively removes the adventitious form of sacrificial anode CP” (cathodic protection) “that was formerly being applied to the steel in the neighbouring regions. Hence, the potential of the metal in these less severely contaminated areas can rise to a value at which pitting is liable to be initiated”* [3].
- ii. *“If only concrete near the corroded reinforcement is replaced, the attack may start in the areas near to those repaired because they no longer benefit from the cathodic polarisation and, moreover, pitting corrosion may even be stimulated by anodic polarization from the repassivated steel in the repaired zone”* [5]
- iii. *“If a structure with extensive chloride attack is to be patch repaired then it must be recognised that patching the corroding areas can accelerate corrosion elsewhere”* [7].
- iv. *“The repair of only those sites which are actively corroding in a chloride-contaminated structure is likely to stimulate corrosion at sites adjacent to the repair. This phenomenon is known as the incipient anode, ring anode or halo effect”* [8].
- v. When *“an anode develops on reinforcing steel in concrete, particularly due to chloride attack, it provides “natural” cathodic protection to the adjacent steel.”* When this anodic site is repaired it *“allows the previously “naturally cathodically protected” adjacent areas to start corroding”* [9].

As indicated by the above citations, a widely held view is that the cause of incipient anodes is the loss of the natural cathodic protection provided by the corroding steel to the steel in the parent concrete adjacent to the patch repair. Some works suggest that repairing concrete structures can accelerate corrosion damage elsewhere. This may be true. The incipient anode phenomenon is shown in Figure 1. This is a photo of a car park deck with a quilt like appearance resulting from successive patch repairs. However publications

suggesting any other diagnosis for this phenomenon that exclude macrocell activity are scarce.

The aim of the work presented here was to assess the impact of macrocell activity on the formation of incipient anodes around the perimeter of repairs in patch-repaired reinforced concrete structures. A multi-storey car park and a bridge, both constructed of reinforced concrete provided first-hand data, which is evaluated alongside data published previously by others [3]. The analysis challenges the view that macrocell activity is a cause of incipient anode formation. Indeed this work shows that the data supporting the existing diagnosis is not convincing and suggests that macrocell activity is primarily a consequence of incipient anode formation and the cause probably, results from other factors.

2. METHODOLOGY

2.1 Structures

The incipient anode phenomenon was discovered on site structures and is not generally observed in laboratory experiments. Thus the specimens on which data were obtained in this work were a multi-storey reinforced concrete car park in the East Midlands, UK and a 180m long multi-span reinforced concrete bridge in North Scotland, UK. Both structures were approximately 40 years old. The structural arrangement of the car park was a one-way spanning ribbed slab. The 80 mm thick slab was lightly reinforced with 8mm steel mesh. The 180 m long reinforced concrete bridge comprising 18 spans, had steel piles capped with reinforced concrete capping beams, supporting longitudinal prestressed concrete beams with a concrete infill deck.

Both structures suffered extensive corrosion-induced damage resulting from reinforcement corrosion. Both structures were exposed to de-icing salts in winter months. The bridge structure was also exposed to a marine environment. In the case of the car park, deteriorated elements included the reinforced concrete decks, parapets and deck soffits adjacent to leaking expansion joints. In the case of the bridge structure, the deteriorated elements included the reinforced concrete pile caps and the prestressed concrete beams.

All areas of concrete deterioration were repaired by removing damaged concrete by jack hammer on the car park and hydro-demolition on the bridge, cleaning the steel using rotary steel wire brushes and restoring the profile with proprietary cementitious materials. Several concrete repairs were monitored for the formation of macrocells and incipient anodes.

By studying site structures we gain valuable insights into incipient anode phenomena affecting such structures. The data may then be compared with previously published laboratory data that was used to support the existing diagnosis for the incipient anode phenomenon.

2.2 Materials

Three proprietary repair materials, labelled A, B and C in this work were used to restore the concrete profile. All the materials are widely used in the construction industry and comply with existing standards [10]. Materials A and B were produced by the same manufacturer, material C was produced by another manufacturer. The nature of commercial contracts and their risk allocation require that a contractor uses specialist repair materials conforming to a standard. Because of the nature of this study it is not possible to give an equivalent material detail to that provided in laboratory experiments.

Material A is a Portland cement based, flowable, polymer modified, shrinkage compensated micro-concrete. 25 kg of material is mixed with 2.50 litres of water. It is placed directly into the repair area then trowel finished. It is mainly used for deck repairs and repairs involving shuttering. Material B is a Portland cement based, polymer modified, shrinkage compensated repair mortar with silica fume. The material is placed by dry spraying with a water to cement ratio of 0.35 to 0.4, and then trowel finished. It is used for repairs with large surface areas. Material C is a magnesia-phosphate cement based, non-shrink, repair mortar. 25 kg of material is mixed with 1.50 litres of water. Like material A, it is placed directly into the repair area and trowel finished. It is mainly used for deck repairs requiring very high early strengths. All of the materials are certified as class R4 repair mortars in accordance with BS EN 1504-3 [11].

The repair materials are tailored for the specific requirements of a repair area. Table 1 provides a summary of the monitored areas where each material was used.

2.3 Testing

2.3.1. Chloride profiles

For the car park, historical chloride data were available for a large number of locations over the period 1997 to 2008. For the reinforced concrete bridge, 27 dust samples were taken from the prestressed concrete beams and from the reinforced concrete pile caps, at depths between 25 mm to 125 mm in 25 mm increments. The chloride content was determined by an independent laboratory in accordance with the current standards [12].

2.3.2. Carbonation

Concrete samples taken from the areas of repair were tested for carbonation. The samples were cleaned and tested in accordance with the current standard using the indicator phenolphthalein [13].

2.3.3. Potential mapping

The performance of the repairs was assessed by means of concrete surface potential mapping [14 - 16]. Potential maps were obtained on a 50 mm square grid to detect macrocell activity. Typically the steel potential was measured against the potential of a portable reference electrode (Ag/AgCl/0.5M KCl) using a high impedance multi-meter. When a direct steel connection was not possible relative measurements were taken to determine the change in the potential within the concrete as previously described [15]. In some cases the potential values are reported relative to the reference electrode, while in other cases they are reported relative to the most positive value obtained at the time of the measurement. This is indicated in the Figures.

3. RESULTS

3.1 Multi-Storey Car park

The available chloride data for the car park exceeded the suggested limit of 0.3% by weight of cement [17] at the depth of the steel at 85% of the locations tested. No significant carbonation (less than 5mm) was identified on the concrete decks of the car park. The parapets were carbonated beyond the reinforcement at all areas tested. No data from the parapets is reported in this work because carbonation has a dramatic effect on pH and therefore potential. Only chloride induced corrosion damage was considered.

The steel potential after 30 days as a function of distance across a concrete surface that included a repair with material A is shown in Figure 2. It is clear that the potentials of the steel within the repaired area are substantially more negative than the potential of the steel in the parent concrete.

Contour plots showing potential mapping results both before and after repairing an area of corrosion damage with material A are given in Figure 3. The repair material had cured for 30 days when the data for the post repair contour plot was recorded. It is evident that, before the repair (Figure 3(a)), the potential in the area of the corroding steel was about 100 mV

more negative than the potential in the adjacent parent concrete. 30 Days after the repair this difference increased to approximately 200 mV.

Figure 4 shows the change in the potential difference between an area repaired with material A and the adjacent parent concrete over a period of 246 days. The early age results (15 days) show that the potentials within the patch repair were about 200 mV more negative than the potentials in the parent concrete. This difference reduced with time but the changes were relatively small. After 246 days the potential difference was somewhere between 150 and 200 mV. The potentials were measured in a variety of naturally occurring conditions including a very wet day on day 88.

3.2 Bridge Structure

Of the 27 samples for chloride analysis from the prestressed concrete beams and reinforced concrete pile caps, (taken at depths of 25 mm to 125 mm at 25 mm increments) only one was below the suggested chloride limit of 0.3% by weight of cement [17]. Chloride levels of up to 1.89% by weight of cement were identified in the depth band of 75-100mm. Carbonation depths on the reinforced concrete pile caps and the prestressed concrete beams of the bridge were insignificant (approximately 5mm) and they did not reach the depth of the reinforcement. Thus only the case of chloride-induced corrosion was considered on the bridge structure.

The potential data obtained on patch repairs on the bridge structure illustrated similar behaviour to that obtained on the car park. Figure 5 shows data obtained at an area repaired with material B. The potentials of the steel within the repair material were about 200 mV more negative than the potentials of the steel in the adjacent parent concrete at the start. After 83 days the change was still greater than 100 mV.

Figure 6 shows the steel potentials within the repair area measured before and after repair with material C. The data again shows that the potential of the steel within the repair area may be depressed to values that are more negative than the values observed in the parent concrete.

In some areas repaired with the pourable materials A and C, cracks were observed at the visible interface between the parent concrete and the repair material (Figure 7). The full extent of a crack is usually concealed due to the trowel finish of the repair that extends over to the parent concrete. It was only uncovered following surface preparation by mechanically

shot-blasting in preparation for an applied coating. For the spray applied material B, no cracks were identified.

4. DISCUSSION

This discussion firstly considers whether the available data suggests that macrocell activity is a cause or a consequence of incipient anode formation. Factors affecting the potential that may have a bearing on the analysis are then considered. The repair material interface and other factors that may induce incipient anode activity are then described and finally the corrosion risk resulting from repairing chloride induced corrosion damage is summarised.

4.1 Cause or Consequence

Figure 8 illustrates three possible cases schematically showing the steel potential change between repair material and parent concrete in the situation where a repair has been performed to address chloride-induced corrosion damage. The effect of an incipient anode on the steel potential in the parent concrete adjacent to the repair is taken into account in the potential plot in cases 1 and 2.

Case 1 represents one textbook understanding of the cause of incipient anode formation [see, for example, Figure 2(b) in reference 3]. In this hypothesis, the steel within the repair passivates as a result of the alkalinity of the fresh repair material, the absence of chlorides and the abundance of dissolved oxygen in the pore solution of the freshly mixed concrete or repair mortar. The steel potential in the repair rises above the passive steel potential in the parent concrete resulting in a macrocell that induces passive film breakdown causing an incipient anode to form adjacent to the repair. No data was uncovered either in the measurements recorded within this study or a review of the literature to support this hypothesis.

Case 2 represents the situation where the repair results in the removal of the corrosion site that used to be an anode. Previously published laboratory data [3] has shown that this situation may occur. Figure 9 reproduces the best data available supporting the widely held diagnosis (challenged in this current work) that macrocell activity causes incipient anode formation. To obtain this data a concrete slab was cast and then repaired under laboratory conditions. The parent concrete was not aged in the same way that concrete on a structure is aged and a proprietary repair material conforming to existing standards was not used to repair the damage.

Figure 9 shows that the potential of the steel in the repaired area did not differ substantially from the potential of the steel in the parent concrete. Two possible areas of incipient anode formation were identified. Only one of these was located adjacent to the repair area. A macrocell was also present between steel in different areas of the parent concrete in Figure 9. This data does not show that the incipient anodes were stimulated by the formation of a new macrocell. The parent concrete already contained passive steel that was as positive as the steel in the repaired area. The data suggests that the residual chloride content was sufficient on its own to cause corrosion at at least one of the identified areas of incipient anode formation.

Some natural cathodic protection that may have been provided by a previously corroding area of steel to its adjacent steel was removed in the repair process, but it is unlikely that this would cause any accelerated deterioration within the parent concrete. Indeed, the benefit provided by cathodic protection delivered from a corroding steel anode in concrete is questionable because corrosion of a steel anode results in expansive products that cause disruption to the surrounding concrete [18,19]. Reinforcement corrosion tends to spread laterally along the steel bars in conditions that also result in expansive corrosion products and the areas that receive the most protection from a corroding steel bar are the next areas to start corroding [20]. Thus, it is likely that a corroding steel anode causes more damage than it prevents and the removal of such an anode in the repair process should, in theory, slow the deterioration process if the deterioration was dominated by macrocell activity.

A related observation has been made with reference to the influence of a macrocell caused by coupling stainless steel to carbon steel in concrete. The impact of a stainless steel/carbon steel couple on inducing corrosion on the carbon steel has been reported to be no different to that of a passive carbon steel/carbon steel couple and did not increase the corrosion damage reported on the carbon steel [21 - 23]. By the same argument, it is unlikely that a macrocell formed by coupling the steel in the repair area to steel in the parent concrete will have any substantial impact on inducing additional corrosion on the steel in the parent concrete.

Case 3 in Figure 8 represents the findings of our study on two full-scale reinforced concrete structures, after being patched with three proprietary repair materials. The steel potential in the patch was always more negative than the steel potential in the parent concrete over the period of time tested (Figures 2 to 6). While the measurements were obtained on real structures made with different concretes repaired using different proprietary repair materials that were exposed to a variety of environmental conditions and subject to many other

unknown variables associated with repair contracts, there was not a single instance where the potential within the repaired area rose to or above that in the parent concrete.

Such an observation is not unique and has also been made by Cleland et al. [24] over a period of 2 years and by Morgan [25] when testing proprietary repair materials under laboratory conditions. These results support the hypothesis that, on balance, macrocell activity is a consequence, not a cause, of incipient anode formation in repaired concrete structures.

4.2 Factors Affecting Potential

Factors affecting the measured steel potential in a repaired area include passive film formation, pH, membrane effects and oxygen availability.

The steel passive film has to form on the steel in the repaired area and this will take time. However, the formation of the passive oxide film should have been complete after at least some of the periods tested, and should no longer have been affecting the potential within the repaired area. Thus, the formation of the passive film may only impart some limited time dependence to the potentials within the repaired area.

The pH of the environment has a strong impact on equilibrium potentials with a higher pH resulting in more negative equilibrium potentials. An increase in pH by just one pH unit in the alkaline region found within concrete will result in a 60 mV negative shift in both the equilibrium potential between iron and its products and the equilibrium potentials for the oxygen and hydrogen reactions [26]. Fresh repair concrete may well have a higher pH than aged concrete because the reaction between hydroxide and silica within the concrete or between hydroxide and carbon dioxide in the air will tend to reduce the pore solution pH in aged concrete to that sustained by one of the more abundant solid phases of cement hydration [27].

The change in pH between the repair material and the parent concrete can give rise to a membrane (or streaming) potential between the parent and the repair material [28]. This is due to diffusion of hydroxide ions from the repair material to the parent concrete and a charge on the walls of the pore system in concrete [29]. A charge on the pore walls results from incongruent dissolution of the solid phase and produces a membrane. The effect of the charge results in positive and negative ions diffusing at very different rates through the pore system and the movement of such ions in response to a concentration gradient induces the membrane potential. Studies on membrane potentials in concrete suggest that large

membrane potential effects are transient, i.e. they diminish with time [30]. Furthermore, membrane potentials in excess of 100 mV seem unlikely [31]. In many cases the potential differences observed in the present work exceeded 100 mV.

Passivity and oxygen availability affect the anodic and cathodic kinetics. Oxygen is consumed to passivate the steel in the repaired area. Many proprietary repair materials have a low permeability that restricts oxygen access and increases resistance. Thus Morgan [25] concluded that the use of polymer, styrene butadiene or acrylic modified cement mortars with such properties did not affect corrosion of steel in adjacent unrepaired areas. The effects of pH and permeability also suggest that any macrocell activity between parent concrete and proprietary repair materials will have less effect than macrocell activity that resides exclusively within the parent concrete.

Membrane potentials and formation of the passive oxide film probably give rise to some of the time dependence. However, they do not dominate the time dependence to the extent that steel potentials in the repaired areas rise above that in the parent concrete. The data from this study, like that of Cleland et al. [24] and Morgan [25] provided no evidence to indicate that macrocell activity is a cause of incipient anode formation in aged concrete structures repaired with proprietary repair materials.

4.3 Repair material interface

Cracks may occur at the interface between the parent concrete and the repair material following patch repair. The presence of such cracks can be attributed to drying, or plastic shrinkage, thermal or stiffness incompatibility, poor curing, surface preparation or a combination of the above [32, 33]. Admixtures can be used to increase the volume of the repair material during early age hardening of shrinkage compensated materials. However, the material will often undergo an S-shaped expansion-contraction cycle [34]. Although close to zero net unrestrained shrinkage can be achieved in such shrinkage compensated materials, there may be some limited retained shrinkage which can give rise to cracking because the early expansion part of the cycle is restrained by the parent concrete.

Chadwick [35] examined the corrosion protection afforded by single cast, cast in two halves and patch repaired specimens. He observed a major reduction in the corrosion protection for the latter two types of specimens and suggested that it is not necessary for chlorides to be present in the parent concrete for incipient anodes to form at the interface. He suggested that it is only necessary to expose the repaired concrete element to a chloride-contaminated

environment, as the interface between the two concrete or mortar materials provides easier access for chloride penetration.

Thus, the interface between repair material and parent concrete may provide a path for chlorides to penetrate preferentially into the substrate. The extent of this effect will be dependent on surface preparation, application techniques, curing, material properties and compatibility with the parent concrete. The presence of visible cracks may be obscured by trowel finishing the repair.

Crack formation in reinforced concrete structures and its relationship to corrosion has been established by a number of studies [36, 37]. In particular, it has been shown that the reinforcement within and around the crack zone will start to corrode first. Chadwick [35] also observed that the presence of construction joints in the same material resulted in corrosion initiating at lower apparent chloride levels at the construction joint interface.

4.4 Incipient Anode Formation

The repair of corroding areas removes the anode in this location and any “sacrificial” cathodic protection effects resulting from such an anode. However, it is very unlikely that simply turning a corroding steel anode into a passive cathode would result in more damage occurring than if nothing was done [20,21]. Other factors associated with the repair process that might cause incipient anodes to form include repair material interface effects, residual chloride contamination and damage to the steel-concrete interface during repair preparation.

Cracks and interfacial effects between parent concrete and repair material provide an easier path for the chlorides to penetrate into the substrate. The parent concrete may have a higher permeability than the new repair material and this will aid the diffusion process from the interface into the parent concrete. The parent concrete is also likely to have some residual chloride contamination that may promote corrosion. The preparation of the repair area usually requires the mechanical removal of concrete that puts a lot of energy into the steel reinforcement. This may cause damage to (or defects at) the interface between the unexposed steel and the parent concrete adjacent to the repair area. Such defects increase the corrosion risk by lowering the chloride threshold level [27].

4.5 Corrosion Risk

This analysis has suggested that there is no obvious increase in corrosion risk following patch repair of reinforced concrete structures that results from macrocell activity, beyond

what would be the case if the steel had remained passive (i.e. there is no increase in the macrocell voltage). Indeed, steel reinforcement in an aged parent concrete may remain cathodic relative to steel in proprietary repair materials for a substantial period after the repair is undertaken. The results of this study are in line with previously reported findings by Bertolini et al. [21] and Qian et al. [22] on the corrosion risk presented by a galvanic couple of stainless steel to carbon steel. The damage caused by a corroding steel anode in an unrepaired area probably outweighs any electrochemical protective effects that such a corroding area may deliver [20, 21].

Incipient anodes may form around patch repairs and their presence can be detected with potential mapping. As noted above, alternative causes of incipient anodes include a permeable interface between the parent and repair materials, residual chloride contamination of the parent concrete and damage to the steel interface within the parent concrete during the preparation of the repair area.

The results of this research help to inform the development of corrosion management strategies that may include rehabilitation methods such as cathodic protection, surface coatings and hydrophobic impregnations, to increase durability of reinforced concrete structures.

CONCLUSIONS

- i) While the incipient anode phenomenon often occurs on repaired reinforced concrete structures, potential measurements taken on structures repaired with a variety of proprietary repair mortars over a period of up to 250 days suggest that macrocell activity does not stimulate incipient anode formation. No evidence was found from potential measurement data obtained in this work to support the diagnosis that macrocell activity is a cause of incipient anode formation. The evidence suggests that, on balance, the detrimental effect of a corroding steel anode in concrete will outweigh any beneficial effects that it may provide. In other words, a corroding steel anode causes more damage than it prevents.
- ii) The use of proprietary repair materials may permanently depress steel potentials within the repair area. The reasons for this include the typically low permeability and high pH of these materials. A high pH in an area of repair would result in a negative shift in steel potentials because equilibrium potentials of steel in concrete are more negative at the high end of the pH range. Macrocell activity that might be damaging is less likely to occur between parent and repair concrete than within the parent concrete.

- iii) Cracks can develop at the repair/substrate interface, even with shrinkage-compensated repair materials, providing an easier path for chlorides to penetrate into the substrate. This cracking results from their “S” shaped strain curve so that, even in an unrestrained case (where no net strain occurs) shrinkage occurs in the final phase. The extent of these cracks will be dependent on surface preparation, application techniques, material properties, adhesion between the repair material and parent concrete and curing conditions. Such cracks may be obscured by trowel finishing of the repair.
- iv) The diagnosis of the cause of the incipient anode phenomenon adjacent to areas of concrete repair may reside in one or more of the following reasons:
 - a. Chlorides may enter the concrete through the interface between the parent and repair material,
 - b. the parent concrete adjacent to the repair area may have an above average level of residual chloride contamination that is sufficient on its own to cause corrosion, and/or
 - c. preparation of a repair area may result in vibration damage at the steel interface with the adjacent parent concrete.

ACKNOWLEDGEMENTS

The authors would like to thank AECOM and the EPSRC (through the Centre for Innovative and Collaborative Engineering at Loughborough University) for their commercial and financial support.

REFERENCES

1. M. Dugarte A.A. Sagüés, Galvanic point anodes for extending the service life of patched areas upon reinforced concrete bridge members, Contract No. BD544-09, Final Report to Florida Department of Transportation, Tampa, Florida, USA, September 2009.
2. C. Christodoulou, G. Glass, J. Webb, S. Austin, C. Goodier, A new approach for the patch repair of car parks using galvanic anodes, Concrete Solutions 2011, 4th International Conference on Concrete Repair, 26-28 September 2011, Dresden, Germany, ISBN 978-0-203-13468-9.
3. C.L. Page, G. Sergi, Developments in cathodic protection applied to reinforced concrete, J. Mater. Civ. Eng. 1 (2000) 8-15.

4. S. Qian, J. Zhang, D. Qu D, Theoretical and experimental study of microcell and macrocell corrosion in patch repairs of concrete structures, *Cem. Concr. Compos.* 28 (2006) 685 – 695.
5. L. Bertolini, B. Elsener, P. Pedeferri, R. Polder, *Corrosion of steel in concrete, prevention, diagnosis, repair*, Wiley-VCH, Germany, 2004.
6. C.L. Page, K.W.J. Treadaway, Aspects of the electrochemistry of steel in concrete, *Nature* 297, (1982) 109-115.
7. J.P. Broomfield, *Corrosion of steel in concrete: understanding, investigation and repair*, 2nd ed., Taylor and Francis, UK, 2007.
8. Concrete Society, Technical Report 73, *Cathodic Protection of Steel in Concrete*, Surrey, UK, 2011.
9. British Standards Institution, BS EN ISO 12696:2012, *Cathodic protection of steel in concrete*, London, BSI, 2012.
10. Concrete Society, Technical Report 69, *Repair of concrete structures with reference to BS EN 1504*, Surrey, UK, 2009.
11. British Standards Institution, BS EN 1504:2005 *Products and systems for the protection and repair of concrete structures — Definitions, requirements, quality control and evaluation of conformity — Part 3: Structural and non-structural repair*, London, BSI, 2005.
12. British Standards Institution, BS 1881–124:1988 *Testing concrete, Methods for analysis of hardened concrete*, London, BSI, 1988.
13. British Standards Institution, BS EN 14630:2006 *Products and systems for the protection and repair of concrete structures — Test methods — Determination of carbonation depth in hardened concrete by the phenolphthalein method*, London, BSI, 2006.
14. Concrete Society, Technical Report 60, *Electrochemical tests for reinforcement corrosion*, Surrey, UK, 2004.
15. G K Glass, N Davison, A C Roberts, *Monitoring Method*, UK Patent GB 2449039 B, 2010.
16. C. Christodoulou, G. Glass, J. Webb, S. Austin, C. Goodier, Assessing the long term benefits of Impressed Current Cathodic Protection, *Corros. Sci.* 52 (2010) 2671 – 2679, DOI: 10.1016/j.corosci.2010.04.018
17. Design Manual for Road and Bridges, Volume 3, Section 3, Part BA 35/1990 *Inspection and Repair of Concrete Highway Structures*, Departmental Standard, UK, 1990.

18. K. Lau, A.A. Sagüés, Corrosion of steel in locally deficient concrete, Contract No. BD544-31, Final Report to Florida Department of Transportation, Tampa, Florida, USA, February 2009.
19. Y. Zhao, J. Yu, Y. Wu, W. Jin, Critical thickness of rust layer at inner and out surface cracking of concrete cover in reinforced concrete structures, *Corros. Sci.* 59 (2012) 316 – 323.
20. G K Glass, N Davison, A C Roberts, Hybrid corrosion protection of chloride-contaminated concrete, *Proceedings of the Institution of Civil Engineers, Constr. Mater.* 161 (2008) 163 – 172
21. L. Bertolini, M. Gastaldi, M.P. Pedferri, P. Pedferri, T. Pastore, *Proceedings of the International Conference on Corrosion and Rehabilitation of Reinforced Concrete Structures*, Orlando, USA, 1998.
22. S. Qian, D. Qu, G. Coates, Galvanic coupling between carbon steel and stainless steel reinforcements, *Can. Metall. Q.* 45 (2006) 475-484.
23. C.M. Abreu, M.J. Cristobal, M.F. Montemor, X.R. Novoa, G. Pena, M.C. Perez., Galvanic coupling between carbon steel and austenitic stainless steel in alkaline media, *Electrochim. Acta* 47 (2002) 2271 – 2279.
24. D.J. Cleland, K.M. Yeoh, A.E. Long, Corrosion of reinforcement in concrete repair, *Constr. Build. Mater.* 11 (1997) 233 – 238.
25. D.R. Morgan, Compatibility of concrete repair materials and systems, *Constr. Build. Mater.* 10 (1996) 57 – 67.
26. M. Pourbaix, Thermodynamics and corrosion, *Corros. Sci.* 30 (1990) 963 – 988.
27. G.K. Glass, B. Reddy L.A. Clark, Making reinforced concrete immune from chloride corrosion, *Proceedings of the Institution of Civil Engineers, Constr. Mater.* 160 (2007) 155 – 164.
28. Y. Schiegg, M. Büchler, M. Brem, Potential mapping technique for the detection of corrosion in reinforced concrete structures: Investigation of parameters influencing the measurement and determination of the reliability of the method, *Mat. and Corr.* 60 (2009) 79–86.
29. G. K. Glass, N. R. Buenfeld, Chloride-induced corrosion of steel in concrete, *Prog. Struct. Engng. Mater.* 2 (2000) 448 – 458.
30. J.L. Marriaga, P. Claisse, Effect of the non-linear membrane potential on the migration of ionic species in concrete, *Electrochim. Acta* 54 (2009) 2761-2769.
31. U. Angst, Ø. Vennesland, R. Myrdal, Diffusion potentials as source of error in electrochemical measurements in concrete, *Mat. and Struct.* 42 (2009) 365-375.
32. Concrete Society, Technical Report 22, Non-structural cracks in concrete, Surrey, UK, 2010.

33. Concrete Society, Technical Report 54, Diagnosis of deterioration in concrete structures, Surrey, UK, 2000.
34. K. Szilágyi, I. Zsigovics, C. Szautner, Advanced shrinkage compensation of concretes by a combined admixture system, *Építőanyag* 59 (2007).
35. R. Chadwick, Performance of concrete repair materials as corrosion protection for reinforcement, PhD thesis, University of Surrey, 1993.
36. M. Raupach, Chloride-induced macrocell corrosion of steel in concrete – theoretical, background and practical consequences, *Constr. Build. Mater.* 10 (1996) 329 – 338.
37. P. Schiessl, M. Raupach, Laboratory studies and calculations on the influence of crack width on chloride-induced corrosion of steel in concrete, *ACI Mater. J.* 94 (1997) 56-62.

Tables

Materia	Structure type	Repair location
A	car park	Deck
B	Bridge	Soffits and vertical faces
C	Bridge	Deck

Table 1: Repair materials and location

Figure Captions

Figure 1: A concrete deck showing the quilt-like appearance associated with the incipient anode phenomenon arising from successive repair contracts.

Figure 2: Steel potential showing the effect of material type A on a car park deck repair.

Figure 3: Surface potential mapping on an area of the car park (a) before and (b) 30 days after repair (material A). The dashed line in (b) illustrates the extent of the repair.

Figure 4: Effect of a repair (material A) on the relative potential determined at the concrete surface after it had cured for various times.

Figure 5: Effect of a repair on the steel potential on a bridge repair at various times after applying repair material B.

Figure 6: Effect of a repair on the steel potential on a bridge repair at various times after applying repair material C.

Figure 7: Cracks at the interface of a patch repair in the car park using material A, before and after surface preparation with mechanical shot-blasting.

Figure 8: Three schematic cases showing potential changes between parent and repair concrete.

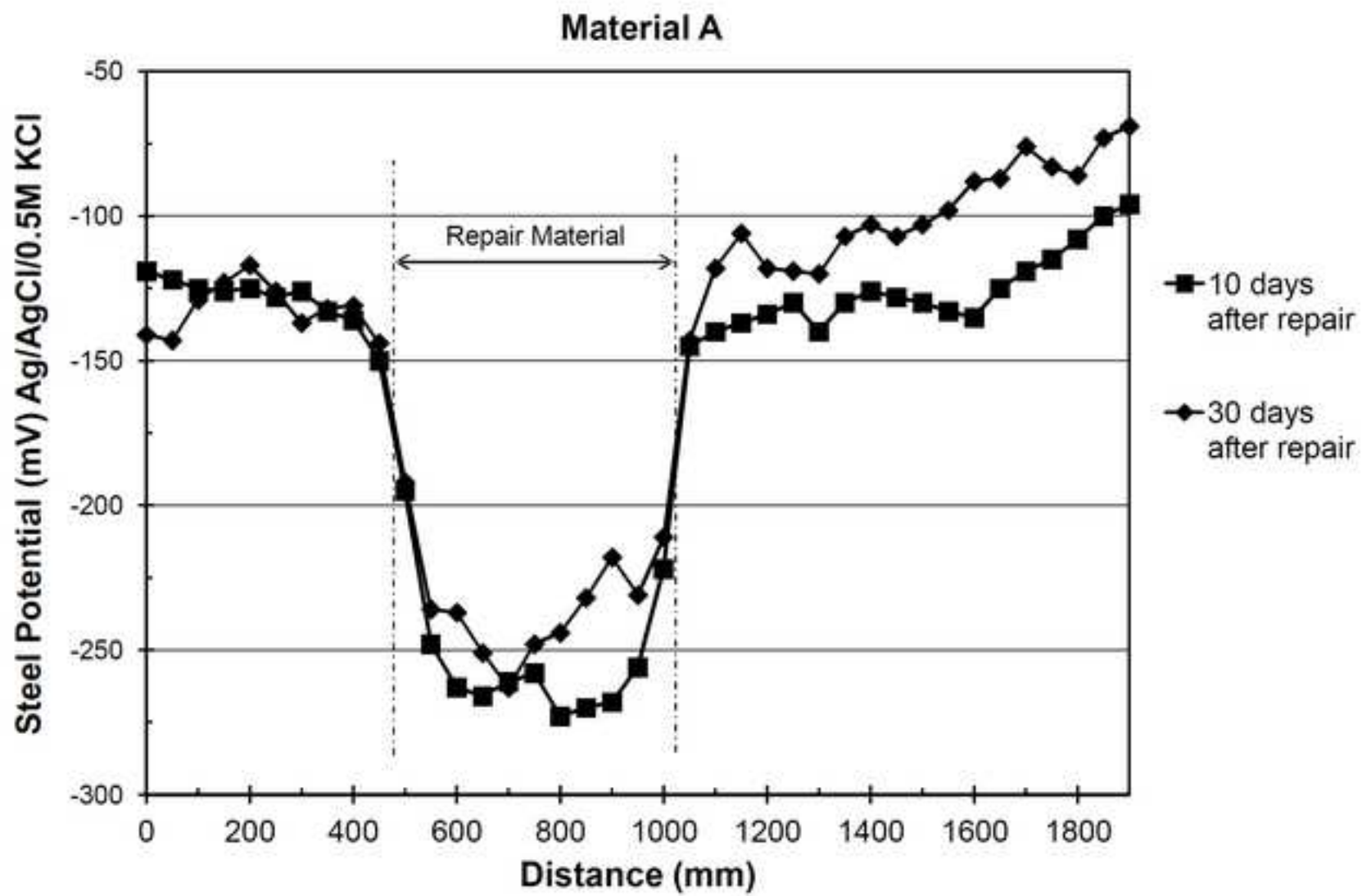
Figure 9: Steel potentials relative to a saturated calomel electrode in a laboratory concrete specimen 2 months after repairing an area of the specimen [5].

Figure

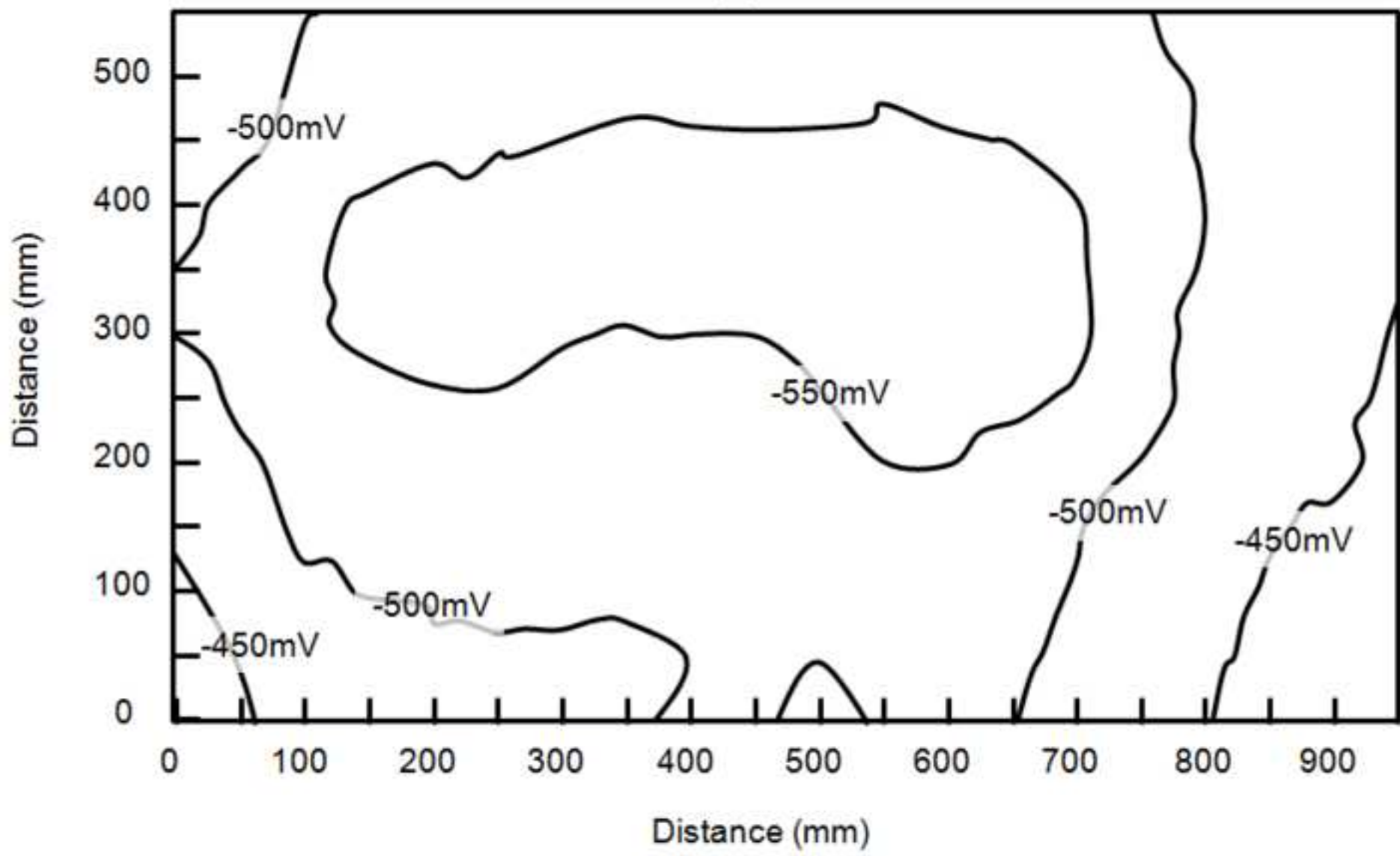
[Click here to download high resolution image](#)



Figure
[Click here to download high resolution image](#)



(a)



(b)

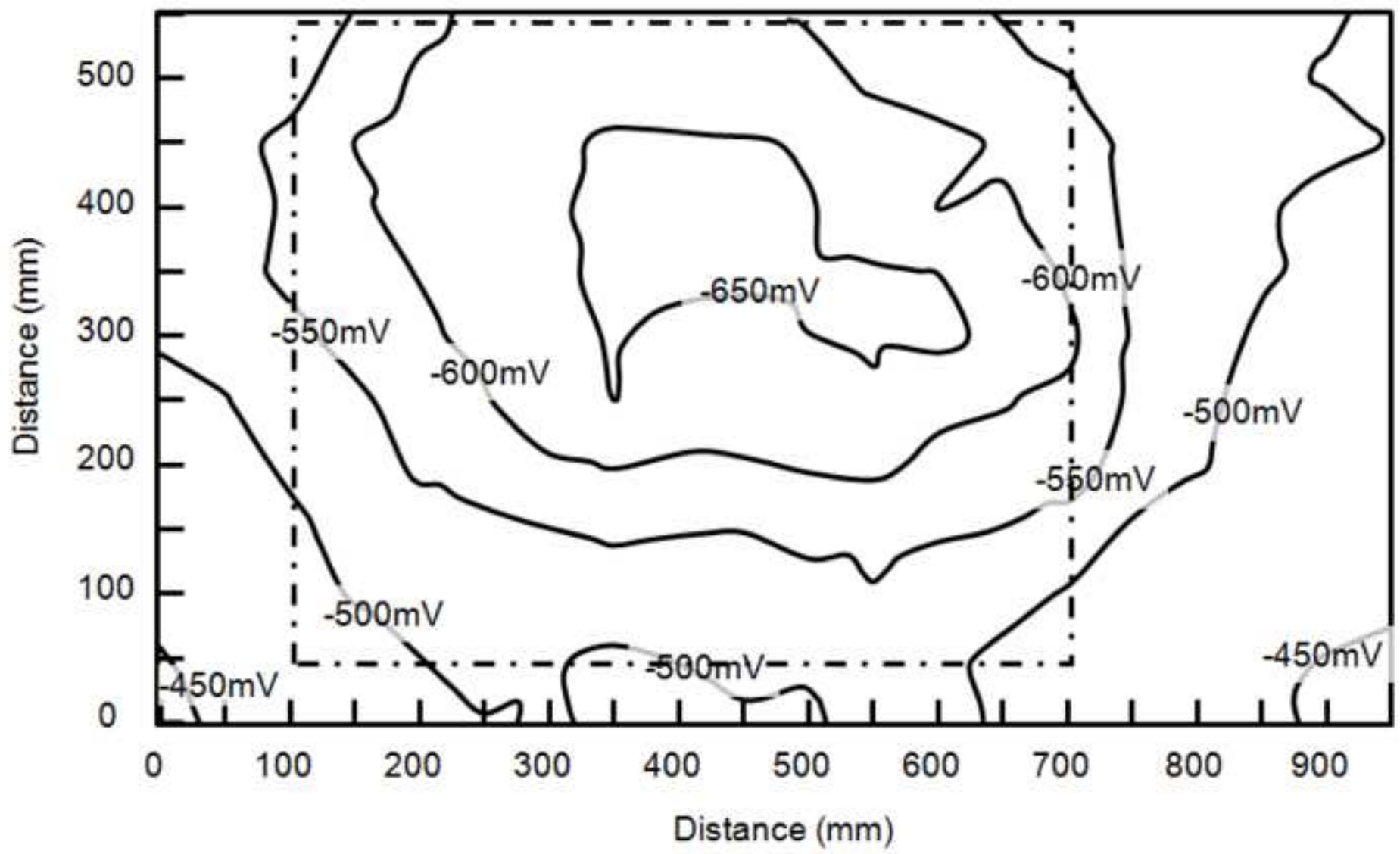


Figure
[Click here to download high resolution image](#)

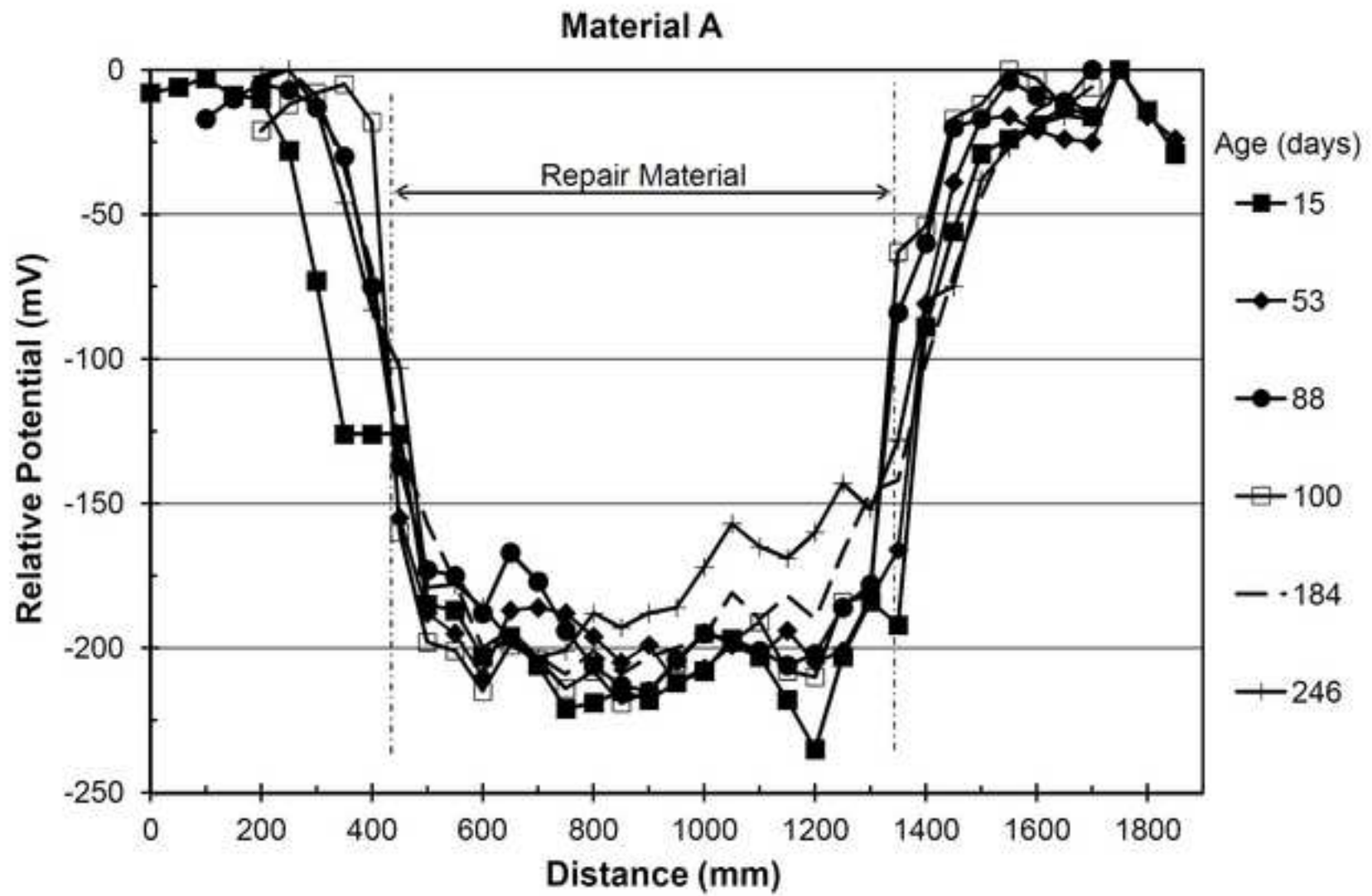


Figure
[Click here to download high resolution image](#)

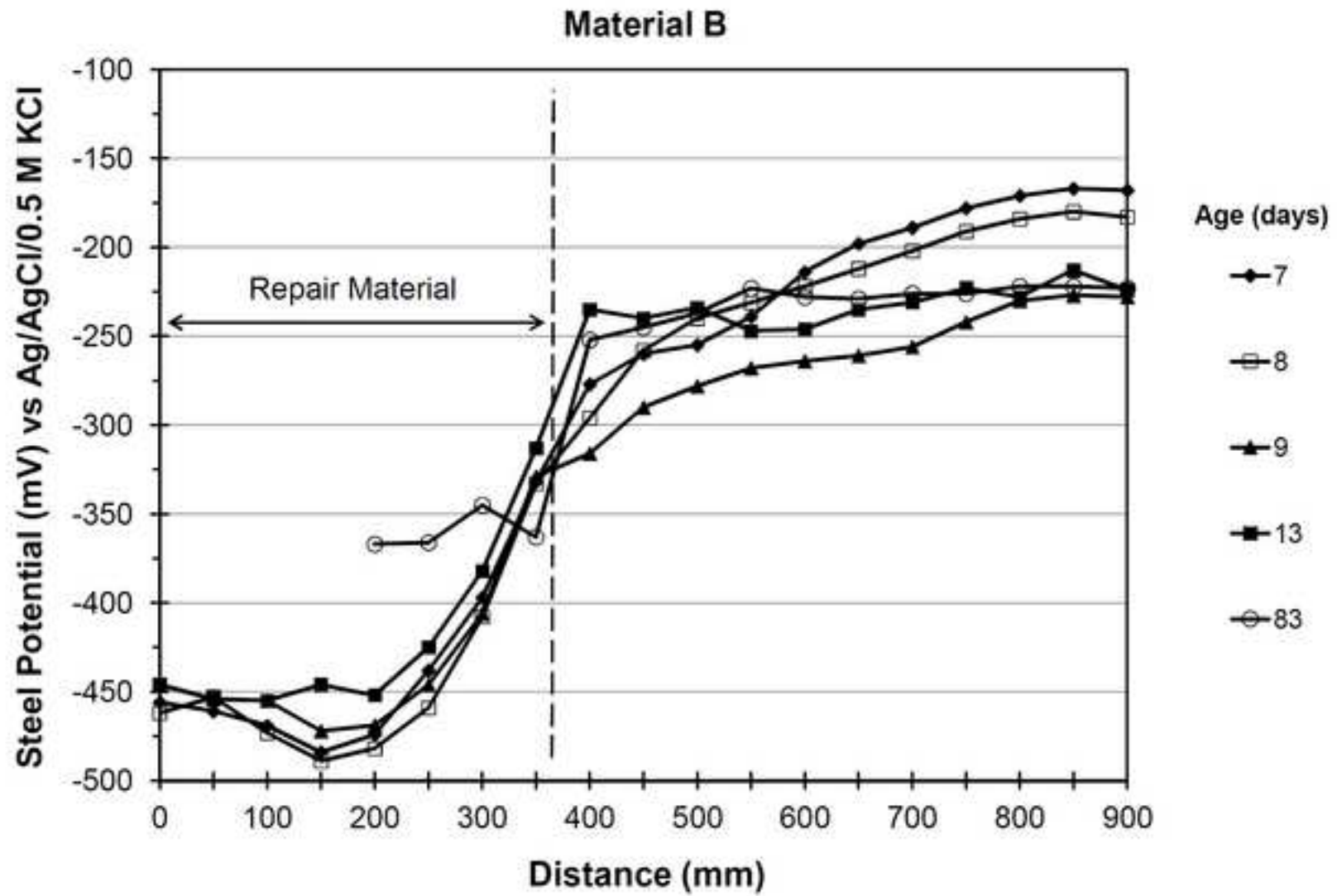
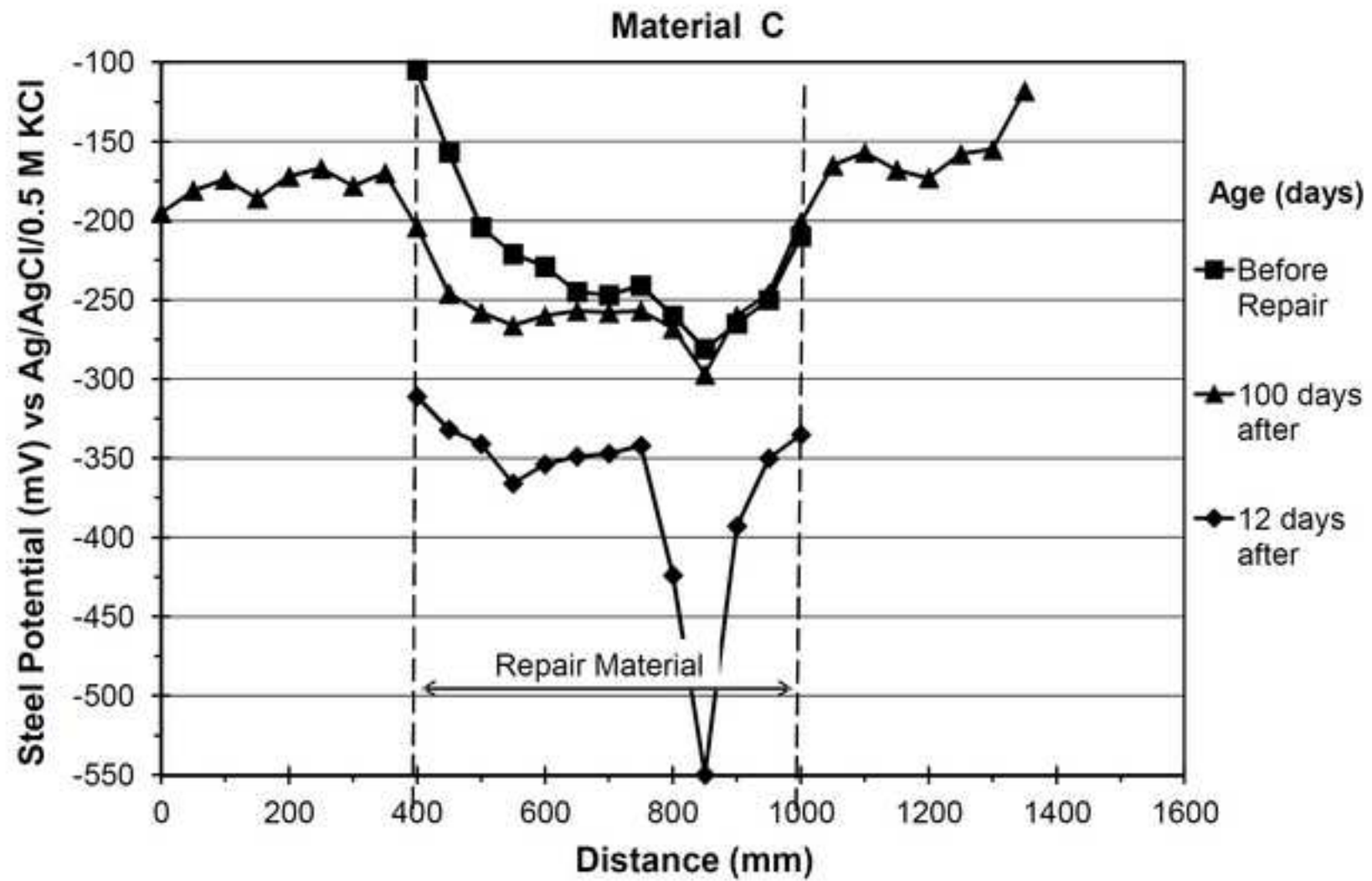


Figure
[Click here to download high resolution image](#)



Figure

[Click here to download high resolution image](#)



Figure
[Click here to download high resolution image](#)

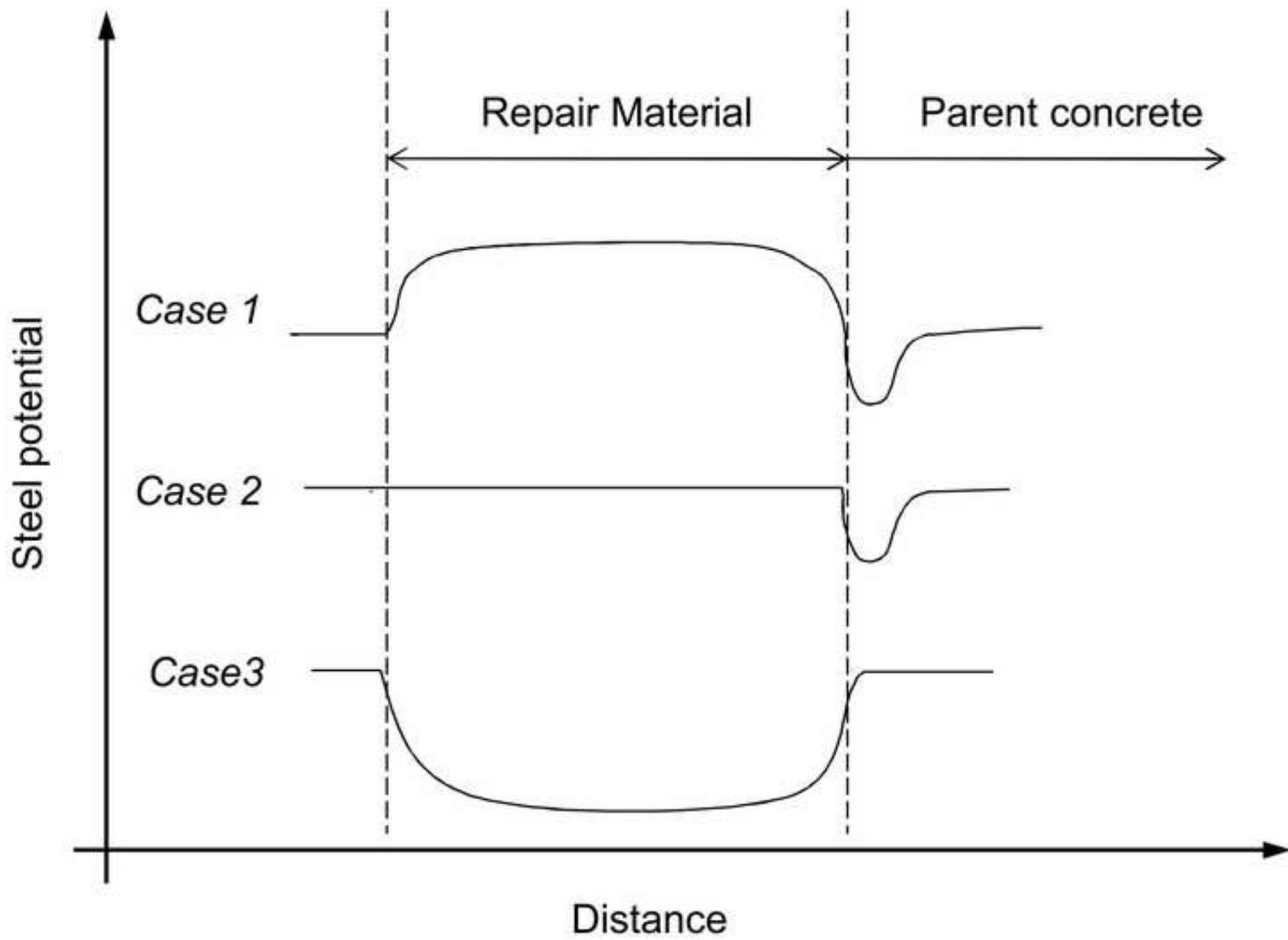


Figure
[Click here to download high resolution image](#)

