Reka Buana : Jurnal Ilmiah Teknik Sipil dan Teknik Kimia, 9 (1), 2024, page 41 - 54

Tersedia *online* di https://jurnal.unitri.ac.id/index.php/rekabuana

ISSN 2503-2682 (*Online*)
ISSN 2503-3654 (Cetak)

Shear Capacity on Corroded Fly Ash Reinforced Concrete Beam Using Galvanostatic Method

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ARTICLE INFO

Article history
Received : 12 January 2024
Revised : 29 March 2024
Accepted : 04 April 2024
Available Online : 18 April 2024
Published Regularly : March 2024

DOI :
https://doi.org/10.33366/rekabuana.v9i1.5577

Keywords :
corrosion; fly ash; galvanostatic method; reinforced concrete beam; shear capacity

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UNITRI PRESS
Jl. Telagawarna, Tlogomas-Malang, 65144, Telp/Fax: 0341-565500

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ABSTRACT

Corrosion can be triggered by a chemical reaction to the materials, establishing reinforced concrete's failure. For a long time, researchers have tried to find out how to prevent corrosion, a main structural construction issue. As a technology of waste material, fly ash has predominance, i.e., it is safer and greener than Portland cement. The finer size of fly ash can be an advantage in filling the concrete materials well. This research is about using fly ash as supplementary material on reinforced concrete beams and the galvanostatic method to accelerate corrosion. This research will compare the shear strength after corrosion of each normal beam and fly ash as a supplementary beam. A shear test of fly ash and a normal reinforced beam has been applied. Results showed that fly ash beams have 14% higher compressive strength and 3% higher shear strength with 14% smaller crack width than normal beams after corrosion. It also has a 3,5 times lower rate and 62% level of corrosion than normal beam.

Cara Mengutip : Mooy, M., Manubulu, C. C., Bees, A., Bela, K. R. (2024). Shear Capacity on Corroded Fly Ash Reinforced Concrete Beam Using Galvanostatic Method. *Reka Buana : Jurnal Ilmiah Teknik Sipil dan Teknik Kimia,* 9(1), 41-54. doi: https://doi.org/10.33366/rekabuana.v9i1.5577

1. INTRODUCTION

Corrosion is one of the main attacks that can cause mass loss of reinforcement due to electrochemistry reaction on reinforced concrete. When the appearance of corrosion begins, it can hardly be visually monitored in a short time unless a crack or spalling of the structure happens. Due to the flexure load, a crack occurred in the transverse direction in the incubation phase, so chloride ions could be quickly absorbed into the beam [1]. When this happens, reinforcement as an anode without protection will have a chemical reaction and be damaged by chloride ions. Sahmaran *et al.* [2] found that crack width on reinforced concrete is 0.48 mm when there is a 5% mass loss and increases to 4.92 mm when there is a 15% mass loss of reinforcement due to corrosion. It means that crack width enhancement can increase mass loss percentage along with the emersion of corrosion.

When the load is applied on reinforced concrete until the crack is formed, there is a linear pattern followed by the crack of deflection – load correlation nonlinearly. Crack occurs when tensile strength is smaller than tensile stress and will affect the durability of concrete, even establishing whether flexure or shear failure is enhanced [3]. However, continuous diagonal patterns by shear crack can involve shear failure without concrete crack. Whereas Z – crack will be the pattern on concrete when it has cracked. Thus, it will prevent diagonal crack propagation to produce higher shear strength on concrete without precrack [4].

Research about reinforced concrete with pre-crack is conducted to determine the effect on concrete flexure and shear capacity. If the crack width by reinforcement corrosion is about 0.005 to 0.2 mm [5], then the pre-crack width must be smaller than 0.35 mm due to the maximum crack of 0.55 mm [6]. Some results from the experiment were given by Siad *et al.* [7] about 60% maximum load are 0.3 mm pre-crack width, 15% corrosion rate, and 8.7% ultimate load lower than concrete beam without precrack. Hence, it proves that the greater the pre-crack and corrosion rate on reinforced concrete beams, the greater the load reduction.

Galvanostatic is a method to accelerate corrosion on reinforced concrete. It uses small amplitude, short electric current anode interval, and electrodes on concrete surfaces to analyze reinforcement potential [8]. Galvanostatic can be defined as an electrical method from the power supply to the reinforcement as anode and stainless as the cathode in a NaCl solution mediator. When using this method, temperature, and humidity are the important factors that are noticed. The need for an artificial climate with 40°C temperature and 80% humidity in a continuous 5% NaCl wetting–dry cycle was researched by Yuan, 2007 [9]. It used wetting – dry in one hour and infrared in seven hours with a stainless steel bar as a negative pole to conduct electric current. The result shows that corrosion appeared in three months with a 0.8 mm crack width on reinforced concrete.

Shear failure is an issue of construction that can not be perceptibly and calculated accurately [10]. Various calculation methods to predict shear failure in structures, such as reinforced concrete beams, inflict differences with direct observation. This happened due to internal mechanisms, e.g., effective depth (d), the longitudinal strain amount, and the beam's crack level. Cracks on beams with longitudinal and transversal reinforcement are uniform, and loads are in triangle truss form, where compression (strut) is made of concrete and tensile (tie) is made of steel reinforcement. Shear compression failure can occur when shear span and effective depth ratio $1 \leq a/d \leq 2.5$ for pointed load and span-effective depth ratio $(Ln/d) > 6$ for uniform load [11].

Fly ash has been produced since the 1920s, and its primary components are silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium (CaO), with varying amounts of carbon per measurement using loss on ignition (LOI) [12]. It was even significantly used in concrete (for example, USBR 1948) following the pioneering research at the University of California. It grew dramatically, with almost 15 million tons used in concrete products in the last 50 years [13]. Fly ash has been used as a supplementary material at levels ranging from 15% to 25% by mass of the cementitious material. Fly ash has been proven to increase shear capacity and be safer than Portland cement [11]. Mooy *et al.* [12], with the research about the shear capacity of fly ash and normal beam, demonstrated that the shear capacity of the fly ash beam was higher than the normal beam due to compression strength, and the crack width was smaller than the normal beam. This research is about to assess the shear behavior of two kinds of concretes, normal beam and supplementary beam, using fly ash based upon the common issue of brittle and sudden without warning shear failure due to the disturbed region with weak tensile. As a supplementary material, fly ash has been proven to improve concrete's durability and structural performance [14]. However, the previous research explained the combination of fly ash and other materials such as geopolymer [15], mineral soil, petrasoil [16], fiber [17], etc. In contrast, this research compares the shear strength after the corrosion of a fly ash beam with that of a normal beam. This will be an additional excuse for the advantage of using fly ash as supplementary material.

2. RESEARCH METHODS

The test specimens of this research used a normal beam and 20% fly ash class F as a supplementary beam. The two beams use the same dimension with 20 bars of transversal reinforcement, two bars of compression reinforcement, and three bars of tension reinforcement (figure 2). A cable to conduct electric current was placed on longitudinal reinforcements, and a strain gauge to measure strain was placed on transversal reinforcement in the region of interest. After the preparation of tools and materials, the analysis of materials for each beam based on ASTM will be the excuse for the materials used. The tensile properties of reinforcing bars are available in Table 1. The mix proportions had a cement ratio (w/c) of 0.3 and Portland cement Grade 42.5 used for the two beams referred to as CEM I 42.5 R-NA in DIN 1164 [18].

A compression test was used in a cylinder 10 x 20 cm before the shear test to determine the compressive strength of each specimen (table 2). The fabrication of specimens used a 150-liter pan mixer and a vibrating poker to compact the fresh concrete during casting. Afterward, the specimens were regularly wetted with normal temperature water 20 – 30°C during the curing period to ensure the availability of water hydration [19].

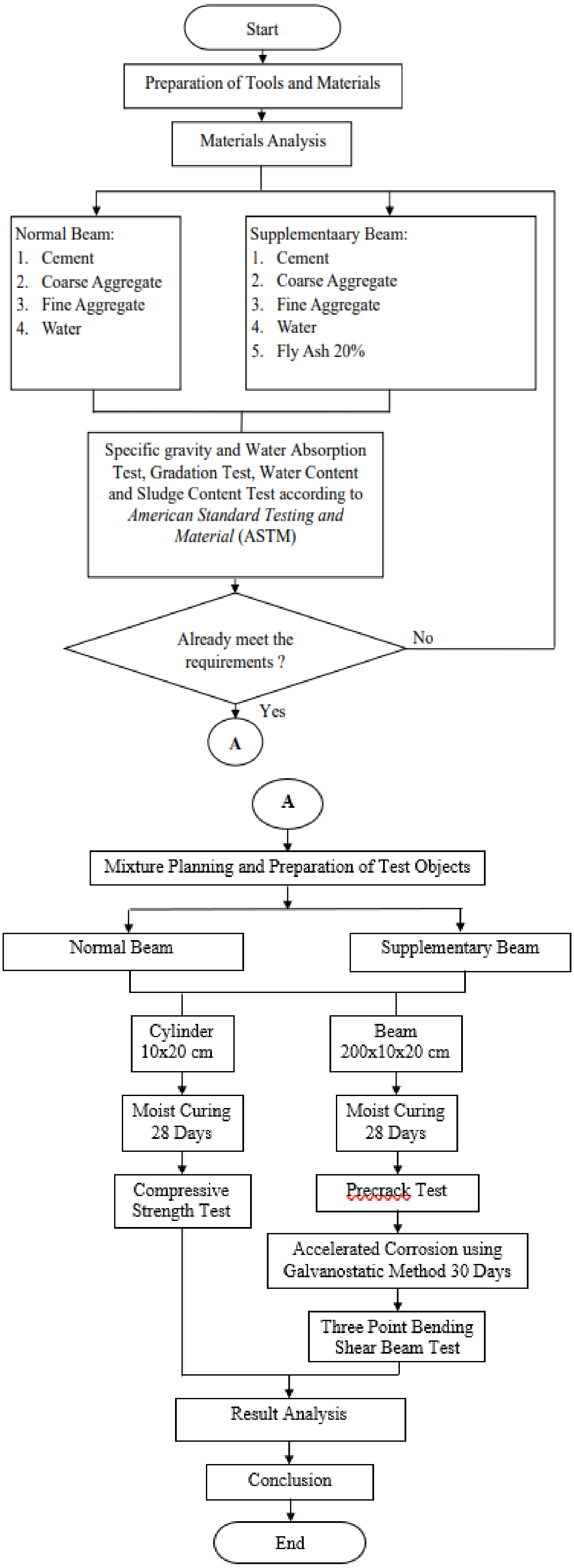


Figure 1. Flowchart of research

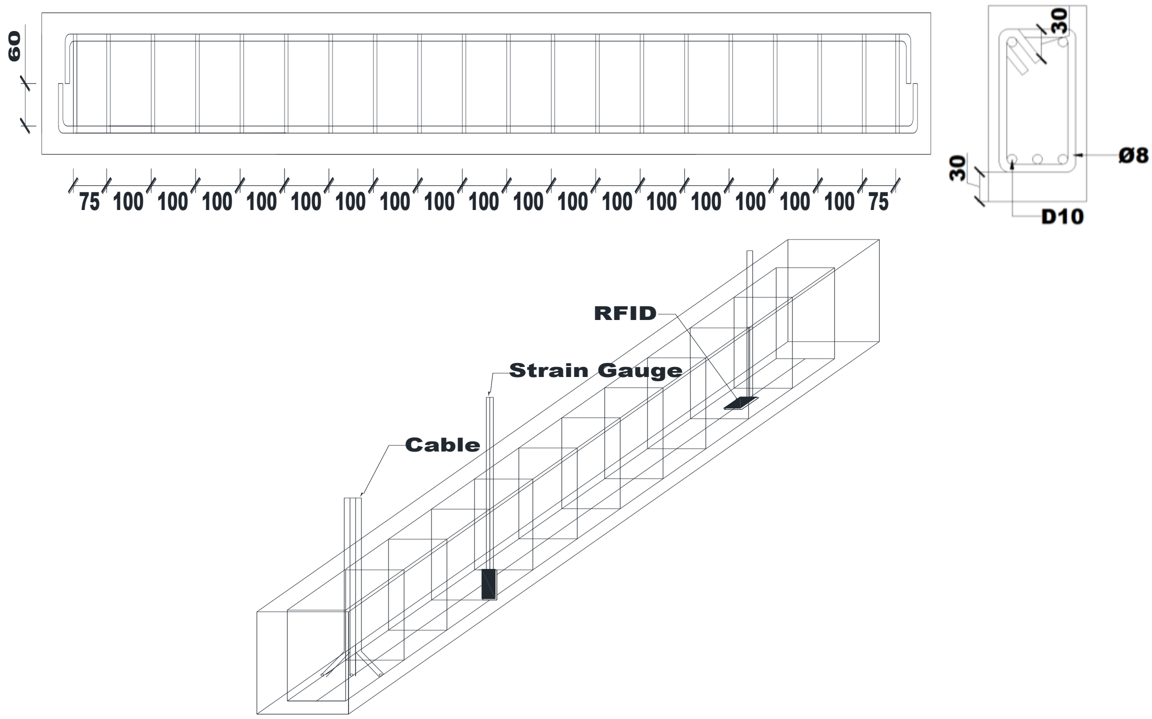


Figure 2. Details of beam geometry and test setup

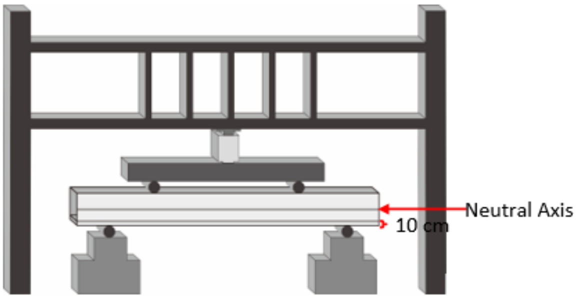
Table 1. Tensile properties of reinforcing bars

Reinforcements (mm)	Area (mm^2)	Yield Strength f_y (MPa)	Ultimate Strength f_u (MPa)	Modulus of Elasticity E_s (GPa)	Ultimate Strain, ε_s (%)
ø 8	50.3	405	551	1.1	15.8
D10	78.5	484	618	1.4	10.3

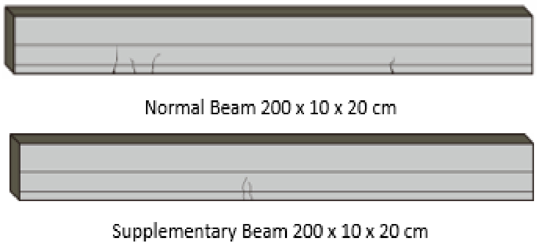
Table 2. Compressive strength of 10 x 20 cm cylinders

Beam	Mean (MPa)	Standards of Deviation (MPa)	Coefficient of Variation
Normal	45.9	9.6	21.1
Supplementary	53.1	7.6	14.4

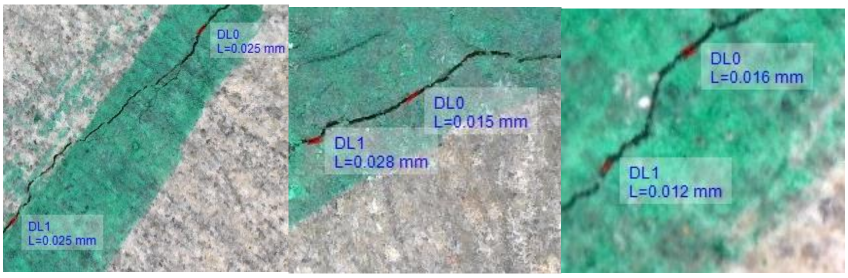
After curing time, precrack will be applied on beams (figure 3). The setup of the prerack used four four-point bending methods with two points of load. Before the load was applied, the front surface of the beam was signed on a neutral axis and 10 cm from the bottom of the beam. Beams were observed every 50 kg or 0.5 kN, and cracks were marked with a color marker. The load will be stopped when the crack is in the middle of the neutral axis and the bottom of the beam. Cracks that bore the beam were measured by a digital microscope (figure 3). It is known that the precrack load was 17.69 kN for the normal beam and 19.55 kN for the supplementary beam. Meanwhile, the result shows that the normal beam bore more cracks than the supplementary beam. The average crack width on the normal beam was 0.020 mm, and the supplementary beam was 0.018 mm. It means that the two beams' load, crack amount, and crack width are not significantly different.



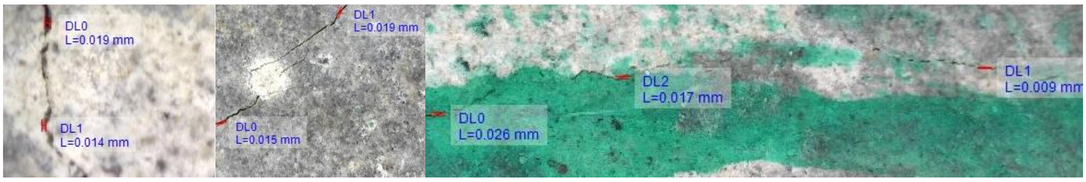
a) Setup of pre-crack



b) Galvanostatic method



c) Crack width on the normal beam



d) Crack width on the supplementary beam

Figure 3. Precrack test of beams

Furthermore, galvanostatic after precrack test was used for corrosion testing, i.e., beams were placed in a holding tank filled with 3.5% NaCl on a 3 cm high (figure 4). A wood beam on the bottom of the concrete beam was used to ascertain the solvent wetting on the bottom side. Cables from the beams were connected to the power supply as positive poles, and cables from stainless steel were connected to the power supply as negative poles with 0.3 Amp electric current. The calculation shows that the corrosion rate category based on Table 1 was moderate.

Corrosion rate, corrosion level, and reinforcement time can be calculated using formulas 1 to 3. The corrosion rate can be found in the calculation of the weight of reinforcement, the actual mass after corrosion, and the current of the electrical system. The corrosion rate category is shown in Table 3 below.

$$CR = \frac{3600\ M_{ac}}{dAT} \qquad \text{.......}(1)$$

where:

CR = corrosion rate (mm/year)
M_{ac} = actual mass loss of reinforcement after corrosion (gr/cm^2)
d = reinforcement density (7.85 gr/cm^3)
A = reinforcement area (cm^2)
T = corrosion time (days)

Reinforcement area:

$$A = (\pi DL)\left(2x\frac{1}{4}\pi D^2\right)$$

$$A = (3.14x1x200)\left(2x\frac{1}{4}x3.14x1^2\right) = 629.57cm^2$$

The initial weight of reinforcement:

$$W_i = \left(\frac{1}{4}\pi D^2\right)\rho L$$

$$W_i = \left(\frac{1}{4}x3.14x1^2\right)x7.85x200 = 1232.45\ gr$$

Weight of reinforcement after corrosion:

$$W_f = W_i - \left(\frac{\gamma W_i}{100}\right)$$

$$W_f = 1232.45 - \left(\frac{20\ x\ 1232.45}{100}\right) = 985.96\ gr$$

Actual mass of reinforcement due to corrosion:

$$M_{ac} = \frac{\left(W_i - W_f\right)}{\pi DL}$$

$$M_{ac} = \frac{(1232.45 - 985.96)}{3.14\ x\ 1\ x\ 200} = 0.39\ {}^{gr}/_{cm^2}$$

An electric current of power supply:

$$I_{app} = \frac{M_{ac}\ F}{vt}$$

$$I_{app} = \frac{0.39\ x\ 96487}{27.93\ x\ 2592000} = 0.000523\ {}^{Amp}/_{cm^2}$$

$$I_{app} = AI_{app}$$

$$I_{app} = 629.57\ x\ 0.000523 = 0.33\ Amp\ \approx 0.3\ Amp$$

Corrosion rate:

$$CR = \frac{3600\ M_{ac}}{dAT}$$

$$CR = \frac{3600\ x\ 0.39}{7.85\ x\ 8.19\ x\ 30} = 0.73\ {}^{mm}/_{year}$$

$$\gamma = \frac{100\ (W_i - W_f)}{W_i} \qquad \text{...(2)}$$

where:

γ = level corrosion
W_i = reinforcement mass before corrosion (gr)
W_f = reinforcement mass after corrosion (gr)

Then, the level of corrosion known as 0,2%

$$t_{corr} = \frac{Q_{corr}}{j_r} \qquad \text{...(3)}$$

where:

t_{corr} = corrosion time (year)
Q_{corr} = corrosion amount when crack occur (x 10^{-4} gr/cm^2)
jr = corrosion rate immediately ($gr/cm^2/s$)

Table 3. Corrosion rate category

CR	mil/year	mm/year	µm/year	nm/hour	pm/second
Excelent	< 1	< 0,025	< 25	< 2,89	< 0,8
Very good	1-5	0,025-0,1	25-100	2,89-10	0,8-4,0
Good	5-20	0,1-0,5	100-500	10-50	4-16
Moderate	20-50	0,5-1,0	500-1000	50-150	16-40
Poor	50-200	1-5	1000-5000	150-500	40-161
Very poor	> 200	> 5	> 5000	> 500	> 161

Jones, 1996 [20]

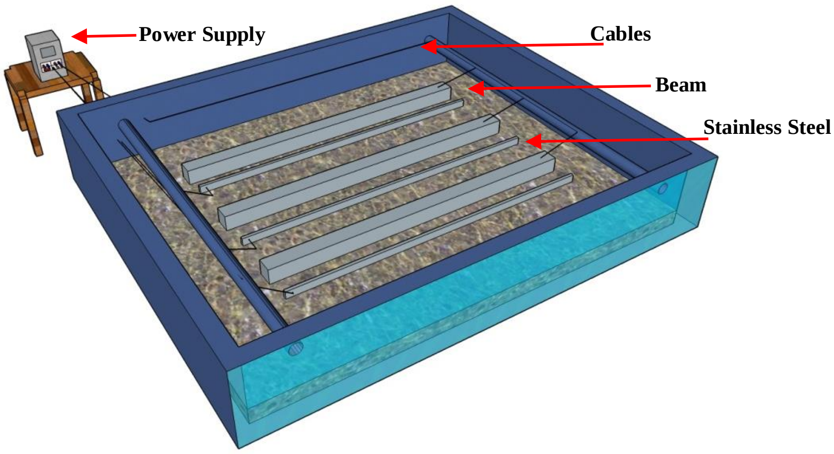
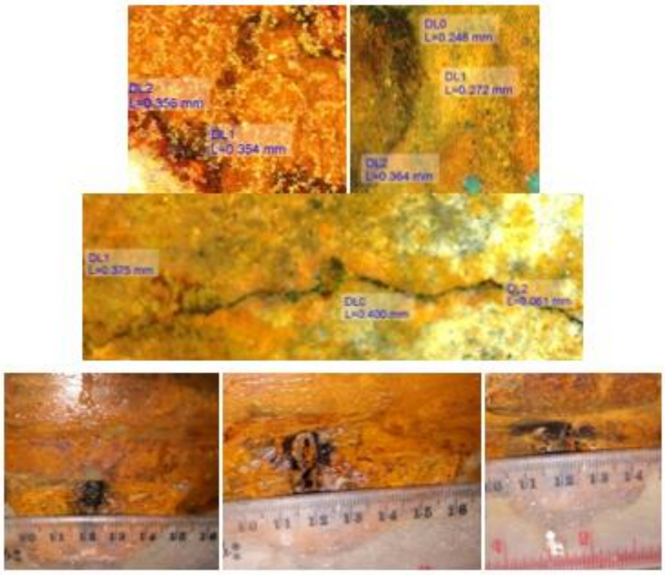
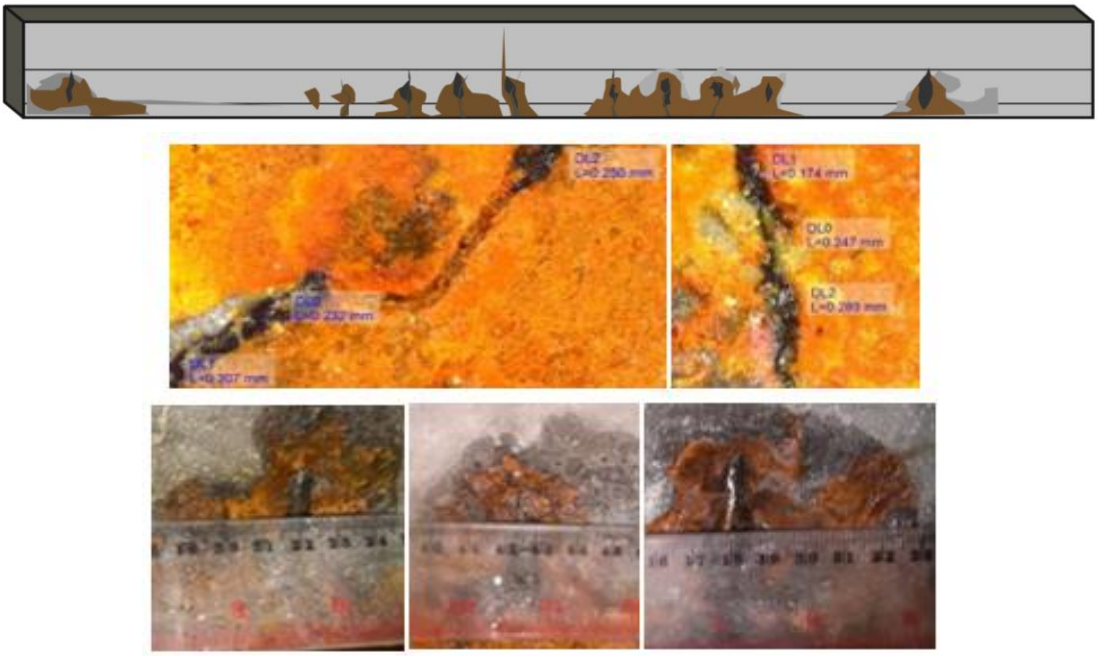


Figure 4. Setup of galvanostatic method

After 30 days, the beams were placed In a holding tank with 3.5% NaCl and 0.3 Ampere electric current. The beams were measured about crack width using a digital microscope. The result shows that the average crack width of the normal beam was 0.35 mm, and the average crush width was 47.00 mm. The average crack width of the supplementary beam was 0.23 mm, and the average crush width was 44.17 mm. This proves that the crack width after the corrosion of the supplementary beam was smaller than that of the normal beam. This can be the consequence of precrack showing the same thing. The crack width on each beam is in Figure 5.



(a) Normal Beam 200 x 10 x 20 cm



(b) Supplementary Beam 200 x 10 x 20 cm

Figure 5. Cracks on beams after corrosion

3. RESULTS AND DISCUSSION

Shear Strength and Crack Width

The shear test after corrosion used a three-point bending method (figure 6). The load that bore the loading cell was placed in the middle of the beam, and supports were placed 31.50 cm from the load to the left and right. Hereafter, a linear variable differential transformer (LVDT) was placed beneath the beam at the center to obtain deflection. It is known from the load cell and LVDT data that the supplementary beam produced 97 kN load and a normal beam 94 kN after corrosion (figure 7). It was about 3% load of supplementary beam higher than normal beam. Deflections of the supplementary and normal beams were 4.56 cm and 4.42 cm, similar to the load produced by each beam. This can be the explanation of some previous research that fly ash can be the supplementary material that has strength as well as cement due to the content of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium (CaO), with varying amounts of carbon per measurement using loss on ignition (LOI). In addition, the size of fly ash, which is finer than cement, can be an excuse for its porosity and ability to prevent corrosion.

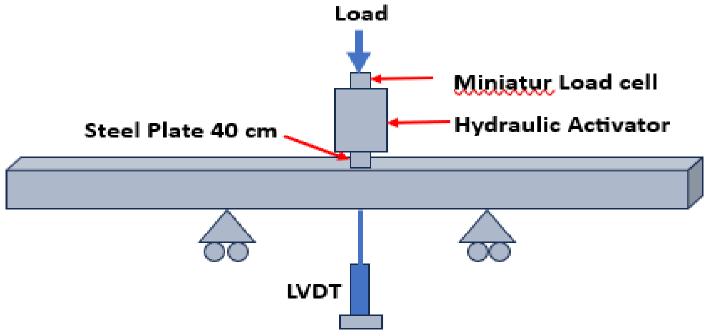


Figure 6. Setup shear test

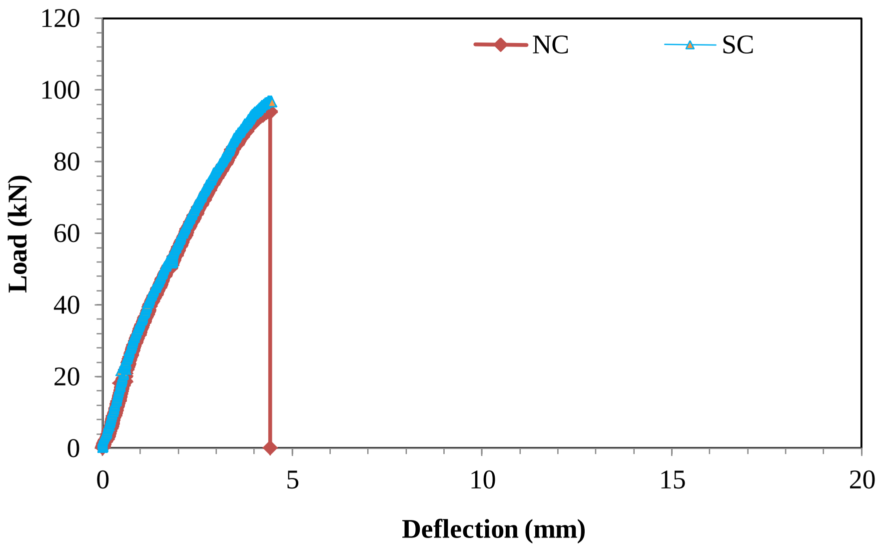
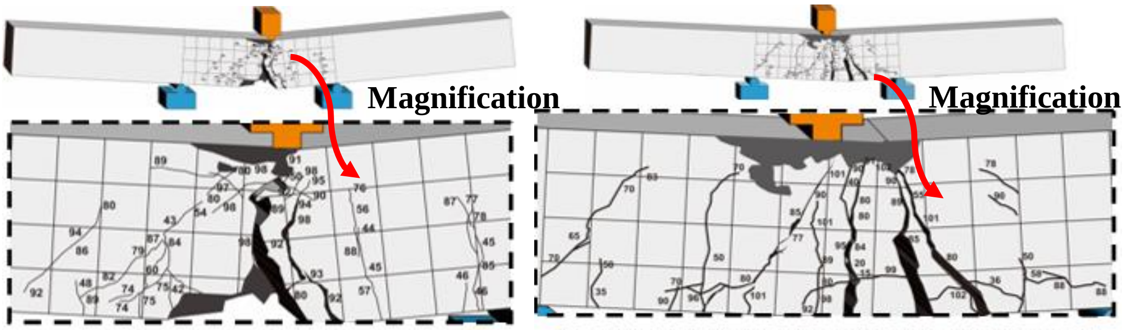


Figure 7. Load–deflection relationship

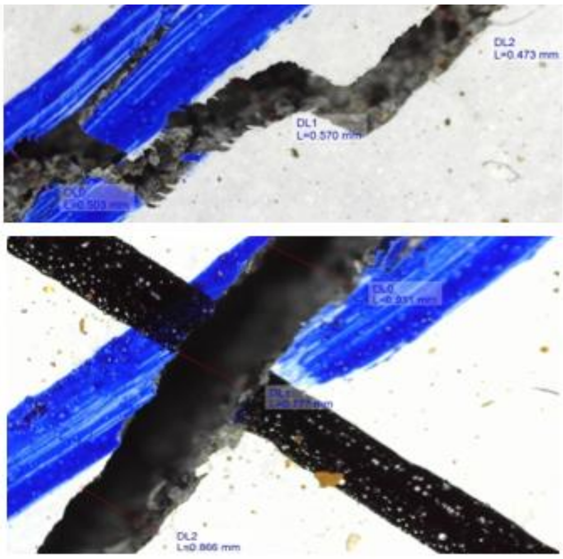
From the shear test result, both beams have diagonal shear cracks that begin from support to the load conversely (figure 8). Normal beam has excellent crushes in the middle above to the bottom, and supplementary have smaller crushes near the support. The result also suggests that the shear strength and delaying the occurrence of brittle shear failure by transverse reinforcements. Moreover, using fly ash as a supplementary concrete material did not alter the structural performance behavior.



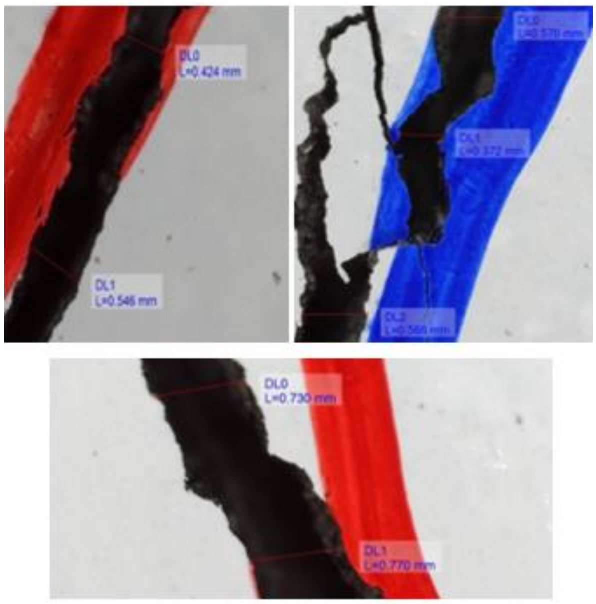
(a) Normal Beam 200 x 10 x 20 cm After Shear Test (b) Supplementary Beam 200 x 10 x 20 cm After Shear Test

Figure 8. Crack pattern after shear test

Based on the observations by a digital microscope, the average crack width after the shear test of the normal beam was 0.7 mm and 0.6 mm on the supplementary beam (figure 9). There was an insignificant result for both beams.



(a) Normal Beam Crack Width



(b) Supplementary Beam Crack Width

Figure 9. Crack width of beams after shear test

Reinforcement Corrosion

Beams were investigated after a demolition breaker broke the shear test to observe the reinforcements' corrosion. Each longitudinal and transversal reinforcement was cut 60 cm and pondered. Furthermore, the reinforcements were cleaned using rust combat liquid to remove corrosion and pondered. The results were compared to the mass loss of reinforcements. The result shows that the mass loss of the normal beam's transverse reinforcement was 0.0072 gr, and the supplementary beam was 0.0026 gr. The mass loss of longitudinal reinforcement of the normal beam was 0.0130 gr, and the supplementary beam was 0.0053 gr. It can be proven that the finer aggregate size of fly ash filled and established bond strength with the other materials is better than the normal beam.

Table 4. Corrosion rate, corrosion level, and corrosion time of reinforcements

Beam	Diameter (mm)	Corrosion Rate (mm/year)	Corrosion Level (%)	Corrosion Time (year)
Normal	Ø8	0.0219	3.37	34
	D10	0.0246	3.60	43
Supplementary	Ø8	0.0079	1.27	34
	D10	0.0101	1.54	43

Table 4 shows the corrosion rate, corrosion level, and corrosion time for reinforcements using formulas 1 to 3. It can be concluded whether longitudinal and transversal reinforcements in the supplementary beam have a corrosion rate and corrosion level lower than the normal beam. However, it has the same corrosion time as supplementary beam reinforcements. This can prove that fly ash can be a supplementary material with corrosion resistance.

4. CONCLUSION

The conclusion drawn from this research is that fly ash can be an alternative to concrete supplementary material due to its corrosion resistance being better than that of the normal beam. With finer aggregate size than Portland cement, it can produce about 14% smaller crack width and crush on concrete. In addition, fly ash's corrosion rate and corrosion level as supplementary material are about 3,5 times and 62% lower than normal concrete materials. Fly ash, such as waste material, is green and safer and has not altered structural performance behavior, though it will be a better innovation in the technology of structural material. Furthermore, the galvanostatic method can be the choice to determine corrosion rate, corrosion level, and corrosion time with an accurate calculation.

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