

15 **Abstract**

16 In this paper the impact resonance (IR) test method is used as a non-destructive tool to examine
17 the curing progression, freeze/thaw (f/t) resistance, and healing potential of cement-stabilized
18 soils. Resonant frequency (RF) measurements on specimens moist-cured for up to 241 days
19 indicate that the main portion of the hydration process is completed after about 60 days. Results
20 of RF measurements on immature (i.e. cured for 16 days) and mature (i.e. cured for over 110
21 days) specimens exposed to 12 cycles of f/t indicate that the initial f/t exposure had a significant
22 effect on the degradation of the structure. After the initial f/t cycle, some specimens exhibited
23 continued reductions in RF values to as low as 10 percent of the initial measurements, while
24 several specimens showed signs of recovery leading to minor increases in the RF values.
25 Changes in RF values are compared to the hydraulic conductivity changes measured on the same
26 specimens reported in a previous publication by the authors. Based on the results, a pre-screening
27 scheme is proposed that can significantly reduce the time required for f/t studies of cement-
28 stabilized soils. Also, RF measurements after 120 days of a post-exposure healing period show a
29 significant potential for recovery in RF values for f/t exposed specimens. However, the
30 recoveries in RF values are not proportional to the hydraulic conductivity recovery of the
31 specimens.

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33

34 **Keywords:**

35 Freeze, Thaw, Soil, Cement, Resonant Frequency, Hydraulic Conductivity, Impact Resonance.

INTRODUCTION

36

37 Cement-treatment of soils is an established method for improving their strength and hydraulic
38 performance (ACI 1990; ACI 1999). Previous studies (e.g. Klich et al. 1999; Fitch & Cheeseman
39 2003) showed that despite improved mechanical properties after treatment, cement-treated
40 materials can undergo degradation under environmental exposure such as freezing/thawing (f/t)
41 cycles. Currently there is no standard method for assessing the hydraulic performance of cement-
42 stabilized materials in cold regions. Durability studies for cement-treated materials intended for
43 applications requiring low hydraulic conductivity values, such as cement-based
44 solidification/stabilization, have suggested percent mass loss as an indicator of acceptability for
45 performance under f/t exposure (e.g. Stegemann & Côté 1996; Paria & Yuet 2006; ITRC 2011).
46 While percent mass loss may sufficiently correlate with the changes in strength related
47 parameters (e.g. Shihata & Baghdadi 2001), Jamshidi & Lake (2014) showed that it is not a
48 reliable indicator for predicting changes in the hydraulic conductivity of cement-stabilized soils
49 exposed to f/t cycles. Further, conducting performance monitoring experiments, such as
50 hydraulic conductivity measurement, prior to and after f/t exposure can add a significant amount
51 of time to an already laborious testing process of these materials. Hence, development of quick
52 predictive tools for assessment of hydraulic conductivity changes in cement-stabilized soils
53 during freezing exposure would appear to be beneficial.

54 Vibration-based, non-destructive techniques are commonly used to evaluate the dynamic
55 properties of structures incorporating different materials in civil engineering applications. These
56 techniques have been used in evaluation of cement-based materials, mainly concrete, to predict
57 dynamic modulus of elasticity (Swamy & Rigby 1971; ASTM-C215 2008), monitor changes due
58 to progression of the hydration process (Nagy 1997; Jin & Li 2001), or track damage formation

59 during cyclic loads (Shah et al. 2000; Gheorghiu et al. 2005) and f/t exposure (El-Korchi et al.
60 1989; Ababneh & Xi 2006; ASTM-C666 2008). These techniques rely on the principle that the
61 resonant frequency (RF) of a structure is related to its physical properties including density,
62 shape, and the dynamic modulus of elasticity (Malhotra 2011). Any changes in the physical
63 properties of a structure will subsequently alter the measured RF of the system. Therefore,
64 vibration-based, non-destructive techniques are potentially efficient tools for monitoring
65 degradation or improvement (e.g. curing processes) in cement-based materials.

66 Preliminary work by Jamshidi et al. (2014) showed that the variations in the RF values measured
67 using the impact resonance (IR) method during different f/t exposure scenarios was consistent
68 with the observed changes in the hydraulic conductivity and unconfined compressive strength
69 (UCS) of a cement-stabilized silty sand. The purpose of the current study was to further assess
70 the suitability of the IR technique in replacing or supplementing the current industrial practice
71 for evaluating the f/t performance of cement-stabilized soils. To achieve this objective, the IR
72 method was used to monitor changes in the structure of several cement-treated soils due to
73 cement hydration (i.e. curing), f/t damage, and post f/t exposure healing processes. The results of
74 the IR tests from the latter two experiments were compared to the hydraulic conductivity changes
75 measured on the same specimens, presented in a previous publication by Jamshidi & Lake
76 (2014). Based on the results a potential pre-screening system is proposed for assessing damage
77 (i.e. changes in the hydraulic performance) in cement-stabilized soils under exposure to f/t
78 cycles.

79 **EXPERIMENTAL PROGRAM**

80 The IR method testing conditions and experimental program are discussed in the current section.
81 The majority of the IR experiments presented herein were performed on specimens in a previous

82 study by Jamshidi & Lake 2014. A comprehensive discussion on the materials used, specimen
83 preparation, and f/t testing conditions were presented by Jamshidi & Lake (2014). For the sake of
84 completeness, only a summary of this information is presented herein.

85 **Specimen Preparation**

86 Three different soils (i.e. SI, SII, and SIII) were manufactured by blending “soil A” (size fraction
87 between 0.08 mm and 9.5 mm of a glacially derived silty sand (SM) (ASTM-D2487 (2011))) and
88 “soil B” (size fraction smaller than 0.08 mm of a silt (ML) (ASTM-D2487 (2011))) derived from
89 quarry operations) according to the proportions presented in Table 1. X-ray diffraction tests
90 performed on powdered samples (i.e. <0.044 mm) of soil A and B suggest quartz and feldspars
91 as the main mineralogical components of these materials (Jamshidi (2014)).

92 After blending, SI, SII, and SIII soils were stabilized by adding ten percent Portland-limestone
93 blended cement (CSA type GUL) at different water/cement (w/c) ratios (i.e. 1, 1.5, and 2)
94 resulting in nine different mix designs as presented in Table 1. The three soil-cement blends used
95 in the study had an optimum water content in the range of 8 to 11% and a maximum dry density
96 ranging from 1976 to 2050 Kg/m³ (ASTM-D558 2011). Based on a visual assessment of the mix
97 workability at the time of casting, specimens from each mix design were either compacted in
98 standard compaction molds (ASTM-D558 2011), or placed into plastic molds (with a nominal
99 size of 101 mm diameter and 118 mm height) for self-consolidation (see Table 1). For all mix
100 designs, the constituents were mixed using a drill-mounted paddle until uniformity was reached.
101 After the soil-cement mixture was placed in the molds, they were sealed for 5 days in air-tight
102 plastic bags to minimize water evaporation prior to extrusion. Specimens were then stored in a
103 humidity-controlled curing room until the required age for the start of each experiment.

104 **Impact Resonance (IR) Test**

105 A detailed procedure for conducting IR tests to measure fundamental transverse, longitudinal,
106 and torsional RF of concrete specimens can be found in ASTM-C215 (2008). The set-up used in
107 the current study is presented in Fig. 1. The impact load was generated using a 9.5 mm in
108 diameter steel ball attached to a plastic band, with a combined mass of 5.3 g and was applied to
109 the axial centerline of the specimens. An accelerometer (PCB model 352C68) was magnetically
110 connected to a small piece of steel glued on the opposite side of the specimen. The accelerometer
111 captured the vibration response of the specimen due to the impact and transferred the signals to
112 an amplifier and a computer data acquisition system (Freedom Data PC Platform, Olson
113 Instruments Inc.) for recording and signal processing. A sampling rate of 500 kHz and record
114 size of 8192 samples was used to provide a frequency resolution of 61 Hz for each test. A
115 bandpass filter of 500 to 15000 Hz was applied during the test to isolate frequency components
116 within the expected range of resonances. A fast Fourier transformation (FFT) was then used to
117 transfer the signal to the frequency domain to determine the longitudinal RF of each specimen as
118 the peak spectral amplitude within the response. Each test consisted of five replicate trials on the
119 specimen and the average of the RF values were calculated for comparison in the results section.
120 An average Relative Standard Deviation (RSD) value of less than 1 percent, with a range of 0 to
121 16.6 percent was calculated based on the five RF measurement trials on each specimen.

122 **Testing Program**

123 *Monitoring the Curing Progress*

124 Given that the hydration of cement becomes a slow diffusion-controlled reaction during its initial
125 stages (Mindess et al. 2003), the structure of cement paste continues to change over time as the
126 material moves towards being completely cured. Reductions in the hydraulic conductivity and

127 increases in the strength are expected as a result of the curing progress in cement-based materials
128 (e.g. Powers et al. 1954; ACI 1990). Understanding the rate of changes and the time span over
129 which curing process occurs can be beneficial for implementation of cement-treatment projects
130 in cold regions, as specimens cured for only 16 days have shown slightly better performance
131 under f/t exposure compared to specimens exposed at longer curing times (i.e. over 110 days)
132 (Jamshidi & Lake 2014). This may be due to the ductile behavior of specimens at early curing
133 ages and/or the possible counteractive effect of the curing process with the development of f/t
134 deterioration.

135 In this research, the curing progress of four different mix designs (i.e. SI(1), SI(2), SIII(1), and
136 SIII(2)) was monitored using the IR method. Longitudinal RF measurements were performed on
137 duplicate specimens at different specimen ages ranging from 5 days when they were de-molded,
138 to 241 days after the specimens were prepared. During this period, specimens were kept in a
139 humidity-controlled curing room in order to provide optimal curing conditions required for the
140 hydration process. UCS tests were performed on duplicate specimens at curing times of 16 and
141 241 days for each mix design to evaluate the possible relationship between changes in the RF
142 and strength development in the specimens.

143 *Monitoring the Degradation of Specimens Due to F/T Exposure*

144 According to Powers' theory of hydraulic pressure (Powers 1945), when water in the capillary
145 pores of cement paste freezes, ice formation results in the water expanding 9% from its initial
146 volume. In near-saturated conditions, this process results in the development of excess pore
147 water pressures in the structure that forces the water to escape to the nearest unsaturated
148 voids/spaces. If the magnitude of the hydraulic pressure developed during this process exceeds
149 the bursting strength of the material, it can result in development of cracks/micro-cracks within

150 the structure (Powers 1945; Chatterji 2003). Flaws which form during the freezing process can
151 lead to an increase in the hydraulic conductivity, a reduction in the modulus of elasticity, and
152 subsequently decrease in the RF of the material.

153 Specimens from different mix designs presented in Table 1 were exposed to 12 f/t cycles at
154 immature and mature curing conditions. In the current paper, immature and mature exposed
155 specimens are simply referred as immature and mature specimens. For immature specimens, the
156 initial f/t cycle occurred 16 days after specimen preparation; for mature specimens, f/t cycling
157 began after over 110 days of curing had occurred. It was assumed that after this age, changes in
158 the soil-cement structure due to the curing process were negligible. For each f/t cycle, specimens
159 were initially kept in a freezer at $-10\pm 1^\circ\text{C}$ for approximately 24 hours, after which they were
160 transferred to a humidity-controlled curing room and were kept at a temperature of $22\pm 1^\circ\text{C}$ for
161 thawing for approximately 24 hours.

162 The IR testing was performed on each specimen prior to the initial f/t cycle (control conditions)
163 and at the end of the thawing phase at different intervals through the f/t exposure.

164 The normalized changes in the longitudinal RF at the m^{th} f/t cycle (β_m), was calculated based on
165 the following equation:

$$\beta_m = \frac{\text{RF}_m}{\text{RF}_0} \quad \text{Equation 1}$$

166 where RF_m and RF_0 are longitudinal resonant frequency values at the end of the m^{th} f/t cycle, and
167 at control conditions (i.e. unexposed), respectively.

168 Results of RF changes in this experimental study are compared to hydraulic conductivity
169 measurements on the same specimens presented in Jamshidi & Lake (2014).

170 ***Recovery Potential for Exposed Specimens***

171 Autogenous (self) healing in concrete structures was reported by Abrams (1913) over a century
172 ago. Different mechanisms including the hydration of unreacted cement, swelling of C-S-H gel,
173 blocking of flow paths by impurities, and crystallization of calcium carbonate may lead to
174 autogenous healing, however the latter is believed to be the mechanism most responsible
175 (Edvardsen 1999). This healing process is believed to be more effective for crack widths smaller
176 than 50 μm , while widths as high as 150 μm have been reported to exhibit partial recovery (Yang
177 et al. 2009).

178 To evaluate the healing potential under various exposure and mix design scenarios, specimens
179 tested in the previous sub-section were kept in a moist room for a period of at least 120 days
180 after the 12th f/t cycle. IR testing was then performed on the specimens and RF values (i.e.
181 $\text{RF}_{\text{healed}}$) were compared to the previous measurements on each specimen. All the measurements
182 were normalized with respect to RF values measured for control conditions (i.e. β_{healed}). Results
183 of the hydraulic conductivity measurements on selected specimens before and after the post-
184 exposure healing period presented in Jamshidi & Lake (2014) are also compared to the recovery
185 potential for RF values in the current study.

186 **RESULTS AND DISCUSSIONS**

187 Results of the current study are discussed in the following three sub-sections. First, the curing
188 progression in specimens from selected mix designs is evaluated by presenting the changes in the
189 RF and UCS values over time. Then, damage development in specimens exposed to f/t cycles is
190 discussed using the results from IR tests. Results from this sub-section are compared to hydraulic
191 conductivity changes measured on the same specimens previously presented in Jamshidi & Lake
192 (2014). Finally, the recovery potential for specimens from different mix designs are evaluated

193 using the IR method for f/t damaged specimens after a period of post-exposure curing in a
194 humidity-controlled room.

195 **Assessment of the Curing Progress**

196 Duplicate specimens from four mix designs (i.e. SI(1), SI(2), SIII(1), and SIII(2)) were tested for
197 RF values at different time intervals ranging from 5 to 241 days after casting. Specimens were
198 cured in a humidity-controlled curing room during this period. Average RF values for each mix
199 design are plotted in Fig. 2. Immediately after de-molding, RF values ranged from 6700 to 11600
200 Hz for the different mix designs. Values increased sharply until a curing age of nearly 60 days,
201 after which they reached about 80 percent of the total observed increase. After this age, the
202 changes in the RF values continued, but at a reduced rate.

203 Table 2 presents the average RF and UCS values for specimens cured for 16 and 241 days. UCS
204 values ranged from 2.8 to 10.9 MPa for specimens cured for 16 days and from 4.1 to 14.1 MPa
205 for specimens cured for 241 days, showing between a 23 to 52 percent increase in the values (i.e.
206 UCS_{241}/UCS_{16} of 1.23 to 1.52). Comparing the RF between day 16 and 241 shows 11 to 25
207 percent increase (i.e. RF_{241}/RF_{16} of 1.11 to 1.25). Table 2 shows that within each soil type,
208 specimens with higher RF ratios (RF_{241}/RF_{16}) exhibit higher increases in the UCS values (i.e.
209 higher UCS ratio).

210 Comparing the results for each soil in Table 2 also shows that mix designs having a lower w/c
211 ratio (i.e. SI(1) and SIII(1)) exhibit higher RF and UCS values. Further, these specimens exhibit
212 smaller increases in RF and UCS values at the longer curing times, which may be due to the
213 unavailability of sufficient amount of water for complete hydration in these specimens.

214 Relative Standard Deviation (RSD) values for measurements in Table 2 show a maximum of 1.7
215 and 12.4 percent for IR and UCS tests, respectively. Small RSD values for RF measurements
216 indicate strong reproducibility of results from IR test.

217 **Damage Progression Due to F/T Exposure**

218 RF measurements were performed on duplicate specimens from different mix designs presented
219 in Table 1 prior to f/t exposure (i.e. control conditions) and at subsequently increasing f/t cycles.
220 Fig. 3 shows the typical normalized acceleration responses of a specimen (i.e. SI(1.5)-mature)
221 which was damaged through consecutive f/t cycles. It should be noted that damage is defined as
222 an increase in the hydraulic conductivity value after f/t cycling. It can be seen that the damping
223 (i.e. reduction in the amplitude of the acceleration response after each oscillation) dramatically
224 increases after f/t exposure, resulting in fewer oscillations in signals from cycle 1 and 12
225 compared to the healthy signal obtained for control conditions. Applying a fast Fourier
226 transformation (FFT) on the signals in Fig. 3, one can plot the frequency spectrum of the SI(1.5)-
227 mature specimen at different f/t exposure levels as presented in Fig. 4. Results show a decrease
228 in RF value as a result of damage progression in the specimen; dropping from about 11700 Hz
229 for control conditions to less than 3000 Hz at the end of the 12th cycle. Alterations observed in
230 the acceleration-time domains and the corresponding frequency patterns are a result of the
231 development of cracks/micro-cracks within the specimen. In the damaged specimens, the impact-
232 generated stress waves reflect from cracks/micro-cracks (formed during f/t cycling) and are
233 forced to travel around them, resulting in energy loss (i.e. increased damping) and reduction in
234 the observed frequencies (Sansalone 1997).

235 Changes in the RF ratios at different f/t cycles (β_m) are presented in Fig. 5. Results of RF ratios at
236 the end of the 12th f/t cycle (β_{12}) show reductions as high as 90 percent and increases as high as

237 12 percent in the values. There is no clear trend in the changes of RF ratios (i.e. β_{12}) with respect
238 to the variations in the mix design and soil type. However, within each mix design, mature
239 specimens generally exhibit lower RF ratios (i.e. β_{12}) as compared to immature specimens,
240 indicating a higher degree of structural degradation for mature specimens. This is in agreement
241 with observations reported by Jamshidi & Lake (2014) for hydraulic conductivity changes of
242 immature and mature specimens, which showed higher increases in the hydraulic conductivity
243 values for mature specimens after exposure to f/t cycles.

244 Immature specimens from some mix designs in Fig. 5 (e.g. SI(1)-immature, SIII(1.5)-immature,
245 and SIII(2)-immature), exhibited some increase in the RF values after exposure to 12 f/t cycles
246 (i.e. $\beta_{12} > 1$) compared to values obtained for control conditions (i.e. β_0). This is likely due to the
247 counteractive interference of the hydration process in these specimens, given that f/t exposure
248 occurred at an early curing age, compared to the deteriorating effect of f/t damage. The same
249 specimens exhibited hydraulic conductivity ratios ranging from 0.3 (decrease) to 2 (minor
250 increase) after 12 f/t cycles.

251 Results in Fig. 5 show that exposure to the initial f/t cycle has a significant influence on the
252 creation of damage. For most cases, even specimens that exhibit higher RF values at the end of
253 the 12th cycle (i.e. $\beta_{12} > 1$) show minor drops in values at the end of the first cycle (β_1). This can
254 be explained by the fact that specimens are in near saturated conditions before the initial f/t
255 exposure due to the permeation process during the hydraulic conductivity tests prior to f/t
256 exposure. Considering Power's theory of hydraulic pressure (Powers 1945), after the initial f/t
257 cycle, the possible cracks/micro-cracks developed in the specimens can create a pressure relief
258 opportunity similar to air entrainment in concrete. Assuming that specimens did not fully re-
259 saturate during the thawing phase in the moist room, cracks/micro-cracks can reduce the travel

260 distance for releasing the excess pore water pressures developed during the subsequent freezing
261 phases. Therefore, less damage can be expected in the following f/t cycles as compared to the
262 initial exposure.

263 After the initial cycle, varying behaviors were observed for specimens at subsequent f/t
264 exposures as noted in Fig. 5. Those include:

265 - Some specimens exhibited small changes in the RF values after the initial f/t cycle (β_1), with an
266 increase or minor reduction in the frequency values at further f/t exposure. Immature specimens
267 from SI(1), SII(1), SIII(1.5), and SIII(2) fall into this category.

268 - Some specimens showed a substantial reduction in the RF values after the initial f/t cycle (β_1),
269 but exposure to subsequent cycles resulted in only minor changes in the RF. Immature specimens
270 from SII(1.5), and mature specimens from SII(1), SII(1.5), SIII(1.5), and SIII(2) are in this
271 category.

272 - Some specimens exhibited a continuous drop in RF values even after the initial f/t cycle. This
273 includes immature specimens from SI(2), SII(2), and SIII(1), and mature specimens from
274 SI(1.5), SI(2), and SIII(1).

275 Some of the specimens in Fig. 5 did not follow any of the previously mentioned patterns. For
276 instance, RF measurements for SII(2)-mature shows some reduction between cycle 1 and 4,
277 however, no significant variation was observed at subsequent f/t cycles. Also, mature specimens
278 from SI(1) showed an unusual increase in the RF ratios between cycle 8 and cycle 12. For
279 SI(1.5)-immature, due to the unavailability of equipment, RF values were only measured for
280 control conditions and cycle 12. No trend in RF changes can be concluded from these
281 measurements.

282 Results of RF ratios at the end of the 12th f/t cycle (β_{12}) are plotted against hydraulic conductivity
283 ratios obtained at the end of the 12th cycle (i.e. K_{12}/K_0) in Fig. 6 (a). As previously noted,
284 measurements were performed on the same specimens for both tests. A distinctive behavior was
285 observed for the RF ratio of approximately 0.85. Most specimens having a RF ratio higher than
286 this value, exhibit minor increases or reductions in the hydraulic conductivity values after 12 f/t
287 cycles (i.e. K_{12}/K_0 values close to or smaller than 1). However, specimens with frequency ratios
288 less than approximately 0.85 appeared to exhibit a higher degree of degradation in terms of
289 hydraulic conductivity changes. Similar behavior was observed for RF ratios at the end of the
290 first f/t cycle (i.e. β_1) as presented in Fig. 6 (b).

291 As mentioned earlier, one of the drawbacks of current test methods for durability assessment of
292 cement-stabilized soils is the long testing time required for f/t cycling of the specimens. This is
293 in addition to an already long curing process, and the need to conduct performance (e.g.
294 hydraulic conductivity) measurement for these materials. A practical application of findings
295 presented in Fig. 6 (b) is to develop a pre-screening scheme based on RF measurements at the
296 end of the initial f/t cycle (i.e. β_1) to enable the prediction of possible hydraulic conductivity
297 changes (in terms of the magnitude) in specimens after exposure to 12 f/t cycles (i.e. K_{12}/K_0).
298 According to the RF ratios, Fig. 6 (b) has been divided into three zones designated as I, II and
299 III. In zone I, for specimens with RF ratios greater than 0.9 at the end of the first f/t cycle (i.e.
300 $\beta_1 > 0.9$), one can conclude with a great certainty, that there will be minor changes in the
301 hydraulic conductivity values after 12 f/t cycles. As a result, all the specimens in zone I would
302 “pass” the f/t tests performed under conditions demonstrated earlier in the study, if less than an
303 order of magnitude change in hydraulic conductivity values is desired. In zone III, specimens
304 with RF ratios less than 0.7 at the end of the first f/t cycle (i.e. $\beta_1 < 0.7$), all the specimens seem to

305 show a significant increase (over one order of magnitude) in the hydraulic conductivity values at
306 the end of the 12th cycle, and hence would fail the f/t study tests. For specimens in zone II, with
307 RF values between 0.7 and 0.9 at the end of the initial f/t cycle (i.e. $0.7 < \beta_1 < 0.9$), IR test results
308 are inconclusive and further testing (i.e. exposure to 12 f/t cycles and measurement of hydraulic
309 conductive changes) would be necessary to evaluate the hydraulic performance of specimens.
310 The proposed pre-screening scheme can eliminate the need for completing the 12 f/t cycling of
311 the specimens in zones I and III in order to predict the acceptability of changes in the hydraulic
312 conductivity values as a result of f/t exposure under the conditions demonstrated in this study.

313 **Recovery Potential after the Post-Exposure Healing Period**

314 After exposure to the 12th f/t cycle, previously tested specimens were kept in a moist room for
315 over 120 days. Fig. 7 shows that all specimens exhibited some improvement in their structure
316 after the post-exposure healing period (i.e. $\beta_{\text{healed}} > \beta_{12}$). For most cases of immature specimens,
317 with the exception of SI(1.5) and SII(2), average RF values at the end of the healing period
318 reached or exceeded the values obtained as control measurements prior to f/t damage (i.e. β_{healed}
319 ≥ 1). SI(1.5) and SII(2) specimens also showed a noticeable increase in the RF values after the
320 healing periods resulting in an average β_{healed} value of about 0.6.

321 Considering the case of mature specimens, it can be assumed that the hydration process of
322 cement is nearly complete at the end of the 12th f/t cycle (at the age of over 134 days). In
323 addition, hydraulic conductivity measurements prior to and after f/t cycling minimizes the
324 potential for presence of unreacted cement in the specimens as a result of water permeation
325 within the pore structures. Interestingly, in Fig. 7, mature specimens still exhibit a considerable
326 amount of healing potential as suggested by increases in the RF ratios after the healing period.

327 Fig. 7 shows that specimens with similar RF ratios after the 12th f/t cycle (β_{12}) do not necessarily
328 exhibit similar recovery potential after the healing period. SII(1)-mature and SII(1.5)-immature
329 both showed a RF ratio of about 0.8 at the end of the 12th cycle; but after the healing period, the
330 RF ratio (β_{healed}) of SII(1.5)-immature increased to a value of about 1, while the RF ratio of
331 SII(1)-mature showed only a small increase. Also, mature specimens from SIII(1), SIII(1.5), and
332 SIII(2) had a RF ratio (β_{12}) ranging from 0.3 to 0.6 at the end of the 12th cycle, however after the
333 healing period, all these specimens reached an average RF ratio (β_{healed}) of about 0.7.

334 Jamshidi & Lake (2014) discussed the recovery of hydraulic conductivity values for selected f/t
335 damaged specimens from mix designs in Table 1 after the post-exposure healing period. Results
336 are presented in Table 3 and are compared to the changes in the RF values for the same
337 specimens. Based on the results in Table 3, the healing potential for the hydraulic conductivity
338 and RF values do not seem to be proportional. For most of the specimens tested, increases in the
339 RF values after the healing period are significantly more than the improvements in the hydraulic
340 performance. This is potentially a result of the nature of the IR test which involves applying low
341 stress levels to specimens for measurement of the RF values (Jacobsen & Sellevold (1996)). As a
342 result, it is possible that during the healing process minor improvements in the structure of the
343 damaged specimens can improve the RF values, while the overall hydraulic performance of the
344 specimens remains unchanged. Jacobsen & Sellevold (1996) previously showed only minor
345 increases in UCS values for f/t exposed concrete, despite noticeable recovery of RF values after
346 the healing period.

347 The recovery ratio, defined as the ratio of RF after the healing process (RF_{healed}) divided by RF
348 measured at the end of the 12th f/t cycle (RF_{12}), was calculated and plotted against the hydraulic
349 conductivity ratios (i.e. K_{12}/K_0) in Fig. 8. There seems to be a scattered trend suggesting that

350 specimens with higher hydraulic conductivity ratios (K_{12}/K_0), which indicates higher amount of
351 damage in their structure, also show a higher potential for healing (in terms of recovery of RF
352 values). This observation is likely due to the presence of more cracks/micro-cracks in the highly
353 damaged specimens, which creates a better potential for RF gain during the healing period.
354 However, it should be noted that the superior recovery potential of highly damaged specimens
355 does not necessarily result in a better final performance of these specimens. Considering the case
356 of immature and mature specimens in Fig. 7, mature specimens have an inferior performance
357 under f/t exposure, compared to immature specimens within each mix design. Despite the higher
358 recovery rate for some of the mature specimens (for instance about five times increase in RF for
359 SI(2)-mature between healed conditions and cycle 12), they still exhibit lower RF ratios at the
360 end of the healing period (β_{healed}) as compared to similar conditions for immature specimens
361 exhibiting less initial damage.

362 **SUMMARY AND CONCLUSIONS**

363 The IR method was used as a non-destructive tool to monitor curing progress, f/t damage, and
364 healing process in soil-cement specimens prepared at different mix designs. Results of the RF
365 measurements using this technique were compared to the strength and hydraulic performance of
366 the same specimens. Results showed that IR can be an effective tool in predicting changes in the
367 performance of cement-treated soils. A summary of the specific conclusions from the
368 experimental studies discussed in the previous sections is as follows:

369 1. RF changes were monitored for specimens from four different mix designs for curing ages
370 ranging from 5 to 241 days. A rapid increase in RF values was observed in the initial 60 days of
371 curing, after which the changes in the RF continued at a slower rate. Comparing RF and UCS

372 measurements for specimens cured for 16 and 241 days showed that within each soil type,
373 specimens with higher increases in RF values exhibited higher UCS gains.

374 2. RF measurements on specimens exposed to 12 cycles of f/t showed that the initial cycle has a
375 significant effect in the degradation of the structure. At the end of the 12th f/t cycle, a wide range
376 of behaviours was observed varying from minor increases to decreases of up to 90 percent in the
377 RF values as compared to control measurements performed before f/t exposure.

378 3. RF ratios at the end of the first (β_1) and 12th (β_{12}) f/t cycles were compared to the hydraulic
379 conductivity ratio (K_{12}/K_0) measurements on the same specimens. Results show IR may have the
380 potential to be used as a non-destructive tool in predicting changes in the hydraulic conductivity
381 of cement-stabilized soils exposed to f/t cycles. Based on the RF measurements at the end of the
382 first f/t cycle, three zones (I, II and III) were proposed. Specimens in zones I ($\beta_1 > 0.9$) would
383 likely to pass the hydraulic performance requirements after 12 cycles of f/t exposure. Specimens
384 in zone III ($\beta_1 < 0.7$) would likely fail the hydraulic performance requirements and would result in
385 significant increases in the hydraulic conductivity values after 12 f/t cycles. The test on
386 specimens with RF ratios between 0.7 and 0.9 ($0.7 < \beta_1 < 0.9$) in zone II is inconclusive, and
387 further f/t cycling and performance monitoring would be required. Using the proposed scheme
388 can significantly reduce the testing time in f/t studies on cement-stabilized soils intended to be
389 used for applications that requires low hydraulic conductivity over the life span of the material.

390 4. Increases in the RF values were observed for both immature and mature specimens after a
391 post-exposure healing period. Specimens with higher degree of damage seemed to exhibit a
392 higher potential for RF recovery, which is possibly due to the higher number of cracks in these
393 specimens. Healing potential for RF values was not proportional to the recovery of the hydraulic
394 conductivity values for the specimens tested in this study.

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Table 1: Summary of soil particle distributions and w/c ratios used in different mix designs (adapted from Jamshidi & Lake (2014)).

Soil name	Mix designation	Water/cement ratio	Mixing method*	Composition by dry weight, %					Classification of blended soil (ASTM-D2487 (2011))
				Soil A				Soil B <0.08 mm	
				9.50-4.75 mm	4.75-1.20 mm	1.20-0.30 mm	0.30-0.08 mm		
Soil I (SI)	SI(1)	1	C	13	42	30	15	0	Well graded sand
	SI(1.5)	1.5	S						
	SI(2)	2	S						
Soil II (SII)	SII(1)	1	C	11	36	25	13	15	Silty sand
	SII(1.5)	1.5	C						
	SII(2)	2	S						
Soil III (SIII)	SIII(1)	1	C	9	30	21	10	30	Silty sand
	SIII(1.5)	1.5	C						
	SIII(2)	2	S						

*C: Compaction, S: Self-consolidation

Table 2: Comparison of UCS and resonant frequency values at 16 and 241 days.

Soil type	Mix design	Day 16		Day 241		Frequency ratio (RF_{241}/RF_{16})	UCS ratio (UCS_{241}/UCS_{16})
		RF, Hz (RSD, %)	UCS, MPa (RSD, %)	RF, Hz (RSD, %)	UCS, MPa (RSD, %)		
Soil I	SI(1)	13006 (0.2)	10.9 (0.7)	14435 (0.6)	14.1 (0.5)	1.11	1.30
	SI(2)	9234 (1.7)	2.8 (12.4)	11292 (0.0)	4.1 (7.7)	1.23	1.45
Soil III	SIII(1)	11865 (0.5)	10.0 (3.9)	13520 (0.2)	12.3 (1.5)	1.14	1.23
	SIII(2)	8391 (0.4)	3.2 (1.4)	10437 (0.6)	4.9 (2.2)	1.25	1.52

Table 3: Comparison of the healing potential between RF and hydraulic conductivity of the damaged specimens.

Curing condition	Mix design	Specimen #	After the 12 th f/t cycle		After the post-exposure healing period	
			Hydraulic conductivity ratio, K_{12}/K_0	RF ratio, β_{12}	Hydraulic conductivity ratio, K_{healed}/K_0 (% decrease)	RF ratio, β_{healed} (% increase)
Immature	SI(1.5)	1	49.2	0.14	5.5 (89)	0.63 (350)
		2	43.5	0.44	2 (95)	0.56 (27)
	SII(1.5)	1	7.8	0.74	1.7 (78)	0.98 (32)
		2	5.4	0.75	2.3 (57)	1.0 (33)
	SII(2)	1	112.5	0.34	54.2 (52)	0.62 (82)
		2	75.0	0.40	13.5 (82)	0.51 (28)
Mature	SI(1.5)	1	298.5	0.39	129.9 (56)	0.74 (90)
		2	1714.3	0.23	1571.4 (8)	0.70 (204)
	SI(2)	1	5250.0	0.10	1250.0 (76)	0.52 (420)
		2	3818.2	0.11	1682.8 (56)	0.51 (364)

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Fig. 1: Set-up used to perform the IR tests.

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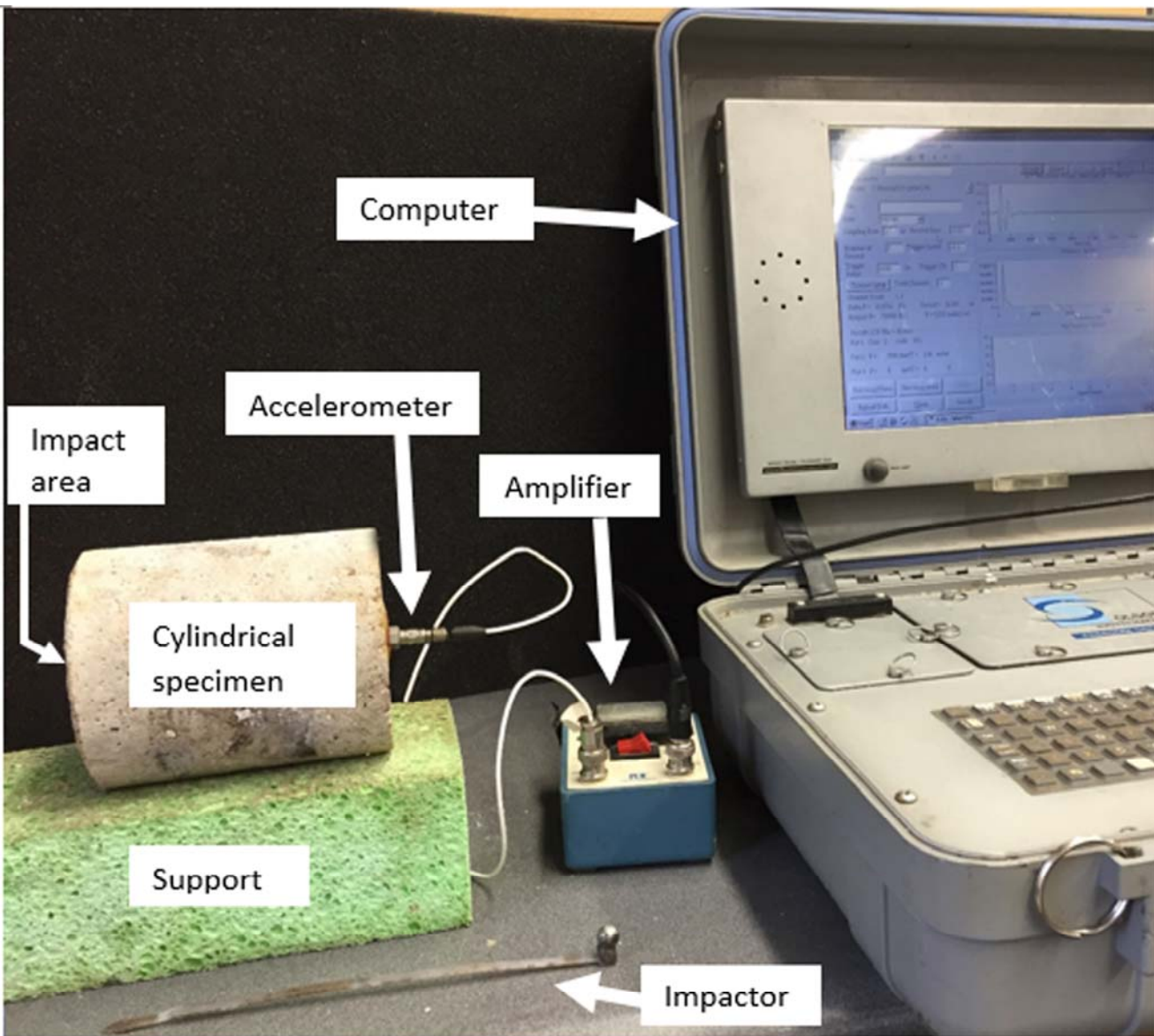
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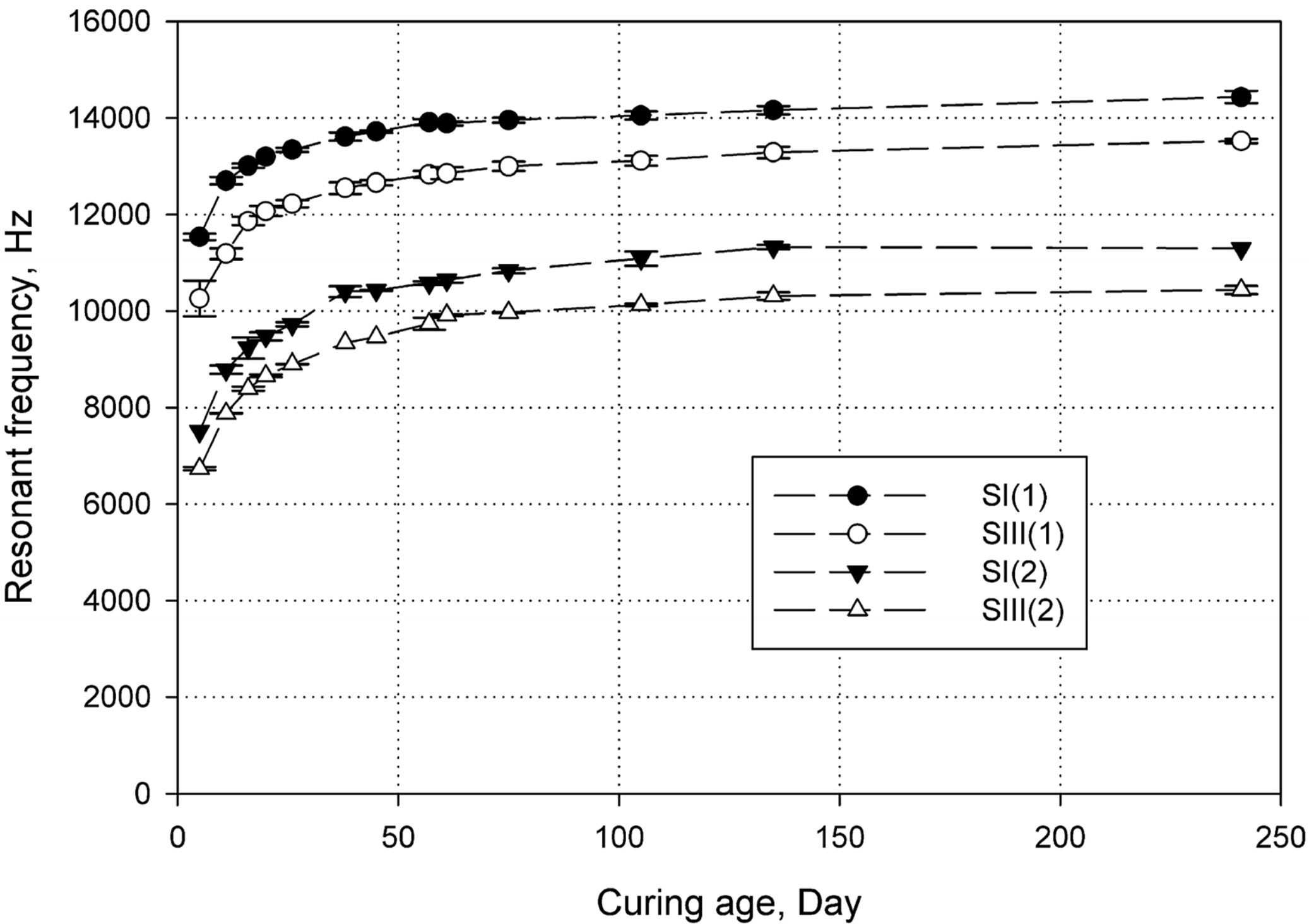
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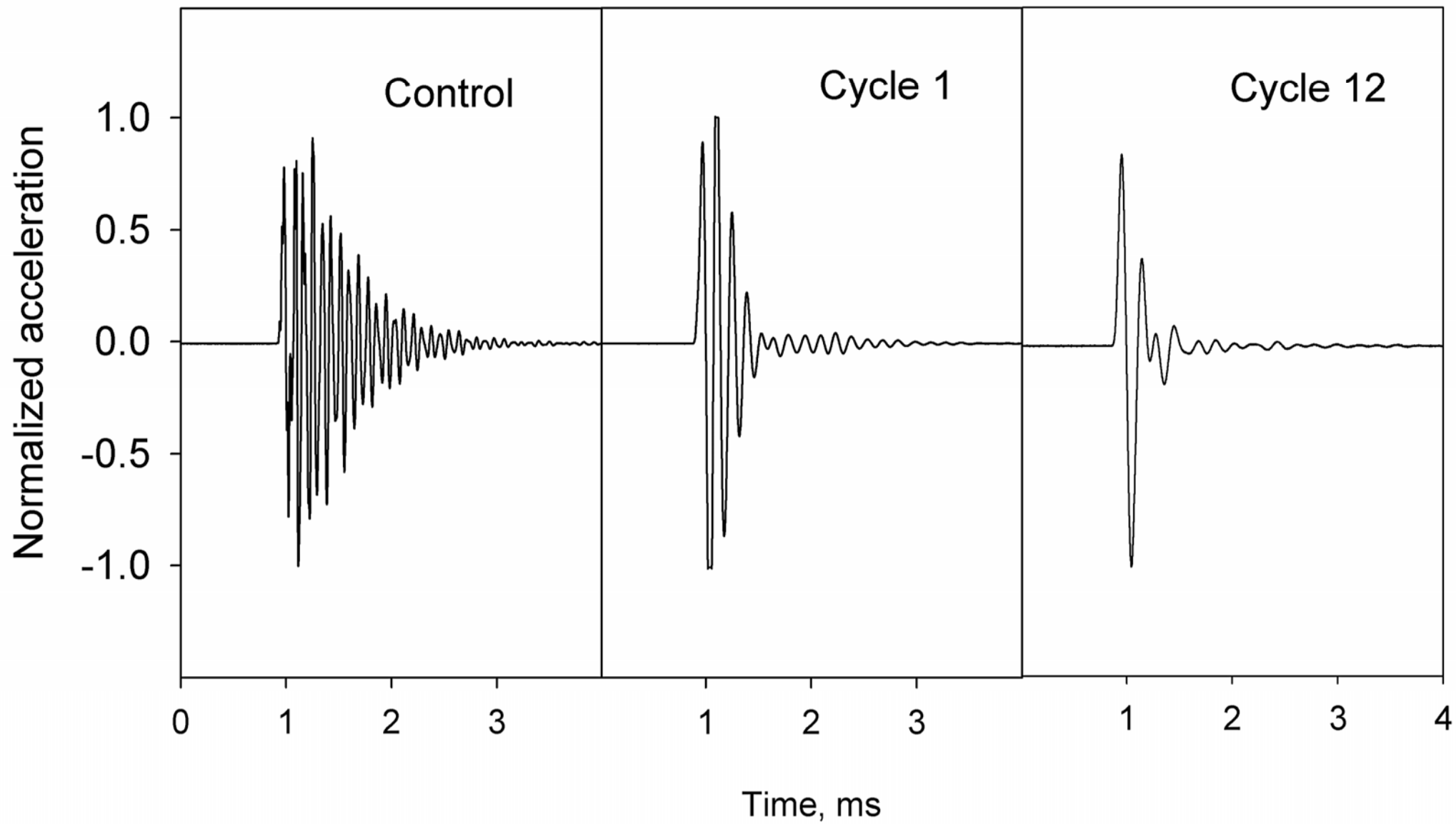
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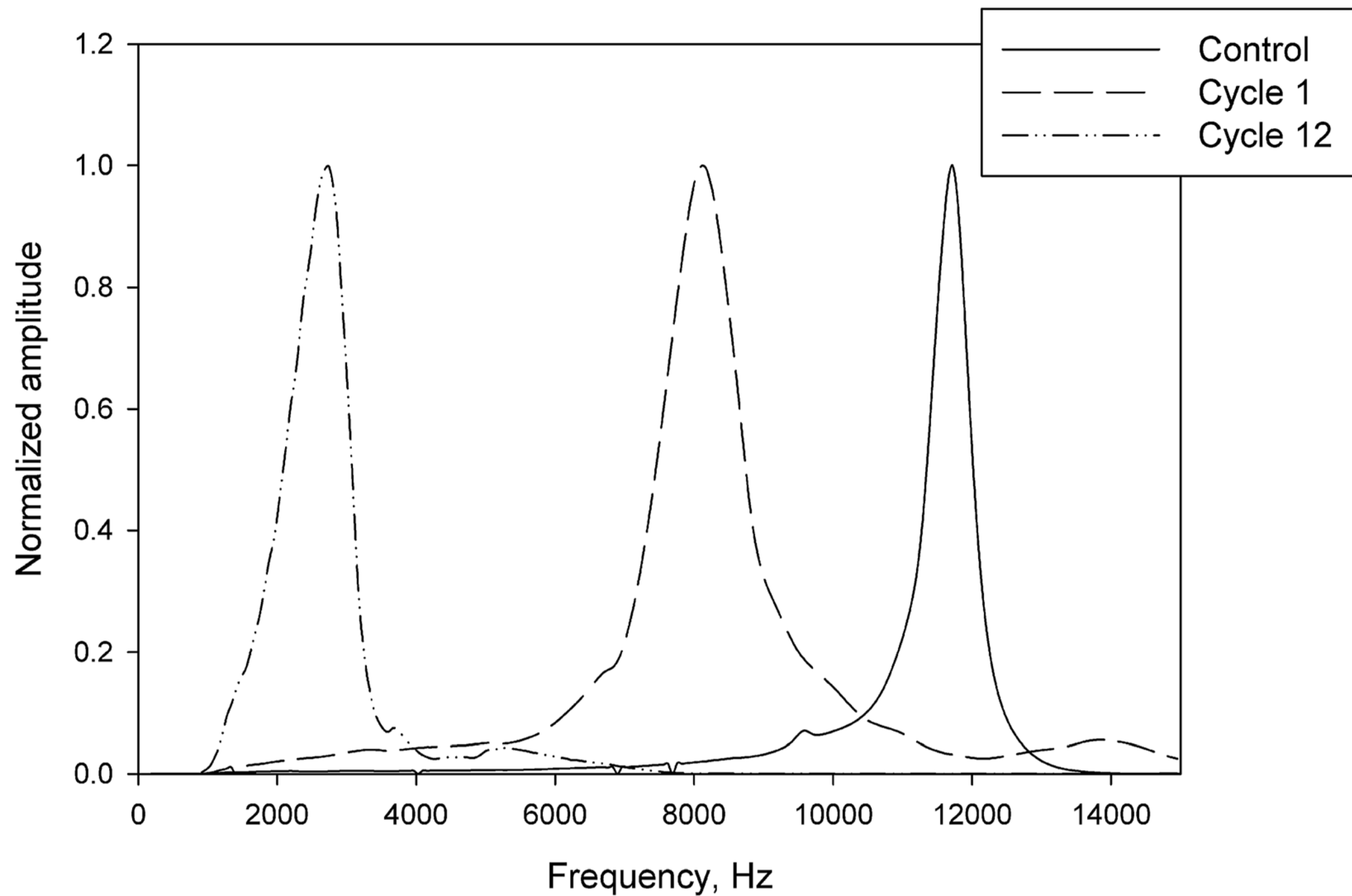
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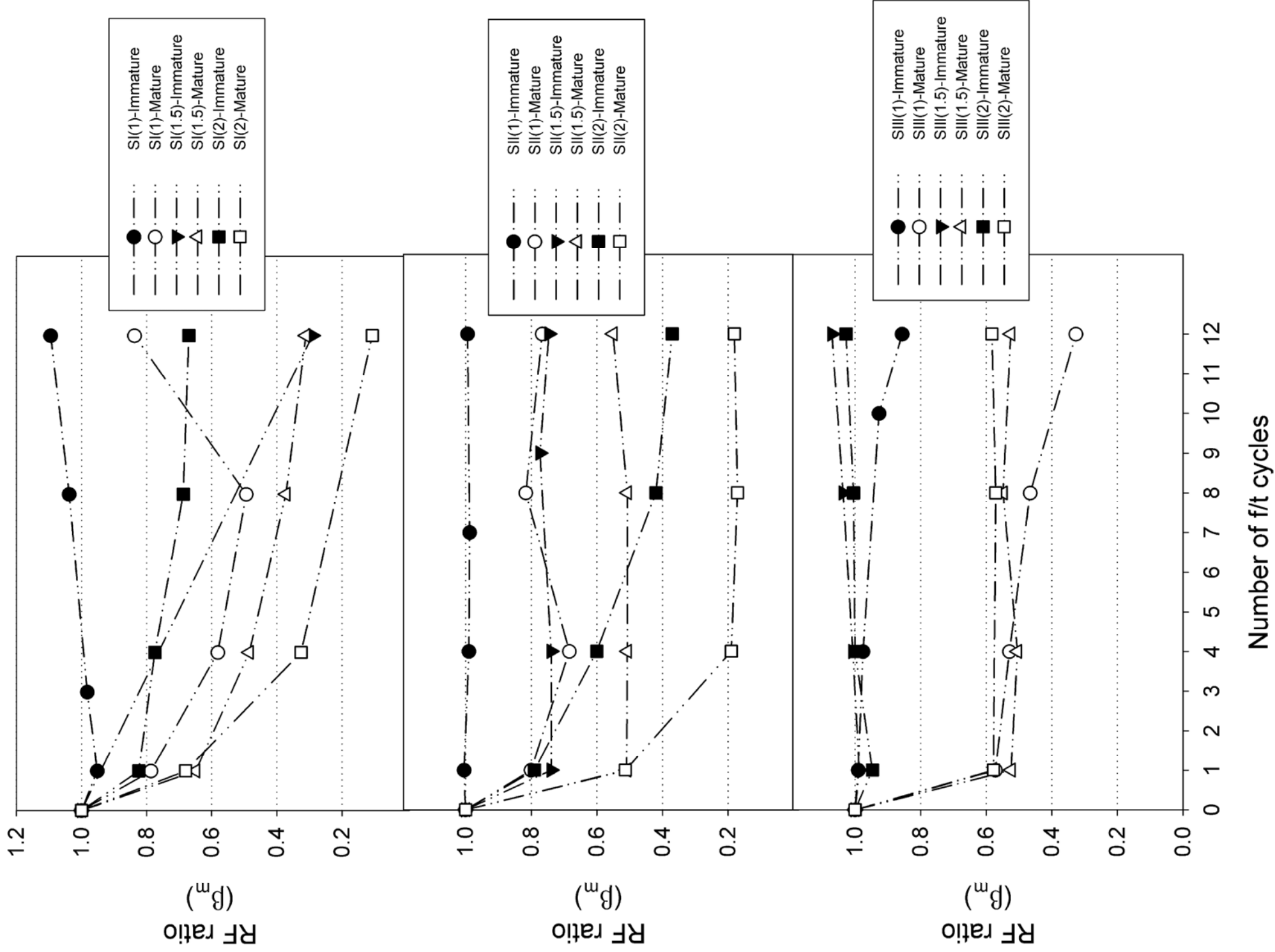
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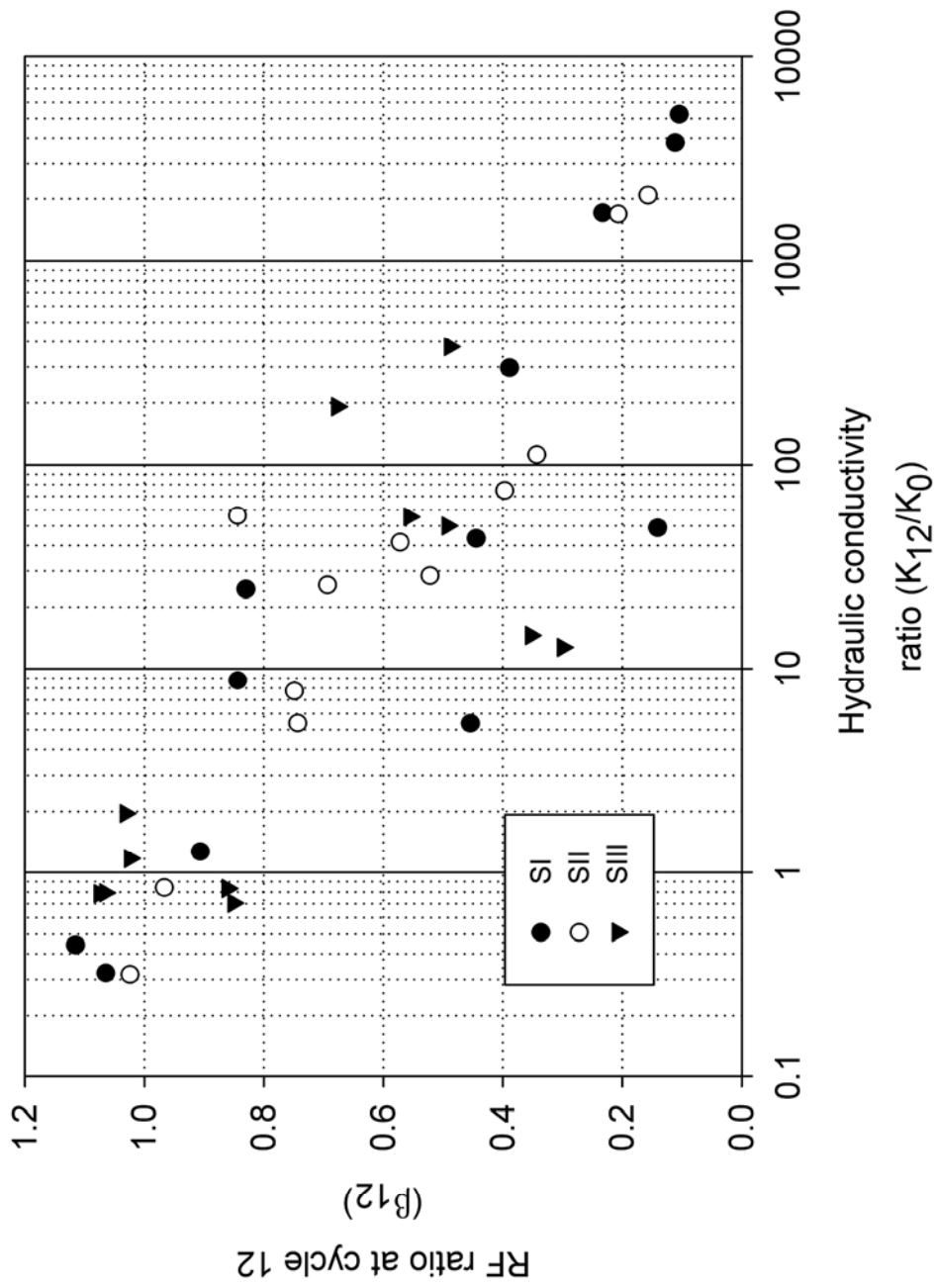




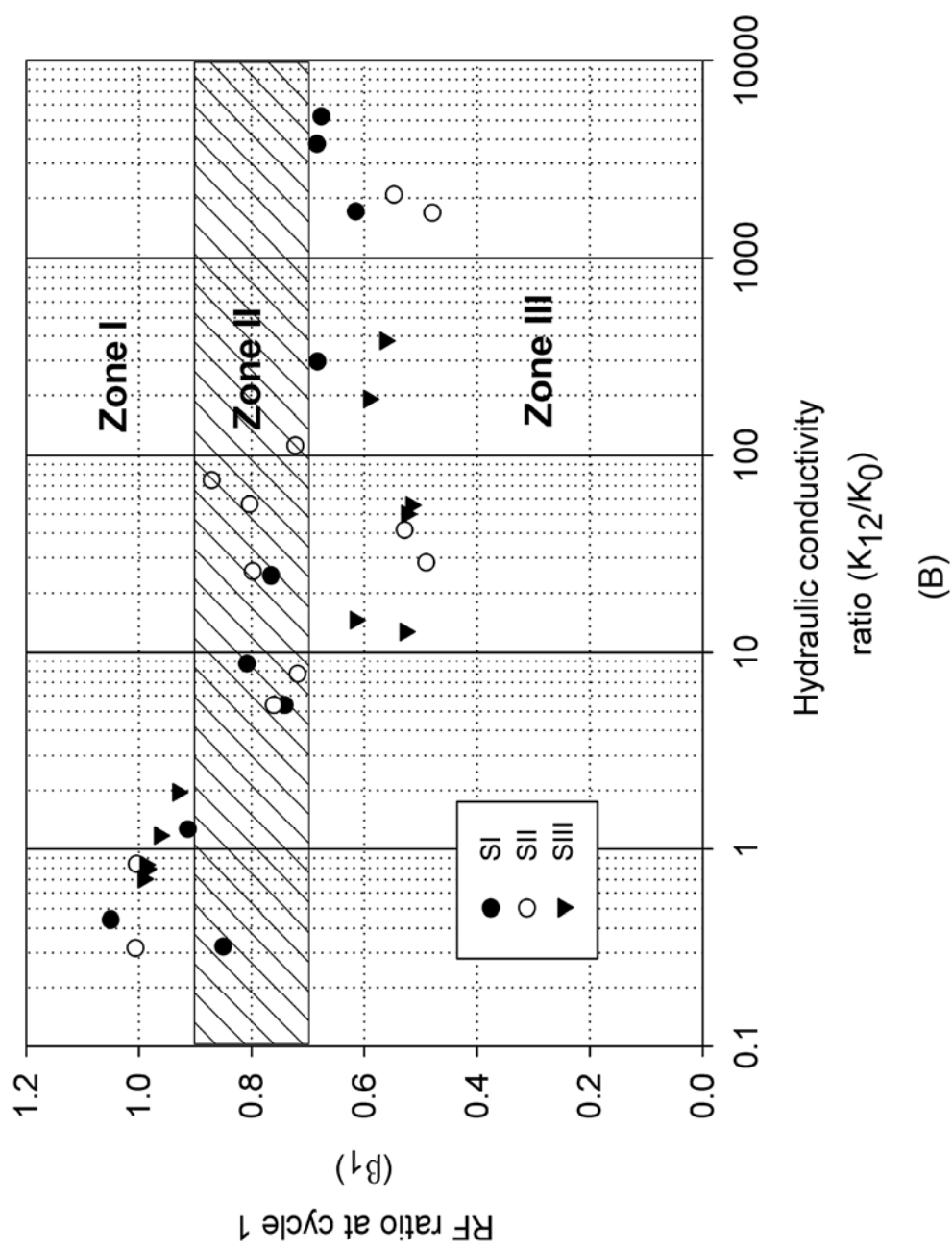








(A)



(B)

