Valorization of plastic waste aggregate in concrete: A study on durability and microstructural properties.

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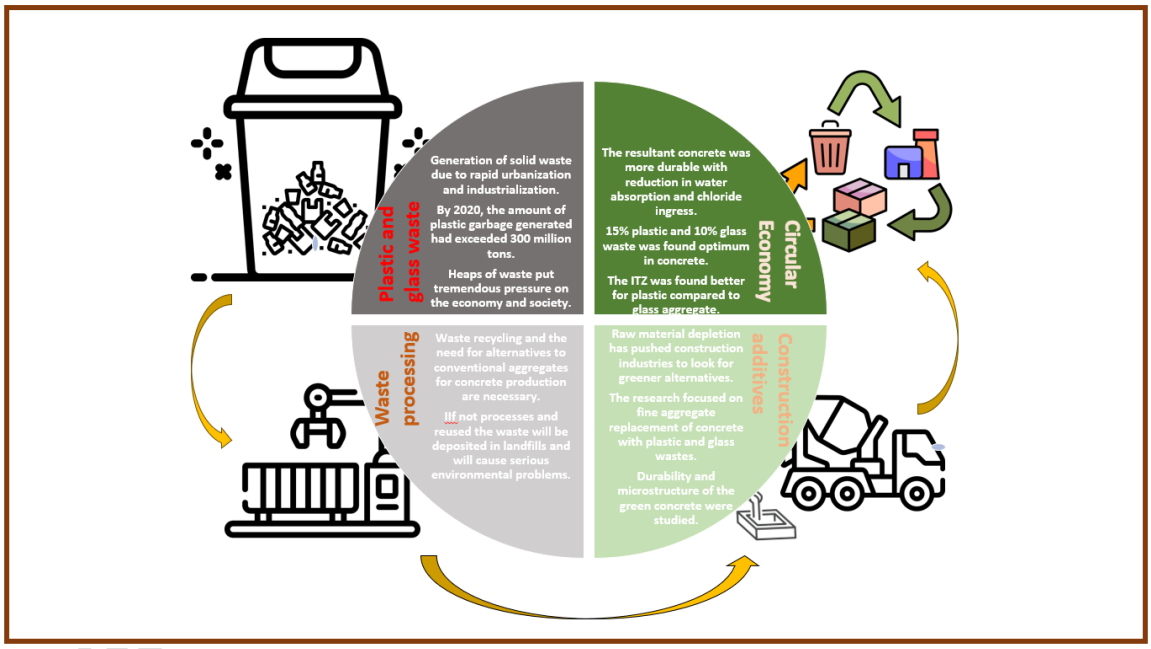
Graphical Abstract



ABSTRACT

Efficient valorization of plastic waste is widely investigated by numerous researchers. The need for an alternate to conventional aggregate in concrete production has led to the evolution of numerous artificial aggregates. This research investigates the impact of adverse environmental exposure conditions in plastic waste aggregate concrete. Conventional concrete of M30 grade designed as per IS- 10262 (2019) specification serves as control mixture. The conventional fine aggregate was volumetrically substituted

at 5, 10 and 15 percentages with recycled waste plastic granule aggregate. Further, these three variants of plastic aggregate concrete mixtures were introduced with an additional substitution of 10% of glass cullet. The concrete mixtures were subjected to water absorption, sorptivity, chloride penetrability, acid and alkali exposure conditions to test their durability characteristics. The 15% PWA concrete mixture exhibited good resistance to water absorption which accounts to be 5.7% less when compared to water absorption of conventional concrete (M0) mixture. The compressive strength loss experienced in acid exposed concrete cubes was noted as 51.3% in conventional concrete mixture and 34.5% in M15PA10G mixture (15% PWA with 10% glass cullet). The 10% PWA concrete mixture exhibited 48.7MPa compressive strength after 60 days of sulphate immersion, which accounts for 43% gain in strength as compared to its normal 28 days cured compressive strength, 34MPa. Concrete mixtures with 10% glass cullet performed with very low chloride ion permeability of 300 coulombs to 500 coulombs.SEM analysis revealed a strong bond between plastic aggregate and concrete matrix. Concluding that, the plastic aggregate concrete mixture along with glass cullet satisfies the basic durability characteristics of normal strength concrete.

Keywords: Plastic aggregate concrete; Acid attack; Chloride penetration; Water absorption; Sorptivity; Microstructure.

NOMENCLATURE

HDPE	High density polyethylene
UT	Union Territory
LDPE	Low density polyethylene
WG or GC	Waste Glass or Glass Cullet
PET	Polyethylene terephthalate
fck	Cube compressive strength at 28th day
M0	Conventional concrete mixture of grade M30
PWA	Plastic waste aggregate
FA	Fine aggregate
CA	Coarse aggregate
M5PA, M10PA, M15PA	Concrete mixtures with 5%, 10% and 15% PWA
M5PA10G, M10PA10G M15PA10G	5%, 10%, 15% PWA concrete mixtures with 10% WG

1. Introduction

The Indian Republic is experiencing rapid population expansion, urbanization, and industrial development, which has led to changes in urban middle-class life (Narayana, 2009). Consequently, raw materials are being depleted and waste is accumulating as a

result of this rapid growth. There is tremendous pressure on the economy and society due to limited natural resources and heaps of waste. Waste recycling and the use of conventional aggregates for concrete production are therefore necessary (Pappu et al., 2007). There are several negative environmental effects associated with plastic garbage generation. By 2020, the amount of plastic garbage generated will have exceeded 300 million tons (Almeshal et al., 2020). There is only 9 percent recycling of plastic generated worldwide, according to estimates (Geyer et al., 2017). In the end, the remaining plastic garbage was either burned or discharged into the environment, ending up in landfills (Barnes et al., 2009). The major obstacle to the wide acceptance of recycled plastic as a new product is its additional processing cost associated with degradation in material quality (Siddique et al., 2008). This reduces the likelihood of using these recycled materials in new products. Also, attempting to put waste plastic in landfills or burn it is not a good solution because the toxic and dangerous gases that are released can cause a lot of damage to the environment (Rahman et al., 2012).

The search for a complete or partial replacement for traditional natural aggregates to meet its rising demand sustainably is been triggered in recent times (Rahmani et al., 2013). Recycled waste plastic is one new and popular material that is being utilized in place of natural aggregates since it not only lessens the exploitation of natural aggregates but also helps to address the critical issue of plastic waste accumulation (Saikia and de Brito, 2014). It entails creating a second phase of recycling plastic trash to produce concrete aggregates or fibers. Numerous studies, tests, and reviews have been conducted on the use of plastic waste as fibers when it is cut or extruded or as lightweight aggregates when it is shredded (Bassuoni and Nehdi, 2007; Alam et al., 2012). Since aggregate makes up the majority of any concrete mixture, it plays a crucial role in the behavior of concrete, including its workability, durability, and dimensional stability (Sivamaniet al., 2023). However, depending on the level of replacement, using plastics in place of aggregate concrete can significantly reduce the workability of the concrete while also lowering its strength properties (Ge et al., 2013). Concrete is susceptible to chemical attacks resulting in a severe impact on its mechanical and physical properties (Fanget al., 2020). Concrete is weakened and corroded by acids found in environmental groundwater or chemical wastewater (Dawood et al., 2021). It is possible for various contaminants to infiltrate into concrete components, leading to failures such as cracking, strength loss, and corrosion of the cement paste (ACI 201.2R, 2016; Belmokaddemet al., 2020). Due to their low thermal conductivity, excellent abrasion behavior, high toughness, and high heat capacity, plastic aggregates might enhance some of the durability and mechanical qualities of concrete. Concrete with PET particles have better carbonation resistance and permeability according to Akcaozoglu et al., (2010) PET mortars have a very low water absorption rate. Researchers claim that because of its strong resistance to erosion, it might be employed as a component of concrete in severe locations (Babafemi et al., 2022). The sulfate attack in concrete results in the generation of expansive products and the decomposition of hydration products of cement (Adamu et al., 2022). Gypsum in concrete interacts with mono-sulfate to form ettringite. The primary cause of the growth and devastation of sulphate-attacked concrete structures is considered to be the development of ettringitis(Aldahdoohet al., 2018). Therefore, further studies focusing on their durability features are required before using plastic aggregate concrete in the

construction sector (Almeshalet al., 2020). The ability of concrete to withstand weathering, chemical attack, abrasion, or any other process of deterioration that could change the original quality of concrete is known as durability, and it is influenced by the concrete's permeability to the ingress of substances like oxygen, water, CO_2, sulfate, and chloride as well as other potentially harmful ones (Araghi et al., 2015). In this context, a few researches on the impact of acidic and alkaline environments on the deterioration of plastic aggregate concretes have been carried out. With the knowledge gained from the literature, it is clear that the plastic aggregates require an additional enhancing material to be included along with it to compensate the loss evolved due to plastic addition. In this study, glass cullet is included as the compensating material along with plastic aggregate, which is a novel approach. This study aims to investigate experimentally how different quantities of PW aggregates used as fine aggregate replacement affect erosion caused by acidic and alkaline media in concrete. Furthermore, the study aimed to observe how the influence related to the physical and mechanical changes these plastic aggregates impart. Individually, the correlation between weight loss from sulfate and acidic attack and a decrease in concrete crushing load was also established. It is envisaged that this study will help and deepen our knowledge of the causes behind the degradation of plastic concrete in harsh environments.

2. Materials and Mixture proportioning

Portland pozzolona cement conforming to IS 1489-1991(Part 1) for PPC (Fly-ash based) was utilized as the cementing material. Crushed granite rock of 12.5 mm nominal size with a 6.67 fineness modulus was used as coarse aggregates. The coarse aggregate had a specific gravity of 2.7 and absorbed 0.7 percent of water during 24 hours. The fine aggregate for all mixtures was locally purchased manufactured sand. The water absorption and specific gravity of M-sand were 0.96 and 2.6 %, respectively, confirming to Zone II with a fineness modulus of 2.72. Plastic waste aggregate (PWA) was the raw product of plastic recycling industries. The plastic bag waste, made out of low- and high-density polyethylene (LDPE and HDPE), recycled at a local recycling unit in Mettupalayam, Puducherry (UT), India, was utilized as a partial replacement for fine aggregate in this study. Glass cullet with a nominal size of 10 mm, specific gravity of 2.45, and a water absorption percentage of 0.01 was hand-crushed from scrap glass. It was determined that the initial and final setting time of the cement were 310 and 160 minutes, respectively. The soundness, standard consistency and specific gravity of the cement were found as 0.5mm, 33.5 %, and 2.9 respectively. A high-range water reducer based on sulfonated naphthalene formaldehyde that complied with IS 9103-1999 made up the superplasticizer, which had a specific gravity of 1.2. Throughout the investigation, local potable water meeting the requirements of IS 456 (2000) was utilized.

The conventional concrete mixture of M30 grade strength (M0) served as the reference concrete mixture was proportioned with IS 10262 (2019). The M5PA, M10PA, and

M15PA mixtures were plastic waste aggregate (PWA) mixtures in which the conventional fine aggregate was replaced volumetrically at 5, 10, and 15 %. The M5PA10G, M10PA10G, and M15PA10G, mixtures were developed from PWA concrete mixtures with additional substitution of 10% glass cullet by weight of total aggregate of the respective PWA concrete mixtures. A laboratory pan mixer was employed for mixing the concrete ingredients thoroughly. Following this, the concrete was placed in the requisite numbers of 100 mm cube moulds and other respective moulds at three equal layers. Care was given to ensure proper compaction of each layer through the laboratory table vibrator was done. The cast specimens were water-cured for 28 continuous days following which they were subjected to experimental investigations. The ratios of the different concrete mixtures studied in this work are given in Table 1.

Table 1. Proportions of investigated concrete mixtures and its compressive strength.

Concrete mixture	***FA (kg/m^3)***	***CA (kg/m^3)***	***PWA (%)***	***PWA (kg/m^3)***	***10% WG (kg/m^3)***	***f_{ck} (MPa)***
M0	*816*	*956*	*0*	*0.00*	*0*	*37.8*
M5PA	*775*	*956*	*5*	*16.5*	*0*	*36.5*
M10PA	*734*	*956*	*10*	*33.0*	*0*	*34.0*
M15PA	*693*	*956*	*15*	*49.4*	*0*	*31.0*
M5PA10G	*697*	*860*	*5*	*16.5*	*173*	*37.2*
M10PA10G	*660*	*860*	*10*	*33.0*	*169*	*36.4*
M15PA10G	*624*	*860*	*15*	*49.4*	*165*	*35.2*

3. Experimental Program

This experimental program encompasses seven variants of concrete mixtures. Requisite numbers of cube specimens were cast and water cured for 28 days curing period. At the which, the cubes were subjected to durability tests such as, water absorption, sorptivity, acid and alkali medium exposure conditions and chloride ion penetrability. The results of the experimental investigations throw light on the pore structure of the PWA concrete mixtures. The durability characteristics of concrete mixtures are directly dependent on its pore structure. The microstructure of the concrete was further analyzed using SEM and EDX.

3.1. Durability Performance

3.1.1 Water absorption test

The test was carried out with the specifications of ASTM C642-2013. Requisite numbers of 100 mm cubes from each type of investigated concrete mixtures were oven-dried at 100 ± 5°C for 24h. Following which, the cubes were cooled in the laboratory at 24 ± 2°C. Figure 1, shows specimens in the oven. The oven dried cooled specimens were noted for its initial weights (W_1), and then submerged in a water tank (21°C) for 48hours. At the end of the water immersion period, the specimens were removed from water tank made surface dried and their final weights (W_2) were recorded respectively. The increase in their respective weights caused by water absorption was demonstrated as percentage of the mass of the dry specimen. Thus, the water absorption computation of each test specimen was performed using Eq(1).Where,W_1 and W_2 is the oven dry and surface dry weight of cube specimens.

$$\text{Water absorption } \% = \frac{(W_2 - W_1)}{W_1} \times 100 \qquad \text{-----(1)}$$

Figure 1. Cubes placed in Oven

3.1.2. Sorptivity test

The capillary ingress of water in concrete is measured directly using the sorptivity test. Concrete's sorptivity or capillary suction is thought to be a good indicator of the quality of its surface. It gives essential details regarding the pore structure, pore diameters, and capillary continuity, as well as how well the concrete can absorb and transport water under unsaturated circumstances (Adamu et al., 2022). The test was performed as per ASTM C 1585-2013. The samples were dried for 72 hours at 100 °C in an oven. The samples were then maintained at room temperature for 24 hours. Subsequently, an epoxy

coating was applied to the peripheral sides of the specimens. The initial weights (W_1) of the specimens were recorded using the weigh balance shown in Figure 2 (a). The specimens were then placed in a tray containing water to a depth of 5 mm. Care was taken to ensure that the specimens were exposed to water only on its bottom side, as shown in Figure 2 (b). At pre-determined time interval specified in ASTM C1585-2013, the specimens were taken out from the water tub, wiped off the excess water from the bottom surface and the weights were recorded in order accordingly. The test starts initially at 2 min time interval, followed by doubling the time intervals till initial 6 hours. The specimen weights were noted at 24 hours' time intervals for continuous 7-day time period. Sorptivity was calculated from the following Eq(2) Where, I is the absorption in mm, m_i is specimen mass at time t in g, a is the exposed area of the specimen in mm^2, d is the density of water in g/mm^3.

$$I = \frac{m_t}{a \times d} \qquad \text{-----(2)}$$

(a) (b)

Figure 2. (a) Weighing balance (b) Cubes placed in 5 mm depth water bath

3.1.3. Acid exposure

The requisite number cubes pecimens of various concrete mixtures of this study were allowed to dry for one day at room temperature following their 28 days water curing period. The initial weights were recorded respectively. The cubes were subjected to lab test that simulated the environment of sewage pipes, by placing the specimens in a tub filled with diluted acid (5 % sulphuric acid) for a period of 60 days. As per the ASTM C1898-20 standards, sulphuric acid (H_2SO_4) solution with a pH value of 2 was prepared by adding 5 % by weight of sulfuric acid in the water of required volume to accommodate the cubes. Figure 3, depicts the process of storing and submerging the concrete cubes in this acidic solution for 60 days. The pH of the acid solution was maintained at 2 throughout the test period. The specimens were removed from the acid medium and rinsed with tap water to get rid of any lingering reaction products during the 60-day test period. The cube surfaces were dried at room temperature for 30 min

following which their relative final weights after exposure to acid were noted. The cubes were then subjected to compressive crushing load in the laboratory compressive testing machine. Concrete degradation exposed to sulfuric acid assaults was evaluated using the percentage of strength loss and weight loss of the acid-immersed cubes as compared to its initial values.

Figure 3. Cube specimens subjected to acid medium exposure condition

3.1.4. Sulphate exposure

The sulphate exposure test was performed with sodium sulphate solution with 5 % concentration at lab temperature (23±2°C). To ensure complete immersion of test specimens in the solution, the volume of the sulphate solution was taken to be four times the volume of the submerged concrete specimens. As shown in Figure 4, specimens were submerged in the solution for 60 days. Every week, the exposure solution was mixed, and it was changed accordingly to match its initial concentration. Throughout the test period the pH of the sulphate water content was checked and maintained. The concrete cubes were taken out of the sulphate water after 60-day immersion period, and cleaned of water and debris, their final weights were recorded and the cubes were tested for compressive strength test following the guidelines of IS: 516- 1959.

Figure 4. Cube specimens placed in alkaline medium

3.1.5. Mass loss and strength loss

The mass loss observed demonstrated the concrete deterioration. With a 0.01 g precision, the initial weights of the specimens were recorded as W_1. The final weight at the end of 60 days of severe environment exposure conditions were recorded as W_2. Thus, the loss percent in mass, observed in the respective cubes was determined using the expression given below.

$$\text{Mass loss } \% = \frac{W_2 - W_1}{W_1} \times 100$$

Similarly, strength loss was determined with compressive strength test values recorded for the respective cubes in ambient room temperature as initial strength (f_{ck1}). And the final compressive strength of acid or alkali exposed cubes as (f_{ck2}).The expression below gives the loss percentage experienced in compressive strength.

$$\text{Strength loss } \% = \frac{f_{ck1} - f_{ck2}}{f_{ck1}} \times 100$$

3.1.6. Rapid chloride permeability

The Rapid Chloride-ion permeability test (RCPT) in accordance with ASTM C1202, was conducted to evaluate the concrete's resistance to chloride ions ingress. Concrete disc specimens measuring 100 mm in diameter and 50 mm thick, were fully wet with water is installed in the rapid chloride permeability test (RCPT) apparatus as shown in the Figure 5. The specimen is encased by reservoirs containing, 3.0% NaCl solution in one cell and 0.3 M NaOH solution in the other cell as shown in Figure 5. Electrical charge is allowed to pass through the specimen at a constant potential of 60 Volts for 6 hours duration. The chloride ion movement was recorded in terms of total charge passed in coulombs at every

30 minutes interval and the total charge passed through the specimens were calculated using the expression given in Eq.(3).

Figure 5. Rapid chloride penetrability test apparatus with specimens

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + 2I_{90} + 2I_{120} + \cdots + 2I_{300} + 2I_{330} + 2I_{360}) \quad \text{---(3)}$$

Where,

Q = Charge passed in coulombs

I_0= Initial Current in amperes on application of voltage

I_t = Current in amperes at t minutes after voltage is applied

4. Results and Discussion

4.1. Water absorption test

The test results determined from the weight change experienced in various concrete composites before and after water immersion are given in Table 2. The water absorption values of concrete mixtures with PWA and PWA with GC as partial substitutes for fine aggregate were observed in the same range as that of the conventional concrete mixture. Invariantly, the average water absorption of three samples in each type of concrete mixture was observed to range from 1.28 % to 1.36 %, given in Table 2. A comparative graphical representation of the water absorption witnessed in the concrete composites is shown Figure 6. A maximum of 1.36% water absorption was observed in the conventional concrete mixture and a minimum of 1.28 % water absorption was observed in the PWA mixture with 15% PWA substation. The pozzolanic activity and the water-repellent properties of PWA resisted water absorption in longer curing periods is the main causes of the decrease in water absorption. By incorporating 10% glass cullet into

PWA concrete mixture, water absorption of PWA GC mixtures has been increased. Porosity of concrete got increased by the glossiness of glass culet and the smooth texture of PW aggregate, whereas water absorption got decreased by the larger volume replacement. Nonetheless, PWA GC mixture water absorptions were lower than those of conventional concrete. This finding correlate with the previous studies (Babafemi et. al, (2022) and Steyn et al (2021)).

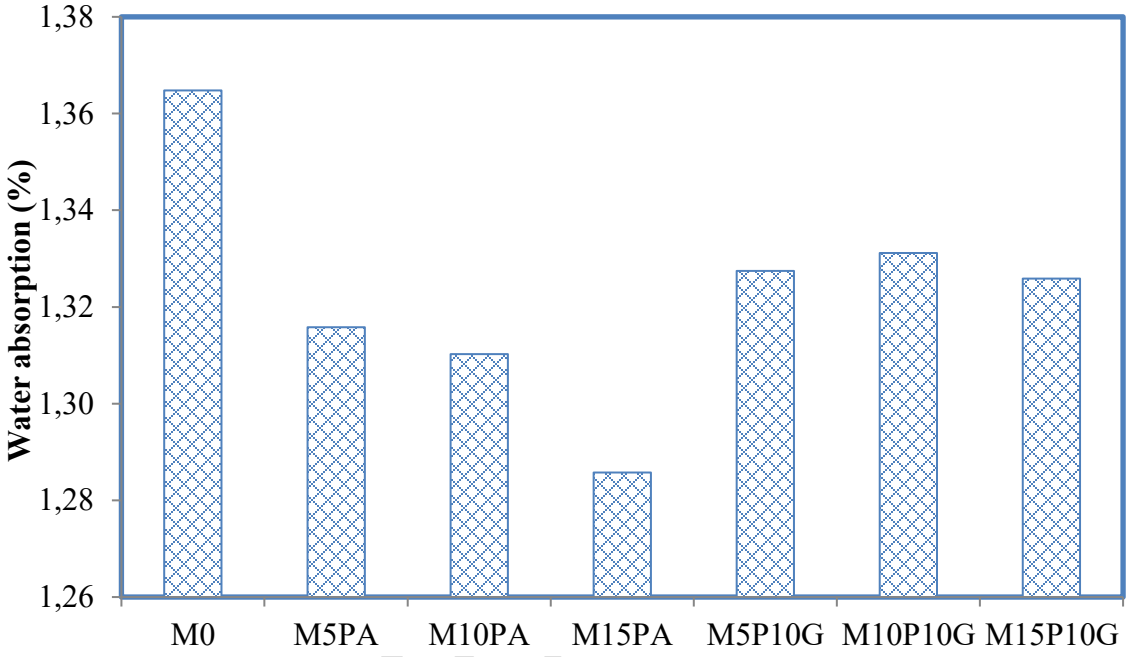


Figure 6. Graphical representation of water absorption in concrete mixtures

4.2. Sorptivity

The water absorption rate in capillary suction is delineated as primary and secondary rate of absorption with respect to time duration. Primary water absorption rate is concerned with the initial capillary suction witnessed by the dry concrete samples from the test starting time to 6 hours duration. Usually, the larger pores in concrete get saturated faster initially, resulting in a rapid water absorption rate during the initial hours of test period (0 to 6 hours). Large capillary holes close to the submerged face were quickly filled with water, continuing the absorption rate, while smaller pores farthest from the immersed face fill more slowly. The Secondary rate of water absorption in the capillary suction of the concrete samples witnessed slower water movement following the 6^{th}hour of the test to the 7^{th}day of the test. Comparative graphical plot was developed for the water absorption rate versus square root of time for the PWA concrete mixtures and PWA GC concrete mixtures with respect to conventional concrete is shown in Figures 7 and 8 respectively. The slope of best-fit line of the primary and secondary water absorption

rates calculated using data records of the specimen's mass variations from 1 min to 6 hrs. for primary absorption and from 6 hrs. to 7 days for secondary absorption are given in Table 2. Except, for the PWA concrete mixtures with 5% and 15% PWA substitutions, the remaining PWA modified concrete mixtures showed decrease in the water absorption rate at both initial and secondary test stage, compared to conventional concrete mixture. This might be due to localized agglomeration of PWA due to improper mixing of concrete ingredient materials. The PWA concrete mixtures with 10 % glass cullet as added substitution performed with lower water absorption rates compared to the reference mixture. The results are found to follow the previous work by (Alani et.al., (2019)).

Table 2. Water absorption of concrete mixtures

S.No.	***Mixture***	***Water absorption %***	***Rate of water absorption (S) mm / $\sqrt{s}$***	
			Primary (0 hr. to 6 hr.)	***Secondary (6hr. to 7 days)***
1	*M0*	*1.365*	*0.0078*	*0.0017*
2	*M5PA*	*1.315*	*0.0110*	*0.0021*
3	*M10PA*	*1.310*	*0.0065*	*0.0014*
4	*M15PA*	*1.285*	*0.0095*	*0.0019*
5	*M5P10G*	*1.327*	*0.0064*	*0.0014*
6	*M10P10G*	*1.331*	*0.0044*	*0.0011*
7	*M15P10G*	*1.325*	*0.0077*	*0.0014*

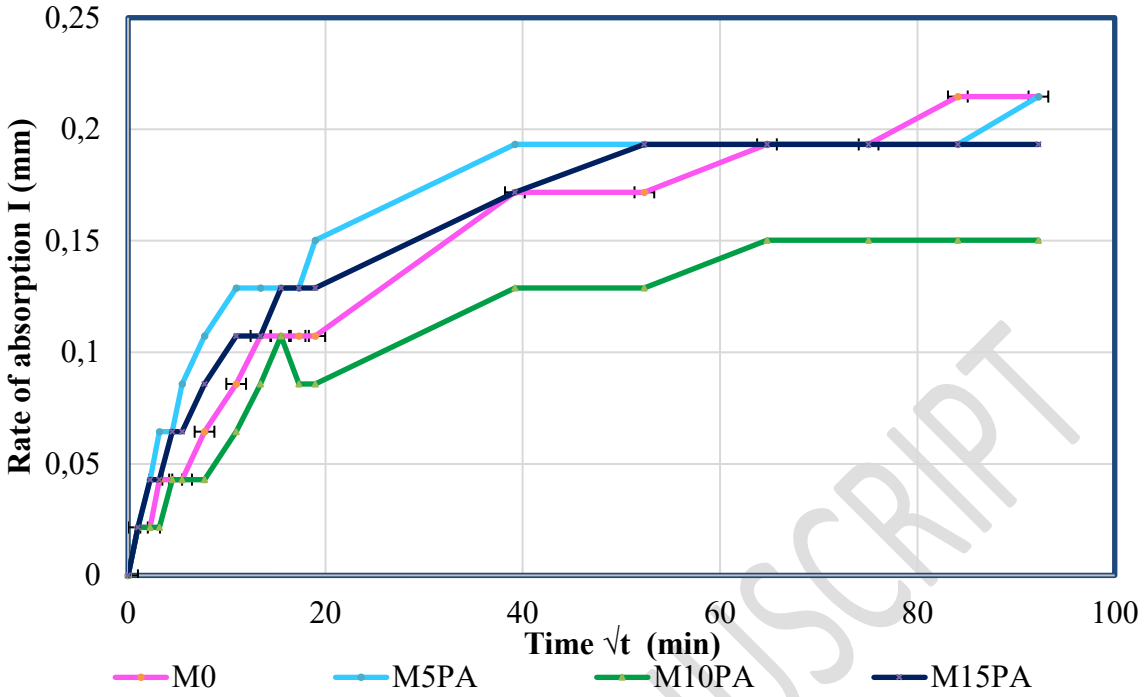


Figure 7. Sorptivity coefficient of PWA concrete versus reference mixture

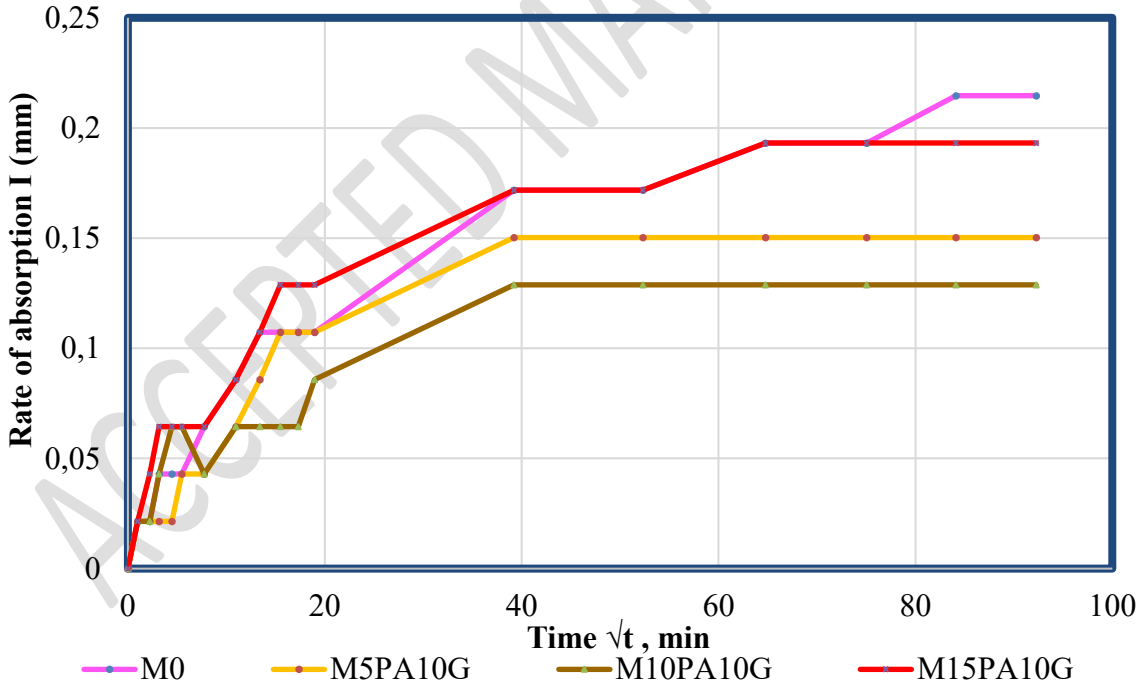


Figure 8. Sorptivity coefficient of PWA GC concrete versus reference mixture

4.3. Exposure to sulphuric acid

Mass loss of the acid exposed concrete specimens results from acid penetrating the concrete and dissolving the cement paste binder creating soft and soluble gypsum which combines with water and tri-calcium aluminate and produces expansive ettringite. This expansion of ettringite induces tensile stresses in concrete leading to development of micro cracks that result in spalling of concrete (Arash et al., 2023; Hama 2022). Conventional concrete cubes experienced the maximum weight loss of 14.7 % and the mixture with 15 % PWA substitution experienced the minimum weight loss of 9.5 %. The PWA granules act as barriers within the cement matrix retarding the formation of ettringite and at the same time accommodates the produced ettringite in the voids at its proximity which reduces matrix deterioration to some extent. A comparative graphical representation of the mass variations observed in the concrete specimens before and after acid exposure is shown in Figure 9. The loss in compressive strengths experienced by acid exposed concrete specimens was gauged with respect to their normal cured 28 days compressive strength and 60 days compressive strength individually and is shown in Figure 10. The residual compressive strength observed in conventional concrete (M0) specimen accounts to be the minimum observed (18.39 MPa) among the investigated concrete mixture compositions. And, it was found to impressively increase with increase in PWA substitution percentage in the concrete. However, the PWA concrete mixtures with GC as added substitution performed comparatively better with the maximum residual compressive strength of 23.7 MPa. The reason that plastics are non-polar materials, they do not react with acids and hence the concrete mixtures with plastic aggregates perform better when immersed in acid medium comparatively. Similarly, glass cullet is also an acid-resistant material for most acids. Therefore, the use of plastic aggregate and glass cullet ensures the concrete to withstand adverse acidic environments.

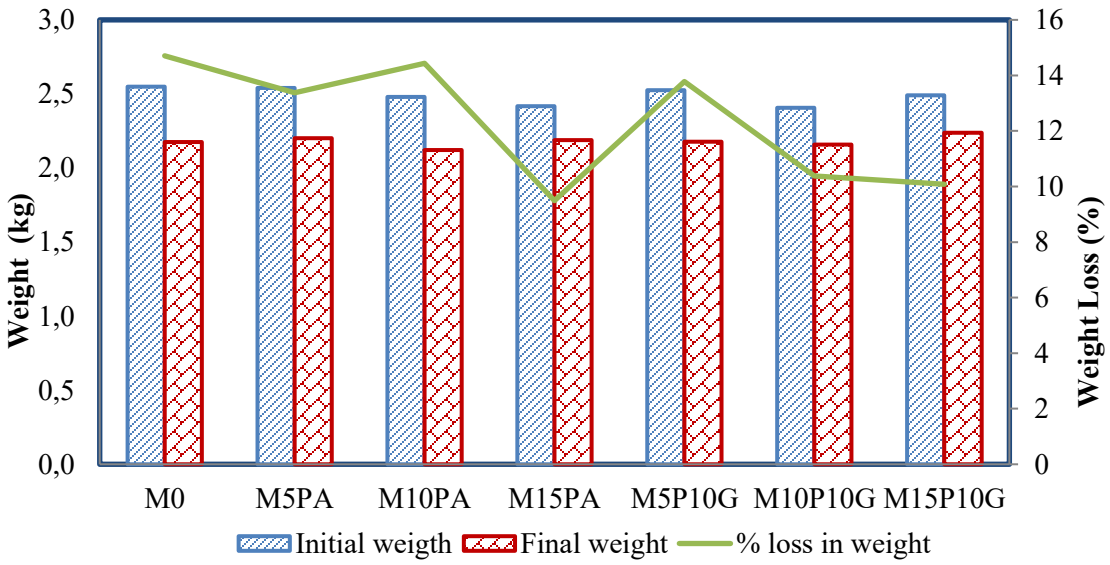


Figure 9. Weight loss observed with respect to initial weight

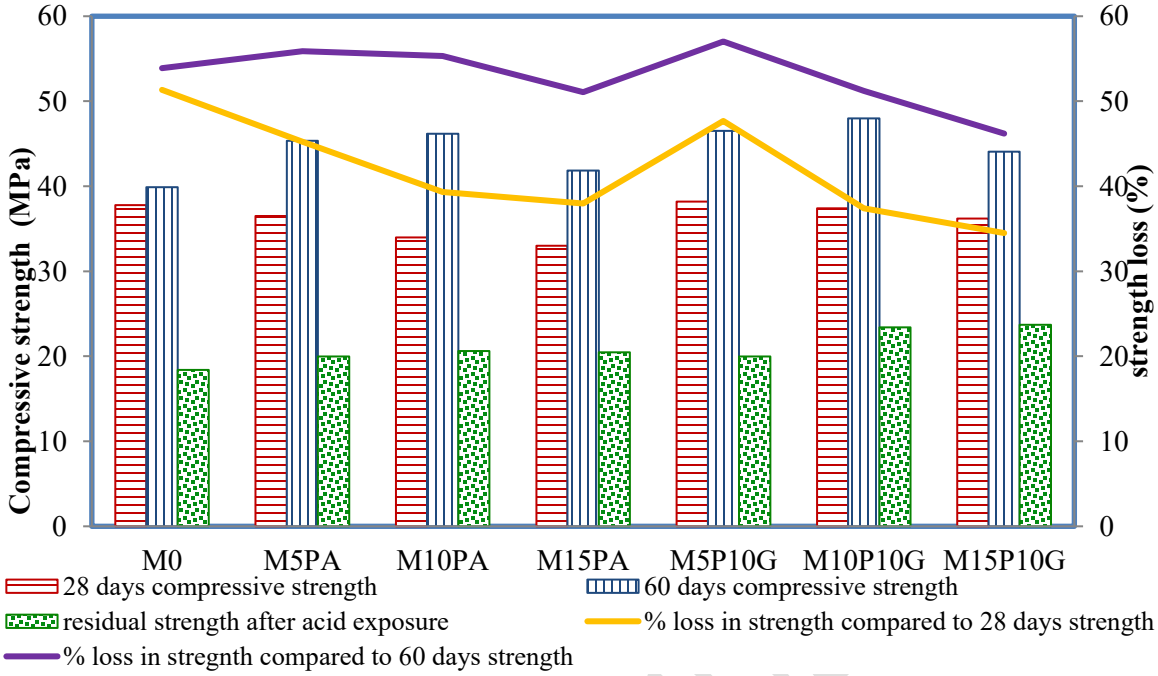


Figure 10. Residual compressive strengths of the mixtures

4.4. Sodium sulphate immersion

Unlike the mass variations observed in acid exposed specimens, the sodium sulphate exposed specimens exhibited negligible mass gain invariant of mixture composition. This positive change in weight followed an increasing trend with an increase in the substitution percentage of PWA in concrete. The weight gain exhibited among the various investigated concrete mixtures ranged from 0.3 % to 0.6 %. The graphical plot comparing the mass variation exhibited in the various PWA and PWA GC concrete composites with the conventional concrete is shown in Figure 11. The weight gain is attributed to the formation of ettringite in concrete mixture. The ettringite increases the solid volume of concrete mixtures leading to expansion which in the absences of sufficient free space leads to cracking. However, the voids around the PWA granules in concrete are filled by the ettringite (calcium aluminate trisulphate) formed by the chemical reaction of sulphate ion with hydrated calcium aluminate in the presence of calcium hydroxide (Abu-Saleem et al., 2021; Mohammadhosseini et al., 2021; Haikuan et al., 2022). The non-reactive plastics retards the ettringite formation to some extent and at the same time accommodates the produced ettringite in the voids associated with it. The maximum weight gain of 0.6 % was noticed in the M10P10G mixture and the minimum weight gain of 0.28 % was noticed in the conventional concrete M0 mixture. A

comparative graphical plot for the strength variations observed in the concrete mixtures with respect to the curing days and exposure condition is shown in Figure 12. In general, the compressive strength of the mixture composites increased with the increase in the curing days. The fly ash based PPC binder employed in this study is the attribute for the increase in strength at later age of concrete. In particular, the PWA and PWA GC concrete mixtures exhibited prominent increase in strength with increase in curing days. The pores associated with the non-hygroscopic PWA afford space for the C-S-H gel expansion at the later curing ages of concrete. The sulphate exposed specimens also witnessed the same trend of increase in strength with increase in the substitution percentage of PWA. In this case the reason being that the pores associated with PWA in concrete affords space for the expansion of ettringite formed when exposed in sulphate medium. The typical M0 combination has a characteristic cube compressive strength of 37.8 MPa and a 60 days compressive strength of 39.8 MPa, whereas, it was observed with 40.35 MPa on 60 days of sulphate exposure. Similarly, the plastics aggregate mixtures and the glass cullet added plastic aggregate mixtures were noted with strength gain percentages ranging from 22.6% to 43%. The micro-pores associated with plastic aggregates provide space for the expansion of sulphate ion-reacted cement paste. Stronger bonding between the constituents, which increases the compressive strength of the composites, maybe the cause of the extended bonding of the thick concrete interface.

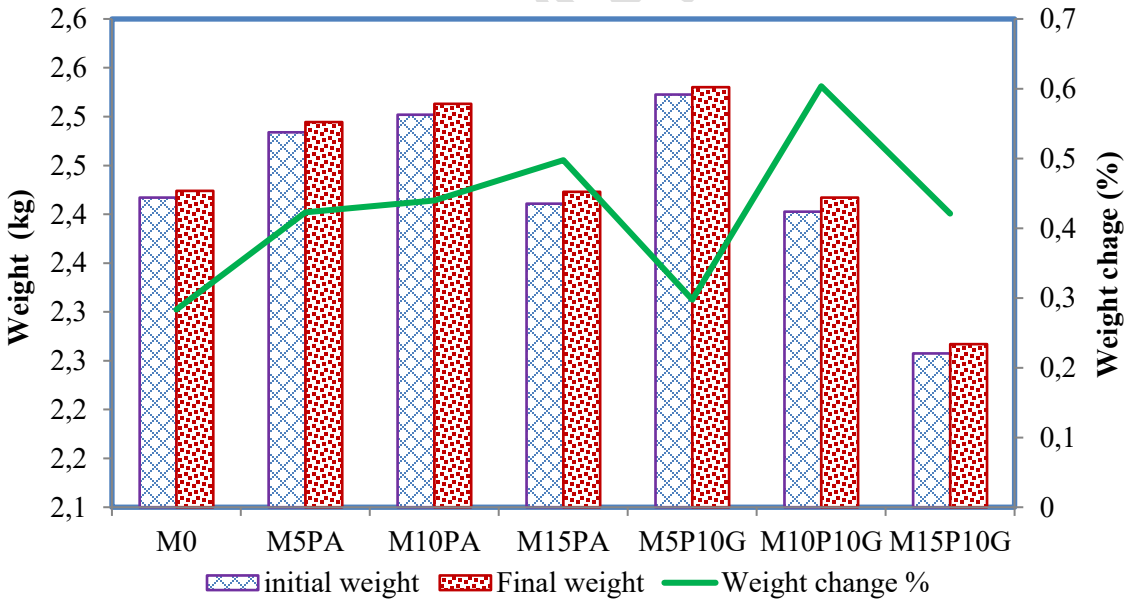


Figure 11. Weight gain of the mixtures with respect to initial weight

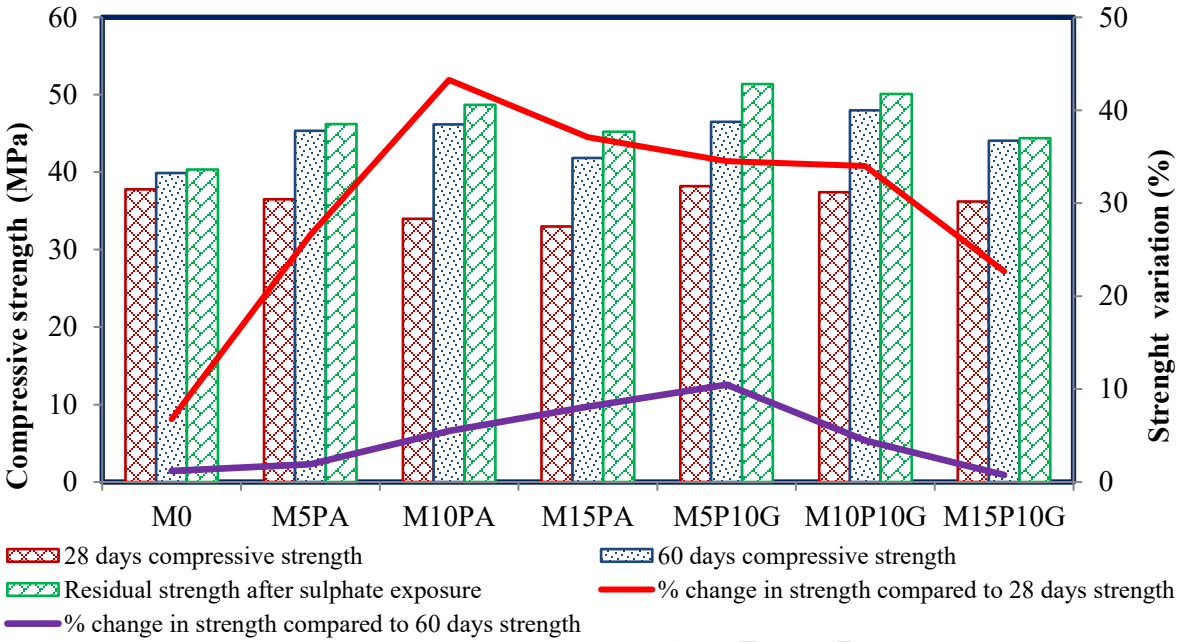


Figure 12. Residual strength observed in the mixtures

4.5. Rapid Chloride penetrability test

The concrete mixtures quality is evaluated from its resistance to chloride ion ingress measured in terms of charge passed. The ASTM C 1202 classifies the chloride ion penetrability of concrete with respect to charge passed (Coulombs) through it. In this study, average charge passed through two specimens from each mixture proportioned was tested for its resistance to chloride ion ingress. The range of chloride ion ingress observed in the studied concrete mixtures was from 363 Coulombs to 1362 Coulombs, which is well within the low chloride ion penetrability range. Anyhow, the chloride ion ingress was found to increase with increase in substitution percentage of PWA in concrete. Nevertheless, it was observed that the chloride ion ingress decreased with the introduction of 10% GC as additional substation in PWA concrete mixtures. Graphical representation of the studied concrete mixtures chloride penetrability along with the range specified in ASTM C 1202 is shown in Figure 13. It is obviously evident that the PWA concrete mixtures with 10% GC showed very low chloride ion ingress comparatively.

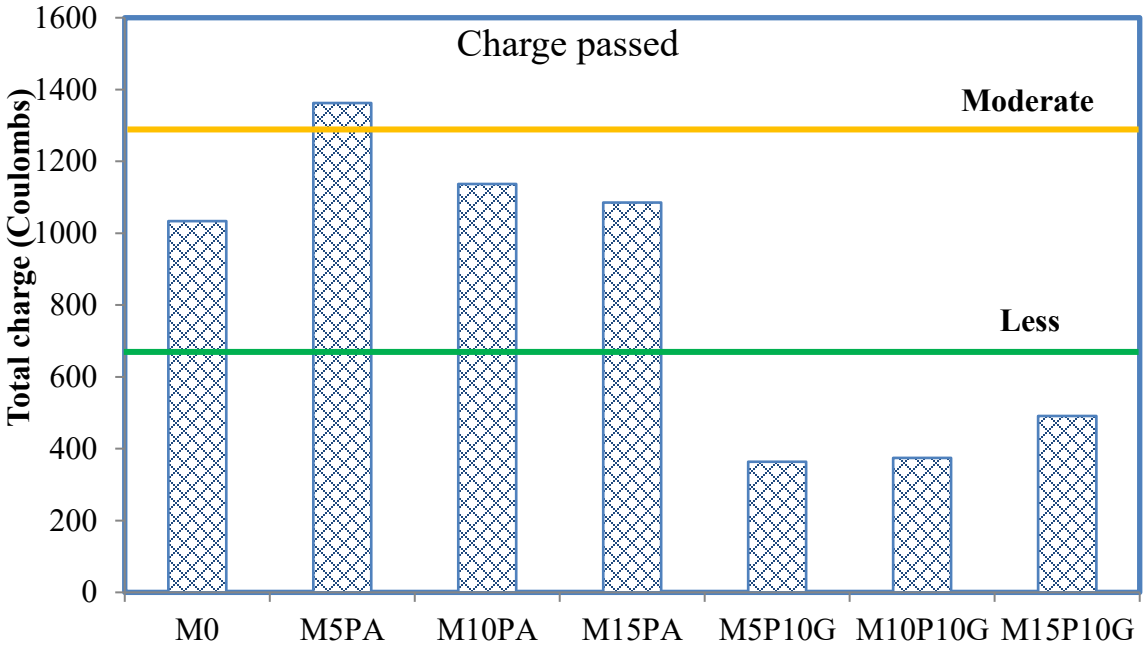


Figure 13. Chloride ion penetrability of concrete composites

4.6. Microstructural Properties

One unique way to determine the microstructural characteristics of concrete is to study its microstructure. A widely utilized tool or technology to depict the microstructural behavior of concrete along the hydration process is the scanning electron microscope (SEM). This allows tovisualize the precise internal characteristics of the concrete. The information gathered from the microstructural investigation helps to comprehend the special behavior of concrete and the presence of small compounds within the solidified paste of cement concrete. The different combinations of concrete mixtures studied in this research work were measured for their respective microstructural characteristics using the SEM pictures created through back scattered electron (BSE) imaging. High-resolution imaging from scanning electron microscopy, or SEM analysis, is helpful for examining different materials for surface cracks, defects, impurities, or corrosion. During the SEM examination process, energy dispersive x-ray spectroscopy, commonly known as EDX, EDS, or EDX, offers further insight into the surface material. The elemental composition of a sample is determined by EDX analysis, which yields more precise results along with SEM. A thorough examination of the metallurgical process is provided by the combination of SEM and EDX analysis, which provides chemical composition and elemental study.In EDX, characteristic Xray's are generated to reveal the elemental composition of specimens. This method uses electron microscopy to generate characteristic X-rays. In this study, the mixture proportions mentioned were tested for its elemental compositions at normal, acid exposed and alkali exposed condition. The

elemental compositions of the produced concrete mixtures were compared with the elemental composition of reference concrete at three exposure conditions.

The elemental composition present in the seven studied mixtures at three different exposure conditions show variations in weight percentage with the various substitution percentages of PWA and PWA GC. From figure 14,15 and 18, it is obvious that the amount of oxygen the dominant element in concrete exhibits negligible variations with varying PWA and PWA GC substitutions at normal exposure condition. Whereas the same element exhibits a decrease with increase in PWA and PWA GC substitutions at acid exposure conditions. In the sulphate exposed condition oxygen in the studied concrete mixtures experiences minimal variations. Except for M5PA and M10PA10G the remaining mixture compositions exhibit decrease with increasing substitution levels of PWA and PWA GC. The elemental composition of Calcium, Iron and Magnesium decreased with increase in PWA and PWA GC substitution percentage in both normal and acid exposure condition of concrete mixture compositions. These three elements react with Oxygen to produce major oxides in concrete which attributes to the reduction of these elements in the mixtures with PWA and PWA GC. The three above mentioned elements showed a fluctuating trend in the variations of their elemental compositions of alkali exposed concrete mixtures. The elemental composition of Silica and Aluminum increased with increase in PWA and PWA GC substitution percentage invariantly in the three exposure conditions of concrete mixtures. Although, PWA is chemically inert at room temperature, the results obtained from this work showed the existence of some level of chemical reactions within the concrete matrix due to PWA and GC during the hydration period of concrete at varied exposure conditions.

The test samples of the concrete mixtures of three varying exposure conditions (Normal, Acid and Alkali) subjected to EDX rays to determine the peak positions of elements in it specifically. The intensity (height) of each element is proportional to its relative abundance in particular concrete mixture. The peak positions of the elements present in the test samples of various investigated concrete mixtures are shown from figures 14 to 20. The spectrum from concrete samples illustrates the mineral's characteristic composition with oxygen (O), ferrous iron (Fe), and calcium (Ca) being dominant elements followed by aluminum (Al) and silica (Si) elements equally dominant. It is measured in kilo-electronvolts (keV) on the horizontal axis. The concrete mixtures showed high intensities of oxygen (O) with peak positions at 0.5 keV invariantly. Calcium exhibited the highest intensity with its peak positions at 0.5 keV and 3.8 keV in almost all the concrete samples invariantly. The concrete mixtures invariantly exhibited high intensities of silica exhibited with peak position at 1.8 keV. The concrete mixtures exhibited comparable intensities of ferrous iron with peak position at 0.5 keV and 6.5 keV. Intensities of ferrous iron was absent in acid exposed reference mixture and normal exposed 5 % PWA with 10 % GC (M5PA10) mixtures. Carbon (C) composition was

noticed in the acid and alkali exposed 15 % PWA (M15PA) concrete mixture. Hence, it is obvious that plastic granules in higher PWA substitutions concrete mixtures when exposed to adverse environments (acid and alkali) involves in chemical reactions with acid and or alkali resulting in the formation of carbon. Nevertheless, the no trace of element carbon is exhibited in the 15% PWA mixture enhanced with 10 % GC as additional substitution. Further, ensuring the enhancement rendered by glass cullet in higher substitution levels of PWA concrete is evident. The other elements such as aluminum, magnesium, titanium, sodium and chlorides are found with lower intensity invariantly in all the studied concrete mixtures. Potassium is exhibited at equally high intensity of peak position at 3.8 keV along with the element calcium in the studied concrete mixtures, except for certain mixtures such as acid exposed reference mixture M0 and 10 % PWA with 10 % GC (M10PA10G), 15 % PWA concrete in all three exposures and in mixture with 15 % PWA and 10% GC at normal and alkali exposure condition.

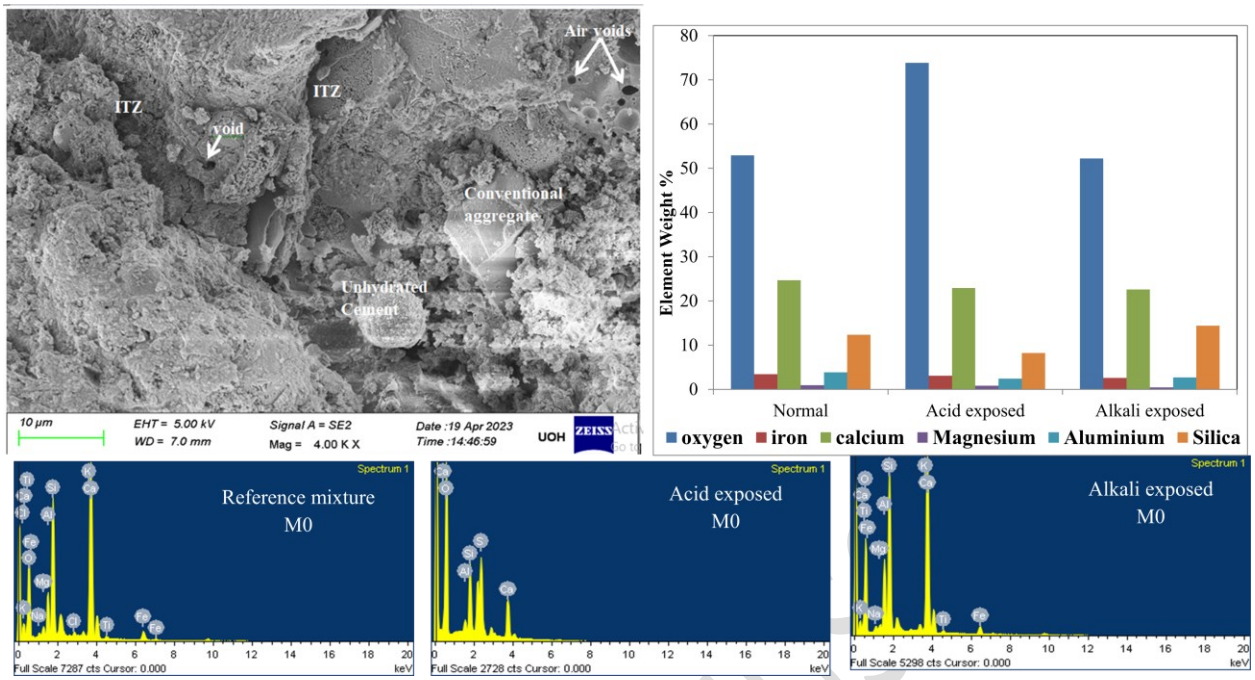


Figure 14.SEM image and its EDX results of Reference mixture

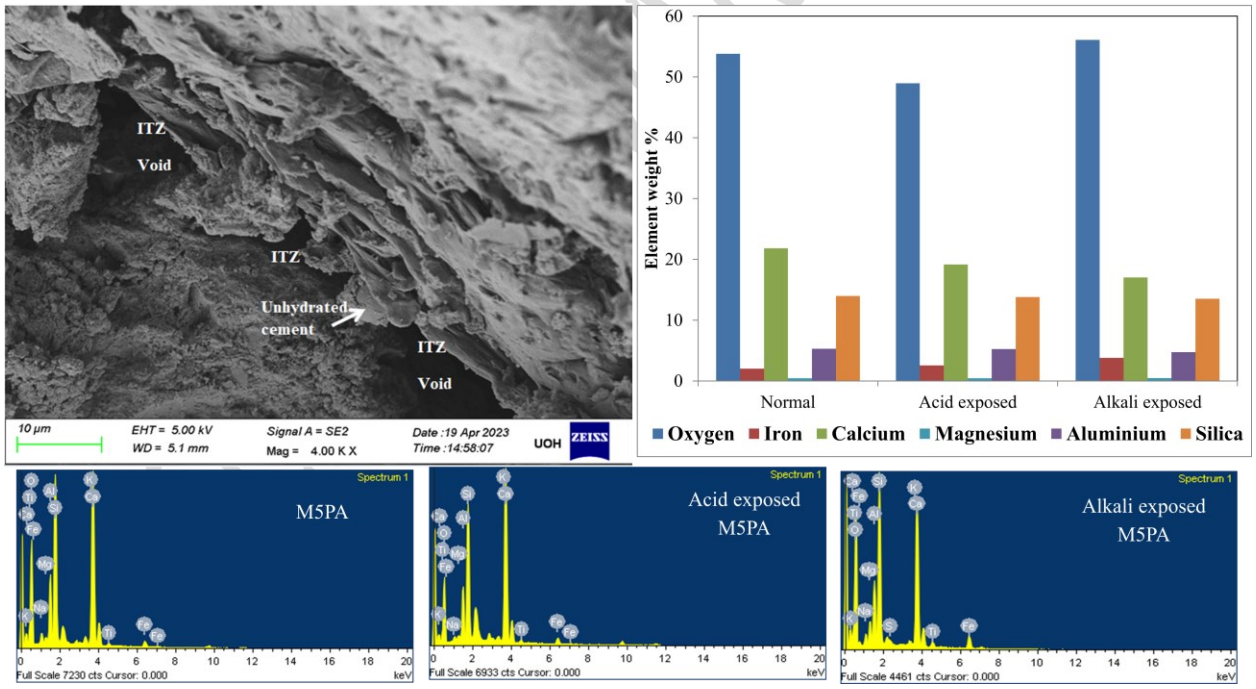


Figure 15.SEM image and its EDX results of M5PA

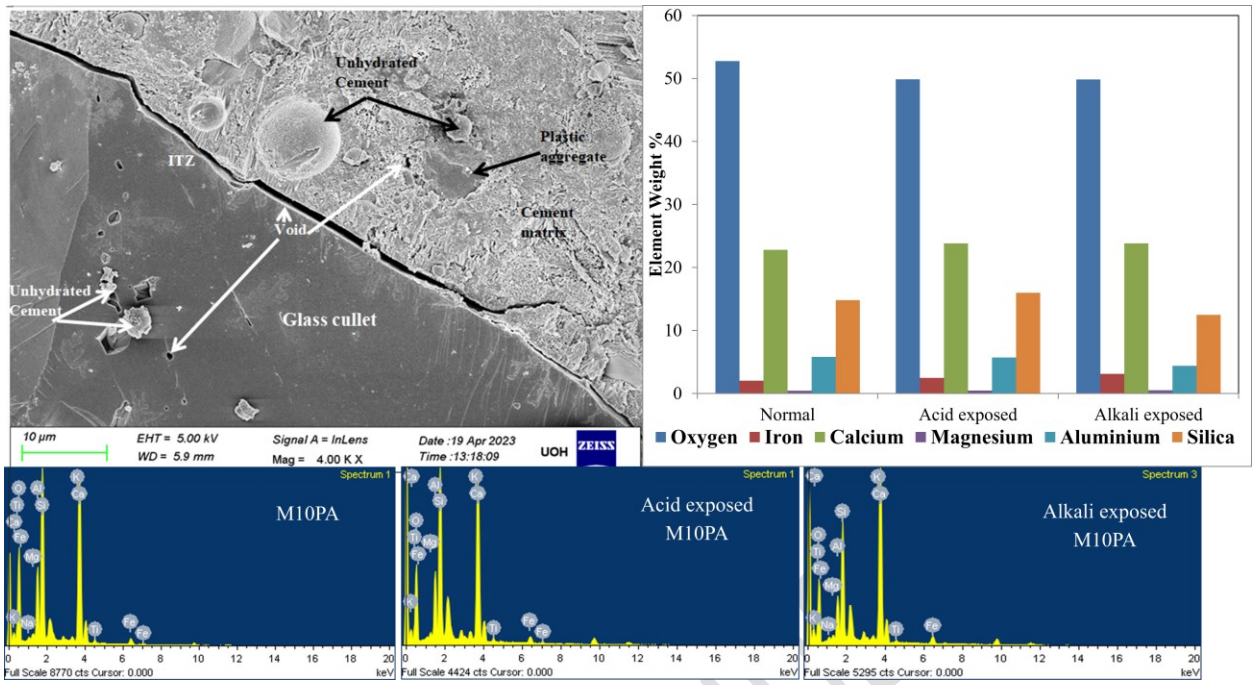


Figure 16.SEM image and its EDX results of M10PA

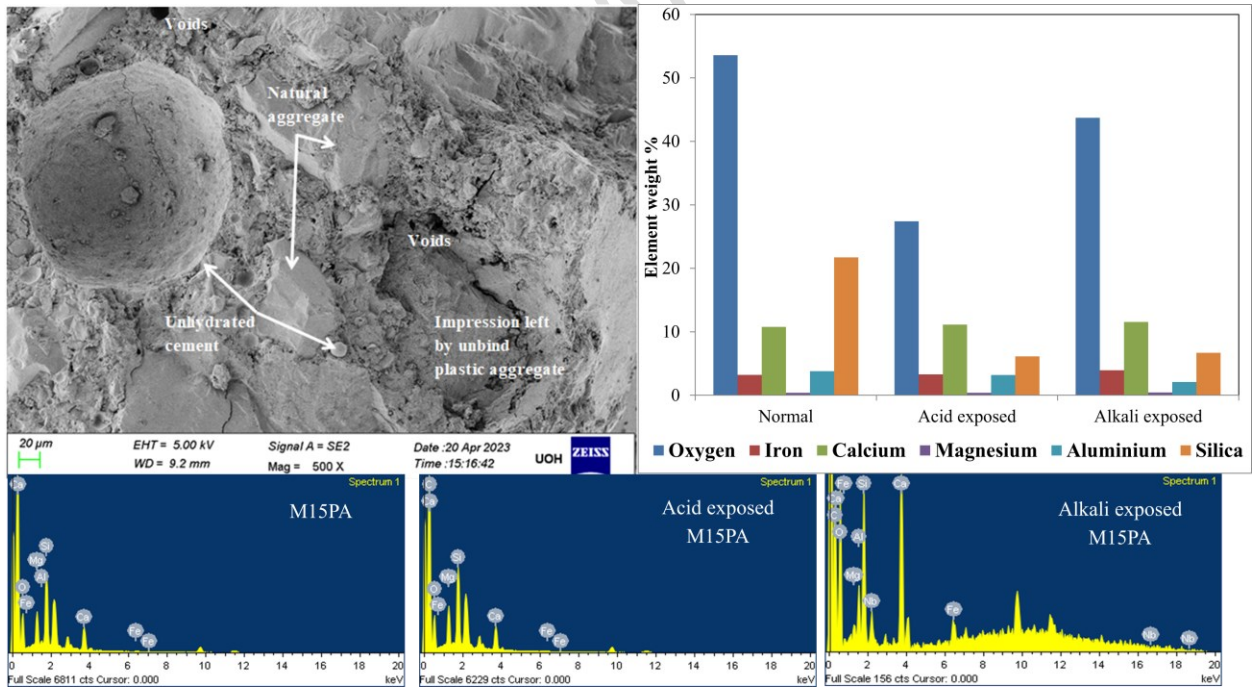


Figure 17.SEM image and its EDX results of M15PA

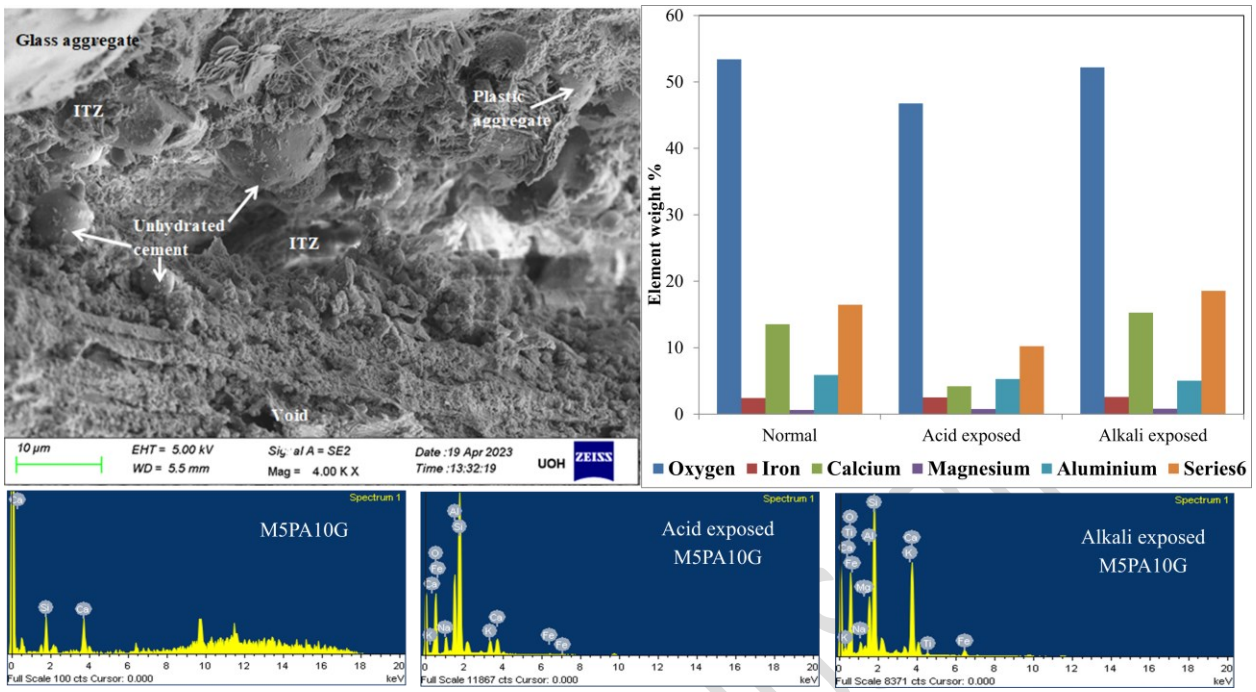


Figure 18.SEM image and its EDX results of M5PA10G

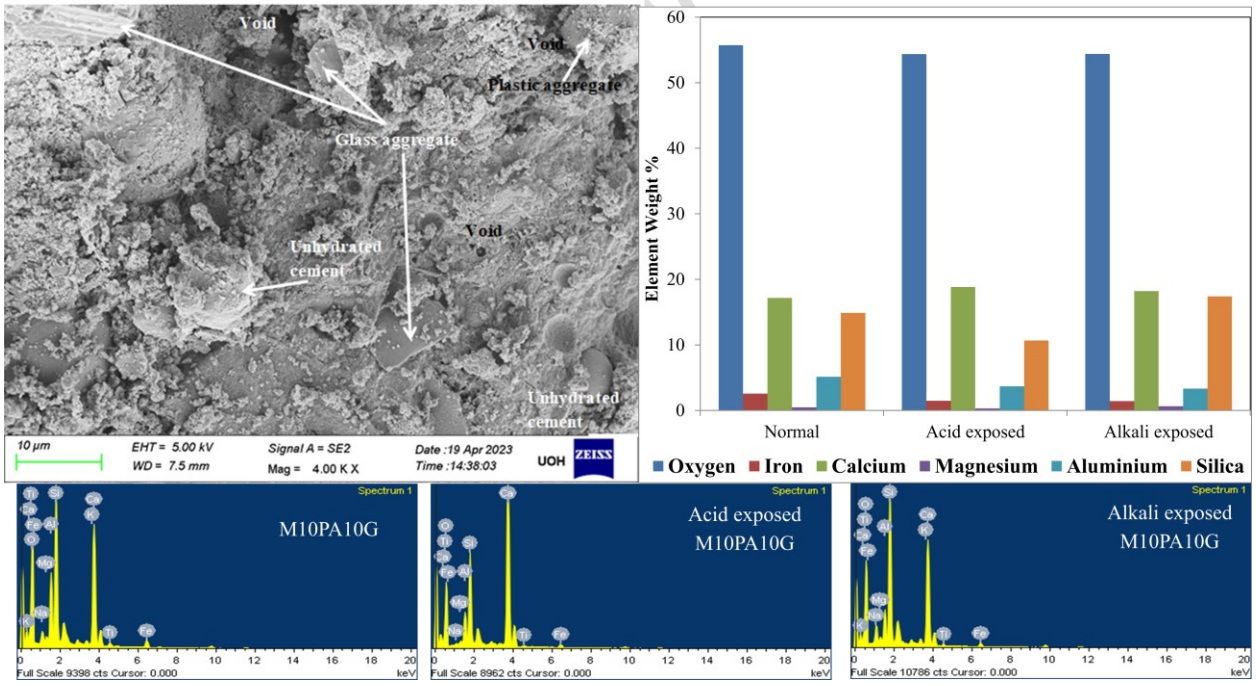


Figure 19.SEM image and its EDX results of M10PA10G

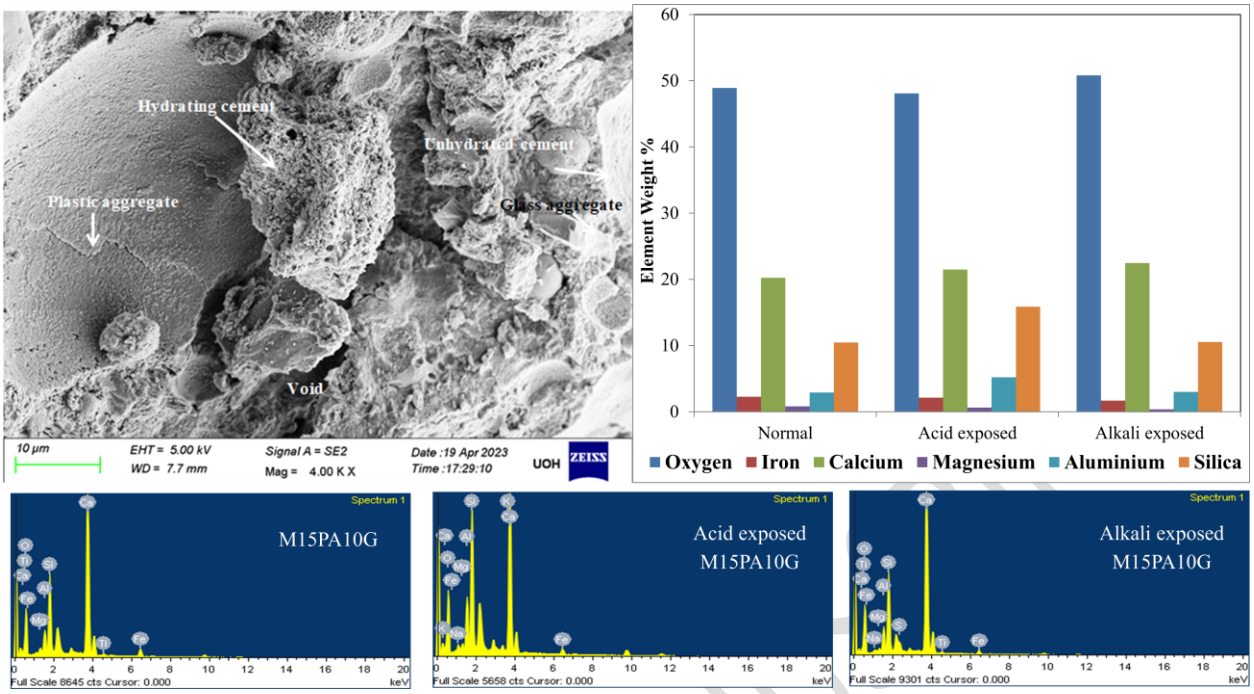


Figure 20.SEM image and its EDX results of M15PA10G

5. Conclusions

In the present work, the durability and microstructural characteristics of concrete mixtures containing PW aggregate and waste glass as partial substitutes for conventional fine aggregate were investigated. Examining the mass change and compressive strength change of the variant concrete mixtures exposed in both acid-alkali exposure conditions along with the water absorption, and sorptivity tests provides the following conclusions:

1. The introduction of PW aggregate into the concrete mixture decreased the water absorption of the mixtures compared to the reference conventional concrete mixture. The water absorption of 15 % PW aggregate mixture was noted as 1.28 % which was observed to be 5.7 % less than the water absorption experienced by the reference mixture (1.36 %). Similarly, the 10 % waste glass plus 15 % PW aggregate mixtures were observed with 1.3 % water absorption which seems to be 2.8 % less compared to the water absorption of the reference mixture.

2. The results of sorptivity analysis of the PW aggregate concrete mixture (M10PA) revealed a lower rate of capillary suction compared to conventional concrete. The addition of a 10 % waste glass cullet to the PW aggregate concrete improved the sorptivity of the mixtures in M5P10G and M10P10G.

3. The sulphuric acid exposure test on the various mixtures studied resulted in mass loss of the cube specimens compared to their respective initial weights. The reference concrete M0 was

noted with a 14.7 % loss in weight. The PW aggregate mixture M15PA was noted with a minimum of 9.5 % loss in weight. Whereas, the glass cullet PW aggregate mixture M15P10G was noticed with a 10 % loss in weight.

4. The compressive strengths of the 60 days acid-exposed cubes were observed with a strength loss of 51.3% (maximum) in reference mixture (M0). The M5PA10 mixture experienced 47.6 % loss in strength as compared to its respective normal cured cube. The loss in compressive strength was observed the minimum in M15PA10G mixture, as 34.5 %.

5. The cubes exposed in sodium sulphate solution for 60 days experienced a minimal percent of weight gain compared to their respective initial weights. A 0.28 % weight gain was noted in the reference mixture M0. The weight gains for the glass cullet PW aggregate mixtures and PW aggregate mixtures ranged from 0.3 to 0.6 percent. The M15PA10G and M10PA10G mixture experienced a 0.5% and 0.6 % weight gain respectively.

6. The reference concrete M0 was noted with a 6.7 % gain in strength, which was the minimum recorded among the studied mixtures. The strength gain experienced by the PW aggregate mixtures and glass cullet PW aggregate mixtures ranged from 22 % to 43 %. The M10PA mixture was noted with a 43 % gain in strength compared to its initial 28-day compressive strength and the M15PAmixture was noted with a 37 % gain in strength.

7. The concrete mixtures demonstrated chloride ion ingress in terms of charge passed values, ranging below 2000 Coulombs, which is specified as low Chloride Ion Permeability as per ASTM C 1202. Concrete mixtures with 10 % glass cullet performed with very low chloride ion permeability of 300 Coulombs to 500 Coulombs.

8. The SEM analysis of the studied concrete mixtures showed the existence of bond between PWA and cement matrix. However, this bond at ITZ of PWA and cement matrix is comparatively less than that exists between natural aggregate and cement matrix. This might be the reason for the decline in the studied properties of PWA concrete. Though glass cullet is used to enhance the PWA concrete, but still, it is evident that the bond at ITZ of GC and cement matrix is comparatively less than that exists between natural aggregate and cement matrix.

9. The chemical analysis showed the decrease in the elements like oxygen, calcium, silicon, with increase in PWA substitution in concrete mixtures. The elements silica and aluminum tend to increase with increase in PWA substitution percentage. The existence of some minimal level of chemical reaction within the concrete matrix due to PWA during cement hydration is obviously evident.

10. The EDX analysis revealed the dominant elements of the studied concrete mixtures at their respective peak positions. The dominance of O, Ca, and Si is evident in all the studied concrete mixtures. At higher levels of PWA substitution in concrete leads to carbon production is obviously evident from the EDX image of 15% PWA concrete. However, the incorporation of

glass cullet as additional substitution in 15 % PWA concrete does not produce carbon, ensuring the enhancement rendered by glass cullet in PWA concrete.

11. The incorporation of Glass cullet as an additional replacement along with the plastic waste aggregates works as an efficient enhancement technique employed from yet another mass waste from the solid waste system which is a novel approach of this study.

Acknowledgement

The authors would like to thank All India Council for Technical Education (AICTE) for providing financial assistance, and those who have directly or indirectly supported the research work.

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