Corrosion permeability resistance of concrete with nanoplastics as admixture

Peter P. K. Yalley

Abstract: This study was conducted to ascertain the effect of nanoplastics on corrosion permeability resistance of concrete. Various percentages of nanoplastics ranging from 5% to 25% were used to replace cement in this study. The corrosion permeability resistance test and bond strength test were conducted in conformity with BS EN 12,504–3:2005 and ASTC 1202, respectively. The results of this study depicted that specimen with 15% nanoplastics lost 40% of their bond strength from the zero corrosion stage to severe corrosion stage, while the specimens with no nanoplastics lost 90% of their bond strength. The addition of nanoplastics as an admixture to concrete provided an average range of 40% to 65% better corrosion protection than the plain concrete. The lower current reading of concrete specimens with nanoplastics compared to that of plain concrete signified the beneficial effect in using nanoplastics as an admixture in concrete to protect the reinforcing bars from corrosion. The study concludes that the initial lower current passing, lower current reading with prolonged time to reach the severe corrosion stage, smaller percentage loss of bond strength, mass and rib profile of concrete specimens with nanoplastics indicated higher resistance of the concrete with nanoplastics. The study therefore recommends that nanoplastics should be used as an admixture to concrete up to 15% replacement level.

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PUBLIC INTEREST STATEMENT
Industrial and agro waste are generated in large amount causing environmental problems. Among the waste materials, plastic poses the most common environmental issues in the contemporary world due to its non-biodegradable nature, making their disposal a big challenge. Estimated yearly production of plastics in the world is about 100 million tonnes. Nano-plastics are produced during recycling. One of the means of addressing the environmental hazards posed by accumulation of nano-plastics in the environment could be rigorous research to establish how nano-plastics would perform in concrete. Again, the economic use of nano-plastics as admixture in concrete would help to reduce the continuous and increasing demand of natural materials used for production of cement, hence reduce the release of carbon dioxide into the atmosphere due to the production of Portland cement. Therefore, the aim of this study is to assess the corrosion resistance performance of nano-plastics as admixture in concrete.
1. Introduction

Industrial and agro waste are generated in large amounts causing environmental problems. Among the waste materials, plastics pose the most common environmental issues in the contemporary world due to their non-biodegradable nature, making their disposal a big challenge (Zhou et al., 2014). Estimated yearly production of plastics in the world is about 100 million tonnes, and was estimated that 12 billion tonnes of plastics waste would be produced in the next 30 years (Greenpeace International Annual report 2019, 2020). Although there is a boost in efforts to recycle plastic waste, nano-plastics (tiny pieces of particle with sizes usually ranging from 1 to 100 nanometres) are ultimately produced during recycling. These tiny particles come with environmental concern due to their chemical and physical properties (Eerkes-Medrano et al., 2015). Nano-plastics end up in landfills and cause air pollution when burnt. This hazard to the environment needs to be mitigated. One of the means of addressing the environmental hazards posed by accumulation of nano-plastics in the environment could be rigorous research to establish how nano-plastics would perform in concrete. Therefore, the use of nano-plastics as building materials would help alleviate their associated environmental challenges.

The use of recycled plastic materials in conventional cement mortar and concrete has been researched into extensively. In the past, plastics were used in concrete mainly in two forms: (i) plastic aggregates (PA), which replaced natural aggregates and (ii) plastic fibers (PF), which were used in fiber-reinforced concrete (FRC). The properties of fresh and hardened concrete incorporating plastic materials were investigated in several previous studies (Pacheco-Torgal et al., 2012; Saikia & de Brito, 2012). However, some of the important properties of concrete, including its stress-strain curve, abrasion, corrosion resistance, creep, and carbonation, were not considered in the studies reported in (Pacheco-Torgal et al. 2012). Furthermore, the studies reported in Saikia and de Brito (2012) were limited to plastics as aggregates. The results of Juki et al. (2013) indicated that the flexural strength was reduced by 5% at 25% substitution level. Frigione (2010) reported the stress-strain relationship of concrete containing plastic waste as substitution for fine aggregate (FA) and the results were similar to those of conventional concrete. Roi et al. (2012) observed a very small reduction in flexural strength when the substitution level of plastic as FA was up to 15%. Akçaözoglu’u and Ulu (2014) also observed a decrease in the flexural strength with an increase in the Polyethylene terephthalate (PET) as FA at all substitution levels in alkali activated slag mortar. Marzouk et al. (2007), Suganthy et al. (2013), Ling (2011), Ohemeng and Valley (2013), and Ferreira et al. (2012) independently studied the physical properties of concrete when aggregate was replaced with waste plastic particles. The results of these studies supported the conclusion that the inclusion of waste plastics in the concrete reduced the density and performed poorly in compressive strength compared to the plain concrete. Further studies by Saikia and de Brito (2014) on abrasion resistance property of concrete when plastic waste was used as aggregate in concrete, concluded that abrasion resistance was improved in comparison to plain concrete. An enhancement in water absorption was observed when waste plastics were used as aggregate in concrete (Akçaözoglu’u et al., 2010; Albano et al., 2009; Marzouk et al., 2007; Saikia & de Brito, 2013; Silva et al., 2013). A study by Silva et al. (2013); Fraj et al. (2010) recorded an improvement of chloride ion permeability when PET was used as coarse aggregate to concrete.

Furthermore, some studies also reported on the use of PF on some strength properties of concrete. For example, Fraternali et al. (2014), Kim et al. (2010), Meddah and Bencheikh (2009), and Pelisser et al. (2012) reported a reduction in the compressive strength of concrete containing PF.

However, none of the previous studies provided any information about concrete containing plastic materials as admixture. The existing studies only considered the use of plastics as FA and PF but have not yet considered the use of micro or nano plastics, which are by-product of recycling.
of plastics wastes. Existing studies also concentrated on some mechanical and durability properties of concrete containing plastics, but disregarded corrosion resistance properties.

Recently, the aspects of durability performance of concrete have become a major subject of discussion, especially when the concrete is subjected to severe environmental conditions. Corrosion of reinforced steel is the main factor influencing both the concrete durability and strength (ACI 318–14, 2014). Among the factors that affect corrosion of steel is chloride ingress in concrete. The chloride permeability in concrete is one of the important properties that had been assessed using different agro and industrial wastes as admixtures.

Nano-plastics as concrete polymer is a relatively new development in the world of concrete technology and a lot of research must be conducted to ascertain the extent to which plastics waste affects corrosion permeability of concrete. The aim of this study is to assess the corrosion resistance performance of nano-plastics in concrete through the following objectives: examine the bond strength, evaluate the percentage mass loss and rib profile height loss after subjecting the concrete to chloride penetration. The scientific motivation of this research is to quantify the contribution of nano-plastics as far as the corrosion durability resistance of concrete is concerned. Again, the economic use of nano-plastics as admixture in concrete would help to reduce the continuous and increasing demand of natural materials used for production of cement, hence reducing the release of carbon dioxide (that is produced during the production of Portland cement) into the atmosphere.

2. Materials and methods

2.1. Materials

2.1.1. Cement and aggregate
Ordinary Portland Cement (OPC) from Ghana Cement (Ghacem) conforming to BS EN 197-1 (2011) was used. The fine aggregate was natural sand conforming to BS EN 197-1 (2011), while the coarse aggregate was crushed granite having a maximum size of 10 mm, which conformed to BS EN 12620: 2002+ A1 (2008).

2.1.2. Nanoplastics
Nano-plastics waste, a fallout from a plastic waste recycling plant (Accra Composite Plant, Ghana), was used as an admixture and conformed to BS EN 934–2:2009+ A1 (2012). The nano-plastics used are dust-like plastic waste particles that are generated during the recycling of waste plastics. They are usually disposed off at the landfills much of which are found in the environment causing air and water pollution. Scanning Electron Microscope (SEM) was used to determine the shape and the particle size distribution of the nanoplastics.

2.1.3. Water
Potable water was used for the preparation and curing of the concrete specimens. The water conformed to the requirements of BS EN 2002.

2.2. Preparation and testing of specimen

2.2.1. Mixing procedure
A total of 72 cylindrical specimens with cross sectional area of 100 mm² and height of 300 mm was prepared using concrete mix ratio of 1: 1.8: 2.8 (cement: fine aggregate: coarse aggregate) with water cement ratio of 0.55. The specimens were divided into six mixes by percentage weight fractions of the nanoplastics (NP) as an admixture to concrete. The specimens were cast for each of the mixes: NP0 (plain concrete) and NPX (i.e. specimens with X% of NP). The concrete was mixed in a 2 m³ concrete mixer. A number of the specimens of cylinders were cast for each mix as indicated in Table 1.


| Specimen type | Number of specimens per batch | Test conducted                      |
|---------------|-------------------------------|-------------------------------------|
| Cylinders     | Three                         | pullout strength at Zero Corrosion stage |
| Cylinders     | Three                         | pullout strength at severe Corrosion stage |
| Cylinders     | Three                         | mass loss and rib profile loss at severe Corrosion stage |

2.2.2. Curing
The specimens were stripped from the moulds 24 hours after casting and submerged in water (at 23 ± 2°C and 100% relative humidity) until testing according to BS EN 12390-2 (2019) requirements. The cylinders were removed from the water after 28 days to test for the bond strength, mass loss and rib profile loss before and after subjecting it to chloride penetration test.

2.2.3. Bond strength test before and after chloride penetration test
Cylindrical concrete specimens were reinforced axially with a single steel bar protruding at one end to study the bond strength under zero corrosion and severe corrosion stages as per BS EN 12504-3 (2005) procedures. After the pullout specimens were cast and cured for 28 days, three specimens, which had not been subjected to accelerated chloride penetration test, were taken from each batch and tested for their bond strengths. The bond strengths were determined for another three specimens per batch after subjecting them to accelerated chloride penetration test. The bond stresses were calculated from the ultimate pullout load using Equation 1.

\[ P_u = F_u / \pi \cdot \phi \cdot L \]  
(Equation 1)

where:

- \( P_u \) — the ultimate bond stress (N/mm²),
- \( \phi \) — the rebar diameter (mm),
- \( L \) — the bond length (mm), and \( F_u \) — the ultimate pullout load (N).

2.2.4. Percentage mass loss and rib profile height loss
The mass and the rib profile height of each steel bar were taken and recorded before it was embedded into the cylindrical concrete specimen. After the completion of the accelerated chloride penetration test, the specimen was broken to remove the reinforcing bar. The bar was cleaned and scrubbed with a stiff non-metal brush to ensure that the bar was free from any adhering corrosion effect and then cleaned with a vinegar. The mass and the rib profile height of each steel bar were taken to determine the percentage mass loss and rib profile height loss.

The mass loss of the steel reinforcing bar was calculated using the formula (Equation 2):

\[ \text{Percentage mass loss} = \frac{\text{Uncorroded mass} - \text{corroded mass}}{\text{Uncorroded mass}} \times 100 \]  
(Equation 2)

The degradation in the rib profile height of the steel was determined by measuring the rib height before embedding it in the concrete and re-measuring it at the end of corrosion test. The rib loss was determined as follows (Equation 3):
Percentage of rib lost = \frac{(\text{Rib height of uncorroded bar} - \text{Rib height of corroded bar})}{\text{Rib height corroded bar}} \times 100 

(Equation 3)

2.2.5. Accelerated chloride penetration test
Each of the concrete specimens with steel rod embedded was placed in a glass bowl with 5% NaCl solution by weight of water. Both the concrete specimen embedded with the steel re-bar and the naked steel bar were placed in the NaCl solution (Figure 1). The cathode and the anode from the ammeter were connected to the steel re-bar embedded in the concrete and the naked steel rebar respectively. The electrolyte solution was changed on a weekly basis. After establishing the specified levels of corrosion, the specimen was removed from the accelerated chloride penetration bowl and a standard pullout test was performed according to the requirements of BS EN 12504-3 (2005). The corrosion test was adapted from ASTM C 1202-97 (1997) requirements.

Four stages of chloride penetration were used to assess the performance of NP against corrosion resistance. The four stages of corrosion were: zero corrosion (before subjecting the specimen to corrosion test), the pre-cracking stage (when the current started to increase but before any cracking occurred) cracking stage (when the first crack appeared in the concrete specimen) and, severe corrosion stage (when any crack extended up to 4 mm).

2.2.6. Statistical analysis
Regression models were proposed based on Best-of-fit test using NP as independent variable and the various dependence variables (current passing, % bond loss, % weight loss, and % Rib loss). Also Pearson’s Bivariate Correlation matrix was used to access the correlation among the exogenous variables of % Loss of Bond, % Weight loss, % Rib loss and current passing of concrete. Minitab 7 was the statistical tool used for the analysis.

3. Results and discussion

3.1. Particle size of nano-plastics
A scanning electronic microscope (SEM) image of the Nanoplastics was studied. The particle size was estimated from average of 5 particles. The average particle size was 40 nm making it suitable to be classified as a nano-particle.

**Figure 1. Accelerated corrosion test set up.**
3.2. Chloride penetration test

Chloride penetration was used to assess the corrosion of the steel embedded in the concrete specimen. Corrosion was assessed on the following parameters: quantity and time of current passing through the concrete, percentage loss of bond strength, weight and rib profile height. The effect of NP on these parameters was studied and reported.

3.2.1. Effect NP on current measurements and time-induced corrosion

The results in Table 2 detailed the performance of NP in relation to corrosion resistance of concrete at the four degrees of corrosion. The plain concrete (NP0) on the third day had the highest initial current reading (pre-cracking stage) of 18 mA. The best-performed specimen, NP15, had 1.2 mA of current passing at the 21st day of testing. The current readings of the plain concrete showed higher average value of 308 mA at the cracking stage and this was recorded on the 12th day. Concrete with NP namely: NP5, NP10, NP15, NP20, NP25 had average current passing values of 190, 150, 105, 140 and 145 mA respectively at the cracking stage and these took 20, 28, 36, 30 and 30 days respectively to occur. The maximum current reading at the crack width of 4 mm, corresponding to severe corrosion stages for the plain concrete was 400 mA. The maximum current readings corresponding to severe corrosion stage for NP5 NP10, NP15, NP20 and NP25 were 250, 200, 140, 180 and 190 mA respectively. The plain concrete took 4 days to reach severe corrosion stage from the cracking stage, while NP, NP10 NP15, NP20 and NP25 concrete took 12, 15, 24, 21 and 21 days respectively to reach severe corrosion stage from the cracking stage. The addition of NP provided an average of 35%-65% better corrosion protection than using only Ordinary OPC.

The lower current reading in NP concrete specimens compared to that of the plain concrete specimen signified the beneficial effect in using NP in concrete to protect the reinforcing bars from corrosion. The initial lower current passing through the concrete specimens with NP was an indication of lower permeability and hence, higher resistivity of the NP concrete. This could be attributed to the presence of the fineness nature of NP which might have sealed the pores in the matrix, thereby, improving permeability resistance of the concrete composite.

Regression models were proposed based on Best-of-fit test using NP as independent variable and current passing (C) as the dependent variable. The inclusion of NP in the concrete specimen was significant in the reduction of current passing as indicated at $p = 0.001 < 0.05$ (Table 3). From Equation 4, if the NP content was increased by 1%, the current would have decreased by 6.58%. The negative relationship between the NP and the current passing in the concrete specimen confirmed the role of the NP in reducing the current passing, hence better chloride permeability resistance leading to better corrosion resistivity of concrete specimens with NP replacement. It was noted that equation 3 was limited to when the NP content was up to 15%. The coefficient of variation, $R^2 = 75.68\%$, signified that the variation in current was explained by the presence of NP.

| Specimens | Pre-cracking | Cracking | Severe cracking | Pre-cracking | Cracking | Severe cracking |
|-----------|--------------|----------|----------------|--------------|----------|----------------|
| NP0       | 3            | 12       | 16             | 18           | 308      | 400            |
| NP5       | 9            | 20       | 32             | 10           | 190      | 250            |
| NP10      | 17           | 28       | 43             | 4.5          | 150      | 200            |
| NP15      | 21           | 36       | 60             | 1.2          | 105      | 140            |
| NP20      | 19           | 30       | 51             | 6            | 140      | 180            |
| NP25      | 19           | 30       | 51             | 6.5          | 145      | 190            |
The overall factor, F-value (12.45) showed significant impact of the presence of NP in the current passing in the concrete specimen.

Current passing, \( C = 362.2 - 6.58\%NP \) \hspace{1cm} \text{(Equation 4)}

The accuracy of the proposed model is affirmed by Figure 2 as the residuals of the normal probability plot aligns themselves very closer to the trend line with least variation. And also the zero error line of Figure 3 had no particular form of pattern of residuals and this also affirmed the accuracy of the proposed model.

3.2.2. Effect of NP on bond strength

The effect of NP on bond strength of the concrete specimen from the un-corroded bars (zero corrosion level) to severe corrosion stages was demonstrated in this section. As seen from Table 4, at the zero corrosion stage, the plain concrete recorded the lowest bond stress compared to NP concrete specimens. For example, NP0 had an average of 3.7 N/mm\(^2\) which was 70% lower in bond stress than the best performed concrete specimen, NP15. As seen in Table 4, all concrete specimens at zero corrosion stage showed higher bond strength than those of the severe corrosion stage. For example, at the zero corrosion stage, the plain concrete (NP0) was 80% higher in bond...
strength than that of the severe corrosion stage. The concrete specimens with 15%NP lost 40% of the bond strength at the zero corrosion stage to the severe corrosion stage.

Figure 4 shows the influence of NP on loss of bond strength of the concrete specimens. The linear equation points out that NP content in the concrete specimen had negative relationship with percentage loss in bond strength. It should be noted that the equation was valid up to 15% replacement of NP. It was also observed that about 75% variation in % bond loss could be explained by the inclusion of NP ($R^2 = .7467$).

### 3.2.3. Effect of NP on mass loss

The results as indicated in Table 5, revealed that the plain concrete specimen had the highest % mass loss of 0.75% followed by specimen with 5% NP which lost 0.65% of its mass after the chloride penetration test. The best performed specimen, NP15, lost 0.32% of it mass after the chloride penetration test. The 15% replacement of NP was the optimum percentage replacement.

The regression analysis is shown in Table 6. From Equation 5, the % mass loss (M) was found to be negatively related to NP content. If the NP content was increased by 1%, the % mass loss would
The P-value of 0.023 showed that NP had a significant influence on % mass loss. $R^2$ equal to 76.27% showed that the NP was a better predictor of % mass loss. The F-value of 12.85 suggested that the overall factor also showed significant impact of 0.023 on % mass loss. The proposed model was considered to be effective with % replacement of NP up to 15%.

$$\% \text{Weight loss, } M = 0.7365 - 0.01295\%NP \quad \text{(Equation 5)}$$
Table 7. Effect of NP on loss of rib profile

| Properties                        | NP0  | NP10 | NP15 | NP20 | NP25 | NP30 |
|-----------------------------------|------|------|------|------|------|------|
| Rib height at zero corrosion      | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| Permeability (mm)                 |      |      |      |      |      |      |
| Rib height after corrosion        | 0.263| 0.310| 0.328| 0.335| 0.329| 0.326|
| Permeability (mm)                 |      |      |      |      |      |      |
| Rib profile loss %                | 27   | 14   | 9    | 7    | 8.5  | 9.5  |

3.2.4. Effect of NP on loss of rib profile

The severer the corrosion, the greater the loss of rib profile height. From Table 7, the results depicted that the effect of NP on percentage rib profile loss was similar to the relationship between percentage mass loss and loss in bond strength. There was a decline between 7% and 9.5% rib profile loss for concrete with NP, while, plain concrete experienced a decrease of 27% loss of the rib profile. The smaller percentage loss in rib profile implies that using NP in concrete protected the reinforcing bars from severe corrosion.

In the regression equation (Equation 6), the percentage of NP replacement is negatively related to the % Rib loss profile (R) with p-value of 0.020. The p-value demonstrates good level of significance as it is less than 0.05 confidence intervals.

\[
\%\text{Rib loss}, \ R = 23.58 - 0.532\%\text{NP} \quad \text{(Equation 6)}
\]

Increasing NP by 1%, implies that the % Rib loss (R) would have a decline of 0.532%. However, the model is valid up to 15% replacement. In Table 8, the coefficient of variation, $R^2$ of 77.88%, indicates that about 78% of % Rib loss is explained by the addition of NP to the concrete. The F-value = 14.09 suggests a significant (p = 0.020) impact on % Rib loss in the steel bar with addition of %NP replacement.

3.2.5. Correlation among current passing, % bond loss, % weight loss, and % Rib loss

Pearson’s Bivariate Correlation matrix was used to access the correlation among the dependent variables of current passing, % Loss of Bond, % Weight loss, and % Rib loss of concrete with NP addition. From Table 9, it was observed that, loss of bond stress correlated strongly with mass loss ($r = 0.94$, $p < 0.01$) and rib profile loss ($r = 0.932$, $p < 0.01$) whereas it negatively correlated strongly with NP percentage ($r = -0.812$, $p < 0.05$). The results also showed that an increase in the percentage of NP in the concrete specimen caused a significant decrease in the loss of bond stress, weight loss, and rib profile loss of the concrete specimens.

4. Conclusion

The findings of this study showed that the effect of corrosion on the concrete specimens with NP was less than concrete specimens without NP at the various stages of corrosion. The specimens with 15% NP lost 40% of their bond strength from the zero stage to the severe stage of corrosion, whilst the specimens with no NP lost 90% of their bond strength. In addition, the inclusion of NP materials provided an average of 55% better corrosion protection than the plain concrete. The lower current

Table 8. Regression analysis on % weight loss in % of concrete of NP

| Parameter | Coeff | SE Coeff | R.sq | F-Value | P-Value | VIF |
|-----------|-------|----------|------|---------|---------|-----|
| Constant  | 23.58 | 0.0857   | 77.88| 14.09   | 0.001   |     |
| %NP       | -0.532| 0.00361  |      |         | 0.020   | 1.00|
reading of concrete specimens with NP signified the beneficial effect of using NP materials in concrete to protect the reinforcing bars from corrosion. The initial lower current passing the concrete specimens with NP indicated lower permeability, and hence, higher resistivity of the concrete specimens with NP replacement. The degree of degradation of mass and rib profile of the embedded steel was less in concrete specimens with NP replacement than the plain concrete. This is an indication that nanoplastics improved the corrosion permeability resistance of the concrete specimen. Comparing the current passing with percentage bond strength loss, mass loss, and rib profile loss, it could be deduced that severer the corrosion the greater the percentage bond strength loss, mass loss and rib profile loss.

These findings support the conclusion that nanoplastics improved the corrosion permeability resistance of the concrete specimen when used as an admixture to concrete. Application of nanoplastics as corrosion enhancer to steel bars in concrete specimens would mitigate the hazard caused by the presence of nanoplastics in the environment and also reduce the demand of cement, subsequently, decreasing continuous demand of natural materials used for production of cement. This study therefore recommends that nanoplastics should be used as an admixture in concrete to cement up to level of 15%.

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