Innovative Use of Plastic Waste in Concrete: A Durability Assessment through Absorption and Abrasion Metrics

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Abstract— The use of microplastics (MPs) into concrete has gained increasing research interest due to its potential to address plastic waste management challenges while influencing concrete performance. The advancements of MP-modified concrete is gaining attention, focusing on sustainability, durability, and economic feasibility. This study investigates the long-term durability effect of different MPs particle sizes (fine, coarse and mixed) on the properties of concrete. Concrete was produced with 0%, 2% 4%, 6%, 8% and 10% MPs by weight of cement. A mix proportion of 1:1.5:3 with a water-cement ratio of 0.53 was used to produce the concrete. A concrete mould measuring 100mm × 100mm × 100mm was used for casting. The concrete cubes were cured for up to 180days. The results indicated significant improvement in the durability properties. The properties of the concrete improved as as the MPs percentages increase. The investigation revealed that fine MPs better void-filling and densification. MPs-modified concrete reduces permeability and improves durability, which could have long-term benefits in terms of reducing water-related deterioration. Abrasion resistance findings suggest that the right combination and dosage of MPs can enhance concrete's durability under frictional forces, making it suitable for applications where surface wear is a concern. These results highlight the potential of MPs-modified concrete for construction application.

Keywords— Microplastics (MPs), Water Absorption, Abrasion Resistance, Fine microplastic, Mixed microplastic, Coarse microplastic, Concrete cubes

INTRODUCTION

Incorporating microplastics (MPs) into concrete has garnered increasing research interest due to its potential to address plastic waste management challenges while influencing concrete performance. This study examines the advancements in MP-modified concrete, focusing on sustainability, durability, and economic feasibility. MPs, defined as plastic particles smaller than 5 mm, originate from primary sources (manufactured microplastics) and secondary sources (fragmented larger plastics) [36] Common contributors include industrial byproducts, synthetic fibers, and deteriorated plastic waste [12]. Research indicates that MPs alter the mechanical properties of concrete. For example, Hossain et al.,[20] observed that polyethylene terephthalate (PET) MPs at 0.5% by weight reduced compressive strength of concrete by 10% but enhanced ductility. However, excessive MPs content weakens interfacial bonding, leading to compromised mechanical integrity [37]. Durability concerns have also been raised, as MPs can increase concrete permeability, leading to water absorption and vulnerability to freeze-thaw cycles [35]. Additionally, potential MPs leaching raises ecological concerns regarding long-term environmental impacts [18]. To optimize MP incorporation, studies suggest chemical surface treatments and coupling agents to improve MPs-cement matrix interactions [38]. Blending MPs with supplementary cementitious materials (SCMs) has also been explored to mitigate strength reductions [11].

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While challenges remain, including mechanical stability and environmental risks, MPs-modified concrete presents opportunities for sustainable material innovation. Siddique et al.,[35] found that blending MPs with supplementary cementitious materials (SCMs) reduces permeability and improves resistance to freeze-thaw cycles. González-Pleiter et al. [18] also discussed the potential for MPs to act as internal reinforcement, enhancing fatigue resistance. Using MPs in concrete presents economic advantages by reducing raw material costs. As plastic waste is readily available and inexpensive, incorporating it into concrete can lower production expenses. Jiang et al. [26] highlighted that MPs-modified concrete could be particularly beneficial in low-cost construction applications. Additionally, Li et al. [26] explored the potential for treated MPs to replace a portion of fine aggregates, leading to cost savings without significantly compromising performance. Despite the benefits, challenges remain, including the need for standardized guidelines on MPs dosage and treatment methods. Zhu et al. [38] recommended further research into optimizing MPs surface treatments to improve compatibility with cementitious materials. Additionally, a critical assessment should be conducted to evaluate the long-term impact of MPs on the durability properties of concrete structures. The use of microplastics in concrete offers a promising approach to waste reduction, sustainability, and enhanced material performance. While challenges such as mechanical integrity and durability need to be addressed, advancements in material science can help optimize MPs incorporation. Future research should focus on long-term durability, standardized testing, and environmental impact mitigation.

Incorporating MPs into concrete to address plastic waste challenges and promote sustainability, significant research gaps remain regarding their long-term durability and standardization. While previous studies [36,12] have highlighted the environmental and economic advantages of repurposing MPs in construction, there is limited consensus on their optimal dosage, treatment methods, and impact on concrete performance over extended service life. Research suggests that MPs influence mechanical properties, with controlled additions improving ductility and toughness [20] while excessive quantities may weaken compressive strength. Additionally, surface modification techniques [37] and supplementary cementitious materials [35] have been explored to mitigate potential durability concerns such as increased porosity and water absorption. However, investigation is required to establish standardized testing protocols and assess the long-term effects of MPs on environmental and structural performance [38]

Despite the growing interest in incorporating MPs into concrete for economic and environmental benefits, limited research has comprehensively examined the long-term durability implications of different MPs particle sizes. This study addresses this gap by investigating the effects of fine, mixed, and coarse MPs on key durability properties, specifically water absorption and abrasion resistance, over extended curing periods. While prior studies have explored the potential of MPs-modified concrete to reduce raw material costs and support circular economy principles, a critical evaluation of its long-term performance remains underdeveloped. Establishing the durability characteristics of MPs-incorporated concrete is essential to ensure its structural integrity and practical viability in sustainable concrete.

MATERIALS AND METHOD

Materials

The main materials used for the experimental study are cement, coarse aggregate, fine aggregate, Polyethylene Terephthalate, and water. The binder utilized for the concrete production was Ordinary Portland Cement (OPC) with a strength grade of 42.5R (Figure 1a)manufactured by Ghana Cement Company Limited (GHACEM). This cement type complies with the requirements outlined in BS EN 197-1 [10]. Clean pit sand (Figure 1b), devoid of silt, salt, and other impurities, was employed as the fine aggregate in accordance with BS EN 12620 [8]. To assess its engineering suitability, a series of tests were conducted on the material, including specific gravity, water absorption, silt content, sulphate content, pH (alkalinity), organic impurities, moisture content, chloride content, and particle size distribution.

Figure 1: Materials for concrete: (a) cement, (2) fine aggregate, (3) coarse aggregate

Coarse aggregate (Figure 1c) with a maximum particle size of 10 mm, meeting the specifications of BS EN 12620 [8] was selected for this study. Portable drinking water, free from impurities and harmful chemicals, was provided to the laboratory by the Ghana Water Company Limited (GWCL) and used in mixing the main concrete ingredients. This water met the requirements of BS EN 1008 [5].

Polyethylene Terephthalate (PET) was chosen as the plastic material for the study due to its widespread use in packaging, especially for beverages, food containers, and other consumer goods. Renowned for its strength, durability, and recyclability, PET is one of the most commonly used plastics worldwide. However, discarded plastic drinking water bottles have become a significant environmental concern.

Materials preparation

For this research, waste PET water bottles of various sizes were intentionally sourced from designated collection points. Only plain-coloured bottles were selected for consistency. Before processing, bottle caps and labels were manually removed before the bottles were ground for use in the study. Separate particle size distribution tests were conducted for fine and coarse aggregates. The fine aggregates were oven-dried at 105°C using a vacuum oven before testing. Sieve analysis was carried out, using a standard set of sieves following BS EN 933-2 [9]. Separate particle size distribution tests were conducted for both fine and coarse aggregates. Before testing, the fine aggregates were oven-dried at 105°C using a vacuum oven. Sieve analysis was performed using a set of sieves by BS EN 933-2 [9], comprising upto 5 mm. Similarly, the coarse aggregates were oven-dried at 105°C using a vacuum oven. For their analysis, sieves conforming to BS EN 933-2 [9] were selected, including up to 14 mm. A 1-gram sample of coarse aggregate was measured and placed on a sieve stack arranged from largest to smallest aperture. After covering, the set was vibrated using a mechanical shaker for 10 minutes. The mass retained on each sieve was measured, and both the percentage retained and the cumulative percentage passing through were calculated to evaluate the aggregate gradation. A custom-designed grading machine was fabricated specifically for grinding the PET bottles. The ground plastic was subsequently sieved into different categories based on size: large microplastics (ranging from 5 mm to 1 mm), small microplastics (between 1 mm and 1 µm), and nanoplastics (less than 1 µm). The classification was done to suit the requirements of the study and followed the standards set in BS EN 12620 [8] for particle size distribution. For purposes of this work, it was further categories in 0-5mm, 2mm-5mm and 0-2mm.

Pulverising plastic bottles

Before being fed into the machine, the waste plastic drinking water bottles were manually compressed. This step was crucial, as initial trials showed that uncompressed bottles tended to pass through the machine without being properly ground. In contrast, the compressed bottles yielded significantly more plastic powder and finer particles.

The custom-designed grading machine (see Figure 2) had the capacity to process up to fifteen (15) compressed bottles per load. It was capable of producing a 3.6 grams of ground plastic per hour. During operation, a wooden plunger measuring 400 mm × 250 mm × 30 mm was used to apply pressure, pushing the compressed bottles firmly against the grater's teeth. This pressure enhanced friction, resulting in more efficient grinding. It was observed that without sufficient applied pressure, only a small quantity of microplastics was produced. On average, it was estimated that for every bottle processed, about one-third was successfully converted into microplastic particles, while the remaining two-thirds emerged as larger residual fragments.

Figure 2: Plastic grinding machine

Preparation of concrete

A concrete mix design ratio of 1: 1.5: 3, for cement, fine and coarse aggregate, and water/cement 0.53 were used for the batching by weight. Three batches of concrete material mix design in mass (kg) proportions. This contains various percentages of MPs admixture 0%, 2%, 4%, 6%, 8%, and 10% by weight to cement. In addition to a constant water/cement ratio (W/C) of 0.53. An electric concrete mixer was employed for the mixing process. Initially, the sand and cement were blended until a uniform grey colour was achieved, indicating proper mixing. The designated quantity of MPs for each batch was then introduced into the mix, followed by the addition of coarse aggregates.

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The mixture was allowed to blend for an additional 2 minutes before gradually adding the required amount of water. Mixing continued until a uniform, consistent paste was formed. To ensure optimal workability, the concrete was further mixed for an additional 3 to 5 minutes. The mixing was carried out under BS EN 206:2013+A2:202 [6] and its complementary standard BS 8500-2:2023 [40] which governs the production and conformity of concrete. Steel moulds measuring 100 mm × 100 mm × 100 mm were used for casting the concrete cubes. The moulds were thoroughly cleaned to remove any debris and then lightly oiled to facilitate easy demoulding after set

Each mould was positioned on a vibrating table. Concrete was poured into the moulds up to approximately three-quarters of their height. The vibrating table was then activated to compact the concrete and eliminate air voids. While the vibration continued, additional concrete was added to fill the moulds to the top. The surface was leveled and finished using a hand trowel to ensure it was flush with the top of the mould. Once completed, the moulded cubes were left undisturbed on laboratory tables for initial setting.

The concrete cubes remained in the moulds for 24 hours to allow for initial setting (see Figure 3a). After this period, the moulds were carefully removed to avoid damaging the edges of the cubes. The demoulded cubes were immediately submerged in curing tanks filled with water maintained at an average temperature of 24°C. Care was taken to ensure that the cubes were fully immersed, with no part exposed to air, to prevent uneven curing. The curing water was regularly monitored to prevent contamination, and the cubes were neatly arranged in the tank to allow for proper circulation and consistent curing (see Figure 3b). At 180days of curing , the cubes were removed from the tanks and allowed to surface dry (see Figure 3c) before undergoing testing

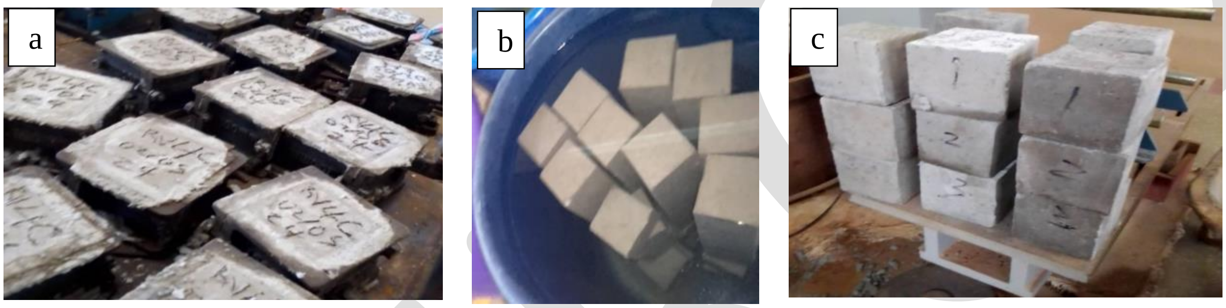

Figure 3: Concrete cubes: (a) initial setting, (b) curing, (c) ready for testing

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Testing of concrete Water absorption test: To assess the porosity and permeability of the concrete, a water absorption test was conducted in accordance with [39]. This test measures the quantity of water absorbed by the concrete specimen, thereby evaluating its resistance to water ingress and predicting its long-term performance in damp environments.

Concrete cubes cured at different curing ages were selected for testing. These specimens were oven-dried (see Figure 4a) for 72 hours and then cooled (see Figure 4b) in a dry, airtight container to prevent moisture absorption from the surrounding environment. Each dry specimen was weighed using an electronic scale (see Figure 4c), and the reading was recorded as the dry weight (DW).

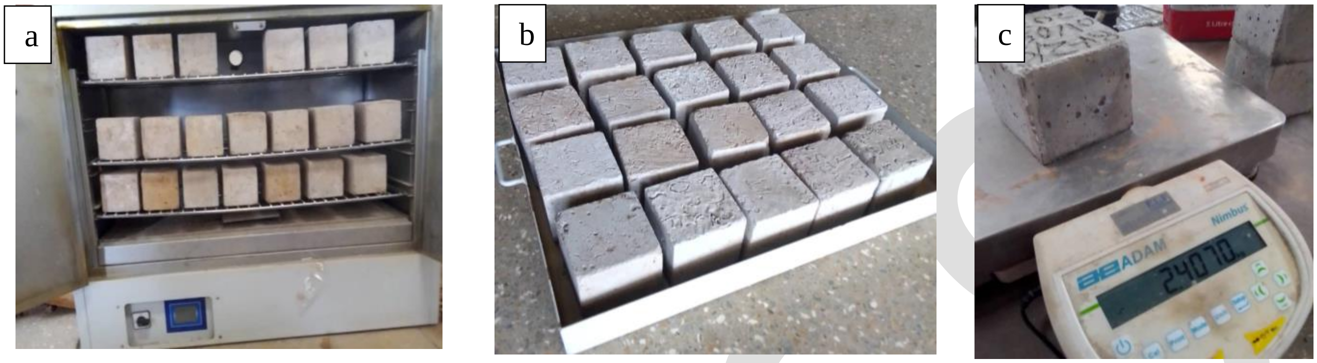

Figure 4: Water absorption test: (a) oven-drying of specimens, (b) air-drying of specimens after oven-drying, (c) weighing of specimen

Afterward, the specimens were submerged in water maintained at a temperature of approximately 20°C for 30 minutes. Upon removal, surface moisture was gently wiped off with a clean cloth to ensure only absorbed water contributed to the final weight. The specimens were then reweighed, and the readings were recorded as the wet weight (WW).

The percentage of water absorbed was calculated using the formula:

Water Absorption = $\left(\frac{Ww-Dw}{Dw}\right) \times 100$ ……..Eq (1)

Where:

WW = Wet weight of the specimen (kg) w

DW = Dry weight of the specimen (kg)

Five samples were tested for each batch, and the average water absorption percentage was computed for analysis.

Abrasion test: The abrasion resistance test was carried out to evaluate the surface wear resistance of the concrete after 180 days of curing. Prior to testing, the concrete cubes were inspected and cleaned to remove any loose debris. The initial weight of the specimen was measured and recorded as W_1.

A specific portion of the surface was marked to maintain consistency in the test area. Using a wire brush, the marked surface was scrubbed back and forth under uniform pressure for a total of 100 strokes. After brushing, all loose materials from the surface were removed, and the specimen was reweighed. The final weight was recorded as W_2.

The loss of material due to abrasion was determined using the following formula:

Abrasion Loss (g) = $(W1 - W2)$ ……………...Eq (2)

Where:

W_1 = Initial weight before brushing (g)

W_2 = Final weight after brushing (g)

This value represents the surface wear resistance of the concrete and is critical for evaluating its performance under abrasive conditions.

RESULTS AND DISCUSSION

Water absorption

The results in Table 1 and Figure 5 indicate that MPs play a significant role in influencing the water absorption of concrete. As MPs content increases, the water absorption generally decreases indicating that MPs are obviously suitable for water resistance concrete production.

Table 1 Water Absorption

Sample %	Fine	Mixed	Coarse
0%	4.72	4.72	4.72
2%	1.52	1.96	1.68
4%	1.28	1.87	1.52
6%	1.04	1.66	1.44
8%	0.46	1.52	1.15
10%	0.36	1.32	1.02

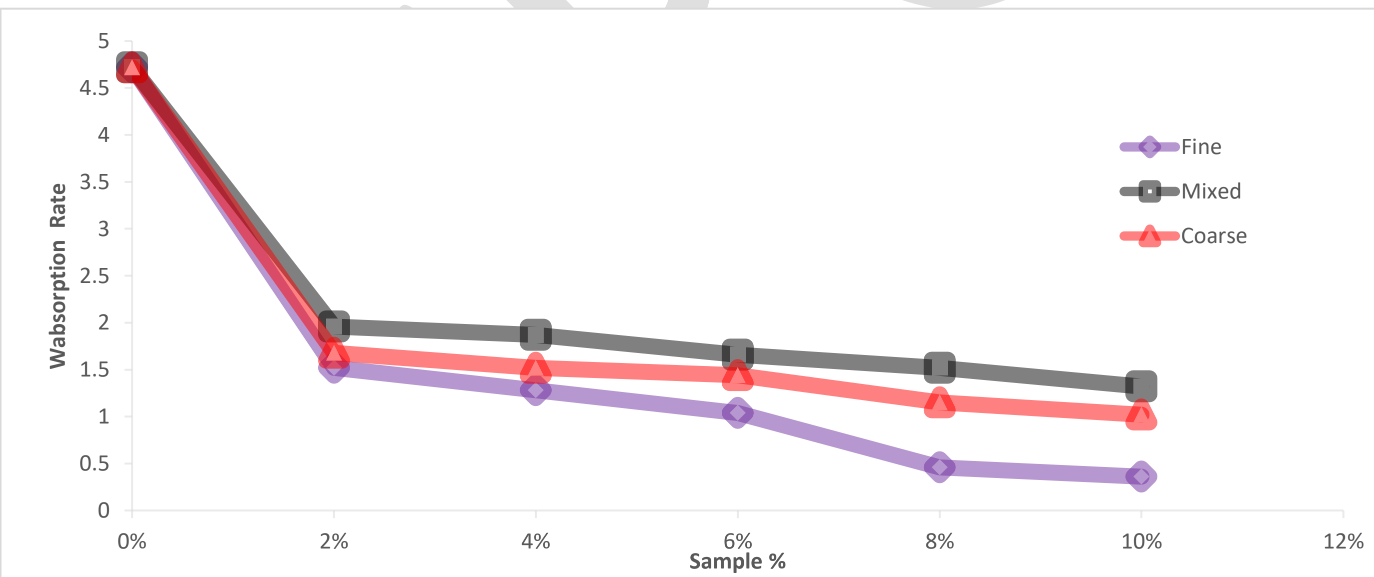

Figure 5: Water absorption of MPs-modified concrete

The water absorption test was conducted on concrete cubes at 180days of curing age to determine long term effect of MPs particles on the durability property of concrete. The three MPs particle sizes: mixed, fine and coarse were used to determine the optimal dosage. The samples were treated with dosage of 2% interval from 0% to 10%.

The control sample 0% recorded 4.72 as a water absorption baseline for the analyses. The fine MPs particles demonstrated sturdy low water absorption with constant decline in the values obtained. The 2% recorded 1.52 below 4.72 of the control which signifies 210.53% reduction in water absorption. The 4% of the fine declined in absorption with 1.28 making it 268.75% below the control. The 6% gave a further reduction in water absorption from 4.72 control to 1.04 indicating 353.85% below 0% and approximately

23.03% below 4% of 2.28 addition of fine MPs. The 8% recorded 0.46 water absorption was further fall in absorption at 926.09% below the control. The 10% demonstrated remarkable drop in water absorption of 0.36 approximately 1211.11% below the control and 27.78% below 8% of 0.46. This outermost lower water absorption can be attributed to the fact that the fine MPs may reduce the number of voids in the concrete matrix leading to lower water absorption. The fine MPs particles filled the gap in the concrete, leading to less permeable concrete. The mixed MPs particle size showed lower water absorption below control sample but higher than the fine and coarse MPs additions at the same percentage inclusion. The 2% had 1.96, 4% of 1.87, 6% of 1.66, 8% of 1.52 and 10% of 1.32 of the mixed MPs water absorption. The 10% with the lower water absorption of 1.32 was 257.58% below the control of 4.72. The mixed MPs particles could create more complex pore structure, with a wide range of pore sizes. This could increase porosity that can lead to higher water absorption. This could also attribute to the fact that combination of fine and coarse MPs can create a more irregular surface, which can increase surface area available for water penetration and increase water absorption. The coarse MPs particles exhibited a lower water absorption in all percentages of MPs addition than the control sample. The 10% coarse MPs particles size inclusion recorded 1.02 represents 363.75% below the 0% water absorption. As 8%, 310.43% by 1.15, 6% had 227.78% by 1.44, 4% had 172.95% by 1.73 and 2% had 210.53% by 1.52 to the addition MPs percentage. This is lower than mixed MPs because coarse particles tend to pack more efficiently than the mixed to reduce the number of voids in concrete.

To analyse the significance percentages between various inclusion of MPS particles, it portrays that the increase in MPS particles in all forms reduces the water absorption rate in concrete. Assessing water absorption with the three MPS particle sizes, the fine particles consistently demonstrated the lowest water absorption values compared to the mixed and coarse MPS particles. The MPS addition from 2% indicated over 100% reduction in water absorption relative to the control sample. At 10% MPS content addition, all the three MPS categories gave significant lower values. The fine MPS at 10% achieved the optimum and the lowest value of 0.36 water absorption. This phenomenon can be attributed to several factors. Confirming that microplastics can reduce capillarity voids in the cement matrix, leading to decreased permeability [34,17]. As MPS fill the gaps, they enhance concrete density, thereby limiting water ingress [2,19,]. Ramesan et al. [31] endorse that MPS are less hydrophilic than cement or aggregate, which may reduce the affinity for water absorption. In as much as the particle size is concern, finer MPS are more effective at filling smaller voids and increase matrix compactness [3,13]. In contrast, coarse MPS particles lack this fine packing effect, resulting in smaller reduction in water absorption. All these improvements are likely due to the finer MPS having higher surface area and more extensive interaction with the cement paste, which aide in void filling and densification [27,1].

The regression model has an R value of 0.792, indicating a strong correlation between the independent variables, MPS particle sizes and sample %, and the dependent variable the water absorption. The R Square value is 0.628; meaning that 62.8% of the variance in water absorption can be explained by the predictors MPS particle sizes, curing period and Sample %. The Adjusted R Square is 0.578, which accounts for the number of predictors in the model, suggesting a reasonably strong explanatory power. The Standard Error of Estimate 0.8873 provides a measure of how much the observed values deviate from the regression line. In the ANOVA table, F-statistic is 12.657, with a p-value of 0.001. Since the significance value is less than 0.05, the regression model is statistically significant, meaning that at least one of the independent variables significantly predicts water absorption. The Constant, which is intercept of 3.700, with a p-value of 0.000, indicating it is statistically significant. The Sample % with $\beta = -0.611$, $p = 0.000$, signifies that variable has a negative, and significant effect on water absorption. For each 1% increase in sample %, water absorption decreases by 0.611 with MPS ($\beta = 0.167$, $p = 0.525$). This variable has a positive but non-significant effect on water absorption. Since the p-value is greater than 0.05, it does not significantly influence water absorption in this model. Therefore, sample % is the most influential predictor and has a statistically significant negative impact on water absorption. MPS does not significantly impact water absorption % based on this model. The overall model is statistically significant and explains about 62.8% of the variability in water absorption.

Regression equation

$\hat{y}=\beta_0+X_1 \beta_1+X_2 B_2$……………………………………………Equ: (3)

β_0= Constant , where β_i are the coefficients of the independent variables.

X_1= Sample %

X_2= Microplastics

$\hat{y}$=3.700-0.611 Sample %+0.167 Microplastic…………Equ: (4)

Abrasion resistance

This analysis focuses on how different sizes of MPs particles (coarse, fine, and mixed) can influence the abrasion resistance of concrete in the long term. Abrasion resistance is a crucial property of concrete, particularly in structures exposed to continuous wear and friction [32,30]. The samples were cured for 180 days before testing. The control sample at 180 days of curing as can be observed by Figure 6 and Table 2 had an abrasion resistance value of 0.005. The effect of MPs, especially the coarse MPs particles, increased the value to 0.012 at 2%, 0.013 at 4%, 0.014 at 6%, peaking at 0.015 at 8%, and dropping to 0.013 at 10% indicating susceptibility to surface wear. These results suggest that coarse MPs compromise abrasion resistance due to their irregular shape and larger particle size, which can weaken the interfacial transition zone [22,15]. At lower dosages, coarse MPs may bond with the matrix, but as the dosage increases, their structural inefficiency becomes more evident. A similar pattern was observed for fine MPs, although they recorded lower abrasion values than coarse particles. At 6% replacement, abrasion peaked at 0.013 (160% above control) but dropped to 0.010 at 10%, showing that finer particles better integrate with the cement matrix and improve durability due to enhanced pore filling [31,2]. The best performance was recorded for mixed MPs particles. At 2%, the abrasion value was 0.009 (80% higher than control), with 4% peaking at 0.011. From 6% onward, abrasion resistance improved, declining to 0.007 at 8% and further to 0.004 at 10%, 25% lower than the control, indicating improved surface wear resistance. This improvement may be attributed to the better packing density and distribution effect of mixed particle sizes, which leads to a more compact and abrasion-resistant matrix [3,17]. These findings affirm that MPs inclusion affects abrasion resistance based on particle size and dosage. Fine and mixed MPs may be optimized for better surface durability, while coarse plastics should be used sparingly due to their negative effect on abrasion resistance. This study highlights that higher inclusion rates (8–10%) of mixed MPs particles can reduce surface wear, offering a more sustainable and durable concrete for long-term structural use [34].

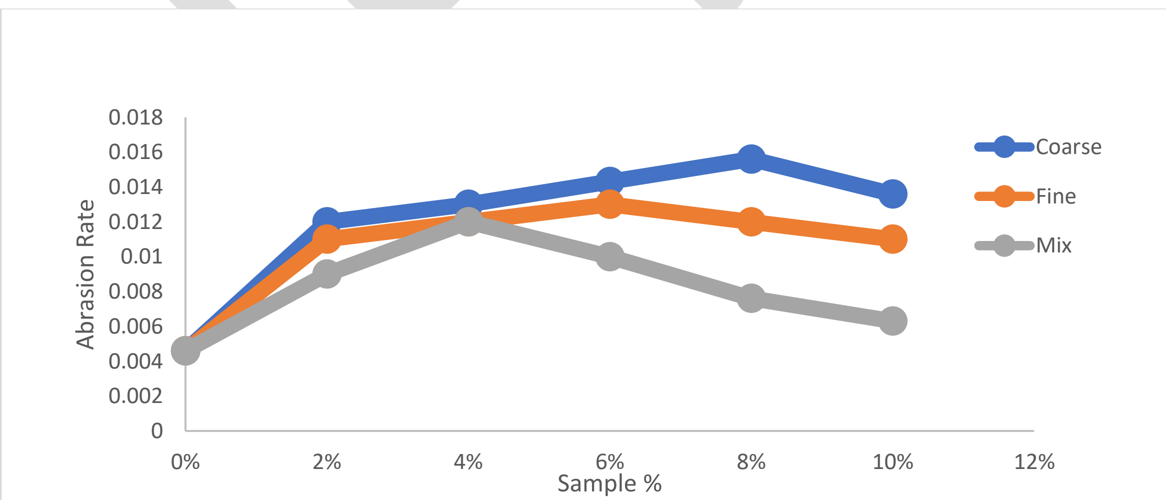

Table 6: Abrasive resistance of MPs-modified concrete

Table 2: Abrasive resistance of MPs-modified concrete

Sample	Coarse	Fine	Mixed
0%	0.005	0.005	0.005
2%	0.012	0.011	0.009
4%	0.013	0.012	0.011
6%	0.014	0.013	0.01
8%	0.015	0.012	0.007
10%	0.013	0.01	0.004

The multiple regression models, which include the predictor MPs and sample %, has an R value of 0.619, indicating a moderate correlation between the independent variables and the dependent variable Abrasion. The R Square 0.383 means that approximately 38.3% of the variation in Abrasion is explained by the model. The Adjusted R Square 0.301 means value accounts for the number of predictors in the model, slightly lowering the explained variance to 30.1% to provide a more accurate measure. The Standard Error of the Estimate 0.002889 represents the average deviation of observed values from the predicted values.

The ANOVA test evaluates whether the regression model significantly predicts the dependent variable. The $F (2, 15) = 4.654$, $p = 0 .027$: Since $p < 0.05$, the model as a whole is statistically significant, meaning that at least one of the predictors has a significant relationship with abrasion. The information provides how each predictor contributes to the model. Constant = 0.012, $p < 0.001$. This is the predicted value of abrasion when both sample % and MPs are zero. Sample % ($B = 0.001$, $p = 0.130$). The positive coefficient suggests that as sample % increases, abrasion tends to increase. However, $p = 0.130 > 0.05$, indicating that this effect is not statistically significant. MPs particle sizes ($B = -0.002$, $p = 0 .020$) indicates negative coefficient suggests that as MPs increases, abrasion decreases. Since $p = 0.020 < 0.05$, this predictor is statistically significant and has a meaningful effect on abrasion.

Therefore, the regression model is statistically significant overall ($p = .027$), meaning it has predictive value. MPs is a significant predictor ($p = .020$) and has a negative impact on abrasion. Sample % does not significantly predict abrasion ($p = 0.130$), though it has a positive relationship. The model explains 38.3% of the variance in abrasion, indicating that other variables not included in the model may also influence the outcome.

$\hat{y}=\beta_0+X_1 \beta_1+X_2 B_2$……………………………………..Equ. 1

β_0= Constant, where β_1 are the coefficients of the independent variables.

X_1= Sample %

X_2= Microplastic

$\hat{y}=0.012+0.001$ Sample-0.002 Microplastics………….Equ. 2

CONCLUSION

The incorporation of MPs in concrete, especially fine particles, significantly enhances the durability of concrete by drastically reducing its water absorption rate. This is attributed to better void-filling, densification of the matrix, and the hydrophobic nature of plastics. These improvements suggest that MPS-modified concrete is highly suitable for water-resistant applications and structures exposed to moisture over time. The findings confirm that optimal durability performance is achieved with fine MPS at 10% inclusion, which led to the most substantial decrease in water absorption by over 92%. This study also confirms that abrasion resistance in concrete is significantly affected by MPS particle size and dosage. While both coarse and fine particles increase surface wear at lower dosages, mixed MPs, particularly at 8–10% inclusion, contribute to improved abrasion resistance. The optimal performance is observed at 10% mixed MPs, with abrasion resistance even better than the control. These findings suggest that the right combination and dosage of MPs can enhance concrete's durability under frictional forces, making it suitable for applications where surface wear is a concern.

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