

Experimental investigation into the effects of cast-iron pipe corrosion on GPR detection performance in clay soils

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2 **Title: An Experimental Investigation into the Effects of Cast Iron Pipe**
3 **Corrosion on GPR Detection Performance in Clay Soils**

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37 **Abstract**

38 Cast iron water distribution pipes are used widely in the UK and worldwide. Corrosion of these
39 cast iron pipes often occurs due to an electrochemical process where the pipe is buried directly
40 in a chemically aggressive ground (as is the case for some clays). The electrochemical process
41 changes the pH environment and releases iron ions into the clay. This can cause chemical
42 alteration of the clay minerals and ‘corrosion products’, such as iron oxide, hydroxide and
43 aqueous salts, to form in the soil. These chemical interactions are complex and time dependent,
44 and can potentially result in pipe failure, and thus the conditions under which they occur need
45 to be understood.

46 Ground Penetrating Radar (GPR) has been proposed for routinely detecting, assessing and
47 monitoring buried cast iron pipes, and thus it is important to know how these chemical changes
48 affect the electromagnetic properties of soil. A bespoke set of laboratory experiments was
49 devised to simulate and accelerate cast iron corrosion (using electrokinetics) and ion migration
50 processes in two types of clay, namely Kaolin Clay and Oxford Clay. Tests were conducted for
51 periods of up to 3 months using both inert electrodes and a cast iron disc as the anode. The
52 changes in the geotechnical properties (undrained shear strength, moisture content and
53 Atterberg limits), the geophysical properties (permittivity) and the geochemical properties
54 (iron content, pH and conductivity) were monitored. The results indicated that the Oxford Clay
55 was much more aggressive in terms of the corrosion activity compared to the Kaolin Clay. The
56 laboratory results were used in GPR simulations in relation to the detection of a buried cast
57 iron pipe. The results showed that the chemically induced changes to the Kaolin Clay did not
58 materially affect the performance of GPR to detect the cast iron pipe, whereas a pipe buried in
59 Oxford Clay the (greatly accelerated) chemically-induced changes were sufficiently advanced
60 after approximately 7-8 weeks to cause the GPR to be unable to detect the corroded pipe.

61 **Keywords**

62 cast iron pipe; corrosion; geotechnical properties; geophysical properties; geochemical
63 properties; Ground Penetrating Radar (GPR) modelling

64 **Abbreviations**

65 BSI British Standards Institution

66 EC Electrical Conductivity

67	EK	Electrokinetic
68	FDTD	Finite Difference Time Domain
69	GPR	Ground Penetrating Radar
70	NDT	Non-Destructive Technologies
71	pH	Acidity / Alkalinity of system / $-\log_{10}$ of hydrogen ions activity
72	PVC	Polyvinyl Chloride
73	TDR	Time-Domain Reflectometry
74	USS	Undrained Shear Strength
75	V _p	Propagation Velocity

76 **1 Introduction**

77 Cast iron pipes have been widely used for transferring potable water, being routinely used from
78 the early 1800s, particularly in the USA, (Merdinger, 1955), and extensively used to build
79 water distribution systems in the UK, to the extent that it was called the ‘wonder material of
80 the Victorian era’ (Gagg and Lewis, 2011). Its use continued until ductile iron pipes were
81 introduced in the 1970s (Rajani *et al.*, 1996). Nevertheless, cast iron is still the most common
82 material found in existing pipes, and is also the material that produces the highest number of
83 bursts historically (Marshall, 2001; Makar and McDonald, 2007; Folkman, 2018). The most
84 common corrosion failure mechanism for buried cast iron pipes is localised corrosion, which
85 can lead to leakage (WSAA, 2003). It has been found that cast iron pipes have a very high
86 failure rate in some particular soils, i.e. in soils that are particularly aggressive such as London
87 Clay (Schmidt, 2007). This suggests an involvement of chemical processes, in addition to
88 mechanical deterioration mechanisms (London Clay is also active in terms of shrinkage and
89 swelling behaviour), induced by the prevailing environmental conditions (Bradford, 2000).
90 Cast iron pipe corrosion occurs readily in saturated or partially-saturated zones of clays, where
91 electrochemical oxidation takes place in the presence of oxygenated water. This is called
92 graphitic corrosion and is caused by the creation of a galvanic cell between the cast iron (the
93 anode, where the pH is lowered) and the surrounding high-conductivity clay (the cathode)
94 (Freeman, 1999). Buried pipes are in direct contact with the soil, with different physical and

95 geochemical properties, and therefore the prevalence for corrosion to occur can change over
96 the length of a pipe.

97 Cast iron corrosion in soil occurs due to electrochemical processes and results in the formation
98 of pitting, converting metal substrates to oxides, hydroxides and aqueous salts (in anode-
99 cathode systems) (Romanoff, 1964). These corrosion products are released into the surrounding
100 soil, changing the chemical, geotechnical and geophysical properties of the soil, although the
101 interactions between these properties are not well understood (Figure 1). The release of ions
102 from a corroding buried iron pipe is expected to increase the rate of pipe corrosion due to an
103 increase in ion concentrations in the surrounding soil (Ekine and Emujakporue, 2010). These
104 released ions contaminate the surrounding soil, elevating the iron/cation content and creating a
105 diffuse plume zone around the source, i.e. the cast iron pipe (Yong and Mulligan, 2003). The
106 plume zone is where ion diffusion and migration occur, and this can ultimately lead to
107 modification of the soil, with the concentration of these ion contaminants decreasing away from
108 the cast iron pipe as they form precipitates or complexes with the surrounding soil (Yong and
109 Mulligan, 2003).

110 Routine and yet effective condition assessment of these buried pipes can minimise the negative
111 consequences of deterioration in the utility network. To further minimise the risk of damaging
112 the utility network adopting non-destructive technologies (NDT) for assessment would be ideal
113 as they have the potential for providing routine and effective assessment with minimum
114 disruption (Roberge, 2007; Rainer *et al.*, 2017). Geophysical techniques, such as Ground
115 Penetrating Radar (GPR), have been utilised to locate and map cast iron pipes (Mooney *et al.*,
116 2010; Pennock *et al.*, 2010; Ayala-Cabrera *et al.*, 2011) and assess their condition (Hao *et al.*,
117 2012; Liu *et al.*, 2012; Rogers *et al.*, 2012; Liu and Kleiner, 2013) including determination of
118 the corroded state of cast iron pipes. Having said that, as it is suggested in the literature, e.g.
119 (Pennock *et al.*, 2010), chemical alteration of fine-grained soil by cast iron corrosion products
120 may inhibit GPR's abilities to be used for utility mapping or assessment.

121 The aim of this paper is to investigate the effects of the corrosion of buried cast iron pipes on
122 the geophysical, geochemical and electromagnetic properties of the surrounding clay soils, as
123 these soils are known to be aggressive towards buried metals (Bonds *et al.*, 2005; Veleva, 2005;
124 Cole and Marney, 2012), and hence to explore the reported tendency of deteriorated cast iron
125 pipes being harder to detect using GPR than pristine pipes. This has been done through
126 controlled laboratory experiments that simulate the corrosion and ion migration process.

127 2 GPR Application for Iron Pipe Condition Assessment

128 Over the last two decades, a number of different NDTs have been utilised for inspecting water
129 pipes, including seismic and acoustic methods (Demma *et al.*, 2004; Choi *et al.*, 2017) and
130 infrared thermography (Bach and Kodikara, 2017). Some of these NDT technologies exploit
131 specific pipe materials properties, and consequently they are not suitable for use with all pipe
132 materials (Atef, 2010). However, the GPR technique has been widely used for shallow
133 geophysical investigation (Costello *et al.*, 2007; Demirci *et al.*, 2012). Its main advantage is
134 that it can survey large areas at a speed that makes real time interpretation possible. In this
135 method an electromagnetic wave (generally between 1 MHz to 1 GHz) is transmitted
136 through the ground and the Time-of-Flight (ToF) from the reflected wave is measured (Metje
137 *et al.*, 2007). GPR has been used for investigating and monitoring underground water, locating
138 wet patches, and hence pipe leaks, e.g. Tran and Lambot (2015); Algeo *et al.* (2016); Fedorova
139 *et al.* (2016). Algeo *et al.* (2016) successfully used an analysis method termed ‘early-time’ for
140 monitoring the water content in clay-rich soil, and compared the results with time-domain
141 reflectometry (TDR) data. Cheung and Lai (2018) successfully demonstrated the GPR
142 application for leakage detection during a large scale experiment.

143 There are a number of factors which can limit or eliminate the use of GPR by attenuating its
144 signal reflection, including: the presence of the clayey soil (Rogers *et al.*, 2008), iron oxide
145 produced by a corroded buried cast iron pipe (Van Dam and Schlager, 2000; Pennock *et al.*,
146 2014), dissolved metallic ions (Deceuster and Kaufmann, 2005), depth of the water table
147 (Bano, 2006). Pennock *et al.* (2010) examined the reduction in GPR reflection that could occur
148 with corroded materials, based on altered soil permittivity and conductivity initiated by
149 corrosion processes and/or products. The Finite Difference Time Domain (FDTD) technique
150 was used to model the scenario of surveying a deteriorated cast iron buried in soil contaminated
151 by corrosion products using the GPR technique. The results showed a substantial reduction in
152 GPR reflection, between 20dB to 30dB, which was identified as significant enough to make a
153 deteriorated iron pipe buried in a 5cm to 10cm zone of contaminated soil undetectable by
154 traditional GPR antennas.

155 The performance capability of GPR is strongly dependent on the soil electrical conductivity;
156 where in a high soil conductivity attenuation of the radar signal can severely restrict the
157 maximum penetration depth. Graphitic corrosion in cast iron pipes releases iron ions (Fe^{2+})
158 into the surrounding soil, increasing the total dissolved salt content of the soil, and

159 consequently changing soil conductivity and permittivity (DeBerry *et al.*, 1982; Moghareh
160 Abed *et al.*, 2013; Moghareh Abed, 2016). As for the GPR these electromagnetic parameters
161 are linked with the velocity (m/s) and the attenuation coefficient (Np/m) of the signal. For this
162 reason, fundamental electromagnetic parameters for example dielectric permittivity, electrical
163 conductivity (EC) and magnetic permeability need to be identified. The electrical conductivity
164 of soils increases with increasing water, soluble salt and/or clay contents (McNeill, 1980). In
165 soils, the most significant conduction-based energy losses are due to the ionic charge transport
166 in the soil solution and electrochemical process associated with cations on clay minerals (Neal,
167 2004). These losses can seriously impact the performance of GPR (Campbell, 1990; Olhoeft,
168 2000). Iron oxide in its red rust form is relatively insulating, and it has a relative permittivity
169 that is higher than that of most soils. As the iron pipe is the source of the iron oxide, a higher
170 concentration of the oxide can be expected nearer the pipe. In addition, the corrosion process
171 creates salts at the surface of the pipe, and this produces high conductivity (Pennock *et al.*,
172 2010). For these reasons, the corroded cast iron pipe can become undetectable with GPR.

173 Even though much research has been conducted into GPR applications, there is still a lack of
174 knowledge on the use of GPR for locating and assessing buried utilities in specifically fine-
175 grained soils. Thus, this paper seeks to define GPR boundaries with respect to its ability to
176 assess the condition of cast iron pipes in fine-grained soils, understanding the problem of poor
177 detection of cast iron pipes in fine-grained soils.

178 **3 Methods**

179 This section describes the laboratory-based testing methodology devised to meet the aim of
180 this research, i.e. to help understand how the released ions from corroding cast iron influence
181 changes to the soil properties, particularly those affecting GPR, such as electromagnetic
182 properties, and the extent and degree of influence these changes have with time or increasing
183 corrosion. A series of experimental testing arrangements were designed to help understand the
184 complex interactions occurring when buried cast iron pipes corrode within soils. Furthermore,
185 the FDTD method was utilised to simulate GPR signals investigating impacts of a corroded
186 buried cast iron pipe on the GPR signal by considering the changed conductivity.

187 3.1 Arrangement of the Laboratory Experiments

188 Since corrosion of a pipe buried in soil naturally occurs slowly, the reaction was accelerated in
189 the laboratory experiments by inducing an electrical potential across the test samples, using the
190 principles of electro-osmosis and electromigration (electrokinetics) (Clarke *et al.*, 1990;
191 Schmidt, 2007). This method was selected over alternative options so as to avoid introducing
192 any additional ions apart from the ones generated as by-products of the cast iron corrosion
193 (essentially iron ions) so the changes on clay soil properties could be investigated. Furthermore,
194 it would have been difficult to relate the results to the real *in situ* conditions if other ions had
195 been introduced.

196 This electrokinetic modification induces the migration of H^+ (formed at the anode) and OH^-
197 (formed at the cathode) towards the oppositely charged electrodes, which generates acid (at the
198 anode) and alkaline (at the cathode) fronts across the test specimens, and hence a pH variability
199 occurs (ranging from acidic pH 2 to alkaline pH 12). These fronts migrate towards each other
200 under the electrical gradient, with the clay being neutral where these fronts meet (Tajudin,
201 2012). The acid front produced at the anode causes desorption, dissolution and ionisation of
202 cations, migrating towards the cathode.

203 The experiment was designed to be both practical (i.e. in terms of size and ease of assembly)
204 and accurate (less than 5% variation in results). It was found impractical to design small scale
205 experimental processes within the laboratory that could support a GPR survey. Therefore, the
206 primary focus of the experimental study was shifted to evaluating the conductivity and
207 permittivity, i.e. the electromagnetic properties, of the clay soils via TDR, as well as the
208 physico-chemical characterisation of the test specimens. The TDR results were used as a
209 surrogate for the likely performance of GPR due to underlying principles being analogous
210 (Curioni *et al.*, 2017).

211 Two types of clay were investigated during the experiment, a relatively inactive Kaolin Clay
212 and Oxford Clay, which is more active and has mixed mineralogy, as described in Table 1.
213 These two clay types were chosen to provide a platform for comparison of behaviour, due to
214 their different natures (predominantly single and mixed mineralogy) and properties. Following
215 the lead of many researchers working in the field of electrokinetics (e.g. Barker *et al.*, 2004;
216 Liaki, 2006), it was decided to use a relatively pure form of kaolinite (termed herein Kaolin
217 Clay). However, for translation of the results to practice, while retaining the ability to compare
218 results with previous researchers and therefore aid in extrapolating the results (e.g. Barker *et*

219 *al.*, 2004; Schmidt, 2007), a clay of mixed mineralogy (Oxford Clay, which is illite-rich) was
220 chosen to act as a comparator.

221 Consolidation, rather than compaction, was chosen as the means of soil sample preparation in
222 order to avoid the possible creation of air voids and non-uniformity across the sample, both of
223 which could adversely affect the results (Terzaghi *et al.*, 1996; Venkatramaiah, 2000).

224 A simple schematic of the experimental arrangement adopted for the testing is shown in Figure
225 2. A cast iron disc was used in the accelerated corrosion tests that had similar properties and
226 composition to old cast iron pipelines, in order to help relate the test results to field conditions.
227 Utilisation of the disc rather than a real cast iron pipe section was due to the difficulties of
228 producing consolidated samples in contact with cast iron pipes, and also trying to keep the scale
229 of the experiments to a workable size. The other difference with the field condition was the
230 absence of phosphorous in the composition of the disc, due to health and safety considerations
231 (i.e. potential kidney damage) (Sim *et al.*, 2013). A cathode was created from a graphite-coated
232 electrode (or Electrokinetic Geosynthetic, EKG; the coating prevented corrosion of the
233 electrodes and hence any ions being released from the electrodes) (Figure 2). The experimental
234 cell consisted of a Perspex cylinder for consolidating the clay samples, with dimensions of 210
235 mm height and 102 mm internal diameter. Part 1 in Figure 2 consists of PVC plates placed on
236 top of the specimen for transferring the consolidation load, with holes were provided for water
237 inlet and outlet. In addition, a filter paper (a glass microfiber Whatman 0.20 μm membrane
238 filter) was placed between the PVC plates and the cast iron disc to facilitate to two-way
239 consolidation drainage. Part 2 consisted of a 10 mm thick cast iron disc (the source of corrosion
240 – anode), and wires attached to its upper surface, placed below the filter paper. Part 3 was the
241 experimental cell containing the consolidated soil specimens, which was attached to Part 4, the
242 bottom PVC plate, which housed the cathode and had a single water outlet.

243 Control tests were conducted in which no cast iron disc were used. The control tests were
244 constructed in the same way as described above, the only difference being that the cast iron
245 disc was replaced by EKG to form the anode. The time periods for the experimental tests using
246 the cast iron discs were 2, and 4 weeks, and 3 months, while tests without the cast iron disc
247 lasted for 2 and 4 weeks for both Kaolin and Oxford clay soils.

248 The samples were kept hydrated over the period of current injection by maintaining a water
249 feed with a nominal pressure head at the anode to compensate for cathodic draining due to the

250 electrokinetic processes. This helped to prevent the sample drying out and any potential thermal
251 flux forming at the anode.

252 **3.2 *Geochemical Properties Monitoring***

253 The geochemical assessments were essential to determine component release, and assess how
254 the surrounding soils were chemically modified due to the cast iron corrosion. To evaluate the
255 solubility properties of the iron oxyhydroxides, and the amount of iron that could be absorbed
256 by the clay in addition to the precipitated salts, an ion leaching assessment and compositional
257 analysis [X-ray fluorescence (XRF) method] were carried out, and these were validated by a
258 pH modification assessment. pH Dependence Leaching Test, CEN/TS 14429 (CEN, 2008),
259 determines the pH-dependency of ion solubility, complexation or precipitation which was
260 conducted along with Iron Solubility Assessment, ASTM D4646–03 (ASTM, 2008), to
261 understand the behaviour of iron solubility during the release of iron ions from the buried cast
262 iron pipes.

263 From the corrosion of cast iron, the released iron ions readily form iron oxyhydroxides and are
264 theoretically expected to have low solubility, which therefore mandates an evaluation of the
265 solubility conditions within the experimental clays, as well as the maximum amount of iron
266 ions that can be absorbed or complexed by the clay, in addition to co-precipitation of ions
267 (Schwertmann, 1991). To evaluate the solubility properties of iron oxyhydroxides and the
268 amount of iron ions that could be removed from the soluble fraction by the clay soils in addition
269 to insoluble or precipitated salts, iron solubility tests were adapted and undertaken.

270 The electrokinetic method induces a variable pH modification within the soil, due to ion
271 migration between the anode and cathode. This necessitates an understanding of the solubility
272 and precipitation behaviour of the released ions (of interest) within the pH domain (pH 2-12
273 expected from the anode to the cathode). Therefore, a pH-dependent solubility evaluation was
274 essential to assess the maximum soluble availability of the ions of interest (iron), as well as the
275 solubility behaviour across the pH range.

276 The electrical conductivity (EC) of a solution is the measure of its ability to conduct electricity
277 and serves as an estimate of the total amount of dissolved salt or of dissolved ions. EC
278 measurements were conducted in a temperature-controlled room ($21\pm 1^\circ\text{C}$) as the solubility
279 level is sensitive to temperature. A Hanna Hi 9033 multi-range meter was employed for elute

280 measurements during testing and the test was carried out in accordance with BS 1377-2 (BSI,
281 1990). EC was also measured using the TDR method, as described in Section 3.4.

282 **3.3 *Physical/Geotechnical Properties Monitoring***

283 To fully understand a chemically modified soil, it is important to evaluate the physical changes
284 in the soil properties. The physical changes measured included moisture content, undrained
285 shear strength (USS) and Atterberg limits. Atterberg limit tests are feasible for small sample
286 volumes using methods based on the Casagrande method in BS 1377-2 (BSI, 1990). The USS
287 was measured using the fall cone test (Hansbo, 1957; Moghareh Abed, 2016) and allowed
288 differential changes in shear strength to be observed within the sample induced by the
289 electrochemical treatment and the migration of ions. The USS of clay depends on factors such
290 as cation exchange, salt precipitation and clay mineral dissolution and cementitious product
291 formation and crystallisation, which cause changes in structure and mineralogy. The moisture
292 content was measured before the consolidation process (to check the initial moisture content
293 of the sample) and after the electrokinetic process.

294 **3.4 *Geophysical Properties Monitoring***

295 Changes in geophysical properties, including permittivity and conductivity, of the soil were
296 monitored using the TDR method. The method involves an electrical wave being transmitted
297 through metal rods of a waveguide into the soil and then being reflected back to the generator
298 (Rhoades *et al.*, 1976; Annan, 1977). From an analysis of the travel time or signal propagation
299 velocity (V_p , a function of the cable dielectric constant), it is possible to determine the bulk
300 electrical conductivity of the soil (Castiglione *et al.*, 2006; Curioni, 2013). The ions in the soil
301 provide a path for electrical conduction between the TDR and probe rods (Jones *et al.*, 2002).
302 TDR readings were taken using a TDR100 cable tester and CS645 (with 75mm long probes)
303 supplied by Campbell Scientific Ltd (2019).

304 **3.5 *GPRMax 2D/3D Modelling***

305 GPR modelling was used to demonstrate the practical effect of the experimental results in a
306 simulated scenario. Using the permittivity and conductivity data obtained from the TDR
307 measurements obtained from the test samples at different times, simulations were performed
308 using the GPRMax software (Giannopoulos, 2005). The GPRMax software uses the Finite
309 Difference Time Domain (FDTD) method for modelling GPR, where all electromagnetic

310 phenomena are described by Maxwell's equations. In addition, the compositional, geotechnical
311 and geochemical characterisation results from the test soils were used to undertake the FDTD
312 simulations. A model was created that simulated a cast iron pipe with a radius of 0.1m buried
313 at a depth of 0.5m and surrounded by homogenous clay (Figure 3). The magnetic permeability
314 was not measured directly for the test soils and assumed to equal 1 in the simulation (Machado
315 *et al.*, 2009). Even though the soil close to the corroding pipe is iron enriched, its magnetic
316 permeability is relatively small compared to the conductivity, and therefore had minimal
317 influence on the simulation outcome. The permittivity and conductivity of the soil in proximity
318 to the cast iron pipe was altered in the simulations to represent changes observed in the
319 experiments. The model simulated a GPR antenna, with a centre frequency of 700MHz (a
320 typical value for this type of GPR survey), moving across the ground surface, with readings
321 taken every 25mm along the transect.

322 When trying to apply the methodology presented in this paper for field conditions, care needs
323 to be taken as there are many factors that could affect the corrosion process. These factors
324 include the ground water conditions (e.g. the chemical quality of the water in the ground and
325 also the acidity of the rain falling on the ground), the conductivity and pH of the soil, the
326 temperature conditions, the pipe burial depths, the oxygen levels in the ground (aeration), the
327 chemicals in the soil (e.g. contaminants, bacteria or organic content of the soil), the soil
328 corrosivity and its mineralogy and soil porosity.

329 **4 Results**

330 This section describes the laboratory results, including the geochemical, geotechnical and
331 geophysical results. The GPR modelling results are also presented in this section. As the
332 electrokinetic treatment was used to speed up the corrosion process, the results are presented
333 in two groups; the results for tests in which no cast iron disc was used (the control tests), which
334 shows only the effect of the electrokinetics on the Kaolin Clay and Oxford Clay samples, and
335 the results for tests where a cast iron disc was present.

336 **4.1 Geochemical Results**

337 **4.1.1 Iron Content Concentration**

338 It was necessary to determine the amount of iron (as an oxide element) at different locations
339 within the samples, working from the anode to the cathode, in order to compare the different
340 behaviour throughout the samples.

341 The concentration of iron in Kaolin Clay samples without a cast iron disc did not change to any
342 significant extent as no *Fe* was released into the sample from the electrodes (Figure 4). In this
343 case, the *Fe* behaviour depends on the pH, as the dissolution of the clay minerals is dependent
344 on the pH environment and the only source of *Fe* is from the clay minerals, and the quantity of
345 *Fe* in the Kaolin Clay is relatively small. Only small changes were seen around the anode area,
346 i.e. 1.38% and 1.41% increase for the 2-week and 4-week samples respectively, compared to
347 the ‘natural’ value of 1.10% – and these decreased marginally towards the cathode. When the
348 cast iron disc was used in the tests with the electrokinetic treatment, due to the release of *Fe*
349 from the anode and its migration within the clay samples, these values increased considerably
350 to 8.54%, 8.98% and 9.58% for the 2-week, 4-week and 3-month samples at the anode (i.e.
351 close to the cast iron disc). The iron concentration decreased rapidly away from the anode and
352 more generally towards the cathode, due to the low solubility of the iron oxyhydroxides
353 released from the cast iron disc, but the concentrations through the clay profile remained higher
354 than those without any *Fe* introduced from the cast iron. There was also an increased iron
355 concentration at the cathode, due to electro-osmotic migration from the iron ions introduced at
356 the anode, with the concentration at the cathode increasing with time from 2 weeks to 3 months.
357 Added to this pattern of iron oxyhydroxide migration, dissociation of the Kaolin Clay at the
358 cathode will also induce the complexation of migrated iron to form stable precipitates towards
359 the cathode.

360 The ‘natural’ value of iron concentration in the Oxford Clay was determined as 7.11%. For the
361 samples that had no cast iron disc (only EKG), the electrokinetic treatment caused an increase
362 to 7.33% and 7.36% after 2 weeks and 4 weeks respectively, and the amount decreased toward
363 the cathode, reaching 7.09% and 7.07% (after 2 weeks and 4 weeks respectively) (Figure 8).

364 When a cast iron disc was introduced in the tests with Oxford Clay, the amount of iron
365 increased to 10.76%, 29.39% and 32.98% for 2 weeks, 4 weeks and 3 months respectively, i.e.
366 after 3 months the value of the iron oxide concentration increased to 3 times that of the 2-week

367 sample and nearly 5 times that of the 'natural' measurement. In the 2-weeks sample, i.e. the
368 initial phase of cast iron disc degradation, almost all the introduced Fe complexes and there is
369 minimal movement through the sample as there is enough exchangeable ion in Oxford Clay
370 sample. Thus, the amount of iron in the clay away from the anode (i.e. at 10mm from the anode
371 at 2 weeks and 20mm from the anode at 4 weeks) did not increase until the treatment had been
372 applied for 3 months, where evidence of iron (possibly as precipitation as oxyhydroxides,
373 though the pH will govern whether or not precipitation has occurred) in the middle of the
374 sample was found: it reached a maximum of 18.69% 50mm from the anode and, although
375 reducing towards the cathode, the concentration remained elevated at all points until the
376 cathode is reached.

377 4.1.2 pH

378 The pH of both soils was changed by electrokinetic treatment such that it ranged from
379 approximately 3 to 12 (see Figure 5). Both soils had the same behaviour in relation to the test
380 without a cast iron disc. However, when a cast iron disc was involved in the test, there was a
381 'jump' in the pH trend for Kaolin Clay samples at 2-weeks, 4-weeks and 3-months (e.g. this
382 'jump' occurred midway along the sample (50-60mm away from the anode) from a baseline of
383 approximately 3.5-4.5 at 3-months in Figure 5); this trend was attributed to the meeting of acid
384 and alkaline fronts where migrated H^+ and other cations from the anode interact with OH^- ions
385 migrating away from the cathode.

386 The 3-month sample of Oxford Clay was more acidic at the anode, due both to the high Fe
387 release from the cast iron disc and also due to the increased potency of the hydrolysis reactions
388 releasing H^+ ions with time of treatment (see Figure 5). The pH curve for the Oxford Clay
389 sample, in contrast to the Kaolin Clay, showed a clear uniformly-rising trend with increasing
390 distance from the cast iron disc. At 50mm away from the cast iron disc, the pH of the Kaolin
391 Clay drops to 3.53 (i.e. becomes more acidic) at an iron concentration of 4.06% (which
392 increased from 1.80% to 4.06% between 4 weeks and 3 months). However, at 70mm away
393 from the disc, the amount of Fe concentration increased to 4.59% which is associated with a
394 significant incremental change in pH to 8.67. Developing highly acid and alkaline
395 environments at the anode and cathode, respectively, equated with a significant increase in
396 USS (see Figure 6).

397 Figure 6 presents the relationship between the USS and water content for the treated Kaolin
398 Clay samples with and without a cast iron disc. The data above the control line (in red) shows

399 soil strengthening, i.e. due to chemical reactions, in accordance with ideas presented by Rogers
400 *et al.* (2003) and Liaki *et al.* (2008). This is mainly due to mineral dissolution, and subsequent
401 crystallisation. Therefore, it can be proposed that the arrows in the figure (left corner side of
402 the figure) show soil weakening (i.e. chemical deterioration). In Figure 6, the circled points
403 denote the data points adjacent to the anode, while the squared points represent data points
404 close to the cathode. The general observation is that all the points close to the cathode are
405 markedly weaker than the anode points when a cast iron disc was used. A lower pH at the anode
406 and a higher pH at the cathode at 4 weeks shows some strengthening from the low points at 2
407 weeks, with the data at the cathode being significantly closer to the control line. The cast iron
408 disc (the source of iron ions) and the more extreme range of pH evidently cause the undrained
409 shear strength to increase. As for the 2-weeks and 4-weeks samples the stronger acid ($\text{pH} < 3$)
410 and base ($\text{pH} > 11.6$) environments have developed and the shear strength has increased
411 considerably. The increased iron content near the anode caused the greatest increase in
412 undrained shear strength, for the reasons stated above, while the described reactions near the
413 cathode account for the more modest strength increases in this region. These chemical effects
414 are shown to be evidently greater for the 3-month sample, i.e. the data points exist farther above
415 the control line.

416 4.1.3 Conductivity

417 Figure 7 presents the results of the conductivity measurements for the Kaolin Clay and Oxford
418 Clay for the 3-month sample with a cast iron disc. The first major difference between these two
419 types of clay is that the Oxford Clay has higher conductivity due to its more mixed mineralogy
420 (hence soluble ion content). Both graphs show a similar trend, i.e. a high conductivity at the
421 anode, which was attributed to high H^+ and Fe concentrations, and also due to the solubility
422 of ions at low pH in the case of Oxford Clay. Figure 7 also shows high conductivity at the
423 cathode for the Kaolin Clay, which was attributed to ion solubility at high pH in a clay that is
424 relatively stable at low pH. The conductivity of Oxford Clay follows a similar trend to the iron
425 concentration. It is therefore evident that the amount of iron released through the clay soil has
426 a direct relationship with soil conductivity. This trend is also evident in Figure 7 for the Kaolin
427 Clay sample with the exception of the measurements at the cathode, where the Fe concentration
428 remains relatively low (hence the attribution of the raised conductivity to clay mineral
429 dissolution, stated above). However, the conductivity for Oxford Clay did not follow the same
430 trend as that for Kaolin Clay, which can be attributed to three reasons: the extent of Fe

431 migration, the precipitation of ions complexing with cations (a factor related to inherent
432 solubility), and cementation and crystallisation at the cathode.

433 **4.2 Geotechnical Results**

434 *4.2.1 Undrained Shear Strength – Cone Penetration Test*

435 Figure 8 shows that at 3-months, the Oxford Clay produced a higher USS than the Kaolin Clay,
436 due to both higher concentrations of *Fe* (causing a greater, although similar, pattern of thinning
437 of the diffuse double layer and salt precipitation than in the Kaolin Clay), and also higher
438 availability of other cations to engage in these processes. Figure 8 also shows a marked rise in
439 USS in the lower half of the Oxford Clay sample, this being attributed to the formation of
440 Calcium Silicate Hydrate (CSH), Calcium Aluminate Hydrate (CAH) and/or Hydrated
441 Calcium Aluminosilicate (CASH) gel and crystallisation reactions noting that calcium is
442 available in Oxford Clay but not Kaolin Clay.

443 In general, the results for the Oxford Clay compared with the Kaolin Clay showed that the
444 Oxford Clay had been more affected by the cast iron corrosion, and in turn accelerated *Fe*
445 release (hence corrosion). Therefore, failure of cast iron pipes is more likely in Oxford Clay
446 than in Kaolin Clay, in spite of the fact that the Kaolin Clay is more acidic. The higher
447 conductivity of the Oxford Clay relative to Kaolin Clay supports this argument, and would
448 suggest that the clay also has higher corrosivity as a result of these features.

449 *4.2.2 Moisture Content*

450 Moisture content was measured before the consolidation process and after the electrokinetic
451 process. The moisture content values were found to lie between approximately 41% and 58%
452 for Kaolin Clay and approximately between 50% and 58% for Oxford Clay both with a cast
453 iron disc. The moisture content of some samples, such as at 3 months, is lower at the bottom
454 of the sample where the cathode was located. This was expected since when iron ions are
455 released through the system, the changes in the diffuse double layer (i.e. thinning of this layer)
456 cause the solid particles to move closer together, and hence the moisture content decreases. In
457 addition, the sample was kept moist at its top end (anode) during the experiment.

458 4.2.3 Atterberg Limits

459 The Liquid Limit of the Kaolin Clay and Oxford Clay samples increased generally over time
460 between 2 weeks to 3 months (Figure 9). The increase was attributed to the higher valency
461 (iron) ions coming into the system from corrosion of the cast iron disc (the anode). Another
462 reason was the thinning of the diffuse double layer via cation exchange as the treatment period
463 became longer (although the iron ion concentrations increased only marginally, along with a
464 marked increase in conductivity at the anode that was attributed to a fall in pH at the anode to
465 values significantly below 4.0). Conversely in the alkali environment at the cathode (pH>11.5),
466 the opposite phenomenon occurs where the diffuse double layer thickness increases and,
467 combined with conditions in which salt precipitation is encouraged, therefore a reduction in
468 Liquid Limit was observed.

469 Figure 9 illustrates that after an initial rise from the 'natural' value of 23.6%, the Plastic Limits
470 generally decreased over time for Kaolin Clay between 2 weeks and 3 months, although the
471 data for the 2-week and 4-week tests were approximately similar throughout the sample and it
472 was only after 3 months that a significant fall occurred. Bohn *et al.* (2002) stated that a low pH
473 (pH < 4.7) in general caused multivalent cations of Al, Fe and Mg to be released from
474 degradation of the clay minerals into the pore fluid. These multivalent cations are strongly
475 attracted by the negatively charged clay surface and contribute to thinning of the diffuse double
476 layer, hence raising of the Plastic Limit.

477 The main contributory factors to the increasing shear strength values (the accumulation of
478 precipitates and modification of the mineralogy via cation exchange) as a result of the
479 electrochemical reactions, are thus reflected in the results of the Liquid Limit tests, and are
480 linked to the pH gradient and *Fe* concentration.

481 Based on the results presented it was found that the Kaolin Clay soil was less aggressive than
482 the Oxford Clay soil, i.e. the corrosion activity was stronger in the Oxford Clay, and this led to
483 cementation, precipitation and complexation. At the end of the tests the cast iron discs were
484 examined, and this difference in corrosion activity could clearly be seen. An example of the
485 cast iron discs for the 3-months samples are shown in Figure 10, with the disc in the Oxford
486 Clay showing a much more uneven and pitted surface compared to the disc in the Kaolin Clay.
487 Essentially the Oxford Clay presented a much more aggressive environment due to its mixed
488 mineralogy (including the more active smectite clay mineral) and the different ions released
489 and migrating through the soil.

490 4.3 *GPRMax 2D/3D Modelling Results*

491 FDTD simulations were used to simulate GPR signals to investigate buried cast iron pipes in
492 clay soil in relation to the measured soil conductivity, permittivity and other factors influencing
493 clay modification induced by cast iron pipe corrosion (the values used as input to the simulation
494 which were measured during the experiment are listed in Table 2). The simulation was based
495 on the model shown in Figure 3.

496 The results from the simulation of a cast iron pipe buried in Kaolin Clay showed that the pipe
497 could be clearly observed by the GPR for all the values input from the laboratory tests at the
498 different time intervals (Figure 11). This meant that the properties of the soil had not been
499 modified in a way that prevented the pipe from being detected by a GPR unit with a 700MHz
500 antenna at 0.5m depth.

501 The simulations for Oxford Clay showed different results. Although the results using the input
502 values from the 4-weeks sample showed that the characteristics of the pipe were clearly
503 detected by the GPR (Figure 12a), the results for the 3-months sample (Figure 12b) showed
504 that the GPR was unable to detect the pipe. This was attributed to the Oxford Clay modification
505 due to the corrosion process. Since the major difference between the Kaolin Clay and the
506 Oxford Clay reactions to accelerated cast iron corrosion concerned the stabilisation reactions
507 involving CAH, CSH and/or CASH, as noted previously, then this aspect of ground
508 modification in relation to GPR applications is worthy of further investigation, although other
509 features (such as the markedly raised *Fe* concentrations away from the cast iron pipe) might
510 also have an influence.

511 Additional simulations were conducted using interpolated and extrapolated input values. For
512 example, to see at what approximate time (in relation to the laboratory test results) the pipe
513 became undetectable in the Oxford Clay, which was determined as about 9-weeks (Figure 13).
514 For the simulation involving the pipe buried in Kaolin Clay, the laboratory values were
515 extrapolated to 60-weeks and input into the simulation, and the pipe still remained visible by
516 the GPR.

517 These are obviously relatively simple simulations using values obtained from small scale
518 laboratory tests. However, these do illustrate the potential effect of changing soil parameters
519 locally to a cast iron pipe could limit GPR surveys from locating corroded cast iron pipes.
520 Conversely, if GPR surveys are done 'regularly' at a particular location, the results could

521 provide an indication of when there might be considerable corrosion occurring in a cast iron
522 pipe and hence a condition assessment might be warranted.

523

524 **5 Discussion**

525 Kaolin Clay and Oxford Clay have different mineralogies, therefore their physical and
526 chemical properties change differently during the corrosion process. These changes could be
527 expected to be correlated with the amount of iron concentration, which depends on the amount
528 of iron released from the corrosion and transported through the surrounding clay. There is a
529 high content of iron in Oxford Clay as a relatively active soil compared to Kaolin Clay. The 3-
530 month sample (the longest test) produced the largest values for the migration of Fe and
531 formation (hence concentration) of iron oxyhydroxides in the soil. Also, due to the precipitation
532 of iron hydroxide close to cathode side and extending into the body of the sample of Kaolin
533 Clay the amount of iron was increased for both types of soils, yet in different patterns. These
534 reactions were affected by the soil's pH, as the dissolution of clay minerals is dependent on the
535 pH environment.

536 The pH of both soils was changed such that it ranged from approximately 3 to 12 by
537 electrokinetic treatment. Developing highly acid and alkaline environments at the anode and
538 cathode, respectively, equated with a significant increase in USS and was accompanied by the
539 ions presence in the soil system. This corresponds to the idea that the corrosion was due to an
540 electrochemical process, which converted metal substrates to oxides, hydroxides and aqueous
541 salts within the cathode-anode system (Pritchard *et al.*, 2013). Also, the rate of corrosion
542 increased with increases in the electrical conductivity of soil, as reported by Ekine and
543 Emujakporue (2010).

544 The results for conductivity measurements of Kaolin Clay and Oxford Clay for the 3-month
545 sample with a cast iron disc, show a major difference between these two types of clay as the
546 Oxford Clay has relatively high conductivity due to its more mixed mineralogy (hence soluble
547 ion content). The conductivity of Oxford Clay follows a similar trend to its iron concentration.
548 It is therefore evident that the amount of iron released through the clay soil has direct
549 relationship with soil conductivity. However, the conductivity for Oxford Clay did not follow
550 the same trend as that for Kaolin Clay, which can be attributed to three reasons: extent of Fe

551 migration, precipitation of ions complexing with cations (a factor related to inherent solubility),
552 and cementation and crystallisation at the cathode.

553 The USS of Oxford Clay was higher than that for Kaolin Clay, due to both higher
554 concentrations of Fe (causing a greater, though similar, pattern of thinning of the diffuse double
555 layer and salt precipitation than in the Kaolin Clay), but also higher availability of other cations
556 to engage in these processes.

557 The findings of this study are in contrast with part of the conclusion drawn by Pennock *et al.*
558 (2010), who suggested that for clayey soil in general only “old” corroded iron pipes that
559 contaminated the surrounding soil can become undetectable. While, the current study show that
560 it depends on the type of clay, as in Oxford Clay the process of becoming undetectable can be
561 quite fast, if the required condition was provided. However, the findings of this study confirms
562 the observations made by von Wolzogen Kühn and Van der Vlugt (1964), where accelerated
563 corrosions of cast iron pipes in some specific clay was reported in the field, and the laboratory
564 experiments on London Clay by Schmidt *et al.* (2006). It has been noted that buried corroded
565 cast iron pipes tend to be less visible to Ground Penetrating Radar (GPR) locating methods
566 than non-corroded pipes, which has implications for detecting these utilities and safe working.
567 Some of the results from this research, in terms of the likely electrical properties of the soil
568 surrounding a corroded cast iron pipe, contributed to research aimed at helping understand the
569 frequencies required for GPR to maximise the chances of detecting such pipes, and this work
570 was reported in Pennock *et al.* (2014). The study by Pennock *et al.* (2014) revealed that the
571 frequency of the GPR antenna is an influential factor in detecting corroded iron pipes when
572 using the GPR method. The results of a series of numerical analyses showed that a corroded
573 iron pipe buried in clay soil would be still detectable at frequencies less than or equal to 100
574 MHz, but at higher frequencies the pipe visibility decreases markedly.

575 As a result, the experimental results presented in the current paper can enhance the decision
576 making process when locating or assessing iron pipes using the GPR method by providing
577 information on the likely electrical properties of the soil surrounding the pipe and hence the
578 choice of GPR to be used. This information could decrease the number of hazardous and costly
579 utility strikes as the use of unsuitable geophysical methods has been identified as one of the
580 main causes of utility strikes (Makana *et al.*, 2018).

581 6 Conclusions

582 The corrosion of cast iron pipes buried directly in clay soils is one of the major challenges to
583 the water industry in managing an ageing water distribution network in countries where cast
584 iron features predominantly in the buried infrastructure. The corrosion occurs in the saturated
585 zone of clay soil by electrochemical oxidation of the cast iron in contact with oxygenated water.
586 The development of the corrosion process results in a galvanic cell being set up between the
587 pipe (the anode) and the clay (a distributed cathode) and the pH change in this system causes
588 iron ions to be released and corrosion products, such as iron oxide, iron hydroxide and aqueous
589 salts, to form in the surrounding clay soil. Excavation to locate buried cast iron pipes, assess
590 their condition and monitor their degradation is both disruptive and expensive and hence
591 remote surveying using geophysical techniques, notably GPR, has been proposed to address
592 this. It is important, therefore, to understand the influences of cast iron degradation on clay
593 soils and their implications for GPR surveying.

594 The aim of this research was to gain a better understanding of how the ions released from cast
595 iron corrosion in clay soils, i.e. Oxford Clay and Kaolin Clay, change the soil properties, and
596 how the extent and degree of this influence changes with time, and additionally to investigate
597 the effect of these changes on the efficacy of GPR surveying.

598 The results for the Oxford Clay, compared with the Kaolin Clay showed, that it had been more
599 affected by cast iron corrosion, and in turn causes enhanced Fe release (hence corrosion).
600 Therefore, failure of cast iron pipes would be expected to be more likely in Oxford Clay than
601 in Kaolin Clay, in spite of the fact that the Kaolin Clay is more acidic, and this lead to
602 cementation as well as the cation exchange, complexation and precipitation reactions. The
603 higher conductivity of the Oxford Clay relative to Kaolin Clay supports this argument, and
604 would suggest that the clay also has higher corrosivity as a result of these features.

605 The FDTD simulation result showed that the properties of the Kaolin Clay, and for different
606 time periods, had not been modified in a way that prevented the pipe from being detected by
607 the GPR with a 700MHz antenna. The simulations for Oxford Clay showed different
608 behaviours, as GPR was unable to detect the pipe after approximately 7-8 weeks, and this was
609 attributed to Oxford Clay modification due to the corrosion process. Further simulation
610 indicated that for a saturated clay soil such as Kaolin Clay, GPR signals are not significantly
611 attenuated and therefore the pipe can be detected while corrosion of the cast iron pipe advances.

612 Some of the key observations from the tests are as follows:

- 613 - Iron ions (Fe) is released as a product of cast iron corrosion, causing the clay soil close
614 to the cast iron (disc) to create a low pH (acidic) condition, lower than when no cast
615 iron disc was used, and this lowered pH developed progressively with time.
- 616 - In Oxford Clay, due to its mixed mineralogy, the low pH conditions, makes Oxford
617 Clay relatively unstable, where evidence suggests dissolution of Oxford Clay minerals,
618 as the Fe and other cations migrated towards the cathode and substituted on the cation
619 exchange sites of the clay
- 620 - USS measurements for Kaolin Clay, showed raised strength for all three periods when
621 simulating cast iron corrosion, which was attributed to chemical modification in the
622 clay. However, in Oxford Clay the increased strength was evident in the lower half of
623 the samples, and especially at the cathode, due to the stabilisation reactions.

624 Based on the findings of this study Oxford Clay should be avoided around a cast iron pipe as
625 it has the potential to cause aggressive corrosion and failure in a relatively short period. The
626 parameters which can be considered in assessing the condition are:

- 627 - Geochemical properties; to evaluate the solubility properties of the iron oxyhydroxides,
628 utilising pH Dependence Leaching Test, and Iron Solubility Assessment
- 629 - Physical/Geotechnical properties; to understand the physical changes in the soil
630 properties including moisture content, undrained shear strength (USS) and Atterberg
631 limits and cone penetrometer test
- 632 - Geophysical properties; to monitor changes in permittivity and conductivity, using the
633 TDR method.

634 Recommendations for further study are provided below:

- 635 • Repeating tests for different types of soil, to gain a more extensive dataset
- 636 • Conducting additional chemical analysis, to understand the behaviour of iron solubility
637 conditions of the iron oxyhydroxides and the maximum amount of iron that could be
638 absorbed
- 639 • Validating the laboratory findings with field experiments; utilising cone penetrometer
640 test as a comparative test for USS in very small samples is also be considered
- 641 • Determining the effect of cast iron corrosion using other methods rather than the
642 electrokinetic system.

643 **7 Data Availability**

644 Some or all data, models, or code that support the findings of this study are available from the
645 corresponding author upon reasonable request.

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847 Table 1: Description and characteristics of Kaolin Clay and Oxford Clay

	Description	Chemical composition (Content %) ²	Mineralogical composition (Content %) ²	Physical and Chemical Properties				
				Liquid Limit	Plastic Limit	pH	Specific Gravity	Conductivity
Kaolin Clay	Clay mineral consists of an isometrical 1:1 aluminosilicate layer formed by an alumina octahedral sheet fused to a silica tetrahedral sheet connected to the other layers by hydrogen bonding. It has no exchangeable cations as it has near zero isomorphic substitution and cationic vacant. It has a chemical inertia property caused by its structure. ¹ Kaolinite dissolves and precipitates reversibly with a thermodynamic equilibrium at 25°C. It forms through weathering of potassium feldspar and muscovite mica existed in rocks such as granite. ²	SiO ₂ (42.2) Al ₂ O ₃ (30.8) K ₂ O (2.85) Fe ₂ O ₃ (1.11) MgO (0.28) P ₂ O ₅ (0.13) Rb ₂ O (0.119) TiO ₂ (0.082) SrO (0.045) MnO (0.034) ZrO ₂ (0.024) CuO (0.017) As ₂ O ₃ (0.01)	Kaolin (66) Feldspar (6) Quartz (1) Mica (23) Montmorillonite (2)	55.6%	23.6%	5.63	2.6	37.6 µs/cm
Oxford Clay	It formed from a marine sedimentary rock from the Jurassic period and underlies much of southeast England, around Oxford, Peterborough and Weymouth. ² Oxford Clay generally consists of clay minerals which make it more liable to weathering compared to the clastic clay minerals.	SiO ₂ (34.9) Al ₂ O ₃ (12.6) CaO (9.68) Fe ₂ O ₃ (7.11) SO ₃ (5.05) K ₂ O (3.09) TiO ₂ (1.23) MgO (1) Na ₂ O (0.27) P ₂ O ₅ (0.27) BaO (0.15) ZrO ₂ (0.071) V ₂ O ₅ (0.061) SrO (0.06) ZnO (0.029) Rb ₂ O (0.021)	Near-illite (21) Illite-smectite(15) Quartz (28) Calcite (12) Kaolinite (7) Feldspar (4) Gypsum (3) Pyrite (2) Chlorite (3)	65.1%	35.2%	7.31	2.6	25.2 µs/cm

848 ¹Belver *et al.* (2002), ²Moghareh Abed (2016) ³Russell and Parker (1979)

849 Table 2: List of input values into the FDTD simulations in relation to the soil, measured by TDR during the lab
 850 experiments

Parameter (Unit)	Type of Soil	Specification	Values ¹ (Average)	Note
Permittivity (ε)	Kaolin Clay	2-week	31.57-53.69 (29.95)	With cast iron disc
		4-week	31.53- 34.56 (32.95)	
		3-month	34.01-36.50 (35.33)	
		2-week	33.92-33.29 (33.41)	Without the cast iron disc
		4-week	32.85- 31.09 (32.23)	
	Oxford Clay	2-week	26.11-31.44 (28.84)	With cast iron disc
		4-week	28.97	
		3-month	21.57	
		2-week	31.44-32.94 (32.38)	Without the cast iron disc
		4-week	34.65-34.01 (34.07)	
Conductivity (mS/m)	Kaolin Clay	2-week	15-127.4 (61.3)	With cast iron disc
		4-week	13.64-154.15 (62.56)	
		3-month	22.93- 409.50 (165.75)	
		2-week	7.53-85.33 (47.06)	Without the cast iron disc
		4-week	8.40-87.27 (48.62)	
	Oxford Clay	2-week	124.16-179.99 (160.0)	With cast iron disc
		4-week	126.6- 276.79 (191.2)	
		3-month	215.34-441.96 (350.29)	
		2-week	52-54.07 (53.16)	Without the cast iron disc
		4-week	58.98-66.75 (62.28)	

¹Range of values are related to the distance away from disc

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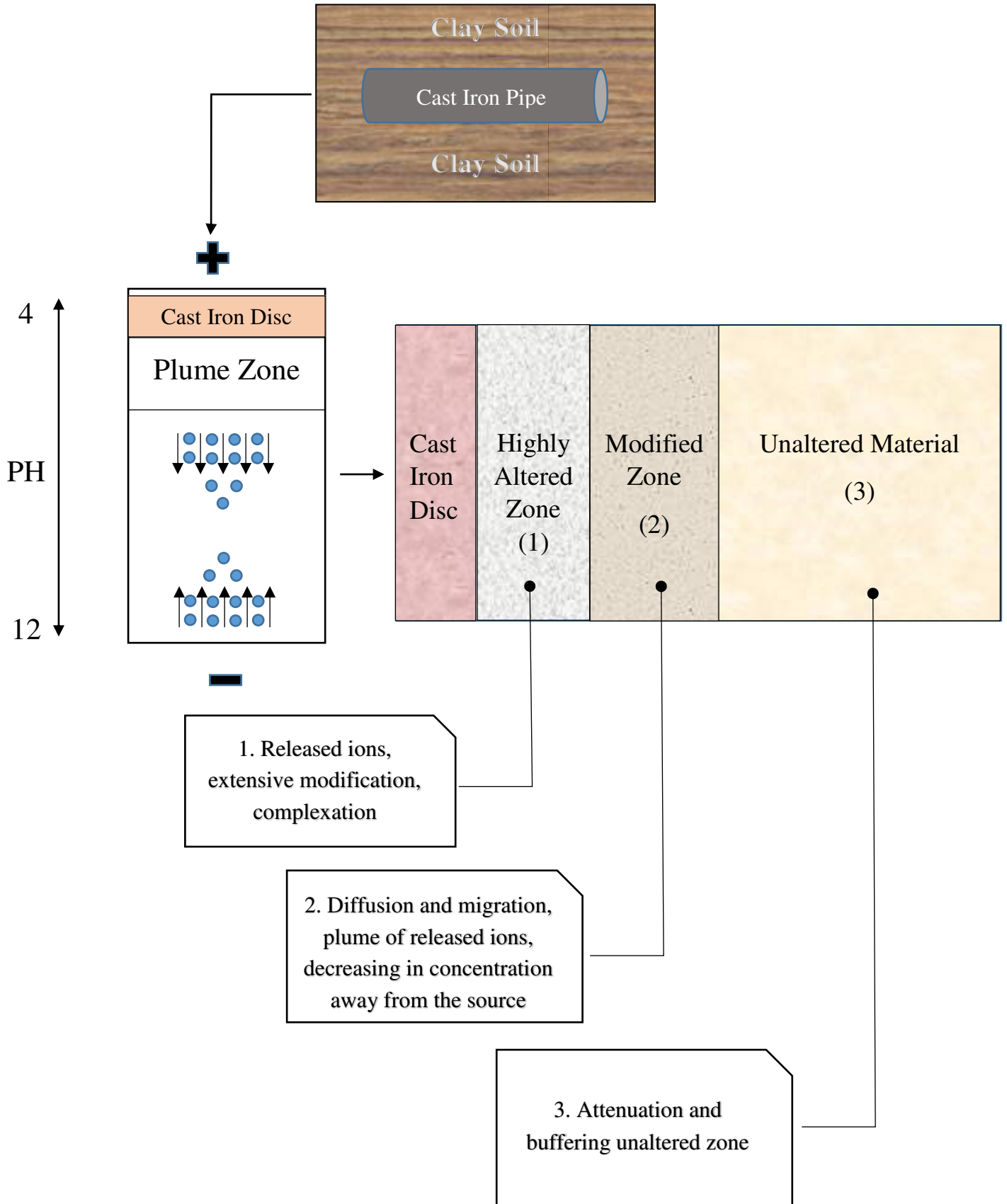


Figure 1: Soil modifications through ion migration

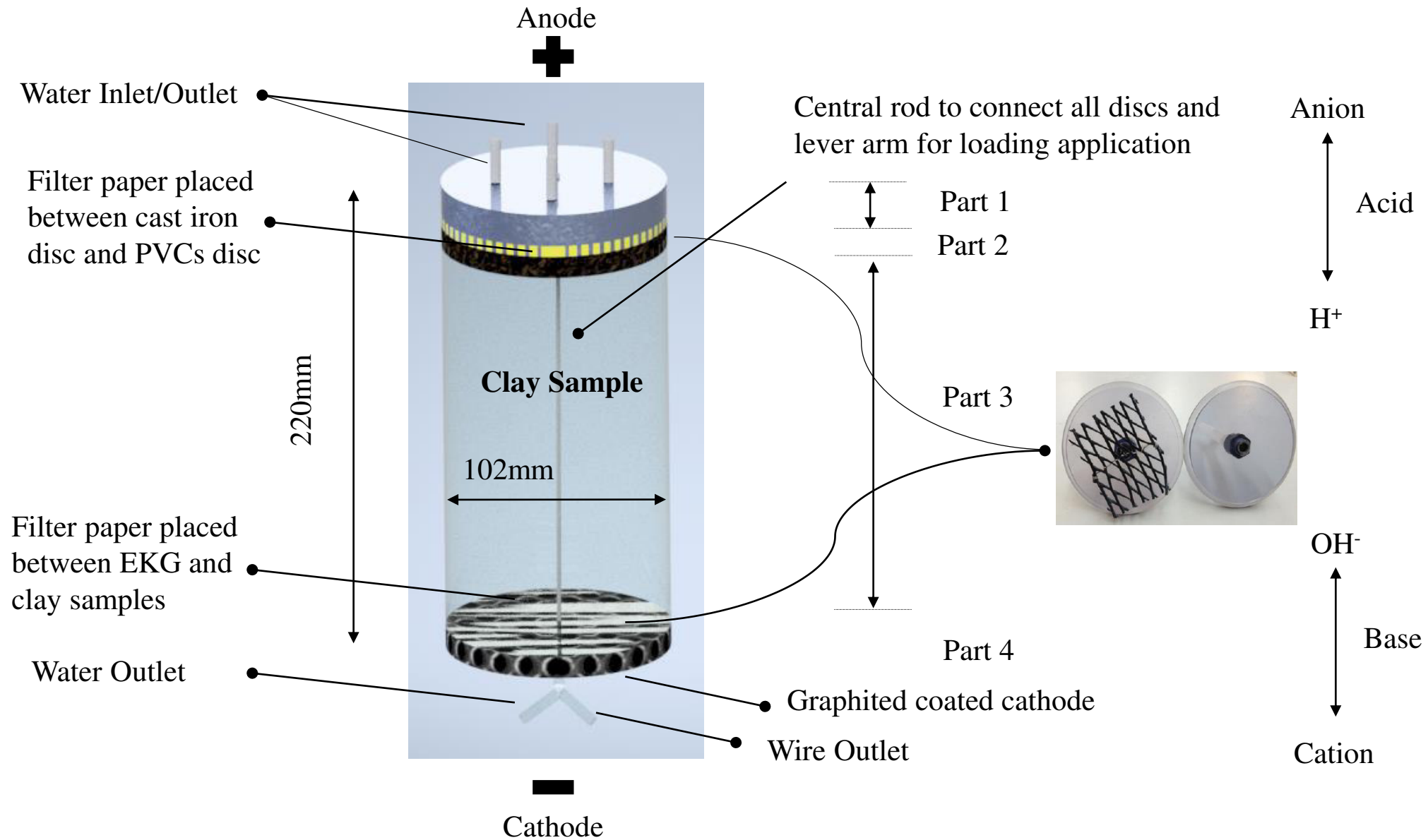


Figure 2: Arrangement of the accelerated corrosion apparatus utilised in the experiments

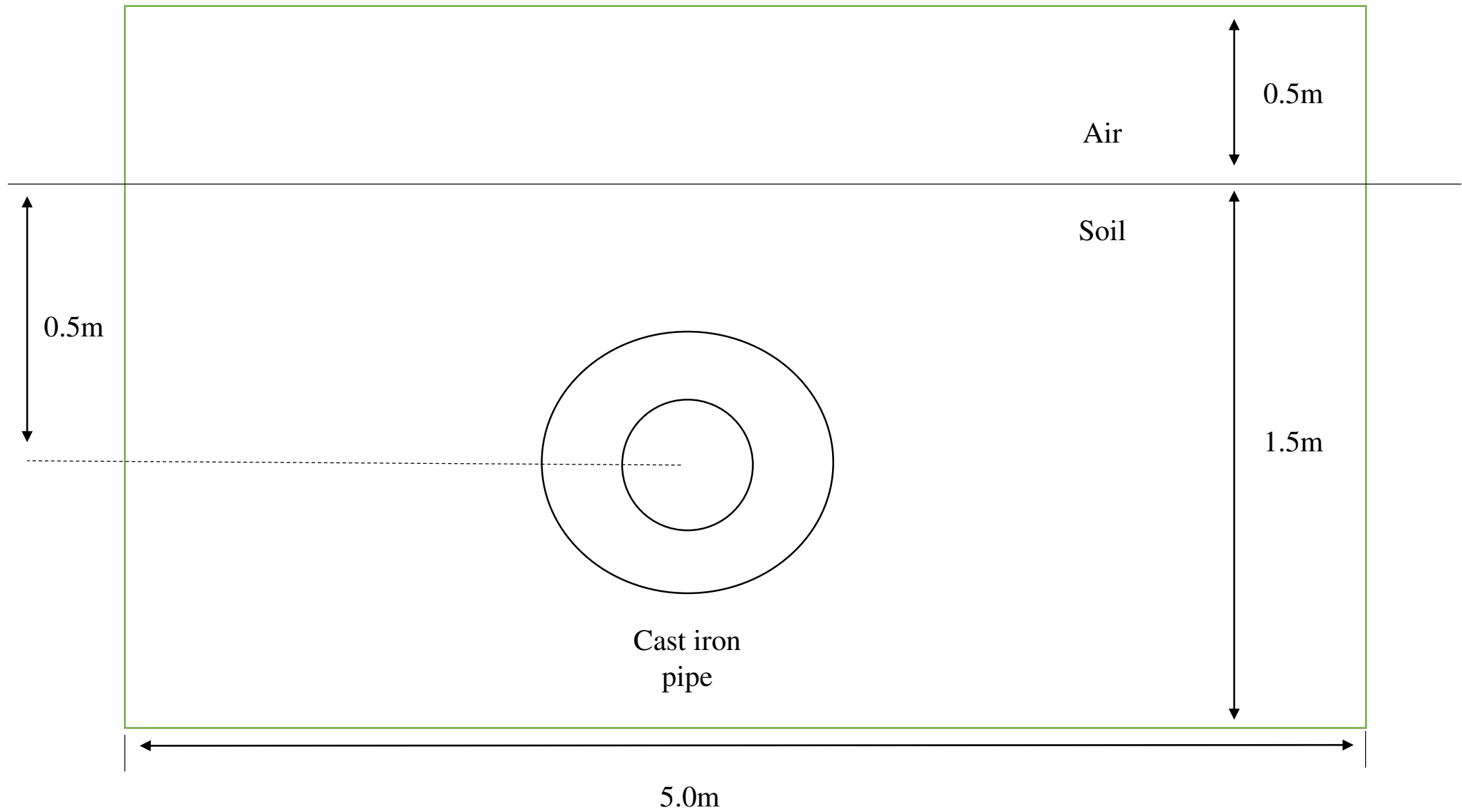


Figure 3: The GPR model used in GPRMax

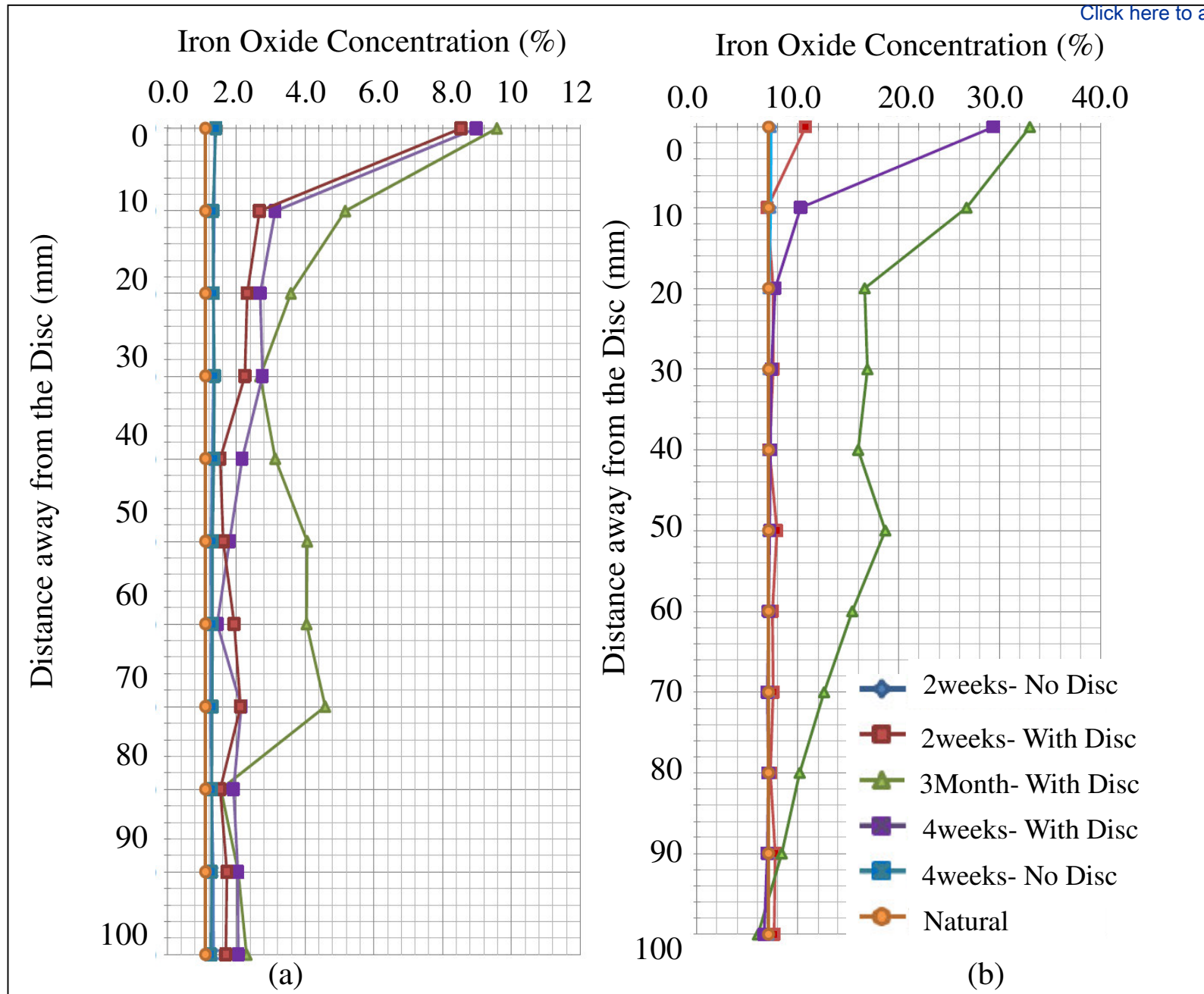


Figure 4: Iron concentration results for (a) Kaolin Clay and (b) Oxford Clay samples

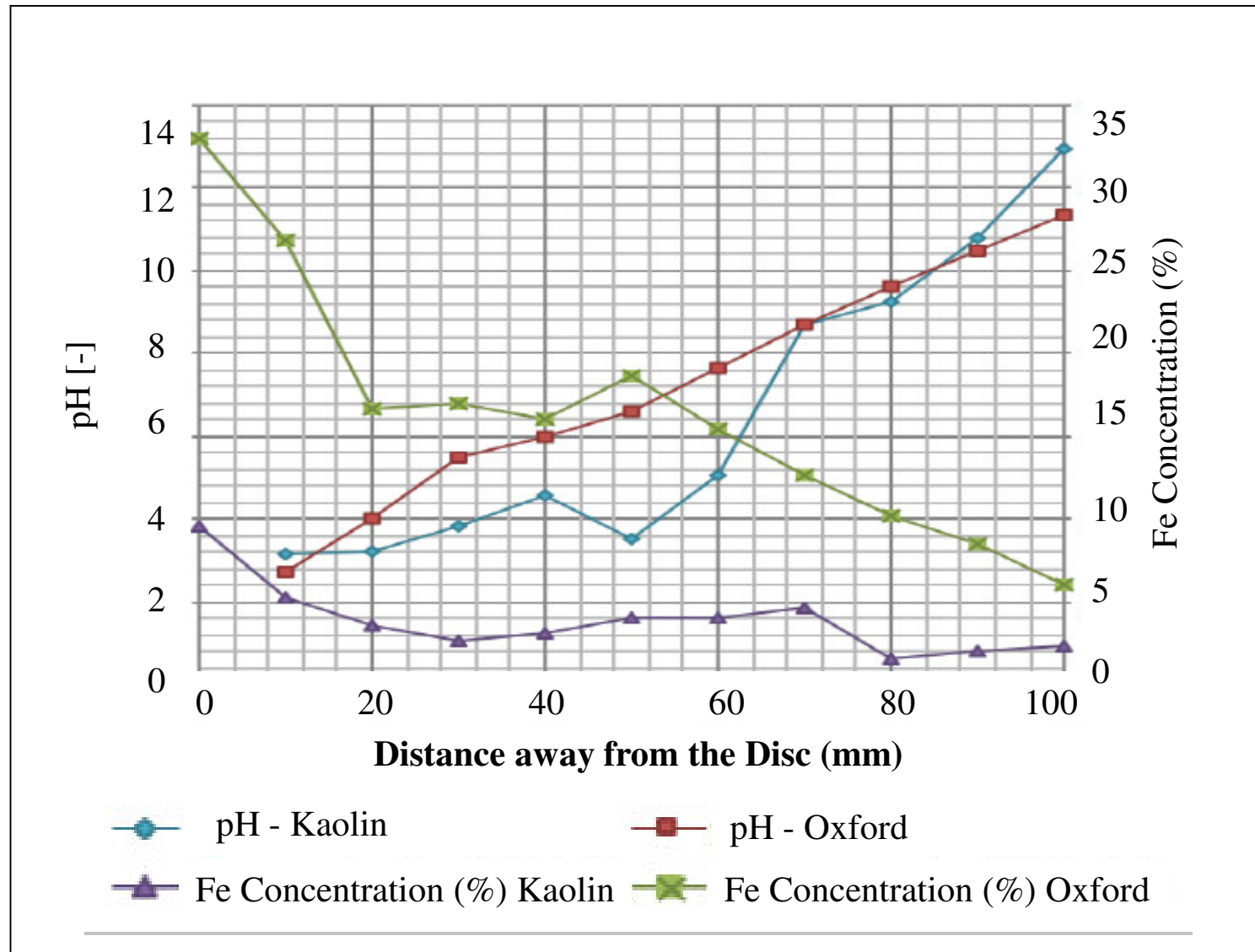


Figure 5: pH and iron concentration results for Kaolin Clay and Oxford Clay for the 3-month samples with a cast iron disc

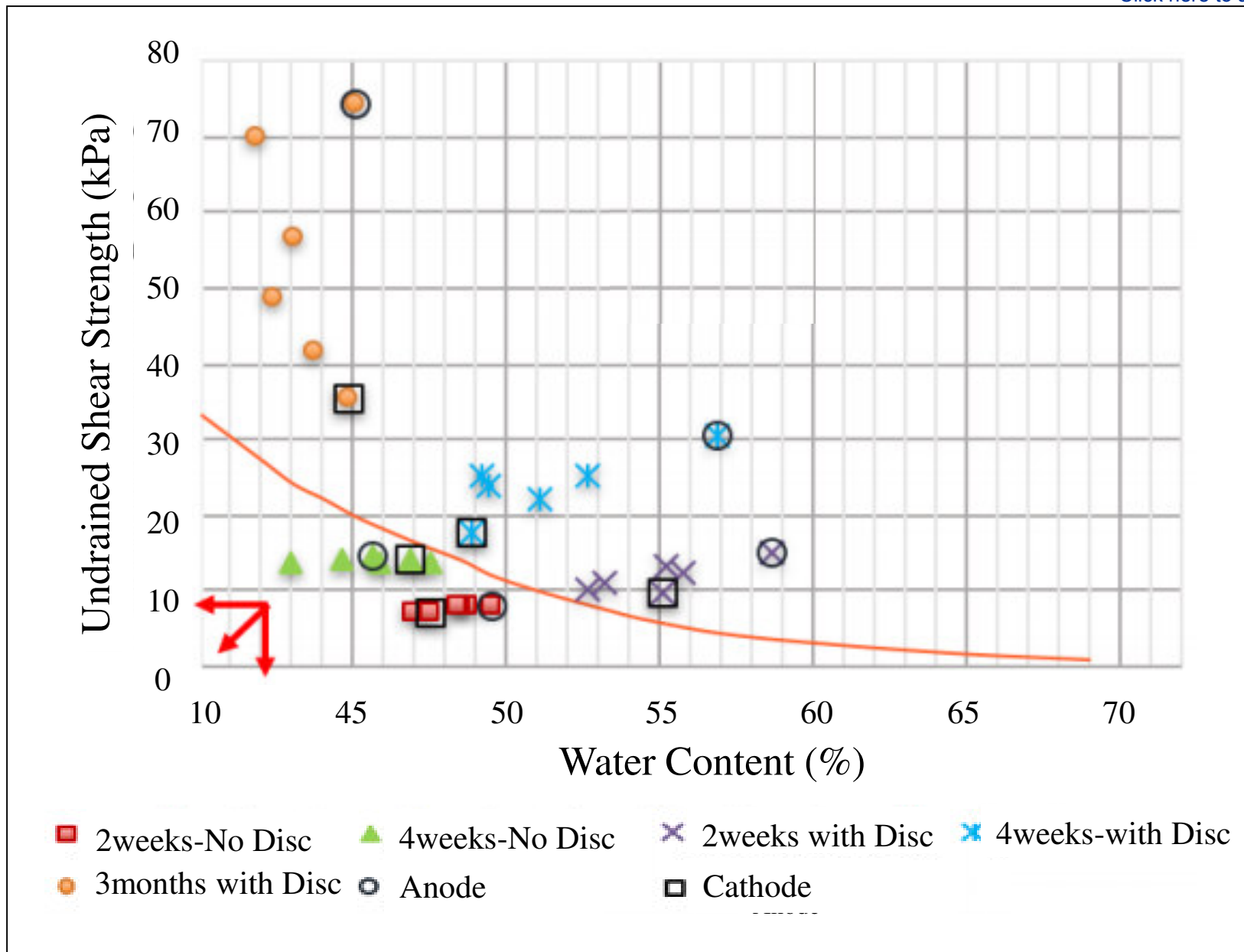


Figure 6: Variation of soil undrained shear strength (kPa) with water content (%) for Kaolin Clay

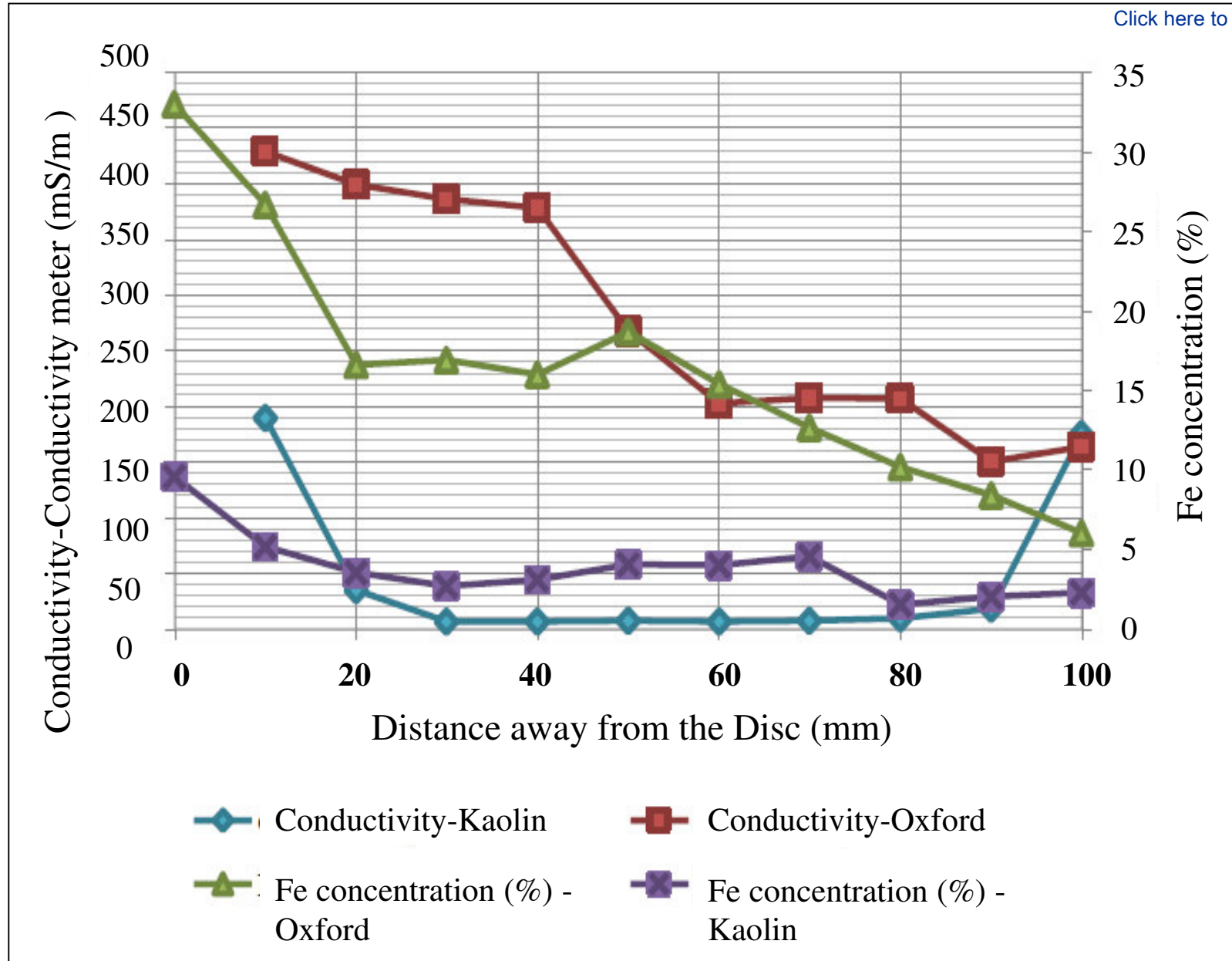


Figure 7: Conductivity and iron concentration results for Kaolin Clay and Oxford Clay with a cast iron disc

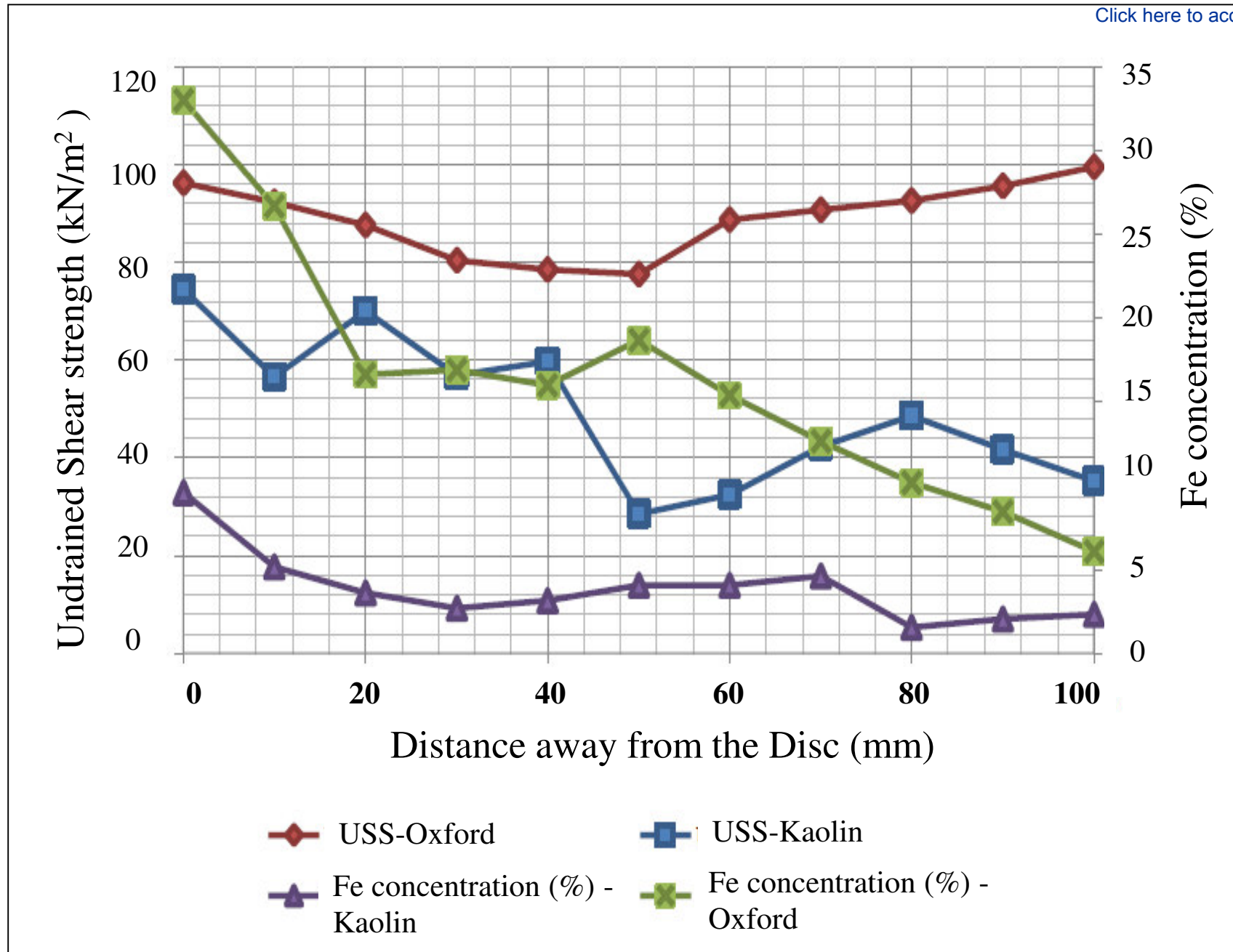


Figure 8: Undrained shear strength (USS) and iron concentration results for Kaolin Clay and Oxford Clay for the 3-months samples with a cast iron disc

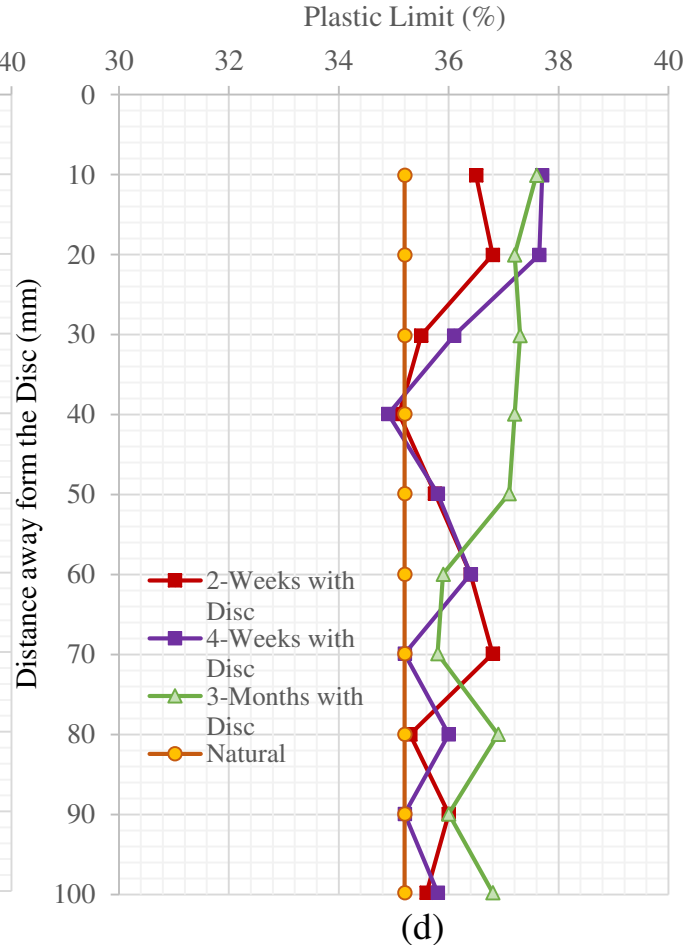
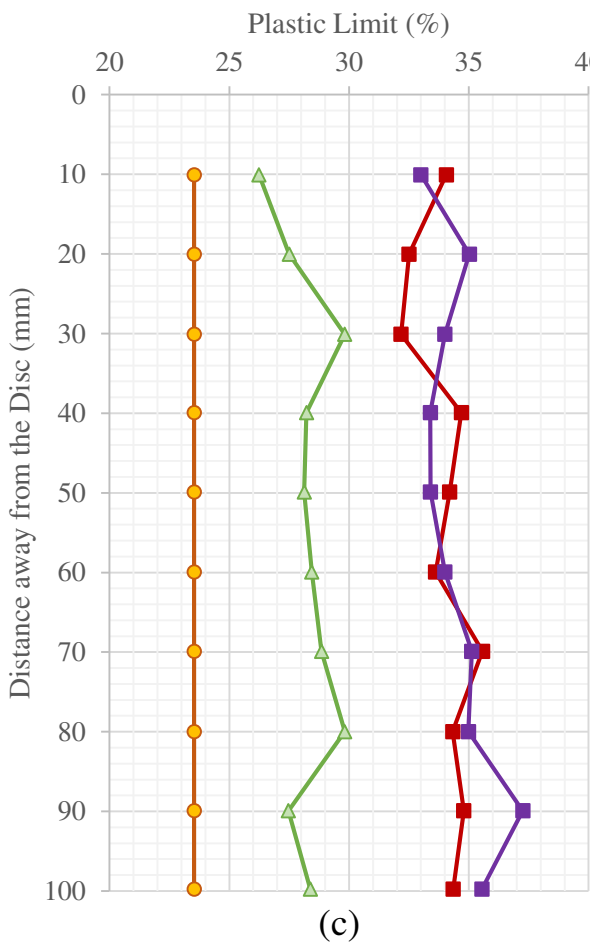
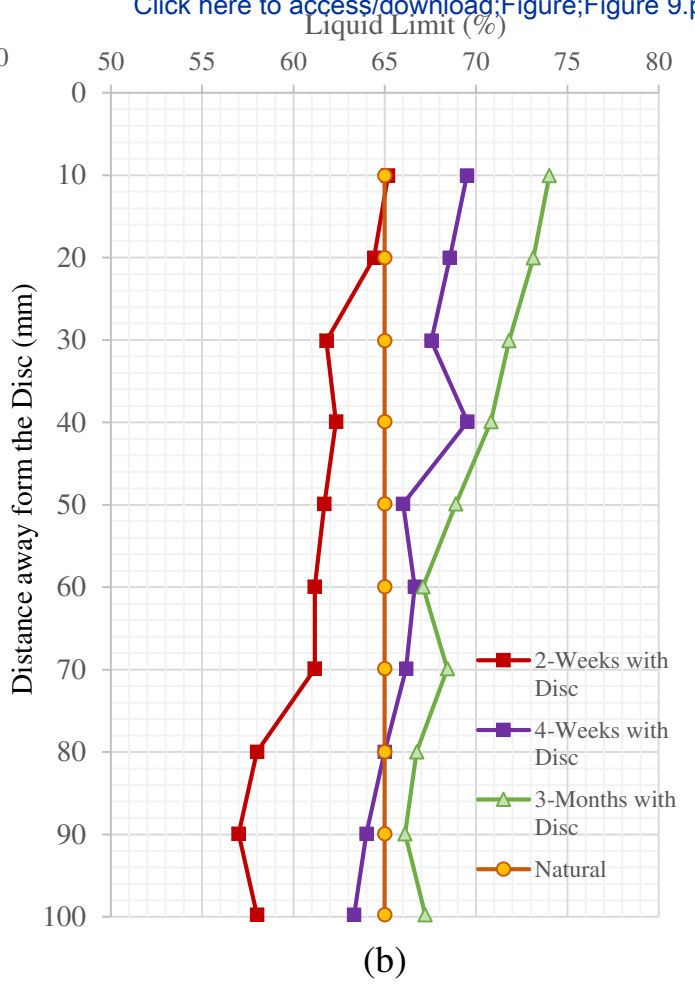
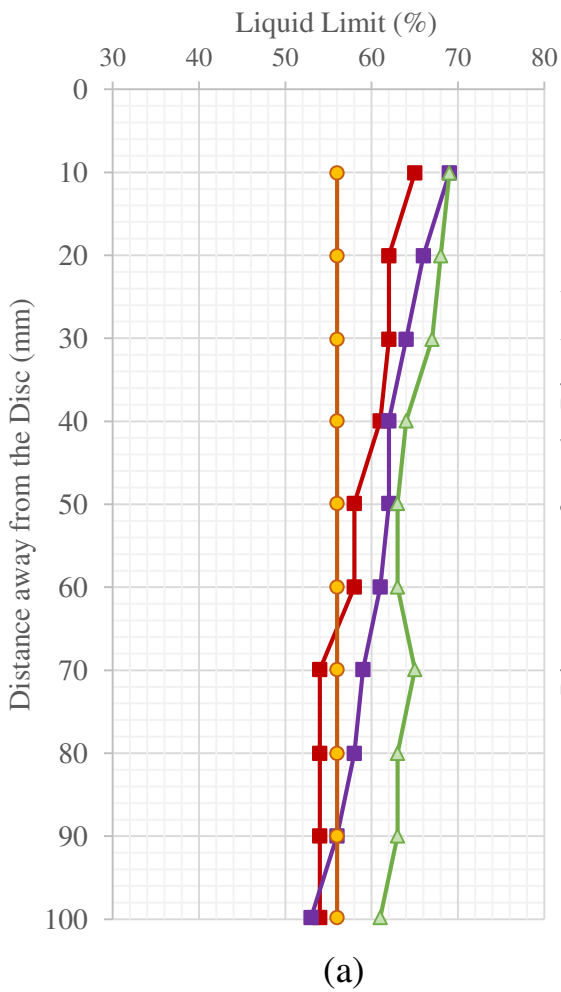
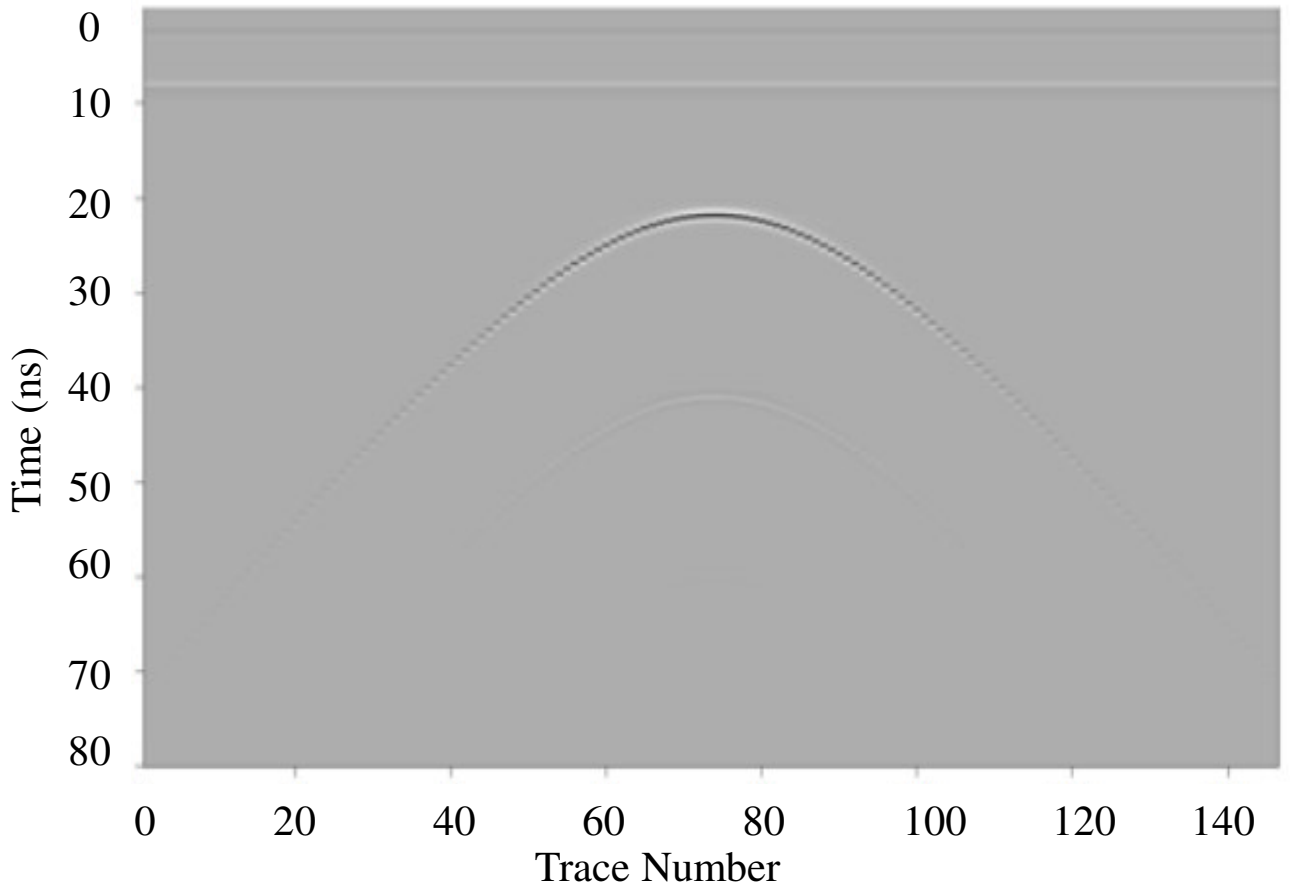


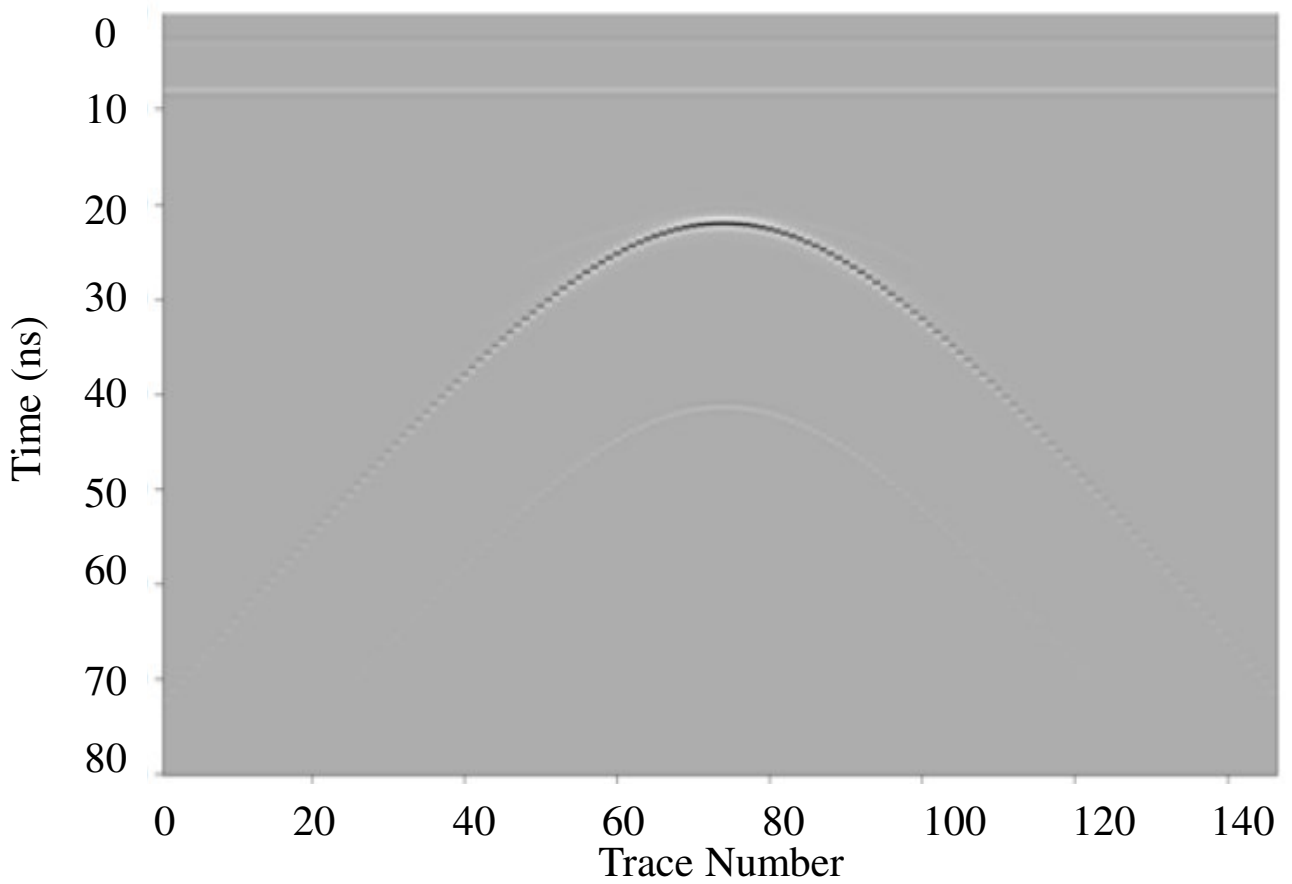
Figure 9: Liquid Limits for (a) Kaolin Clay and (b) Oxford Clay, and Plastic Limits for (c) Kaolin Clay and (d) Oxford Clay samples at different test durations



Figure 10: Cast iron discs removed at the end of the 3-months test for the Oxford Clay (left) and the Kaolin Clay (right)

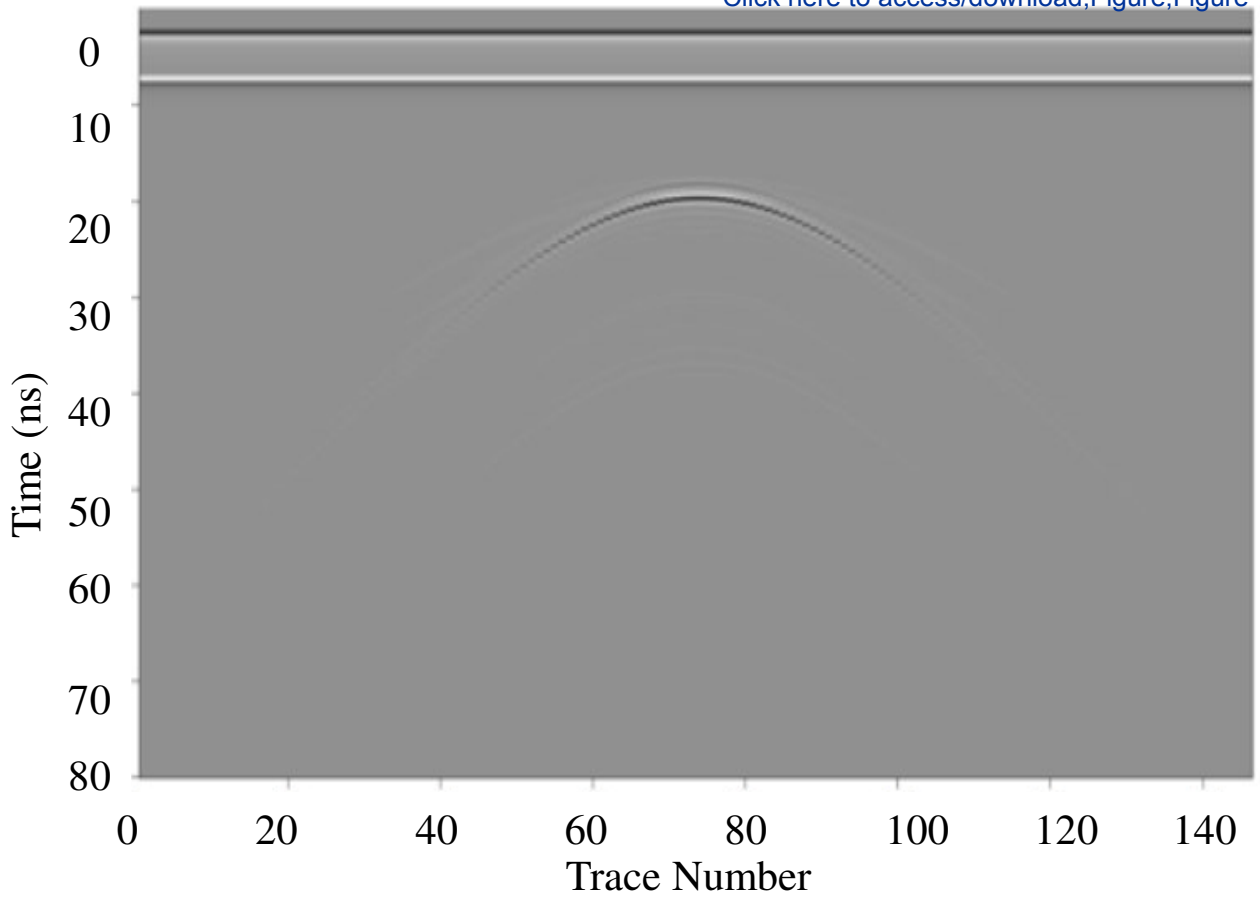


(a)

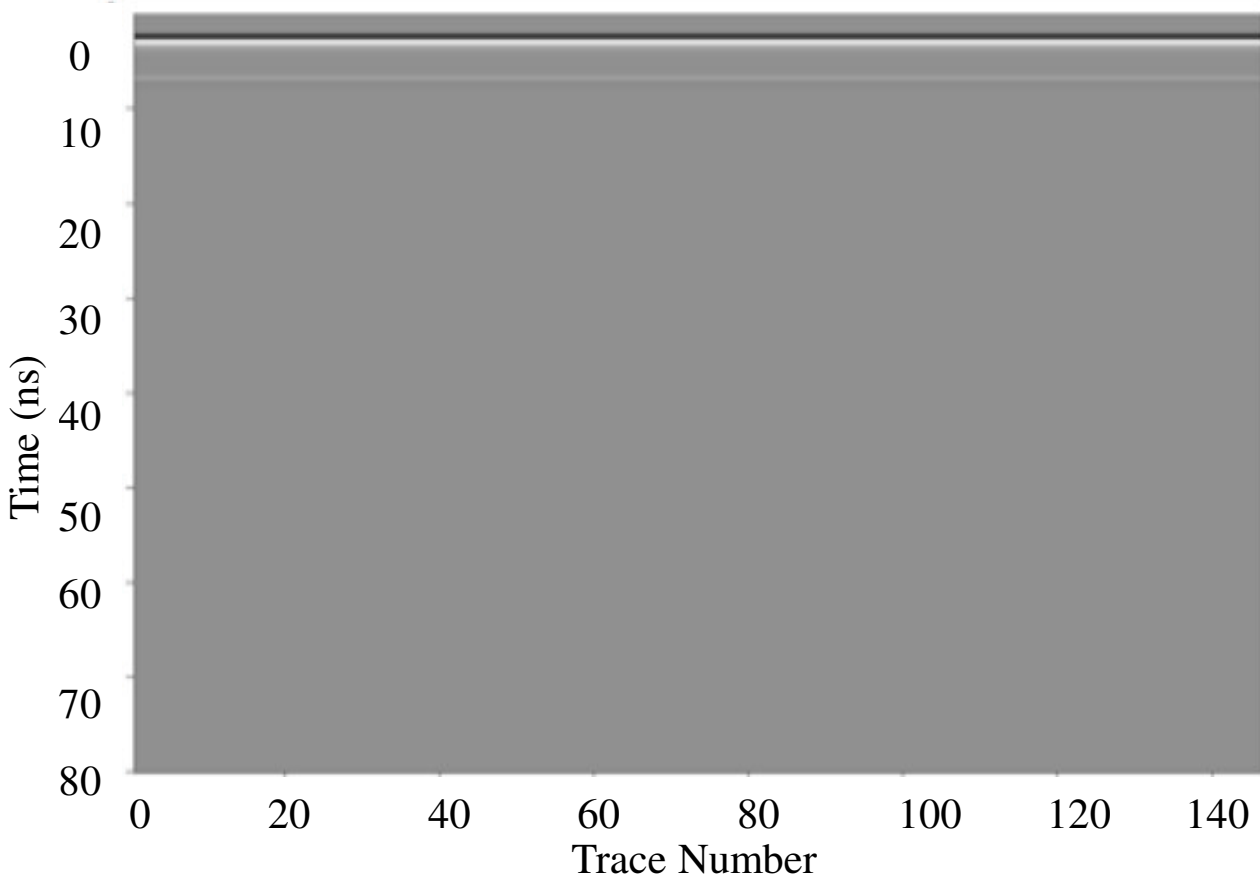


(b)

Figure 11: FDTD simulation using GPRMax utilising the measured test soil parameters for the Kaolin Clay with a cast iron disc at (a) 4-weeks, (b) 3-months



(a)



(b)

Figure 12: FDTD simulation using GPRMax utilising the measured test soil parameters for the Oxford Clay with a cast iron disc at (a) 4-weeks and (b) 3-months

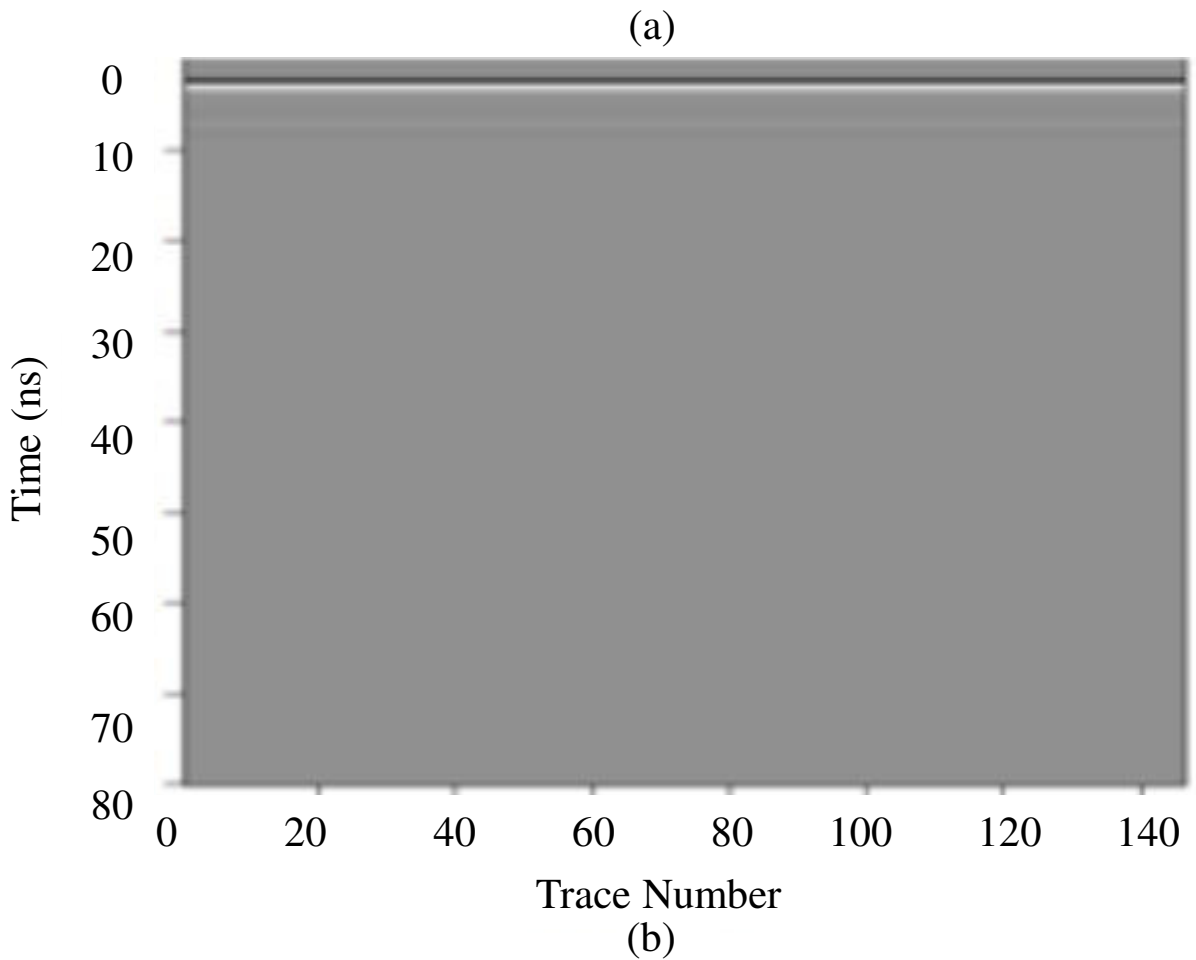
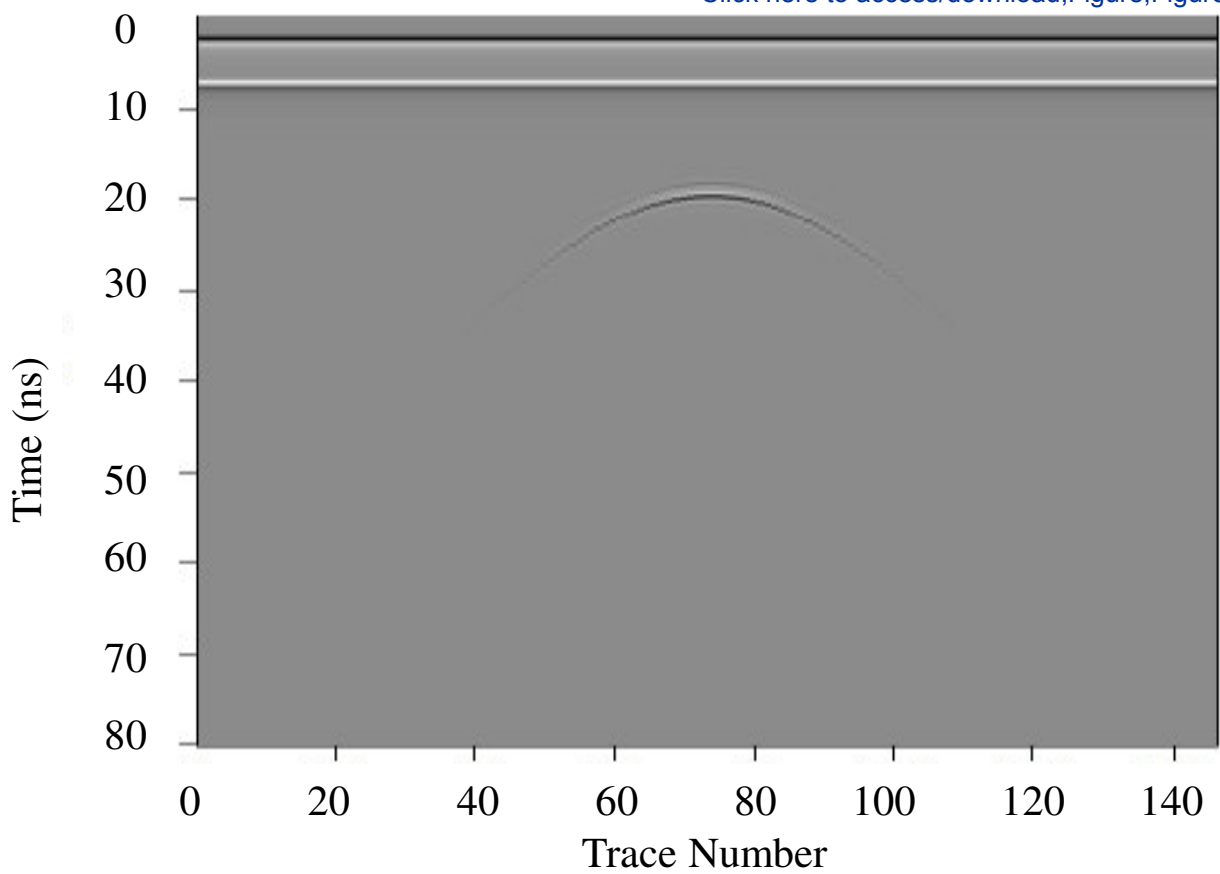


Figure 13: FDTD simulation using GPRMax utilising the interpolated test soil parameters for the Oxford Clay with a cast iron disc at (a) 7-weeks and (b) 9-weeks