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STATE-OF-THE-ART REVIEW: CONCRETE MADE OF RECYCLED WASTE PET AS FINE AGGREGATE

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ABSTRACT

It is well known that the foremost environmental sustainability concern derives from the abundance of the plastic waste. The growing problem of the plastic waste originates from the presence of Polyethylene terephthalate (PET) from plastic bottles. Nevertheless, the versatile performance of PET in terms of its lightweight, strong, flexible, moisture-resistant, and cheap can make it a replacement substance for aggregates in green concrete. On the other hand, PET replacement has mostly been restricted to non-structural uses, generally due to its lower strength/stiffness, larger creep and shrinkage, poorer durability associated to natural aggregate concrete (NAC). This paper presents a comprehensive review of the published studies on waste recycled plastic by means of fine aggregate replacements. Parameters including fresh concrete properties (workability and density) and the hardened concrete properties (compressive strength and splitting strength) have been considered. After a detailed review it was found that most of the studies conducted in the area of using PET as a fine replacement outlined the adherence between concrete and PET.

KEYWORDS: State-of-the-art; Plastic waste; Polyethylene terephthalate (PET); Fresh and hardened concrete properties.

1. INTRODUCTION

New technology and human lifestyle have led to the generation of waste products, in which the question on how to disposal such waste persists. In general, most waste consequences are non- degradable and rest in the environment for thousands of years (E. Rahmani, M. Dehestani, M. Beygi, H. Allahyari, & I. Nikbin, 2013). The bulk of this solid waste was deposited in waste dump sites. This waste treatment is unfavorable because it is environmentally unfriendly operation. Therefore, a new approach for sustainable development is required so that such approach should be able to optimize the elimination, reuse, and recycle of such solid wastes (Oyenuga & Bhamidimarri, 2015). In order to diminish the environmental consequences on the construction sector, studies to use such waste have been conducted. The recycling of solid waste as a partial substitute of the aggregate in construction industry results in decreased demand for natural raw material production along with a reduction in waste disposal capacity. This eliminates the usual need for traditional materials by using plastic wastes in concrete mixes and thus contributes to sustainable production (Singh, Nagar, Agrawal, Rana, & Tiwari, 2016).

In general, plastics can be categorized into two classes: thermoplastic and thermosetting. Thermoplastics plastics such as high-density polyethylene (HDPE), polyethylene terephthalate (PET), polyethylene (PE), polystyrene (PS), and polypropylene (PP), can harden and melt with cooling and heating. On the other hand, Thermosetting plastics, such as epoxy, melamine, silicone, unsaturated polyester, phenolic, and polyurethane, cannot be dissolved by heating (Panyakapo & Panyakapo, 2008; Siddique, Khatib, & Kaur, 2008). Due to the advantages of plastics, like the suitability of using and its lower cost, there is a growing demand around the world. As a consequence, in

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2017, the world generated 348 million tons of plastics, out of which 64.4 million tons was generated in Europe (EuropePlastic, 2018). As a consequence, plastic pollution can cause over 100,000 marine mammals and over one million marine birds to die per year as they are gulping or get entangled. This raises the fact that the increase in the production of plastic waste is serious (Saikia & de Brito, 2012).

Only around 25% of plastic waste worldwide is recycled. Thus recovering and recycling plastics is still inefficient, and millions of tons end up every year in oceans and landfills (Gourmelon, 2015). Some of such recycled plastic proportions can be used in building materials and housing members (Bajracharya, Manalo, Karunasena, & Lau, 2014). A study by Geyer, Jambeck, and Law (2017) shows the cumulative quantity and disposal of plastic waste estimated that over to 33% of waste produced will be recycled by 2050. Even if such estimate will be achieved in the future, however, the volume of non-recycled waste remains highly undesirable.

Some of the researchers investigated the probability of waste disposal utilizing advanced techniques, such as converting plastics to energy or fuel Ouda, Raza, Al-Waked, Al-Asad, and Nizami (2017); Wong, Ngadi, Abdullah, and Inuwa (2015). Nevertheless, most such studies did not state how the amount of plastic produced can be reduced or controlled. Recycling plastic with other components is the better solution for this problem, to create products with advanced characteristics than their original form. One of these products is concrete (Agamuthu & Faizura, 2005; Al-Manaseer & Dalal, 1997; Kim, Yi, Kim, Kim, & Song, 2010). There be an enormous possibility for recycling plastics waste in concrete. As a consequence, the significant utilization of waste plastics as a concrete aggregate will further minimize non-recycled plastic waste. Nevertheless, While the industry offers a wide range of plastic forms, studies clearly indicate that not all of them are acceptable as concrete aggregates. Resin-based sorts of plastic waste and PET have been stated to have the premier utilization average for productions of concrete (Pacheco-Torgal, Ding, & Jalali, 2012; Siddique et al., 2008).

Polyethylene Terephthalate (PET) is one of the key elements of the waste plastic flow mainly from thermoplastic polyester family (Silva, de Brito, & Saikia, 2013). It is composed of ethylene glycol and terephthalic acid, and chemically known as PET (Bhatti, 2010). The molecular formula of PET plastic is $(C10H8O4)_n$, and it is unique among the main polymers due to its high oxygen content (Arora & Dave, 2013). The high oxygen concentration prevented the gas diffusion in this plastic, which is crucial to keep carbonated soft drinks fresh. Worldwide, around 30% of PET is consumed for the manufacture of bottles, since about 107 tons of PET are used to manufacture about 250 × 109 tons bottles annually (Pira, 2014; Saiter, Sreekumar, & Youssef, 2011). The treatment procedures of these materials are different, like burial, incinerate, and recycling (Williams, 2005). The burial issue is, the fact that plastic products gradually dissolve and it takes hundreds of years to come back to the natural cycle; the incinerate matter is, the heat generated during the incineration can be benefit, but the burning of other forms of waste such as PET will produce toxic gases. Therefore, recycling seems to be the safest path for compliance with the ecosystem and economic gains (Albano, Camacho, Hernández, Matheus, & Gutiérrez, 2009). The most economical method is to replace aggregates with PET polymers. As a result, the use of PET waste as an aggregates in concrete has several profits like decreasing the utilize of wastes consumption, renewable resources, contamination in the atmosphere, and energy savings (Silva et al., 2013).

It is well known that the flourish of the manufacture sector results in an increase in demands of construction materials like cement and aggregate. Thus, the substitution of construction materials with PET waste could be one of the solutions to overcome the matter of high demand of aggregates. In general, concrete is constituted by 60% to 80% with aggregate by volume and 70% to 85% by weight. However, the main issue is the fact that the aggregate is a non-renewable source and constant quarrying activities are affecting the environment and can lead to the shortage of aggregates. Thus, the replacement of aggregate is needed to reduce the effects of quarrying (VOON, 2015).

All in all, PET is a sort of waste that is growing that could cause a lack of landfill in the nearest future. Thus, a replacement of concrete

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aggregates by PET can solve or eliminate such problem and preserve the natural environment. For this purpose, several studies have used PET to replace aggregates as green concrete (eco-friendly concrete). Thus, the core goal of this research is to evaluate and summarize the published works in the area of utilizing PET in concrete. This could identify the suitability of the substituted aggregate in concrete and to address the advances in concrete properties of the substituted aggregate This will be useful to evaluate the workability, density, compressive strength, and splitting tensile strength of concrete with plastics waste. The study can highlight the performance of various ratios of PET as a fine aggregate substitute in concrete. Thus, this comprehensive investigation covers associated knowledge of past studies presented on PET incorporation into concrete. For this purpose, fresh and hardened concrete properties in terms of workability, density, compressive and splitting strengths tests are presented.

2. REVIEW OF PLASTIC AGGREGATE CONCRETE PROPERTIES

This section only reviews the findings of the studies on the influence of plastic as aggregate on the properties of both fresh and hardened concrete. The specific properties covered include workability, density, compressive, and splitting strength.

2.1 Fresh Concrete Properties

2.1.1 Workability / Slump

Workability is the consistency of fresh concrete mixture that recognizes the best way that the concrete can be mixed, set, unified, and finished. Whereas slump is used to calculate fresh concrete mixes workability or consistency. Although the concrete should be made in compliance with the specification's requirements; however, the use of both mineral admixtures and waste materials together has an effect on the workability of the concrete. The use of plastics has an impression on the quantity of water in the concrete and as a sequences this will affect the concrete workability. The influence of replacing different forms of plastic waste to the concrete on its workability is discussed in this section. Table 1 presents some details, undertaken from detailed literature.

In this section the impact of plastics as aggregate on concrete slump has been presented. The available studies in the literature have been summarized. Al-Manaseer and Dalal (1997) stated that the plastic aggregates do not absorb nor add water to the mixture. This non-absorption feature will result in much more free water for concrete mixtures contains plastic waste aggregates. The slump then increased. Y.-W. Choi, Moon, Chung, and Cho (2005) and Y. W. Choi, Moon, Kim, and Lachemi (2009) noted that with the addition of blast furnace slag, the concrete workability increased due to an increase in the replacement ratio, w/c ratio, and blast furnace slag percent. Batayneh, Marie, and Asi (2007) found the slump value to be 58 mm can be achieved with a plastic particle content of 20 %, so the mix should be regarded as acceptable and workable. Ismail and Al-Hashmi (2008) assessed the workability and observed that with a growing abundance of plastics waste, the slump dropped sharply. Tang, Lo, and Nadeem (2008) assigned that the polystyrene (PS) gross aggregate concrete had a shut cellular structure with an insignificant ability to absorb water. Albano, Camacho, Hernandez, Matheus, and Gutierrez (2009) showed that PET had an effect on the slump but had a greater impact on the slump as the ratio w/c raised. Frigione (2010) observed that due to small percentages of fine aggregates, such as waste PET, the water absorption has not been affected. B. Rai, S. T. Rushad, B. Kr, and S. K. Duggal (2012b) declared that without adding super-plasticizers to the concrete mixture, waste plastic flakes has reduced the slump from 55 to 35 mm. The same degree of decrease was found in waste workability. Silva et al. (2013) used three various types of PET in concrete, and findings indicated that angular and lamellar form resulted in concrete less workable, whereas regular and spherical forms promoted workability. The variation in internal friction between the plastic aggregation with various forms and binders can explain this. Safi, Saidi, Aboutaleb, and Maallem (2013) investigated the effect of recycling waste plastic aggregate (RWPA) on fluidity of mortar and mentioned that a self-compacting mortar decreases in fluidity as the amount of plastic waste increases by up to 50 %. They related the fluidity rise to the aggregate's smooth surface relative to sand and the reality that plastic has been difficult to absorb water. E.

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Rahmani, M. Dehestani, M. H. A. Beygi, H. Allahyari, and I. M. Nikbin (2013) stated that decreased workability became more pronounced as the amount of plastic waste increased. Approximately 42% lost workability as the contents of plastics raised from 0 to 15 %. Saikia and de Brito (2014) revealed the influence of the shape of PET plastic particles on concrete workability and showed a slight rise in the slump of fresh concrete with the combination of spherical/cylinder heat treatment pellets called (PP) aggregate. Almeshal, Tayeh, Alyousef, Alabduljabbar, and Mohamed (2020) noted that, due to non-uniform and irregular particulate shapes, the workability of concrete containing recycled plastic has been decreased.

2.1.2 Dry Density / Fresh Density /Bulk Density

Density is the uniform weight of the quantity of concrete engaging one cubic meter of vacuum as the concrete is a mixture of some main constituents (i.e., cement, fine and coarse aggregates, and water). Separate constituents such as sand, gravel or cement may be totally or partially replaced by plastic materials, slag or fly ash to produce lightweight concrete or reduce the costs. The shredded plastic has a high strength and lightweight characteristics that can change the normal concrete into lightweight concrete. Typically, the density (mass) of the concrete stands at 2400 kg/m^3, while the lightweight concrete mass density comprises shredded plastic can turn down to 1750 kg/m^3 Dorf (1996). In subsequent sub-sections, the impact from the substitution of particular types of wastes as aggregate on density is shown. Furthermore, some information reviewed in the literature are illustrated in Table 1.

Al-Manaseer and Dalal (1997) evaluated the impacts of waste PA onto the concrete bulk density and found that the decrease in density was due to the depressing weight of the plastics component. Marzouk, Dheilly, and Queneudec (2007) noted that the bulk density reduced with the reducing size of the particle with the same volume ratio of replacement. Ismail and Al-Hashmi (2008) showed that the density of fresh concrete contains 10%, 15%, and 20% of plastic waste aggregates tended to reduce, respectively, by 5%, 7%, and 8.7 %, below on the concrete reference. Y. W. Choi et al. (2009) indicated that the density of concrete mixes has been reduced by raising the volume of the waste PET lightweight aggregates (WPLA). Hannawi, Kamali-Bernard, and Prince (2010) revealed that 50 % substitution of fine aggregates with PET and polycarbonate (PC) decreased dry densities of up to 19, and 24 % of ordinary concrete, mostly due to the low specific weight (SG) of the plastics. Rai et al. (2012b) noted that increasing the content of plastic waste reduces both the fresh and dry density of concrete. E. Rahmani et al. (2013) showed that adding PET particles into concrete and increasing the w/c ratio of concrete contains PET particles contributes to minimum concrete unit weights. Saikia and de Brito (2014) found a reduction of the fresh concrete densities due to growing amount of PET incorporated aggregates. Araghi, Nikbin, Reskati, Rahmani, and Allahyari (2015) noted that for specimens of 0, 5, 10, and 15% of PET particulates, weight-loss rates are 13.47, 10.26, 8.98, and 6.57 %, respectively. Kumar and Baskar (2015) noticed that the fresh density of 10, 20, 30, 40 and 50 % tends to decrease by 1,10, 4,87, 7,58, 10,70 and 13,58 % respectively; below the reference mix. Sosoi, Barbuta, Serbanoiu, Babor, and Burlacu (2018) found that the density of hard polymer concrete in each of the waste forms is smaller than 2000 kg/m^3. Almeshal et al. (2020) showed that the unit weight decreased because of the low plastic density.

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Table (1): Overview of some details reported on concrete fresh properties incorporated plastic aggregates.

No.	Reference	Type of Composite	Type of Plastic Waste	Origin of Plastic Waste	Types of Substitution	Amounts of Substitution	Particle Size (mm) / Shape	**Concrete Properties Reported in the Literature Review**	
								Workability	**Density**
1	Al-Manaseer and Dalal (1997)	Concrete	PP	Cars bumpers	C.A	10, 30 and 50 vol. %	≤ 13 / Angular	✓	✓
2	Y.-W. Choi et al. (2005)	Concrete	PET	PET-bottles	F.A	25, 50 and 75 vol. %	5-15 / Smooth and Rounded	✓	
3	Batayneh et al. (2007)	Concrete	N.M	Waste plastic	F.A	5, 10, 15, 20 vol. %	0.15 – 4.75 / little Particles	✓	
4	Marzouk et al. (2007)	Mortar	Glass + PET	Waste plastic	F.A	2, 5, 10, 15, 20, 30, 50, 70 and 100 vol.%	Type A: ≤ 5, Type C: ≤2Type D: ≤1 Irregular and R.S.T		✓
5	Ismail and Al-Hashmi (2008)	Concrete	PET + PS (Mix 80% PET & 20% PS)	Plastic containers	F.A	10, 15 and 20 vol. %	Length: 0.15–12 & Width: 0.15– 4 / Irregular	✓	✓
6	Tang et al. (2008)	Concrete	PS	Waste EPS	C.A	20, 40, 60 and 80 vol. %	4 / Beads & Granules	✓	
7	Albano, Camacho, Hernández, et al. (2009)	Concrete	PET	PET-bottles	F.A	10 and 20 vol. %	(A) 2.6, (B) 11.4 (C) 50/50% of Both Sizes / Flaky	✓	
8	Y. W. Choi et al. (2009)	Mortar & Concrete	PET	PET-bottles	F.A	Mortar: 25–10 vol. % Concrete: 25–75 vol%	≤ 4.74 / Smooth and Rounded	✓	✓
9	Frigione (2010)	Concrete	PET	PET-bottles	F.A	5 wt. %	0.1–5 / Irregular	✓	
10	Hannawi et al. (2010)	Mortar	PET & PC	Industrial Waste	F.A	3, 10, 20 and 50 vol. %	PET: 1.6–10, PC: ≤ 5 / N.M		✓

N.M: Not Mention; F.A: fine aggregates; C.A: coarse aggregates; vol.: volume; wt.: weight; PET: polyethylene terephthalate; PS: polystyrene; PP: polypropylene; PC: polycarbonate; PVC: polyvinyl chloride; EPS: expanded polystyrene; EVE: Ethylene vinyl acetate; HIPS: High impact polystyrene.

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Table (1): Continue.

No.	Reference	Type of Composite	Type of Plastic Waste	Origin of Plastic Waste	Types of Substitution	Amounts of Substitution	Particle Size (mm) / Shape	**Concrete Properties Reported in the Literature Review**	
								Workability	**Density**
11	B. Rai, S. T. Rushad, B. Kr, and S. Duggal (2012a)	Concrete	Virgin PET	Industrial	F.A	5, 10 and 15 vol. %	N.M / Flaky	✓	✓
12	Silva et al. (2013)	Concrete	PET	PET-bottles	F.A & C.A	7.5 and 15 wt. %	(A) 2–11.2, (B) 1–4 / (A) Flaky for C.A.	✓	
13	Safi et al. (2013)	Concrete	PET	Plastic bags	F.A	10, 20, 30 and 50 wt. %	≤0.01/ Annular Cylindrical	✓	
14	E Rahmani et al. (2013)	Concrete	PET	PET-bottles	F.A	5, 10 and 15 vol. %	0.15 - 7 / Flaky	✓	✓
15	Saikia and de Brito (2014)	Concrete	PET	PET-bottles	F.A & C.A	5, 10 and 15 vol. %	F.A: ≤4, C.A: ≤ 11.2 / (A) Flaky, (B)	✓	✓
16	Araghi et al. (2015)	Concrete	PET	PET-bottles	F.A	5, 10, and 15 vol. %	≤ 7 / N.M		✓
17	Kumar and Baskar (2015)	Concrete	E-plastic	Computer plastics	C.A	10, 20, 30, 40 and 50 vol. %	≤ 12.5 / Flaky		✓
18	Sosoi et al. (2018)	Concrete	PET	Waste plastic	F.A	25, 50, 75 and 100 vol. %	0-4 / N.M		✓
19	Almeshal et al. (2020)	Concrete	PET	PET-bottles	F.A	10, 20, 30, 40 and 50 vol.	0.075 – 4 /	✓	✓

N.M: Not Mention; F.A: fine aggregates; C.A: coarse aggregates; vol.: volume; wt.: weight; PET: polyethylene terephthalate; PS: polystyrene; PP: polypropylene; PC: polycarbonate; PVC: polyvinyl chloride; EPS: expanded polystyrene; EVE: Ethylene vinyl acetate; HIPS: High impact polystyrene.

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2.2 Hardened Concrete Properties

2.2.1 Concrete compressive strength

The concrete compressive strength reveals the capability of the substance to counterattack pressure exposed by the testing machine, where the compression member was shattering when it passes the limits of concrete compressive strength. In a certain experiment, when a cube or a cylinder is subjected to a load that leads to a failure, the condition is termed a pressurized situation. The influence on the compressive strength of substitution of various forms of plastic waste as aggregate is mentioned in the subsequent paragraphs, see Table 2.

Y.-W. Choi et al. (2005) stated that increased substitution rate of PET aggregate increases the loss of compressive strength but not proportionally. Batayneh et al. (2007) described the compressive strength showed a steep decline until 72% of the actual strength for 20% of ground plastic waste substitution. Marzouk et al. (2007) illustrated that the replacing sand at a rate under 50% with granulate PET, whose upper granular limit equals 5 mm, does not influence the composites compressive strength. Ismail and Al-Hashmi (2008) mentioned that by raising the ratio of plastic waste, the findings indicate an inclination to decrease the values of compressive strength under the plain mix at every curing time of plastic concrete mixes. This trend is due to the decrease in adhesion between the surface of the plastic and the cement paste and also the rise of the particles of waste plastic. Albano, Camacho, Hernandez, et al. (2009) indicated that concrete with a 10% PET has a compressive strength that matches standard intermediate strength concrete requirements, which was around for a 28-day curing age between 21 MPa to 30 MPa. Kou, Lee, Poon, and Lai (2009) indicated a decrease of 9.1%, 18.6%, 21.8 % and 47.3 % in compressive strength value for the designed concrete mixture of 5 %, 15 %, 30, and 45 % polycarbonate (PVC) plastic as a partial volume substitution with normal fine aggregates, respectively. Frigione (2010) studied that the effect of rising of curing days from 28 to 365 on concrete compressive strength for both PET and without PET is similar.

For high values of w/c ratio and low content of cement, there a significant strength differences between concrete containing normal and PET aggregate. Hannawi et al. (2010) showed that the reduced compressive strength of the PET aggregate was larger than that of the polycarbonate (PC) aggregate at the same volume of substitution. Akçaözoğlu, Atiş, and Akçaözoğlu (2010) noticed that the PET mortar strength for a mixture generated with OPC-bfs is stronger than for the same property for OPC mortar. Rai et al. (2012b) stated that the compressive strength was reduced to 9.52%, with 15% of the FAs substituted with plastic flakes. The strength was decreased due to the plastic surface's lower adhesive properties compared to cement paste. Wang and Meyer (2012) declared that the decline in strength is possibly due to the weaker link between both the aggregates and cement paste to the smoother surface of the high impact polystyrene (HIPS) granule than the normal sand. Ge, Sun, Zhang, Gao, and Li (2013) found that the recycled constantly graded PET mortar has higher compressive than that of the recycle single-size PET mortar. Silva et al. (2013) demonstrated that the drop in concrete strength is occurred by the weak connection strength of PET and cement pastes regarding to the impermeable nature of the PW aggregates. Ávila Córdoba, Martínez-Barrera, Barrera Díaz, Ureña Nuñez, and Loza Yañez (2013) suggested the optimum PET concrete flakes size is 1.5 millimeters if 2.5% of FAs are substituted in concrete. Juki, Muhamad, et al. (2013) observed, only a concrete mix with a 25 % PET substitution rate reached a structural strength of a minimum of 25 MPa.

E. Rahmani et al. (2013) noticed that the concrete compressive strength reduces more to 10 and 15 % because of poor cohesion between surface and PET particles, as it works as a buffer to stop the adhesion between both cement paste and natural aggregates. Herki, Khatib, and Negim (2013) reported a reduction in strength around 50% with the expanded polystyrene (EPS) of 60% and 20% with flying ash for natural sand and Portland cement substitution, which may be referred to as the low content of cement and the absence of natural coarse aggregate. Saikia and de Brito (2014) found that the compressive strength declines with the increasing content of PET, independent of the form of PET aggregate or curing period. Azhdarpour, Nikoudel, and Taheri (2016) stated that a replacement of 10% PET has improved concrete ductility without

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adverse effects on its compressive strength. This is due to the fact that plastic particles are present at the place of failure. Mohammed (2017b) stated that because of the plastic content introduced to concrete, it was not supportive to control compressing strength losses through the production and sorting of waste PET particles. Al-Hadithi and Alani (2018) indicted that the compressive strength reduces as compared with the reference high-performance concrete (HPC) (M0) with the increases in the PET aggregate for all mixtures and all testing ages. It is noted that the utilize of plastic waste aggregates has a detrimental influence on the HPC compressive strength. Almeshal et al. (2020) analyzed the effects of utilizing PET as a limited substitution for sand in concrete. When the content of plastic in concrete raised, the compressive strength reduced. Compressive strength of the 10, 20, 30, 40, and 50% PET concrete mixtures reduced, respectively, by 1.2, 4.2, 31, 60, and 90.6%, relative with the control samples during the 28-day curing period. This drop-in strength is attributed largely to the lessening in the composites' bulk density. Additionally, this pattern can also be because of the lessening in adhesive strength between the cement paste and surface of plastic waste.

2.2.2 Concrete splitting tensile strength

Hardened concrete is usually able to withstand a considerable amount of pressure applied both directly and indirectly. Therefore, one objectives to study the tensile strength of the concrete is to examine such strength since concrete is a brittle material. The polymer concrete using resin based on recycled PET can achieve a tensile strength higher that concrete at normal case (Byung-Wan, Park, & Cheol-Hwan, 2006). Researchers concentrated on improving this concrete feature, as cracks are actually caused by low tensile strength. The influence on the splitting tensile strength of substitution of different forms of plastic waste as aggregate is mentioned in the following paragraphs. Also, Table 2 offers some details undertaken from the literature review.

Y.-W. Choi et al. (2005) reported the split of the tensile rate of losses is much greater than the compressive strength of the itself mix, this possibly would indicate that the synthetic PET aggregates adhesives weak to the cement paste. Batayneh et al. (2007) found that the declining tensile splitting trend was not as protuberant as compressive strength trend; and the use of small plastic quantities in concrete has led to minor improvements to the tensile strength of concrete. Tang et al. (2008) reported the proportion f_{st}/f_c' increased with increasing the polystyrene (PS) coarse aggregate content and with no fragile splitting failure of the concrete specimens containing a PS coarse aggregate. Albano, Camacho, Hernandez, et al. (2009) noted that the decrease in the split strength of the tensile was due to increases in concrete porosity resulting from incorporation of the PET unit and a rise in the w/c ratio; and the loss of tensile strength depends on the PET waste content as regards the measurements of the PET particle, being is that the mixes with the smallest one's present lesser tensile strength. Y. W. Choi et al. (2009) stated that the testing value of the split tensile strength of WPLA (FA) concrete matched the description for lightweight concrete, an expression has also been found $f_{st}' = 0.23 * f_c'^{\frac{1}{3}}$, for the relation of the 28-days compressive strength to the tensile splitting strength of PET-confined concrete and an expression $f_{st}' = 1.40 * \left(\frac{f_c'}{10}\right)^{\frac{1}{3}}$ for the same relationship for traditional concrete. Kou et al. (2009) observed that with an increase PVC content, the split tensile strength was decreased similarly to for the compressive strength. Frigione (2010) reported replacement of 5 % of the fine aggregates by weight with the same amount of unwashed PET-bottle waste aggregates. Tensile strength was calculated at 28-days, and it was noted that it a little reduced (not lower than 2.5%) when unwashed PET-bottle was added in replacement of natural sand in comparison to control concrete. The tensile strength at 28 days of WPET concrete was of 1.6–2.4% lower than the reference concretes. Akçaözoğlu et al. (2010) pointed that the tensile strength of the mortars, which include PET aggregates, is less than that of the mortars, with combinations for PET and sand. Both mortars had significantly less flexural tensile strength relative to sample reference mortars. Lima, Leite, and Santiago (2010) investigated the impact of the substitute of the coarse aggregate by the vinyl acetate-ethylene (EVA) generated from EVA waste from the footwear industry on lightweight concrete splitting

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strength. The results indicated that lightweight concrete with semi-structural properties could be produced using EVA waste. Wang and Meyer (2012) observed a decrease in the split strength of 1.5%, 11%, and 20% for mortar produced with 10%, 20% and 50%, respectively. E. Rahmani et al. (2013) pointed that as the volume of PET particles rises, the tensile strength reduces. Additionally, the decrease of the splitting strength is more noted as the water-cement ratio decreases. Juki, Awang, et al. (2013) studied the mix ratio of 25%, 50, and 75% of PET as a FA with w/c of 0.45, 0.55, and 0.65. According to the authors, splitting tensile strength of the PET mixed concrete is typically lower than that of normal concrete with the same water-cement ratio. The split tensile strength of plastic aggregates concrete also reduces as recycling plastic aggregate increases. Saikia and de Brito (2014) observed a drop in the concrete tensile strength with different PET aggregates of different shape. Yang, Yue, Liu, and Tong (2015) reported that the tensile strengths indicate a declining trend because the interface connection between plastic and cement paste is exuding and weakening as more free water. Azhdarpour et al. (2016) found that the use of higher PET values decreases concrete tensile strength. As the tensile strength of the plastic components has been greater than other concrete components, it enhanced the tensile strength of the concrete by mixing (up until 10%). Since PET cannot absorb water, there is no hydration of cement on its surfaces. As a result, adding additional aggregates with PET separates the plastic particles and other mortar materials and declines the concrete tensile strength. In addition, Increasing the period of concrete curing also improved tensile strength. Al-Hadithi and Alani (2018) displayed that the splitting strength slowly declines with a raise in the amount of PET aggregates above 2.5 % because of smooth surfaces of PET particles; poor cohesion between both the PET particles and the surface; the strength of the PET aggregates is lower than the natural aggregates and because the free water on the hydrophobia plastic aggregate surfaces will serve as an impediment and deter cement paste of joining to natural aggregates, resulting in a weakness bond between cement paste and PET particles. Almeshal et al. (2020) identified that the addition of PET after 28 days has an adverse impact on the splitting concrete strength as the substitute proportion is raised. This result may be due to the variation in rigidity and aggregate form the behavior of tensile strength identical to the compressive strength. The reference mix was also stated to have the tensile strength of 3.11 MPa, the strength of the splitting mix at 10 %, 30 %, and 50 % PET falls to 2.78, 2.01, and 0.45 MPa, respectively.

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Table (2): Overview of some details reported on concrete hard properties incorporated plastic aggregates.

No.	Reference	Type of Composite	Type of Plastic Waste	Origin of Plastic Waste	Types of Substitution	Amounts of Substitution	Particle Size (mm) / Shape	**Concrete Properties Reported in the Literature Review**	
								Compressive strength	**Splitting Strength**
1	Y.-W. Choi et al. (2005)	Concrete	PET	PET-bottles	F.A	25, 50 and 75 vol. %	5-15 / Smooth and Rounded	✓	✓
2	Batayneh et al. (2007)	Concrete	N.M	Waste plastic	F.A	5, 10, 15, 20 vol.%	0.15 – 4.75 / little Particles	✓	✓
3	Marzouk et al. (2007)	Mortar	PET	PET-bottles	F.A	2, 5, 10, 15, 20, 30, 50, 70 and 100 vol.%	Sort A: ≤ 5, Sort C: ≤2 Sort D: ≤1 /	✓	
4	Ismail and Al-Hashmi (2008)	Concrete	PS + PE (Mix 80% PET & 20% PS)	Plastic containers	F.A	10, 15 and 20 vol. %	Length: 0.15–12 & Width: 0.15– 4 / Irregular	✓	
5	Tang et al. (2008)	Concrete	PS	Waste EPS	C.A	20, 40, 60 and 80 vol.%	4 / Beads & Granules	✓	✓
6	Albano, Camacho, Hernández, et al. (2009)	Concrete	PET	PET-bottles	F.A	10 and 20 vol. %	(A) 2.6, (B) 11.4 (C) 50/50% of Both Sizes / Flaky	✓	✓
7	Y. W. Choi et al. (2009)	Mortar & concrete	PET	PET-bottles	F.A	Mortar: 25–10 vol.%, Concrete: 25–75 vol. %	≤ 4.74 / Smooth and rounded		✓
8	Kou et al. (2009)	Lightweight concrete	PVC	PVC pipes	F.A	5, 15, 30 and 45 vol. %	≤ 5 / Angular	✓	✓

N.M: Not Mention; F.A: fine aggregates; C.A: coarse aggregates; vol.: volume; wt.: weight; PET: polyethylene terephthalate; PS: polystyrene; PP: polypropylene; PC: polycarbonate; PVC: polyvinyl chloride; EPS: expanded polystyrene; EVE: Ethylene vinyl acetate; HIPS: High impact polystyrene.

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Table (2): Continue.

No.	Reference	Type of Composite	Type of Plastic Waste	Origin of Plastic Waste	Types of Substitution	Amounts of Substitution	Particle Size (mm) / Shape	Concrete Properties Reported in the Literature Review	
								Compressive strength	Splitting Strength
9	Frigione (2010)	Concrete	PET	PET-bottles	F.A	5 wt. %	0.1–5 / Irregular	✓	✓
10	Hannawi et al. (2010)	Mortar	PET & PC	Industrial Waste	F.A	3, 10, 20 and 50 vol. %	PET: 1.6–10, PC: ≤ 5 /N.M		✓
11	Akçaözoğlu et al. (2010)	Mortar	PET	PET-bottles	F.A	By vol: Binder = 0.5:1 By wt%: 25.64 & 16.95	≤ 4 / Irregular	✓	
12	Lima et al. (2010)	Lightweight concrete	EVA	Waste EVA	C.A	0, 25, and 50 vol. %	≤ 9.5 / little particles		
13	Rai et al. (2012a)	Concrete	Virgin PET	Industrial	F.A	5, 10 and 15 vol. %	N.M / Flaky		
14	Wang and Meyer (2012)	Mortar	HIPS	HIPS electronics waste	F.A	10, 20, and 50 vol. %	<4 / Irregular	✓	
15	Ge et al. (2013)	Mortar	PET	PET-bottles	F.A	1:1, 2:1, 3:1 and 4:1 by vol.	≤ 9.5 / Flaky	✓	
16	Silva et al. (2013)	Concrete	PET	PET-bottles	F.A & C.A	7.5 and 15 wt. %	(A) 2–11.2, (B) 1–4 / (A) Flaky for C.A. (B) Flaky &	✓	
17	Ávila Córdoba et al. (2013)	Concrete	PET	PET-bottles	F.A	1, 2.5 and 5 vol. %	0.5, 1.5, and 3 / flakes		

N.M: Not Mention; F.A: fine aggregates; C.A: coarse aggregates; vol.: volume; wt.: weight; PET: polyethylene terephthalate; PS: polystyrene; PP: polypropylene; PC: polycarbonate; PVC: polyvinyl chloride; EPS: expanded polystyrene; EVE: Ethylene vinyl acetate; HIPS: High impact polystyrene.

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Table (2): Continue.

No.	Reference	Type of Composite	Type of Plastic Waste	Origin of Plastic Waste	Types of Substitution	Amounts of Substitution	Particle Size (mm) / Shape	**Concrete Properties Reported in the Literature Review**	
								Compressive strength	**Splitting Strength**
18	Juki, Muhamad, et al. (2013)	Concrete	PET	PET-bottles	F.A	25, 50 and 75 vol.%	5 / N.M	✓	✓
19	E Rahmani et al. (2013)	Concrete	PET	PET-bottles	F.A	5, 10 and 15 vol. %	0.15 - 7 / Flaky	✓	✓
20	Herki et al. (2013)	Lightweight concrete	EPS	Waste EPS	F.A	60 and 100 vol. %	≤ 8 / N.M	✓	
21	Saikia and de Brito (2014)	Concrete	PET	PET-bottles	F.A & C.A	5, 10 and 15 vol. %	F.A: ≤4, C.A: ≤ 11.2 / (A) Flaky, (B)	✓	✓
22	Yang et al. (2015)	Lightweight concrete	Modified PP	Waste plastic	F.A	10, 15, 20 and 30 vol. %	Length: 1.5–4 / Short column		✓
23	Azhdarpour et al. (2016)	Concrete	PET	PET-bottles	F.A	5, 10, 15, 20, 25 and 30 vol. %	(A): 2-4.9 & (B): 0.05-2 / N.M	✓	✓
24	Mohammed (2017a)	Concrete	PET	PET-bottles	F.A	5, 10 and 15 vol.%	12, 6 & 3 (constant weight for each size) /	✓	
25	Al-Hadithi and Alani (2018)	Concrete	PET	PET-bottles	F.A	2.5, 5 and 7.5 vol. %	≤ 4.75 /Flaky, fibre form & pellet	✓	✓
26	Almeshal et al. (2020)	Concrete	PET	PET-bottles	F.A	0, 10, 20, 30, 40 and 50 vol. %	4–0.075 / Irregular	✓	✓

N.M: Not Mention; F.A: fine aggregates; C.A: coarse aggregates; vol.: volume; wt.: weight; PET: polyethylene terephthalate; PS: polystyrene; PP: polypropylene; PC: polycarbonate; PVC: polyvinyl chloride; EPS: expanded polystyrene; EVE: Ethylene vinyl acetate; HIPS: High impact polystyrene.

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3. RESULTS AND DISCUSSIONS

3.1 Influence of PET replacement on slump and density

Generally, addition of plastic aggregate appears to have influence regarding workability decrease of concrete or mortar. Moreover, higher substitution level of these aggregates have a habit of superior decrease in workability. The particle size and of shape aggregate was noted to influence the workability. The effect of PET amount (substitution) on the slump flow is shown in Figure 1. It has been noted from all the information undertaken form the literature that increasing the amount of PET granules caused in a substantial decrease in slump. Increasing the PET substitution level above from 0% - 10% resulted in dropping the slump flow. However, for 10% and above PET replacement levels the sharp reduction intensities were detected by many investigators. On the other hand, only a few investigations point out that slump improved with an increasing fraction of plastic aggregates Al-Manaseer and Dalal (1997); Y.-W. Choi et al. (2005); Y. W. Choi et al. (2009); Tang et al. (2008); Rai et al. (2012a); Silva et al. (2013). Such increase might be described by the texture and smoother surface of plastic aggregates as associated with natural aggregates (NA), even though the PET aggregates surface area-to-volume ratio for plastic aggregates was greater than that of the NA. Moreover, smooth surfaces have weaker binding force to cement paste as the area of interaction is smaller.

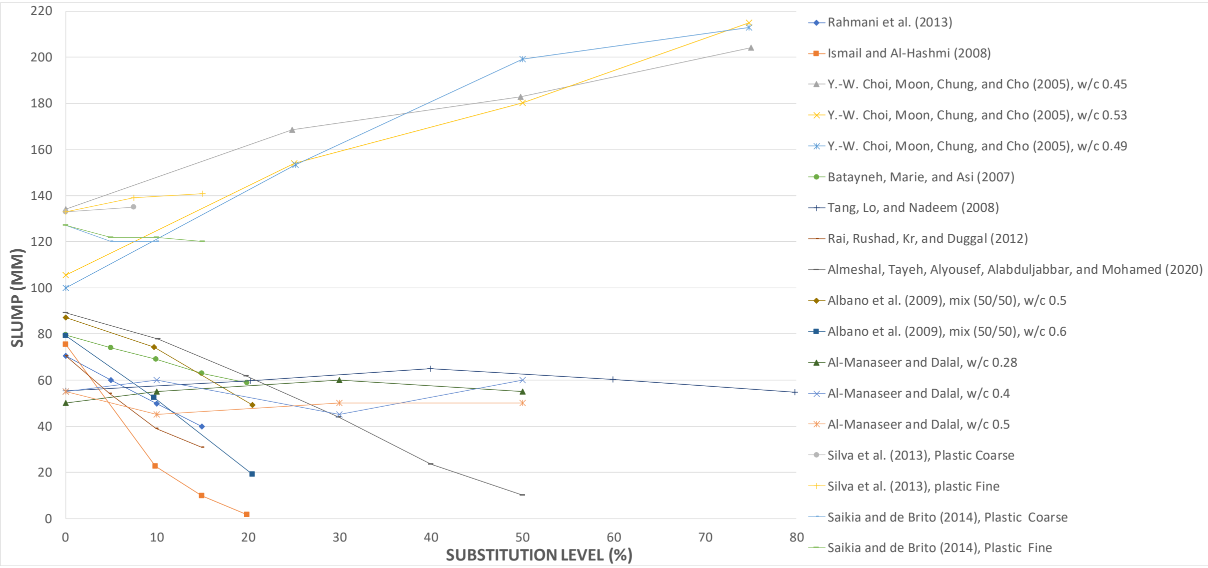

Fig. (1): Variation of the concrete slump with the plastic aggregate replacement rate.

Integrating plastic aggregates into concrete alters the homogeneity and consistency of concrete mixture characteristics such as density. Generally, the densities reduced with increasing the level of plastic aggregates substitution as predicted, see Figure 2. As plastic aggregates have a lesser density than natural aggregates (NA), the whole weight of concrete (density of concrete) is reduced, thus generating a lighter concrete (lower unit weight). The Figure point out that the concrete samples containing 50% of PET and above inclined to decrease in unit weight to 2000 kg/m^3 associated with the control mix, which had a value of 2400 kg/m^3. The most reason of such drop in unit weight was because of the low plastic density, as stated by some investigators.

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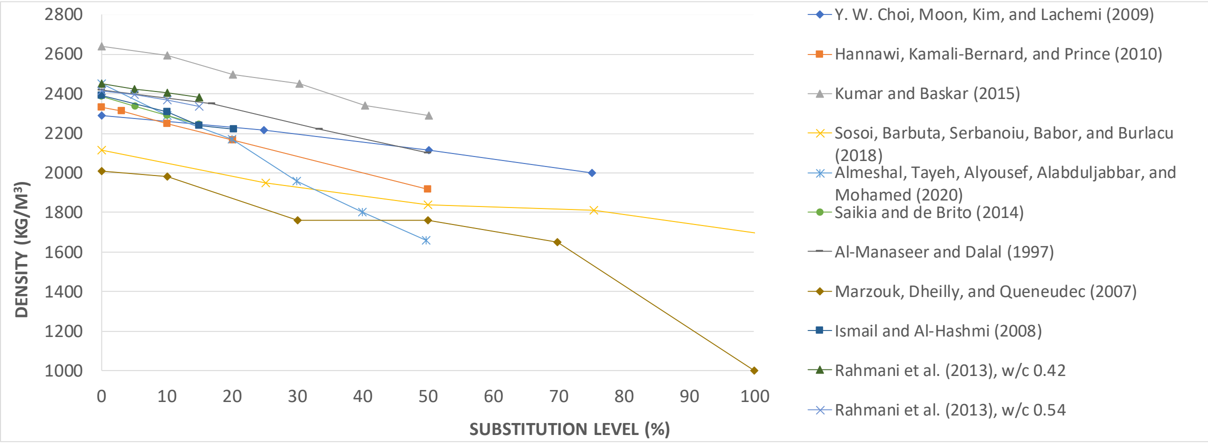

Fig. (2): Variation of the concrete density with the plastic aggregate substitution rate.

3.2 Influence of PET substitution on compressive and tensile strength

The compressive strength of plastic aggregate (PA) concrete relays on many factors such as the w/c, plastic aggregates substitution level, and the types and shapes of PA. This study concludes that the PA concrete compressive strength with the same w/c drops with growing plastic aggregates substitution level. From a comprehensive review of literature, it can be demonstrated that the direct presence of plastic in concrete does not efficiently recover the concrete strength. This is mainly due to the fact that the plastic surfaces have not been treated with reactive materials, such as metakaolin, silica fume and iron slag. Concrete compressive strength containing 10–50% recycled PAs ranged between 48 MPa and 19 MPa. Such strength decreased with the increase in recycled PA replacement content. For concrete containing 10–50% recycled plastic, the reduction in the compressive strength was between 34% and 67% respectively in some cases.

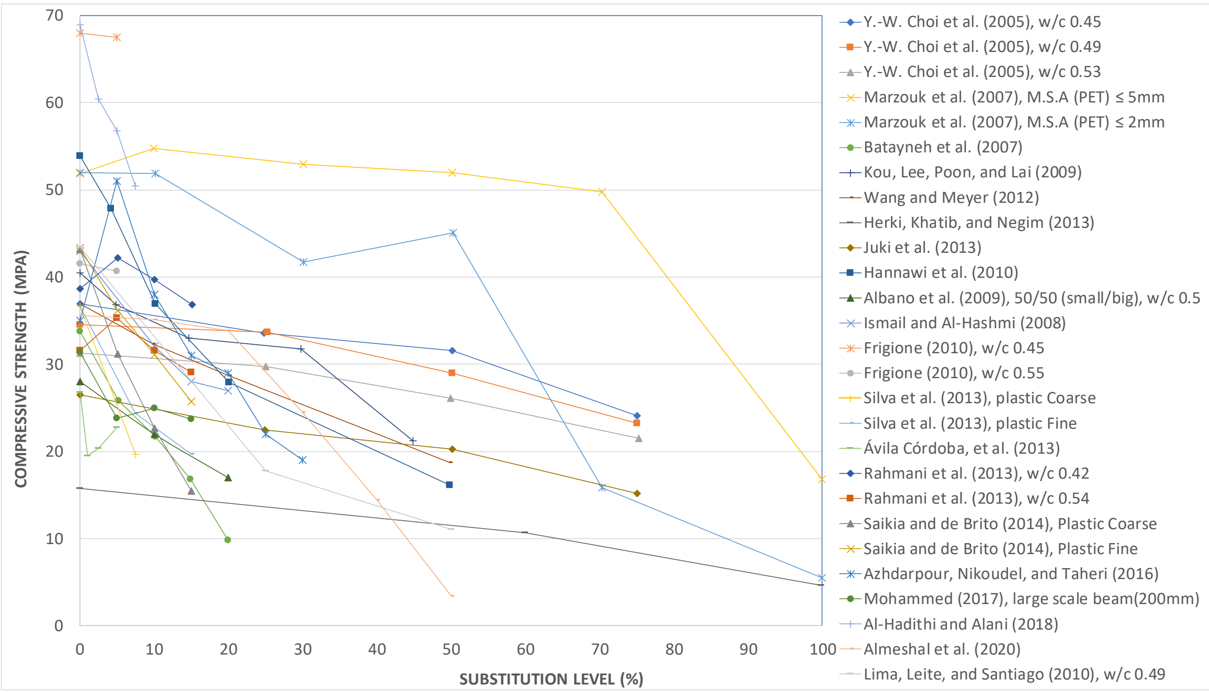

Fig. (3): Variation of the concrete compressive strength with the plastic aggregate replacement rate.

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A similar trend has been observed in the tensile strength of concrete compared to the compressive strength. The concrete tensile strength decreased with the integration of PA. Nevertheless, associated to compressive strength, the such strength was less affected by size of the particles and more by the bonding quality which was associated with the replacement content and shape of the PA. It can be observed from Figure 4 that the concrete split strength in some cases originally tracked an ascending response by adding 5% PET as aggregate replacement. It is clear from the Figure that in most cases, the addition of PET into the concrete decrease the splitting strength with respect to control concrete (0% PET level).

Albano, Camacho, Hernandez, et al. (2009); Ávila Córdoba et al. (2013); and Saikia and de Brito (2014) studies the effect of the size of partially substituted plastic waste particles. They reached to one concept, which is increasing the size of plastic aggregate can negatively affect both compressive and splitting tensile strengths due to the increase of larger smooth surface layer which reduce the aggregate-matrix interface bond.

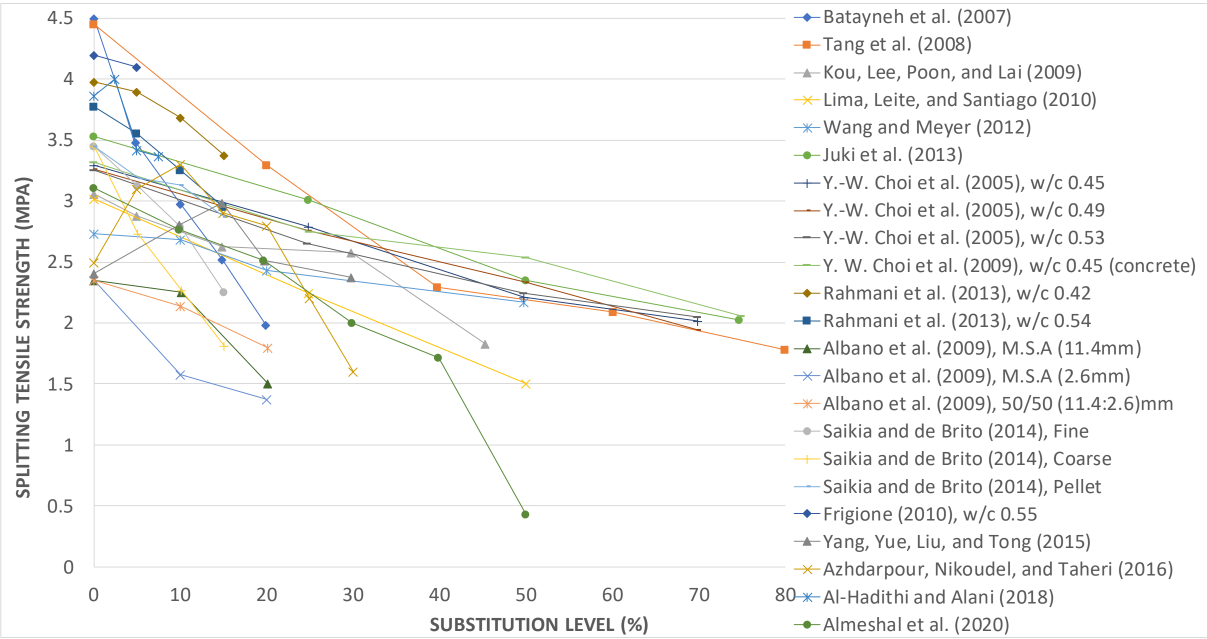

Fig. (4) :Variation of the concrete splitting tensile strength with the plastic FA and CA replacement rate.

4. CONCLUSIONS

Based on the comprehensive review of previously published works, it can be concluded that:

1. In general, there are two comparable perspectives on the workability of concrete comprising waste PAs. commonly, a lesser slump flow of fresh concrete is observed because of the integration of PAs than that of the traditional concrete mix. The sharp edges and angular particle size of PA are two main causes for the lower slump value of the concrete mix enclosing PA. In contrast, a rise in the slump amount because of the incorporation of PA is correspondingly reported in a few papers. It is believed that the existence of more free water in the mixes containing plastic than in the concrete mix containing NA can cause an increase of the slump of concrete mixes due to the incorporation of PAs. In general, the plastic aggregates cannot absorb water during mixing and can result in an increase in the concrete slump value with increasing content of PET-bottle aggregate.
2. Irrespective of the size and type of replacements, the integration of waste plastic as aggregate normally reduces dry and fresh densities. This could be attributed to the lightweight nature of PA. This displays that plastic will be a good aggregate to generate light weight concrete with a proper compressive strength.
3. The concrete compressive strength enclosing non-regularly shaped PA declines more

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considerably than that of concrete comprising consistently shaped PA. Moreover, earlier investigations accredited the relatively low concrete compressive strength containing PAs to high air content and porosity of PA concrete, low bond strength between the cement paste and surface of the PA particles, low elastic modulus of PAs, and the restrained cement hydration reaction near the surface of PA resulting from the hydrophobic nature of PA.

4. The increased surface area and smooth surface texture of plastic aggregate generate a weak interfacial connection because of the gathering of free water. Such bonding had more negative effect on the tensile strength. Due to the flexible nature of PA and increasing the replacement level, the concrete mixtures showed higher plasticity and flexibility which contributed to a ductile failure.

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