Application of gamma irradiation on Polyethylene Terephthalate (PET) for use in asphaltic concrete mixtures as aggregates replacement

A Usman¹, M H Sutanto¹, M Napiah¹, S E Zoorob², M I Khan¹ and M B Ibrahim¹

¹ Civil and Environmental Engineering Department, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia
² Construction and Building Materials program, Kuwait Institute for Scientific Research, P.O.Box 24885, Safat, 13109, Kuwait
*Corresponding author: auzaria83@gmail.com

Abstract. Polyethylene Terephthalate (PET) is one of the most commonly available kinds of plastic present in the municipal solid waste and it is a non-biodegradable semi-crystalline thermoplastic polymer, studied as polyester material. This paper intends to assess impacts of using PET (regular and irradiated) as aggregate that would replace by volume of equal size (10.00-5.00mm) in asphalt blend on the engineering properties of dense graded asphaltic concrete. The volumetric and mechanical properties of the blends incorporating different percent of PET (0, 5, 10, 15 and 20) were determined. In all mixtures, 5.0% optimum bitumen content was utilized. The outcome revealed that aggregate substitution of 10% (equivalent to 2.4% by weight of total mix) with irradiated PET result in optimum Marshall Stability and flow value of 3.6mm. It also showed that mixes with irradiated PET at 100kGy radiation dose have Marshall Stability values higher than mixes with same contents of regular PET. The finding also shows that the addition of PET and utilization of gamma radiation has a critical constructive outcome on the properties of asphalt concrete mixes as the stability increases for mixes with irradiated PET when compared with mixes with regular PET (RPET).

1. Introduction
Rapid increase in Polyethylene Terephthalate (PET) bottle industry has prompted a quick development in worldwide PET utilization [1]. Between the year 2009 to the year 2013, PET bottle industry rose at a standard annual pace of 4.3% [2]. Worldwide PET container utilization is almost 20 million tons and is ascending at a remarkable frequency of 15% every year [3]. In the meantime, PET bottles recycling pace are small at simply 29.3% [4]. In order to overcome contamination threat of plastics generally and waste PET bottles specifically, outlets for repurpose of waste PET are being investigated where it can be utilized in large amounts. One such course of waste PET reuse was in the highway sector where it very well can be utilized as an added substance to bituminous blends or as alternate for fine aggregates [5-7]. Literatures reviewed so far demonstrates that there are a few logical inconsistencies among the studies conducted on the impacts of utilizing waste PET in asphaltic concrete as either additive or aggregate replacement in conventional mixtures. For instance, while Hassani et al., [6] used PET in the form of 3mm diameter granules to substitute a part of conventional aggregate by volume and concluded that the stability decreases with increased PET amount and ascribed the reduction to low friction between PET granules, Ahmadinia et al., [8] and Choudhary et al., [9] reported that Marshall Stability improves with increased waste PET amount in blends to a certain level and thereafter it decreases. These
increases in stability values were ascribed to the improve adhesion between the constituents’ in the blend. Additionally, the waste PET introduced into the mixtures makes it stiffer with higher stability. Thus it is therefore obvious that the task remains of producing a high performance pavement with waste PET that will withstand the more additional traffic loads.

To overcome the threat of waste PET on the environment and additional traffic loads on our roads the use of gamma irradiation on waste PET was employed in this study. Gamma irradiation of waste PET has been carried out in concrete industry and the outcome was promising as the strength lost when regular waste PET was utilized in concrete blends was recovered. In a study by Schaefer et al. [10] it was revealed that exposing waste PET to high dose of gamma radiation of 100 kilo Gray (kGy) resulted in an enhanced compressive strength with reference to the control samples made with regular, non-irradiated plastic. One potential way for recuperating a portion of the lost strength while adding plastic fiber to concrete is to make utilization of irradiation which boost the characteristics of concrete strength [11-13]. PET is semi-crystalline polyester showing an isotropic microstructure because of its amorphous glass composition [14]. PET is therefore one of the polymers most studied. The two most prominent impacts of PET when irradiated are chain splitting and crosslinking [15]. Based on literatures reviewed so far there is no work done on utilizing gamma irradiation of waste PET for highway or pavement application.

It is the goal of researchers and scientists to investigate reuse of waste materials for environmental and economic points of interest and the likelihood of reuse of solid waste in building roads [16]. Reuse of waste materials is one of the numerous approaches to care of the issues caused by unwanted solid waste materials in manufacturing and metropolitan territories. The reuse of waste products can contribute significantly to the environment and economy from various perspectives, to be specific: (i) it diminishes the abuse of natural resources and prevents depletion, (ii) it decreases the ecological contamination amount because of the waste products produced in metropolitan and production regions, and (iii) it helps save energy and money. Reuse of waste is particularly crucial in managing certain discarded products, for example, plastic containers, which, because of their extra extended biodegradation period, are incredibly unsafe to environment and biological system balance. Consequently, the reuse of these waste products in engineering, modern development and manufacturing is consistent in order to reduce their adverse impacts on the environment and nature [17-18].

The fundamental aim of this investigation is to assess the effects of gamma irradiation on PET and to portray Marshall characteristics and volumetric properties of HMA blends made with various percentages of waste PET as coarse aggregate substitutes. The optimum contents of PET and radiation dosage were also determined.

2. Materials and Methods

2.1. Materials
In this research, crush granite aggregate was used and were acquired from a quarry in Ipoh, Malaysia. Bitumen of 60/70 penetration grade was used as the binding material. The bitumen and aggregates source have been kept the same throughout the investigation to limit inconveniences. Ordinary Portland cement was used as the filler material and waste PET flakes passing BS sieve size 10mm and retained on BS sieve size 5mm acquired from Enhanced Plastic Industry, Ipoh, Perak. Malaysia was utilized as the plastic aggregate.

2.2. Methods

2.2.1. Gamma Irradiation
Gamma rays are generated when radioactive atomic nuclei are disintegrated and when certain subatomic particles are decayed. In the electromagnetic spectrum, the commonly accepted definition of the region of gamma rays includes some wavelength overlap. Gamma radiation has wavelength that are considerably shorter than a few tenths of an angstrom and gamma-ray photons with more than tens of thousands of electron volts [19]. PET flakes acquired from Enhanced Plastic Industry, Ipoh, Perak. Malaysia was utilized as the coarse aggregate in this study. Because of imperfections in recycling
facilities, manual sorting process was employed to remove metals and non-plastic impurities. The sorted PET flakes were then irradiated in a cobalt-60 irradiator that works at 58Gy/min at Malaysian Nuclear Research Agency office. Based on some selected literatures [10, 20-21] two doses of gamma radiation were used 100kGy and 200kGy in this study which were referred to as 100kGyPET and 200kGyPET respectively. The 100kGyPET flakes were left in the machine for 29hrs and the 200kGyPET flakes were left in the machine for 57hrs.

2.2.2. Sample Preparation
The modified dry method was utilized in this research, which as opposed to blending the added substance with the aggregate before including bitumen, PET was included after the heated aggregate was first mixed and coated with the bitumen [5, 8-9, 22], the main purpose behind this was to endeavor to maintain PET in its characteristic state (semi-crystalline resin) with insignificant shape modifications and properties. AC blend without PET was utilized as control blend in this investigation. To obtain the control optimum binder content (OBC), three samples were cast at each of the binder amounts of 4.0%, 4.5%, 5.0%, 5.5%, 6.0% and 6.5% by blend weight. For the compaction, a compactive effort of 75 Marshall Impact blows was used. In accordance to ASTM D2726 and ASTM D2041, bulk density and maximum specific gravity of the samples were determined respectively. The samples were then evaluated for volumetric properties and Marshall stability utilizing Multiplex 5.0-E Marshall testing machine. Marshall stability and flow tests were carried out on compact samples with different bitumen contents. The Marshall test is a laboratory test in which cylindrical compact samples with a diameter of 101.6mm over approximately 63.5mm high are drilled in water at 60ºC for 30-40 minutes and then charged to failure using curved steel loading plates with a steady compression speed of 50.8mm/min. OBC was obtained as stipulated the JKR code for AC14 and was also checked for blend design requirements recommended by JKR [23] and discovered to be 5.0% by weight of the blend. The waste PET modified blends were cast with five (5) unique contents of PET, to be specific: 0, 5, 10, 15 and 20% by volume of an equal size of aggregate particles. In the present research, PET modified samples were manufactured using the same bitumen content (equivalent to control mix OBC) to enable the analogy of PET modified mixes with control mix properties without taken into consideration bitumen as a different factor in accordance to ASTM D1559 [6, 9, 22]. Plastiphaltls are bituminous composite blends containing recycled or waste plastics as substitutes for mineral aggregates.

3. Results and Discussion

3.1. Volumetric Properties

3.1.1. Bulk Specific Density
As expected the bulk density reduces with increase in the amount of PET in the mixtures as shown in Figure 1. The reduction in mix density is related to low unit weight of PET when compared with conventional aggregate and also more voids in the PET modified compacted bituminous specimens. As the figure shows, the mix densities diminish with gamma radiation dosage for same PET content in the mixes. This reduction with radiation dosage is attributed to molecular weight decline as the number of chain scission increases. This molecular weight decrease results in expanded molecular mobility that advances orderly molecular arrangement in crystalline structures.
3.1.2. Air Void

Air void (AV) is one of the indispensable parameters of bituminous blend utilized for asphalt design and the determination of optimum bitumen content [24, 25]. JKR recommended AV content of 3-5% for compacted asphalt blends. Increased air voids causes cracking because of deficient bitumen coating the aggregate, while low air voids may incite increased plastic flow (rutting) and asphalt draining under conditions of substantial traffic loading [26]. Another fundamental reason that causes a rise in air void content as PET flakes amount increased in the mixture is the elastic deformation of the PET flakes under compaction effort. As Figure 2 appears, increasing the PET amount results in more air voids in the mixes because of the PET flakes utilized in the mix, which stayed in the form of crystal, along these lines expanding the surface area. The larger surface area, be that as it may, need to be coated with binder, which would at long last lead to lesser workability while mixing and hence lesser bulk densities which in turn causes an increase in voids in the mix. Moreover, when PET was utilized in the mix, it appeared to diminish its compatibility, in this way, a higher air void value may be gotten [26, 27]. As the binder content remains the same for all the PET content in the plastiphalt mixtures there is less binder to coat the added PET for higher percentages which causes the air void to increase as the PET content is increase in the mixes. All the plastiphalt mixes with the exception of 20% PET contents (irradiated) satisfies the JKR recommendation for ACW14 of 3-5% air void.

3.1.3. Voids in Mineral Aggregate

The volume of intergranular void spaces between the aggregates particles in a compacted asphalt blend or essentially volume occupied by air and the quantity of bitumen not consumed by the aggregates. It is an important component considered in design of asphalt mixes to guarantee that thickness of asphalt film is adequate to shield the asphalt during service life from abrasive actions of tires and moisture [28]. Adequate amount of voids in asphalt mixture give adequate space for the bitumen to fittingly coat the aggregate alongside adequate space for the excess binder which was not being absorbed by the aggregate. The durability of mixes increases on the aggregates particles with thickness of asphalt film. The minimum VMA requirements are specified in order to have required durability of the mixtures. As appeared in Figure 3, VMA values in the mixes increases almost linearly with PET content utilizing same bitumen amount of 5.0%. As VMA is inversely related to bulk density of the mix, the patterns are opposite as that observed for mix density in Figure 3.
3.1.4. Voids filled with Bitumen

The VFB obtained results are depicted in Figure 4. Since VFB is inversely proportional to the blend air void, it can be shown to diminish with increase in PET amount in the plastiphalt mixes. All with the exception of plastiphalt mixes with 20% PET contents (irradiated) have satisfied the VFB specification requirements as per JKR [23] of 70-80%. This finding is in line with studies carried by several researchers [8, 9, 22].

3.2. Marshall Characteristics

3.2.1. Marshall Stability

Marshall Stability is among the most critical properties considered in the design of asphalt pavement wearing course. Stability is the measure of asphalt blend capacity to oppose rutting under condition of traffic loading. In this manner, for asphalt blends the stability ought to be sufficiently high to handle traffic loading. JKR standard specification prescribes a minimum stability value of at least 8kN for heavy traffic roads [23]. Figure 5 represents the Marshall Stability values versus different PET amount. After incorporating PET, the stability values were increased until it reached the optimum content, which is 10% of the utilized PET, after which it began to diminish. Marshall Stability values were commonly greater in contrast with the control (blend with 0% PET) and blend with non-irradiated PET (RPET). The blends that showed lesser stability values were those made with 20% PET content except for 100kGyPET blend with same 20% PET amount. This trend is similar for all the three different mixes (RPET, 100kGyPET and 200kGyPET) but for RPET and 100kGyPET mixes stability reaches its maximum value at 10% PET amount. However, for mix with 200kGyPET it attains it peak at a lower PET content of 5%. The increase in Marshall Stability by adding plastic to conventional hot mix asphalt (HMA) is ascribed to improved bond development between the components in the blend [26, 29-30]. In this investigation, the fundamental reason for using PET was based on various properties. PET, is a semi-crystalline resin in its normal state [31-32], and PET glass transition temperature (Tg) is approximately 70°C [33-34]. Semi-crystalline aspect suggests that some PET is amorphous while others are crystalline. The amorphous part of PET exists in fluid form over its glass transition temperature of about 70°C; in any case, crystalline part of PET still exists as solid and rigid structure since the PET melting point (around 250°C) is a much higher than the mixing temperature (155°C) utilized in this investigation. It is likely that the softened/molten part improves aggregate-binder bond, and the stiff crystalline part gives the blend rigidity. The crystalline nature of the PET is maintained in the blend as the technique of modified dry process was employed in the study. However, the diminishing trend observed in stability in mixes with higher PET content might be attributed to lesser rigidity and friction of PET flakes with reference to natural aggregates.
3.2.2. Marshall flow

Marshall Flow is the ability of asphalt mixture to deform in accordance with progressive settlements and movements without cracking. The resistance against deformation is an indication of Marshall Flow. Blends with higher flow values are more likely to deform under loading and very low flow value blends are considered to be stiff and thereby having the tendency to crack. JKR standard specification recommends flow values of 2-4mm. Figure 6 represent the flow values versus PET contents and it depicts that the addition of PET leads the flow value to diminish marginally until 5% PET content then it changes to an upward increment with addition of more PET amount in the mixtures. The same outcome was reported by Taherkhani and Arshadi [35], Ahmadinia et al., [8]. As explained in the previous part, this outcome can leads to a stiffer blend being developed. Notwithstanding, a large percentage of PET makes the flow value to increase while the stability diminishes. This decrease may happen due to bonding between the PET and bitumen in blends that contain less amount of PET. On the other hand, in blends with larger PET amounts, flow experiences an increase while there is a decline in the stability of the mixture. Nevertheless, all flow values meet the range specified by the JKR standard specification of 2-4mm with only 200kGyPET mix at 20% content as an exception.

4. Conclusions

This study mainly focuses on laboratory evaluation of the mix volumetric, Marshall Parameters and the effect of utilizing gamma irradiation on the PET with two different doses (100kGy and 200kGy) and the results were compared with mixes incorporating same content of regular, non-irradiated PET. This part intends to outline the general discoveries accomplished through this study. The critical discoveries of the study are outlined as follows:

- The incorporation of more PET (irradiated and non-irradiated) amount into the mixes resulted in a significant increase in Marshall Stability up to 10% after which it decline as the PET content is increased. However, the Marshall Flow experiences an initial decline with lower PET content and furthermore it increases with an increase in the PET content into the mixture.
- In respective of the amount of PET introduced into the mixture, the bulk specific gravity reduces as expected while causing an increase in the air voids of the plastiphalt mixes.
- The optimum amounts of PET (irradiated) and radiation dosage were observed to be 2.4% by weight of total mix and 100kGy respectively. This percentage and dosage amount results in higher Marshall Stability.
- All the plastiphals mixes satisfies the JKR requirements for mix volumetric and Marshall characteristics. However, the plastiphalt mix with irradiated PET having 100kGy radiation dose showed a better performance based on volumetric and Marshall characteristics.
Based on this investigation, it can be concluded that the usage of gamma irradiation on PET in asphalt mixture is important from both economic and environmental view point, irradiated PET can be utilize in asphalt mixes for enhance performance that will take care of the increasing tire pressure, volume of heavy vehicles and traffics on the roads.

5. References

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