The Influence of Incorporating Plastic within Concrete and the Potential Use of Microwave Curing; A Review

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Abstract

In recent decades, researchers have used plastic to replace natural aggregates (NAs), or as filler and fibre within the concrete. This particular paper puts forward a review that gives comprehensive consideration to the properties and drawbacks, of concrete that contains plastic. As such, it may be hypothesised that poor bond capacity and higher air content due to inclusion of plastic aggregate (PA) within concrete are the predominant factors that reduce the properties in terms of mechanics and durability. In that regard, this study has put forward a new method of curing using microwave irradiation for improvement with respect to those factors. So, that there can be further improvement with regard to overall durability with respect to advanced chemical and hydrophobic resistivity and enhanced performance for conventional concrete with respect to bonding and ductility.

Key words: microwave absorption, microwave curing, plastic, plastic in concrete.

1. Introduction

Nowadays, different types of plastics are an integral and seemingly inseparable aspect of everyday lives, and there has been steady growth in the volume of plastic that is consumed each year. The properties of plastic that are favourable include high durability, a high ratio of strength to weight, low density, long lifespan, less affected by chemical and have higher durability, fabrication capabilities, low cost and ease of manufacture and design; these factors have led to the phenomenal growth in its manufacture and use [1].

Therefore, it has been demonstrated that the properties of plastics are suitable for the development of a new concrete up to certain limits. There has been extensive research into the use of recycled waste and virgin plastic materials within conventional concrete [2-7] There are usually two forms of plastic that are used within concrete, i.e. as plastic fibres (PF) used within fibre-reinforced concrete, and as a form of plastic aggregate (PA) in the replacement of natural aggregates (coarse or fine). Although using plastic within concrete can be beneficial from the point of view of engineering and the environment, with regard to thermal, mechanical and dielectric properties. Dielectric property is a molecular property found in all types of materials that can inhibits the movements of electrons and thereby generate polarization within the product when exposed to the external electrical field [8]. It may be hypothesised, however, that the poor bond capacity and higher air content within the concrete for inclusion of plastic aggregates are key factors for lower performance of concrete that has been modified with plastic [9]. the reason for that is, basically, plastic aggregates have a non-reactive (chemical reaction) behaviour that leads to reduced concrete performance under both durability and mechanical tests. The reduction in mechanical properties such i. e compressive strength was due to the weak adhesive strength between PA and the cement paste, this is due to the hydrophobic nature of plastics. The hydrophobic effect further limited water diffusion in to the concrete, which was necessary for hydration of cement [10]. Therefore, the properties held by concrete that has been modified by plastics depends greatly upon the treatment given to the plastics. Also, bond strength between cement paste and plastic aggregate could be influenced significantly by such treatment. The size, surface texture and shape of plastic utilised within concrete also have importance in relation to performance of concrete modified by plastics.

The partial replacement with plastic (PF and PA) within concrete impacts notably upon concrete properties and, therefore, if there is to be utilisation of plastic within concrete, it is imperative that there is study of the relationships between addition of plastic and properties in engineering terms; this particular review serves as a basis for gaining an understanding of that relationship with respect to size, replacement level, surface texture and shape. There is a review already available in relation to plastic use (virgin and waste) within the preparation of materials that are cement-based (mortar/concrete) [1, 3, 11-13]. Furthermore, information put forward within recent publications offers sufficient knowledge related to the durability and mechanical properties of mortar/concrete that contains plastic as PF and PA. For instance, a peer-reviewed study published by Babafemi et al.[9] showed the experimental outcomes of concrete containg waste plastics and their influence on the fresh, mechanical and durability properties of concrete. However, much of recent focus has been largely on recycling of waste plastics generally rather than its treatment prior to or following its mixing with concrete. Therefore, there is a need for a review to look at potential innovative methods of treating waste plastic before and/or after inclusion within the concrete. There is not only an objective of promotion of plastic reusage but also enhancement of bonding strength between cement paste and plastics, as well as improvement of the durability and mechanical performance of plastic modified concrete. From a search of the literature it was discovered that microwave (MW) type irradiation have been successfully used for acceleration of curing of materials that are cement-based and at an early age [14, 15]. Also, there has been successful use of MW-assisted heating within several industrial processes including for food [16], for biological materials [17], and for wood [18]. In addition, there has also been use of MW energy within polymer material characterisation [19] However, MW power has not been used so far to treat/melt plastics inside the concrete, in order to intense impregnation that will not only enhance the bonding but also reduce the porosity within the concrete, which was aimed to address in this research review. There has not, however, been use of MW power to date for treating/melting the polymer inside of concrete so that there could be impregnation and enhancement of the properties of concrete, which was an aim addressed within this review of previous research. This paper aims at setting the stage for further research into the potential application of microwave curing in solving the growing problem posed due to incorporating plastic in concrete. Therefore, this paper may be employed in putting forward a valuable data source to help researchers in the future since it critically summarizes the recent findings related to the use of plastic within concrete.

2.Research findings concerning Plastic use within concrete

The plastic use within concrete can be beneficial from engineering and the environment prespective. However, plastics have essential differences from cement and natural aggregates, with regard to thermal, mechanical and dielectric properties which is shown in table.

Table1 - Thermal conductivity and dielectric constant for some common polymers and concrete constituents [9, 20-23].

Material	Thermal Conductivity (W/mK)	Dielectric Constant
Polyethylene terephthalate PET	0.15	3.00 - 4.00
Polyethylene PE	0.33 - 0.52	2.30 – 2.70
Polyvinyl Chloride PVC	0.17 - 0.21	3.00
Polypropylene PP	0.12	2.20
Polystyrene PS	0.105	2.50 - 2.60
Quartzite sand	4.45	3 - 5
OPC	0.530	-
Water	0.608	80.1 at 20°C
Limestone gravel	2.29 - 2.78	4 - 8

2.1 Plastic preparation and Particle treatments

Most plastic aggregates employed within literature studies were acquired from plastic waste hailing from various sources of industry. Prior to addition to concrete, plastic waste needs to be prepared; in general, plastic bottles (PET) are ground within the laboratory through use of a type of grinding machine followed by a sieving process so that a suitable distribution of particle sizes can be acquired [24-26]. in order to grind the plastics, various kinds of crusher can be used, with either blade mills or propellers [11]. Also, within certain studies, there is washing of the plastic wastes used to eliminate the impurities [27, 28]. As there is no chemical bond that exists between the cement and plastic materials. Naik et al.[29] and Babafemi et al.[9] suggested the treatment of recycled plastics with various kinds of oxidising chemicals so that the bonding characteristics can be enhanced. The reaction of plastics and oxidising chemicals in assumed to create certain chemical species on the polymer surface which may eventually be involved in the cementitious reaction. Moreover, it was discovered from the literature review that plastic wastes go through numerous kinds of treatment, in order to, improve the properties of concrete containing plastic. Treatments include gamma radiation and e-beam (electron beam radiation). The radiation of the e-beam is a type of ionising energy which can usually be characterised due to its high rates of dosage and low penetration. The e-beam kind of processing is a method employed in modifying the properties of the polymer (plastic) surface with low-energy electrons utilised in crosslinking, modifying or improving adhesion to the surfaces. If polymers are treated with the e-beam irradiation, no additives are needed and no hazardous chemical bi-product are emitted [30]. In recent decades, there has been a steady increase in treatment of polymers through gamma radiation, because of, the polymer materials are modified and improved with respect to their chemical, physical, electrical, structural and optical properties [31]. Gamma rays are electromagnetic radiation photons that emit from an atomic nucleus; this kind of electromagnetic radiation has the greatest energy and smallest wavelength of any type of known waves within the electromagnetic spectrum (see Figure 1). It was stated by Usman et al.[7] that gamma radiation leads to enhancement in mechanical concrete properties with modification of the structure surface. It also assists in the improvement of the adhesion of the matrix and fibre. It was reported by Ochbelagh et al. [32] that the micro-structures of gamma irradiated samples had changed and they were more compressed than the non-irradiated samples. Meaning that the gamma ray removed the micro-pores within the samples, which that demonstrated by scanning electron microscopy (SEM), as well as, the compressive strength was also enhanced. The power of penetration of gamma rays, however, is such that there is a need of several feet width of concrete or several inches width of lead to serve as a barrier in stopping them. Gamma rays are able to pass easily through the entire human body with them, potentially, causing severe tissue damage or even damage to DNA [33].

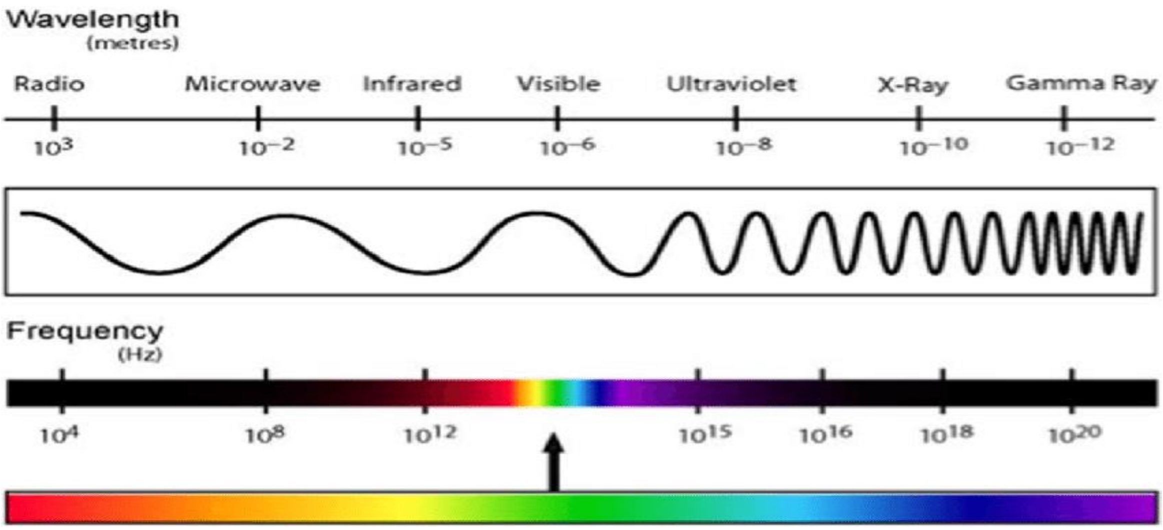


Figure - 1 Comparison of the wavelength and the frequency along the electromagnetic Spectrum [33].

In addition, in order to improve plastic waste quality for use as an aggregate within concrete, plastic waste has been modified by mechanical means, by heating, through soaking within water, by melting then followed with mixture in with other kinds of materials and various other techniques [7].

2.2 Evaluation of the Properties of Plastic materials

There can be significant alteration to concrete properties due to the intrinsic properties in waste recycled or virgin plastic (PF and PA) such as the particle size distribution, surface roughness, shape, water absorption, specific gravity and bulk density. Within the last three decades, lots of researchers have devoted themselves to the study the impact of waste plastic upon concrete. The types, the sizes and the replacement percentages for plastics and their impact upon various concrete properties, as investigated by several researchers from within the literature, are listed below within Table 2. It was found that there has been a steady increase in the number of articles published related to these issues, however several issues do remain unsolved [9, 12, 26]. Within most literature studies, there has, commonly, been evaluation of the properties held by plastics utilised as fine, coarse or fibre aggregate in the preparation of concrete such as their shape, size, bulk density, specific gravity and water absorption. Evaluation of particle size distribution of plastic was undertaken through standard methods of sieving [25, 34, 35]. Also, the other types of mechanical property such as compressive and tensile strength, decomposition temperature, the elastic modulus for the plastic aggregate concrete, heat capacity, thermal conductivity, index flow melt and temperatures of melting and of initial degradation reported by literature studies [26]. It ought to be noted that the properties of concrete that contains plastic depend upon the particular type(s) of pre-treatment that the plastic was given.

Table 2 - Studies with the literature studies related to various properties of concrete that contain waste plastic.

Authors	Type of plastic	Composite type	Plastic particle size (mm)	Plastic replacement	Replacement ratio	Investigated Properties
[36]	Metalized plastic waste (fibre)	Concrete	5 to 20	Mixed with concrete by volume of fractions	0.1%, 0.5%, 1.5% & 2%	Oxygen permeability, corrosion, impact load, sulphate attack, weight loss.
[37]	PET	Concrete	5 to 20	CA	20%, 30%, 40% & 50%	Workability, compressive strength and density.
[38]	PET	Concrete	0.15 to 7	FA	5%, 10% & 15%.	UPV and elastic modulus, and flexural and compressive strength.
[39]	Electronic-waste plastic (E-waste)	Concrete	1.86 to 2.78	CA	4%, 8%, 12%, 16%, 20% & 24%.	Compressive strength, permeability and sorptivity.
[40]	PET	Concrete	0.26 and 1.14 cm (the average size for two fractions)	FA	10% and 20%.	Flexural, tensile and compressive strength, pulse velocity and elastic modulus.
[25]	PVC pipe	Light-weight aggregate concrete	≤5 mm	FA	5%, 15%, 30% and 45%.	Dry and fresh density, tensile and compressive strength, water absorption, carbonation, shrinkage and elastic modulus.
[41]	PET	Concrete	0.5 to 16	CA & FA	5%, 10% and 15%.	Compressive, flexural and tensile splitting strength, .and modulus of elasticity.
[35]	PET	Concrete	1 to 1.5	FA	5%	Flexural, compressive and tensile strength, pulse velocity and elastic modulus.

2.3 Preparation and curing of concrete containing plastic aggregate and plastic fibres

Concrete that contains PA is usually manufactured through the replacement of natural aggregate (fine or coarse) with the same weight (volume) of polymer; this is called direct volume replacement. Unsurprisingly, PA has a bulk density that is at a very much lower than the bulk density for typical natural aggregates; so, PA is well suited for the production of lightweight concrete. Plastic fibre PF, however, is employed as an admixture within concrete; the use of plastic fibres within concrete has the purpose of enhancing the durability and mechanical properties of the conventional concrete as well as securing several environmental benefits. Within most previous research, the plastic fibre dosage employed was lower than 3% in terms of total concrete volume. Generally, concrete that contains PF and PA have a lot of similarities with conventional concrete in respect to their preparation, their casting and their curing [12, 26, 42].

3. Influence of Plastic on the Properties of Fresh Concrete

Concrete stays within its fresh state, from the initial mixing time until setting. Within the fresh state, the greatest degree of attention is normally paid to the handling of the concrete, its placement and its compaction. The properties of concrete when hardened relate to its state when fresh since there is a gradual decrease in consistency from mixing time until completion. Moreover, the mix consistency and its compaction are essential to the consequent potential durability and strength of the concrete [9]. The most vital properties of fresh concrete have association to its consistency and workability. When there is introduction of thermoplastic polymers in either PF or PA form within a mix of concrete, there would be significant alteration to the properties of the fresh concrete. Within this section, research findings on the effect of PA and PF on the physical properties of concrete, including; workability and density are presented.

3.1 Workability

workability can be defined in relation to the energy needed for the friction between particles in the concrete to achieve maximum compaction. The slump test is utilised to assess the workability of concrete mixes; the test is very beneficial to detect variations within the uniformity of mixes that have known nominal proportions [43]. The concrete workability is directly related to factors such as the water-cement ratio, the particle size grading, the volume of plasticiser within the mix and the particle shape. Numerous researchers have undertaken investigations and reported the impact of recycled and virgin waste plastics in the form of coarse and fine aggregate (CA and FA) replacement upon concrete workability [9]. The properties of the used plastics and natural aggregates are shown in table 3 and their influence on concrete workability has been illustrated in figure 2. The findings of these research have demonstrated conflicting performance with respect to concrete workability as shown in figure 2.

Table 3- Various properties plastic and natural aggregate used to compare workability.

Authors	**Plastic type**	**Specific gravity of PA**	**Density of PA Kg/m^3**	**Plastic size (mm)**	**FA size (mm)**	**Specific gravity FA**	**CA size (mm)**	**Specific gravity CA**	**w/c**
[44]	PVC	1.3	810	0.2-4.79	3.66	2.69	≈12.5	2.72	0.52
[45]	HDPE	0.93	840	4.75-20	Grading zone II 2.6-2.9	2.638	>20	2.836	0.5
[46]	Polycarbonate (PC)	1.2	650	1.18-3.15	0.3-3.15	2.65	>10	2.64	0.5
[47]	LDPE	0.76	-	≤ 2.36	63µm-2.36	2.61	>20	-	0.6
[48]	e-plastic	1.1	-	7.59-20	Grading zone III 2.2-2.6	2.68	12.5-20	2.825	0.5
[49]	HDPE	0.94	-	≈20	Grading zone I 2.9-3.2	2.697	12	2.748	0.5

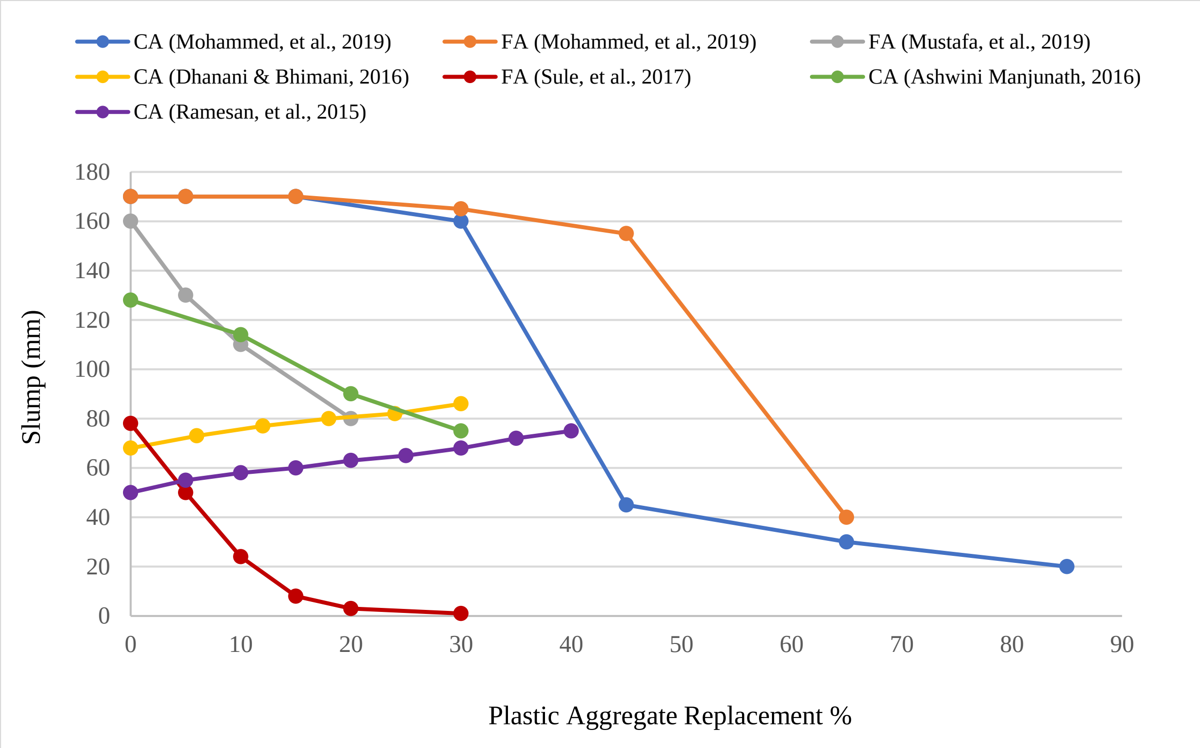


Figure - 2 Influence of ne and coarse aggregates (FA and CA) upon the workability of concrete.

Within studies undertaken by Ramesan et al [50] and Dhanani and Bhimani [45] recycled plastic aggregates, i.e. HDPE (high density polyethylene) and LDPE (low density polyethylene) replaced natural aggregates of the concrete at various percentages. It was noted by the authors that there was an increase in concrete workability with replacement with increasing amounts of PA up to a level of 40% (see Figure 2). The reason for the slump increase was the PA surface texture and the lower water absorption of plastic aggregates meaning that there was more water made available in the mixture because of reduced level of absorption with decreasing the quantity of natural aggregate and so there was more free water within the fresh concrete mix. A similar finding was reported by Tang et al [51] i.e. an increase in slump for a coarse polystyrene aggregate in a lightweight concrete up to a replacement level of 40%. Choi et al.[52] also reported an increase in slump value because of PA up to 75% incorporation. Therefore, the increase in the workability of concrete mixes is because of the presence of greater amounts of free water within the mixes that contain plastic when compared to mixes that contain natural aggregate; this is because plastic aggregates are unable to absorb water whilst the mixing takes place [11]. An opposite outcome of workability was observed, (see figure 2) the workability was found to decrease slightly when coarse aggregate replaced by 30% PVC aggregate, and sharp reduction in workability was noted when coarse aggregate replaced by 45% PVC aggregate reported by Mohammed et al.[44] (see Figure 2). Moreover, it was claimed by Ashwini et.al [48] that there was a reduction in concrete workability when various percentages of electronic waste plastics (E-plastic) were added into the concrete by weight of cement. In another study undertaken by Kew et al [53], coarse rubber aggregates that were angular and long were investigated; with a maximum 20mm in size, obtained concretes with an reasonable workability for low rubber content. The authors noted a workability reduction for higher content of rubber, with a 50% rubber content leading to a zero-slump value. Similar findings were reported by Güneyisi et al [54], in relation to concrete that contained silica fume, rubber crumb and chips of tyres; they reported a workability decrease with increase in rubber content, with 50% rubber content leading to mixtures that have no workability. The explanation for that reduction in concrete workability may lie in the partial replacement of natural CA by PA; generally, PAs have lower bulk density compared to natural aggregates, and so, the ratio of total surface-area-to weight increases and, consequently, water content needs to be increased in order for these particles to be surrounded. Whilst, there was use of the same water cement ratio for all of the concrete mixtures, the effective ratio of w/c will be at a low level and this leads to a reduced workability of the concrete.

Other researchers showed that the surface texture and roughness and size of plastic particles also has an effect upon the workability of concrete; lamellar particles have been shown to promote concrete mixture workability, whilst particles that are flaky have a tendency to reduce workability[9, 40, 44]. Also, the PA aggregate size has a tendency to impact upon concrete workability; Albano et al [42]. studied the impact of replacing natural sand with two different types of PET (polyethylene terephthalate) particles (3.34 and 2.23 mm) at 10% and 20% on the concrete slump. The mixes that contained PET with a larger size of particle at 3.34mm showed a slump that was lower in comparison to mixes with a particle size that was smaller at 2.23mm and with the reference that contained just natural sand. This is because of the effect of PET on the mixture. The homogeneity of the mixture and also, the rheological properties are alerted by the addition of PET plastic, in particular compaction and the flow; increasing PET content decreased the consistency and plasticity of the concrete mixture. It was reported by Mohammed et al.[44] that there was no change to the value of concrete slump if there was replacement of fine aggregate with 15% PVC plastic aggregate. There was a slight reduction in workability, however, if the replacement was increased to 45% and there was observation of a rapid workability reduction at a 65% level of PVC aggregate replacement and zero slump was recorded for further concrete at a replacement level of 85% (see Figure 2). Furthermore, within studies undertaken by Sule et al [47] and Mustafa et al [46], wherein there was use of recycled plastic waste as a fine aggregate within concrete, the findings showed a decrease in concrete workability with increase to the percentage of plastic replacement. These reductions were due to the fact that some plastic particles were angular in shape, while others had non-uniform shapes which resulted in less fluidity.

In regard to plastic fibre, research undertaken by Bhogayata and Arora [36] looked at addition of various lengths of metallised plastic waste of (5, 10 and 20mm) as fibres within concrete of various percentages of (0.5%, 1%, 1.5% and 2%). The researchers claimed that fibres that were longer reduced the workability to a greater extent than the shorter fibres did for the ranges given. Concrete that contained 5mm long fibre led to a slump reduction of 5%, 8%, 12% and 16% for the ranges given from 0.2% to 2% if compared to the control mixture. A greater slump reduction was seen for fibre of 10mm length in the range that was between 8%, 12%, 15% and 18%, and for fibre length of 20mm, slump reduction was noted at 10%, 14%, 18% and 25%. The addition of macro-fibres is reported to affect both the consistency and the viscosity of the fresh. Concrete mixture. Also, the greater macro-fibre surface area occupies a significant portion of the cement paste leaving less paste for the aggregates, and this can also contribute to a lower concrete slump [9].

As a result, there are two parallel views of concrete workability behaviour exists with respect to inclusion of plastic aggregate. Within the bulk of studies, a lower value for slump in fresh concrete was recorded; this is due to the inclusion of several forms of plastic aggregate was observed compared to conventional mixes of concrete, with increase in addition of PA leads to a further lowering of the slump value. The primary reasons for lower slump value of concrete containing plastic aggregate are the angular shape of the PA and its sharp edges. Also, from the above discussion, it can be seen that the size of PA's greatly affects concrete's fresh properties.

3.2 Fresh and Dry Density of Concrete

The fresh and dry density for concrete depends on the specific gravity of the concrete mix compositions. Usually, plastics aggregate as coarse or fine have a density that is lower in comparison to natural aggregates; therefore, PA inclusion within concrete results in reduction of both fresh and dry density [12, 35, 41]. Several studies have recorded a decrease in concrete density as the replacement level of PA increases. The properties of the used PA and there influences on density have been summarised in table 4 and figure 3 respectively. Tang et al [51] reported a reduction in fresh concrete density with the inclusion of both fine and coarse PA; however, there was found to be a higher loss with the plastic particles becoming progressively flakier and larger. Kumar and Baskar [55] carried out an experimental analysis upon structural concrete and the partial replacement of natural coarse aggregate with e-plastic waste; replacing the natural coarse aggregate with various percentages of e-plastic waste by volume. Concrete fresh density was reducing gradually with the increase in e-plastic. A reduction of 13.58% was noted with a 50% e-plastic replacement; the reason for this reduction was that that e-plastic aggregate density was lower than that of the coarse aggregate resulting in reduction to the fresh density. Similarly, Lima et al.[56] reported that at 50% substitution of waste ethylene vinyl acetate (EVA) with natural course aggregate, the fresh density of concrete reduced by approximately 26% when compared with the control samples. Therefore, the reduction of fresh density of concrete was observed when natural fine or coarse aggregates were substituted with plastic aggregates results are presented in figure 3. Other studies Kou et al [25] and Ismail & AL-Hashmi [57] investigated the fresh concrete density contained polyvinyl chloride (PVC) as the replacement of fine aggregate. Their results showed that increase in percentages of the recycled PA resulted in reduced concrete fresh density; see Figure 3. Moreover, similar findings were revealed by Mustafa et al [46] when there was replacement of natural fine aggregate with different percentages of polycarbonate plastic. The main reason for lowering fresh density of concrete with PA's can be explained by the specific gravity of plastics which is lower than that of natural aggregate ranging between (0.24 to 1.3) see table 4.

Within Figure 4 there is a demonstration of the results conducted from literature review on the effect that PA has upon concrete dry density. Through the experimental outcomes , Mohammed et al [44] showed that dry density of concrete that contains aggregate of PVC was not decreased considerably at low level of replacement; however, it was noted that there was a significant reduction was noted when 85% of fine aggregate replaced with PVC. The primary reason for this reduction was that the PVC aggregate employed within the study had a relatively high density compared to that utilised by other researchers. On the other hand, there was a steady decrease in the dry density of the concrete when coarse aggregate replaced PVC. An average of 16% reduction achieved for the substitution of fine aggregate with PVC, and 31% reduction for substitution of coarse aggregate. Furthermore, (Lokeshwari, et al., 2019) [?] substituted various percentages of fine and coarse aggregate with shredded Polypropylene (PP) waste. waste by Mahzuz H et al [58]; It was noted that there was a reduction in concrete dry density for the samples made with shredded PP. This is possibly due to plastic has lower density than natural coarse aggregate. A reduction of dry density of concrete by 15% was also revealed by

Sule et al [47], when fine aggregate substituted by 30% of plastic waste. Similarly, other studies undertaken by Kou et al [25], Lima et al.[56], and Kumar and Baskar [55], agreed with the findings and they claimed further concrete density reduction with increasing plastic replacement percentage.

Table 4- Various properties of plastic aggregate and natural aggregate used to evaluate concrete density.

Studies	Plastic type	PA size (mm)	Specific gravity	Density kg/m3	FA size (mm)	CA size (mm)	FA Specific gravity	CA Specific gravity	w/c
[56]	EVA	4.78-9.5	0.24	1000	1.77-4.8	5.35 to 12.5 max	2.61and 2.57	2.73-2.52	0.49,0.6 & 0.8
[55]	E-plastic	12.5	1.29	595.30	>2.36	>12.5	2.65	2.79	0.49
[25]	PVC	<5	-	546		6-15LWA	-	-	0.32
[59]	PP	0.1-3 8-10	-	-	Grading zone II	>10	2.57	2.60	0.45
[44]	PVC	0.2-4.79	1.3	810	>3.66	12.5	2.69 fine	2.72	0.52
[60]	HDPE	12-19	0.86	425.22	-	>19	2.54	2.8	0.5
[51]	Polystyrene	4mm dia?	-	24	>2.75	10	-	-	0.5
[46]	Polycarbonate (PW)	1.18- 3.15	1.2	650	0.3-3.15	10	2.65	2.64	0.5
[57]	polyethylene & polystyrene	0.15-12	-	386.7	0.15-4.75	>20	2.57	-	0.53

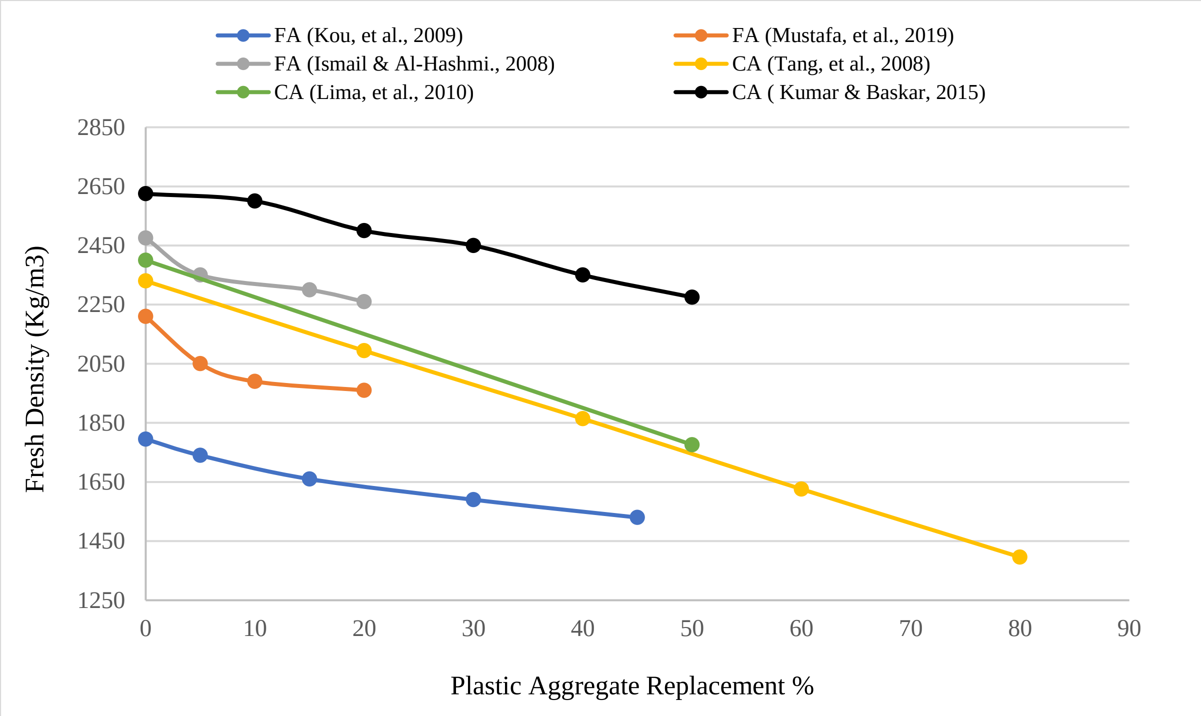


Figure - 3 The effect of fine and coarse aggregates (FA and CA) upon the density of fresh concrete.

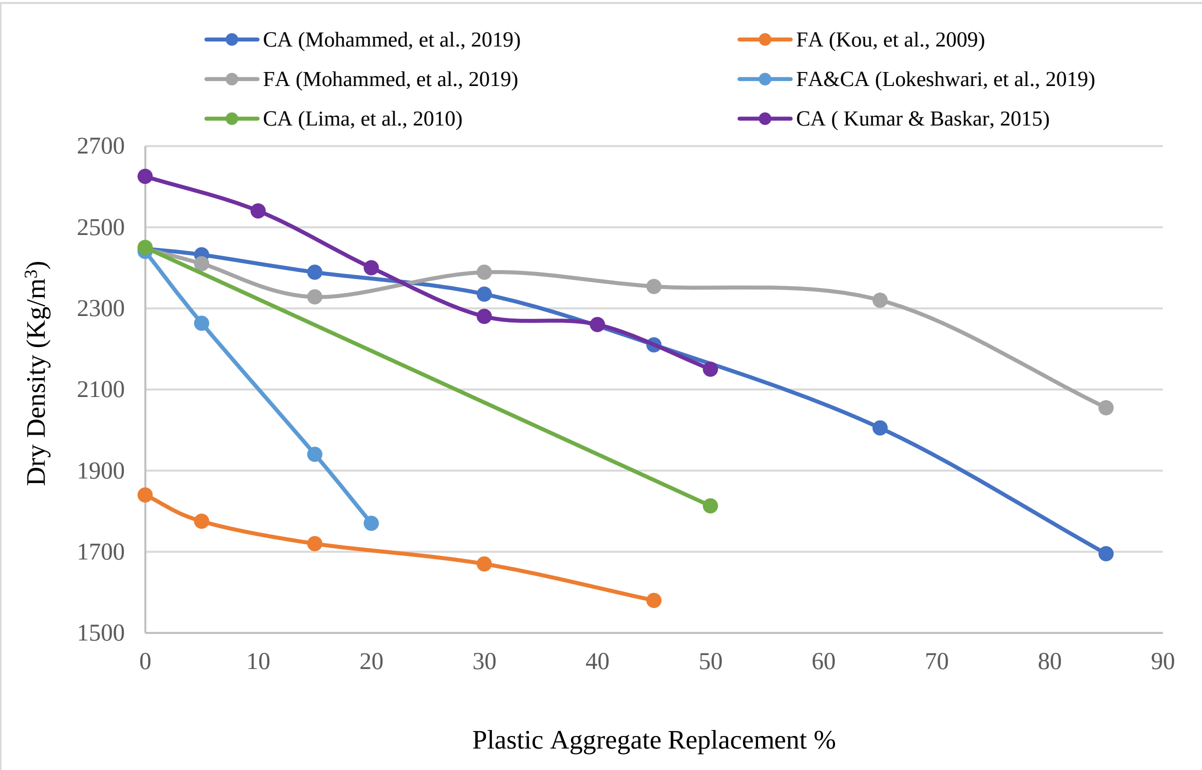


Figure - 4 The effect of fine and coarse aggregates (FA and CA) upon the density of dry concrete.

4. Mechanical properties of concrete containing polymers

The mechanical properties of cement-based materials are considered to be the main important parameters in determining their suitability for practical application. the purpose of this section is to summarise the mechanical properties of the concrete made with waste plastic.

4.1 Compressive Strength

For cementitious materials, their compressive strength is a fundamental property that has been studied extensively within almost all the research studies within the literature, that have an association with plastic aggregate. It was discovered that plastic usage as a coarse or fine aggregate replacement decreases the concrete compressive strength [24, 25, 36, 47, 48, 51, 52, 55, 56, 61-63] Figure 5 shows the strength of concrete that contains various percentages of PA with a minimum of 2% to a maximum of 100% as a coarse or fine aggregate replacement as assessed previously by literature researchers.

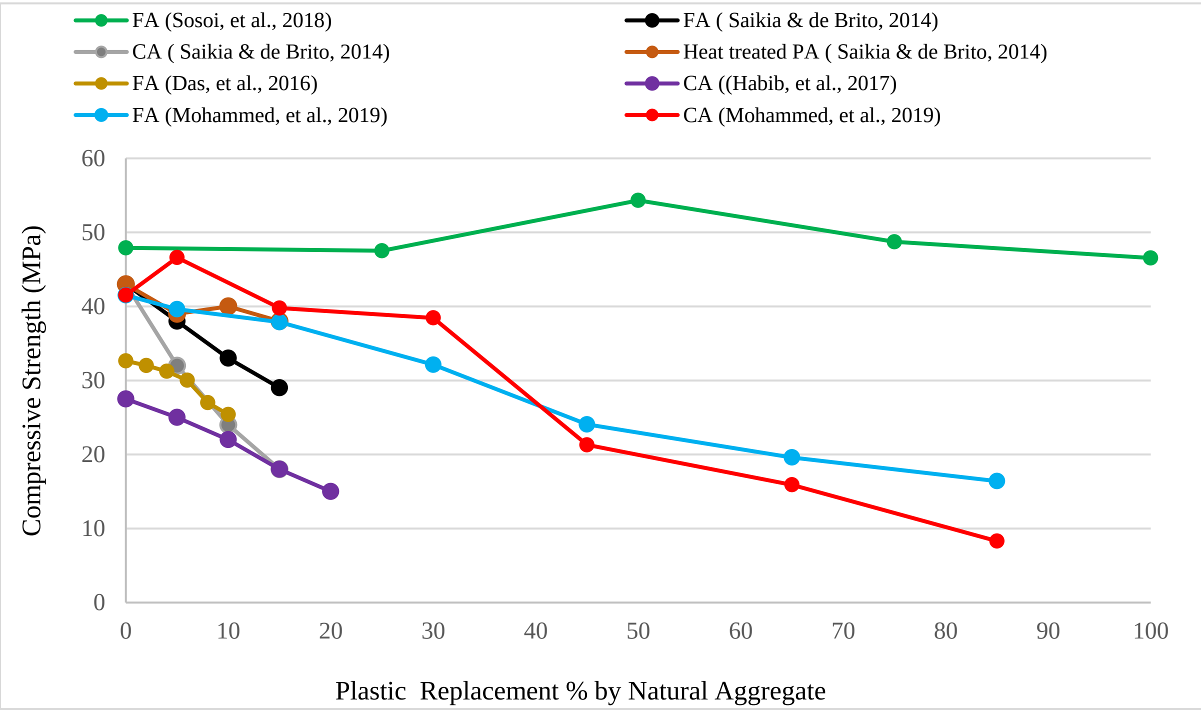


Figure 5 - Compressive strength of concrete containing coarse and fine plastic aggregate (CA&FA) at 28 days.

Saikia & de Brito [41], investigated the impact of three different forms of PET aggregate on fresh and hardened concrete properties, including the compressive strength. The plastics that were used within the study were different in size and shape, shredded fractions had a flaky shape with two particle size ranges, coarse (CAPET), fine (FAPET) and heat-treated pellet-shaped PET. Figure 5 presents the trend of compressive strength for concrete with increasing ratios of incorporation of PET- aggregates to replace natural aggregates (NA) at various ratios. The experimental outcomes show that, regardless to the concrete age and the type of PET-aggregate, there was continuous reduction in compressive strength as the PET content increased. Unlike NA, PET- aggregate is unable to interact with cement paste; so, the interfacial transition zone (ITZ) within concrete that contains PET-aggregate is weaker than within the control sample (reference concrete) which results in a lower compressive strength. The strength of concrete that contains heat-treated PET-aggregate at all substitution levels and for concrete that contains 5% of fine PET-aggregate is at a higher level than 75% of compressive strength in the reference concrete. However, concrete that contained 10% and 15% of fine PET-aggregate are, respectively, 59% and 71% and for the concrete that had coarse aggregate of PET, 73%, 52% and 35%. The strength of PA concrete is affected by a number of parameters including size, type, surface texture and shape of the plastic, as well as w/c content. The higher concrete strength achieved with heat-treated PET-aggregate is possibly associated to its w/c ratio, which less water required for obtaining the targeted slump when compared to other two types of PET-aggregate. This is due to the two other types of PET-aggregate vary in shapes, the FAPET surface texture is rough whilst the heat-treated PET pellets are very smooth; as such, this improves the bonding between the cement paste and FAPET. Another possible explanation is the particle size distribution (PSD) difference between both types of PET-aggregate. The PSD of FAPET almost similar to natural fine aggregate, whereas nearly all heat-treated PET pellets fall within small size range, as they are nearly equal in size. Therefore, substituting NA with heat-treated pellets changes the grading curve, which could impede any possible enhancement of the concrete compressive strength with heat-treated pellets attributable to the benefits of a lower w/c ratio.

Besides, Albano et al.[64], reported that concrete that contained 10% recycled PET has a compressive strength that meets the standard values of strength for moderate strength concrete. In another work undertaken by Das et al [63], the impact of e-plastic waste on compressive strength for concrete was investigated; the plastic waste utilised as partial replacement of natural fine aggregate at various replacement levels, the experimental findings are set out in Figure 5. It was discovered that there was a steady decrease in compressive strength for concrete with the increasing addition of e-plastic waste. A rapid strength reduction was noted for concrete that contained 8% and 10% of plastic waste. Relying on the experimental findings, the authors claimed that plastic can be used in concrete as partial replacement of natural aggregates. Ranges between 2%, 4% and 6%, in order to provide sufficient compressive strength, however, concrete loses its strength beyond these ranges. Habib et al.[60] observed that HDPE inclusion as the replacement for coarse aggregate resulted in reduction of concrete strength; the strength reduced by 11.6%, 21.5%, 34.4%, and 44% for 5%, 10%, 15% and 20% substitution shown in Figure 5. Moreover, Mohammed et al[44], looked into the effect of PVC plastic aggregate on the properties of concrete for various percentages of substitution of coarse and fine aggregate; Figure 5 shows the trend for compressive strength. From the experimental findings, it can be seen that a replacement of 30% was the optimum ratio for the CA, as loss of strength was around 7.4%. However, it was noted that there was continuous strength reduction as PVC aggregate inclusion was increased; the strength loss reached to 60% and 80% for both coarse and fine aggregate with 85% substitution of crushed PVC plastic. The results, overall, showed that CA substitution by PVC plastic led to greater reduction in strength when compared to replacement for FA, and that the optimum ratio of replacement was around 45%. As a consequence, concrete achieves better performance when FA substituted with PVC plastic. A key possible explanation behind this reduction is actually the particle size distribution (PSD) of both PVC plastic aggregates. The PSD for fine grinded PVC plastic is roughly similar with that for sand (natural fine aggregate), whereas, crushed PVC coarse plastic are irregular in shape and differ in size; see Figure 6 A and Figure B. Those factors change the grading curve and that probably hinders any possible improvement for the concrete compressive strength [41].

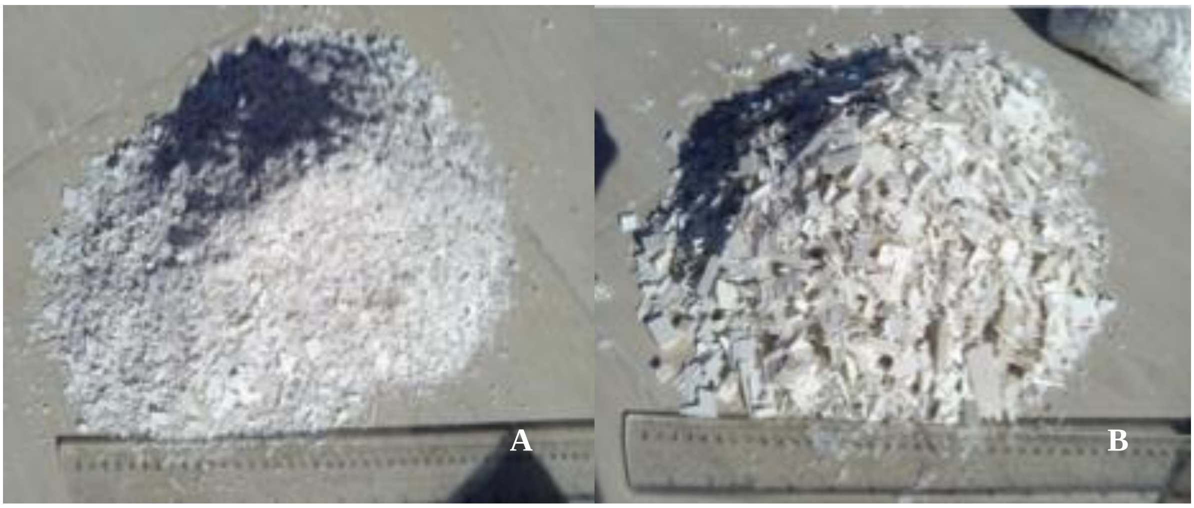


Figure 6 - (A) fine PVC aggregate, (B) coarse PVC aggregate [44].

A different trend has been reported, however, within a limited number of studies. For example, the investigation of Sosoi et al [65]. looked at epoxy resin concrete that contained FA (fly ash) and chopped PET waste plastic as the replacement of FA of different percentages; see Figure 5. The authors recorded an improvement in strength of 13.4% with 50% replacement of natural aggregate by PET plastic aggregate, when compared to the control samples, as well as a small improvement was also noticed with substitution of 75%. The higher degree of replacement resulted in compressive strength reduction. This improvement is attributed to the behaviour of the plastic employed within the study; the epoxy resin used was a product from Romania of Policolor S.A. Bucaresti that was activated using a Ropoxid P40 type hardener, which meant that the used plastic was harder than the other plastics utilised within other studies. An evaluation of the thermal and mechanical properties of rubber modified epoxy concrete was undertaken by Wang et al,[66]. With the study, the author recorded an increase in concrete strength by 9.1% epoxy composite specimens with 5% rubber particles in comparison to control samples. Nevertheless, the compressive strength of concrete was reduced by 10% rubber content. The epoxy concrete structure is composed simply of aggregates and epoxy resin binder; with addition of 5% of rubber particles, the epoxy resin must be properly toughened and therefore, slowing down the progress of the cracking. In addition, it was found to be good bonding behaviour between small size of rubber particle (0.279mm) and the hardened epoxy resins, as illustrated within Figure 7. With the area in the vicinity of the rubber particle, a consistent and dense structure was presented by the hardened form of epoxy resin. However, following application of more rubber as with the samples of 10% rubber, there was a reduction in integrity of the samples of the modified concrete. In addition, the rubber particle added is a material that is relatively soft in comparison to the epoxy matrix; as such, there was a reduction in the loading carrying ability of the specimen. Compressive strength for specimens that contain 10% of rubber particles was, therefore, slightly lowered. Güneyisi et al.[54] and Kew et al.[53] reported similar results in showing a systematic strength reduction as rubber content increased.

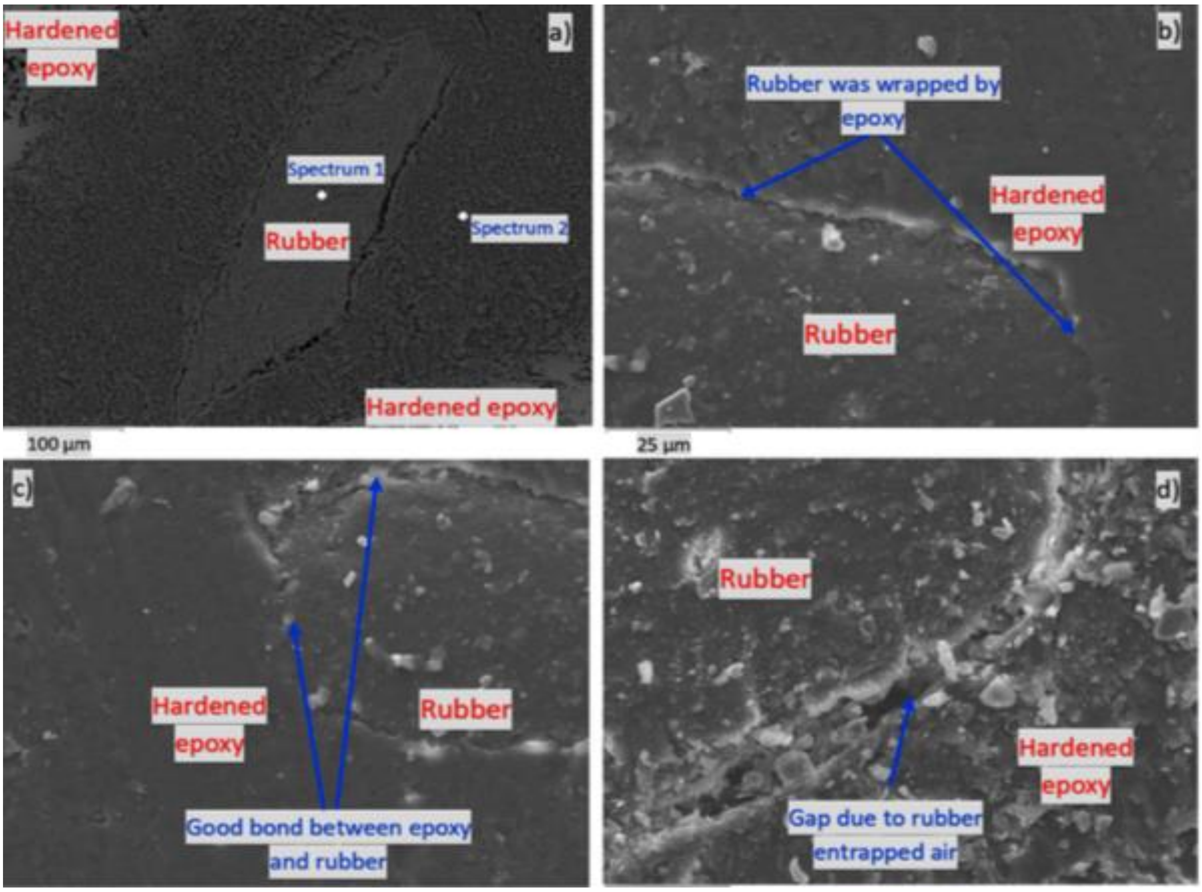


Figure - 7 SEM imaging for the sawed section of epoxy concrete modified with solid rubber: a) A good bond shown between the hardened epoxy and the rubber particle; b) the rubber particles wrapped by the hardened epoxy; c) a good bond between the hardened epoxy resin and the rubber; d) the gap between the hardened epoxy and the rubber particle.

Azhdarpour et al.[67], discovered strength improvement when FA replaced with 10% of PET plastic aggregate, this was due to the presence of plastic particles at the failure starting points. According to the experimental findings, the authors stated that, as flexible plastic fragments are dealt with, a part of the shear stress transforms to tensile stress and this is consumed in overcoming the plastic segment tensile strength. However, increasing the plastic amount led to a drop in compressive strength. So, the authors claimed that at low levels of substitution of FA with PET plastic results in increase to the compressive strength. With the help of numerical simulations, the researchers attributed that kind of behaviour to the redistribution of stress between soft inclusions (plastic) and hard inclusions (sand) at moderate levels of replacement that results in stress transfer to the strong inclusion (sand) and to delay failure. At higher levels of addition of complaint inclusions, there was an increase in stresses at the paste/inclusion interface which led to a strength decrease.

Potentially, similar mechanisms happen within composites that have partial aggregate replacement with waste plastics.

Similar findings were reported when there was utilisation of waste plastic as fibre within concrete. A research conducted by Bhogayata & Arora [36], claimed that the strength of concrete reduced as the percentages and the length of metalized plastic fibres content increased. Concrete compositions with 5mm fibre length and 0.5%, 1%, 1.5% and 2% content recorded lower compressive strength of 2%, 10%, 15% and 21%, respectively. For the same amount of fibre content, however, with lengths of 10 and 15mm, the concrete strength lowered by 8%, 13%, 18% and 26% and 8%, 15%, 21%, and 28%, respectively. The explanation for the lower compressive strength was addressed by Hosseini et al [68], in which identical methodologies had been implemented for concrete up to 1.25% MPW content. The study revealed that the addition of fibres led to an increase in number of air voids within the matrix and this led to a lower compressive strength. Also, it was discussed within earlier sections, the untreated surfaces of the PF are not properly bonded to the cement paste. As a result, a weaker ITZ is actually formed between the binders and PF and this, ultimately, results in lower strength of concrete.

The main reasons for lowering the compressive strength of concrete that contains PA, includes; weak bonding strength between the cement paste and the plastic waste surface. And the hydrophobic nature of plastic waste that may inhibit the reaction of cement hydration through restriction of the movement of water. In addition, in comparison to natural aggregates, plastic aggregates are less stiff and lower in strength and may, therefore, act as stress concentration zones favours the propagation of damage. Plastic aggregate is unable to chemically interact with cement paste; and consequently the ITZ in plastic containing concrete weak, and this further increases the air void content voids within the mixture Choi et al.,[52]; Saikia and de Brito,[41]; Babafemi t al.,[9]. It was reported by Islam et al.[37] that, as PA have almost no capacity to absorb water, there will be accumulation of water within the ITZ and this causes it to have greater porosity that will lead to reduction in the compressive strength. Normally, most PA have a smooth surface that leads to create a poor bond between the aggregates and the cement matrix which resulting to lowering the strength of concrete.

4.2 Flexural strength

Flexural strength is characterised as the ability of the materials to withstand deformation under the flexural loading, and is measured against stress [11]. The cracking and deflection behaviour for concrete structures depends upon concrete flexural tensile strength; structural safety can be ensured within highly active seismic region and whilst structures are overloaded by having an adequate capacity for deformation [69]. Results acquired from previous studies on the effect of recycled PA and PF on flexural strength of recycled PF and PA is shown within Figure 8 [41, 60, 70-72]. As with compressive strength, there is a decrease in concrete flexural strength with increases in both PF and PA. Saikia & de Brito, [41] reported on the flexural strength for concrete that contained three different kinds of PET plastic aggregate that replaced a various percentages of natural aggregate. The findings revealed that concrete flexural strength decrease as the substitution level for PET PA was increasing. Farooq et al.,[71] observed an almost linear reduction of flexural strength with increases in e-plastic waste as partial replacement of FA within concrete. The findings showed that there was an 18% lowering of flexural strength at a substitution level of 20% when compared with the control samples.

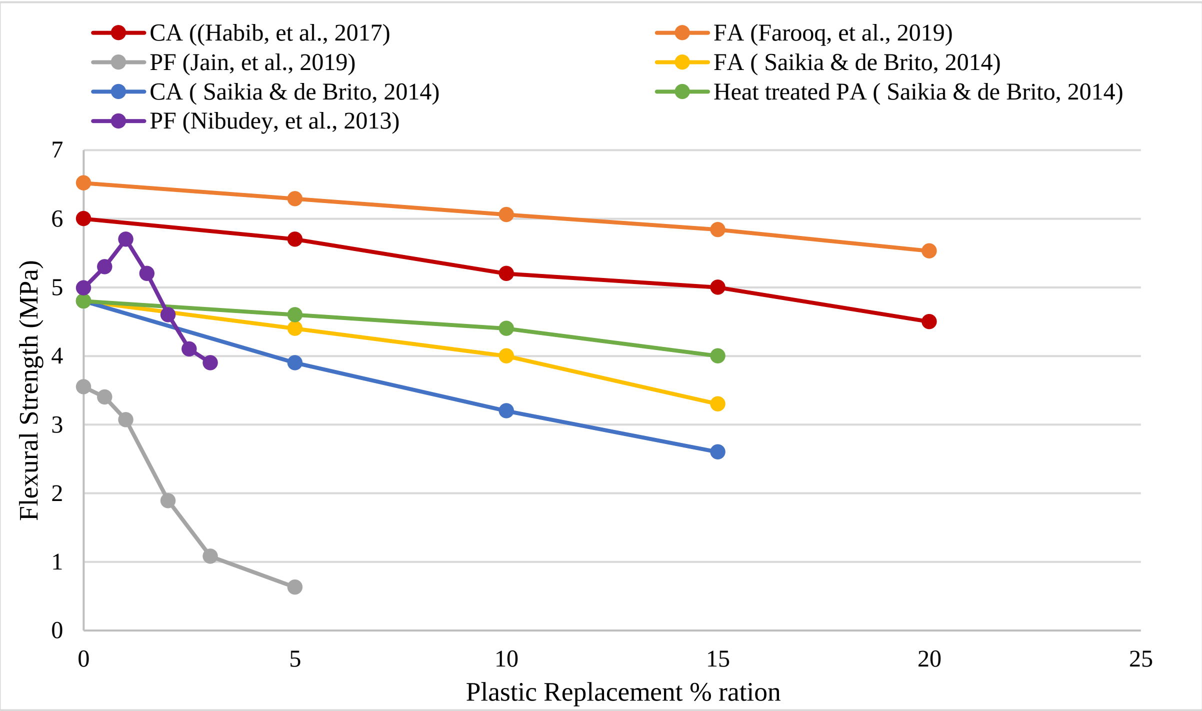


Figure 8- Flexural strength of concrete containing plastic fibre (PF) & coarse and fine plastic aggregate (CA&FA) at 28 days.

Most research in the field has claimed gradual reduction of concrete flexural strength as PF or PA was increased. A reduction of 5.3% to 24.4% of flexural strength was reported by Habib et al [71] for concrete that contained 5% to 20% of recycled HDPE plastic . Kew et al [53] noted a decreasing trend of flexural strength with an increasing PA content. Likewise, Ismail & AL-Hashmi [57], reported flexural strength for concrete that contained 0% to 20% of waste plastic in replacement of natural fine aggregate. Their findings demonstrated that there was prone to be a decrease in the flexural strength of concrete mixes with plastic waste at each age of curing as the ratio of waste plastic increased within those mixes.

Plastic fibre use within concrete and flexural performance has been investigated within several of studies. Jain et al [72] for instance, utilised waste plastic bags (WPBs) within their research, the WPBs cut into the form of fibre by use of a shredding machine, the shredded particle sizes that ranged from 15 to 30mm in length and from 3 to 5mm of width. The experimental findings showed that the flexural strength trend steadily decreased as the replacement amount of WPBs increased within the concrete; as a consequence, the flexural strength decreased by 13.52% with 1% of WPB, and a reduction of 82.25% with a 5% replacement with WPB. However, Ochi et al [73] claimed that the flexural strength of concrete with PET fibres enhanced by 36.1% with gradual increase in fibre content up to 1.5%. Also, Suji et al [74] reported that flexural strength in concrete mixes that with 0.3% of PP plastic fibre by volume increased from 16.6% to 23.0% when compared to the conventional concrete flexural strength. On the other hand, some studies showed that the flexural strength only improved when the concrete had a small amount of fibre content, when the fibre increased above a particular threshold it's degrading of the flexural strength. It was found by Nibudey et al.[70], that there was an increase in concrete flexural strength by 20% with PET fibre at 1%, and this fell by 16.4% with 3% fibre content. It was claimed by Khadakbhavi et al.[75] that the impact of HDPE fibre aspect ratios upon flexural strength for fibre reinforced concrete (FRC) did not have as much significance as the influence on slitting tensile and compressive strength.

There was a gradual decrease in concrete flexural strength as the PA and PF replacement rates in concrete increased. Mostly, this was attributed to the same factors that caused a compressive strength reduction with the addition of waste plastic aggregate, in particular, the weak bond between cement paste and PA. Most of the plastic particles within the concrete matrix do not fail after reaching the ultimate strength, but are de-bonded from the cement paste, and this is further evidence for poor bonding. Therefore, in order to achieve better performance of concrete containing plastics, surface treatment of PA's may be useful, which may enhance the bonding behaviour between cement paste and plastic. However, the hardened properties of

PA concrete are not only dependent upon the percentages of the plastic content within the mix but also are influenced by the size and shape of the PA and its surface texture, in addition to the compositions of the mixes. The information available on the use of plastics as aggregate in concrete is not enough, there is still lack of information several concrete properties which contains PA. Clearly, further research is needed for investigation of these issues.

4.2 Modulus of elasticity

Concrete elastic-modulus is influenced by numerous parameters such as size of plastic waste aggregate [12] and its type [76] The w/c ratio also impacts greatly upon the performance of modulus of elasticity of concrete [41]. Olugbenga [77] consider the w/c ratio have a significant impact upon final properties due to generation of porosity within concrete; that porosity may be related inversely to modulus of elasticity. The result acquired from existing research into the impact of PA upon elastic modulus is shown in Figure 9 [25, 72].

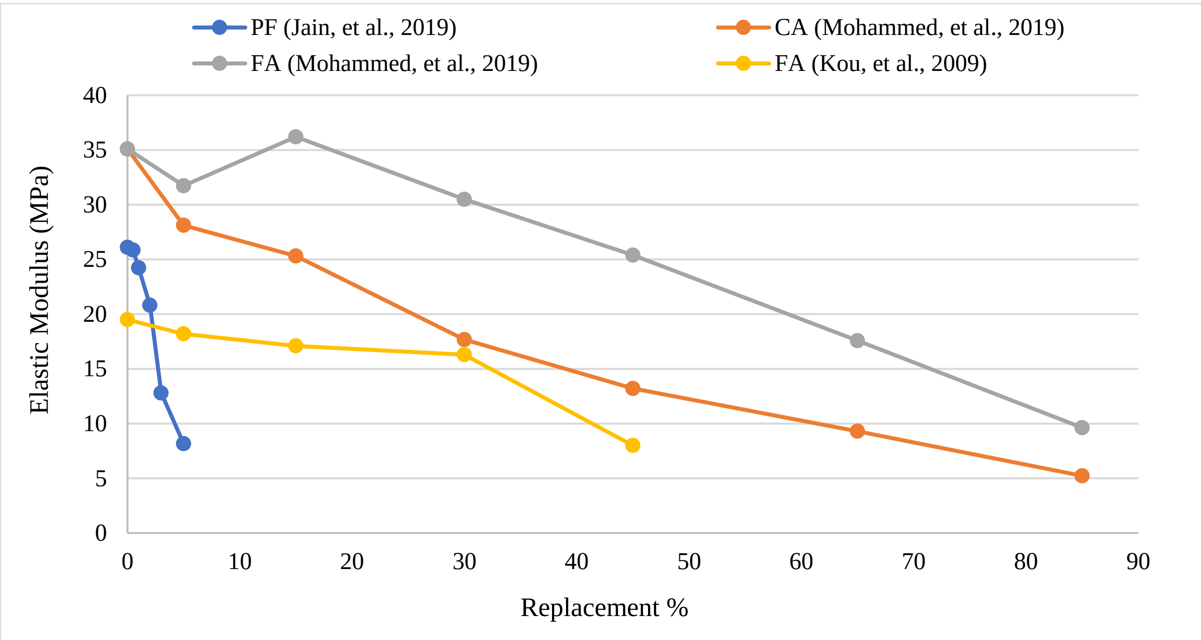


Figure 9 - Elastic Modulus of concrete containing plastic fibre (PF) & coarse and fine plastic aggregate (CA&FA) at 28 days.

Jain et al.[72] reported a reduction in concrete elastic modulus that contained WPBs in fibre form at a various percentages with increasing the percentages of WPBs. the modulus of elasticity reduced by 7.17% for 1% and a reduction of 68.70% for 5% of WPBs. the elastic modulus reduction was potentially because of the low elasticity modulus for plastic bags and also because of weak bonding between the cement matrix and WPB. Similar findings have been observed previously by other authors; Hannawi et al.[78] and Rahmani et al [38]. In another study undertaken by Mohammed et al.[44], PVC plastic aggregate was replaced with coarse and fine aggregate at various of percentages; see Figure 9. As is the case with compressive strength, the elastic modulus for PA concrete is typically lower than that for conventional concrete with the same w/c. It is observed that there is a continuous reduction in elastic modulus as the replacement of PVC plastic aggregate is increased. As the PA incorporation increases the need for w/c ratio increases, so, PVC-containing concrete are more porous than other kinds of concrete and so, naturally have a lower modulus of elasticity. It is also indicated in the figure 9, that the replacement of CA with PVC plastic aggregate has a greater impact on the reduction of elasticity modulus than replacement of FA. Therefore, as the PA shape becomes less uniform the elastic modulus becomes more significant. Also, plastic's elastic modulus greatly affects the concert's elastic modulus, and any substitution of NA with plastic typically affects this property. Similarly, Kou et al.[25] undertook an investigation on the mechanical properties of lightweight aggregate concrete prepared using scrapped waste PVC pipes to substitute river sand as FA. There was partial replacement of the river sand by waste PVC plastic granules by volumes of 5%, 15%, 30%, and 45%. The experimental findings are shown within Figure 9; it is shown clearly that the concrete elastic modulus was reduced further by increase in PVC content. In comparison with the control sample, the reductions were, respectively, 6.1%, 13.8%, 18.9% and 60.2%. This may refer back to PVC granules having a lower modulus of elasticity in comparison to the cement past, also, and the author recorded the lower compressive strengths for PVC-lightweight aggregate, it is commonly accepted that the concrete with lower compressive strength also have lower values of elastic modulus.

Figure 10 shows the experimental findings that was conducted by Albano et al [42], the main objective of this research was to study the mechanical behaviour of recycled PET plastic concrete. The average PET particle sizes were 0.26 and 1.14cm FA was substituted with 10% and of 20% by PET volume. The figure demonstrates the elasticity modulus acquired for the concrete with the addition of PET at various sizes and proportions. In the case of a fixed particle size, a higher modulus with 10% PET is obtained, as a consequence of the effect that the aggregate has on elasticity. Therefore, the aggregate type has an influence upon the modulus as the deformation that is produced within the concrete is related partially to the aggregate elastic deformation. As such, the implication is that partial FA substitution by PET will lead to a gradual decrease as PET has less resistance than sand and there will be less deformation when an equal stress has applied. The particle size, therefore, has a small impact on the modulus of elasticity of the concrete mixture. The elasticity modulus is directly influenced by the fraction of the constituents that make up the concrete. As such, the modulus for the concrete PET blends ought to lie between those for PET and pure concrete in accordance with the ratio of the component; for this reason, the size of particle has less impact upon the elasticity modulus.

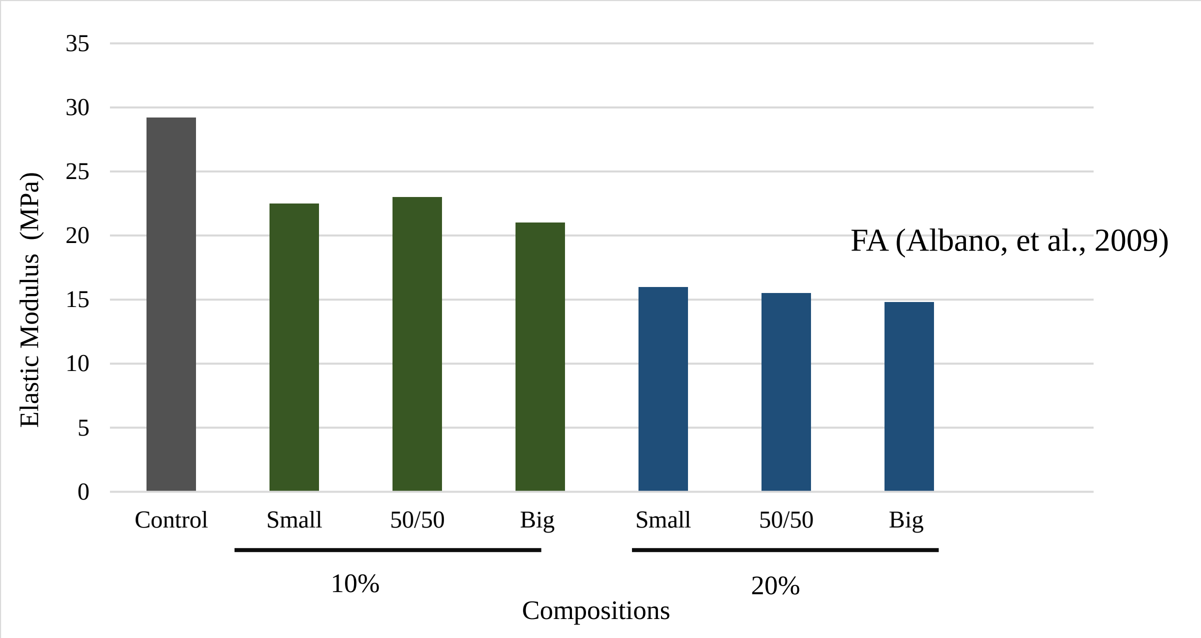


Figure 10 - Elastic Modulus of concrete containing PET aggregate with different grain size (small, 50% of small and coarse, and big) at 28 days [42].

4.4 Splitting Tensile Strength

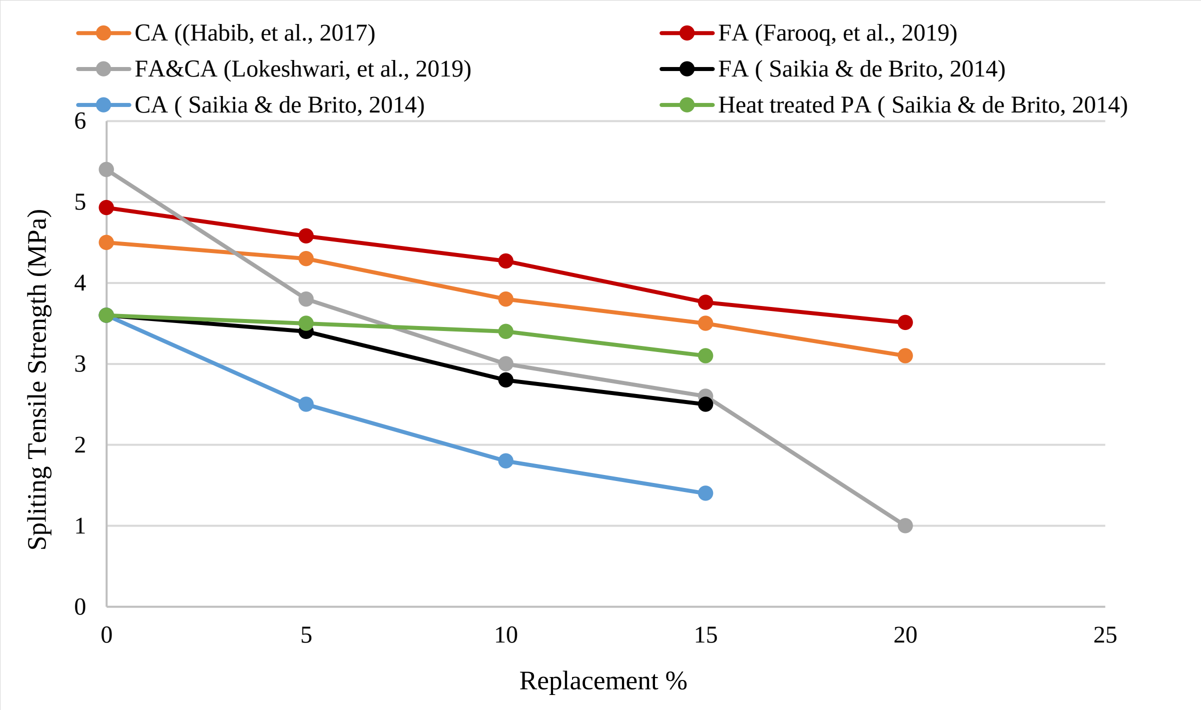


Figure 11 - Splitting tensile strength of concrete containing plastic fibre (PF) & coarse and fine plastic aggregate (CA&FA) at 28 days.

Most literature researches available have claimed a gradual reduction of splitting tensile strength as the replacement percentages of waste plastic aggregate increased. Figure 11 shows different literature findings on the impact of NA substations with plastic on the splitting tensile strength on concrete. For instance, Habib et al.[60] used HDPE plastic at a various of percentages to substitute CA. The experimental result showed a decrease in splitting tensile strength from 6.7% to 30% for concrete with recycled PA at 5% to 20%, respectively. It was observed by Lokeshwari et al [59] that there was a decrease in splitting tensile strength for concrete that contained shredded PP waste as the replacement amount of PP plastic increased. Moreover, Farooq et al [71] utilised e-waste plastic as a substitution for FA within concrete at the same ratios of replacement as mentioned within the researches above. Their findings showed that there was a decrease in splitting tensile strength for the concrete mixes as the e-plastic content increased; that observation agreed with the work of Habib et al.[60] and Lokeshwari et al.[59]. It was reported by Saikia & de Brito [41] concrete splitting tensile strength was significantly influenced by the properties of the PET plastic aggregate, the ITZ and the cement paste matrix. The study found that the concrete splitting tensile strength with any substitution pattern of PET plastic has a linear relationship with the compressive strength (see Figure 11). A similar explanation can be given for tensile strength behaviour as for concrete compressive strength loss because of PET plastic incorporation (see Figure 5, Section 4.1). The minimum and maximum reductions of tensile strength can be observed within concrete with CA and heat-treated PA. the concrete splitting tensile strength is highly affected by the ITZ characteristics. The smooth surface area of the PAs as well as the free water across the plastic aggregate surface will result in a weaker bonding among these particles and the cement paste. As shown in Figure 12 (in relation to the pellet-shaped PET plastic (PP)), the majority of the plastics do not fail in the concrete matrix, once after reached the ultimate strength, but rather they are de-bonding of them from the cement paste, which is further evidence of weaker bonding between cement paste and the PP.

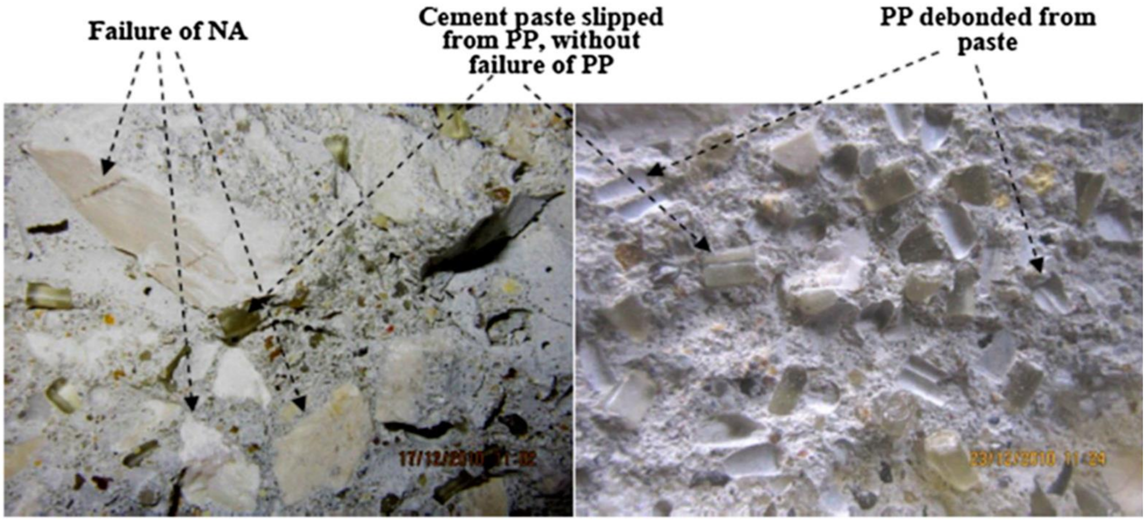


Figure 12 - Concrete specimens containing PP after failure [41].

The effect of higher replacement percentage of plastics upon splitting tensile strength is shown within Figure 13. For example, Kumar & Baskar[55], conducted an experimental investigation of structural concrete when CA was partially replaced with e-plastic waste. The study recorded a decrease in splitting tensile strength as the e-plastic were increased. It was found that splitting failure for concrete specimens with e-plastic waste were not exhibiting the usual brittle failure that was observed in the case of control samples. The failure was found to be a lot more ductile when there was an increase in the percentage of e-plastic waste. The tensile properties of the e-plastic waste show the splitting tensile failure as a gradual failure and resist the splitting load after failure without there being a full cylinder specimen breakdown, as Figure 14 illustrates. The trend shown within Figure 13 gives indication of how there is a decrease in concrete split tensile strength with an increase in the percentage of e-plastic, with a 47.89% loss in splitting tensile strength when there is 50% replacement of e-plastic. In another study undertaken by Mohammed et al.[44], waste PVC sheets were used to partially replace coarse and fine aggregate in concrete; see Figure 13; variation in the splitting tensile strength can be seen within the figure along with the ratio of PVC plastic. A continuous tensile strength reduction recorded as the content of PVC aggregate was increased; however, there was a slight recovery in tensile strength was observed with 15% five PVC plastic content. This was possibly due to the distribution of the size when sand partially replaced with fine PVC plastic. However, that tensile strength improvement is not significant, as there is no compressive strength improvement at the given content of PVC (see figure 5) since, as it is well known, for various kinds of concrete, a strong relationship exists between compressive strength and splitting tensile strength. Also, the results show that the loss in splitting tensile strength has compatibility with the loss of compressive strength when PVC plastic is used as replacement of FA. When CA substituted with PVC plastic, there is a lower reduction in splitting tensile strength (63% for a level of 85% replacement of aggregate) while compared to the reduction in compressive strength.

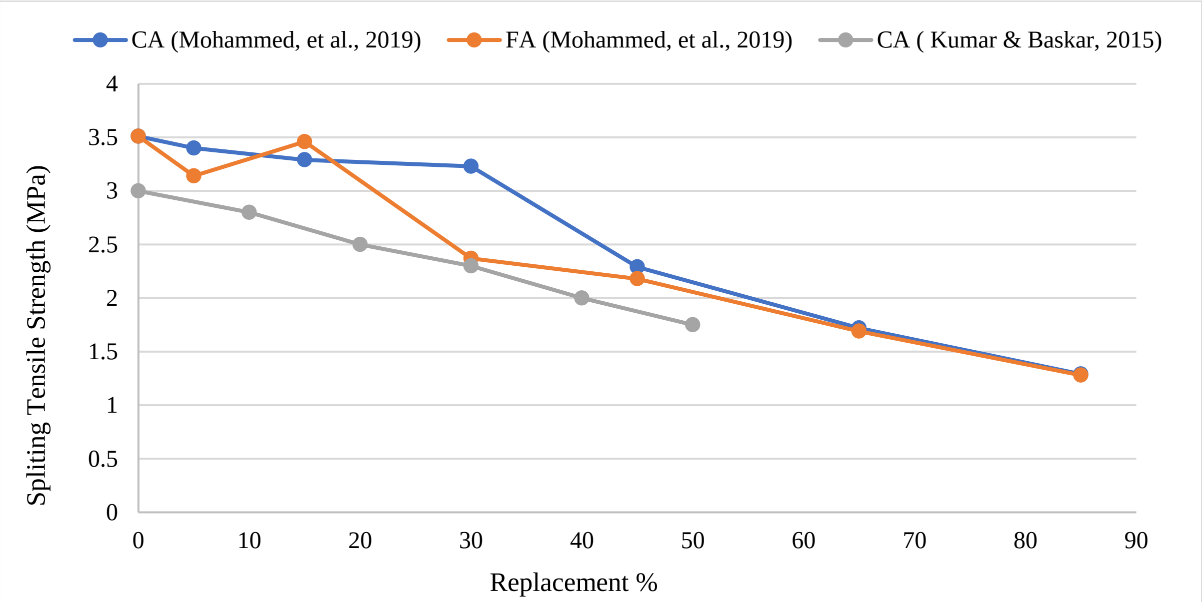


Figure 13 - Splitting tensile strength of concrete containing plastic aggregate (CA&FA) at 28 days.

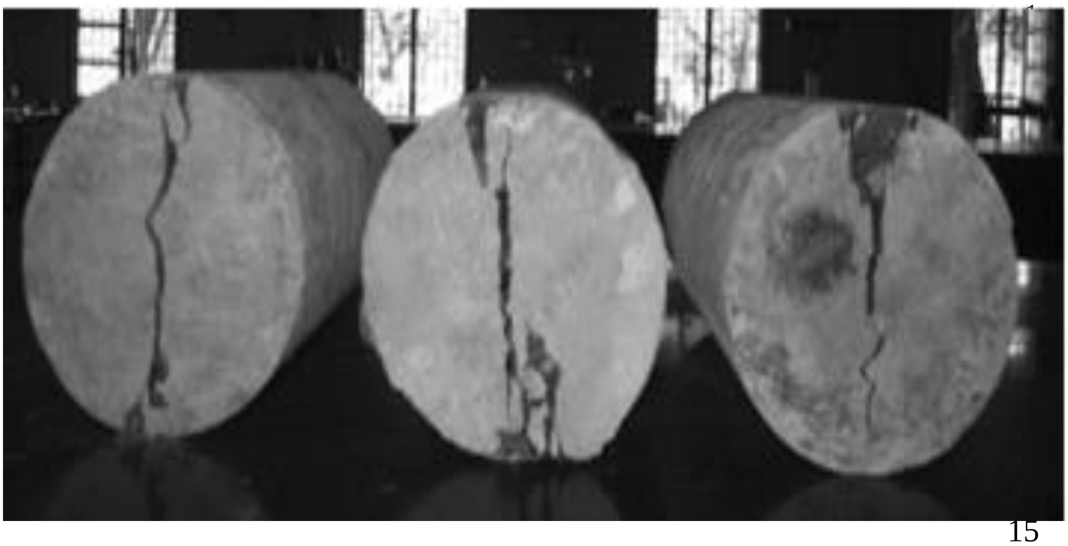
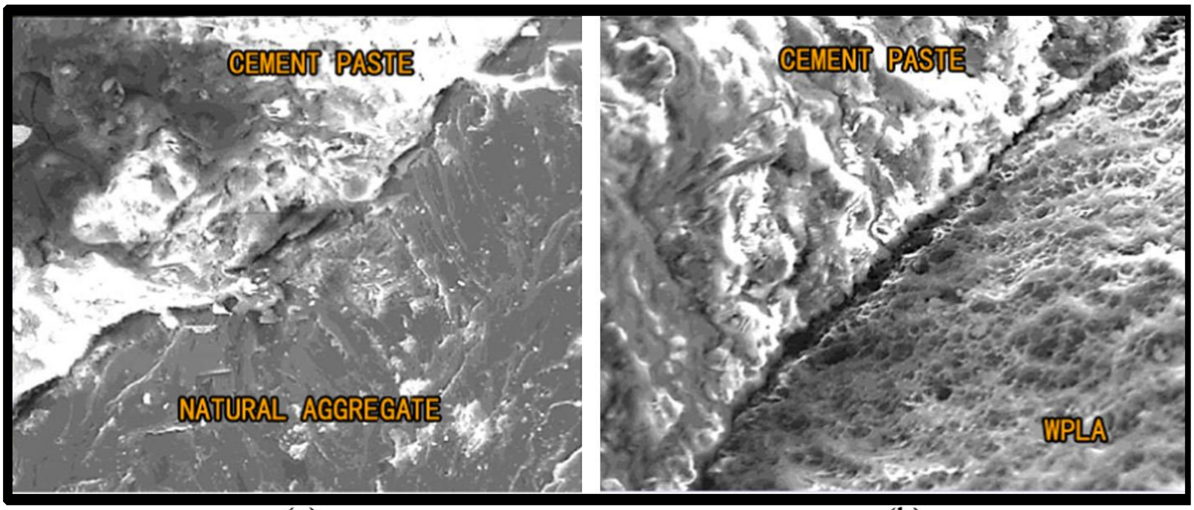


Figure 14 - splitting tensile strength mode of the E-plastic concrete cylinders after ultimate load [55].

4.5 Morphology

Morphology of concrete that contains PF or PA is affected by numerous parameters such as type, size and shape of the plastic. These morphological variations may explain the decrease observed in mechanical properties and bulk densities for concrete with increasing plastic aggregate level [12]. Research undertaken by Choi et al [79] revealed that the ITZ for concrete that contained PA was different to that for conventional concrete that was made using natural aggregate. The scanning electron microscopy (SEM) Images for concrete with lightweight aggregate of PET bottles (WPLA) is shown within Figure 15; the figure illustrates the ITZ amongst hardened cement paste and fine natural aggregate and between cement paste and PET plastic aggregate. There was a consistently wider ITZ between the cement paste and the WPLA than between the natural aggregates and the cement paste. This attributable to not just the smooth and spherical PA shape, but also that PA has a nature that is hydrophobic, and this inhibits the cement hydration reaction near to the PA surface through restriction of water movement. in fact, the PA anchoring points within the cement matrix are extremely poor due to the smooth PA surfaces. This particular ITZ probably forms the weakest as well as strength limiting phase within the PA concrete as it behaves as a wall between the phases of the matrix and the aggregate within the concrete. That phenomenon is actually known as the 'wall effect'. Figure 16a and 16b, shows the SEM images taken at magnification of 100x and 200x for concrete that contains WPBs [72]. These images clearly demonstrate the gap and the weak connection between the WPB and concrete matrix interfaces. The red line within Figure 16 is pointing the ITZ between the WPB and the concrete matrix. The poor connection between

WPB and the concrete matrix within this current work was a rationale behind the drop in flexural strength, elasticity modulus and compressive strength of the concrete with plastic waste. As well as, the weak microstructure also contributed to increased water penetration into the concrete samples composed with WPB.



(a) (b)

Figure - 15 The ITZ between WPLA/natural aggregate and cement paste in mortar [79]: (a) natural aggregate (at 28 days, with magnification of 700); (b) WPLA (at 28 days, with magnification of 700).

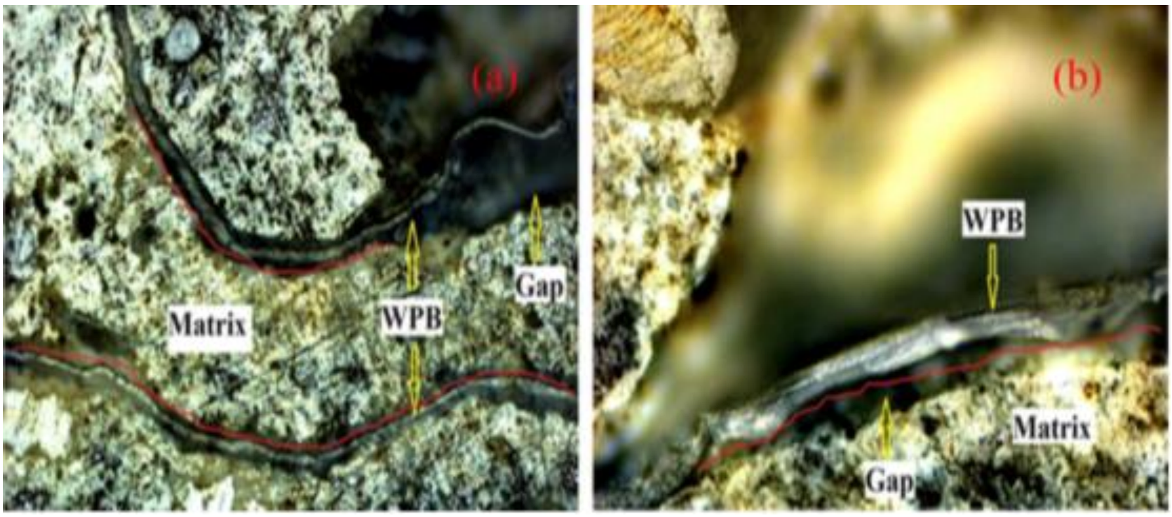


Figure 16 The microstructure for WPC (a) magnification of 100 ×; (b) magnification of 200 × [72].

The overall performance can be considerably enhanced through the modification of the surface layer of PA using foaming or granulation technology. For instance, the modified EPS (expanded polystyrenes) [80] and the plastic granules [25]. Showed better bonding because of the rougher and more porous surface, which can be seen in Figure 17.

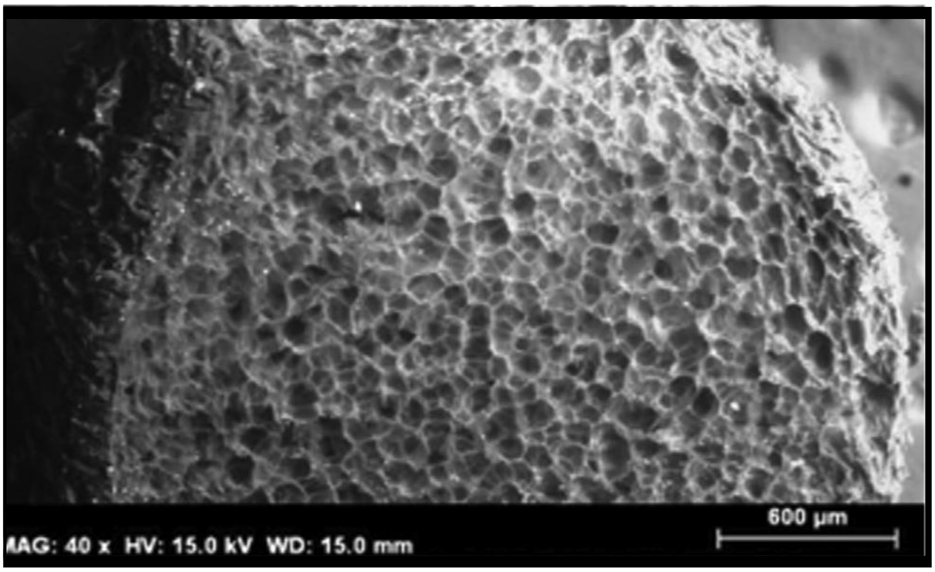
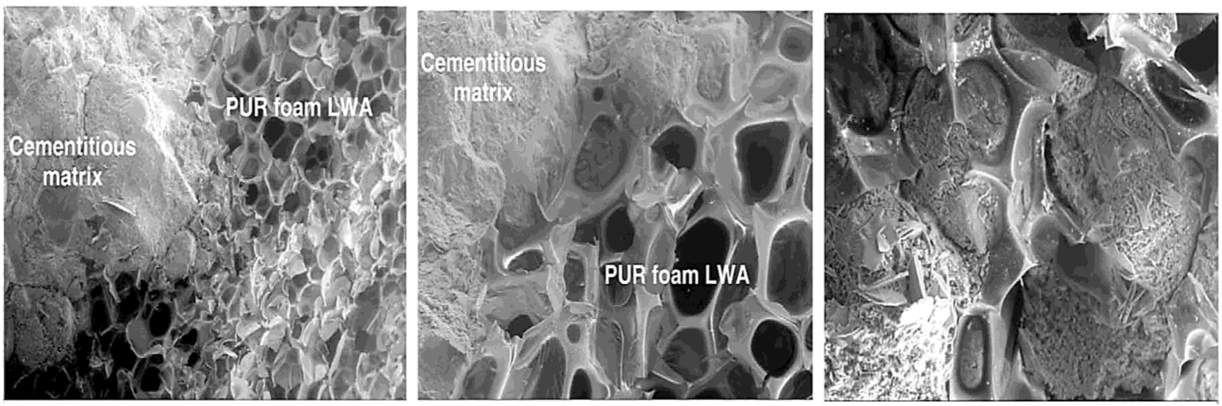


Figure 17 - SEM image of expanded polystyrenes [80].

Figure 18 presents the SEM images for concrete that contains polyurethane (PUR) foam as the replacement of coarse aggregate[81]. The samples that were used were acquired from cylindrical specimen fragments that were tested through compression and investigated without there being any specific kind of pre-treatment, i.e. polishing or drying. Good adhesion is revealed in the images with respect to the PUR foam aggregates and the cementitious matrix; there was penetration of the cement past through the pores of the surface of those lightweight aggregate, since the pores were wide enough to develop cementitious morphology. There was no observation of a wall effect on the interface between the cement mortar and the dry or pre-wetted PUR foam aggregates.



(a) (b) (c)

Figure - 18 SEMs of the field emission kind for the interfacial zone lying between concrete with polyurethane foam aggregates and the cementitious matrix at twenty-eight days[81]: (a) magnification of 100x; (b) magnification of 300x; and (c) magnification of 500 x.

5. Durability Related Properties of Concrete Containing Polymers

Concrete durability is related to gas and fluid permeability, since they are responsible for steel corrosion within concrete. It is, therefore, critically important to select proper kinds of concrete materials in order to enhance the durability. Concerns have been raised about recycling waste materials within concrete because of the potential for presence of contaminants. Existing research has shown that recycled plastics do not possess good durability like natural aggregates [9]. Numerous durability factors are assessed for concrete that contains plastic as natural aggregate replacement; these factors include chloride ion permeation, porosity and water absorption and the resistance against repeated freezing and thawing. However, when compared to the information that is existing on the mechanical performance of concrete with PA, less information is available in relation to concrete behaviour in durability terms [13].

5.1 Water Absorption and Porosity

The water absorption gives an indication of the level of porosity for materials through determination of the percentages for water absorbed in particular conditions [82]. Porosity is indirectly reflected by characteristics of water absorption such as the permeable pore volume connectivity [12]. The porosity measurement of hardened cement paste may be determined through water saturation, with water molecules having the potential to enter the spaces within the microstructure [83].

The water absorption and porosity tests have been undertaken within various investigations of concrete samples that contained PA for evaluation of the capability of that kind of concrete in respect to prevent steel corrosion [11, 27, 52, 64, 78, 81]. In most of the studies, replacement of PA led to higher levels of water absorption and porosity of the concrete. As Figure 19 illustrates, it was noted by Akram et al.[84] that concrete water absorption raised exponentially with increasing percentages e-plastic content. Similar findings were observed by Albano et al [40] reported a higher levels of water absorption in concrete that contained PET plastic when compared to concrete that only contained natural aggregate. There is further increase of the water absorption with increasing PET aggregate content and with increasing PET aggregate size. The poor bonding at the ITZ between PA's and cement paste has led to increased permeability and porosity. Redistribution of (C-S-H) calcium-silicate-hydrate during hydration of cement allows for partial filling of the pores in the ITZ. Aggregates can be interconnected within ITZ, this depends on the width and quality of contained aggregates, which significantly influenced the transport properties and the permeability [10]. Therefore, this could be due to the difference in size distribution in addition to difference in PA shape from the fine natural aggregate. Saikia & de Brito [11] is in agreement with the work of Albano et al.[64] reporting an increase in water absorption capacity for concrete specimens with different substitution levels of PET as CA and FA. Moreover, it was noted that flaky, coarse PET plastic aggregate resulted in a greater increase to the capacities of water absorption than the pellets and fine PET plastic aggregates did. Within the study undertaken by Colangelo et al.[85], waste polyolefin plastic aggregate were used in substitution of natural aggregate within concrete. The authors claimed that there was an increase in open concrete porosity of around 19.5%, 31.2% and 40.1% with a replacement ratio of 10%, 20% and 30%, respectively, whilst there was a corresponding increase in water absorption from 9.0% to 15.2% (see Figure 19). The water absorption and apparent porosity values of various concrete mixtures containing different quantities of waste PET and polycarbonate (PC) plastic aggregate were also measured by Hannawi et al[78]. The findings from their study showed that replacement of 3% of sand (by volume) by an equal amount of PC or PET did not exert influence on water absorption or either the apparent composite porosities when compared to the control samples. However, there were increases in water absorption and apparent porosity with increasing content of plastic, SEM analyses (see figure 20) the result shows cracks and large gaps between the cement matrix and PA's, which proves a weakening in bond.

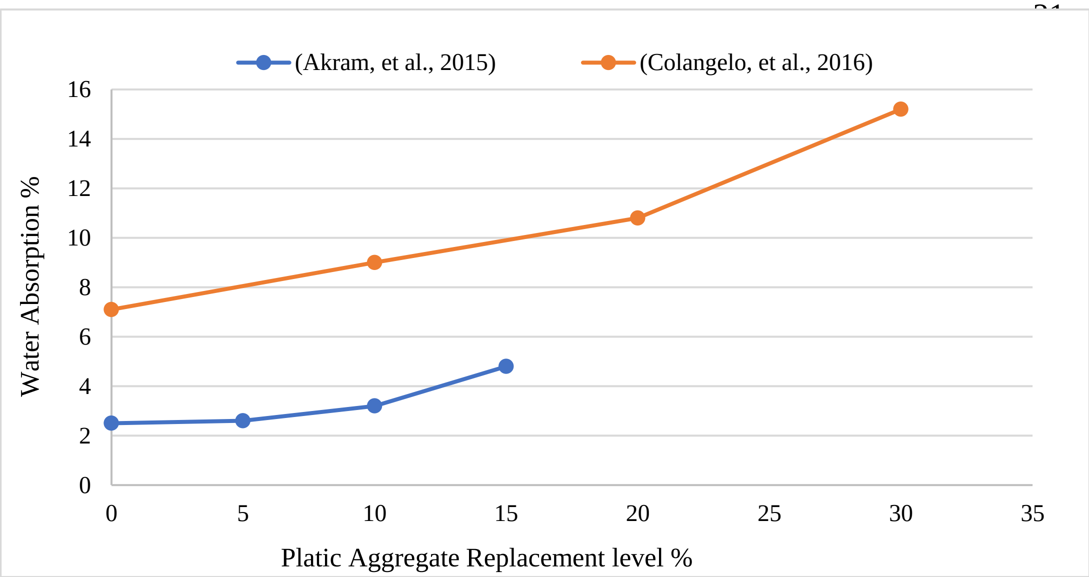


Figure 19 - water absorption capacity of concrete containing plastic aggregate.

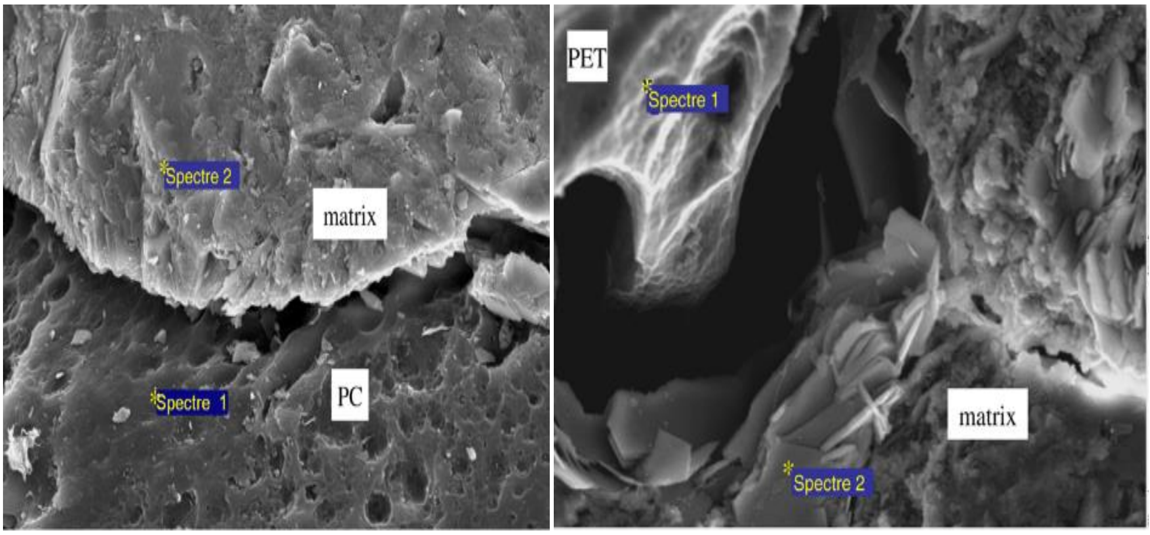


Figure 20 - SEM imaging showing the bonding between cement matrix and PA [78].

5.2 Air/ Gas permeability

In general, permeability of aggressive forms of chemical species through concrete pores is a key factor controlling several properties of durability. Tests such as gas permeability, measurement of chloride permeability and water absorption are able to provide information related to concrete vulnerability to ingress of chemical species that are deleterious [41]. The durability-related properties for rubberised concrete were investigated by Güneyisi et al [86]. Two kinds of tyre rubber waste scrap were utilised as coarse and fine aggregate respectively. There was replacement of the rubber with natural aggregate with three crumb rubber and tyre chips of levels 5%, 15% and 25% for the productions of rubberised concrete. The test for gas permeability was only undertaken at the level of 5% replacement of rubber, because of high porosity of 15% and 25% replacements for the rubber in both series of concrete, there was the gas permeability test failed. Due to the very rapid oxygen flow through the specimen, it was not possible to take readings from the volumetric meters of gas flow. The coefficients of gas permeability had a range from 1.35×10^{-15} m^2 for the control sample and 2.35×10^{-15} m^2 for the concrete with 5% rubber content. Also Hannawi et al[78] assessed the apparent permeability for concrete that was prepared with replacing different percentages of FA by PC and PET plastic aggregate by using helium gas at a pressure of 0.2 MPa. The authors discovered an increase in coefficient of permeability with increasing PA content within the concrete, and that showed an increase in the percolated concrete porosity because of the plastic aggregate incorporation. When, considering aggregates water absorption, the average amounts of the w/c of the matrix in PET and PC mixes are definitely higher than the control sample. However, PA water absorption is around 0.15% are slightly lower than for siliceous sand which is around 0.7%. The poor bonding between cement paste and the PA definitely increases the composite's porosity which can explain the observed increase in plastic mixtures permeability. The porosity of the mixture will be higher with increasing PA content, figure 20 shows SEM images which is highlighting the bonding quality between cement matrix and PET/PC.

5.3 Chloride Migration

Chloride ingress within concrete may lead to de-passivation of the steel reinforcement and begin the corrosion of the reinforcement [87]. The corrosion of the steel bars that are embedded within reinforced concrete (RC) structures affects the durability and decreases the service life and can lead to early structure failure. Which can cost greatly in terms of inspection and the maintenance of deteriorating structures [88]. So, resistance to the ingress of chlorides is a key indicator for assessing the durability in concrete. However, conflicting findings have been claimed with respect to the chloride ingress resistance of concrete that has recycled plastic waste incorporated within it.

An increase in resistance to the penetrability of the chloride ion was noted by Kou et al [25] with increase in the PA content. Total passed charge (measured in coulombs) was reduced from a level of 36.2% to 11.9% when the rate of substitution was increased from 5% to 45%. The chloride ion penetration reduction was attributed to blockage of the chloride ion passage due to the impervious characteristics of plastic. Likewise Fraj et al [81] evaluated the coefficients of chloride diffusion for concrete that contained rigid PUR foam as partial replacement for the natural CA. A lower chloride diffusion coefficient value was observed by the authors for concrete that contained dry PUR compared to concrete that only contained NA. However, the pre-saturated PUR foam aggregate within water, led to a significant chloride diffusion coefficient increase because of the increase in concrete porosity that rose with increasing PUR foam aggregate volume within concrete. It was also claimed that the w/c ratio reduction and increase to the cement content could significantly enhance the performance of chloride resistance for concrete with pre—wetted PUR foam aggregate. Silva et al [89] presented opposite findings in reporting that chloride permeability within concrete that contained waste PET plastic as FA and CA was higher than that with conventional concrete. A greater coefficient of migration was observed with increase of PA content, due to the increase of pore structure within the concrete. Furthermore, the concrete specimens that were cured within the laboratory environment had probably the highest rate of chloride iron, followed by specimens that were cured outdoors, the lower penetration level was for specimens that had been cured within a wet chamber.

6. Concerns of Concrete Containing plastics

Following the brief review above of the published material related to the subject, it is apparent that using plastic within concrete in partial replacement of aggregate clearly has an effect upon material properties. Incorporation of PA's into the concrete changes the homogeneity and the consistency of the fresh mixture such as density and workability. The reduction in mechanical properties (compressive, flexural, splitting tensile strength and elastic modulus) was due to the weak adhesive strength between PA and the cement past, this is due to the hydrophobic nature of plastics. The hydrophobic effect further limited water diffusion into the concrete, which is necessary for hydration of cement. In addition, in comparison to natural aggregates, plastic aggregates are less stiff and lower in strength and may, therefore, act as stress concentration zones favours the propagation of damage. PA's is unable to chemically interact with cement paste; and consequently, the ITZ in plastic containing concrete weak, and this further increases the air void content voids within the mixture. PA have almost no capacity to absorb water, there will be accumulation of water within the ITZ and this causes it to have greater porosity that will lead to reduction in the strength. Normally, most PA have a smooth surface that leads to create a poor bond between the aggregates and the cement matrix which resulting to lowering the strength of concrete. Furthermore, the poor bonding at the ITZ between PA's and cement paste has led to increased permeability and porosity. Redistribution of (C-S-H) calcium-silicate-hydrate during hydration of cement allows for partial filling of the pores in the ITZ. Aggregates can be interconnected within ITZ, this depends on the width and quality of contained aggregates, which significantly influenced the transport properties and the permeability. Therefore, the concrete performance is reduced under both durability and mechanical testing by the non-reactive, intrinsic behaviour of the plastic aggregate. Increased air content and the weak bonding between the natural aggregate and the PA are considered to be the primary causes of the reduction in performance of the concrete containing plastic. The surface texture, size and shape also influence the performance of PA concrete.

7. The Proposed Innovative Method

7.1 Potentiality of Using MW Treatment for Concrete Containing Plastics

Microwaves are a form of electromagnetic wave with a frequency range of approximately 0.3 GHz (no specified actual lower limit of frequency exists) up to 300 GHz with corresponding wavelengths ranging between 1m down to 1mm [90]. There has been widespread use of microwave energy in innovative forms of material processing for a variety of industrial dielectric materials. MW radiation basically interacts with materials by means of dielectric permittivity that results in rapid forms of heating. As a consequence, dipole interaction and the heat generation would therefore take place in dielectric materials that are comprised of polar molecules [91]. Microwave heating would also be beneficial in the cement and concrete industries, since cement making materials display excellent dielectric properties (see table 1) and should be capable of absorbing MW energy very effectively. Moreover, volumetric, internal heating through microwave energy potentially gives many benefits to concrete and cement industries. The potential benefits, as noted by Makul et al.[92], include:

1. Rapid rates of heating and short processing times, that saves time as well as energy;
2. Deep microwave energy penetration. A MW system, at operational of 2.45 GHz, may, typically, penetrate through several centimetres of concrete and cement materials. Which allows for efficient heat generation without direct contact with the cement constituents;
3. Fine and unique microstructural development allows for better properties in the cement production;
4. Clean processes of heating that do not involve generation of secondary forms of waste

Throughout the research of the literature, it was shown that the utilisation of plastics within concrete tended to be of two particular forms, i.e. PF and PA, the properties of fresh and hardened concrete containing plastics were studied. It was concluded by many researchers that the major reasons for all the changes in the concrete properties is the poor bonding and increased air content between PA and the cement paste. Nevertheless, many of the available literature studies randomly substituted PA within the concrete and studied their impacts on the durability and mechanical properties. Also, in general there has been a great deal of focus upon recycling and using waste plastic within the concrete, instead of the treatment of plastic materials prior to or following their mixing with concrete. Some researchers have proposed enhancing the bonds by using chemical treatments on PA's in order to modify the surface texture. However, this research offers a novel technique to improve the bonding strength between cement paste and PA. It was discovered that the MW based techniques have been successfully used for the acceleration of curing of cement-based materials at early age. Makul et al [14] stated that the MW- assisted curing, in practice, has been proven to be useful in respect to reducing the processing time, the cost and energy efficiency and improved material performance, especially during the early ages. When cement based materials exposed to the electromagnetic wave the dielectric loss coupling is the heating mechanism. Therefore, any heat produced is dissipated inside the processed concrete, and the concrete temperature monotonically raises. As a result, accelerated hydration reaction occurs. The water molecules escape within the concrete just before the cement hardens, which leads to the capillary pores collapse and produces a denser internal structure of concrete. Hence, the early age concrete strength development increases dramatically [93]. On the other hand, MW-assisted heating, though, has also been successfully utilised within several types of industrial process such as those related to biological materials [17], wood [18] and food [16]. Also, there has been use of MW energy within polymer material characterisation. In the investigation undertaken by Ateeq et al.[19]. However, there has not been use of MW power so far for the treatment/melting of polymers within concrete in order to impregnate as well as enhance concrete properties. It may be hypothesised that higher air content and weak bonding capacity of PA within concrete are predominant factors in the lowering of durability and mechanical properties; therefore, in that respect, there is a need for future research for improvement of those factors. So, that overall durability with regard to advanced chemical and hydrophobic resistivity and the performance in ductility of conventional kinds of concrete can be improved further, this research proposed a technique that is innovative in its use of MW power in addressing concerns related to concrete that contains plastic. Resonant cavity (a cavity-based sensor of MW) could be employed in determining the rate of the MW energy absorption by numerous kinds of plastics (thermoplastic polymers) and mortar paste that contains plastics. A successful impregnation of a plastic without distressing the hydration of the concrete will enhance the bonding in the concrete matrix further and also this will enhance performance in relation to chloride migration, porosity, flexural strength and compressive strength. Thus, this matter of the research aimed to be addressed by the authors within the following research work.

8. Conclusion

The study findings have given the indication that plastic may be utilised in partial replacement of coarse and fine aggregate within concrete. However, there were adverse effects upon the mechanical, durability and fresh concrete properties when recycled waste plastics were used as PF, CA and PA. The non-reactive, intrinsic behaviour of plastic aggregate reduced concrete performance under both durability and mechanical testing. The size, surface texture and shape of PA were also discovered to have an impact upon concrete performance. Based upon the review of literature that was presented, the conclusions that follow may be drawn:

1. Using PA as partial replacement for NA results in significant increase to the concrete air content because of the irregular shape, immiscibility of plastic and natural sand, and hydrophobic nature that plastics have;
2. Increasing PA content leads to a reduction in concrete density, the reduction is more with the flakier and bigger plastic aggregate particles;
3. There is a gradual decrease of the development of compressive strength with increasing PA content (of both when coarse and fine);
4. In relation to the PF use, compressive strength reduces more with increasing in PF length and the percentage content
5. The splitting tensile strength and elastic modulus reduces linearly with increasing PA content. However, there is a lower reduction of elastic modulus than to the compressive strength;
6. As with mechanical strength, addition of plastic waste also leads to higher chloride ingress, water absorption and the gas and air permeability of the concrete.
7. Resonant cavity can be used in determining the rate of the MW energy absorption by numerous kinds of plastics and mortar paste that contains plastics. A successful impregnation of a plastic without distressing the hydration of the concrete will enhance the bonding between cement paste and aggregates this leads to further improvement in relation to mechanical and durability properties of concrete including; chloride migration, porosity, flexural strength and compressive strength.

Various approaches have been conducted in order to improve plastic performance within concrete; one of these approaches is the treatment of the surface. Chemical surface treatment has been tried that use oxidising chemicals for enhancement of bonding characteristics. There is a belief that reaction between oxidising chemicals and plastics produce certain chemical species upon the polymer surface that could, ultimately, participate somehow within the cementitious reaction. E-beam (electron beam) radiation is another technique that is used for surface modification to plastic materials; the ionising form of energy is normally characterised as having high rates of dosage and low penetration. Processing by e-beam is a method employed in surface modification of the properties of plastics with the low-energy electrons used for crosslinking, modifying or improving adhesion to surfaces. Moreover, in recent decades, there has been a steady increase in polymer treatment through gamma radiation because of modification and improvement to polymer materials in regard to its electrical, chemical, optical, structural and physical properties. The mechanical concrete properties are enhanced by gamma radiation and the structure of the surface is modified. Gamma radiation also helps to improve adhesion of the matrix and fibre. Widespread application of gamma rays is restricted, however, because of the harmful effects they have upon the human body through it potentially leading to severe damage to DNA and tissue.

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