This paper discusses the effect of acidic environments on concrete structures, particularly crack width. This study was conducted to investigate the effect of acid ph on crack width in reinforced concrete beams with different cover depths. Reinforced concrete beams were immersed in phosphoric acid (H_3PO_4) solution with a pH of 5.0 for 28 days using this technique. Three concrete cover thicknesses were tested: 20 mm, 30 mm, and 40 mm. The materials used include coarse aggregate, fine aggregate, cement and phosphoric acid solution. Crack width, concrete compressive strength and steel stress were measured while the two-span beams with different section shapes experiencing point loads. The findings demonstrated that exposure of concrete to an acidic environment led to a decrease in compressive strength between 15% and 40%, cracking becoming significant with the beams having thin layers, while these results range a crack width ranging from no visible cracks until cracks resulted opened up. Crack width is directly dependent upon the thickness of concrete, for thicker concrete layer reducing crack width. On the other hand, steel stress increases crack width, with more the steel stress greater is crack wider. This study is unique in that an empirical formula related to crack width can be used for the prediction and has a good agreement with experimental results. The results yield new understanding on the significance of controlling concrete cover depth and steel stress level in the design methodologies for reinforced-concrete structures to be more acid-resisting. These findings may have implications for the design of reinforced concrete structures that are more resistant to acidic environmental conditions

Keywords: acidic pH, reinforced concrete beams, concrete layers, crack width

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IDENTIFYING THE VARIATION OF ACID IMMERSION AND CONCRETE COVER ON THE CRACK WIDTH OF REINFORCED CONCRETE BEAMS

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1. Introduction

Nearly all big cities in Indonesia build have industrial regions that emit sulphur dioxide (SO_2) and nitrogen oxide (NO_x). This can combine with the acidic gases produced by industrial processes to form acid rain, which has damaged many forms of reinforced concrete structures and buildings throughout much of the developed world. When the acid ions are usually H^+ and in rainwater, they can also oxidize reinforced concrete over a grace period of time possibly creating an internal change which affecting the chemical stability cement components. This damage makes the concrete more porous and weakens it, reinforcing its destructive behavior.

As previously researched, it is proven that the external exposure effect of acid precipitation would result in the microstructure variation and deterioration development on concrete surfaces [1]. If this is too thin, these chemicals can penetrate even faster the concrete reaching reinforcing steel. And water that gets behind the system has nowhere to escape, which means over time in a damp environment where corrosion of the reinforcing steel can occur as well surface cracks revealing the corroded and again back full circle too structural deterioration. Therefore, the depth of concrete cover and quality of concretes are likely variables that need to be carefully considered especially in areas which commonly experieence exposure pollution an acid rain.

In spite of the fast-developing technology in building material, the topic on corrosion remains an evergreen challenge to surrounding way and manner at which concrete would still be susceptible to this chemically progressive attack. Corroded reinforced concrete does not only lose its structural strength, but also poses a long-term threat to the integrity of buildings or infrastructure. Consequently, the corrosion process in reinforced concrete accelerated due to acid immersion.

Numerous studies have been carried out on the effect of acidic environments on the service life of reinforced concrete, but little has yet to be known about what pattern can result due to variations in cover thickness and acid immersion duration that may affect cracking inside strengthened beams.

While the development of science is more advanced, however in terms of how research results are implemented sometimes it still does not exactly correspond to field conditions that have differing characteristics one from another. Hence, more research is still needed regarding this gap for construction practitioners to gain a better understanding. Without more knowledge about what is happening it is struggled to find the correct solutions that should allow to protect our reinforced concrete structures from future distress.

2. Literature review and problem statement

A leading cause of cracks in reinforced concrete is tensile stress surpassing the tensile strength of concrete [2, 3]. These cracks do not just harm the stability of the structure but may lead to corrosion of reinforcement that eventually decomposes concrete. From this study it is found that higher crack widths can also increase the permeability of concrete and allow attack to other environmental factors like water penetration as well as corrosive substances. However, the influence of other factors like concrete composition and acid immersion length in crack formation remains unknown. If to study things over a long time with exposure to various different conditions in the environment, cost is an obvious barrier. An alternative is to carry out laboratory tests in a way that allows strict control over the decrease of pH and time under immersion. In many past studies, this was the only method of simulation although it considered merely on reinforcement type. Their study also emphasized that it is important to conduct further research on both environmental impacts and the behavior of crack formation in concrete reinforced-concrete [4].

Concrete cracks are depending on material properties, for example behavior of reinforcement materials Nonetheless, diffusion's mechanism can further exacerbate the spatial separation of cracks and thus create conduit for water - wood rotting accelerator and corrosion steel rusting marker with a pH potential as low as all along to induce concrete damage [5]. Their response to acidic, and particularly extreme environments is little known. It is difficult to maintain the right environmental conditions without knowledge where exposure comes from and its amount. Further research should focus on the development of full scale more resistance numerical models by taking into account different environmental and material conditions. The effect of acid and corrosion environments on the concrete under different test conditions has been studied to a lesser extent in control and reinforcement materials.

Cracks of higher width initiate corrosion therefore the monitoring of crack-width is imperative for minimizing structural damage [6]. Most importantly, this study highlights the considerable importance of monitoring crack width if damage is to be detected early. Over and above, this study estimated only a specific corrosion rate with the tie width of cracks but has not pointed out briefness directly or indirectly on that relationship further at low pH conditions. One of the causes for this uncertainty is due to estimations by monitoring some values during non-precise field conditions which are untoward corrosion rates in such situations. A proposed way to address this is through the use of advanced sensing systems capable of providing real-time measurements on crack and corrosion growth, relating permeability changes with acidic agent ingress [7].

Work on the development of improved monitoring technology for long-term studies concerning environmental effects like acid action, accommodated against a control using reinforced concrete. In reinforced concrete cracks are a way that harmful substances can more easily reach the reinforcement and thus accelerate the corrosion process [8]. Still, it remains difficult to create tech that can follow along in a focused and precise manner washing-wise through the long term. This is solved by using sensing technology so that the changes can be detected at any given point in time. These results suggest the necessity of additional inquiry to evaluate better monitoring approaches.

Acid corrosion can form cracks and corrode concrete steel bonds [9]. Not with standing, such a study does not yet elucidate the ultimate behavior of reinforcing steel corrosion in crack widths for reinforced concrete structures after long-term atmospheric exposure. Hence the research on interface between crack width and acidic medium surrounding reinforcing steel in concrete is imminent.

3. The aim and objectives of the study

The aim of this study is to identify the effect of acidic pH on the crack width of reinforced concrete beams with varying concrete cover. This will enable concrete structures to be designed to be more resistant to aggressive environmental conditions and reduce maintenance costs.

To achieve this aim, the following objectives were accomplished:

– to identify the effect of immersion in acidic pH on the compressive strength of concrete;

– to examine the influence of immersion in acidic pH on the crack width of reinforced concrete beams with varying concrete cover;

– to predict the relationship between acidic pH and compressive strength.

4. Materials and methods

This study was devoted to the structural behavior of reinforced concrete. The hypothesis under test in this article is the scenario where exposure to acidic pH would decrease concrete compressive strength and induce higher crack width, particularly for those typical with web thin layers of concrete. Crack width is also influenced by the thickness of concrete layer and stress on reinforcing steel.

It is assumed that the pH of an acidic solution will remain constant throughout the course of this experiment and there are no other outside factors besides light exposure like temperature and humidity which may cause deviations in data output.

While the actual environment can differ, this study simplifies by testing only three variations in concrete layer thickness (20 mm, 30 mm and 40 mm) along with an immersion duration of just 24 days.

The application materials in this study included: coarse aggregate, fine aggregate from Lumajang sand, Gresik cement, a solution with acidic pH which was prepared by mixing water and phosphoric acid (H_3PO_4). The concrete was soaked in this acidic solution for 28 days. Tests were performed on the soaking tank every day to confirm that the pH of solution was maintained at 5. Reinforced concrete beams were immersed in acidic pH. The dimensions of each beam were 150 × 200 × 1200 mm, containing one ø12 mm reinforcing steel with a concrete cover difference in 20 mm (Fig. 1), 30 mm, and 40 mm). It was intended to differentiate grades for cylindrical specimens as 25 MPa, 35 MPa and 45 MPa. Acid lastly, all the beams were kept for 28 days in acidic solution (Fig. 2). pH testing of acid solution prior to concrete specimen is dipped (Fig. 3). Besides, 150 mm diameter and a height of 300 mm cylindrical concrete specimens were also made and subjected into acidic pH solution for compression test results (Fig. 4).

The experimental program comprises the three point bending test at 28 days of age. The span of the reinforced concrete beams was 1200 mm, and they were simply supported at both ends with load applied at a central point. Loading was applied with a hand pump, hydraulic jack and load cell.

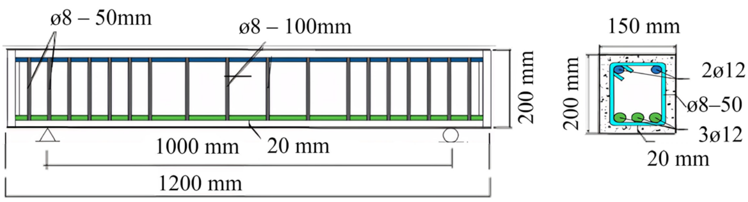

Fig. 1. Reinforced beam with a concrete cover of 20 mm

Fig. 2. Immersion process of concrete beams

Fig. 4. Immersion process of cylindrical concrete specimens

A rigid lateral load distributor was used to transfer the point load, and in this case, it functioned as a line load along the surface of the beams. The actuator position was obtained with a linear variable differential transducer (LVDT), the strain in the reinforcement was measured from a single long gauge bonded to one flanking and central longitudinal bar. Load data was acquired by a load indicator, displacement data has been recorded through a data logger and strain on the reinforcement was measured by using strain gauge.

Initially, a load of 50 kg is imposed to destroy the reverberations in the holding points and after this weight removal all meters are set at zero. The load was then increased slowly in 250 kg increments until failure. During each load stage, deflection and strain in the longitudinal reinforcement bars were recorded wherever possible. At each load stage, measurements of deflection using a USB digital microscope were made. The data of deflection was obtained and then recorded in the form of cracks digital images, which were analyzed by use Excel software.

Fig. 3. Measurement of pH levels

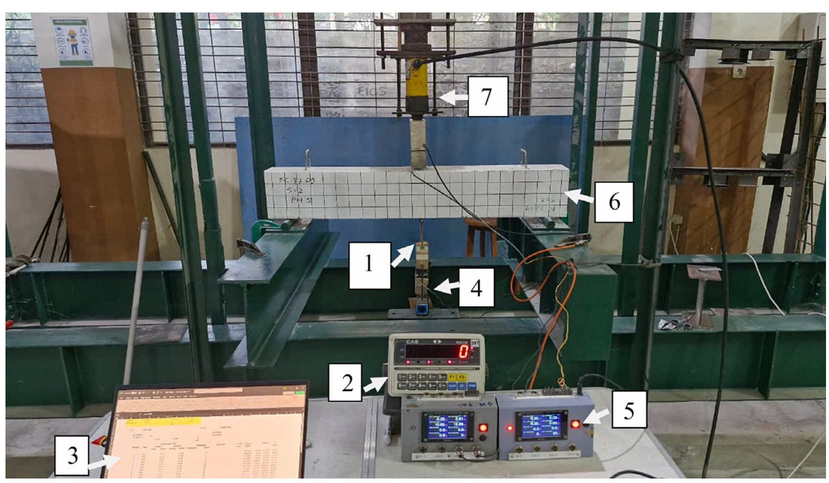

Fig. 5. Principal signature: 1 – load cell; 2 – crack detector microscope; 3 – laptop; 4 – LVDT; 5 – data logger; 6 – specimen; 7 – hydraulic

Fig. 5 describe the instrumentation to be used for measuring and tracking various important parameters during this test on reinforced concrete beams. The load applied on the reinforced concrete specimen is recorded by load cell (1) which is situated at top of test. Adjacent to it used for observation of the cracks developed during concrete beam testing another crack detector microscope (2) is also placed. The testing device is connected with a laptop (3) in order to record the data collected and an LVDT (Linear Variable Differential Transformer) (4) arranged for deflection measurement of reinforced concrete beam. All test information such as load, deflection and strain is recorded by the data logger (5) The load is applied at the top of specimen by a hydraulic jack (7) and the tested specimen (6), i.e., reinforced concrete beam. It also allows measurement of compressive strength, deflection and crack propagation in reinforced concrete beams for testing.

5. Results of the variation of acid immersion and concrete coating on the crack width of reinforced concrete beams

5. 1. The effect of immersion in acidic pH on the compressive strength of concrete

Fig. 6 showing the relationship between crack width of reinforced concrete beams versus steel stress on pH 5. The compressive strength of concrete is 36.94 MPa, the thickness of cover was maintained at 30 mm Variants were also made on the stress values of steel at 200 MPa, 253 MPa.

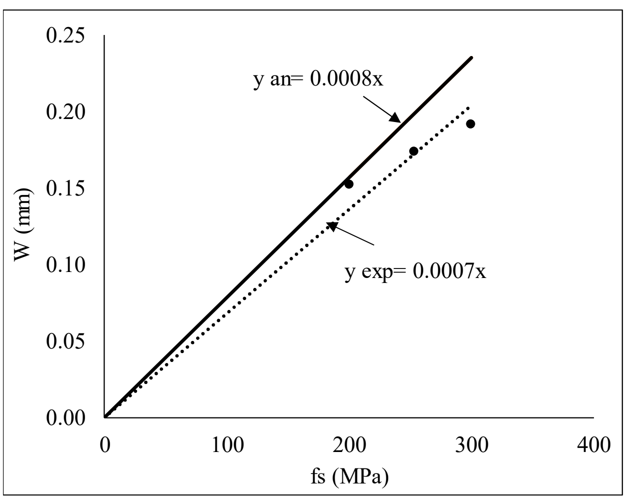

Fig. 6. Effect of steel stress (*fs*) on crack width (*w*)

Fig. 6 illustrates the steel stress on crack width. In the theoretical curve, $y_{an} = 0.0008x$, which means that for each MPa of stress in steel, a crack width deepen by 0.0008 mm) On the other hand, for the experimental curve as used $y_{exp} = 0.0007x$ means that increasing stress in steel by 1 MPa only increase crack width of about 0.0007 mm. The experimental line has a slightly lower slope than the theoretical prediction, which suggests that the effect of steel stress on crack width was somewhat less in practice compared with theory. The width of the crack in theoretical curve is equal to 0.24 mm when steel stress is 300 MPa, and its value on experimental curves occur at around 0.21mm, indicating a large difference between two values (even though both come back an increase level).

Meanwhile, Fig. 7 shows effect of concrete compressive strength on the relationship between crack width in reinforced concrete beams.

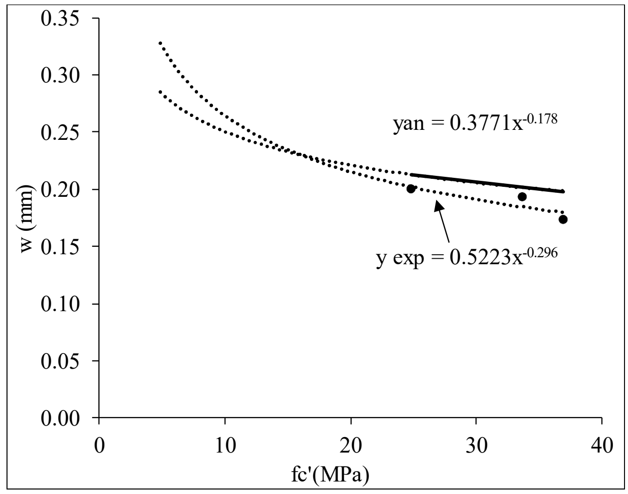

Fig. 7. Effect of concrete compressive strength (*fc*) on crack width (*w*)

Fig. 7 shows relation between compressive strength (fc) and crack width (w). Theoretical curve, formula $y_{an} = 0.38x^{-0.178}$, it is seen that when the concrete compressive strength increases, crack width decreases, like in the case of fc = 30 MPa, where crack width predicted by theoretical model is around 0.17 mm. Whereas, the experimental curve that passes through the raw data points. It is best represented by line with equation $y_{exp} = 0.52x^{-0.290}$ makes a slightly larger prediction. At a compressive strength of 30 MPa, the experimental model predicts an approximately 0.18 mm crack width. This difference means that the experimental model is more sensitive to changes in concrete compressive strength than the theoretical. As a whole, the experimental and theoretical models both point that increasing concrete compressive strength will decrease crack width, but has very steep drop with sub-linear power in regard to two preceding statements based on their overall proposed equations.

5. 2. The influence of immersion in acidic pH on the crack width of reinforced concrete beams with varying concrete cover

Fig. 8 shows the relationship between the width of fissure on the surface of reinforced concrete beams and concrete coverage at pH = 5 The steel stress 253 MPa and the concrete compressive strength was set at 36.94 MPa. The concrete cover was 20 mm, 30 mm and 40 mm to assess the structural performance.

The results of subsequent analysis are presented in Fig. 8, the formulas given by ACI 318-89 (1990).

Fig. 8 exhibited that the elastic crack width (w) of reinforced concrete beams with different dc can be described by one regression equation (1)–(3), equation (1) for JSCE model, equation (2) for ACI model and Equation (3) based on this study results have been summarized as follow [10, 11]:

$$Y_{JSCE} = 0.014dc^{0.78}, \quad (1)$$

$$Y_{ACI} = 0.022dc^{0.67}, \quad (2)$$

$$Y_{exp} = 0.016dc^{0.69}. \quad (3)$$

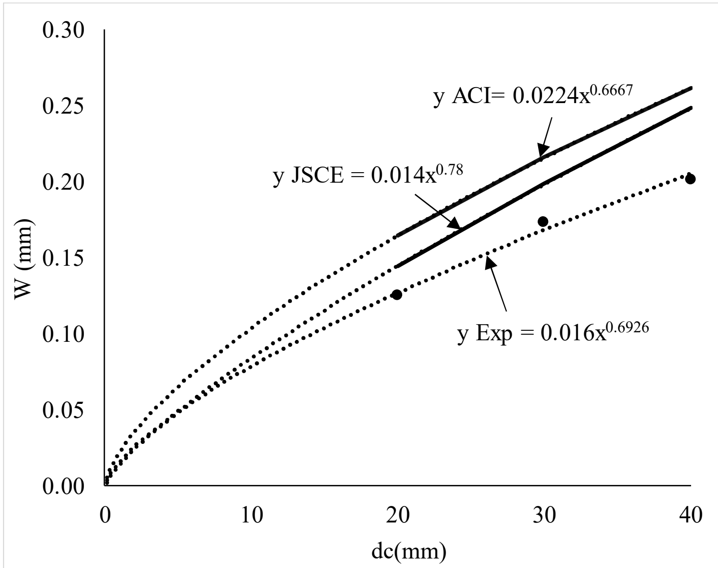

Fig. 8. Crack width (*w*) versus concrete cover (*dc*) based on two codes and experimental results

Equation (1) represents the model of JSCE: a power law, which exponent is 0.78, linking crack width with concrete slab thickness, equation (2) stands for ACI model in which the link would include instead an exponent equal to 0.67. Where an exponent of 0.69 was used to describe the experimental results. The actual data for the three proposed models indicate that all of them show some degree of a direct function relationship between concrete slab thickness and crack width.

5. 3. The relationship between acidic pH and compressive strength

Compressive strength test result depending on the period of time submerged with acid pH results of testing with concrete soaking at 7, 14 and 28 days.

Fig. 9, testing results are related directly with the concrete compressive strength (*Fc*) and then corresponds with a specific class of concrete resistance in MPa. This is true as the 7 days equation ($y = -12.44x^2 + 57.51x - 15.96$) reveals that up till this time, concrete holds very low compressive strength at initial hydration stages, then 7-day compressive strength predicted will be ~151.3 MPa, For 14 days, ($y = -11.43x^2 + 52.86x - 18.71$) is the equation that can be used, which means after each more day from the first week up to now, cement hydration has continued and it's rate decreased accordingly – causing again higher concrete strength compared to yesterday because of stars in a line behavior. For instance, if one is looking for a concrete strength class of 30 MPa; the predicted compressive strength at 14 days produced approximately having more than ten times as strong in compression. With 28 days ($y = -10.56x^2 + 47.37x - 16.98$) and the concrete has already achieved near optimal compressive strength at this age where a predicted ultimate tensile strength of around 1,400 MPa.

This prediction suggests that the increase in compressive strength from 7 to 28 days takes a decrease at around 14 days, hence indicating after some time the contribution of this same later diminishes and thus it does not continue rising over time. Therefore, giving predictions of how concrete reaches its ultimate compressive strength at later age as well and to what extent it will be closing up on its 28 days strength potential. The relationships among concrete strength class (MPa) and the compressive strengths of concrete sample cube test for 7 days, 14 days as well as at an age of 28 days. This relationship follows a quadratic regression equation for each age. The concrete compressive strength increased with increasing the level of class properties, especially at 28 days.

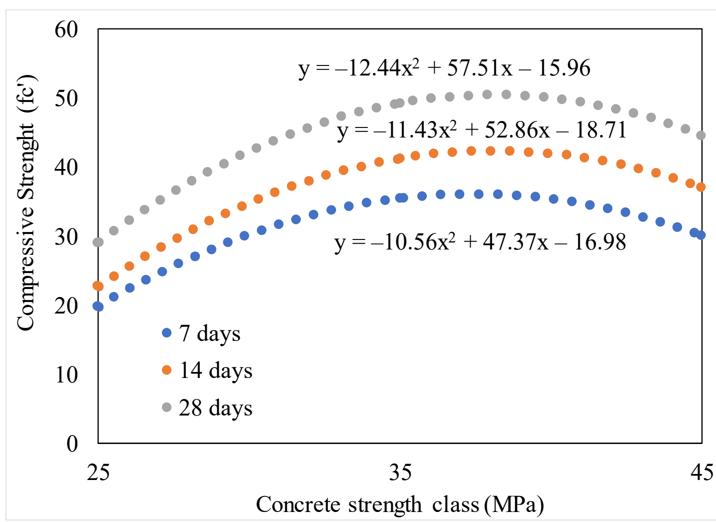

Fig. 9. Relationship between concrete strength class and concrete compressive strength after 7, 14, and 28 days of immersion in acidic pH

6. Discussion of the variation of acid immersion and concrete coating on the crack width of reinforced concrete beams

Fig. 6 shows the crack width in reinforced concrete beams is directly proportional to steel stress. The width of crack become larger then higher stress. This is in accordance with previous studies that have demonstrated the impact of steel stress on deformation behavior in reinforced concrete [12, 17] and where higher level of steel-stress causes a more serious crack width enhancement within specimens. However, the increase in steel stress increases crack width at early ages and is reduced because of aging concrete as well as other effects (moisture history and temperature). The results indicated that the environmental effects were more critical in controlling cracking behavior of reinforced concrete than steel stress.

The greater thickness of the concrete protective layer also has been demonstrated to decrease steel stress effect upon crack width [13, 14]. The results imply that higher protective thickness can lead to slower crack propagation. At the same time concrete and steel material types are being investigated to have influence on cracking. Steel stress is used as the only external factor causing crack width, but steel with higher strength can in some cases result in lower crack width since it undergoes increased strain despite receiving greater stress.

Fig. 7 shows variation of crack width in reinforced concrete beams and the compressive strength of concrete This means that if the concrete is stronger and less likely to crack, it will reduce cracking when subjecting to internal or external loading resulting in increased durability and performance of reinforced concrete structures. Whereas the comparison of experimental results with theoretical model represents minor deviation and hence reflects actual scenario when compared to predictions made by the model.

This study corroborates the conclusion that crack width of reinforced concrete is influenced by tensile strength as seen in previous literature on effect compressive strength [15, 16].

The same results were observed in other researches, which emphasize the fact that a higher strength leads to smaller crack widths and it increases structural safety as well – what may offer an extension of the lifespan for reinforced concrete [17].

Fig. 8 presents the crack width, due to flexural failure in RCC beams and concrete cover thickness (dc) for pH 5. For instance, concrete cover thickness and crack width have a positive relationship (i.e., the thicker the concrete cover is, the less wide cracks can be produced.) This is predicted by the equation established in ACI 318-89 (1990) based on the JSCE and ACI models as well as experimental results. These equations clearly indicate that there is direct proportionality between the crack width and concrete cover thickness but with different powers. In the JSCE it is 0.78, where in ACI – 0.67 and experimental results – 0,69.

Fig. 9 shows relationship between concrete strength class and compressive strength at 7, 14 and 28 days. Every age of concrete that is exposed to moisture will have its own quadratic equation linking strength class and compressive strength at different ages. The higher the class of strength, this greater compressive strength can be achieved which also demonstrates an increase at 28 days age as well showing that time curing is a function for hardening concrete.

The quadratic equations indicated at 14 and 28 days of age, the increase in compressive strength of concrete was more prominent compared to seven-day-old concretes. In the concrete ages, it slows down some once a certain point is reached and mathematically its known as kind of asymptotic. This is an agreement with the higher strength development at 28 days, which was greater than that after seven days of concrete curing.

Moreover, it can cause great harm to the quality of concrete by changing its pH to acidic. Reinforcing steel corrodes from the low pH (acidic) environment and it further deteriorate a concrete structure by increasing cracks. The phenomenon also reduces the compressive strength of a concrete. The lower the pH, or the more acidic environment of concrete, an increased rate corrosion and degradation steel consequently reducing compressive strength. Therefore, the inverse relationship between acidic pH and concrete compressive strength is reasonable to be defined as decreased in acidic pH will negatively affecting on the reduction of its long-term compressive strength, more particularly if a concrete against an acid environment for extended period.

The novelty of this technique is in proposing a benchmark based on different standard codes (i.e. JSCE, ACI) to compare the predicted crack width with experimental data that gives an idea about how good and real were our model predictions. This is consistent with the reported positive correlation between concrete cover thickness and crack width [18]. Nevertheless, the discrepancy in exponents between models demonstrates that additional variables are factors to consider determining how protective thickness affects crack width (e.g., concrete type or construction method). This study is also consistent with the conclusions of other research, which has claimed that an appropriate concrete protective thickness can contribute to a reduction in crack formation in reinforced concrete beams [19]; however, some could argue that it critically depends on construction conditions and material properties.

This study has a limited variation regarding the value of concrete cover thickness to only three values and environmental influence (temperature and humidity) that can change properties which would affect concrete were not considered. Follow up research could continue testing under limited environmental variations and other concrete formulations to arrive at more universally applicable results.

In reality, concrete is one of those substances that are in contact with acids for years and then some more; this study lasted just about four weeks. It will be interesting for future work to employ immersion times ranging from days up to several weeks, and acids other than HCl in order to explore various environmental conditions.

7. Conclusion

1. This study has shown that the application of acid immersion with pH is reduced 0.5 the concrete compressive strength and widening cracks on reinforced beams. The higher the steel stress is obtained, which should be 200 MPa to begin with and increase up until all specimens fail due to concrete crushing, causing a drop in both its tensile strength and width of cracking measured from the median split on either side 15%–40% for each additional MP being used as reference point.

2. In many cases the thickness of the concrete layer also affects how wide a crack can be. Deeper covers reduce crack width, and a 40 mm cover results in the lowest cracking when compared to a 20mm cover or even a thickness of only 30 millimeters showing good correlation between depth and control over cracks.

3. Low pH increases the rate of steel corrosion, resulting in more cracks and lower hardness. The loss of compressive strength is more pronounced after 28 days and long-term exposure to acid may result in a significant reduction in the strength.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Faris Rizal Andardi: Data Curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft; **Agoes Soehardjono:** Conceptualization, Supervision, Writing – review & editing; **Wisnumurti:** Conceptualization, Supervision, Writing – review & editing**; Ari Wibowo:** Conceptualization, Supervision, Writing – review & editing.

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