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Research paper

Analysis of the effect of concrete repair and self-healing due to corrosion using the impact-echo method

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Abstract: Reinforced concrete is a primary component in the construction industry and is susceptible to damage from corrosion, fires, and natural disasters. Steel corrosion in concrete has become a serious global issue, resulting in significant economic losses. Dealing with existing concrete damage requires considerable time and cost, making innovation in repair methods essential. One of the repair methods employed is grouting with cement grout and jacketing. Innovative solutions have emerged in self-healing concrete, allowing concrete to repair small cracks autonomously. One self-healing approach involves using bacteria to seal cracks in concrete. Identifying damage caused by corrosion in reinforced concrete is crucial for implementing appropriate protective measures. Non-Destructive Testing (NDT) methods offer a way to detect damage without compromising the physical structure. NDT methods have been used for evaluating and monitoring steel corrosion in reinforced concrete, including the Impact-Echo (IE) method. The most important result of this study was that the peak frequency values obtained from Impact Echo (IE) testing on concrete before and after corrosion showed a shift towards lower values, indicating a decrease in concrete quality due to corrosion. It was observed that after the repair process, there was an increase in peak frequency values detected with Impact Echo on each specimen, indicating the effectiveness of the repair method. These results are significant as they provide insight into the impact of corrosion on concrete quality, the effectiveness of repair methods, the correlation between concrete quality and structural strength, and the potential for non-destructive testing impact-echo methods to monitor concrete conditions.

Keywords: concrete, grouting, impact-echo, jacketing, NDT, self-healing

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1. Introduction

Concrete is a crucial component widely used in construction [1, 2]. Concrete structures can deteriorate when exposed to severe environmental conditions, such as corrosion [2]. Corrosion is a significant especially for reinforced concrete (RC) structural elements [3–5]. The corrosion of embedded reinforcement steel in infrastructure has become a serious global issue, leading to structural repairs and economic losses [6, 7]. The American Society of Civil Engineers (ASCE) spends billions annually on infrastructure repairs, retrofits, and maintenance due to corrosion [8]. The global cost of corrosion is estimated to reach $2.5 trillion . [9]. Corrosion in reinforcement can impact flexural strength, deformation behavior, ductility, bond strength, and structural failure patterns, negatively affecting the long-term performance of RC structures [10]. Corrosion increases the diameter of the reinforcement, resulting in cracking and spalling of the concrete. The emergence of cracks in concrete can allow the ingress of elements such as water and chemical erosion, further deteriorating the concrete [11, 12]. Some previous studies on the corrosion effects of the reinforcement on reduction of mechanical properties [13–15], reduce the ductility and yield stress and affect the bond between steel and concrete [16], affect the stress-strain behavior of the reinforcement under dynamic loads [17], and decrease in corrosion resistance [18]. Various strategies are available to address the physical damage caused by corrosion. Based on previous research indicating that repairs and rehabilitation of corroded concrete involve significant time and cost, there is a need for innovation in these repair methods [19–21]. One of the methods used for concrete repair is grouting method. The grouting process entails the injection of a fluid into these spaces at a pressure suitable for a water pressure test, where the mixture solidifies over a specific period, both physically and chemically [22]. On the other hand, jacketing is a method that involves enlarging the cross-sectional area of old RC by applying a new layer of high-quality concrete [23, 24].

Recently, a solution to address cracking issues in concrete has emerged in the form of the latest technology involving self-healing by adding healing agents to the concrete [25–27]. These healing agents represent the development of self-healing concrete. Self-healing concrete is primarily defined as the ability of concrete to repair small cracks autonomously [28–31]. The self-healing approach can produce long-lasting, rapid, and active crack repairs while environmentally friendly [32]. One application of self-healing concrete involves the use of bacteria, where these bacteria will seal cracks in the concrete and prevent further damage from existing cracks [33]. Bacillus subtilis, a type of bacterial healing agent, is often used to enhance the concrete strength by filling voids within the concrete [34, 35]. The advantage of using this healing technology lies in its ability to repair micro-cracks in concrete that are difficult to access. From the issues and physical handling solutions mentioned above, the identification of damage caused by corrosion effects in RC structures should be detectable early before the structure deteriorates severely. Early detection enables suitable protective methods and anticipates early repair actions, thus reducing repair costs, and extending the structure's lifespan [36]. In identifying damage without the need to damage the structure during the inspection, Non-Destructive Testing (NDT) methods can be used [37, 38]. NDT is a method that can be employed for initial building condition assessments without altering the building [39]. Various NDT methods have been applied for monitoring corrosion in RC structures [37].

Detection of corrosion monitoring on concrete using the Impact-Echo (IE) method holds great potential. The IE method is a technique for detecting flaws in concrete [40, 41]. It is based on monitoring surface movement generated by a short-duration mechanical impact. One key feature of this method is transforming waveform data recorded from surface movement into the frequency domain [42]. However, there is very limited research on concrete quality after repair and self-healing concrete using the IE method. Therefore, this research aims to assess concrete conditions before and after repair and self-healing using the IE method.

2. Materials and method

2.1. Materials

The materials used to RC beam include coarse aggregate (CA), fine aggregate (FA), cement, and water. The FA used was sourced from Merapi, Yogyakarta, with particle sizes ranging from 4.8 mm to 0.0075 mm (Fig. 1a). The CA comes from Kulon Progo, Yogyakarta, with a maximum size of 19 mm (Fig. 1b). The cement used is Type I Portland Cement. Encapsulated Bacillus Subtilis bacteria were used as the healing agent for the self-healing process. These bacteria were obtained from the Agrobiotechnology Laboratory, Universitas Muhammadiyah Yogyakarta (Fig. 1c). As for the reinforcement used in creating the specimens, there were four main reinforcement with a diameter of 8 mm and five stirrup reinforcement with a diameter of 6 mm (Fig. 2). The results of designing the proportions of this concrete mixture can be seen in Table 1. Some material tests conducted include density measurement, water absorption, moisture content, mud content, and aggregate abrasion according to ACI 211.1-91 [43]. The material mixing process is carried out according to the mix design with the quality plan set for this test sample to achieve a compressive strength of 30 MPa. The proportion of encapsulated bacteria was added to the concrete dough mixture. This is so that bacterial encapsulation is not damaged when mixing fresh concrete due to the addition of water and collision between aggregates. The RC beams used in the testing have the dimensions of $62 \times 15 \times 15$ cm.


(a)


(b)


(c)

Fig. 1. Aggregates: (a) sand, (b) gravel, (c) encapsulated bacteria

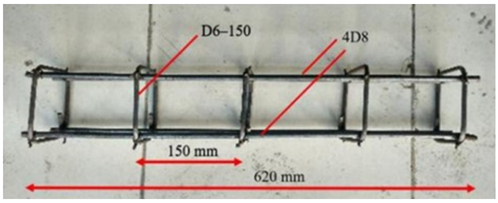


Fig. 2. Configuration of reinforcing bar spacing

Table 1. Mix Design of specimens

Specimen	Bacteria (% weigh sand)	Cement (kg)	Water (kg)	Sand (kg)	Gravel (kg)	Corrosion Level (%)
BAK 0,1	0.1	5.82	2.49	11.46	16.53	20
BAK 0,6	0.6	5.82	2.49	11.46	16.53	20
BAK 1,5	1.5	5.82	2.49	11.46	16.53	20
GRT 5	–	5.82	2.49	11.46	16.53	20
GRT 10	–	5.82	2.49	11.46	16.53	25
GRT 15	–	5.82	2.49	11.46	16.53	30
JKT 5	–	5.82	2.49	11.46	16.53	20
JKT 10	–	5.82	2.49	11.46	16.53	25
JKT 15	–	5.82	2.49	11.46	16.53	30
NOR A	–	5.82	2.49	11.46	16.53	20
NOR B	–	5.82	2.49	11.46	16.53	20

BAK = Bacteria specimen, GRT = Grouting specimen, JKT = Jacketing specimen, and NOR = Normal specimen

2.2. Corrosion acceleration mechanism

Corrosion processes within RC generally occur relatively slowly [44]. The galvanostatic method, based on ASTM G1-03 [45] and ASTM G31-72 [46], is often employed to accelerate reinforcement corrosion. It offers several advantages, including efficiently controlling the corrosion rate [47,48]. This method uses a direct current (DC), anode and cathode electrodes [49–51]. The anode represents the reinforcement in the RC, connected to the positive terminal, while the cathode using sacrificial steel, connected to the negative terminal. To determine the corrosion rate in terms of the percentage (%) of mass loss, Faraday's Law is employed.

2.3. Repair method

The grouting method is used to seal cracks that serve as joints or to cover and provide structural repair that restores the strength and continuity of displacement in concrete [52, 53]. In the grouting method, the mixture comprises cement, fine aggregate, and water. The complete scheme of the grouting method can be seen in Fig. 3. Concrete repair involving the addition of an additional layer to an existing RC is jacketing method. Many experimental studies have demonstrated that concrete's strength, performance, and deformation can be improved using jacketing techniques [54–56]. In this study, the jacketing method begins with increasing the dimensions of the concrete by adding a 20 mm thick concrete cover layer using larger formwork than the specimen (Fig. 4). The mixture used in this method consists of cement, fine aggregate, and water. Bacillus subtilis bacteria as self-healing are encapsulated to be used as an additive in concrete mixtures. The bacteria is commonly adopted as a crack-healing agent because it can form spores and withstand high mechanical strength in harsh environments [57]. The scenario in RC involves the bacteria on the surface of newly formed cracks becoming active when exposed to water, beginning to deposit minerals, ultimately closing the cracks, and protecting the reinforcement from further external chemical attacks [58].

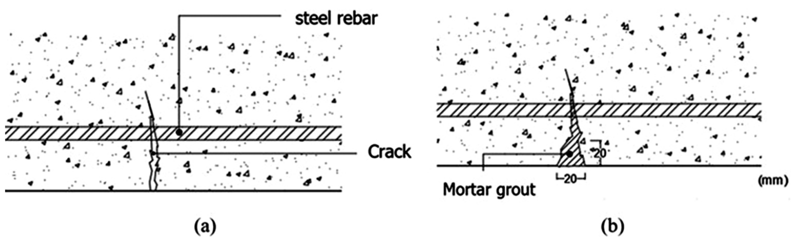


Fig. 3. Grouting method: (a) before grouting, (b) after grouting

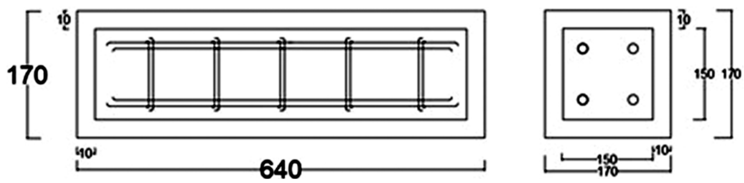
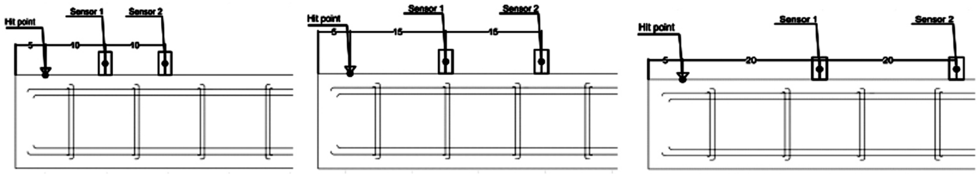


Fig. 4. Jacketing method

2.4. Impact-echo method

The basic principle of Impact Echo (IE) involves striking the specimen's surface with a tool such as a hammer or an impactor, generating and transmitting stress waves at a specific frequency, and measuring the response from the nearest source [59]. In this study, the IE tool consists of several key instruments used to generate and record stress waves generated by impacts on RC, such as impact hammers, wave sensors (transducers), signal recorders, and signal analyzers using SASW (Spectral Analysis of Surface Wave) software. Both before and after the repair and self-healing processes on the concrete, NDT is performed on the RC using the IE method. The details of the placement of the impact point and the positioning of the two wave sensors can be seen in Fig. 5. The sensor placement is varied into three different distances: 10, 15, and 20 cm. Regression analysis is a statistical approach utilized to evaluate the relationship between one or more independent variables and one dependent variable [60]. In the analysis, how much influence one variable has on another and how strong their correlation is. The result of the analysis is called the correlation coefficient [61].



(a) (b) (c)

Fig. 5. IE method procedure: (a) 10 cm interval, (b) 15 cm interval, (c) 20 cm

3. Result and discussion

3.1. Aggregate testing

Laboratory testing results for FA and CA indicate that the characteristics of both aggregates for use as constituents of normal concrete mixes as shown in Table 2.

Table 2. Aggregate test results

Fine Aggregates	**Result Obtained**	**Coarse Aggregates**	**Result Obtained**
Specific gravity	2.64	Specific gravity	2.72
Water Absorption (%)	1.10	Water Absorption (%)	1.20
fineness modulus	2.40	Water Content (%)	0.83
Weight Content (g/cm$^{3)}$	1.52	Sludge Content (%)	1.00
Water Content (%)	2.00	Weight Content (%)	1.49
Sludge Content (%)	1.60	Abrasion (%)	21.0

3.2. Accelerated corrosion and cracking

The corrosion acceleration process after a curing period of 28 days uses a DC Power Supply with a NaCl concentration of 10% of the water weight used to immerse the specimens. Table 3 shows each specimen's acceleration and corrosion rate variation results. There is a difference in the corrosion rate between the estimated and actual corrosion. The difference between the mass loss calculated based on Faraday's Law and the actual mass loss is due to the assumption that corrosion is a uniform process, whereas in reality, there are localized corrosion phenomena [62], and there are barriers or inhibitors to the movement of ions from the anode to the cathode. The formation of cracks on the specimens was carried out using a two-point loading method using a universal testing machine, applying a load between 2500 to 3000 Kgf. This approach was applied because cracks did not occur naturally after the corrosion process was performed. These cracks in the concrete are necessary for the repair process and for comparing the peak frequencies obtained from the IE testing.

Table 3. Corrosion acceleration results of specimens

Specimen	Estimated corrosion rate (%)	Initial weight of rebar (g)	Weight after corrosion (g)	Actual mass loss (g)	Actual Corrosion Rate (%)
BAK 0,1	20	500	428	72	14.40
BAK 0,6	20	500	418	82	16.40
BAK 1,5	20	500	432	68	13.60
GRT 5	20	500	399	101	20.2
GRT 10	25	500	372.5	127.5	25.5
GRT 15	30	500	346.5	153.5	30.7
JKT 5	20	500	397.5	102.5	20.5
JKT 10	25	500	374.5	125.5	25.1
JKT 15	30	500	347.5	152.5	30.5
NOR A	20	500	395.5	104.5	20.9
NOR B	25	500	373	127	25.4

3.3. Impact-echo testing

3.3.1. Comparison of IE testing frequency at each sensor distance

Frequency analysis is an effective parameter in IE testing [42]. Frequency is the number of vibrations that occur in one second and is measured in Hertz (Hz). The frequency obtained from IE testing indicates the quality of the concrete being tested, and the result of this frequency is highly dependent on the predetermined sensor distance. Therefore, this study tested using three different sensor distances to achieve consistent frequency results, which will facilitate identifying the IE test results. Figure 6 illustrates the differences in wave results from IE testing with different sensor distances. These test results show that the difference in sensor distance can affect the frequency of the obtained test results. Figure 7 shows that the frequency difference at a distance of 20 cm is more consistent compared to distances of 10 cm and 15 cm. The correlation coefficient value obtained at a 20 cm distance is 0.9329, close to 1. According to Olusula (2013) [63] implies that if the correlation between the variables is within the range of 0.5 to 1.0, then a significant correlation is assumed. This indicates that at this sensor distance, there is a strong correlation. It can be concluded that the effective distance for obtaining the quality and consistency of IE frequency is at a 20 cm sensor distance.

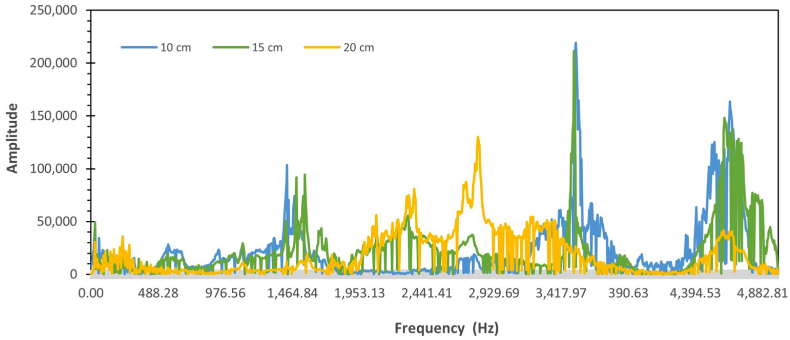


Fig. 6. Impact-Echo at distances of 10, 15, and 20 cm

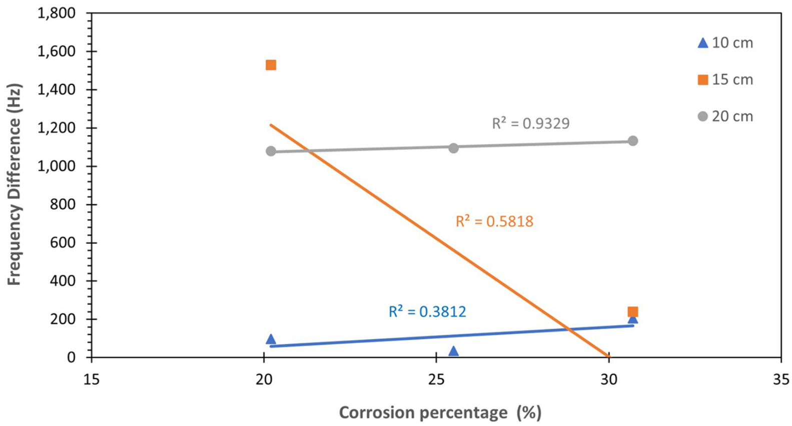


Fig. 7. Impact Echo Frequency

3.3.2. Comparison of wave results due to corrosion and cracking

After accelerated corrosion, the specimens were tested using the IE method. The differences in waveforms and peak frequencies of the 30.7 % corrosion specimens can be seen in Fig. 8. There is a shift in the peak frequency obtained from the IE testing at each corrosion percentage. This is consistent with the research conducted by Kristýna Timčaková-Samarkova et al. [64], which states that the deteriorating condition of concrete structures due to corrosion can reduce dominant frequencies. Figure 9 shows the relationship between corrosion rate and IE peak frequency value graph. The coefficient of determination (R^2) is 0.3899, which means that the corrosion percentage can only affect the frequency (Hz) by 39%.

The specimens undergoing the corrosion acceleration process were subjected to compression testing. The waveform graphs obtained from the IE on concrete with 30.7% of corrosion levels are shown in Fig. 10. There is a shift in the peak frequency towards higher values compared to before. This shift is attributed to cracks in the concrete, which create voids and result in higher-frequency waveforms. According to Çam et al. [65] Waves passing through solid particles tend to have lower frequencies than those passing through voids.

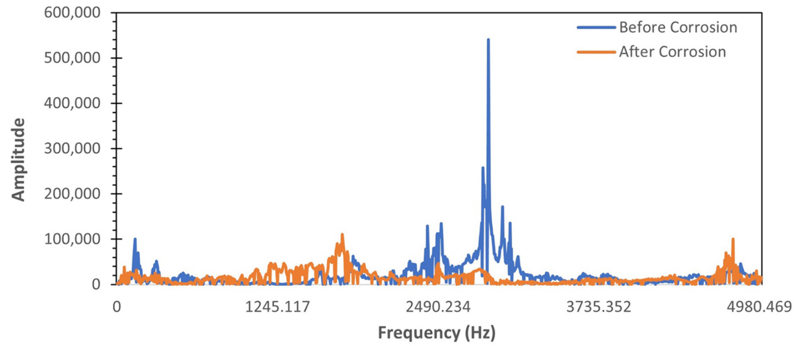


Fig. 8. Wave difference before and after corrosion 30.7%

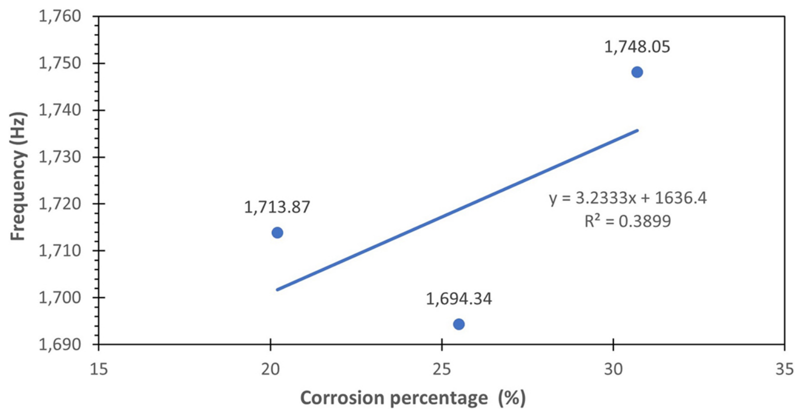


Fig. 9. Relationship between peak frequency value and corrosion rate

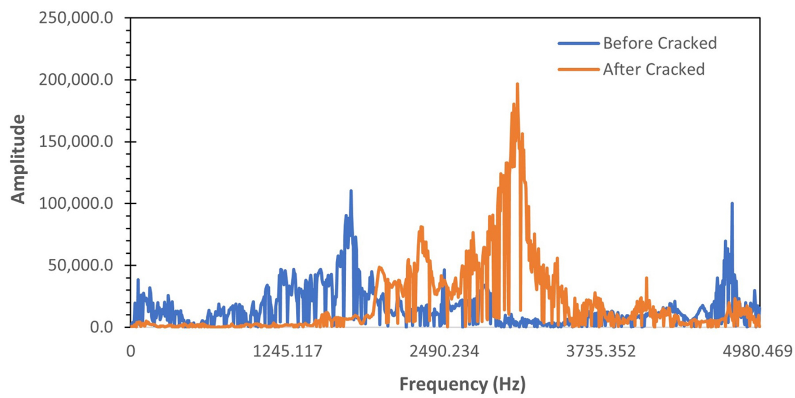


Fig. 10. Comparison of waves before and after the cracking process at 30.7 corrosion

3.3.3. Correlation between frequency value and percentage of bacteria in corrosion self-healing concrete

Figure 11 shows the relationship graph between the percentage of bacteria content and the IE peak frequency value of corrosion self-healing concrete. The coefficient of determination (R^2) obtained is 0.6666, which means that the percentage of bacteria content can affect the frequency (Hz) of impact-echo by 67%, and other factors or variables influence the rest.

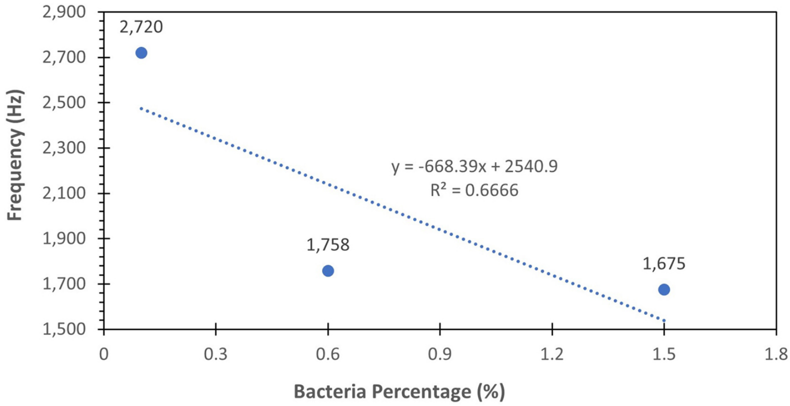


Fig. 11. Correlation of frequency value with the percentage of bacteria content after corrosion

3.3.4. Comparison of wave results after self-healing concrete

Self-healing concrete specimens that have undergone cracking were then subjected to curing using burlap sacks for 14 days to activate the Bacillus subtilis bacteria in the concrete. The graphs of the IE results for 1.5% bacteria content specimen are shown in Fig. 12. It can be observed that there is a shift in the peak frequency for each specimen with varying bacterial contents. This indicates that the IE method can monitor concrete conditions before and after

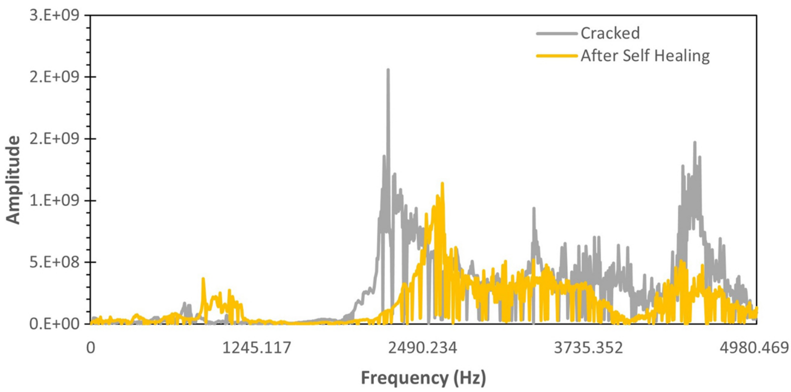


Fig. 12. Comparison of self-healing waves with 1.5% bacteria content

the self-healing concrete process. Figure 13 displays the graph of the peak frequency shift for each specimen. It can be seen that there is a shift towards higher values in specimens with bacterial contents of 0.6% and 1.5%. Meanwhile, a shift towards lower values occurs in specimens with 0.1% bacterial content. It can be concluded that concrete specimens with 0.1% bacterial content cannot repair the condition of cracked concrete.

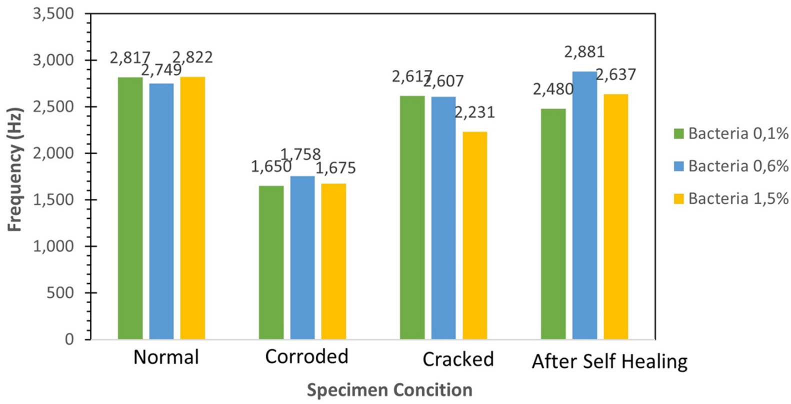


Fig. 13. Frequency comparison of self-healing concrete

3.3.5. Comparison of wave results after repair grouting

The specimens that have undergone cracking were then subjected to the grouting method using a mortar mixture for repair. Afterward, a 28-day immersion curing process was carried out to maximize the strength of the concrete mortar. The waveforms of the IE results for 20.2% corrosion specimen is displayed in Fig. 14. It can be observed that there is a shift in the peak frequency for specimen before and after grouting, indicating a shift towards higher peak frequency values compared to the cracked condition. Figure 15 shows a graph comparing the peak frequency values for each specimen under different conditions. It can also be seen that after the grouting process, there is an increase in the peak frequency values in the specimen. This indicates that the IE method can monitor concrete conditions before and after the grouting.

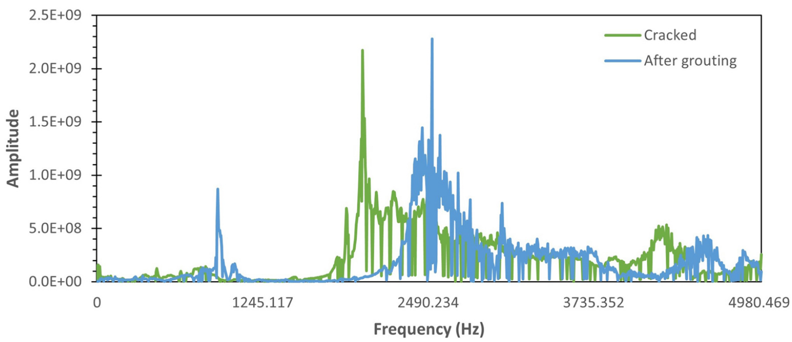


Fig. 14. Comparison of wave repair grouting with a 20.2% corrosion rate

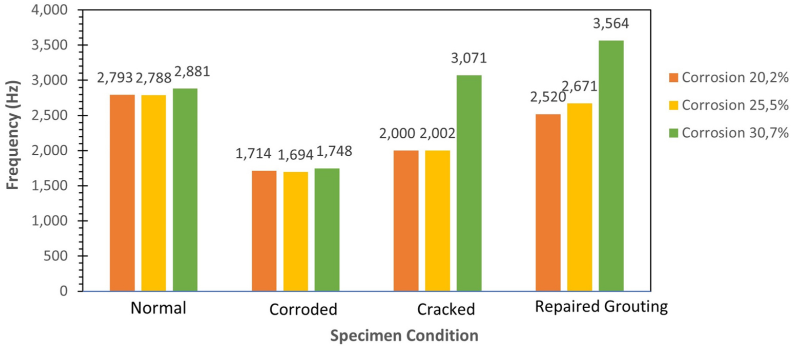


Fig. 15. Frequency comparison of concrete repair grouting with different corrosion levels

3.3.6. Comparison of wave results after jacketing repair

The specimens that have undergone cracking were subsequently repaired using the jacketing method with a 1 cm thick mortar mixture. Following this, a 28-day immersion curing process was carried out to maximize the strength of the mortar. Then, IE testing was performed to determine the differences in peak frequency values. The graph of the IE results for 20.2% corrosion specimen is shown in Fig. 16, there is a shift in the peak frequency value. Figure 17 presents a graph of the peak frequency values for each specimen. Based on this graph, it can be seen that there is an increase in the peak frequency value from the cracked condition to the condition after the jacketing repair. This occurs because voids or cracks formed during the cracking process are sealed by the jacketing mortar, thereby improving the quality of the concrete, which directly increases the peak frequency value. This indicates that the IE method can monitor concrete conditions before and after the jacketing repair. This monitoring is based on the loss of mass of the concrete reinforcement, indicating the corrosion process in the reinforcement, as well as the addition of dimensions to the concrete cover due to the jacketing repair process.

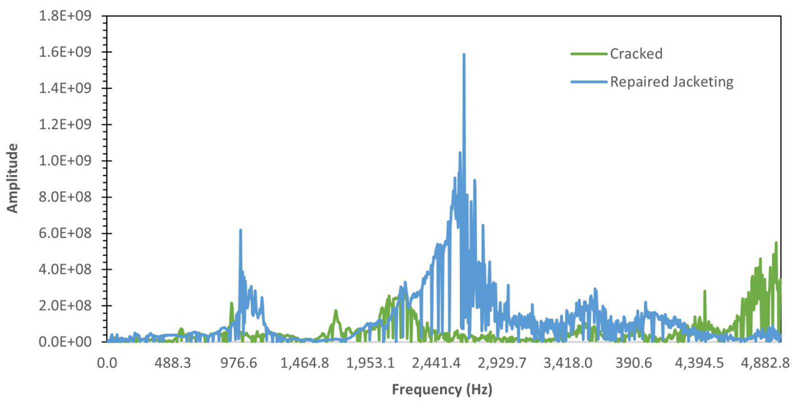


Fig. 16. Comparison of wave repair jacketing with a 20.2% corrosion rate

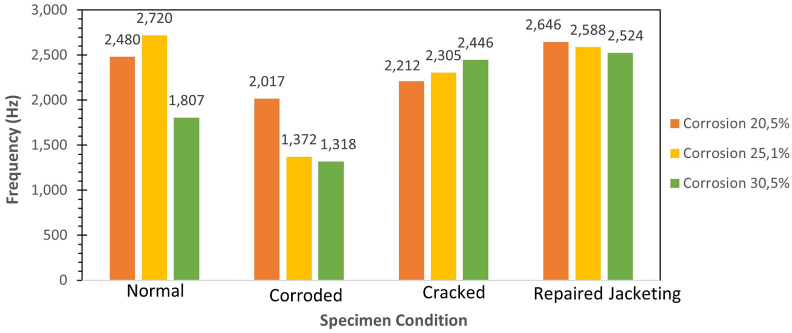


Fig. 17. Frequency comparison of concrete repair jacketing with different corrosion levels

3.4. Comparison of flexural strength and frequency result

After the repair process, the specimens were tested for flexural strength to obtain the flexural strength value of the specimen. Table 4 shows the flexural strength values of each specimen. Figure 18 shows the comparison graph of flexural strength value with peak frequency for each type of specimen. The coefficient of determination (R^2) is also given, which measures how well the data fits the trend line (regression model). The relationship between flexural strength and frequency indicates that specific repair methods influence the effectiveness of increasing or maintaining the material's flexural strength, as the IE frequency obtained shows. The jacketing repair has an R^2 of 0.8617, which shows a reasonably strong correlation between frequency and flexural strength. Self-healing has an R^2 of 0.7270, which shows a moderate correlation. Both repair methods have a relationship that the higher the flexural strength, the higher the frequency obtained, which is seen according to the consistency of the trend line which is higher. Meanwhile, repair grouting has an R^2 of 0.9574, which shows a very strong correlation. However, it has an inversely proportional relationship, where there is a relationship that the

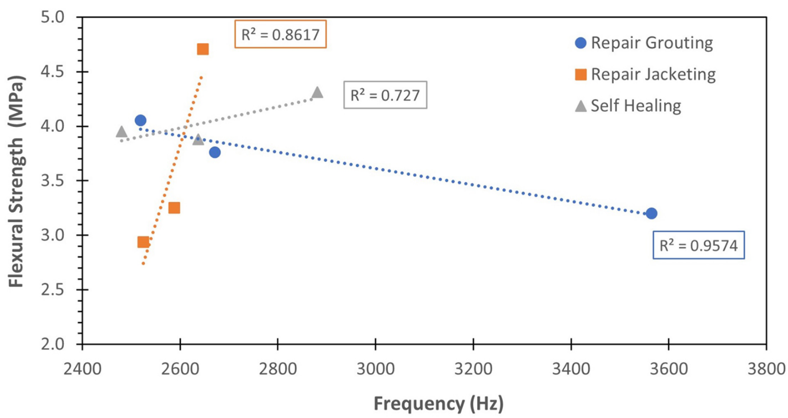


Fig. 18. Comparison of flexural strength values with peak frequency

higher the flexural strength value, the lower the peak frequency value obtained. This happens because the cavity inside the concrete is not entirely covered by mortar in the repair grouting process because the repair jacketing process only covers the cavity on the concrete's surface.

Table 4. Comparison of flexural strength results

Specimen	**Actual Corrosion (%)**	**Flexural Strength (MPa)**	**Peak Frequency (Hz)**	**Bacteria Content (%)**
BAK 0,1 A	14.8	3.95	2480.47	0.1
BAK 0,6 A		4.31	2880.9	0.6
BAK 1,5 A		3.88	2636.72	1.5
GRT 5A	20.2	4.05	2519.53	–
GRT 10A	25.5	3.76	2670.9	–
GRT 15A	30.7	3.20	3564.45	–
JKT 5A	20.5	4.71	2646.48	–
JKT 10A	25.1	3.25	2587.89	–
JKT 15A	30.5	2.94	2524.41	–

4. Conclusions

Based on the testing and data analysis conducted in the research. several conclusions can be drawn as follows:

1. The peak frequency values obtained from the IE testing on concrete before and after corrosion showed a shift towards lower values. This shift is due to the deterioration in the quality of corroded concrete, which affects the resulting peak frequency values.
2. The peak frequency values obtained from the IE testing on concrete before and after cracking showed a shift towards higher values. This occurs because the cracks in the concrete create voids, causing the generated frequency to be higher.
3. Bacteria in normal concrete specimens do not affect the peak frequency values obtained from IE testing. The percentage of bacteria content in the specimens can affect the peak frequency values obtained from IE testing on concrete undergoing accelerated corrosion.
4. The peak frequency values obtained from IE testing on concrete undergoing self-healing processes change to higher values at 0.6% and 1.5% bacterial content levels. However, a shift towards lower values occurs at a bacterial content level of 0.1%. Therefore, concrete specimens with 0.1% bacterial content cannot repair the condition of cracked concrete based on monitoring with the IE method.

5. The peak frequency values obtained from IE testing on concrete that has undergone repair grouting and jacketing increases compared to the condition of cracks. This indicates that the IE method can monitor concrete conditions before and after the repair process.
6. The comparison of flexural strength values in self-healing and repair jacketing specimens is correlated, with higher flexural strength values corresponding to higher peak frequency values obtained from IE testing. However, in repair grouting specimens, an inverse relationship is observed.

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