PERFORMANCE OF SUSTAINABLE CONCRETE INCORPORATING RECYCLED POLYETHYLENE TEREPHTHALATE (PET) GRANULES

A Thesis submitted by

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ABSTRACT

The use of wastes as a supplementary material in concrete manufacturing is of great interest due to the potential cost savings, preservation of natural resources and reduction in environmental pollution. This study focused on the performance of sustainable concrete containing recycled polyethylene terephthalate (PET) waste in the form of granules. The mix was designed for normal strength concrete using PET granules as a partial replacement for fine aggregates (0%, 10%, 30%, and 50% by volume). Firstly, the mechanical properties were evaluated by conducting compressive strength, tensile strength, elastic modulus, flexural strength and crack mouth opening displacement tests along with microscopic analysis. The test results showed that PET granules improve the mechanical properties and ductility of the concrete, although the improvement was more noticeable for 10% PET concrete. The Australian and American design guidelines accurately predicted the experimental results for mechanical properties of PET concrete. Secondly, the bond behaviour between steel reinforcement and concrete mixes, as well as flexural and cracking performance of reinforced concrete (RC) beams were examined together with porosity of the concrete mixes. The findings revealed that the inclusion of 10% PET granules positively impacted the bond strength, flexural strength and cracking behaviour, and porosity of concrete. However, the performance was deteriorated with increasing PET granule percentage. The cracking and flexural moments of PET-RC beams were conservatively predicted by the American and Australian standards. The flexural behaviour of RC beams was simulated using finite element method, and the results agreed well with experimental findings. Thirdly, the long-term durability properties were investigated by performing alkali-silica reactivity (ASR), creep strain, shrinkage strain, rapid chloride penetration (RCP), water absorption and apparent volume of permeability (AVPV) tests. The results showed that ASR expansion of concrete prisms and mortar bars decreased with increasing PET aggregate percentage. Including 10% PET aggregates improved chloride resistance and creep strain while having almost no effect on shrinkage, water absorption and AVPA of concrete. A shrinkage model was proposed for concrete containing PET aggregate and the results corresponded well with the experimental results. An in-depth understanding of the behaviour of sustainable concrete incorporating recycled PET granule aggregate was the significant outcome of this study.

CERTIFICATION OF THESIS

I Mohammad Eyni Kangavar declare that the PhD Thesis entitled *performance of sustainable concrete incorporating recycled polyethylene terephthalate (PET) granules* is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.

This Thesis is the work of Mohammad Eyni Kangavar except where otherwise acknowledged, with the majority of the contribution to the papers presented as a Thesis by Publication undertaken by the student. The work is original and has not previously been submitted for any other award, except where acknowledged.

Date: 26 August 2023

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Student and supervisors' signatures of endorsement are held at the University.

STATEMENT OF CONTRIBUTION

The scientific journal manuscripts produced from this study are a joint contribution of the authors. The authors' scientific contributions are detailed below:

Manuscript 1:

Kangavar, M. E., Lokuge, W., Manalo, A., Karunasena, W., Frigione, M., (2022). Investigation on the properties of concrete with recycled polyethylene terephthalate (PET) granules as fine aggregate replacement. *Case Studies in Construction Materials*, *16*, e00934. https://doi.org/10.1016/j.cscm.2022.e00934. (Q1 journal; Impact Factor: 4.934).

The overall contribution of Mohammad Eyni Kangavar was 65% to the concept development, design of experiments, experimental works, analysis and interpretation of data, writing of original draft and revising the final submission. Weena Lokuge, Allan Manalo and Warna Karunasena contributed 30% to supervision, writing, reviewing, and editing. Mariaenrica Frigione contributed 5% to reviewing and editing.

Manuscript 2:

Kangavar, M. E., Lokuge, W., Manalo, A., Karunasena, W., Ozbakkaloglu, T., (2023). Development of sustainable concrete using recycled polyethylene terephthalate (PET) granules as fine aggregate. *Developments in the Built Environment*. https://doi.org/10.1016/j.dibe.2023.100192. (D1 (top 10%) journal; Impact Factor: 5.563).

The overall contribution of Mohammad Eyni Kangavar was 70% to the concept development, design of experiments, experimental works, analysis and interpretation of data, writing of original draft and revising the final submission. Weena Lokuge, Allan Manalo and Warna Karunasena contributed 25% to supervision, writing, reviewing, and editing. Togay Ozbakkaloglu contributed 5% to reviewing and editing.

Manuscript 3:

Kangavar, M. E., Lokuge, W., Manalo, A., Karunasena, W., Siddique, R., (2023). Effect of recycled polyethylene terephthalate (PET) granules on the long term durability of concrete. Submitted to Journal of Cleaner Production (under review). (D1 journal; Impact Factor: 11.1).

The overall contribution of Mohammad Eyni Kangavar was 75% to the concept development, design of experiments, experimental works, analysis and interpretation of data, writing of original draft and revising the final submission. Weena Lokuge, Allan Manalo and Warna Karunasena contributed 20% to supervision, writing, reviewing, and editing. Rafat Siddique contributed 5% to reviewing and editing.

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CHAPTER 1: INTRODUCTION

1.1. Background and motivation

Global concrete manufacturing is constantly growing with an annual production of about 7 billion tons, resulting in depletion of natural resources such as sand and gravel (Ahmad et al., 2017). It is important to note that sand accounts for 35 to 45% of concrete volume (Martínez-García et al., 2021). Another major challenge of our time is solid waste management due to rapid population growth and urbanisation, contributing significantly to adverse environmental effects in landfills. Of particular interest is the use of waste materials in concrete. The use of waste materials including waste glass, steel, and plastic in concrete manufacturing has been the subject of previous studies for at least the past 2 decades (Batayneh et al., 2007; Frigione, 2010; Tamanna et al., 2020). China has imported around 45% of the world's plastic waste since 1992, and it is anticipated that 111 MMT of plastic waste will be displaced by 2030 as a result of China's plastic waste import ban imposed in 2017 (Shi et al., 2021).On average, plastics make up 8-12% of the overall municipal waste stream, and depending on variables, such as lifestyle, quality of life and income level, this proportion varies from country to country (Wong et al., 2015). This figure is estimated to be around 16% in Australia, with an annual plastic waste production of 2.24 million tons (Bajracharya et al., 2016). Approximately 190 million tons of plastics are manufactured annually in the world, of which 77 million tons are polyethylene (Wong et al., 2015). Polyethylene terephthalate (PET) is one of the most used plastics in the packaging industry due to high stability, high pressure resistance, non-reactivity with substances and high consistency of gas trapping that can retain the gas in gaseous drinks (Akçaözoğlu et al., 2010). In 2021, global PET bottle consumption was approximately 583 billion, with only 31% being recycled and the rest ending up in landfills (Khan et al., 2022). In Australia, PET waste accounts for 34.9% of domestic plastic waste (Wurm et al., 2020). Figure 1.1 illustrates an overview of PET bottle life cycle. Waste PET bottles are a major contributor to adverse environmental effects in landfills, and take more than 500 years to degrade in nature (Lundell & Thomas, 2020). Hence, there has been an urgent need for a sustainable solution to overcome the detrimental impact of PET waste on the ecosystem.

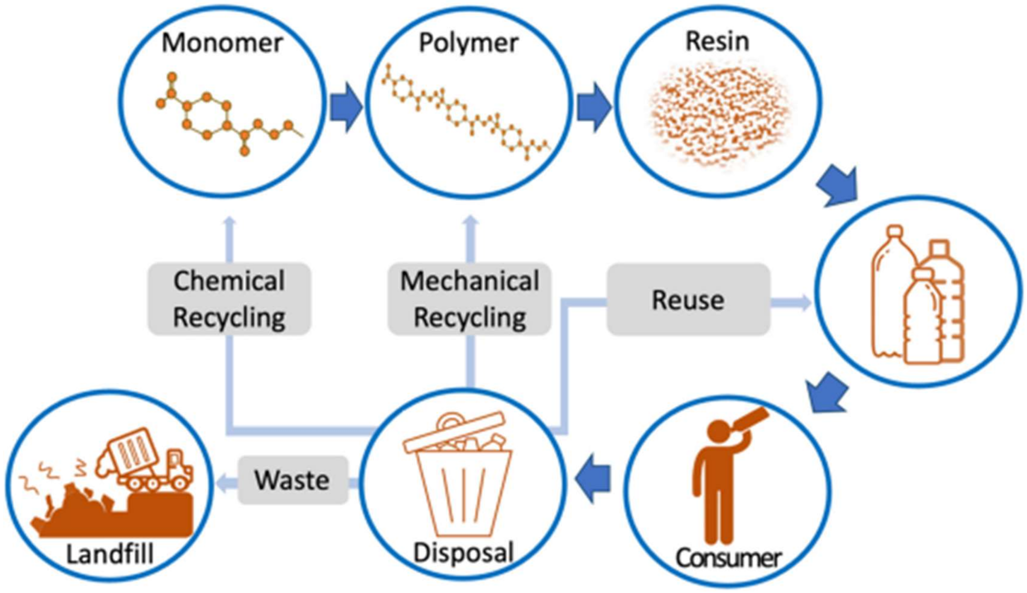

Figure 1.1 Life cycle of PET bottle (Benyathiar et al., 2022)

Plastic waste recycling in the concrete industry is a promising approach to reduce the environmental impact in terms of natural resources, pollution, and waste management (Behera et al., 2014). Previous research reported that addition of plastic aggregates into concrete alters the uniformity and homogeneity of mixed characteristics such as workability and density (Babafemi et al., 2018). For instance, Akçaözoğlu et al. (2010) evaluated the fresh and dry unit weight of concrete containing shredded waste PET bottles as fine aggregate replacement. They found that replacement of sand with low-density PET has the potential to reduce the overall unit weight of concrete, thereby reducing the dead weight, which in turn reduces the seismic risk of the structure. A similar study by Kumari and Srivastava (2016) evaluated the impact of shredded Polyvinyl chloride (PVC) plastic and fly ash on concrete as partial replacement for fine aggregate and cement, respectively. They observed that the use of Polyvinyl Chloride (PVC) as a fine aggregate substitute in concrete without fly ash content reduced the workability and mechanical characteristics of the concrete. However, incorporating fly ash as a 10% replacement for cement in conjunction with PVC in concrete mix compensated for the loss of mechanical properties to some extent with having no impact on the workability of concrete. Concrete containing plastic aggregate is a sustainable material towards circular economy, as it could be recycled and reused in road pavements at the end of its life cycle (Lumauod, 2019; Santos et al., 2021). The use of PET waste in concrete manufacturing has previously been investigated. However, there has been a significant variety in the size, shape and texture of the PET waste used in previous studies, with fibres being the most commonly used. The use of PET waste in the form of granules has not yet received much attention. Granular PET has a sub-rounded shape and dimension comparable to sand, which may contribute to mix homogeneity, resulting in improved performance compared to strip, flake and fibre shapes with a larger surface area (Quiroga, 2003). The use of PET granules in concrete could be both ecologically and economically beneficial as no additional treatment or colour removal is required unlike other traditional recycling methods, and it saves time and energy by eliminating the need to transform them into fibres (Albano et al., 2009). Furthermore, the production of PET granules is more economical than that of PET fibres as PET granules are obtained by granulating waste PET bottles using a granulator machine, whereas PET fibres are produced by melt spinning process of the PET granules (Camlibel, 2018; Telli & Özdil, 2015).

This thesis systematically investigated the performance of concrete containing recycled PET waste in granular form as partial fine aggregate replacement (0%, 10%, 30% and 50% by volume). First, the impact of varying PET granules percentage on fresh and hardened properties, as well as crack mouth opening displacement behaviour of concrete was investigated. Second, the bond behaviour between concrete containing different percentage of PET granules and steel reinforcement was evaluated together with flexural and cracking performance of reinforced concrete (RC) beams with different PET granules content. Theoretical study was conducted to define a bond strength model for concrete containing PET aggregate. Furthermore, finite element modelling was carried out to simulate the flexural performance of the RC beams with PET content. Third, the long-term durability properties of concrete mixes including Alkali silica reactivity, shrinkage strain, creep strain, rapid chloride penetration, apparent volume permeable voids and water absorption were examined. Moreover, a shrinkage model for concrete with PET granule aggregates was proposed. The findings of these studies provided a more detailed understanding of the behaviour of concrete containing PET granule aggregates, as well as encouraging outcomes for promoting sustainable construction material.

1.2. Objectives

The main aim of this study is to evaluate the effect of PET granules (replacing fine aggregate by 10% to 50% by volume) on the performance of concrete through experimental, theoretical and numerical investigations. The specific objectives are as follows:

1. To investigate the effect of PET granule aggregate on the mechanical properties as well as crack mouth opening displacement of concrete.
2. To evaluate bond behaviour of the steel reinforcement with surrounding concrete containing PET granules, as well as flexural performance and cracking behaviour of the RC beams containing PET granule aggregate.
3. To investigate the effect of PET granules on the long-term performance of concrete.

1.3. Scope

This thesis studied the impact of PET granules on mechanical, structural and durability properties of concrete with target strength of 30-32 MPa. The PET granules were used as a partial volumetric replacement for fine aggregate (0%, 10%, 30%, and 50%). The sieve analysis was caried out to ensure particle size distribution is comparable to sand. The crack mouth opening displacement test was performed on the pre-notched beam specimens with dimensions of 150 mm x 150 mm x 700 mm under four-point bending test. The single notch with a depth of 25 mm and a width of 2 mm was made on the CMOD test specimens prior to the test. The digital image correlation (DIC) system was used to examine crack propagation of the beams. The bond behaviour was investigated on the cylindrical specimens (100 mm diameter and 200 mm height) with a 12 mm deformed bar placed in the middle of each specimen. The flexural behaviour of RC beams (100 mm x 250 mm x1400 mm) was evaluated under four-point bending test. The beams were under reinforced by design. 10 mm deformed bars were used for flexural reinforcement, and 6 mm plain bars were used for transverse reinforcement. The measurements for creep strain, rapid chloride penetration, water absorption and apparent volume permeable voids tests were taken for 90 days. The drying shrinkage of the specimens was measured for one year. The alkali-silica reactivity measurements for mortar bars and concrete prisms were taken for 21 days and one year, respectively.

1.4. Thesis organisation

This study is presented as a thesis by publication. It consists of six main chapters. Chapter 1 provides research background and motivation, objectives, and limitations of this research. Chapter 2 presents critical review of the literature and research gap in the field. Chapter 3 to 5 presents the significant findings of the main objectives of this research. The conclusions that summarise the general findings and contribution of this study, as well as the recommendations for future research are highlighted in Chapter 6. The flow chart of the thesis is presented in Figure 1.2.

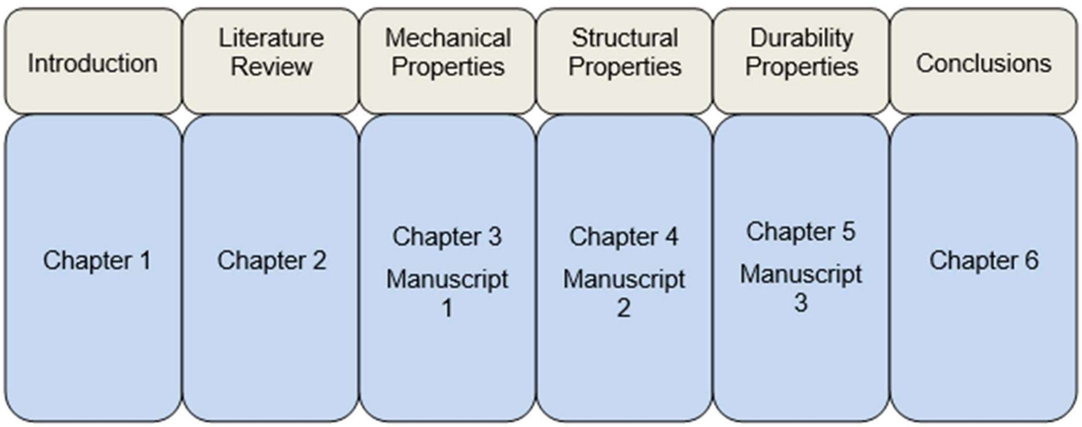

Figure 1.2 Thesis flow chart

Three journal manuscripts were prepared from the findings of this study which are published or under review in Q1 and D1 journals. In addition, a manuscript related to key findings of part of this research is accepted for publication in a national conference, which is presented in Appendix A.

Manuscript 1:

Kangavar, M. E., Lokuge, W., Manalo, A., Karunasena, W., Frigione, M., (2022). Investigation on the properties of concrete with recycled polyethylene terephthalate (PET) granules as fine aggregate replacement. *Case Studies in Construction Materials*, *16*, e00934. https://doi.org/10.1016/j.cscm.2022.e00934. (Q1 journal; Impact Factor: 4.934).

This manuscript addressed the first objective of the study. The manuscript presents the mechanical properties of sustainable concrete with PET granules as volumetric replacement (0%, 10%, 30%, and 50%) for fine aggregate. The important parameters such as density, compressive strength, tensile strength, elastic modulus and flexural strength were evaluated along with the microstructure of concrete mixtures. In addition, post-crack behaviour of the concrete beams was investigated by conducting crack mouth opening displacement test. The crack patterns of the beams were analysed using strain map generated from DIC system. From this study, it was concluded that the concrete containing 10% PET granules achieved the optimum performance in terms of mechanical properties and post-crack behaviour. Moreover, the American and Australian design equations were found reliable in predicting the strength parameters of concrete containing PET granule aggregates.

Manuscript 2:
Kangavar, M. E., Lokuge, W., Manalo, A., Karunasena, W., Ozbakkaloglu, T., (2023). Development of sustainable concrete using recycled polyethylene terephthalate (PET) granules as fine aggregate. *Developments in the Built Environment,* 100192. https://doi.org/10.1016/j.dibe.2023.100192. (D1 journal; Impact Factor: 5.563).

This manuscript addressed the second objective of the study. The manuscript presents the structural performance of concrete incorporating PET granules as fine aggregate replacement (0%, 10%, 30%, and 50% by volume). The bond behaviour between steel reinforcement and the concrete mixes was investigated. In addition, the flexural and cracking behaviour of the RC beams with different PET content were evaluated. The results showed that incorporating 10% PET granules had positive impact on bond behaviour, and flexural performance of the RC beam. The inclusion of PET granules at all replacement ratios improved the crack width and crack propagation of the RC beams. However, the improvement was more noticeable for concrete with 10% replacement ratio. In addition, a theoretical model was developed for bond behaviour of concrete containing PET content with steel reinforcement, and the predicted values were in close agreement with the experimental findings of this study and previous research. The finite element modelling was conducted to simulate flexural performance of the RC beams with PET content, and the results corresponded reasonably well with the experimental findings.

Manuscript 3:

Kangavar, M. E., Lokuge, W., Manalo, A., Karunasena, W., Siddique, R., (2023). Effect of recycled polyethylene terephthalate (PET) granules on the long term durability of concrete. Submitted to Journal of Cleaner Production (under review). (D1 journal; Impact Factor: 11.1).

The final objective, the investigation on the long-term performance of concrete containing PET granules as partial volumetric replacement for fine aggregate (0%, 10%, 30%, and 50%) is presented in this manuscript. The important durability parameters including ASR expansion, creep strain, shrinkage strain, rapid chloride penetration, water absorption and AVPV were investigated. From the results, it was concluded that the increase of PET granules in concrete mix decreased the ASR expansion for 21-day mortar bar test and one-year concrete prism test. The incorporation of 10% PET granules had negligible impact on one-year shrinkage of concrete, while shrinkage strain increased with increasing PET replacement level. Incorporating 10% PET granules slightly improved creep strain and chloride resistance and had almost no impact on water absorption and AVPV of concrete. Moreover, a theoretical model was proposed for shrinkage strain of concrete with PET aggregates and the predicted values agreed well with the experimental results.

1.5. Summary

The incorporation of PET granules in concrete fabrication as a partial fine aggregate replacement provides a sustainable solution to depletion of natural resources, as well as disposal of plastic waste by diverting PET bottles from landfills. However, the behaviour of concrete is affected by the percentage of PET granule aggregates in the mixture. The brittle behaviour of conventional concrete is a major issue in construction industry. The plastic nature of PET granule aggregates can potentially improve the ductility and long-term performance of concrete. Therefore, the main motivation of this research was to fully understand the overall performance including mechanical, structural and durability properties of this sustainable construction material.

CHAPTER 2: LITERATURE REVIEW

While global plastic production is increasing rapidly, recycling of plastic waste is as low as 9% in many countries including Australia (Peng et al., 2023). As a result, a large amount of plastic waste ends up in landfills. PET waste is the fifth most produced plastic waste worldwide, contributing significantly to detrimental environmental effects in landfills (Limami et al., 2020). The use of PET waste in concrete manufacturing is one of the possible methods for recycling PET waste in the construction industry (Siddique et al., 2008). This chapter provides critical information as to the available literature on the use of PET waste in concrete manufacturing. The state of the art review highlights the fresh and hardened properties of PET concrete, including workability, mechanical, structural and durability parameters. It also identifies the effect of varying shape, size and quantity of PET waste (either as a reinforcement or partial replacement of one or more concrete constituents) on the properties of concrete.

2.1. Plastics

Plastics are made of polymers and additives, where polymers synthesised from petroleum, gas derivatives and natural resources such as cellulose and wool, and additives are chemical compounds such as lubricants and blowing agents (EPA, 2015). Plastic production has been growing exponentially due to its design flexibility, corrosion resistance, shatter resistance and light weight properties (Pal et al., 2021). Plastics are classified into seven broad categories, including Polyethylene Terephthalate (PET), High Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low Density Polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS) and miscellaneous plastics (Polyester, Polyamides and Polycarbonate) (Nanda & Berruti, 2021) (Figure 2.1). Plastics are extensively used in the construction industry for a variety of applications such as flooring, cladding, insulation, sealants, and waterproof membranes (Agarwal & Gupta, 2018). The benefits of using plastics in construction industry include durability, low maintenance costs, easy installation and transportation, insulation and fire resistance (Ramli Sulong et al., 2019).

Figure 2.1 Plastics categories (Parmer, 2021)

2.2. Polyethylene terephthalate (PET)

Polyethylene terephthalate (PET) is a form of polyester produced from the composition of ethylene glycol and terephthalic acid (Akçaözoğlu & Ulu, 2014) (Figure 2.2). Ethylene glycol is a colourless liquid derived from ethylene, whereas terephthalic acid is a crystalline solid produced from xylene (Al-Sabagh et al., 2016). Ethylene glycol and terephthalic acid are heated in the presence of chemical catalysts to produce molten viscous PET which can either be treated instantly into fibres or hardened to be processed later into plastic (Britannica, 2019). PET is one of the most extensively used polymers in the packaging industry, particularly in drink bottles, because of its lightweight, high pressure resistance, high stability, non-reactivity with chemicals, and gas barrier features (Akçaözoğlu & Ulu, 2014; Nisticò, 2020).

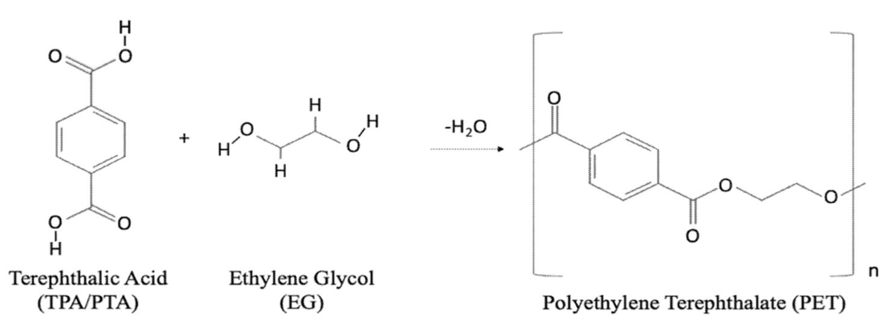

Figure 2.2 Formation of Polyethylene terephthalate (PET) (Benyathiar et al., 2022)

2.3. Recycling of waste PET bottles

Figure 2.3 depicts the existing methods for recycling waste PET bottles. Waste PET bottles may be recycled using two recycling methods including closed loop and open loop systems (Andrady, 2015). While the closed loop method involves combining waste PET bottles with virgin materials to manufacture new PET bottles, the open loop method turns waste PET bottles into a new forms that may be used in various applications (Kasmi et al., 2023). The closed loop method requires rigorous cleaning of waste PET bottles using chemicals and technologies to ensure elimination of pollutants and impurities (Schwarz et al., 2021). The procedure includes a heating process at temperatures between 180 and 230 °C, inert gas stripping and re-extrusion at temperatures ranging from 280 °C to 290° (Welle, 2011). The open loop approach, on the other hand, involves sorting and prewashing waste PET bottles without any chemical treatment. Subsequently, PET bottles are converted into different forms such as flakes, pellets and granules with the desired particle size (Andrady, 2015).

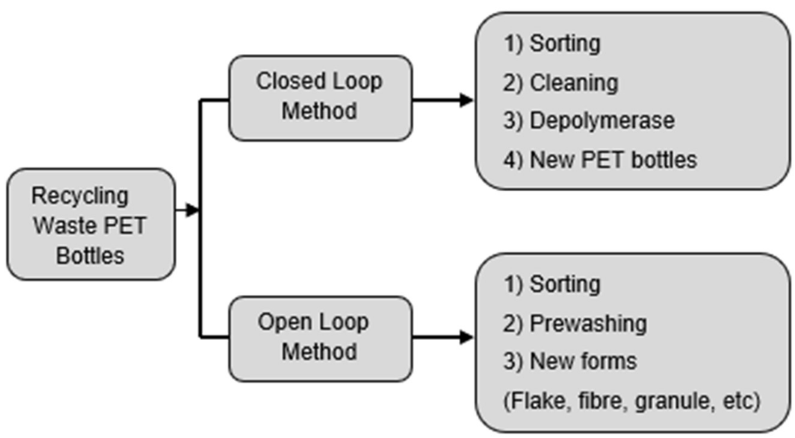

Figure 2.3 Recycling procedures of waste PET bottles (Andrady, 2015)

2.4. Recycled PET application in textile industry

Recycled PET flakes have been used in a variety of staple fibre applications in textile sector, including carpets, blankets, clothing and fibrefill in sleeping bags, pillows, and bedding (Park & Kim, 2014). However, the precise sorting of waste PET bottles as well as thorough impurity elimination are critical for obtaining recycled fibre quality comparable to virgin fibre (Shen et al., 2010). Furthermore, the use of recycled PET for the production of partially oriented yarn (POY), drawn textured yarn (DTY), and fully drawn yarn (FDY) type textile yarns has significant limitations due to decreased performance specifications such as higher stiffness, more fatigue action, lower tensile strength and reduced fabric burst strength with increasing recycled PET content (Sarioğlu & Kaynak, 2017).

2.5. PET waste as reinforcement in concrete manufacturing

This section presents previous research findings on the performance of concrete reinforced with PET waste (as a percentage of weight or volume fraction of one or more concrete ingredients).

2.5.1. Workability

Previous studies reported a decrease in workability with adding PET waste in concrete mix. Wiliński et al. (2016) investigated the workability of concrete mixtures reinforced with 0.1%, and 0.3% PET fibres (aspect ratio = 0.04, thickness = 0.25 mm) by volume of concrete (Figure 2.4). They found that workability of concrete decreased substantially with increasing PET fibres in the mix, with the slump value of concrete containing 0.1% and 0.3% PET fibres decreasing by 50% and 80%, respectively, compared to control. Pandya and Purohit (2014) evaluated the workability of PET fibre reinforced concrete. PET fibres (aspect ratio = 0.45, thickness = 0.55 mm) were added at 0%, 0.5%, 1.5%, and 3% of the cement weight. They found that workability of concrete decreased with increasing PET fibre in the mixture, where the slump value for the control and the mixture with 0.3% PET fibres were 96 mm and 35 mm, respectively. Similar study by Pelisser et al. (2012) examined workability of concrete with recycled PET fibres with aspect ratio of 75 and thickness of 0.45 added (0% - 0.3%) by volume of concrete. They found that the workability of concrete was inversely associated with the quantity of PET fibres in the concrete, with the slump value of 50 mm for concrete with 0.3% PET fibres, down from 100 mm for control. Shahidan (2018) reported a similar result, where the concrete specimen with 2% PET fibre (50 mm in length and 5 mm in width) as a percentage of total volume exhibiting a slump value of 42 mm compared to 96 mm for the control specimen. Similar findings were reported by the other researchers (Afroz et al., 2013; Dinesh & Rao, 2017; Lee et al., 2019). However, a study by Ochi et al. (2007) found that 0.5% PET fibre (diameter = 0.7 mm and length = 30 mm) as volumetric percentage of concrete mix had no impact on the workability of concrete which could be due to higher w/c ratio of 0.65, and the performance started to decline with increasing PET fibre percentage. Previous studies attributed the decrease in concrete workability with increasing PET fibre to the frictional resistance between PET fibres and concrete mix (Nkomo et al., 2022).

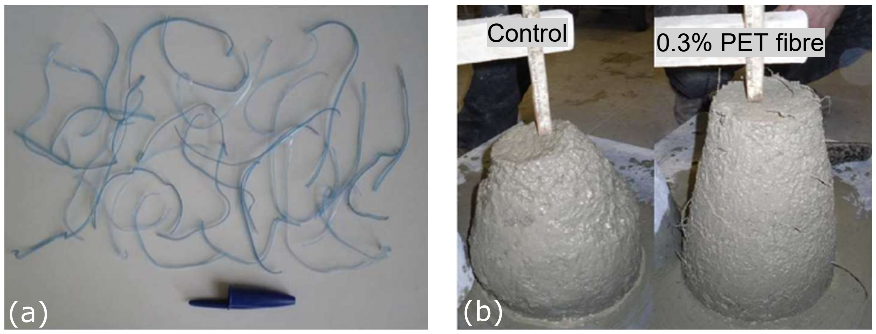

Figure 2.4 (a) PET fibres from waste bottle, (b) slump test (Wiliński et al., 2016).

2.5.2. Density

de Oliveira and Castro-Gomes (2011) evaluated the density of mortar reinforced with PET fibres (0.5%, 1.0%, and 1.5% by volume of mortar). PET fibres had aspect ratio of 31 and thickness of 0.5 mm. The results revealed a slight decrease in density with increasing PET fibres in mortar, with the value for specimen with 1.5% PET fibres decreasing by 5% compared to the control. A similar study by Ochi et al. (2007) reported that 0.5% PET fibre (diameter = 0.7 mm and length = 30 mm) as volumetric percentage of concrete mix decreased the density of concrete by 2% compared to control mix. Al-Hadithi and Hilal (2016) examined properties of self-compacting concrete with 0.5% - 2% waste PET fibres (dimension = 10 x 2 mm^2, Thickness = 0.3 mm) by volume of concrete. They noted that that density was inversely related to the PET content in the mixture, where the specimens containing 0.5% - 2% waste PET fibres had reduced density by 1% - 5% relative to control specimen. The decrease in concrete density with increasing PET fibres was attributed to the lower density of PET fibres compared to concrete mix.

2.5.3. Compressive strength

Most studies reported that compressive strength increased up to a certain amount of PET content in the mixture, and then declined with further addition of PET. Maqbool and Sood (2016) added PET fibres (aspect ratio = 35) to concrete as a 2-5% volume fraction of cement in the mix. They observed a change in compressive strength compared to control after 7, 28 and 56 days. They found an increase in compressive strength by 3-4 MPa on average at each time interval, with optimal values at 3% fibre content. Further increase of PET fibres resulted in reduced compressive strength compared to control concrete. The performance reduction beyond this percentage was due to the weak bonding between fibres and concrete matrix. Some studies have experimented with PET fibre addition in a variety of sizes, textures and shapes. Asha and Resmi (2015) evaluated the compressive strength of concrete reinforced with straight and crimped PET fibres added (0.5% - 1.5%) as a percentage of the overall weight of cement in the mixture (Figure 2.5). Peak compressive strength was achieved at 1% fibre addition, with the performance decreasing thereafter. Moreover, the use of crimped fibres provided better results than the straight fibres due to improved bond behaviour between crimped fibres and concrete matrix. The addition of 1% PET fibres resulted in an increase in compressive strength relative to control by 16% and 18% for straight and crimped fibres, respectively. Taherkhani (2014) added PET fibres of different lengths (1-3 cm) and thickness of 2 mm at 0.5% and 1% of the total volume of the concrete mixture. In contrast to other studies, it was found that PET fibre reinforced mixtures for all lengths had lower compressive strength than control mix. Shahidan (2018) added PET fibres (50 mm in length and 5 mm in width) to concrete as 0.5%-2% volume fraction of concrete and reported that the compressive strength of concrete decreased proportionately with increasing PET fibres in the mixture. Specifically, there was a decline in performance up to 20% for concrete containing 2% PET fibres. This behaviour was attributed to bundling of PET fibres during specimen preparation, producing areas of weakness within the spaces between PET fibres. The variation in compressive behaviour of concrete reported in previous studies might be explained by the varying size and shape of PET fibre in the concrete mix (Saikia & de Berita, 2014; Yesilata et al., 2009).

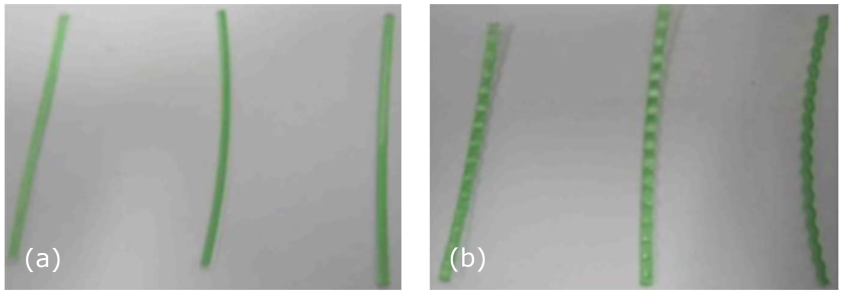

Figure 2.5 (a) straight fibres, (b) crimped fibres (Asha & Resmi, 2015)

2.5.4. Tensile strength

As with compressive strength, tensile strength appeared to peak following incremental addition of PET up to certain amount (depending on the shape and size of PET fibre), after which the performance declined with further fibre addition. Shahidan (2018) evaluated splitting tensile strength of concrete by adding 0.5%, 1% and 1.5% PET fibres (50 mm in length and 5 mm in width) by volume of concrete. They noted that tensile strength of concrete improved up to 1% PET fibre addition and started to decrease with further PET addition. The specimen containing 1% PET fibre displayed a 12% increase in tensile strength compared to conventional concrete. This behaviour was due to the bridging mechanism of PET fibres at lower percentages (Figure 2.6). However, the performance reduction with increasing PET content in concrete was attributed to the bundling of PET fibres in the concrete mix resulting in poor bond between fibres and cement paste. Similar study by Dinesh and Rao (2017) studied the splitting tensile strength of concrete reinforced with 0.5%, 1% and 1.5% PET fibre (50 mm in length and 2 mm in width) by weight of cement in the mix. They noted that tensile strength of specimen with 0.5% PET fibre was increased by 15% compared to control. Although the performance reduced with increasing PET fibre content, The specimens with 1% and 1.5 % still had positive impact on tensile behaviour, increasing by 14% and 11%, respectively, compared to control. The performance improvement of PET concrete was related to the interlocking effect of PET fibres in concrete mix, while the performance reduction of PET concrete with increasing PET content was related to the uneven distribution of PET fibres in concrete with higher PET content. Krishnamoorthy et al. (2017) investigated the effect of adding PET fibres of different aspect ratios (0.15, 0.3 and 0.45) as volume fractions of 0.5%-2.0% of the concrete mixture. They observed that concrete containing 1.5% PET fibre with aspect ratio of 0.15 provided the optimal performance relative to the control across all aspects, with value for tensile strength showing improvement of 42.8% over conventional concrete. Irwan et al. (2013) found that split tensile strength of concrete reinforced with 0.5, 1%, 1.5% PET fibres (aspect ratio = 0.15, thickness = 10 mm) by volume of concrete increased by 9%, 15% and 23% compared to conventional concrete. This behaviour was attributed to the bridging effect of PET fibres in the mixture.

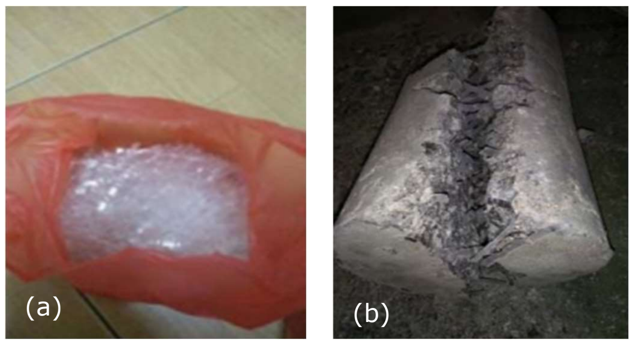

Figure 2.6 (a) PET fibres, (b) bridging effect of PET fibres (Shahidan, 2018)

2.5.5. Modulus of Elasticity

Irwan et al. (2013) studied the modulus of elasticity of concrete reinforced with PET fibres (0.5%, 1.0%, and 1.5% by volume of concrete). They reported that the elastic modulus of concrete with 0.5% PET fibres increased by 8.3% compared to control concrete. However, the performance started to decline with increasing PET fiber percentage, with specimens reinforced by 1.0% and 1.5% PET fibres showing 8.3% and 20.8% decreases, respectively, relative to control. In a similar manner, Taherkhani (2014) investigated the modulus of elasticity of concrete with addition of PET fibres (1-3 cm) by 0.25% to 1.5% of the volume of concrete. It was found that longer PET fibres increased the modulus of elasticity, in particular the 0.5% PET concrete specimen containing 3 cm PET fibres (an increase of 5% over conventional concrete), which was explained by stiffening effect of longer PET fibres and improved interlocking behavior in concrete mix. On the other hand, specimens with shorter fibres had reduced modulus of elasticity, with the reduction being less apparent at 1% PET content. In this category, the performance decrease was less than 3% relative to conventional concrete. The performance reduction of shorter fibres was attributed to the reduced interlocking effect of short PET fibres with concrete matrix.

2.5.6. Flexural strength

Dinesh and Rao (2017) studied the flexural strength of concrete containing 0.5%, 1% and 1.5% PET fibre by weight of cement in the mixture. PET fibres were 50 mm in length and 2 mm in width. It was concluded that while the specimen containing 1% PET fibre exhibited the least amount of shrinkage cracking, it was the specimen containing 0.5% PET fibre that achieved the optimal flexural strength with an improvement of 8.6% over conventional concrete. The performance improvement was attributed to the interlocking effect between PET fibres and concrete matrix at low replacement level. In a similar manner, Wiliński et al. (2016) examined the flexural strength of concrete with addition of PET fibres (aspect ratio = 0.04) by volume fraction of concrete (0%, 0.1%, and 0.3%). They evidenced that increasing PET content had minimal effect on the flexural strength of the mixture, as evidenced by a flexural strength value of 3.6 MPa for the 0.3% PET concrete specimens, down from 3.7 MPa for the control specimens. Kumar (2014) examined the flexural strength of concrete reinforced with PET in different forms, including hollow bars, short and long strips. It was found that addition of long PET strips to concrete reinforced with steel bars yielded the best overall performance in terms of flexural strength, with a nearly threefold improvement (23.96 N/mm^2) over conventional unreinforced concrete (8.4 N/mm^2) and a 31% increase over concrete reinforced with steel bars only (18.3 N/mm^2). Reinforcement of concrete with PET bars only resulted in a decrease in flexural strength to a level below that of conventional concrete.

2.5.7. Structural property

Marthong and Marthong (2016) studied the behaviour of exterior RC beam-column connection (half a column on either side of the joint and part of the beam up to mid-span) subjected to reversed cyclic loading with addition of 0.5% PET fibres (aspect ratio = 25) by volume of concrete (Figure 2.7). Three types of external beam - column joints were evaluated, namely beam weak in flexure (BWF), beam weak in shear (BWS), and column weak in shear (CWS). It was reported that load capacity of BWF, BWS, and CWF increased by 27%, 10%, and 10%, compared to the reference sample, respectively. An overall improvement in lateral stiffness, energy dissipation, toughness, and ductility were noted, which was explained to the macro crack bridging behaviour of PET fibres. In similar study, Mohammed and Rahim (2020) investigated structural behaviour of high strength RC beams (120 mm width, 150 mm depth and 1200 mm length) reinforced with PET fibres (0.75 and 1% by volume of concrete). PET fibres were added to concrete with different length (20 mm, 40 mm, or mixture of both) and hybridized in order to produce hybrid polymer fibres. It was found that ultimate flexural strength decreased moderately for RC beams containing PET fibres. This performance reduction was more pronounced for RC beam with 0.75% PET fibre (20 mm length), decreasing by 23.3% compared to the reference beam. This behaviour was supported by Taherkhani (2014), who reported that concrete reinforced with PET fibres of 1 cm length outperformed concrete reinforced with PET fibre of 3 cm length. However, the cracking and ductility behaviour improved with addition of PET fibre to RC beams, where the beam with 1% PET fibre content (mixture of both length) demonstrated optimum performance, increasing by 2% compared to reference beam. The improved ductility behaviour was explained by bridging ability of PET fibres across the cracked region. Foti (2011) used PET fibres in both O-shape and lamellar conformations (Figure 2.8) and reported an improvement in toughness with both conformations when added to concrete, although the effect was more significant with the O-shaped fibres. It was hypothesised that the shape of the O-fibres bound the concrete more effectively from each side of the cracked section.

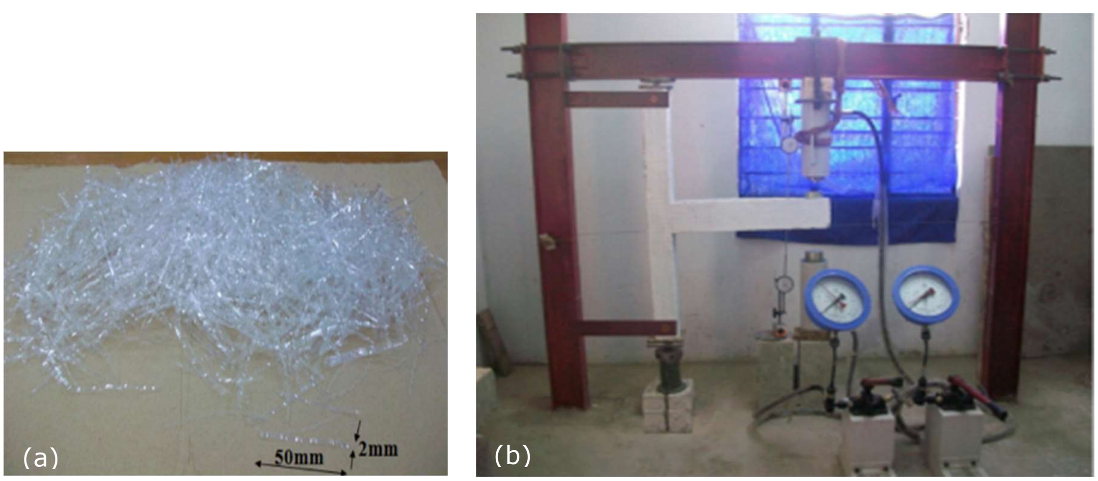

Figure 2.7 (a) straight slit PET fibres, (b) test set up (Marthong & Marthong, 2016)

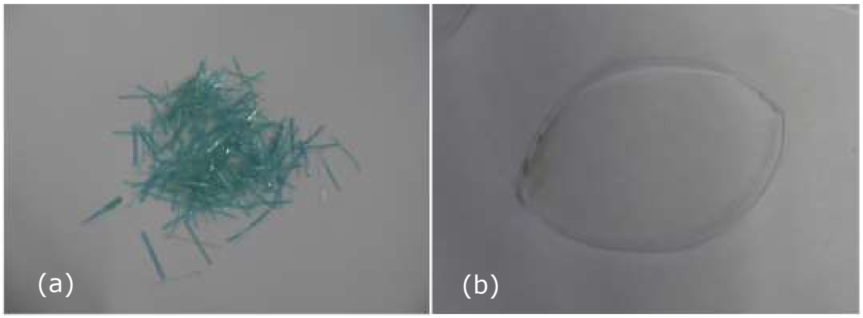

Figure 2.8 (a) short lamellar fibres, (b) O-shaped fibres (Foti, 2011)

Al-Hadithi and Abbas (2018) evaluated shear strength of RC beams (100 mm width, 150 mm depth and 1200 mm length) with addition of PET fibres (0.25%-1.5%) by volume of concrete. They observed that addition of PET fibres up to 1% increased the shear strength of concrete, achieving the maximum increase of 8.4% for the beam with 1% PET fibre compared to the reference beam, and performance started to decline with increasing PET fibre percentage. It was also found that ductility of RC beam increased with increasing PET fibres in concrete which was explained by the crack bridging behaviour of PET fibres. A similar study by Prabha and George (2017) added PET fibres to RC beams with different aspect ratios (4, 8, and 12) as a percentage (0%-1.5%) of the overall volume of concrete and noted an increase in shear capacity of RC beams (100 mm width, 100 mm depth and 500 mm length) with addition of PET fibre. The peak shear capacity was achieved at 0.5% fibre addition (aspect ratio = 12), increasing 15% over reference beam. Further addition of PET fibres resulted in reduced shear capacity compared to reference beam. The RC beam with aspect ratio of 12 achieved the optimum performance which was attributed the improved interlocking effect of PET fibres with higher aspect ratio.

2.5.8. Durability property

There is limited literature on the durability properties of concrete with PET content. Pereira de Oliveira and Castro-Gomes (2011) studied water absorption of mortar with addition of 0.5%, 1%, and 1.5% of PET fibres (Figure 2.9) by volume of mortar. PET fibres had aspect ratio of 31 and thickness of 0.5 mm. They found that water absorption of the specimens containing 0.5%, 1%, and 1.5% increased by 48%, 48%, and 55% respectively, compared to control specimen. The behaviour was attributed to increasing porosity of the mixture, notably around the PET fibres and increasing number of capillary pores in the mix. Yesilata et al. (2009) investigated thermal insulation behaviour of concrete with addition of PET waste in various shapes (square, strip, irregular) as 0.9% volume fraction of concrete. They noted that specimen containing square shape PET waste exhibited 10% more thermal insulation than control. However, the performance was further improved for specimens containing strip and irregular shape PET waste, increasing by about 17% for both shapes compared to control. This behaviour was related to the stronger adherence of strip and irregular shapes of PET waste to concrete matrix than square shape as the strip and irregular PET were closer to each other in the mix, creating a better thermal barrier. A similar study by Won et al. (2010) experimented the chloride permeability and freeze/thaw properties of concrete reinforced with recycled PET fibre (50 mm) as 1% volume fraction of concrete. They found that 1% PET fibre increased chloride permeability and freeze/thaw performance of concrete by 11% and 5%, respectively, compared to control specimen. The reason for optimal performance of 1% PET concrete was not provided by this study. However, the improved performance of concrete with PET fibres might be attributed to the improved microcracking behaviour of concrete with PET fibres compared to control (Al Rikabi & Sargand, 2018; Richardson & Coventry, 2012).

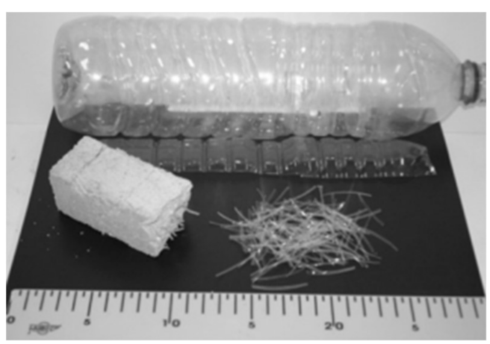

Figure 2.9 Recycled PET fibres (de Oliveira & Castro-Gomes, 2011)

2.6. PET waste as substitution in concrete manufacturing

The effect of PET waste as a partial replacement of one or more concrete constituents (fine or coarse aggregates) on concrete properties is presented in this section.

2.6.1. Workability

Frigione (2010) studied the workability of concrete containing waste un-washed PET particles with the size ranging from 300 μm to 2.36 mm as a 5% replacement of fine aggregate by weight. It was found that all specimens with PET waste aggregate maintained the same VeBe time and consistency as control specimen. Furthermore, it was reported that 5% PET particle had no impact on the workability of concrete mix. Similar study by Almeshal et al. (2020) evaluated the workability of concrete containing shredded PET waste with sizes varying from 0.075 to 4 mm as a partial (10%-50%) volumetric replacement of sand in the mixture. It was found that increasing PET content had a negative effect on the workability of the concrete mix, as demonstrated by a slump value of 10 mm for the 50% PET concrete specimen, down from 90 mm for control specimens. Similarly, Dawood et al. (2021) examined the workability of concrete incorporating shredded PET waste with sizes ranging from 1.18 mm to 2.36 mm as a partial replacement of fine aggregate (5% to 20% by volume). They found that the workability of concrete was inversely related to the increase of shredded PET waste in concrete mix, with the specimen containing 20% PET showing a 62.5% decrease in concrete workability compared to control. This was explained by the larger surface area of shredded PET waste particles, allowing the saturation of larger amount of water in its surface, leading to decreased workability.

2.6.2. Density

Rahmani et al. (2013) tested the fresh and dry unit weight of concrete specimens containing PET particles (7 mm) as a partial replacement of fine aggregate by volume (5%-15%). They found that both fresh and dry unit weight of the specimens decreased with increasing PET content in the mixture, with the 15% PET concrete specimen exhibiting a 30% decrease in both fresh and dry unit weight relative to control. Similar findings were reported by Almeshal et al. (2020), who found that shredded PET waste (0.075 mm - 4 mm) as a partial (10% - 50%) volumetric replacement of sand decreased the density of concrete, with the density of 50% PET concrete decreasing by 40% compared to control. The authors attributed this finding to the lower density of the PET aggregate compared to natural sand.

2.6.3. Compressive strength

Almeshal et al. (2020) studied compressive strength of the concrete containing shredded PET waste (0.075 - 4 mm) as a partial (10% - 50%) volumetric replacement of sand in the mixture. They reported that compressive strength was negatively correlated with increasing PET content in the mixture, with the value for 50% PET concrete mixture decreased by 60% relative to control. Frigione (2010) investigated compressive strength of concrete by partially replacing fine aggregate with 5% of waste un-washed PET particles. The particle size of sand and PET particles ranged from 300 µm to 2.36 mm. It was found that incorporating 5% PET waste particle slightly reduced compressive strength, decreasing by 2% compared to the conventional concrete. Rahmani et al. (2013) conducted a similar study in which they tested the compressive strength of concrete containing PET particles as a partial replacement of fine aggregate by volume (5%, 10%, and 15%). The size of sand and PET particles was smaller than 7 mm. However, the PET particles were predominantly distributed between 2.36 mm and 4.75 mm, with no significant variation in sand dispersion between 0 and 4.75 mm. They found that 5% PET particle slightly improved the compressive strength, increasing by 9% compared to control. This improvement was attributed to shape and flexibility of PET particles. However, the performance declined for the specimens containing 10% and 15% PET particles, decreasing by 5% and 13%, respectively, compared to control specimen. The performance reduction was explained by the weak adhesion between PET particles and cement paste. The discrepancy between the findings of previous studies could be attributed to the size and shape of PET particles, which affected mix homogeneity and concrete strength (Saikia & de Berita, 2014; Yesilata et al., 2009).

2.6.4. Tensile strength

Dawood et al. (2021) studied the split tensile strength of concrete incorporating shredded PET waste as partial volumetric replacement of fine aggregate (5%-20%). While the size of fine aggregate and PET fibres were less than 4.75 mm, there was a significant variation in their gradation (0 - 4.47 mm), with the most of PET fibres ranging from 1.18 mm to 2.36 mm, whereas sand was evenly distributed. They noted that split tensile strength increased with increasing PET content in the mixture up to 12% replacement ratio, as evidenced by an increase of almost 26.9% for the specimen with 12% PET content relative to control. This behaviour was attributed to the increased ductility and sharp edges of the PET waste particles, resulting in less slipping compared to sand particles. However, the performance declined for specimens containing more than 12% PET fibres, which was due to the larger amount of PET fibres that accumulated in one place in the mix, resulting in larger interfacial transition zone between cement paste and PET fibres. Similar study by Saikia and de Berita (2014) used PET flakes as a partial (5% - 15%) volumetric replacement of fine (FA) and coarse (CA) aggregates in the concrete mixture. They noted that increasing size and content of PET flakes were correlated with decreases in split tensile strength proportional to the amount of PET replacement. The split tensile strength was seen to decrease by 54% for the specimens containing 15% PET as replacement for CA compared to 14% for the specimens containing 15% PET replacing FA. Almeshal et al. (2020) studied the split tensile strength of concrete with shredded PET waste as a partial replacement for fine aggregate (10% - 50% by volume). The particle size for sand and PET particles varied from 300 mm to 2.36 mm. The split tensile strength was seen to decrease with increasing PET content in the mixture, as evidenced by a decrease of almost 86% for the 50% PET concrete specimen relative to control. Further explanation for these findings were attributed to the decrease in adhesive strength between the PET particles and the cementitious matrix, as well as the difference in shape and stiffness of the PET particles compared to sand.

2.6.5. Flexural strength

Hannawi et al. (2010) evaluated the flexural strength of mortars containing PET waste with two different thicknesses, namely 1mm (PET1) and 0.1 mm (PET0.1) (Figure 2.10). The maximum size of PET particles was 10 mm. PET particles were used to replace sand volumetrically (3%, 10%, 20%, and 50%). They observed that concrete containing PET 1 had better flexural performance than the concrete with PET 0.1 content. It was found that up to 10% of PET1 and 3% of PET0.1 aggregates had almost no impact on flexural strength. However, the flexural performance of specimens with 20% and 50% of PET1 aggregates was reduced by 9.5 and 17.9%, respectively, compared to the control specimen. The flexural strength of mixtures with 10%, 20% and 50% of PET0.1 aggregates decreased by 5.8%, 15.6% and 46.4%, respectively, relative to the control mix. This behaviour was attributed to the weak bond between the cement paste and PET aggregate. A similar study by Rahmani et al. (2013) investigated the flexural strength of concrete using PET particles as a partial replacement of sand (5%, 10%, and 15% by volume), where the sand and PET particles were less than 7 mm in size (Figure 2.11). They noted that the inclusion of 5% PET particles increased flexural strength by 6% compared to control. However, performance declined for 10% and 15% PET concrete, decreasing by 5% and 13% respectively, compared to control. The slight performance improvement at 5% replacement ratio was related to the flexibility and interlocking effect of PET particles, while the performance reduction was attributed to the poor adhesion of PET particles with concrete matrix.

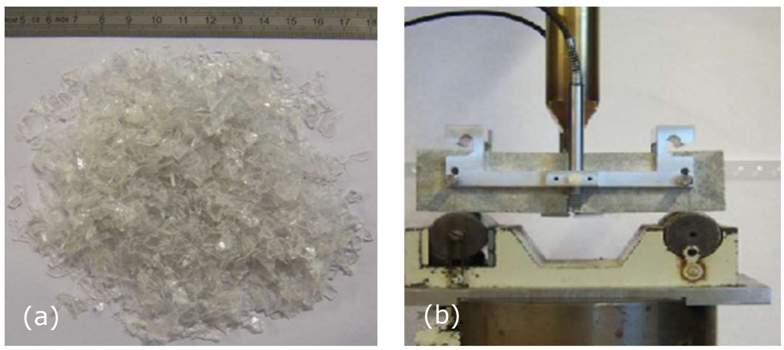

Figure 2.10 (a) PET aggregates, (b) flexural test (Hannawi et al., 2010)

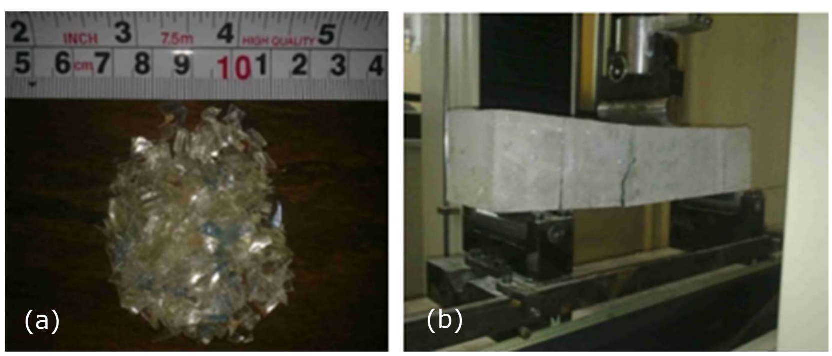

Figure 2.11 (a) PET particles, (b) flexural test (Rahmani et al., 2013)

2.6.6. Bond behaviour

The literature on the bond strength of concrete containing PET waste and steel reinforcement is very limited. Fakoor and Nematzadeh (2021) evaluated pull-out behaviour of steel rebar in high strength concrete containing shredded PET waste (2.36 - 9.5 mm) as a partial (5%-10%) replacement by volume of sand (Figure

2.12). They found that incorporating PET aggregates negatively affected the bond strength of concrete, as evidenced by bond values of 24.50 MPa and 18.82 MPa for 5% and 10% PET concrete specimen, respectively, down from 25.52 MPa for the control specimen. This behaviour vas explained to increased ITZ area and weakened PET-cement paste cohesion.

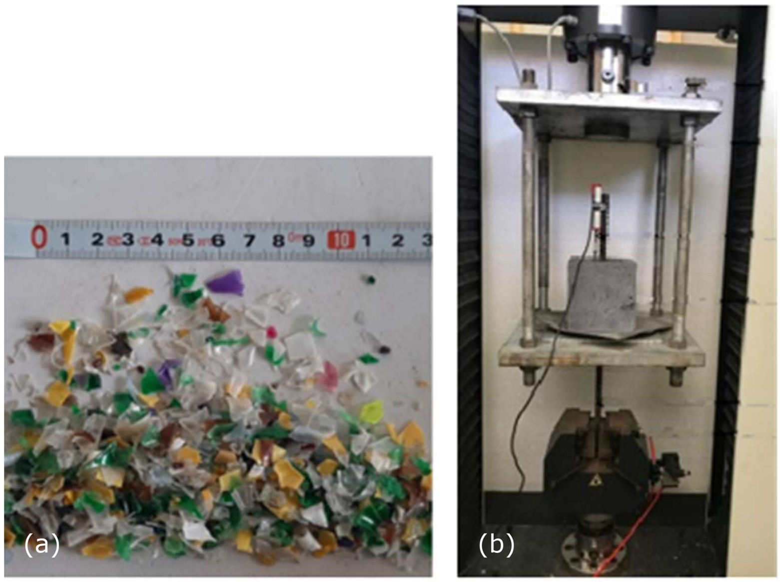

Figure 2.12 (a) shredded PET, (b) Pull-out test (Fakoor & Nematzadeh, 2021)

2.6.7. Durability property

Akçaözoğlu et al. (2013) investigated the thermal conductivity of concrete containing 30%, 40%, 50%, and 60% PET waste aggregate. The maximum size of PET aggregate was 4 mm. PET aggregate was used as a volumetric replacement for total aggregate constituents (fine and coarse aggregates). It was noted that the thermal conductivity coefficient decreased from 0.9353 W/m-K for control specimen to 0.3924 w/m-K for concrete with 60% PET aggregates, indicating improved insulating property of concrete containing PET aggregates. This behaviour was attributed to lower thermal conductivity coefficient of PET aggregates (0.15 W/m-K) than natural aggregates (2 W/m-K). Moreover, a linear correlation was found between thermal conductivity and unit weight of the concrete mixtures. Similarly, Azhdarpour et al. (2016) studied the ultrasound velocity of concrete containing sheet- shaped PET waste as partial replacement of sand (0% - 30% by volume)

(Figure 2.13). The PET particle size was between 0.05 mm and 4.9 mm. They concluded that the speed of ultrasound decreased by increasing PET particles in concrete mix. This behaviour was related to differences in the speed of ultrasound pulses in plastic particles and natural aggregates, as well as sheet-shaped structure of PET waste, acting as refraction barrier for ultrasound pulses. Choi et al. (2009) investigated the sorptivity coefficient of cement mortar by replacing 25% to 75% of the fine aggregate with PET particles (5-15 mm). They found that sorptivity of the cement mortar with 25% PET particle attained the optimum performance, outperforming control concrete by 56%. The performance deteriorated as the PET particle in the cement mortar increased, which was attributed to the higher porosity of cement mortars with a larger replacement ratio. A similar study by Saikia and de Berita (2014) studied the impact of flaky PET waste (1 - 11 mm) as a partial (5%-15%) replacement for coarse and fine aggregates on abrasion resistance of concrete. They observed that PET waste up to 10% replacement ratio enhanced concrete abrasion resistance, with highest improvement of 84% for concrete containing 10% PET waste compared to control. The performance declined with further replacement ratio. The performance improvement up to 10% PET waste content was attributed to the higher toughness and crack thinning effect of PET particles while the performance reduction beyond 10% replacement ratio was related to substantial drop in compressive strength behaviour.

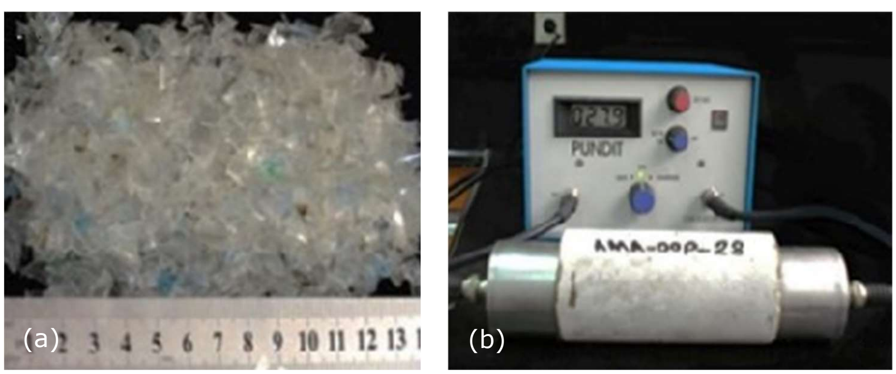

Figure 2.13 (a) sheet-shaped PET, (b) ultrasound test (Azhdarpour et al., 2016)

2.7. Summary

A thorough research review revealed that the amount of PET waste used in concrete manufacturing (either as reinforcement or as a substitute for concrete constituents) has a significant impact on the properties of concrete. Despite several research on the use of PET waste as a reinforcement in concrete fabrication, there is limited knowledge on the properties of concrete incorporating PET waste as a substitute for concrete constituents. While the use of PET waste in concrete fabrication as an aggregate (fine aggregate, coarse aggregate, or both) replacement has previously been studied, the results have been variable for varying shape and dimensions of PET waste, with fibres being the most commonly used whereas the subject of PET granules has not yet received much attention. Moreover, processing waste PET bottles into PET granules is easier than PET fibres as it eliminates the effort of turning PET granules to PET fibres, which in turn significantly reduces the cost associated with the melt spinning process of PET granules into PET fibres (CFDA, 2016; Elias, 2021; Quiroga, 2003). PET granule features sub-rounded shape and dimension comparable to sand, which may contribute to mix homogeneity, resulting in improved performance compared to PET fibre with a larger surface area (Quiroga, 2003). Previous studies mostly focused on the mechanical properties of PET concrete. Therefore, there is a lack of understanding as to the effect of PET aggregates on the structural behaviour including flexural performance of large-scale reinforced concrete beams, and bond strength between steel bar and surrounding concrete containing PET granule aggregates. In addition, no research studies have focused on numerically examining the performance of PET concrete, particularly the flexural performance of reinforced concrete beams, and its variation with the PET aggregate content. The investigation on durability characteristics of concrete containing PET aggregates is critical for understanding its long-term serviceability, especially when exposed to adverse environmental conditions. There is a lack of knowledge on the long-term performance of concrete with PET aggregates, such as creep, shrinkage, alkali silica reaction, rapid chloride penetration and water absorption. Hence, a comprehensive study on the properties of concrete with PET granule aggregates, including mechanical, structural, and long-term performance together with theoretical and numerical analysis is required to fully understand the viability of this sustainable material in the construction sector. This was the primary focus of this study.

CHAPTER 3: PAPER 1 – INVESTIGATION ON THE PROPERTIES OF CONCRETE WITH RECYCLED POLYETHYLENE TEREPHTHALATE (PET) GRANULES AS FINE AGGREGATE REPLACEMENT

3.1. Introduction

The literature review in **Chapter 2** demonstrated that the quantity, size and shape of PET waste affected the characteristics of concrete. This paper investigated the effect of PET waste in the form of granules on the mechanical properties of concrete to address the **objective 1** of the study. The PET granules were used as a partial replacement (0%, 10%, 30%, and 50% by volume) for fine aggregate. The concrete mix was designed for a target characteristic strength of 32 MPa. The particle size distribution of PET granules was relatively comparable to that of sand in order to mitigate the impact of grading variation on concrete characteristics. The workability, density, compressive strength, tensile strength, elastic modulus and flexural strength were evaluated along with the microstructural analysis. The crack mouth opening displacement of concrete beams were examined using DIC system under four-point bending test. The normalised mechanical properties of the available literature on concrete with PET aggregates were compared with the experimental findings of this study. The applicability of AS3600 (AS3600, 2018) and ACI (ACI Code, 2022) equations for predicting the mechanical properties of concrete containing PET granules was evaluated. Moreover, an analysis for PET waste reduction when incorporated in concrete manufacturing was conducted.

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Investigation on the properties of concrete with recycled polyethylene terephthalate (PET) granules as fine aggregate replacement

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ABSTRACT

Waste management is an area of significant global concern. The reuse of waste materials (such as: plastics, glass, wood, etc.) in concrete manufacturing has been studied for potential cost savings, improvements in quality, and reduction of environmental impact leading to sustainability. This study examines the performance of concrete containing recycled polyethylene terephthalate (PET) waste in granular form to replace the fine aggregate. A series of concrete specimens for Grade 32 concrete mix were cast using PET granules as partial replacement to fine aggregates in the mixture (0%, 10%, 30%, and 50% replacement by volume of fine aggregate). Important properties such as workability (slump), density, compressive strength, elastic modulus, tensile strength, flexural strength, and crack mouth opening displacement (CMOD) were evaluated together with the microstructural observations. The experimental results indicated that volumetric replacement of fine aggregates with 10% recycled PET granules positively impacted the characteristics of the concrete. The findings further revealed an improvement in the ductility of concrete with recycled PET granules content, albeit the effect was more pronounced with the concrete containing 10% PET granules. The experimental results for the mechanical properties were compared against available Australian and American design guidelines and a strong linear relationship is observed. Lastly, the findings of this study on mechanical properties revealed an optimum performance relative to those reported in the available literature, particularly for the concrete with 10% of fine aggregate replaced by PET granules.

1. Introduction

The overall quality of concrete, in terms of its durability, physical, structural and mechanical properties, is of great importance to the construction industry, as are the financial and environmental costs of production. These factors are influenced by the type and ratio of the key components used in mixing of concrete; water, cement and aggregates (both fine and coarse aggregates) together with other additives may also be used. However, the increasing cost and scarcity of materials as result of depletion of natural resources such as sand and gravel, has recently been of a great concern. Of particular interest is the use of waste materials in place of aggregates due to

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potential benefits of cost savings, reduction in environmental pollution, preservation of resources, and even possible improvements to the properties of the final product [1]. The usage of waste materials in concrete fabrication has been the subject of previous research, with waste glass, plastic and construction demolition waste being areas of interest [2]. Polyethylene terephthalate (PET), widely coming from plastic bottles, is a major contributor to adverse environmental effects in landfills. Global plastics output increased from 180 million tons in 2000–360 million tons in 2020 [3]. On average, plastics make up 8–12% of the overall municipal waste stream, although this proportion varies from country to country depending on variables, such as lifestyle, quality of life and income level [4]. This figure is estimated to be around 16% in Australia, with an annual plastic waste production of 2.24 million tons in 2008 [5]. In 2011, global PET bottle consumption was 232 billion litres (61.4 billion gallons), with an expected growth to 513 billion litres by 2025 [6]. In 2017, a total of 41.5 million metric tons of PET waste was generated globally [7]. Moreover, the total weight of PET recycled bottles in the United States was 2.65 million tons, accounting for 31% of total PET waste [8]. One of the possible methods for recycling PET waste in the construction industry is its use in concrete in the form of granules, fibers or strips [9]. Granules are raw products produced by granulator machines, which save cost and effort by bypassing the need to convert them into strips or fibres [10]. When preparing specimens containing PET waste for research, previous studies have either chosen to incorporate PET into the concrete mixture as a reinforcement (as a volume fraction or percentage of weight of one or more concrete constituents) [11–13], or as a partial replacement of one or more concrete constituents (cement or aggregates) [14–16].

2. State of the art in using PET waste in concrete

2.1. PET waste as reinforcement

Previous researchers reported a decrease in workability following the addition of PET to the concrete mixture. However, a study by Ochi et al. [17] found that the workability of concrete remains unchanged for the mixture containing 0.5% PET fibre as volumetric percentage of concrete mix relative to control and started to decrease thereafter. Nibudey et al. [18] studied the addition of PET fibre to concrete as a percentage of the overall volume (0–3%) and noted that slump was inversely proportional to the PET content in the mixture. Similar findings were reported by other researchers for PET fibres [12,19].

Generally, the addition of PET as reinforcement increases the compressive strength of concrete, although this relationship was not always linear. Most researchers reported that, up to a certain amount of PET content in the mixture, compressive strength increased and subsequently declined with further addition of PET. Maqbool and Sood [20] added PET fibres with an aspect ratio of 35 to concrete as a 2–5% volume fraction of cement in the mixture, and observed a change in compressive strength relative to control over 7, 28 and 56 days. They reported an increase in compressive strength by an average of 3–4 MPa at each of the time intervals, showing optimum values at 3% fibre content. Further addition of PET fibres resulted in reduced compressive strength compared to conventional concrete. The reduction beyond this percentage was attributed to the weak bonding of fibres to concrete matrix. Some studies have experimented PET fibre addition in a variety of sizes, textures and shapes [21].

2.2. PET waste as substitution

Frigione M. [22] studied the effect of partially replacing fine aggregates in the concrete mixture with 5% by weight of waste un-washed PET particles, examining the effects on workability, compressive strength and split tensile strength. The particle size of sand and PET particles were in the range of 300 μm to 2.36 mm. The results indicated a slight reduction in compressive strength (not greater than 2%) and split tensile strength (in the range 1.6–2.4%), with no significant changes in workability for the specimens containing waste PET as fine aggregate replacement. Almeshal et al. [23] investigated the workability, unit weight, compressive strength of concrete containing shredded PET waste (0.075–4 mm) as a partial (10%−50%) replacement of sand by volume in the mixture. It was found that increasing PET content negatively affected the workability of the mixture, as evidenced by a slump value of 10 mm for the 50% PET concrete specimens, down from 90 mm for the control specimens. The reduction in workability was attributed to the lower density of the PET aggregate compared to conventional sand, a theory that was extended to cover the performance of the PET concrete specimens in terms of compressive strength. Compressive strength was negatively correlated with increasing PET content in the mixture, decreasing by 31% and 60% relative to control for the 40% and 50% PET concrete mixtures, respectively. Dawood et al. [24] investigated the physical and mechanical properties of concrete containing shredded PET waste as partial volumetric replacement of fine aggregates ranging within 5%− 20%. Although the size of fine aggregates and PET fibers were less than 4.75 mm, there was a substantial variation in their gradation (0–4.47 mm), with the majority of PET fibres ranging from 2.36 mm to 1.18 mm, whilst sand were uniformly distributed. They noted that the workability of concrete was inversely proportional to the increase of shredded PET waste in concrete specimens, with the specimen containing 20% PET exhibiting a 62.5% decrease in concrete workability relative to control which was attributed to the larger surface area of the shredded PET waste particles compared to the sand particles. They also found that the compressive strength increased when the PET replacement percentage ranges from 0% to 15% with the highest increase of 7.5% in compressive strength for the concrete containing 12% PET relative to control and started to decrease thereafter.

3. Research significance

While the use of PET waste as a partial replacement of concrete constituents (fine and coarse aggregates) has previously been investigated, the results have been variable for varying shape and dimensions of PET waste, with fibres being the most commonly used whereas the subject of PET granules has not yet received significant attention. As a result, it is crucial to match the parameters such as particle size distributions of PET waste close to the replacement ingredient such as fine or coarse aggregates in an attempt to get a closer replacement characteristic. This study bridged these research gaps by using PET waste in the shape of granules, which have a texture and dimensions close to that of fine aggregate than fibre and shredded form. Furthermore, the particle size distribution of PET granules was generated to be relatively comparable to that of river sand so as to provide a comparison base between conventional concrete and concrete with PET content. The flexural performance and CMOD together with microstructure of concrete containing PET granules have not been evaluated in the past which will be beneficial for the detailed analysis of flexural performance.

4. Experimental program

4.1. Materials

Ordinary Portland Cement (general purpose) was used for the preparation of all of the concrete mixtures. The coarse aggregate component was comprised of two nominal sizes, 7 mm and 10 mm. The PET granules were produced by using granulator machine comprising of rotary blades and water. The PET granules had a sub-rounded shape and relatively smooth surface. The grain size of sand and PET granules used for this study were smaller than 4.75 mm as shown in Fig. 1. Particle size distribution (PSD) for sand, PET granules and grading limits of AS 2758.1 [25] are plotted as shown in Fig. 1(c). The PSD of PET granules is generally different compared to river sand. Therefore, the partial replacement of fine aggregates with PET granules needed to be justified to fulfil the grading requirements of fine aggregates according to AS 2758.1 [25]. Thus, the analysis of PSD of sand was performed in order to produce the similar PSD with PET granules, which in turn created the similar conditions and a basis for comparison by mitigating the impact of varied grading on the properties of concrete.

4.2. Concrete mix design

Table 1, presents the results of the physical properties of the coarse, fine aggregates and PET granule in accordance with AS 2758.1 [25]. The volumetric design approach was used due to the difference in specific gravity between natural aggregate (sand) and PET granules. PET granules partially replaced sand as a proportion of its volume by (10%, 30%, 50%). The concrete mix was designed for a target strength of 32 MPa at 28 days with water cement ratio of 0.45. For the concrete mix design, the ratio of cement, fine aggregate, coarse aggregate followed the formula 1:1.5:3. A total of four concrete batches were prepared including the control specimens without PET granules. The amount of water, coarse aggregates and cement were constant in all batches with the values of 200 (L),1334 (kg) and 445 (kg), per m^3 respectively. The quantities of fine aggregates for each batch is outlined in Table 2.

4.3. Sample preparation

Concrete mixing was carried out according to AS 1012.8.1 [26]. In order to increase the reliability, two specimens were fabricated for all four batch. As shown in Fig. 2(a) the cylindrical specimens with dimensions of 100 mm × 200 mm were used to evaluate density, compressive strength, indirect tensile strength, and modulus of elasticity of each concrete mix as described in the next sections. Concrete beams measuring 150 mm × 150 mm x 700 mm was fabricated for flexural strength test as per the standard AS 1012.11 [27], Fig. 2(b). The pre-notched beam specimens with dimensions of 150 mm × 150 mm x 700 mm were fabricated for CMOD test as per the standard BS-EN 14651 [28]. The concrete specimens were taken out of the moulds after 24 h according to AS 1012.8.1 [26]. The specimens were stored in the curing room with 50% relative humidity at a temperature of 20–27 Celsius for 28 days. The single notch with a depth of 25 mm and a width of 2 mm was made on the CMOD test specimens prior to the test by using wet saw according to the standard BS-EN 14651 [28]. As illustrated in Fig. 2(c), Speckle patterns were stamped at the mid-span of the beam samples, where the primary cracks are expected to occur in order to provide sufficient contrast and measurement accuracy by DIC technique described in the following section.

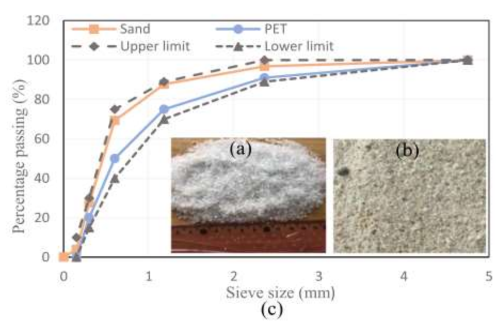

Fig. 1. (a) Recycled PET granules, (b) Sand, (c) Particle size distribution for sand, PET granules, AS 2758.1 [25].

Table 1
The characteristics of fine, coarse aggregates and PET granules.

Characteristics	Coarse aggregate	River sand	PET granules
Specific gravity	2.82	2.84	1.47
Bulk density (kg/l)	1.61	1.40	1.38
Water absorption	0.86	0.75	0.02
Density (g/cm^3)	2.17	1.65	1.34

Table 2
Mix design for 32 MPa concrete (per m^3).

Material	Fine aggregate (kg)	
	Sand	PET granule
Control	667	–
10% PET	610	47
30% PET	496	144
50% PET	382	241

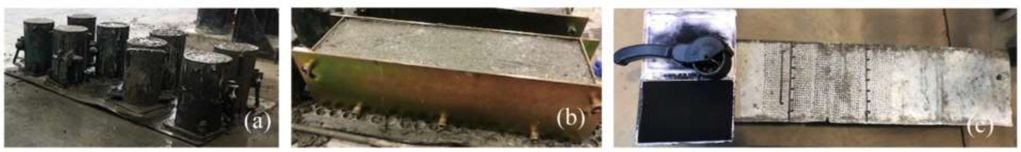

Fig. 2. Sample preparation.

4.4. Instrumentation and test procedure

The fresh property of the concrete mixtures was evaluated using the slump test as per the standard AS 1012.3.1 [29]. The hardened properties of the concrete specimens were investigated by performing the compressive strength, density, modulus of elasticity, indirect tensile strength and flexural strength according to AS 1012.9.1 [30], AS 1012.5 [31], AS 1012.17 [32], AS 1012.10 [33] and AS 1012.11 [27], respectively. The Crack Mouth Opening Displacement test (CMOD) was conducted according to the standard BS-EN 14651 [28] with using three-point loading system as illustrated in Fig. 3(a). The machine was adjusted to a constant loading rate of 0.5 mm/min increment in CMOD. The Digital Image Correlation (DIC) technique was used to measure the CMOD of the specimens. DIC is a contactless full-field measurement that enables to determine the displacement and strain field of the specimen under test [34]. One of the most significant advantages of DIC over the conventional techniques is its ability to generate a comprehensive map of displacement and strain instead of a single point measurement over the whole fracture. The DIC system consists of a high-resolution camera, a lighting source, and a software for image processing as shown in Fig. 3(b). The load deflection curve was produced using data obtained from the DIC system to analyse the toughness and ductility of the concrete specimens. Toughness, also referred as energy absorption of each specimen is defined as the area under load-deflection curve and ductility index of each specimen was calculated by

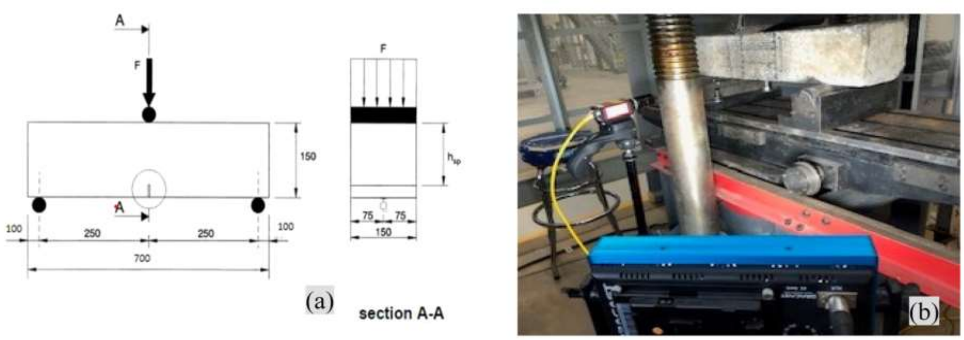

Fig. 3. (a) CMOD test schematic (BS-EN 14651–2005 [28]), (b) example of DIC set up.

dividing the ultimate deflection by first yield deflection [35]. The residual flexural tensile strength (f_{rj}) is calculated by Eq. (1). Scanning electron microscopic (SEM) analysis was conducted to evaluate the microstructure of the specimens in terms of porosity and homogeneity of the specimens. The microscopic examination of the concrete samples was carried out on small thin sections (30 mm depth).

$$f_{rj} = 3Fl / 2bh_{sp}^{2} \quad (1)$$

Where F = load measured during the test (N), l = length of specimen (mm), b = width of the specimen (mm), h_{sp} = distance between the tip of the notch and the top of the beam (mm).

5. Results and discussions

5.1. Workability

A slump value of 98 mm was obtained for the control concrete mix. The concrete mix with 10% PET replacement ratio yielded a slump similar to that of the control concrete mix. As the content of PET granules increased from 30% and 50%, the slump value reduced to 94 mm and 90 mm, respectively. However, although the workability of concrete decreased gradually by the increment of PET granules, replacement percentage as fine aggregates, the reduction was insignificant relative to the reference concrete contrary to the previous studies [36–38], who reported considerable reduction in concrete even with small percentage replacement. This improvement could be attributed to the low w/c ratio, sub-rounded shape of PET granules as well as comparatively smooth surface of PET granules, which aids fine aggregate dispersion in the mixture.

5.2. Density

The test results of density of the specimens are presented in Fig. 4. It can be seen that the density of concrete decreased with the increment of PET content in concrete. The density for concrete with 10% and 50% replacement ratios were found to be 2340 kg/m^3 and 2125 kg/m^3, respectively, which were relatively close to that of the control sample (2417 kg/m^3). Yet, this value for the concrete with 50% PET granules content was found to be 1845 kg/m^3, demonstrating significant drop of 21.16% relative to that of the control sample. These findings are consistent and supported by other studies [23,36,38,39].

5.3. Compressive strength

Fig. 4, depicts the results of the compressive strength test. It is evident that compressive strength increased by 9.07% for the concrete specimen with 10% PET granule replacement relative to the control sample. The average compressive strength of specimens with 30% replacement ratio is close to that of the reference concrete. However, it was noticed that there was a significant reduction of 26.3% for the concrete with 50% PET granules replacement ratio relative to that of the reference concrete. The positive trend of compressive strength value for the concretes with 10% volumetric replacement ratio, and also virtually identical compressive strength value for 30% volumetric replacement ratio compared to the control mix is mainly attributable to the shape and flexibility of PET granule particles as well as the uniform distribution in the mixture (as it is illustrated in Section 5.8). However, the significant decrease in compressive strength for the concrete with 50% replacement ratio is attributed to the significant reduction in its bulk density compared to the reference concrete [40]. Moreover, the improper distribution was caused by the higher amount of PET granules in the mixture, leading to higher porosity and weak bonding between cement paste and PET granules which adversely impacted the compressive strength of concrete [40,41]. While some studies agree on improving compressive strength up to certain PET replacement percentage [24,38], other studies [15,22,23,42] noted a decrease in compressive strength for the concrete with PET content. The discrepancies in the findings are due to the different grading, shape, and size of PET particles, as well as the w/c ratio used in the reported research in the past. The failure behaviour of concrete specimens is shown in Fig. 5. The failure modes of the specimens with

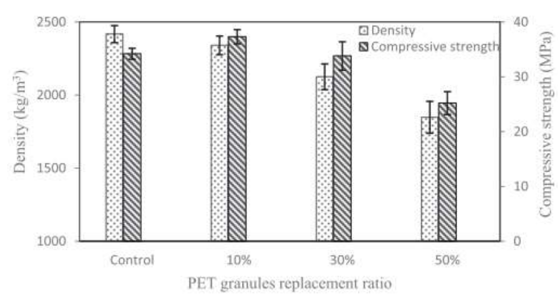

Fig. 4. Density and compressive strength results.

PET granules is influenced by the shape and flexible nature of PET granules in such a way that when applied load reaches the ultimate load, the internal stresses are converted from shear stress to tensile stress. Furthermore, concrete specimens containing PET granules appear to retain their shape even after reaching peak load indicating lower chance to collapse while the control sample is brittle and exhibit shear failure which could be due to the flexibility of PET granules compared to sand.

5.4. Modulus of elasticity

The modulus of elasticity is calculated from the stress- strain curve shown in Fig. 6(a). The test results are plotted against the relationship between the modulus of elasticity and PET granules replacement ratio in Fig. 6(b). The gradual reduction of modulus of elasticity was observed by increasing PET content in the concrete mix. Nevertheless, the inclusion of PET granules at replacement level of 10% had almost no impact on the modulus of elasticity with only 1.10% reduction relative to that of the reference sample whereas the difference was more significant for the specimens containing 30% and 50% PET granules replacement ratios, with the reductions of 17.02% and 22.48% respectively relative to that of the control sample. While other studies [18,22,38] also reported the decrement of elastic modulus with increasing PET replacement ratio, the reduction of elastic modulus in this study is less apparent especially for the concrete with 10% PET granules content. Since the density of the principal constituents of concrete is one of the important factors that impacts the modulus elasticity of concrete [43], the decline in modulus of elasticity could be attributed to the decrease of density with addition of PET content in the concrete mix especially for the specimens with 30% and 50% PET granules content.

5.5. Indirect tensile strength

Fig. 7, depicts the results of indirect tensile strength test. The tensile strength increased by 3.4% for the specimen with 10% substitution rate relative to that of the conventional concrete, and the performance began to deteriorate with further increase of PET granules in the mixture, where the specimen with 30% substitution rate exhibited a slight reduction of 2.8% compared to that of the reference concrete. However, the performance deterioration was more pronounced when the proportion of PET granules increased beyond 30%, as evidenced by a 15.2% reduction for the specimen with 50% replacement percentage compared to the control specimen. Further explanation for these observations is that the flexibility of PET granules, as well as their uniform distribution in the mixture at low replacement ratio, provided enhanced adhesion between aggregates and cement matrix. Nevertheless, the decrease in indirect tensile strength beyond 10% replacement ratio is due to the fact that PET granules tend to detach from the cement around them after attaining ultimate strength as a result of a larger proportion of PET granules. This behaviour is validated by SEM images in Section 5.8. Despite achieving higher tensile strength than other studies [15,23,42], this conclusion is consistent with that of Azhdarpour et al. [39]. The discrepancies between the findings of the previous studies could be due to the fact that the variable gradations, shapes and sizes and surface finishing of PET particles influenced the bonding strength between the concrete components and PET particles.

5.6. Flexural strength

The flexural strength test results are shown in the Fig. 7. The test results revealed that the specimen with 10% PET achieved the optimum flexural strength of 4.3 MPa, increasing by 7.9% over the reference concrete. Despite the fact that flexural performance declined as the amount of PET granules in the mixture increased, the specimen with 30% replacement ratio still had a positive impact on flexural strength, demonstrating 2.2% increase over the control sample. In contrast, the flexural strength of specimen with 50% replacement ratio declined by 7.9% relative to that of the control sample. The improvement in flexural strength of the specimens with

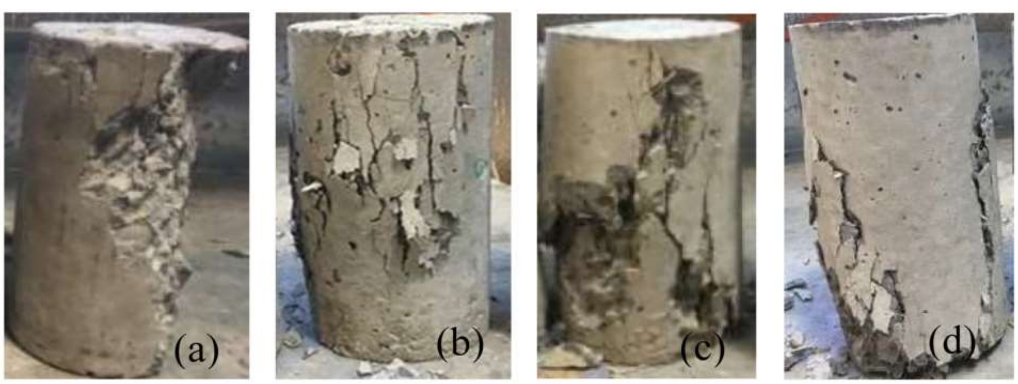

Fig. 5. Failure pattern of compressive strength test specimens: (a) control sample (b) 10% PET (c) 30% PET (d) 50% PET.

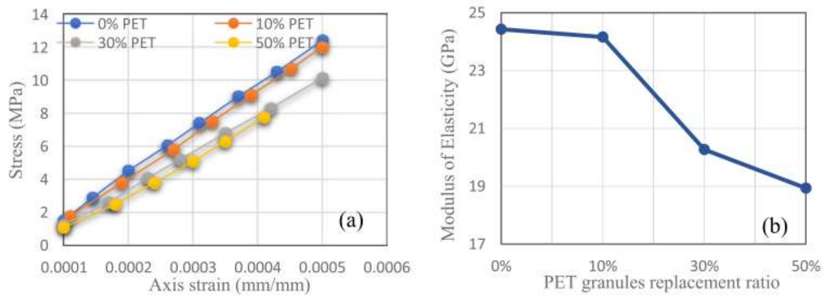

Fig. 6. (a) Stress-strain relationship, (b) MOE values.

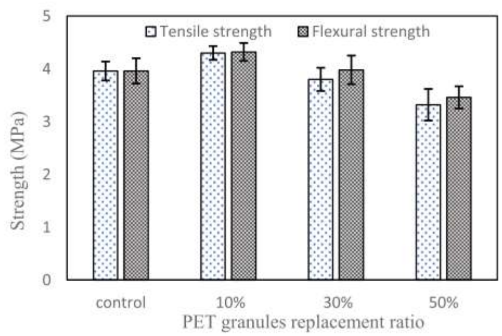

Fig. 7. Tensile and flexural test results.

10% and 30% replacement rates relative to the control sample might be explained by the fact that PET granules are more flexible than fine aggregate and also elastic modulus reduced as the proportion of PET granules in the mixture increases, indicating that the specimens containing PET granules are more ductile and deformable than conventional concrete. The perceptible decreasing trend in flexural strength for the specimen with 50% substitution rate is attributed to the higher PET granules content in the mix, which led to bundling of PET granules in the mixture due to their low density compared to river sand, resulting in a weak zone in the concrete. This conclusion is in line with those of Rahmani et al. [38] and Azhdarpour et al. [39] who reported higher flexural strength than other studies [15,23,42]. The discrepancies between results reported before could be related to the percentage of PET substitution in relation to the total weight of concrete along with varying gradations, shapes, and sizes of PET particles. Fig. 8, depicts the failure pattern of the concrete beams tested for flexure. It is evident that conventional concrete split in half after reaching ultimate strength due to its brittle nature. The specimens containing PET granules appeared to be more ductile, with only minor cracks in the specimens with 10% and 30% replacement ratios, and a slightly wider crack in the specimen with 50% replacement ratio, albeit it still retained its shape.

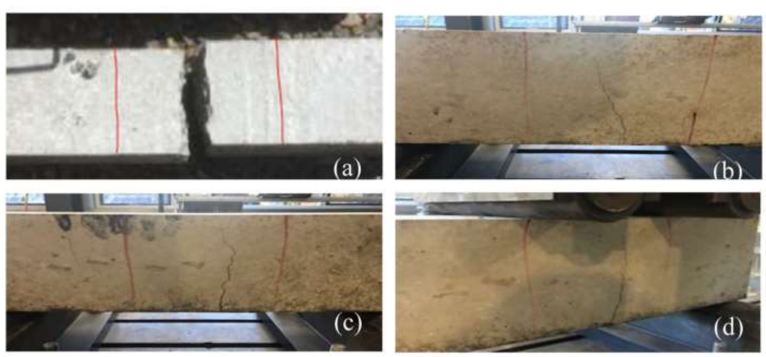

Fig. 8. Failure pattern of flexural strength test specimens: (a) control sample (b) 10% PET (c) 30% PET (d) 50% PET.

5.7. Crack mouth opening displacement (CMOD)

Fig. 9(a), depicts the load-CMOD relationship of the concrete specimens. It is apparent that the specimen fabricated with 10% PET granules substitution demonstrated outstanding post crack performance with slightly higher load bearing capacity relative to that of the reference concrete. Nevertheless, the increment of the PET granules content in the concrete mixtures corresponds to the decrement of the ultimate load bearing capacity of the specimens where the ultimate load value of specimens containing 30% and 50% PET granules decreased by 7.2% and 16.2% compared to the reference concrete. However, it is noteworthy that following peak load, the post crack performance of the specimens with larger PET granules contents (30%, 50%) was still higher than reference concrete, with CMOD of 2 mm and 1.5 mm, respectively, compared to the control sample with the value of 0.5 mm. As shown in Fig. 9(b), the test results for residual flexural tensile strength - CMOD shows the similar trend to that of the load-CMOD. The specimen with 10% PET contents demonstrated optimal performance due to its highest value compared to the control sample. It should be noted that following CMOD of 0.5 mm, the specimens containing 30% and 50% PET granules presented marginally higher residual strength compared to the reference concrete. This improvement could be explained by the flexible nature of PET granule particles in the mixture, which prevents concrete specimens from collapsing as rapidly as the conventional concrete specimen.

Fig. 9(d), depicts the results of toughness and ductility calculated from load- deflection curves Fig. 9(c). The results showed that the specimens with 10% and 30% PET granules content had toughness values of 6.3 and 4.9 kN.mm, respectively, which were higher than the control sample with the value of 2.37 kN.mm. However, this value for the specimen with 50% PET granules dropped by 1.13% compared to the control sample. The higher flexural strength of the specimen with 10% PET granules content may explain its improvement in toughness performance over the specimens with 30% and 50% PET granules content. Additionally, the calculated ductility of the specimens with PET granules content was approximately 2–4 times greater than that of the control sample. Notably, the specimen with 10% PET granules had the highest ductility compared to the specimens with 30% and 50% PET granules content. The reduction of ductility for the specimens containing more than 10% PET granules could be attributed to the fact that incorporating higher amount of PET granules to the mixture resulted in the uneven distribution of the PET granules due to its lower density compared to sand.

The crack path of the specimens detected automatically relying on the strain map generated by means of the DIC system as shown in Fig. 10. For all the beam specimens, the cracks originated at the tip of the prefabricated notch and propagated to the top. The control sample (Fig. 10a) reached its highest strain soon after first crack and continued rapidly to the top of the beam, whereas the strain at the specimens containing PET granules subsided after achieving their maximum strain and gradually approached to the top of the beam specimens. Nonetheless, the specimen with 50% PET granules content (Fig. 10d) achieved its maximum strain sooner than the specimens with 10% and 30% PET granules content (Fig. 10 (b) and (c), respectively), which might be explained by the fact that the increased PET granules content in the concrete resulted in weaker adhesion between cement matrix and PET granules.

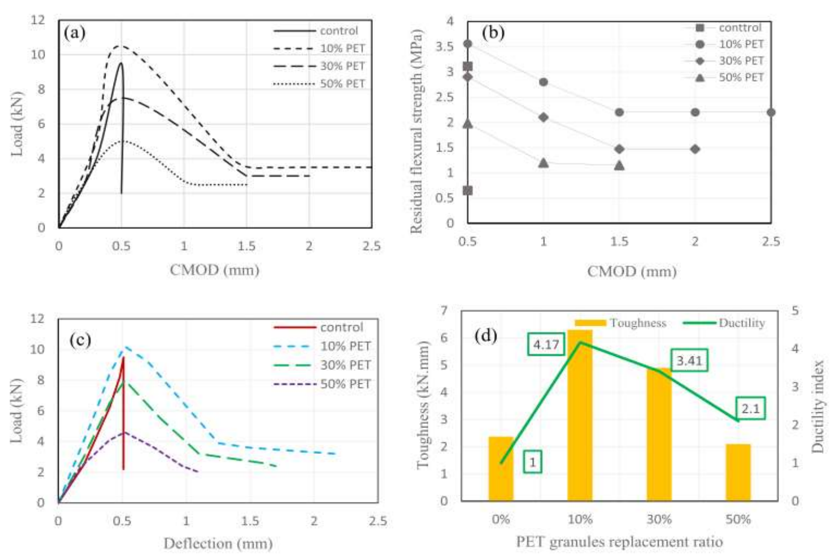

Fig. 9. Load-CMOD curves, (b) Residual flexural tensile strength results, (c) Load-deflection curves, (d) Toughness and ductility values.

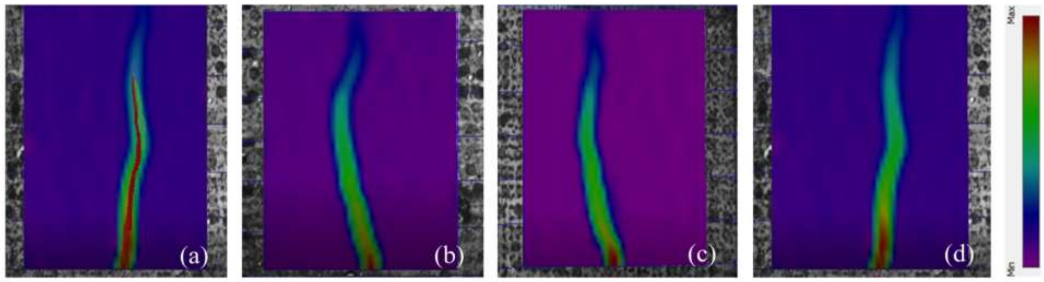

Fig. 10. Evolution of strain map for the crack path detection of the specimens: (a) control sample, (b) 10% PET, (c) 30% PET, (d) 50% PET.

5.8. Scanning electron microscopic (SEM) analysis

SEM images of a sample with a 10% substitution shown in Fig. 11 (b), demonstrated decent matrix and aggregate adhesion as well as a homogeneous composition due to the uniform distribution of PET granules in concrete mixture which is comparable with the reference sample in Fig. 11 (a). This phenomenon can explain the improvement in mechanical characteristics of concrete with 10% substitution rate as PET granules due to its their flexibility tend to redistribute and transfer applied stress to the natural aggregates, which acts as reinforcement and delays the failure. As shown in Fig. 11 (e) and (c), the specimen with 50% substitution rate has a larger interfacial transition zone (ITZ) between cement matrix and PET granules relative to that of the specimen with 30% substitution rate. Consequently, the adhesion between cement matrix and PET granules weakens due to the fact that higher quantity of PET granules in the mixture resulted in increasing voids and large gap between cement matrix and plastic aggregates [40,41]. The structure of concrete incorporated with PET granules appears to be more cavernous with larger air bubbles when the substituted volume exceeded 30% as shown in Fig. 11 (d) and (f). This difference in morphology can explain the observed reduction in bulk density and mechanical properties of concrete as the amount of PET granules in the concrete mixture increases.

5.9. Normalised properties of concrete with PET content

The test data from nine published papers as well as this study is collated in order to investigate the normalised mechanical properties (compressive strength, tensile strength and flexural strength of concrete with PET content against corresponding plain

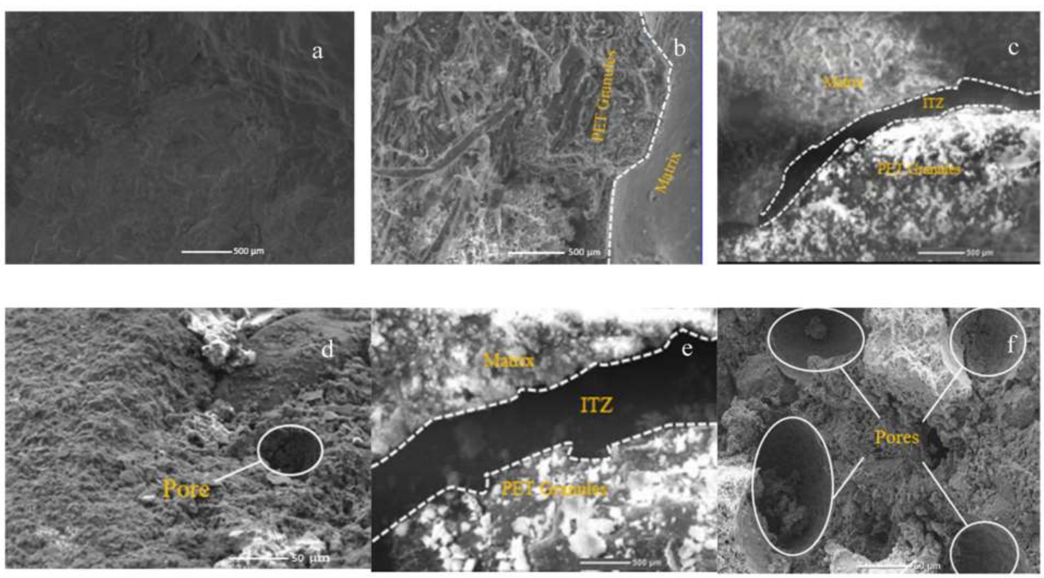

Fig. 11. SEM images (a) Control sample, (b) 10% PET, (c, d) 30% PET, (e, f) 50% PET.

concrete). The details of the parameters evaluated in previous studies are summarised in Table 3.

The variation of normalised parameters for different studies are presented in Fig. 12. As shown in Fig. 12 (a) and (b), most data points are well below the $f_{c(PET)} = f_{c(plain)}$ line, suggesting that compressive strength and tensile strength reduce as PET percentage in the mixture increases. However, the normalised compressive strength findings reported in this study are relatively greater than those from the reported literature, particularly for the mixture with 10% and 30% replacement ratios. This improvement could be attributed to the granular structure of PET waste and the homogeneous dispersion of PET granules, especially at 10% replacement ratio as demonstrated in Section 5.8. As illustrated in Fig. 12 (c), Although most data points of normalised flexural strength lie below the $f_{r(PET)} = f_{r(plain)}$ line, the reduction is less pronounced than that of normalised compressive and tensile strength. Yet, the normalised flexural strength reported in this study, particularly for the concrete with 10% and 30% PET granules content, indicated optimal behaviour when compared to prior studies. This phenomenon might be explained by the granule shape of PET waste, the comparable gradation of PET granules to sand, the resistance provided by PET granule for crack propagation and their even distribution in the mixture.

5.10. *Comparison of tensile strength, flexural strength and modulus of elasticity results with AS3600 [47] and ACI [48,49] design methods*

As illustrated in Fig. 13, the theoretical values calculated from Australian and American design guidelines for mechanical properties were compared with experimental results so as to determine the applicability of existing equations in predicting the strength parameters for the concrete incorporating PET granules. The indirect tensile strength and flexural strength were calculated by using compressive strength of each concrete mixture, whereas the modulus of elasticity was calculated by using density and in situ compressive strength of each concrete mix. The value of the in situ compressive strength was considered 90% of the experimental compressive strength in both American and Australian standards.

The solid and dashed lines extrapolated from the findings obtained from aforementioned standards, whereas the scattered dots represent the experimental results. The correlation coefficient (R^2) was used to verify the relationship between the experimental findings and the predicted design methods. The correlation coefficient ranges from − 1 and 1, with 1 denoting the strong linear relationship, 0 showing no linear relationship and − 1 indicating negative correlation [50]. As shown in Fig. 13(a), the experimental tensile strength values were in good agreement with the values predicted from Australian and American design specifications with the correlation coefficients of 0.999 and 0.996, respectively. Fig. 13 (b) and (c) revealed that the experimental results for flexural performance and elastic modulus of the concrete incorporating PET granules at all substitution levels demonstrated comparatively similar behaviour to that of the AS3600 [47] and ACI 318 [48], where the correlation coefficients for flexural strength were 0.995 and 0.993, respectively, and the correlation coefficient for elastic modulus was 0.996, as both standards use the same equation for estimating elastic modulus.

5.11. *Waste reduction potential*

As shown in Table 4, a significant amount of PET waste could be used in the fabrication of Grade 32 concrete even with a partial replacement ratio as fine aggregate. Application of this approach in small-scale projects has the potential to efficiently exploit a city's daily waste plastic bottle production. Furthermore, implementation of this strategy in larger projects, such as dams and bridges, may potentially use PET waste from multiple metropolitan areas for an extended period of time.

1 PET bottle (500 ml) = 10 (g) PET granules [51].

1(kg) PET granules = 100 PET bottles (500 ml).

6. Conclusions

This study presents the impact of PET granules on the fresh, hardened and microstructure properties of Grade 32 concrete. The PET granules were used as partial replacement (10%,30%, and 50%) for fine aggregates on a volumetric basis. PSD of PET granules was matched with that of the replaced river sand in order to minimise the influence of size discrepancy. Based on the findings of this study, below conclusions are drawn:

- The inclusion of PET granules up to 10% had no impact on the workability of concrete mix, beyond which the workability of concrete was inversely proportional to the increase of PET granules in the concrete mix, despite the fact that the reduction was insignificant. Similarly, the density was negatively correlated with increasing PET granules in the concrete mix due to the lighter weight of the PET compared to sand.
- Concrete with 10% and 30% PET granule content fulfilled the target compressive strength for Grade 32 concrete. Therefore, their potential use in fabrication of reinforced concrete beams, floor slabs, driveways and footpaths could be justified as per AS 1379 [52]. Additionally, the drop in compressive strength for concrete with 30% PET content was insignificant. In contrast, concrete with 50% PET granule content failed to achieve the target strength. However, it yielded a density of 1845 kg/m^3 and compressive strength of 25.7 MPa which fulfilled the requirements of structural light weight concrete according to AS 2758.1 [25].
- The modulus of elasticity decreased with increasing of PET content in the concrete though the difference was less apparent for the concrete specimen with 10% replacement percentage. In contrast to the elastic modulus, the indirect tensile strength tended to peak with increasing PET granules content in the mixture up to 10%, after which the performance tended to decline.

Table 3
Description of test data used in the prior studies.

Compressive strength (mm)	Tensile strength (mm)	Flexural strength (mm)	PET Waste particles size	PET waste shape	Volumetric ratio	References
100 × 200 (cylinder)	100 × 200 (cylinder)	100 × 100×500	5 mm	Shredded	20%,50%,75%	Juki et al. [44]
100 (cube)	100 × 200 (cylinder)	-	5 mm	Particle	25%,50%,75%	Juki et al. [45]
100 × 300 (cylinder)	150 × 300 (cylinder)	130 × 150×450	0.05–2 mm 2–4.9 mm	Shredded	5%,10%,15%,20%,25%,30%	Azhdarpour et al. [39]
150 (cube)	150 × 300 (cylinder)	-	300 μm – 2.36 mm	Particle	10%	Frigione [22]
150 × 300 (cylinder)	150 × 300 (cylinder)	ASTM C78	206 mm, 11.4 mm	Particle	10%, 20%	Albano et al. [11]
50 × 100 (cylinder)	-	40 × 40×160	10 mm	Shredded	3%, 10%, 20, 50%	Hannawi et al. [46]
150 (cube)	150 × 300 (cylinder)	100 × 100×50	Length 25 mm Breath 1 mm, 2 mm	Fibre	0.5%,1%,1.5%, 2%,2.5%,3%	Nibudey et al. [18]
150 × 300 (cylinder)	150 × 300 (cylinder)	100 × 100×500	Up to 7 mm	Fibre	5%, 10%, 15%	Rahmani et al. [38]
150 (cube)	100 × 150 (cylinder)	150 × 150×600	4–11.2 mm	Pellet	3%, 10%, 15%	Saikia and De Brita [15]

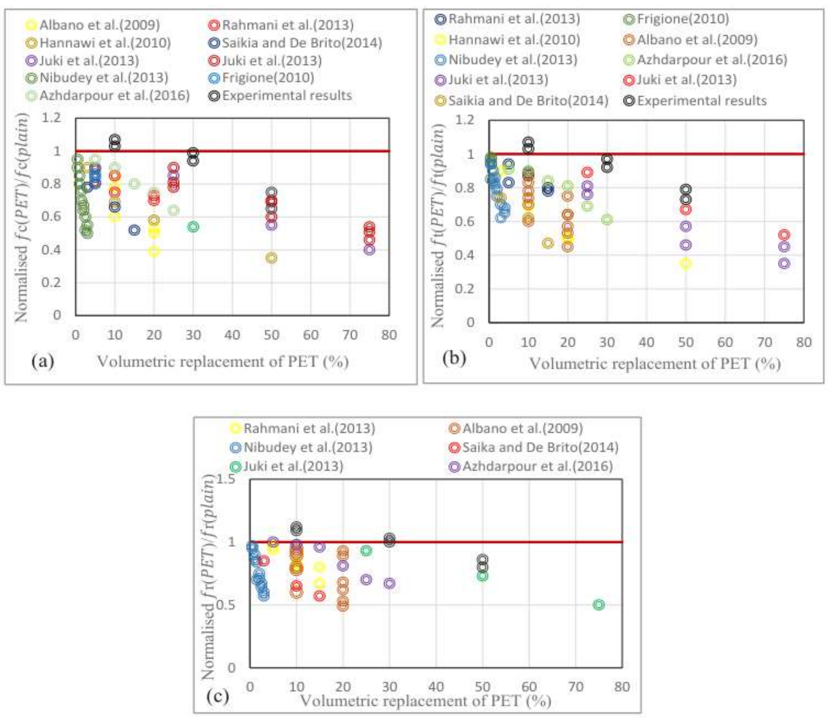

Fig. 12. Variation of the normalised properties with PET volume (a) compressive strength (f_c), (b) tensile strength (f_t), (c) flexural strength (f_r).

- The presence of PET granules up to 30% replacement ratio effectively contributed to the flexural strength and toughness behaviour with highest contribution obtained for the concrete specimen with 10% PET granules content. However, both characteristics decreased with further increase of PET granules in the concrete. The residual flexural tensile behaviour of the concrete improved

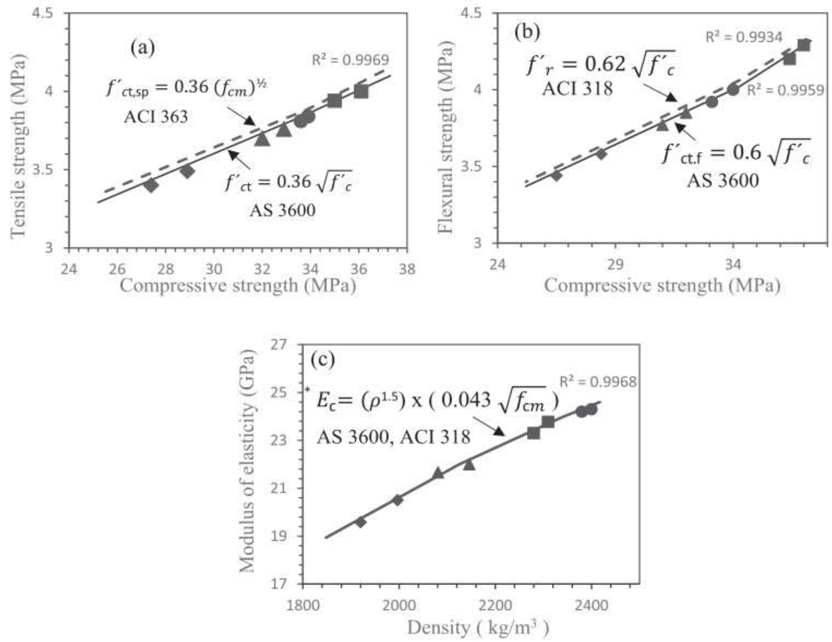

Fig. 13. Correlation between the properties and available equations in AS3600 [47] and ACI [48,49] $f_c^{'}$= characteristic compressive (cylinder) strength of concrete at 28 days (MPa). $f_{ct}^{'}$,$f_{ct,sp}^{'}$ = characteristic indirect tensile strength of concrete (MPa). $f_{ct.f}^{'}$,$f_r^{'}$ = characteristic flexural strength of concrete (MPa). ρ = density of concrete (kg/m^3). f_{cm}= mean value of the in situ compressive strength of concrete (MPa). E_c= Modulus of elasticity of concrete at 28 days (GPa). * both standards have the same equation for elastic modulus.

Table 4
PET waste reduction (per m^3).

PET granules volume replacement (%)	Weight of PET granules (kg)	Number of PET bottle (500 ml)
10	57	5700
30	171	17,100
50	285	28,500

with the inclusion of 10% PET granules to the mixture. Post peak performance of the specimens with 30% and 50% PET granules content improved slightly compared to the control sample due to the flexibility and bridging effect of the PET granules.

- The measurement of CMOD obtained by DIC technique revealed significant post-crack performance of concrete with 10% PET granules content, whereas the control sample failed abruptly after peak load. Moreover, the concrete specimens with 30% and 50% PET granules content demonstrated ductile post peak behaviour despite having lower ultimate load bearing capacity than control sample. Therefore, their prospective usage where the concrete is subjected to the dynamic and recurring load, such as pavements may be considered.
- SEM images showed uniform distribution of PET granules within the concrete mix with up to 10% substitution, whereas increasing substitution level to 30% and 50% resulted in uneven distribution and larger boundaries between PET granules and cement matrix due to the higher porosity. Additionally, when compared to the available literature, the test findings of this study on compressive strength, tensile strength, and flexural strength demonstrated considerably higher performance, especially for the concrete with 10% PET granules content.
- The tensile strength, flexural strength and elastic modulus of concrete with PET granules were found to be in close agreement with the results predicted by AS3600 [47] and ACI [48,49] indicating its similarity with the normal concrete and its broader utilisation. Moreover, the incorporation of PET granules in Grade 32 concrete revealed a considerable reduction in environmental pollution.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

influence the work reported in this paper.

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ANNEXURE TO PAPER 1

Annexure to the paper 1, **"**Investigation on the properties of concrete with recycled polyethylene terephthalate (PET) granules as fine aggregate replacement**"**, in Case Studies in Construction Materials.

1. Section 4.1, *"The PET granules were produced by using granulator machine comprising of rotary blades and water."*:
   The PET granules were produced from PET bottles using granulator machine comprising of rotary blades and water.

2. Section 4.2, *"The volumetric design approach was used due to the difference in specific gravity between natural aggregate (sand) and PET granules."*:
   Previous studies (de Brito & Agrela, 2018; Gu & Ozbakkaloglu, 2016; Saikia & De Brito, 2012; Sharma & Bansal, 2016) on the use of plastic aggregates with sizes ranging from 0 to 20 mm in concrete reported a decrease in concrete properties with increasing plastic aggregates more than 5% volumetric replacement of natural aggregate in concrete due to the lower elastic modulus and density of plastic aggregates compared to natural aggregates. Hence, in this study, PET granules were used as a partial replacement for sand.

3. Section 4.2, *"Concrete mix design"*:
   At first, coarse and fine aggregates were mixed together. The PET granules were then added to the mix in four stages (every 15 seconds) for the PET concrete mixes. Subsequently, the cement was added to the mix, followed by water. This mixing technique was followed for each batch to ensure uniform dispersion of PET granules in the concrete mix (Adnan & Dawood, 2021; Ahmad et al., 2021). Subsequently, the SEM analysis was performed on the small thin sections (30 mm depth) cut from cylindrical samples after 28 days curing to verify homogeneous dispersion of PET granules in concrete mixtures.

4. Section 4.4, *"The DIC system consists of a high-resolution camera, a lighting source, and a software for image processing as shown in Figure 14(b)."*:

The camera with the resolution of 5472 x 3648 pixels was mounted on the tripod stand in front of the concrete beams to cover across the mid-span of the beams. The LED camera light was pointed to the measuring surface of the specimens to ensure that the specimens are appropriately illuminated during the tests.

5. Section 4.4, Figure 3(b) with indication of the DIC components:

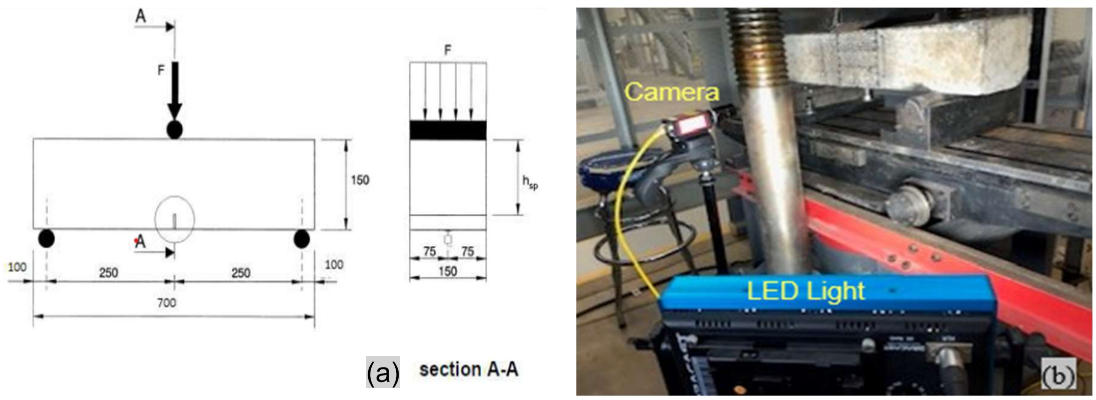

Fig 3. (a) CMOD test schematic (BS-EN 14651-2005 [28]), (b) example of DIC set

6. Section 4.4, *"Scanning electron microscopic (SEM) analysis was conducted to evaluate the microstructure of the specimens in terms of porosity and homogeneity of the specimens. The microscopic examination of the concrete samples was carried out on small thin sections (30 mm depth) which was taken from the specimens after elastic modulus test."*:
   Scanning electron microscopic (SEM) analysis was conducted using a VEGA3 – TESCAN SEM with 10 kV accelerating voltage to evaluate the microstructure of the specimens in terms of the porosity, presence of voids, and the homogeneity of the specimens. The microscopic examination of the concrete samples was carried out on small thin sections (30 mm depth). These samples were obtained by means of a diamond cutter under running water without applying mechanical force from cylindrical sample elastic modulus test. Samples were dried before being placed in the sample chamber. Software analysis was conducted on the images of the

microstructure to form an evaluation of the specimen in terms of the aforementioned factors.

7. Section 5.11, *“Waste reduction potential”*:
   It is noteworthy that concrete incorporating PET aggregate is a sustainable material for circular solutions as it could be recycled and reused in road pavements at the end of its life cycle (Lumauod, 2019; Santos et al., 2021). Concrete containing PET granule aggregate may be repurposed as recycled concrete aggregates to construct sustainable roads. According to the Australian Council of Recycling (ACOR), recycled concrete aggregate can be used in road infrastructure such as footpaths, roads, pavements and kerbs as a partial replacement for natural aggregate up to 30% replacement ratio (Australian council of Recycling, 2023). Since plastic is unable to absorb water, it can effectively resist water, weathering, and abrasion, lowering maintenance and upkeep expenses (Lumauod, 2019).

3.2. Links and implications

The test findings revealed that concrete mixtures with 10% and 30% PET granule content fulfilled the target compressive strength for M32 concrete. Although concrete with 50% PET granule content failed to achieve the target strength, it fulfilled the requirements of structural light weight concrete according to the Australian standard. Furthermore, the crack mouth opening displacement and flexural test results showed improved post-crack performance of the concrete containing PET granules, particularly for the specimen with 10% PET content. The experimental results of mechanical properties agreed well with the predictions of AS3600 (AS3600, 2018) and ACI (ACI Code, 2022). In addition, the PET waste reduction analysis revealed that Incorporating PET granules in concrete even at 10% replacement level contributes significantly to the reduction in environment pollution. The substantial findings of this study encouraged additional research into the structural behaviour of concrete with PET granule aggregate. Therefore, the impact of PET granules on the flexural behaviour of RC beams, and bond behaviour of concrete with steel reinforcement was evaluated in **Chapter 4**. The mechanical properties obtained from this study will be used as input parameters for the FEM in **Chapter 4**.

CHAPTER 4: PAPER 2 – DEVELOPMENT OF SUSTAINABLE CONCRETE USING RECYCLED POLYETHYLENE TEREPHTHALATE (PET) GRANULES AS FINE AGGREGATE

4.1. Introduction

Chapter 3 provided a comprehensive knowledge of the overall mechanical characteristics of concrete with PET granule aggregate. However, it is important to understand the impact of PET granule aggregate on structural applications. This paper provided in-depth research on the structural performance of concrete with PET granule content and addressed the **objective 2** of the study. The PET granules were used as a partial replacement for fine aggregate (0%, 10%, 30%, and 50% by volume). The bond strength between concrete containing PET granules and steel bar was investigated together with pore structure analysis of the concrete mixtures. The flexural and cracking performance of the large-scale RC beams were examined using four point bending test. The applicability of ACI 318 (ACI Code, 2022) and AS3600 (AS3600, 2018) in predicting the flexural and cracking moment of the RC beams with PET content was evaluated. In addition, finite element method was used to numerically simulate the flexural performance of the RC beams and its variation with different PET content.

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Development of sustainable concrete using recycled polyethylene terephthalate (PET) granules as fine aggregate

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ABSTRACT

Solid waste management has become a significant environmental challenge globally. This study aims to examine the performance of sustainable concrete incorporating polyethylene terephthalate (PET) granules as partial (0%, 10%, 30%, and 50%) volumetric replacement of sand. The mechanical properties including compressive strength, tensile strength and elastic modulus were examined. The flexural and cracking performance of the reinforced concrete (RC) beams, as well as bond behaviour of concrete mixes with steel reinforcement were investigated. Incorporating 10% PET granules demonstrated positive impact on the mechanical properties, flexural strength and cracking behaviour of RC beam, as well as bond strength. A theoretical model was proposed for predicting bond strength of concrete containing PET granules and the results corresponded well with both experimental and previous research findings. The American and Australian standards conservatively predicted cracking and flexural moments of the RC beams. Finite element modelling was conducted on the RC beams and the results corresponded well with the experimental findings.

1. Introduction

Nowadays, disposal of waste materials has been one of the major concerns of communities across the world. The widespread production of plastic wastes as a result of modern lifestyles and technology advances is contributing significantly to the waste management crisis. The global plastic waste generation was around 7000 million metric tons in 2020 with an expected growth to 26,000 metric tons by 2050 (Ncube et al., 2021; Babafemi et al., 2018). In Australia, this quantity is estimated to be 2.24 million metric tons annually, accounting for 16% of municipal waste stream (Bajracharya et al., 2016). Polyethylene terephthalate (PET) as synthetic polymer is mostly used in plastic bottle owing to its low cost, lightweight, and ease of handling (Frigione, 2010). Australian households produce 1.2 million tons of plastic waste, with PET waste accounting for the vast majority (34.9%) of domestic plastic waste (Wurm et al., 2020). Vast proportion of PET bottles are typically discarded after use, and thus are regarded as one of the major contributors to land and water contamination (Nkomo et al., 2022). The waste PET bottles take 400 years to disintegrate in nature due to its poor biodegradability (Ilyas et al., 2022). The PET bottle consumption increased from 480 billion in 2016 to 583 billion in 2021 globally (Benavides et al., 2018).

Despite the progress that has been made over the years with respect to traditional recycling, only 7% of PET waste are being recycled and a large percentage ends up in landfill (Aslani et al., 2021). Likewise, the global concrete production has been increasing rapidly due to expanding urbanisation, with annual demand exceeding 12 billion tons (Mehta and Monteiro, 2014). Consequently, natural resources such as sand and gravel are depleting, causing scarcity of material and adverse environmental impact (Saikia and de Berita, 2014; Letelier et al., 2023). Substitution of concrete components with PET waste represents a potential means of reducing waste as an adjunct to traditional recycling methods as well as preserving natural resources (Batayneh et al., 2007). The size and shape of PET waste plays an important role in concrete characteristics (Saikia and de Berita, 2014) when used either as reinforcement (Ochi et al., 2007; Adnan and Dawood, 2020) or partial substitution of concrete components (cement, aggregate) (Frigione, 2010; Akçaözoğlu et al., 2010; Dawood et al., 2021). While previous research mainly evaluated mechanical characteristics of concrete incorporating PET waste, less attention has been given to the bond behaviour of PET

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concrete with steel reinforcement, and flexural behaviour of RC beams containing PET waste as fine aggregate replacement. Kim et al. (2010) examined flexural performance of the RC beams with volumetric addition of PET fibres to concrete (0.5%, 0.75%, and 1.0%). It was reported that ultimate flexural capacity of the specimens with 0.5%, 0.75%, and 1.0% PET fibre increased by 25%, 31%, and 32%, respectively, relative to specimens without PET fibre. Similarly, deflection ductility of beams containing PET fibres were about 7.56–10.34 times greater than that of the reference specimen. Further explanation for these findings was the ability of fibres to enhance tensile resistance and delay macro crack formation. Koo et al. (2014) reported that flexural capacity and deflection ductility index of RC beam with 0.5% PET fibre (by volume of cement) increased by 15% and 80%, respectively relative to reference RC beam. This behaviour was related to PET fibre's ability to transfer stress and control cracking in tensile area (bottom) of RC beam. Al-Hadithi and Abbas (2018) investigated shear capacity of RC beams in which PET fibres were added by volume (0.25–1.5%) of concrete. They found that shear strength increased as the PET addition varied between 0 and 1%, reaching the maximum increase of 8.4% for the beam containing 1% PET compared to reference beam and then started to decline. It was also observed that deflection ductility of RC beam increased with adding PET fibres in concrete mix which was attributed to the crack bridging behaviour of PET fibres. To date, there has been little research on bond strength of concrete incorporating PET waste with steel reinforcement. Assaad et al. (2022) added shredded PET waste (1–6 mm) as a 0–4.5% volume fraction of concrete in the mixture. They reported that bond strength slightly increased by 9% and 7% for the specimens with 1.5% and 3% PET waste relative to the control specimen, showing optimum value at 1.5% PET content. The bond strength decreased as the PET proportion in concrete increased, which was attributed to lower density and poor bond between shredded PET waste and concrete matrix.

Incorporating PET granules in place of fine aggregates is beneficial, as granules have sub-rounded shape and dimensions close to fine aggregates. Granules are also economically advantageous since they save time and energy by eliminating the need to transform them into fibre or strip (Arulrajah et al., 2013). The flexural performance of large-scale RC beams, and bond strength between steel bar and surrounding concrete containing PET granules as fine aggregate replacement have not been previously studied. This study aims to address these research gaps. In addition, the flexural performance of RC beams and its variation with the PET content was numerically simulated using finite element method (FEM).

2. Experimental investigation

2.1. Materials and mix design

The ordinary Portland cement, water, fine aggregate, coarse aggregate, and PET granules were used in this study. The coarse aggregate sizes were 7 mm and 10 mm. The fine aggregate was river sand (specific gravity = 2.5). The PET granules were produced from waste PET bottles. A granulator machine with rotary blades and water were used to produce the PET granules. PET granules had a specific gravity of 1.26, relatively smooth texture and sub-rounded form without any surface treatment (Kangavar et al., 2022). The PET aggregates had particle size distribution comparable to sand so as to minimize the impact of grading variation on concrete properties (Kangavar et al., 2022). Table 1 shows the sieve analysis of PET granules, sand, and AS 2758.1 (AS2758.1, 2014) limitations. All reinforcements used in the concrete beams met the requirements of AS 4671 (AS4671, 2001). The 10 mm deformed bars (yield strength = 500 MPa) were used for flexural reinforcement. The stirrups were composed of 6 mm plain bars (yield strength = 300 MPa). The 12 mm deformed bar (yield strength = 500 MPa) were used for pull-out specimens (AS/NZS4671, 2001).

The concrete mix of grade 30 was designed. The water/cement ratio was 0.45. PET granules volumetrically replaced sand by 10%, 30%, and 50% (Kangavar et al., 2022). The mix proportion of all batches for coarse aggregate, cement and water remained constant with the values of 1250 (kg), 388 (kg) and 175 (L) per m^3, respectively. Table 2 shows the fine aggregate proportions.

Table 1
Sieve analysis of fine aggregates.

Sieve (mm)	Percentage passing (%)			
	Sand	PET granules	Upper limit (AS 2758)	Lower limit (AS 2758)
4.75	100	100	100	100
2.36	96.80	92	100	89
1.18	87.74	80	89	70
0.60	69.30	60	75	40
0.30	27.52	22	30	15
0.15	3.93	0	10	0

3. Instrumentation and test procedures

3.1. Material properties

The material properties of all concrete mixes, such as elastic modulus, compressive strength, and tensile strength were evaluated at the age of 28 days according to the Australian standards (AS1012.9.1, 2014; AS1012.10, 2014; AS1012.17, 2014). Furthermore, the compressive stress-strain was measured using a strain gauge attached to the middle of the specimens. For each test, three cylindrical samples (100 mm diameter and 200 mm height) were fabricated for each batch to enhance reliability of results.

3.2. Pull out test

The cylindrical samples with dimension of 100 mm in diameter and 200 mm in height were used for the test. Two samples were cast for each concrete mix. The deformed bars were placed in the centre of specimens (Hanjari et al., 2011; Abousnina et al., 2021). The deformed bars were secured at the centre of the moulds during casting using specially designed plastic fixtures. Fig. 1(a) illustrates the schematic diagram of pull-out test. The test procedure was carried out according to the RILEM RC6 (Rilem, 1994). A linear variable differential transducer (LVDT) was used to measure slip of deformed bar, with deformation controlled at speed of 1 mm/min (de Almeida Filho et al., 2008). Eq. (1) was used to calculate the bond strength (Abousnina et al., 2021), where τ represents bond strength (MPa), P is the ultimate load (N), l_d represents bond length between bar and concrete (mm), and d represents bar diameter (mm). A uniform stress distribution was assumed along the bond length (Mak et al., 2019).

$$\tau = P/\pi d l_d \tag{1}$$

3.3. Scanning electron microscopic (SEM) observations and pore analysis

The SEM observation was conducted using electron backscattered imaging (BSE) mode to analyse the morphology of the concrete specimens containing different PET percentage (Kangavar et al., 2022). The

Table 2
Fine aggregate proportion.

Material	Fine aggregate (kg/m^3)	
	Sand	PET granules
Reference	625	–
10% PET	566	49
30% PET	462	166
50% PET	348	235

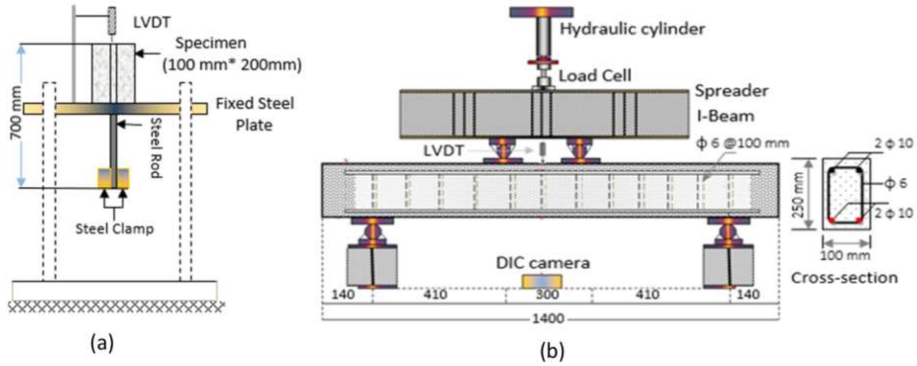

Fig. 1. Schematic diagram, (a) pull out test, (b) four point-bending test.

BSE images were captured in the vicinity of aggregates for the whole interfacial transition zone (ITZ) to evaluate porosity of concrete mixtures. BSE images were further analysed using ImageJ (Java-based image processing program) software to evaluate the average diameter and area of the pores (Thiam and Fall 2021) and their correlation with bond strength of concrete.

3.4. Flexural test

The flexural test was conducted on RC beams with dimension of 100 mm in width, 250 mm in depth and 1400 mm in length, with a clear span of 1110 mm. For each mix, one beam was fabricated, with a total of four beams. The beams were under-reinforced by design, with shear stirrups provided according to AS 3600 (AS3600, 2018). The beams were simply supported and loaded with two concentrated loads 300 mm apart. The loading speed was maintained at 1.2 mm/min throughout test. A (LVDT) was mounted to the middle rear face of beams to measure deflection at mid-span. The crack propagation of RC beams was evaluated using Digital Image Correlation (DIC) system. The design specifications and schematic diagram are shown in Fig. 1(b).

4. Results and discussion

4.1. Material properties

Table 3 shows the average test results. The average compressive strength and tensile strength of the 10% PET specimen increased by 6% and 7% compared to the control specimen. However, the compressive and tensile properties of concrete deteriorated as the amount of PET aggregates increased. Incorporating 30% and 50% PET aggregates decreased the compressive strength by 5% and 17%, respectively, compared to the control. Similarly, tensile strength of the 30% and 50% PET specimens decreased by 3% and 16.5%, respectively, compared to the control. Fig. 2 illustrates the average compressive stress-strain behaviour for each concrete mix. The inclusion of PET aggregates

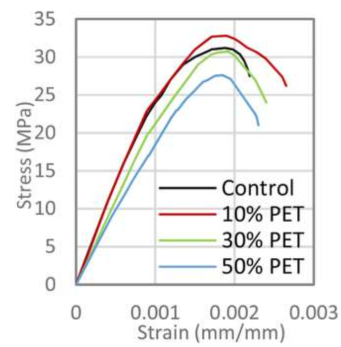

Fig. 2. Stress-strain behaviour.

improved the maximum strain (at failure) of the concrete, where the maximum strain of the 10%, 30% and 50% PET specimens increased by 23%, 14% and 10%, respectively, compared to the control. The increased compressive and tensile behaviour of the 10% PET specimen could be related to the flexibility of PET aggregates as well as even dispersion of PET aggregates at a low replacement level, while the decreased performance of the 30% and 50% PET specimens may be explained by the increased porosity of the specimens with increasing PET aggregates, resulting in a poor bond between PET aggregates and cement paste (as demonstrated in section 4.3). PET granule aggregates reduced the elastic modulus of the concrete at all replacement level although the reduction was less noticeable for the 10% PET specimen. The elastic modulus of the 10%, 30% and 50% PET specimens decreased by 1.5%, 17%, 23%, respectively, compared to the control. The reduction in elastic modulus behaviour could be due to the lower specific gravity of PET aggregates compared to sand (Mehta and Monteiro, 2014).

Table 3
Strength parameters of concrete mixtures.

Specimens	Compressive strength (MPa)	*Sd	Tensile strength (MPa)	*Sd	Elastic modulus (MPa)	*Sd
Reference	31.8	1.7	3.92	0.50	24.45	1.25
10% PET	33.6	1.9	4.20	0.53	24.15	1.55
30% PET	30.3	1.6	3.81	0.36	20.22	1.30
50% PET	26.4	1.3	3.28	0.23	18.91	1.22

*Sd: Standard deviation (MPa).

4.2. Bond behaviour

Fig. 3 illustrates the bond-slip behaviour of the concrete mixtures. Fig. 4 depicts the ultimate bond strength and corresponding ultimate slip. The average ultimate bond strength of specimen with 10% PET content was close to the control sample with only a 3% increase. However, the bond strength values were inversely related to the increment of the PET granules content, where 30% and 50% PET aggregates reduced bond strength by 19% and 32%, respectively, in comparison to control

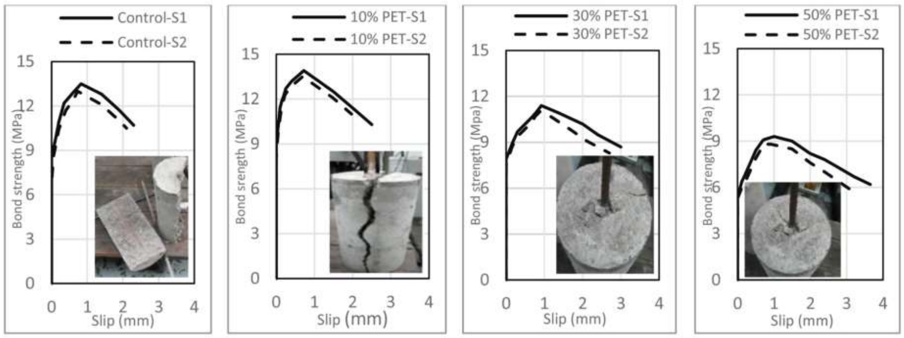

Fig. 3. Bond-slip curves.

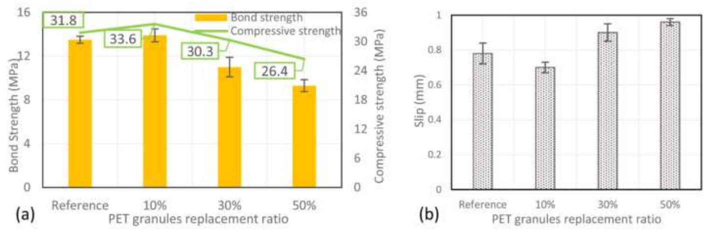

Fig. 4. Test results for (a) ultimate bond strength (b) ultimate slip.

specimen. The slight improvement in bond strength of specimen containing 10% PET might be attributed to even dispersion of PET aggregates in the mixture (as illustrated in section 4.3) and flexible quality of PET aggregates relative to natural aggregates which causes stress to transfer and redistribute to the natural aggregates and thus delaying failure (Kangavar et al., 2022). The bond strength reductions with increasing PET aggregates in the mixture could be due to uneven distribution of PET granules at high replacement ratios (Kangavar et al., 2022), leading to formation of voids and poor bond between PET granules and cement matrix (as demonstrated in section 4.3). Fig. 4(a) illustrates that the bond behaviour of the specimens followed the same trend as corresponding compressive behaviour, suggesting that bond capacity was influenced by compressive strength behaviour (Al-Azzawi et al., 2018; Fakoor and Nematzadeh, 2021; ACI-408R, 2003). Fig. 4(b) demonstrates that the ultimate slip associated with maximum bond strength increased for specimens containing more than 10% PET content. The slip reduction for the control and 10% PET concrete might be related to the improved compressive strength, resulting in smaller bar slip (Dancygier et al., 2010).

4.2.1. Failure mode

The proportion of PET granules in the mixture affected failure mechanism of the concrete specimens. Fig. 3 depicts that splitting failure occurred in both control and 10% PET concrete. The splitting failure happens once maximum tensile capacity of the concrete is less than forces generated between steel and surrounding concrete (Al-Azzawi et al., 2018). However, the specimens with 30% and 50% PET percentage experienced pull-out-splitting failure. This type of failure is caused by degraded loading capacity and crushed concrete, with splitting crack limited to the area around the steel bar (Fakoor and Nematzadeh, 2021; Concrete, 2000). This behaviour might be related to higher percentage of PET aggregates in concrete, resulting in more porosity (as demonstrated in section 4.3), and thus a weak bonding between concrete and steel bar. Moreover, splitting failure of both control and 10% PET specimens might be caused by the fact that the concrete's failure was governed by their compressive strength capacity, where increasing compressive strength corresponded to increasing brittleness of concrete (ACI-408R, 2003).

4.2.2. Bond strength analysis using available equations

Table 4 presents the bond strength models proposed by previous researchers and FIB code (CEB-FIB, 2010). It is evident that previous empirical models were developed using experimental compressive strength. The proposed models related the bond strength to compressive strength by the equation: $\tau = \lambda f_c^{'\beta}$ (Al-Azzawi et al., 2018; Fakoor and Nematzadeh, 2021). Therefore, the power regression law was adopted to develop a model using best fit line based on experimental findings of this study. The power (β) and intercept (λ) values of the model were determined using the logarithm approach (Blaesser et al., 2015). Subsequently, a model was proposed as given by Eq. (2), with the correlation coefficient (R^2) of 0.97. Where τ = bond strength (MPa), and $f_c^{'}$ = compressive strength (MPa). ±95% confidence intervals ($\tau_{\%95c}$) and ±95% prediction intervals ($\tau_{\%95p}$) were calculated by Eqs. (3) and (4), respectively (Brown, 2001), where $Y_{pred.}$ is the predicted value of Y (actual value), x and $\bar{x}$ are true value and mean value of samples, $t_{0.05}$ is t

Table 4
Previous bond strength models.

Reference	Equation
CEB-FIB (CEB-FIB, 2010)	$\tau = 2.51 f_c^{'0.5}$
Shen et al. (Shen et al., 2016)	$\tau = 1.65 f_c^{'0.7}$
Hadi (Hadi, 2008)	$\tau = 1.33 f_c^{'0.5}$
Esfahani and Ragan (Esfahani and Rangan, 1998)	$\tau = 1.5 f_c^{'0.5}$
Harajli et al. (Harajli et al., 2002)	$\tau = 2.57 f_c^{'0.5}$

critical value, i is the sample size and SS_x denotes total square of standard errors for x.

$$\tau = 2.63 f_c^{'0.53} \quad (2)$$

$$\tau_{\%95c} = \tau_p \pm t_{0.05} \left(\sqrt{\frac{\sum (Y - Y_{pred.})^2}{(i-2)}} * \sqrt{\frac{1}{i} + \frac{(x-\bar{x})^2}{SS_x}} \right) \quad (3)$$

$$\tau_{\%95p} = \tau_p \pm t_{0.05} \left(\sqrt{1 + \frac{\sum (Y - Y_{pred.})^2}{(i-2)}} * \sqrt{1 + \frac{1}{i} + \frac{(x-\bar{x})^2}{SS_x}} \right) \quad (4)$$

Fig. 5 shows the comparison of the predicted bond strength of previous models with the experimental results in regards to compressive strength. The experimental findings were generally greater than those predicted by the previous models. Nonetheless, the prediction results of (CEB-FIB, 2010; Shen et al., 2016; Harajli et al., 2002) yielded more compatible results with the experimental findings than those of (Hadi, 2008; Esfahani and Rangan, 1998). The discrepancies might be related to the fact that the prediction models of (Hadi, 2008; Esfahani and Rangan, 1998) were derived from the experimental data of high strength concrete, whereas this study deals with normal strength concrete. Furthermore, the model developed in this study was evaluated using the test data from prior studies (Fakoor and Nematzadeh, 2021; Mahdi et al., 2013; Osifala et al., 2015) on the bond strength of concrete incorporating PET waste in the shape of fibre and shredded (Fig. 5). The bond strength results reported by Fakoor and Nematzadeh (2021) were underestimated by the developed model, which might be because of the adoption of higher curing temperature, impacting bonding behaviour of reinforcement with PET concrete (Al-Azzawi et al., 2018). However, experimental findings of other studies (Mahdi et al., 2013; Osifala et al., 2015) agreed well with the developed model, where the findings fitted 95% predicted ranges.

4.3. SEM analysis

As shown in Fig. 6(a), the specimen with 10% PET content displayed uniform distribution and high level of compactness in a similar manner as for conventional concrete. Nonetheless, Increasing PET granules appeared to induce larger voids due to their inability to absorb water, leading to accumulation of free water in the concrete mix.

Fig. 6 (b) depicts the porosity of the specimens in red throughout the entire ITZ. It is obvious that the reference concrete and 10% PET concrete demonstrated smaller and less interconnected pores than the

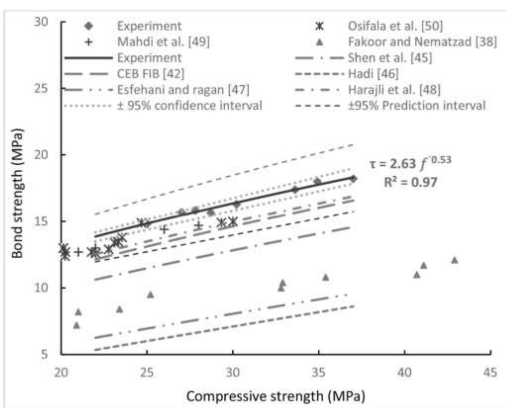

Fig. 5. Relationship between experimental results and predicted bond strength.

concretes with 30% and 50% PET content. As shown in Fig. 7(a), the average diameter and area of the pores in the specimen containing 10% PET were comparable to those in the reference concrete, with only 5% and 3% decrease, respectively. However, these values began to rise as proportion of PET aggregates increased, where specimens containing 30% PET and 50% PET exhibited an increase of 28% and 49% in diameter of the pores and 50% and 110% in area of the pores over the reference concrete, respectively. Fig. 7(b) and (c) depict the correlation between the average pores area and experimental findings of the compressive, and bond strength, respectively. It is apparent that average pores area is inversely proportional to the compressive and bond strength behaviours. Moreover, the average pores area and strength parameters (compressive strength and bond strength) revealed a linear relationship with the correlation coefficients (R^2) of 0.9094 and 0.8964, respectively. Previous studies also found a strong correlation between porosity and strength parameters in various construction materials (Liu, 1997; Park and Seo, 2011).

4.4. Flexural load-deflection behaviour

The load-midspan deflection behaviour of RC beams are depicted in Fig. 8. It is obvious that flexural stiffness of RC beams decreased with increasing PET aggregates in concrete mixture. However, the beams with 30% and 50% PET aggregates appeared to have substantial decrease in flexural stiffness relative to that of the beam with 10% PET content. This behaviour might be due to lower elastic modulus of PET granules relative to fine aggregates (Adnan and Dawood, 2020; Kangavar et al., 2022). Table 5 summarises the experimental findings for the tested beams. The beam containing 10% PET aggregates attained the maximum load capacity of 169 kN, improving marginally by 1.39% over the control beam. The performance started to decline with increasing PET aggregates in concrete mix, where RC beam with 30% PET aggregate showed a decrease of 5.9% in comparison to reference beam. Nevertheless, the performance deteriorated more noticeably as the replacement ratio exceeded 30%, as seen by a 10.1% decrease for the beam with 50% PET content compared to the reference beam. The slight improvement of the RC beam incorporating 10% PET granules might be related to even dispersion of PET aggregates in the mix, and flexibility of PET granules which causes stress to be redistributed to the aggregates and delays failure (Kangavar et al., 2022). However, the performance deterioration with increasing PET granules in RC beams could be explained by the poor bond between concrete matrix and PET granules owing to increasing voids in concrete mix (as demonstrated in section 4.2 and 4.3).

The deflection at yield load was determined as the deflection at the intersection point of two straight lines. The first line is the best-fit regression line to the linear part of the load-deflection curve, and the second line is a horizontal line that passes the peak flexural load point (Otoom et al., 2022). The load corresponding to the deflection at yield was then used to determine the yield load. The yield load of the beam containing 10% PET granules was comparable to that of the reference beam with only 2.1% increase. Nevertheless, the gradual reduction of load at steel yielding point was observed when the percentage of PET aggregates in concrete mix increased, where the yield load for the beams with 30% and 50% PET content reduced by 13.5% and 22.8%, respectively, compared to the reference beam. This behaviour could be explained by a decrease in concrete tensile strength when PET replacement ratio exceeded 10% as indicated in Table 3 (section 2.2). Moreover, incorporating PET granules at all replacement ratio enhanced the RC beam deflection associated with peak load. The beam with 10% PET content demonstrated optimal performance with a deflection at peak load of 18.1 mm, increasing by 12% over the reference beam.

4.4.1. Ductility and energy absorption

The deflection ductility index was calculated as the ratio of the deflection at ultimate failure (Δ_u) (when the load-deflection curve was

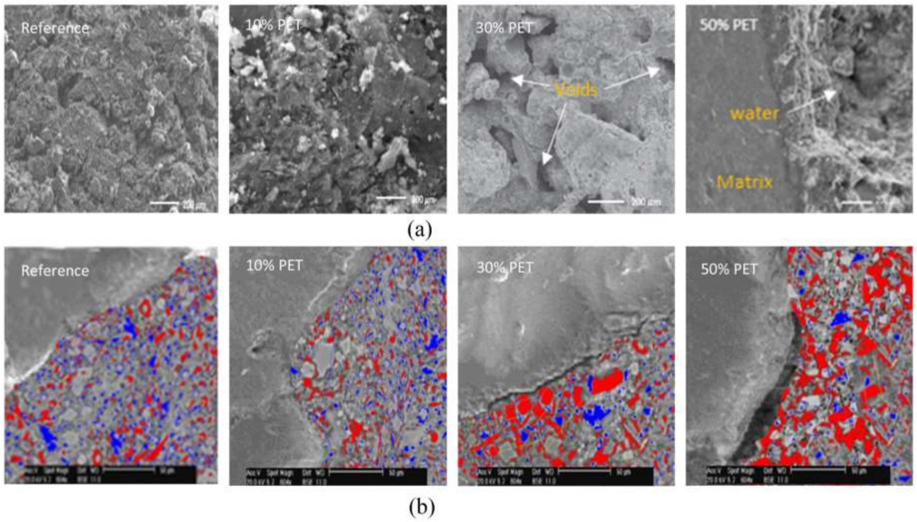

Fig. 6. (a) Morphology, and (b) porosity analysis of the specimens.

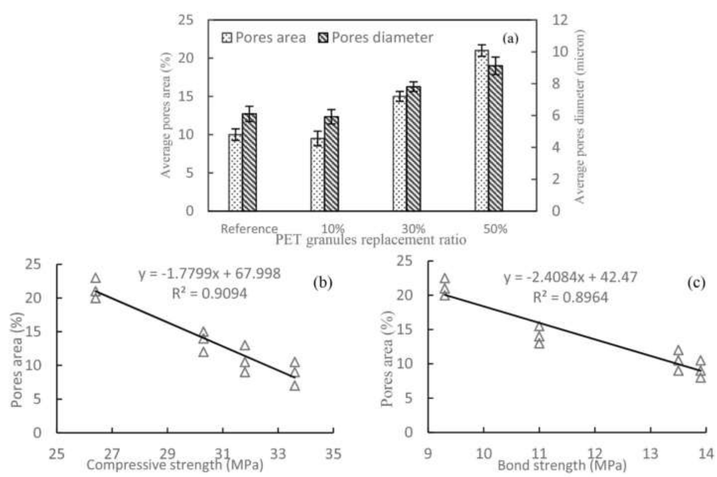

Fig. 7. (a) Pores area and diameter of the specimens, (b) correlation of pores area with compressive strength, and (c) bond strength.

stopped) to the deflection at tensile reinforcement yielding point (Δ_y) (Ibrahim et al., 2021) (Fig. 9). This approach was also implemented by Hussein et al. (2012) and Otoom et al. (2022) to calculate the deflection ductility of RC beams. Energy absorption capacity is defined as the area under the load-deflection curve up to failure (when the load-deflection curve was stopped) (Otoom et al., 2022; Topçu and Unverdi, 2018) (Fig. 9). Table 5 presents the deflection ductility index and energy absorption results for all RC beams. The ductility of the beam containing 10% PET granules was found to be 2.21, increasing 13% over the reference beam with a value of 1.95. Although increasing the ratio of PET aggregates decreased the ductility of the RC beam, the beams incorporating 30% and 50% PET aggregates still demonstrated higher ductility than the reference beam with values of 2.07 and 1.98, respectively. The decrease in ductility for beams with 30% and 50% PET aggregates may be due to reduction of concrete density and improper PET distribution in the mixture with increasing PET aggregates in concrete (Kangavar et al., 2022; Salazar et al., 2020). The energy absorption of the reference beam was 1957 kN mm, whereas the values for the beams incorporating 10% and 30% PET aggregates were 2334 kN mm and 2040 kN mm, respectively. Incorporating 50% PET decreased the energy absorption by 6.2% relative to reference beam. The enhanced energy absorption capacity of the RC beam with 10% PET granules could be related to its higher load bearing capacity relative to beams containing 30% and 50% PET. This performance deterioration of RC beam with 50% PET aggregate could be related to considerable decrease in flexural capacity due to the presence of high PET content.

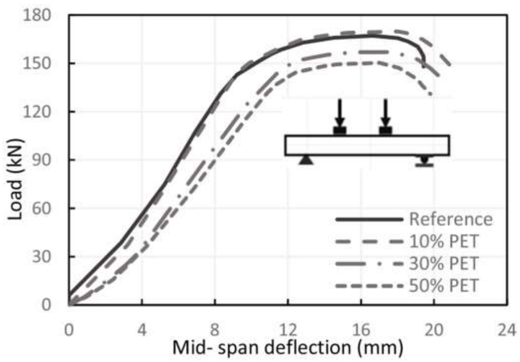

Fig. 8. Experimental load-deflection curves.

4.4.2. Cracking behaviour

The cracking performance of RC beams was determined using strain map generated by DIC technique. The flexural cracks of the beams started in maximum moment region and propagated across loading area and support regions with increasing load. Fig. 10 depicts the main crack width propagation with respect to height of the beams. The beams with 10% and 30% PET content had positive impact on the initial main crack load, displaying 28.2% and 13.4% increase over the reference beam. However, the performance declined as the percentage of PET granules exceeded 30%, as demonstrated by a 6.20% decrease for the beam containing 50% PET granules compared to reference beam. Notably, incorporating PET granules into the RC beams reduced the initial main crack width (corresponding to the initial main crack load), where this value for the beams containing 10%, 30%, and 50% PET content reduced by 29%, 25.4% and 18%, relative to the reference beam, respectively. However, the improvement was more noticeable for the RC beam with 10% PET content. It is also apparent that the beam with 10% PET content at the load of 150 kN reached the crack width of 0.88 mm, reducing by 52% over the reference beam. Even though the crack width at the same load increased with increasing PET granules replacement ratio, the beams incorporating 30% and 50% PET still had positive effect on the crack width, demonstrating 37% and 18% decrease over the reference beam. The maximum crack width of reference beam was 2.1 mm whereas the value for the beams containing 10%, 30% and 50% PET aggregates reduced to 1.1 mm, 1.4 mm, and 1.8 mm, respectively.

It is noteworthy that the main crack in the reference beam extended to 190 mm in height whereas this value decreased to 169 mm, 175 mm, and 182 mm for beams containing 10%, 30%, and 50% PET aggregates, respectively. The positive behaviour of PET beams may be explained by the plastic nature of PET aggregates which improved the matrix structure of concrete by delaying crack initiation and resisting crack propagation. This findings are in line with those of (Hama, 2021; Marzouk et al., 2007; Ibrahim et al., 2022; Al-Darzi, 2022), who reported improved cracking behaviour in RC beams incorporating plastic aggregates. Yet, the gradual performance deterioration with larger percentage of PET granules may be related to uneven PET distribution caused by larger proportions of PET granules, and accumulation of free water surrounding PET granules due to their lack of water absorption, resulting in higher porosity in the mix (Kangavar et al., 2022; Gu and Ozbakkaloglu, 2016; Abu-Saleem et al., 2021) as illustrated in section 4.3. These findings are in line with those of (Hama, 2021; Marthong and Marthong, 2016), who agreed on the reduction of structural properties with increasing PET particles in the mixture. Furthermore, the maximum crack width at 40% of maximum load (service load) (Fathifazl et al., 2009) for the beams with 0%, 10%, 30%, and 50% PET content was 0.33 mm, 0.22 mm, 0.23 mm and 0.28 mm, respectively. The maximum crack width for beams containing PET aggregates were smaller than the recommended maximum crack width at service load for the external exposure environments specified by ACI 224 R (ACI Committee 224, 2001) (0.3 mm), BS 8110 (Standards, 2007) (0.3 mm), and ACI 318 (ACI Code, 2022) (0.33 mm), which could potentially extend the incorporation of PET granules in concrete safely for exterior-exposed structures (Ismail and Hassan, 2017).

4.4.3. Cracking moment and ultimate moment capacity

The first flexural crack was identified using the DIC technique and validated by initial slope change of load-deflection response. Table 5 presents the impact of the PET granules on cracking moment (M_{cr}^{exp}) as well as flexural load capacity (M_u^{exp}) of RC beams. 10% PET aggregate increased cracking moment of the beam by 20.8% compared to the reference beam. The inclusion of 30% PET granules had little effect on cracking moment, with only a 1.1% decrease compared to the reference beam, while the reduction was more pronounced for the RC beam incorporating 50% PET aggregates, decreasing by 2% relative to the reference beam. The negative trend of cracking moment values for the beams incorporating PET granules is mainly due to decreasing concrete tensile strength with the increase of PET aggregates in mixture (Kangavar et al., 2022). It is evident that M_u^{exp} increased slightly by 1.25% for the beam containing 10% PET granules compared to the reference beam. Increasing PET replacement ratio from 10% to 30% and 50% decreased

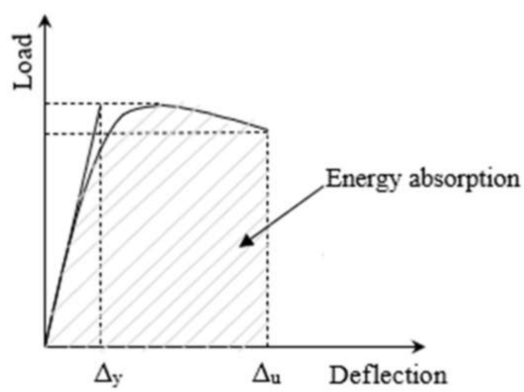

Fig. 9. Ductility and energy absorption measurements.

Table 5
Experimental flexural test results.

Beam	Peak load (kN)	Yield load (kN)	Deflection (mm)			Deflection ductility	Energy absorption (kN. mm)	Cracking moment (kN.m)	Ultimate moment (kN.m)
			Yield	Peak	Ultimate failure				
Reference	167	141	9.7	16.1	18.9	1.95	1957	6.16	57.0
10% PET	169	145	9.4	18.1	20.8	2.21	2334	7.44	57.7
30% PET	157	122	9.8	17.6	20.3	2.07	2040	6.11	53.5
50% PET	150	109	10.1	17 .0	20.0	1.98	1838	6.08	51.1

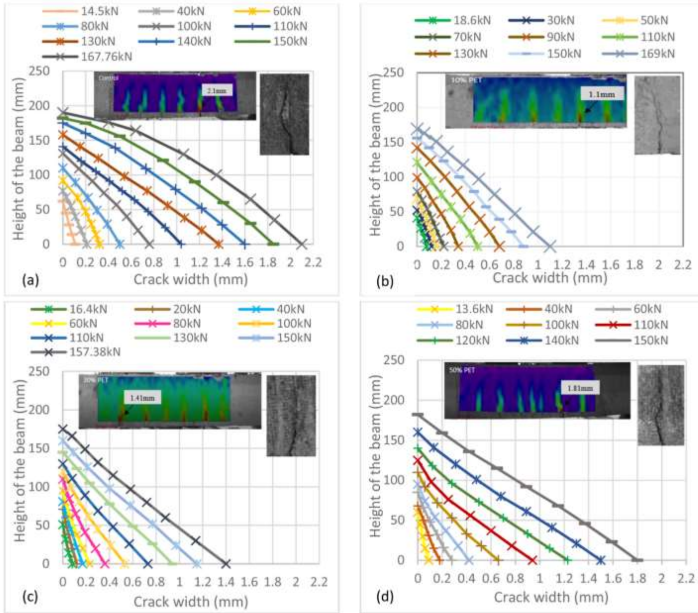

Fig. 10. Main crack propagation (a) reference beam, (b) 10% PET beam, (c) 30% PET beam, (d) 50% PET beam.

M_u^{exp} by 6.15% and 10.4% compared to the reference beam. These explanation is that increasing PET aggregates in the mixture expanded the pore area and weakened the PET-mortar interface in concrete composite (as illustrated in section 4.3), thus greatly reduced the beams' capacity to withstand higher loads.

5. Theoretical evaluation

The theoretical analysis of the cracking and ultimate moments of the RC beams was conducted according to the ACI 318 (ACI Code, 2022) and AS 3600 (AS3600, 2018) standards, and the results were compared with the experimental findings to evaluate the applicability of both standards for concrete containing PET granule aggregates.

5.1. Cracking moment (M_{cr})

The cracking moments of the RC beams were calculated using Eq. (5) (ACI Code, 2022) and 6 (AS3600, 2018) as recommended by the ACI 318 (ACI Code, 2022) and AS 3600 (AS3600, 2018) standards, respectively. Fig. 11(a) depicts the theoretical to experimental cracking moments. The cracking moment predictions of ACI 318 (ACI Code, 2022) for concrete containing 0%, 10%, 30%, and 50% PET granules showed $M_{cr}^{theo} / M_{cr}^{exp}$ ratios of 1.02, 1.04, and 1.06, and 1.08, respectively, while AS 3600 (AS3600, 2018) predictions provided $M_{cr}^{theo} / M_{cr}^{exp}$ ratios of 1.04, 1.06, and 1.08, and 1.09, respectively. Although the cracking moment of the beams with PET content were slightly overestimated by both standards, the results were still within the permissible accuracy range of 1 ± 0.2 (Fathifazl et al., 2009). The accuracy of standard equations may typically be increased by using experimental results of concrete tensile strength (ETS) rather than that calculated proportionately from the compressive strength (Ismail and Hassan, 2017) as proposed by Fathifazl et al. (2009). The cracking moment estimated from American and Australian standards using (ETS) provided better results, with the $M_{cr}^{theo} / M_{cr}^{exp}$ ratios ranging from 0.97 to 1.05, as shown in Fig. 11(a). However, the values obtained from AS 3600 (AS3600, 2018) were marginally higher than those of ACI 318 (ACI Code, 2022; ACI Committee 318, 2008), yet still within the range of 1 ± 0.2. This could be attributed to the fact that, in contrast to ACI 318 (ACI Code, 2022), AS 3600 (AS3600, 2018) considers the influence of longitudinal reinforcement when computing second moment of the uncracked section area (Ismail and Hassan, 2017).

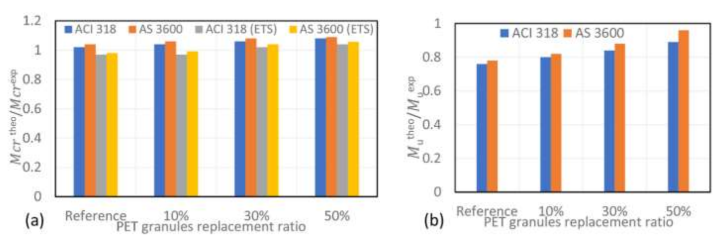

Fig. 11. Theoretical to experimental (a) cracking moment ratio (b) ultimate moment ratio.

$$M_{cr}^{theo} = f_r \times I_g / y_t \quad f_r = 0.62\,\lambda\,\sqrt{f_c^{'}} \tag{5}$$

$$M_{cr}^{theo} = Z f_{cf}^{'} \quad f_{cf}^{'} = 0.6\,\sqrt{f_c^{'}} \tag{6}$$

where f_r and $f_{cf}^{'}$ are flexural tensile strength (MPa), $\lambda = 1$ for normal-density concrete, $f_c^{'}$ = is the mean value of compressive strength (MPa), y_t = distance between the extreme tension and gross section's centroidal axis (mm), I_g = moment of inertia, Z = section modulus of uncracked section.

5.2. Ultimate moment (M_u)

The rectangular stress block analysis was conducted in order to calculate theoretical design moment of beams according to the ACI 318 (ACI Code, 2022) and AS 3600 (AS3600, 2018) guidelines, and the results were compared to experimental ultimate moment (Ismail and Hassan, 2017). Rectangular stress block analysis consists of "βc" (height) and "$\alpha f_c^{'}$" (width), where β and α are stress block parameters, and $f_c^{'}$ is the mean value of compressive strength (MPa). The proposed stress block parameter values of ACI 318 (ACI Code, 2022) and AS 3600 (AS3600, 2018) standards are presented in Table 6. Fig. 11(b) depicts theoretical to experimental ratio of the ultimate moment for each beam. The ultimate moment predictions of ACI 318 (ACI Code, 2022) and AS 3600 (AS3600, 2018) for the RC beam with 10% PET content showed M_u^{theo}/M_u^{exp} ratios of 0.8 and 0.82, respectively, up from 0.76 to 0.78 for the reference beam, respectively. Increasing PET granule aggregates to 30% and 50% in RC beams slightly increased the prediction values of ACI 318 (ACI Code, 2022) and AS 3600 (AS3600, 2018), with M_u^{theo}/M_u^{exp} ratios ranging from 0.84 to 0.96. However, both standards conservatively predicted the ultimate moment capacity with the M_u^{theo}/M_u^{exp} ratios less than 1.

6. Finite element modelling

The FEM is adopted in this study to simulate maximum flexural load and corresponding midspan deflection of RC beams with varying PET content, and the results were validated with the experimental findings. Previous research demonstrated that finite element method with adopting concrete damaged plasticity (CDP) model, is an efficient prediction method for analysis of RC structures (Mahmud et al., 2013).

6.1. Constitutive model for concrete

The test findings from this study, as listed in Table 3, are used to calibrate the CDP model parameters such that the material properties of the concrete with different PET content are accurately represented. The uniaxial stress-strain behaviour is transformed into the stress-plastic strain behaviour in ABAQUS utilising the inelastic strain (Eqs. (7) and (8)). The degradation of stiffness, which is a defining characteristic of damage, is determined using Eqs. (9) and (10) for damage variables in compression and tension, respectively. These variables have values ranging from zero to one, where zero representing undamaged state and one representing entirely damaged material. The post peak tensile behaviour was determined using tension stiffening model (Otoom et al., 2022; Massicotte et al., 1990).

$$\sigma_c = (1 - d_c) E_0 \left(\varepsilon_c - \varepsilon_c^{pl}\right) \tag{7}$$

$$\sigma_t = (1 - d_t) E_0 \left(\varepsilon_t - \varepsilon_t^{pl}\right) \tag{8}$$

$$d_c = 1 - (\sigma_c / \sigma_{cu}) \tag{9}$$

$$d_t = 1 - (\sigma_t / \sigma_{tu}) \tag{10}$$

where d_c = compression damage and d_t = tension damage, E_0 is initial elastic modulus ,σ_c = compressive strength, σ_t = tensile strength, σ_{cu} and σ_{tu} are effective compressive cohesion strength and effective tensile cohesion strength, respectively, ε_c = compressive strain, ε_t = tensile strain, ε_c^{pl} = plastic strain for compression, ε_t^{pl} = plastic (cracking) strain for tension.

The fundamental input variables required for the plastic properties of CDP models were kept at their default values including second stress invariant of tensile meridian to compressive meridian *(k)*, eccentricity (*e*), initial biaxial to initial uniaxial compressive yield stress (f_{b0}/f_{c0}), and dilation angle (ψ) with the value of 0.667, 0.1, 1.16, and 31°, respectively, with the exception of the viscosity parameter (μ, which was given a value of 0.0003 to encourage better convergence (Otoom et al., 2022).

6.2. Reinforcement modelling

The elastic-isotropic hardening material was used for longitudinal and transverse reinforcement which responds elastically up to the yield stress before creating plastic strain with further loading. The Poisson's ratio and elastic modulus for reinforcements were set at 0.3 and 200 GPa, respectively. The Von-Mises yield criterion was used for the yielding of reinforcements (Godínez-Domínguez et al., 2015). The yield strengths of longitudinal and transverse reinforcements were 500 MPa and 300 MPa, respectively, with strain hardenings of 1% and 0.5%, respectively.

6.3. Model convergence and verification

The beams were modelled using 8 node linear brick element (C3D8R) for concrete, and 3D truss element (T3D2) (axial deformation only) for reinforcements. The interaction between concrete and steel reinforcement was simulated by embedding reinforcement into concrete and defined using tension stiffening in the CDP constitutive models. The perfect bond between concrete and reinforcements was assumed since no debonding was observed during the experimental flexural test (Godat et al., 2020; Miah et al., 2019). The supports were modelled by 8 node brick elements (C3D8R) with steel material characteristics. The hard surface to surface interaction between beams and supports was assumed. Fig. 12(a) depicts the configuration of FEM models. The non-linear behaviour of each model was determined using displacement-controlled approach, in which the models were subjected to a monotonic loading with a tabular amplitude ranging from 0 at time zero to 1 at time 20 s. As shown in Fig. 12(b), the mesh sensitivity analysis was conducted using load-deflection behaviour to identify the appropriate mesh size for the modelling. The results convergence occurred when decreasing the mesh element size had minimal impact on the numerical results, with consideration given to correspond with experimental findings (Otoom et al., 2022). Five different mesh sizes between 10 mm and 25 mm (mesh 10, mesh 18, mesh 20, mesh 23, mesh 25) were developed to model concrete beam in the analysis of reference beam. The results were relatively similar with respect to peak load and associated deflection with the exception of mesh 25 configuration, displaying maximum variation of 5%. All in all, the mesh with a size of 10

Table 6
Stress block parameters.

Beam	Compressive strength (MPa) (Mean value)	ACI 318 (ACI Code, 2022)		AS 3600 (AS3600, 2018)	
		α	β	α	γ(=β)
Reference	31.8	0.85	0.82	0.80	0.89
10% PET	33.6	0.85	0.81	0.80	0.88
30% PET	30.3	0.85	0.83	0.80	0.89
50% PET	26.4	0.85	0.85	0.81	0.90

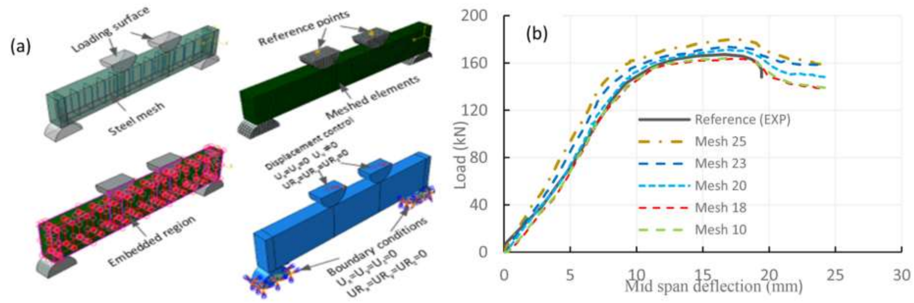

Fig. 12. (a) Geometry of FEM models, (b) mesh analysis.

mm (mesh 10) was chosen for the entire modelling as its result was closer to the experimental result.

6.4. FEM results relative to the experiments

Fig. 13 demonstrates the experimental and FEM results. Table 7 presents experimental and numerical ultimate load and associated deflection of the RC beams. The findings demonstrated that experimental flexural ultimate load and mid-span deflection for the reference beam correlated well with the numerical results, with only 2.4% variation. However, the FEM prediction for the beam incorporating 10% PET granules slightly overestimated the experimental ultimate load and associated deflection by 6.2% and 9.3%, respectively. Conversely, the FEM results for the beams containing 30% and 50% PET marginally underestimated the experimental ultimate load by 7.4% and 6.3%, respectively. Nevertheless, the deflection associated with ultimate load of the beams with 30% and 50% replacement ratio was reasonably associated with the experimental results with the values of 17.5 mm and 16.9 mm, respectively. Furthermore, the load-deflection curves after peak load for FEM models declined at a slower rate than those of the experiments. The numerical analysis of all beams was stopped at a deflection within 26–29 mm, which was greater than the experimental deflections at failure of 18.9–20.8 mm. This behaviour could be related to the perfect bond assumption between concrete and steel reinforcements (Godat et al., 2020; Colombo et al., 2018). The minor discrepancies between the FEM and the experimental results can be explained by changes in the real and numerical conditions as well as variations in the material properties. Furthermore, the FEM models of the reference beam and the beams with 10% and 50% PET content appeared to have slightly higher flexural stiffness than those of the experiments, which might be attributable to degree of precision in presuming surface interaction of different model elements (Otoom et al., 2022). Overall, load-deflection behaviour of the developed FEM models agreed reasonably well with the experimental data. As illustrated in Fig. 14, cracking pattern of the FEM model was relatively comparable to that of the experimentally tested beam.

Table 7
Comparison of finite element models with experimental results.

Beam	Ultimate load (kN)		Ultimate deflection (mm)		EXP/FEM	
	U_{EXP}	U_{FEM}	Δ_{EXP}	Δ_{FEM}	U_{EXP}/U_{FEM}	$\Delta_{EXP}/\Delta_{FEM}$
Reference	167	171	16.1	16.5	0.97	0.97
10% PET	169	179	18.1	19.8	0.94	0.91
30% PET	157	146	17.6	17.2	1.07	1.02
50% PET	150	142	17.0	16.8	1.05	1.03

7. Conclusions

- Incorporating 10% PET aggregates increased the compressive and tensile strengths of concrete due to the flexibility and even dispersion of PET aggregates in the mix. The performance declined at higher replacement level because of increased porosity with increasing PET aggregate percentage. Increasing PET aggregates in the mix decreased the elastic modulus of concrete because of the lower specific gravity of PET granules compare to sand.
- Incorporating PET granules in place of fine aggregates at 10% replacement ratio marginally improved the bond strength, yet the bond performance deteriorated with further increase in the PET

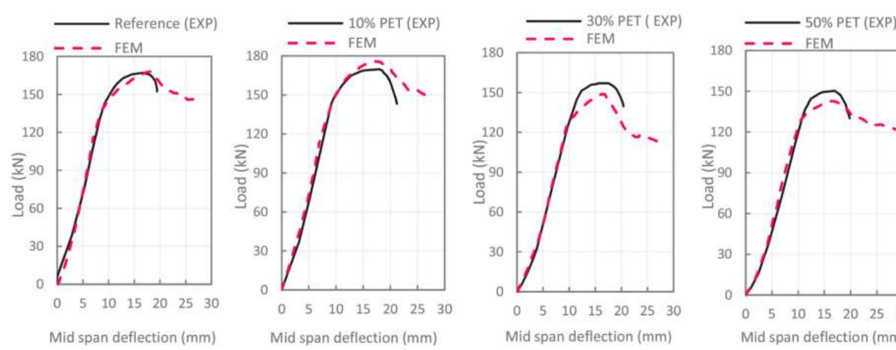

Fig. 13. Comparison between numerical and experimental load deflections.

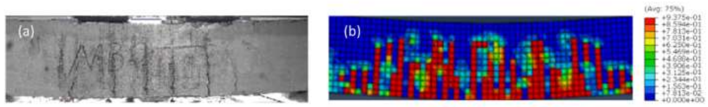

Fig. 14. Cracking pattern of reference beam (a) tested beam (b) FEM model.

replacement ratio. Bond strength variation of concrete with PET content was accurately estimated by the developed model.

- The rather even distribution of PET aggregates at 10% substitution rate resulted in a relatively lower porosity and smaller pore diameters, whereas a higher porosity and larger pore diameters were observed with a higher PET substitution rate.
- Incorporating 10% PET granules had a positive effect on the flexural capacity of the RC beam, with performance declining as the PET replacement ratio increased. PET granules also positively contributed to the ductility of the beams.
- Incorporation of PET granules improved crack width as well as cracking moment of RC beams, with the highest improvement observed in the beam containing 10% PET.
- Cracking and flexural moment of RC beams corresponded well with ACI 318 (ACI Code, 2022) and AS3600 (AS3600, 2018) predictions using the mean values, suggesting that these design equations can be applicable for RC beams incorporating PET granules.
- FEM results matched experimental results reasonably closely, suggesting that FEM model can safely simulate the ultimate load and associated deflection of RC beams incorporating PET granules.

Declaration and competing interest.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit author statement

Mohammad Eyni Kangavar: Conceptualization, Investigation, Methodology, Formal analysis, Writing - Original Draft. **Weena Lokuge:** Conceptualization, Supervision, Writing - Review & Editing. **Allan Manalo, Warna Karunasena:** Supervision, Writing - Review & Editing. **Togay Ozbakkaloglu:** Writing - Review & Editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mohammad Eyni Kangavar reports financial support was provided by Australian Research Council.

Data availability

Data will be made available on request.

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ANNEXURE TO PAPER 2

Annexure to the paper 2, **"**Development of sustainable concrete using recycled polyethylene terephthalate (PET) granules as fine aggregate **"**, in Developments in the Built Environment.

1. Section 3.2., "*Pull-out test"*:

   The sample preparation and testing procedure were carried out according to the RILEM RC6 (Rilem, 1994). Previous studies also implemented the same approach (Hanjari et al., 2011; Meek et al., 2021; Prince & Singh, 2013) to evaluate the bond behaviour of concrete with steel reinforcement.

2. Section 3.3., "*Scanning electron microscopic (SEM) observations and pore analysis"*:

   The scanning electron microscope (SEM) was conducted using a VEGA3 – TESCAN SEM with a maximum voltage of 10 kV to examine the microstructure of the concrete incorporating PET granules compared to the conventional concrete. Three small samples with dimensions of 30 x 30 x 10 mm were obtained from the cylindrical specimens for each concrete mix after 28 days curing.

3. Section 4.3., Figure 6 with clear scale of measurements:

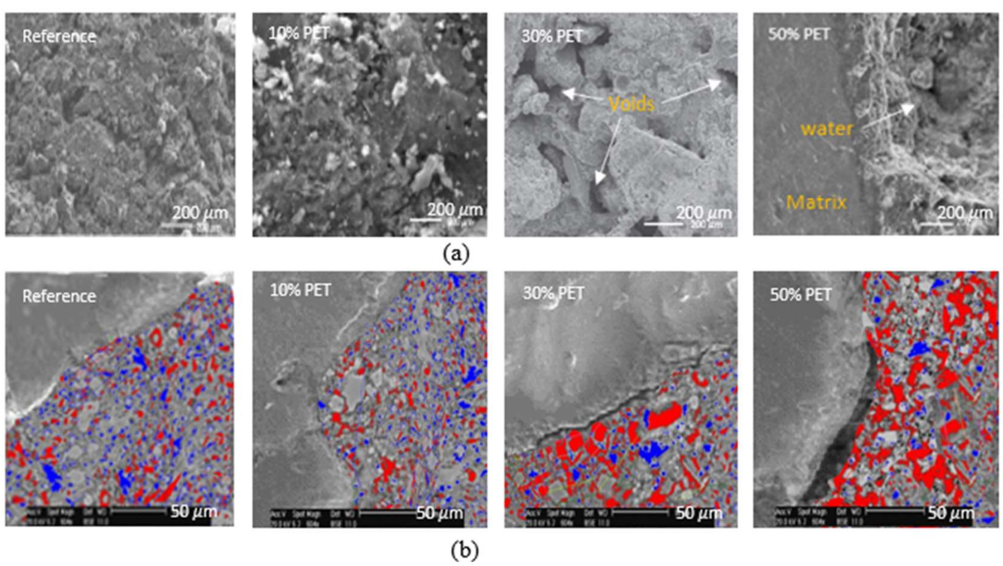

Fig 6 (a) Morphology and (b) porosity analysis of the specimens

4.2. Links and implications

The experimental results revealed that the bond strength of 10% PET concrete was slightly higher than control specimen, increasing by 3% compared to the control. Furthermore, a theoretical model was proposed for predicting bond strength of concrete containing PET aggregate and the results correspond well with experimental findings. The results revealed that inclusion of 10% PET granules had positive impact on flexural capacity of the RC beams. While incorporating PET granules improved cracking moment and crack width of the RC beams at all replacement ratios, the RC beam containing 10% PET granules achieved the optimum performance. Additionally, the ultimate flexural load and corresponding deflection observed through the FE simulations agreed reasonably well with those obtained through the experimental results. The use of a reclaimed resource, PET in structural applications was established using mechanical properties in **chapter 3** and beam analysis experimentally and numerically in **chapter 4**. However, there is a lack of understanding about the durability characteristics of concrete incorporating PET granules which is an integral part if this new construction material is to be used in structural applications. Therefore, the long-term behaviour of this novel material was investigated in **Chapter 5** to ensure its optimum usage in large scale projects.

CHAPTER 5: PAPER 3 – EFFECT OF RECYCLED POLYETHYLENE TEREPHTHALATE (PET) GRANULES ON THE LONG TERM DURABILITY OF CONCRETE

5.1. Introduction

The results of the work done in **Chapter 4** demonstrated the effectiveness of using PET granule aggregate to improve the ductility and cracking behaviour of RC beams. It was also found that 10% PET granule aggregate had a positive impact on the bond behaviour, and flexural strength of RC beam. Based on the knowledge gaps identified in **Chapter 2**, no studies have been found to examine the long-term performance of concrete with PET aggregate content. Thus, this paper presented the durability characteristics of concrete incorporating PET granule to address the **objective 3** of the study. PET granules were used as a partial replacement by volume of fine aggregate (0%, 10%, 30%, and 50%). Important durability parameters including alkali-silica reactivity of 21-day mortar bars and one-year concrete prisms, one-year shrinkage strain, 90-day creep strain, 90-day rapid chloride penetration, 90-day water absorption and apparent volume permeable voids were investigated. Furthermore, the experimental shrinkage strain of the mixtures were compared with the results calculated from four common shrinkage models based on the ACI-209 (ACI-209, 1992), AS 3600 (AS3600, 2018), B3 (Bazant & Murphy, 1995), and Eurocode 2 (Eurocode2, 2004) standards to evaluate reliability of the shrinkage models for concrete with PET granule aggregate.

Effect of recycled polyethylene terephthalate (PET) granules on the long term durability of concrete

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Abstract

Plastic waste management has emerged as a major concern globally. This paper investigates durability characteristics of sustainable concrete incorporating PET granules as a volumetric replacement for fine aggregate (0%, 10%, 30%, and 50%). The important parameters including Alkali silica reactivity (ASR) of one-year concrete prisms and 21-day mortar bars, one-year shrinkage strain, 90-day creep strain, 90-day rapid chloride penetration (RCPT), 90-day apparent volume permeable voids (AVPV) and water absorption were examined. The findings revealed that ASR expansion of concrete and mortar mixes decreased with increasing PET aggregate. Furthermore, incorporating 10% PET granule aggregate improved creep strain and chloride resistance while having almost no impact on shrinkage strain, AVPV and water absorption of concrete. The four commonly used existing shrinkage models underestimated the shrinkage strain of PET concrete. Therefore, a shrinkage model was proposed for concrete incorporating PET granule aggregate and the results corresponded well with the experimental results.

Keywords: PET granules, sustainable concrete, durability characteristics, Alkali-silica reactivity, creep strain, shrinkage model.

1 Introduction

The global concrete production is growing exponentially as a result of population growth and rapid infrastructure development (Lazorenko et al., 2022). As a result, around 5.3 billion cubic metres of concrete are produced globally each year (Hasanbeigi et al., 2012). However, the natural resource depletion for concrete production such as gravel and sand has been a major concern of the construction industry (Merli et al., 2020). It is important to note that sand accounts for 35 to 45% of concrete volume (Martínez-García et al., 2021). Another major challenge of our time is the growing generation of plastic waste as a significant contributor to the waste management problem. The global plastic waste production is approximately 368 million tonnes per year, accounting for about 12% of the waste generated by municipalities (Mendiburu-Valor et al., 2022; Wong et al., 2015). In 2020, around 7000 million metric tonnes of plastic waste were produced worldwide, and over 12000 million metric tonnes of plastic waste are anticipated to be dumped in landfills by 2050 (Ncube et al., 2021; Su et al., 2022). Polyethylene terephthalate (PET) bottles are one of the most commonly used plastics globally because of their high stability, non-reactivity with chemicals, and easy transportation (Rahimi et al., 2016). PET bottles take more than 500 years to decompose, contributing substantially to environmental pollution (Lundell and Thomas, 2020). In 2021, global PET bottle consumption was around 583 billion, with 79% of those ending up in landfills (Khan et al., 2022). The use of PET waste in concrete manufacturing is of great interest. Previous research has mainly used PET waste as reinforcement (Foti, 2013) or as natural aggregate replacement in concrete manufacturing (Nikbin et al., 2016; Sadrmomtazi et al., 2016). Incorporating PET waste into concrete as natural aggregate replacement is more beneficial as it helps preserve natural resources and provides sustainable solution for disposing plastic waste (Tang et al., 2019). However, previous research demonstrated that size, form, and quantity of PET in the mixture greatly impacted mechanical performance of concrete (Babafemi et al., 2018). Despite several studies on strength parameters of concrete incorporating PET waste, there is limited research on durability characteristics of PET concrete, especially when used as fine aggregate substitution.

It is beneficial to highlight durability properties of concrete containing plastic waste before exploring durability characteristics of concrete incorporating PET granules. This is because examining the durability characteristics of concrete containing PET aggregates is critical for understanding its long-term serviceability, especially when exposed to adverse environmental conditions (Maekawa et al., 2015). It is not well understood how PET may deteriorate with time in a cement binder and affect the interracial transition zone (ITZ). Mohammed et al. (Mohammed et al., 2019) investigated abrasion resistance and water absorption of concrete with shredded PVC waste (0 - 10 mm) as partial (5% - 85%) replacement by volume of coarse aggregate. They found that increasing PVC aggregate adversely affected water absorption of concrete, where the specimen with 85% PVC content demonstrated 12% water absorption compared to 5% for reference concrete. This reduction was explained based on the reduced concrete mass packing and a poor transition zone due to the flakiness of plastic particles. The abrasion resistance improved with increasing PVC waste in the mix, where specimen with 85% PVC displayed 111% decrease in abrasion value relative to reference concrete which was attributed to the crack control ability and plasticity of PVC relative to natural aggregate. Won et al. (Won et al., 2010) added recycled PET fibre (50 mm) as 1% volume fraction of concrete. They reported that 1% PET fibre improved chloride permeability, and freeze/thaw performance of concrete by 11% and 5%, respectively, over control specimen. A similar study by Yesilata et al. (Yesilata et al., 2009) added PET waste in varying geometries (square, strip, irregular) as 0.9% volume fraction of concrete. They found that thermal insulation of specimen containing square shape PET waste increased by 10% compared to control. However, the performance further improved for specimens containing strip and irregular shape PET waste, increasing by about 17% compared to control. This behaviour was attributed to the greater adhesion of strip and irregular shape PET waste to concrete matrix than square shape. Choi et al. (Choi et al., 2009) examined sorptivity coefficient of the cement mortar by substituting 25% to 75% of fine aggregate with PET particles (5-15 mm). It was reported that sorptivity of the cement mortar with 25% PET particle achieved the optimal performance, improving 56% over conventional concrete. The performance degraded with increasing PET particle in cement mortar, which was caused by higher porosity of cement mortars with a larger replacement ratio.

While previous research has used PET waste in various size and shapes, including fibre, flake, and strip, the granule form has not been given much attention (Kangavar et al., 2022). The granular PET has a sub rounded form and dimension close to sand which may contribute to homogeneity in the mix, leading to better durability performance than fibre, strip, and flake shapes with a larger surface area (Quiroga, 2003). The use of granular PET in concrete could be of tremendous ecological and energy saving advantages in recycling industry as no additional treatment or colour removal is required unlike other conventional recycled materials, while also being economical as they do not need to be converted into strips or fibres (Albano et al., 2009; Kangavar et al., 2022). Incorporating PET granules as partial replacement for sand demonstrated positive impact on ductility, crack propagation, and materials properties of concrete up to 30% replacement ratio (Kangavar et al., 2022). Yet, there is limited knowledge on long-term behaviour of concrete incorporating PET granules including alkali silica reaction (ASR), shrinkage, creep, water absorption, and rapid chloride penetration (RCPT). Present study bridges these gaps in literature by employing PET granules with grain sizes comparable to sand so as to mitigate the effect of different grading on concrete characteristics (Kangavar et al., 2022). The apparent volume of permeable voids (AVPV) test was performed to evaluate porosity of concrete with PET aggregate. Additionally, the accuracy of four current shrinkage models for predicting experimental results was evaluated and a multiple linear regression model was proposed for predicting shrinkage of concrete containing PET aggregates.

2 Experimental investigation

2.1 Materials

Portland cement (general purpose) with specific gravity of 3.1 g/cm^3 was used. The coarse aggregate had nominal size of 10 mm. River sand was used as fine aggregate, which had water absorption and specific gravity of 0.7 and 2.7, respectively. The PET granules were made from PET bottles using granulator machines without any treatment. The PET aggregate featured a relatively spherical form and rather fine surface (Kangavar et al., 2023) (Figure 1), with water absorption of 0.02 and specific gravity of 1.24. The sieve analysis was conducted to produce PET granules with a size comparable to sand. Figure 1 depicts grading curves of fine aggregate components and Australian standard limitations (AS2758.1, 2014).

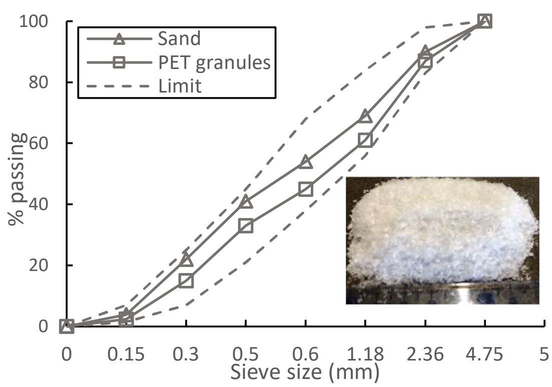


Figure 1 Grading curves for sand and PET granules

Table 1 Fine aggregate quantity of concrete mix (kg/m^3)

Material	Sand	PET granules
Control	650	-
10% PET	589	51
30% PET	485	148
50% PET	375	240

2.2 Mix proportions

The characteristic strength of concrete mix was 32 MPa. The mix ratio by weight was 1:1.5:3 for cement, fine and coarse aggregates (Kangavar et al., 2022). Water/cement ratio was 0.45. PET granules were used as 10%, 30%, and 50% volumetric replacement for sand. The proportion of water, cement, and coarse aggregate per m^3 was constant for all batches at 185

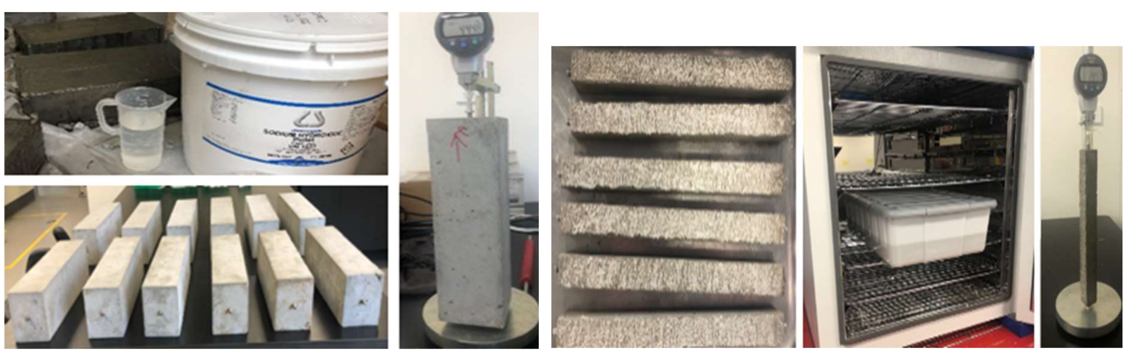
(L), 440 (kg), and 1320 (kg), respectively. Table 1 presents proportions of PET granules and sand in each concrete batch.

3 Instrumentation and test procedure

3.1 Evaluation of alkali-silica reactivity (ASR)

3.1.1 Concrete prism test (CPT)

The long-term ASR expansion of each concrete mix was evaluated using three concrete prisms with dimension of 75 mm width, 75 mm depth and 285 mm length according to AS 1141.60.2 (AS1141.60.2, 2014). Each end of the specimens was fitted with a gauge stud to provide accurate comparator readings as per AS 1141.60.2 (AS1141.60.2, 2014). The water/cement ratio was 0.45 and concrete mix was carried out in accordance with AS 1141.60.2 (AS1141.60.2, 2014). The possible ASR reaction was artificially accelerated by elevating alkali concentration of the mixtures with adding calcium hydroxide by 1.25% of cement's mass, and storing the samples at a high curing temperature (38°C) during the test (AS1141.60.2, 2014). Figure 2(a) depicts the test setup. The expansion measurements were taken for one year according to AS 1141.60.2 (AS1141.60.2, 2014).



(a) (b)

Figure 2 ASR test setup (a) CPT, (b) AMBT

3.1.2 Accelerated mortar bar test (AMBT)

The AMBT test was performed on three mortar bars measuring 25 mm width, 25 mm depth, and 285 mm length, with gauge studs placed at both ends to evaluate potential ASR of each mix according to AS 1141.60.1 (AS1141.60.1, 2014). Figure 2(b) the AMBT setup. All of the mortar batches contained same quantity of cement and water, measuring 440 (g) and 205 (mL), respectively. Table 2 presents the amount of fine aggregate for each mortar batch. Table 3 presents sieve analysis for PET granules according to grading requirements for fine aggregate outlined in AS 1141.60.1 (AS1141.60.1, 2014). The expansion was calculated for 21 days as per AS 1141.60.1 (AS1141.60.1, 2014).

Table 2 Fine aggregate quantity of mortar mix (each batch)

Material	Sand (g)	PET granules (g)
Control	990	-
10% PET	896	84
30% PET	791	172
50% PET	681	264

Table 3 Grading requirements of PET granules (mortar mix)

Sieve size (mm)		Mass (%)	PET granules (g)		
Passing	Retained		10%	30%	50%
4.75	2.36	10	8.4	17.2	26.4
2.36	1.18	25	21	43	66
1.18	0.6	25	21	43	66
0.6	0.3	25	21	43	66
0.3	0.15	15	12.6	25.8	39.6

3.2 Creep test

The creep strain test was performed on the cylindrical specimens (100 mm in diameter and 200 mm in height) after 28 days curing and continued for 90 days according to AS 1012.16 (AS1012.16, 2014). For each concrete mix, two specimens were used for creep strain test, and three companion specimens were used for 28-day compressive strength test prior to the creep test according to AS 1012.16 (AS1012.16, 2014). The specimens for creep test were piled in the hydraulic spring-loaded creep machine and loaded to 40% of average compressive strength for each batch, with the sustained load during the test. One strain gauge was attached to the mid-height of each specimen which was connected to an automated data collecting system. Figure 3 illustrates the creep test setup. The creep strain of each concrete mix was calculated according to AS 1012.16 (AS1012.16, 2014). Subsequently, creep coefficient was calculated by dividing the creep strain by elastic strain.

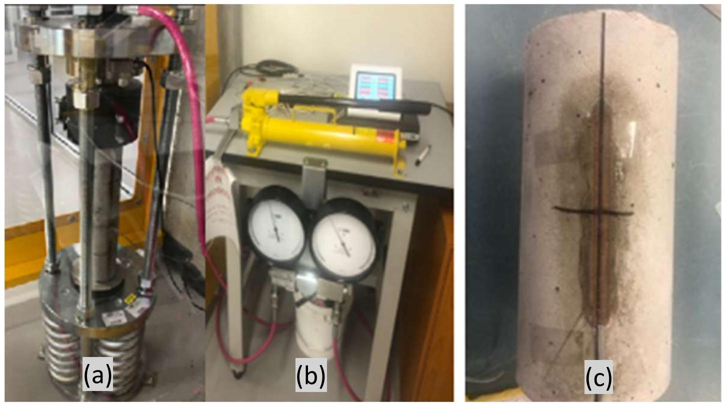


Figure 3 Creep test setup, (a) hydraulic spring-loaded machine, (b) Automated data collecting system, (c) specimen with strain gauge.

3.3 Drying shrinkage test

The drying shrinkage test was performed on three prism specimens (75 mm x 75 mm x 280 mm), with the studs inserted at the ends of each specimen for each mix in accordance with AS 1012.13 (AS1012.13, 2015). The prisms were removed from moulds after 24 hours and submerged in the lime-saturated water for 7 days before being stored at 23°C and 50% humidity room. The shrinkage of each specimen was measured until one year according to AS 1012.13 (AS1012.13, 2015). Figure 4 illustrates the shrinkage test setup.

Figure 4 Shrinkage test setup

3.4 Water absorption and apparent volume permeable voids (AVPV) tests

Both water absorption and AVPV tests were performed on four equal concrete slices cut from a cylindrical specimen (100 mm in diameter and 200 mm in height) for each batch according to AS 1012.21 (AS1012.21, 2014). Both tests were conducted after 28, 60 and 90 days. Figure 5 shows the test setup. The water absorption and AVPV were calculated according to AS 1012.21 (AS1012.21, 2014).

Figure 5 water absorption test setup

3.5 Rapid chloride penetration test (RCPT)

The RCPT test for each concrete mixture was performed on two specimens (100 mm in diameter and 50 mm in height) which were cut out of cylindrical specimen (200 mm height) according to ASTM C1202 (ASTM C1202, 2012). Each specimen was vacuum-saturated using vacuum chamber and placed within two cells. One cell contained 3% sodium chloride (NaCl) solution, whereas the other cell was filled with 0.3 N sodium hydroxide (NaOH) solution. Two liquid cells were subjected to a 60 V direct current for 6 hours. Chloride penetration was measured using total charge passed through each specimen using Rapid Chloride Permeability tester (220V, 60Hz). Figure 6 depicts RCPT setup. The test was carried out after 28 and 90 days.

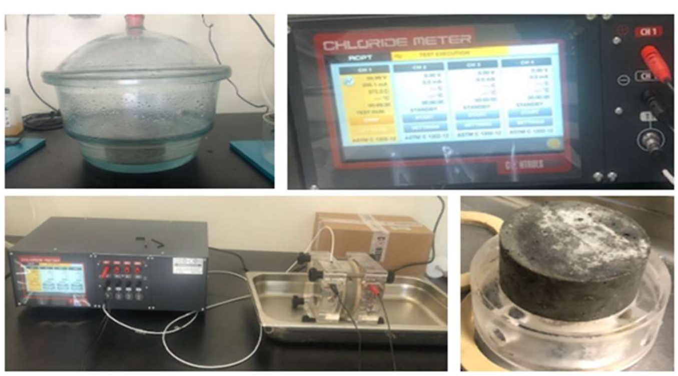


Figure 6 RCPT setup

3.6 Scanning electron microscopy analysis (SEM)

The microstructure of each concrete mix, and its effect on durability characteristics was examined using SEM observations. The analysis was conducted on small samples with 40 mm thickness, cut from cylindrical specimens for each concrete mix after 28 days and one year.

3.7 Fourier-transform infrared spectroscopy (FTIR)

The FTIR analysis was conducted to evaluate any changes in the chemical composition of PET granules when exposed to alkali solution for one year at 38°C. The potential deterioration of PET granules was examined by comparing the standard frequency patterns and chemical bonds of alkali-conditioned PET with reference PET.

4 Results and discussions

4.1 Alkali-Silica reactivity (ASR) expansion

4.1.1 Concrete prism test (CPT)

Figure 7 depicts ASR expansion results of the concrete mixtures over one year. It is evident that the expansion of all the mixes exhibited noticeable increasing trend until 180 days and started to decelerate thereafter. The one year expansion of 10% PET specimen was close to that of the control, with only 2% decrease. However, increasing proportion of PET aggregates resulted in substantial reduction in ASR expansion, where the one year expansion of concrete prisms with 30% and 50% PET aggregates decreased by 15% and 23%, respectively, relative to control prism. Nevertheless, the one year expansion value of all the mixtures was below the allowable limit of 0.03% specified in AS 1141.60.2 (AS1141.60.2, 2014).

The reduction in ASR expansion for the specimens with 30% and 50% replacement ratio could be related to increasing air voids inside the mix (as demonstrated in section 4.4 and 4.6), allowing ASR gel to accommodate inside the voids and eliminating the pressure caused by ASR gel (Hernández-Cruz et al., 2016; Jensen et al., 1984; Kashani et al., 2019). Previous studies also found a reduction of ASR expansion for concrete containing different types of plastic waste compared to conventional concrete (Giaccio et al., 2019; Junco et al., 2012). Figure 8 shows the SEM images of surface morphology of PET granules in concrete mix after 30 and 360 days exposure to the alkaline solution. It is apparent that surface of the PET granules did not deteriorate over time, indicating that PET granules had no chemical reaction in alkaline conditions. Furthermore, the FTIR spectra of the reference and alkali-conditioned PET granule are shown in Figure 9. The spectra of both reference and alkali-conditioned PET granule showed the characteristic peak of C=O groups at 1712 cm^{-1}. It is evident that infrared spectrum pattern of alkali-conditioned PET is comparable to that of reference PET with no changes to the intensities or position of the characteristic peaks, suggesting that there was no reaction or dissolution of PET granules when exposed to alkaline conditions after one year at 38°C. This conclusion is in line with SEM observations.

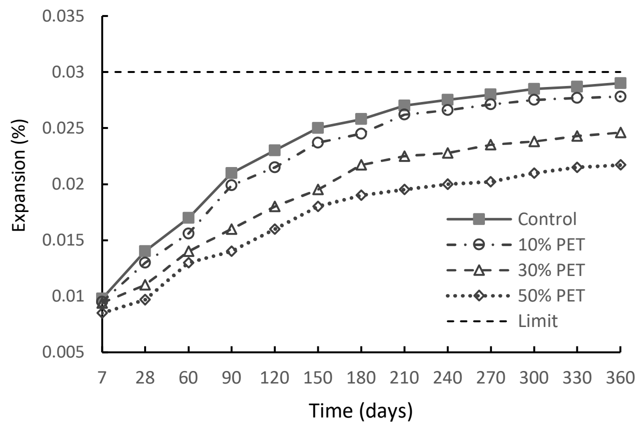


Figure 7 ASR expansion of concrete prisms.

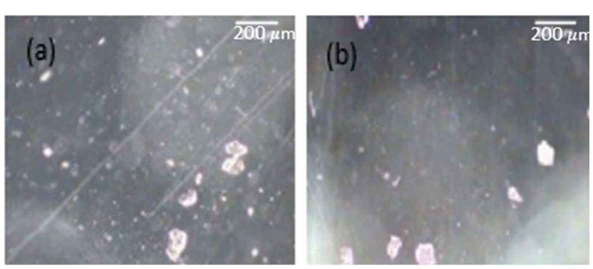


Figure 8 Surface morphology of PET granules in alkaline solution (a) 30 days, (b) 360 days

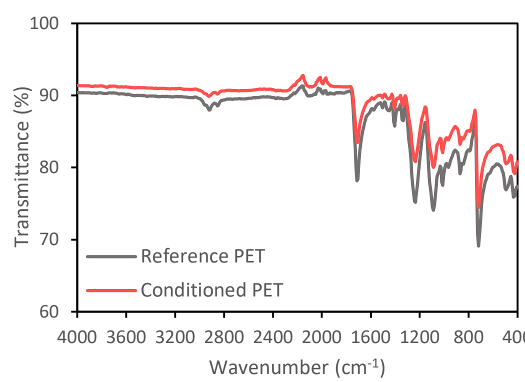


Figure 9 FTIR spectra of PET granule

4.1.2 Accelerated mortar bar test (AMBT)

The ASR expansion of mortar bars was measured for all mixes to evaluate consistency of the results of 21-day AMBT with those of one-year CPT. Figure 10(a) depicts ASR expansion of mortar bars. Although the expansion of mortar bars for all mixtures exhibited an ascending trend with time, the expansion was more pronounced with the control and 10% PET specimens. The specimen containing 10% PET granules exhibited an expansion value of 0.086%, which was very close to the control specimen with the value of 0.089%. However, the expansion value for the 30% and 50% PET specimens reduced noticeably with values of 0.07% and 0.06%, respectively. Overall, the 21 day expansion of all the mixes were less than 0.1%, classifying as non-reactive according to AS 1141.60.1 (AS1141.60.1, 2014).

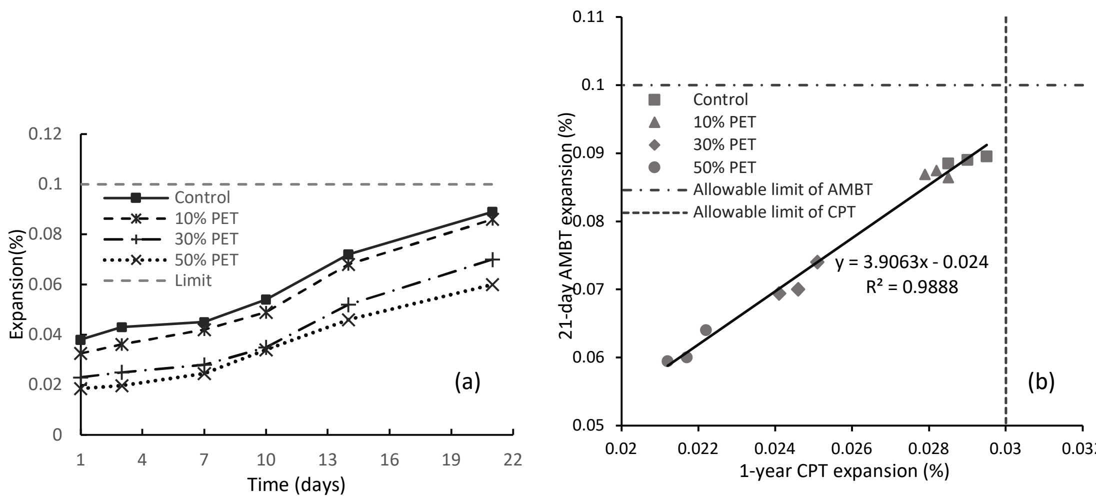


Figure 10 (a) ASR expansion of mortar bars, (b) Relationship between CPT and AMBT

It is noteworthy that the expansions of mortar bars (Figure 10(a)) and concrete prisms (Figure 7) followed a similar trend. Figure 10(b) depicts the correlation between one-year CPT and 21-day AMBT expansions of all the mixtures. It is evident that the AMBT expansions of the mixes corresponded to increase in CPT expansions. Moreover, both test methods revealed a linear correlation with a coefficient (R^2) value of 0.988. Consequently, both AMBT and CPT methods might be used for measuring ASR expansion of the concrete containing PET granules, albeit the CPT approach is typically recommended due to being less aggressive and providing a longer period for aggregates to exhibit any reactivity (Fanijo et al., 2021).

4.2 Creep

In general, creep deformation is caused by evaporation of free water existing in matrix voids because of consolidation of cement paste (basic creep), and drying environment (drying creep) under constant load (Alyousef et al., 2020). Figure 11(a) depicts the creep coefficient results. It is noteworthy that elastic modulus of the specimens with 0%, 10%, 30% and 50% PET aggregate content was calculated by dividing the applied load by average immediate strain under a loading/strength ratio of 40% (AS1012.16, 2014), and the results were 22 GPa, 21.4 GPa, 20 GPa, and 18.5 GPa, respectively. It is apparent that creep coefficient of the PET concrete at all replacement ratios was comparable to the control specimen for the first five days and started to diverge afterwards. Given that early age creep of concrete contributes significantly to early age cracking of concrete structures (Briffaut et al., 2012), this observation indicates that PET granules had no negative effect on the cracking behaviour of concrete. However, the creep coefficient of all the mixtures increased rapidly up to 28 days, which could be due to the rapid development of shrinkage strain and microcracks under constant load, inducing further self-healing and drying of the specimens (Altoubat and Lange, 2001; Rossi et al., 2012). The creep deformation increased at a slower rate after 28 days, which might be explained by increasing hydration process of cement with time (Afroughsabet and Teng, 2020). Incorporating 10% PET granules had minimal impact on the creep coefficient of concrete, decreasing only 1% at 90 days relative to the control. However, the 90-day creep coefficient for the specimens with 30% and 50% replacement ratio increased by 9% and 23%, respectively, relative to the control. Similarly, as illustrated in Figure 11(b), the creep strain of the specimens with 10% substitution rate decreased by 1.5% compared to the control, and performance started to decline with higher substitution rates, where the value for specimens with 30% and 50%

substitution rate increased by 8% and 19%, respectively, relative to the control specimens. The small improvement in creep behaviour of the 10% PET specimen could be related to the fact that PET granules absorb less water than sand, leading to a more homogeneous composition with reduced porosity at low replacement ratios which results in less moisture evaporation and creep deformation (Afroughsabet and Teng, 2020). The performance deterioration with increasing PET percentage could be related to lower modulus of elasticity of PET concrete compared to control concrete (Hannawi et al., 2010), and the increased air voids of the concrete mixes resulted from higher quantity of PET aggregates (as demonstrated in section 4.4 and 4.6), thereby reducing resistance to the creep deformation (Tang et al., 2008). The creep behaviour of concrete incorporating PET aggregates has not previously been studied. Nevertheless, Aslani and Nejadi (Aslani and Nejadi, 2013) investigated the creep strain of concrete reinforced with polypropylene (PP) fibres as a volume fraction of concrete and found that creep strain increased with increasing PP fibres in concrete. Furthermore, average compressive strength of the specimens containing 0%,10%, 30% and 50% PET aggregates were 31.8 MPa, 33.6 MPa, 30.3 MPa and 26.4 MPa, respectively. Figure 11(b) shows that 90-day creep strain and corresponding 28-day compressive strength of the specimens were inversely proportional, indicating that compressive strength influenced the creep strain of the concrete mixtures (Khan et al., 1997).

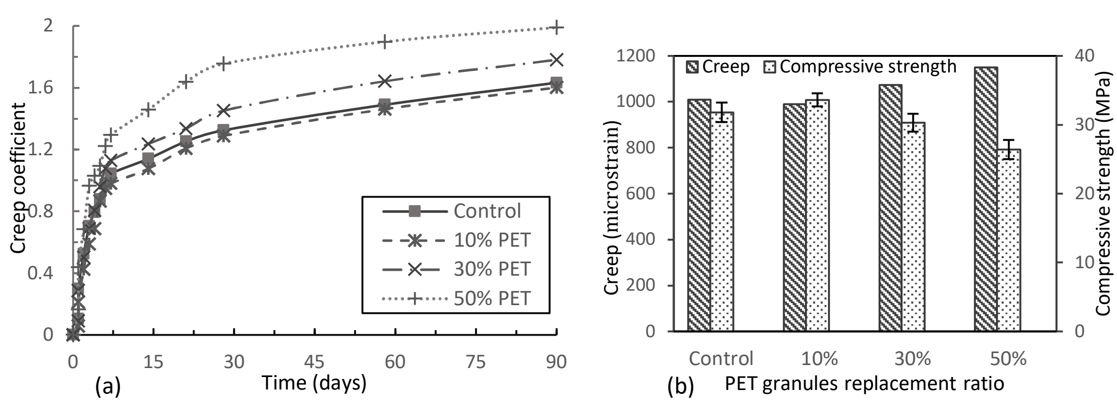


Figure 11 (a) creep coefficient, (b) creep strain and compressive strength of concrete mixes

4.3 Drying shrinkage

The drying shrinkage of concrete is mostly due to capillary water evaporation (Zhang et al., 2022). The average shrinkage results are presented in Figure 12. It is evident that most of the drying shrinkage for all the mixes occurred during the first 90 days and tended to plateau afterwards. This behaviour indicates that the capillary water for all mixes evaporated mostly over the first 90 days, leading to self-desiccation and consequently increased drying shrinkage by producing stress on the pore walls (Afroz et al., 2023). The reduced rate of shrinkage strains after 90 days could be related to the fact that cement hydration process increased over time, resulting in less porosity and lower drying shrinkage (Afroughsabet and Teng, 2020). Since the shrinkage curves for all mixes almost reached a plateau, the shrinkage strains at one year are referred to as ultimate shrinkage. The ultimate shrinkage of 10% PET specimen was close to the control mix with only 1% increase, while showing slightly higher shrinkage for the first 90 days. The specimens with 30% and 50% replacement ratio yielded relatively similar shrinkage strains to control mix during the first 7 days and started to vary thereafter. The ultimate shrinkage strain of 30% and 50% PET specimens increased by 7% and 10%, respectively, relative to control specimen. The negligible impact of 10% PET granules on drying shrinkage strain might be explained by homogeneous composition of PET concrete at low replacement level, resulting in less porosity as illustrated in section 4.4. Conversely, the noticeable increase in drying shrinkage for the 30% and 50% PET specimens could be related to reduction of elastic modulus (Fujiwara, 2008), and the presence of excess water in concrete mix due to increased porosity of the mixes with higher quantity of PET granules (Alsayed and Amjad, 1996). This conclusion is consistent with the previous studies using different plastic waste aggregates in concrete. For example, Sabaa and Ravindrarajah (Sabaa and Ravindrarajah, 1997) found that using polystyrene waste granules as a partial substitution for coarse aggregate had negative impact on drying shrinkage of concrete, with 240-day shrinkage value of 1000 microstrain for

70% polystyrene concrete, up from 625 microstrain for normal concrete. Similarly, Islam et al. (Islam et al., 2022) reported that increasing percentage of polypropylene waste aggregates in concrete as coarse aggregate replacement was proportionate to the increase of drying shrinkage strain. However, the values of the present study for all of the mixes were less than maximum permissible values of 800 microstrain specified by AS3600 (AS3600, 2018) and ACI-209 (ACI-209, 1992).

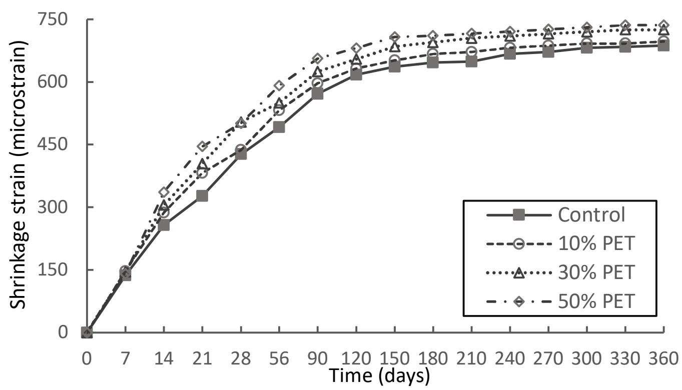


Figure 12 Shrinkage strain of the concrete mixtures

4.4 Water absorption and AVPV

Figure 13 (a) and (b) depict the water absorption and AVPV results, respectively. It is apparent that replacing 10% volume of sand by PET granules had almost no impact on water absorption and AVPV of concrete, with a difference of less than 0.5% relative to the control specimen at all curing ages. However, the performance deteriorated with increasing PET aggregate replacement level in concrete, where the 30% and 50% PET specimens exhibited increases of 7% and 19% in water absorption, and 6% and 17% in AVPV, respectively, over control specimen at 28 days. While water absorption of all the mixtures decreased over time, the values for the 30% and 50% PET specimens remained higher than control specimen at all curing ages which could be due to the increased permeable voids (Sheraz et al., 2023). The reduction in water absorption with time might be due to the fact that concrete matrix becomes denser with extended curing time (Sadawy and Nooman, 2020; Sahoo et al., 2021). It is evident that water absorption and AVPV results followed the same trend, indicating that increasing permeable voids in the 30% and 50% PET specimens resulted in higher water absorption. This behaviour could be caused by uneven distribution of PET aggregates in the mixes with higher replacement ratios as specific gravity of PET granules (1.24) is less than sand (2.7), resulting in increased porosity (Gu and Ozbakkaloglu, 2016). However, the improved performance of the 10% PET specimen could be related to lower water absorption of PET aggregates compared to sand, and relatively uniform dispersing of PET aggregates at low replacement level, resulting in enhanced compactness (Kangavar et al., 2022). This phenomenon is supported by SEM observations (section 4.6). These findings are in line with those of (Gu and Ozbakkaloglu, 2016; Mohammed et al., 2019), who reported that water absorption increased by increasing percentage of plastic aggregate in concrete mix. Figure 14 shows the correlation of compressive behaviour with AVPV and water absorption at 28 days. It is obvious that water absorption and AVPV results are inversely correlated with the compressive strength behaviour. Furthermore, the compressive behaviour demonstrated a strong linear correlation with water absorption and AVPV results, with coefficient (R^2) values of 0.9179 and 0.9212, respectively. Thus, water absorption and AVPV of concrete containing PET granules may be safely estimated from the respective compressive strength.

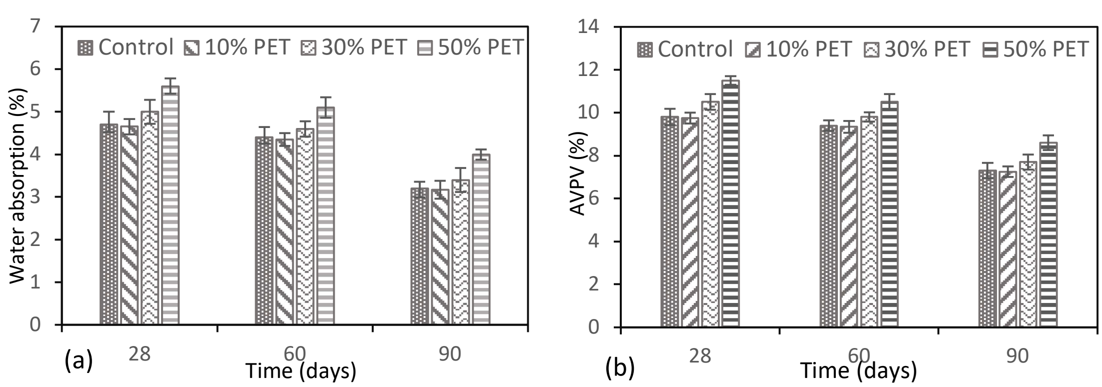


Figure 13 (a) Water absorption, (b) AVPV

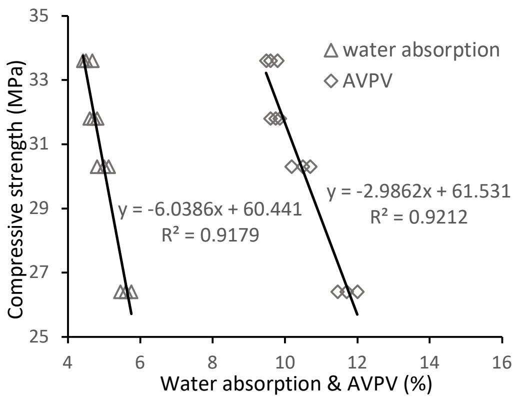


Figure 14 Relationship of compressive strength with AVPV and water absorption

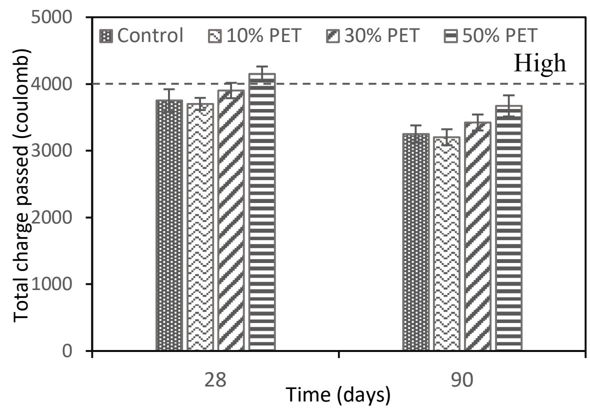


Figure 15 RCPT test results

4.5 Rapid chloride penetration test (RCPT)

Figure 15 depicts the RCPT results of all the mixtures. The specimen containing 10% PET granules demonstrated relatively enhanced resistance against the chloride penetration at both 28 and 90 days, improving by 1.5% and 2.5%, respectively, compared to the control specimen. Incorporating 30% PET granules had minimal impact on chloride penetration at 28 and 90 days, with only 2% and 3.5% increase relative to control specimen. However, the 50% PET specimen exhibited the highest penetration at both 28 and 90 days, increasing by 12% and 13%, respectively, compared to control specimen. The charge passing through the specimen with 50% PET content at 28 days with the value of 4150 coulombs was slightly higher than the maximum limit (400 coulombs) recommended by ASTM C1202 (ASTM C1202, 2012), classifying as high permeable concrete. The optimum performance of the 10% PET specimen could be related to the electrical resistance of PET granules (Bui et al., 2018). However, the gradual increase of chloride penetration for the 30% and 50% PET specimens may be explained by increasing porosity of concrete as the replacement level increased (as illustrated in section 4.4 and 4.6). This conclusion is in line with the previous studies (Silva et al., 2013; Soroushian et al., 1999), who agreed on increasing chloride penetration of concrete with higher plastic waste content.

4.6 SEM analysis

Figure 16 shows SEM images of the mixtures. It is evident that 10% PET concrete exhibited a decent compactness and homogeneity due to the consistent dispersion of PET aggregates throughout the mix, which is comparable with that of control mix. However, increasing PET granule percentage to 30% and 50% increased the porosity of concrete, where the 50% PET specimen exhibited more cavernous structure with larger air void. Figure 16(e) and (f) show the PET granule aggregates in the 50% PET concrete after one year. Although PET granules did not deteriorate over time, relatively large gaps formed between PET granules and the matrix, which could be because of hydrophobic nature of PET aggregates, resulting in the accumulation of free water around PET granules at high replacement level. As a result, the free water evaporated over time, resulting in poor adhesion and increased porosity between the matrix and the PET granules. This phenomenon can explain the reduction of durability properties, mechanical characteristics, structural behaviour as well as bond strength when the substitution rate exceeded 10% (Kangavar et al., 2022; Kangavar et al., 2023). These observations are in line with those of Hannawi et al. (Hannawi et al., 2010), who conducted SEM analysis on concrete samples incorporating PET particles as a partial substitution of sand, the majority of which were 6.3 mm in size. They observed increased porosity with increasing PET percentage in concrete, which resulted in increased gas permeability.

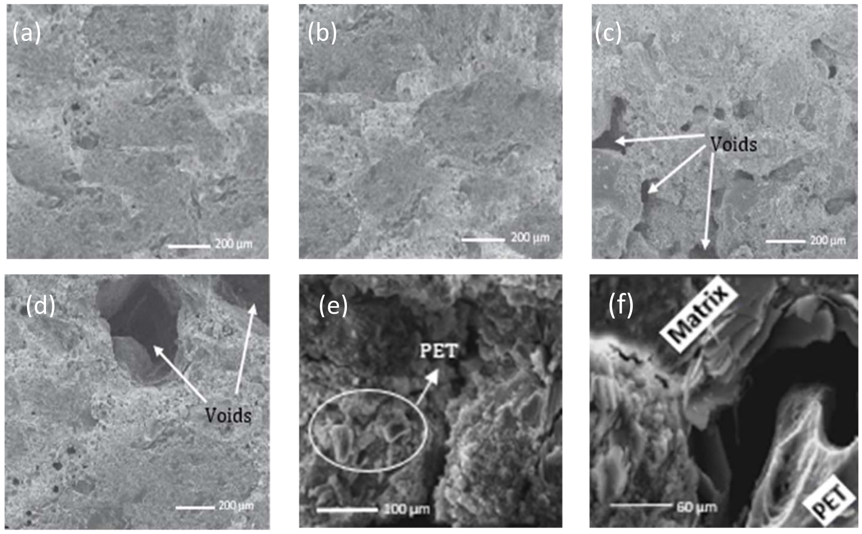


Figure 16 SEM images of (a) control, (b) 10% PET, (c) 30% PET, (d, e, f) 50% PET

4.7 Shrinkage models

4.7.1 Comparison of current shrinkage models with experimental results

The concrete shrinkage prediction throughout its lifespan is an important part of durability design (Liu et al., 2020). The shrinkage values calculated from four current shrinkage models for normal concrete including ACI-209 (ACI-209, 1992), AS 3600 (AS3600, 2018), B3 (Bazant and Murphy, 1995), and Eurocode 2 (Eurocode 2, 2004) (Eqs.1-4) were compared with the experimental findings to evaluate the reliability of the current models for concrete incorporating PET granule aggregate.

ACI-209 model (ACI-209, 1992):

$$\varepsilon_{sh}(t) = \frac{t}{f+t}\,\varepsilon_{shu} \quad (1)$$

Eurocode 2 model (Eurocode 2, 2004):

$$\varepsilon_{cd}(t) = \beta_{ds}\,(t, t_s)\; k_h \varepsilon_{cd,0} \quad (2)$$

B3 model (Bazant and Murphy, 1995):

$$\varepsilon_{sh}(t, t_0) = \varepsilon_{sh\infty}\; k_h\; \mathrm{S(t)} \quad (3)$$

AS 3600 model (AS3600, 2018):

$$\varepsilon_{cs}(t) = (1 - e^{-0.07t})\varepsilon_{cse}^{*} + \; k_1\, k_4 \varepsilon_{csd.b} \quad (4)$$

where $\varepsilon_{sh}(t)$, $\varepsilon_{cd}(t), \varepsilon_{sh}(t, t_0), \varepsilon_{cs}(t)$ are shrinkage strain at any time (μs), t is concrete age (days), t_0 is concrete curing age (days), ε_{shu} and $\varepsilon_{sh\infty}$ are ultimate shrinkage (μs), f = 35 for normal concrete (days), β_{ds} and S(t) are coefficients for the shrinkage development over time, k_h is a coefficient for humidity, $\varepsilon_{cd,0}$ and $\varepsilon_{csd.b}$ are basic drying shrinkage (μs), ε_{cse}^{*} is final autogenous shrinkage strain (μs), k_1 is a coefficient related to time and shape of specimen, k_4 is the coefficient related to influence of the environment, e is logarithm's base number.

Figure 17 depicts the comparison of shrinkage models with experimental findings. It is apparent that predictions of all the models underestimated the experimental results for all mixes, especially for the specimens containing PET granules. However, ACI-209 (ACI-209, 1992) model predictions were closer to the experimental findings, with the maximum difference of 8%, 13%, 17%, and 20% for the control, 10% PET, 30% PET, and 50% PET concrete, respectively. The improved performance of the ACI-209 (ACI-209, 1992) model could be related to the fact that, unlike the other models, the ACI-209 (ACI-209, 1992) model considers fine aggregate percentage in calculating ultimate shrinkage of concrete (Fernandez-Gomez and Landsberger, 2007).

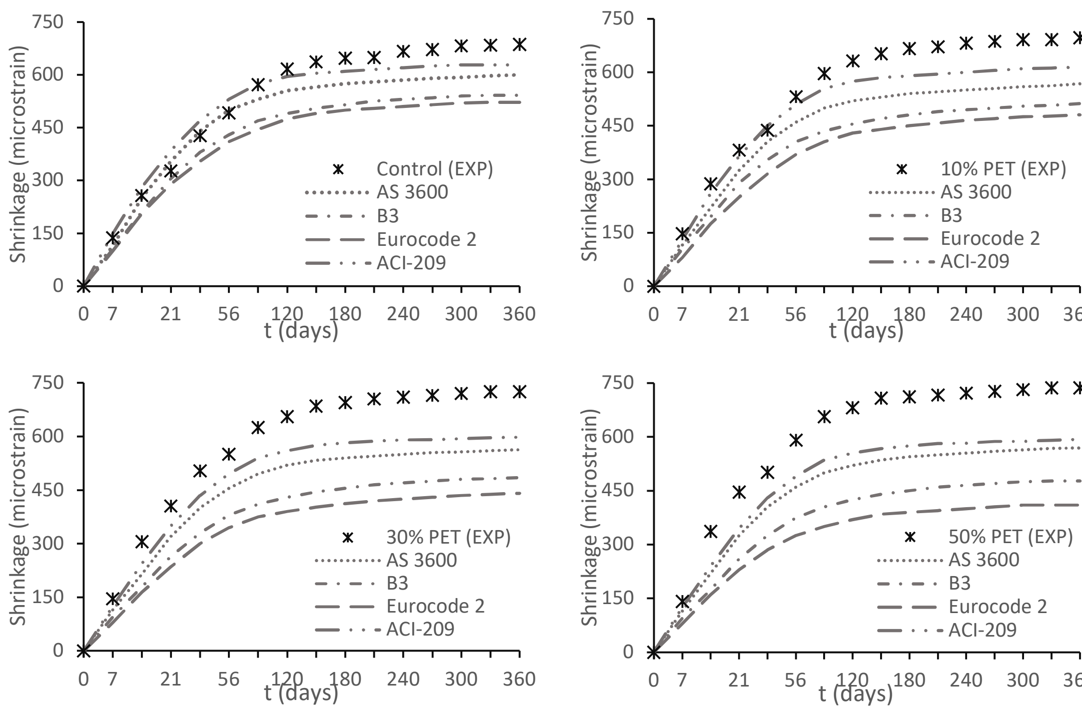


Figure 17 Comparison of current prediction models with experimental results

4.7.2 Proposed shrinkage model

The predictions of ACI-209 model (ACI-209, 1992) were closer to the experimental values than the other models. Therefore, the ACI-209 model (ACI-209, 1992) was modified to account for the effect of varying percentage of PET granules in calculating shrinkage strain. According to the ACI-209 model (ACI-209, 1992), time-ratio = $t/(f + t)$ as shown in Eq (1), where f value is considered 35 for normal concrete. Given that shrinkage strain increased with increasing PET percentage, decreasing f value would increase the time-ratio, leading to higher shrinkage strain (Mushtaq et al., 2021). Therefore, the linear regression analysis was performed for experimental $\varepsilon_{sh}(t)$ / ε_{shu} and time ratio (f < 35) so as to find the best f value with higher correlation coefficient (R^2). The constant f with the value of 22 achieved the highest R^2 of 0.984 as shown in Figure 18, and thus was selected for the proposed model. Subsequently, the multiple linear regression (MLR) analysis was conducted using PET percentage (P_r), time-ratio, and compressive strength (f_c) as independent variables, and shrinkage strain at any time (ε_{sht}) as dependent variable. Table 4 presents the MLR outputs. As shown in Table 4(a), the P-value for f_c was higher than 0.5, suggesting that compressive strength was not contributing significantly to shrinking strain (Kumar et al., 2016). Consequently, the MLR analysis excluding compressive strength variable was run and the results demonstrated that time-ratio and PET percentage are the significant contributors with the P-values of 0.00 as presented in Table 4(b). Equation 5 presents the proposed MLR model for shrinkage strain of concrete incorporating PET granules as a replacement for fine aggregate. In Eq (5), $\varepsilon_{sh(t)}$ is shrinkage strain at any age (μs), t is concrete age (days), and P_r is the replacement ratio of PET granules. Figure 19 depicts the shrinkage predictions of proposed model in comparison to the experimental findings. It is apparent that proposed model accurately predicted the experimental results for all the mixtures with less than 1% variation.

$$\varepsilon_{sht} = \frac{780t}{22+t} + 5.12P_r - 1.1 \quad (5)$$

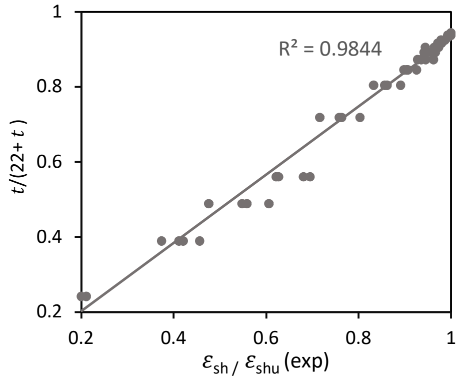


Figure 18 Linear regression of time-ratio and ε_{sh} / ε_{shu}

Table 4 Multiple linear regression outputs.

Variables	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%
(a)						
Intercept	-0.65	6.73	-0.98	0.28	-1.47	0.17
time-ratio	780	2.84	88.7	0.00	762	797
P_r	4.82	0.19	12.6	0.00	4.42	5.22
f_c	-1.22	1.4	-0.87	0.61	-3.71	1.27
(b)						
Intercept	-1.1	2.61	4.18	0.00	0.89	1.51
time-ratio	780	2.83	88.8	0.00	762	797
P_r	5.12	0.12	18.45	0.00	4.87	5.37

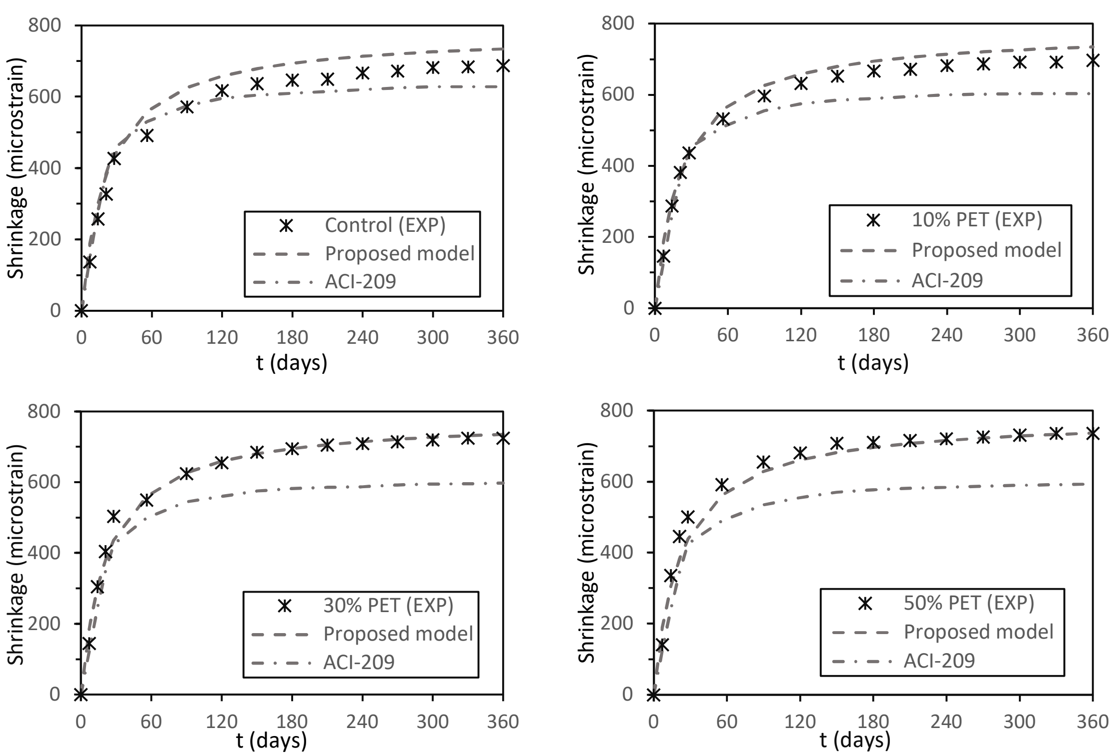


Figure 19 Comparison of experimental results with proposed model predictions

5 Conclusions

This study examined the effect of PET granule aggregates on the durability property of concrete. A series of experiments were conducted, including alkali silica reactivity (ASR) of 21-day mortar bar and one-year concrete prism tests, creep test, rapid chloride penetration test (RCPT), one-year shrinkage test, apparent volume of permeable voids (AVPV) and water absorption tests, along with theoretical analysis of shrinkage behaviour. Based on experimental findings and theoretical predictions, the following conclusions were made:

- Increasing percentage of PET granules in concrete and mortar mix positively contributed to ASR expansion as increased amount of PET granules in concrete/mortar contributed to reduced pressure associated with ASR gel trapped in the air voids, leading to less ASR expansion. The SEM and FTIR observations revealed that PET granules had no chemical reaction in alkaline environment.
- Incorporation of 10% PET granules marginally improved creep rate of concrete because of less water absorption of PET granules compared to sand, resulting in more homogeneous composition at low replacement level. However, performance declined with increasing PET percentage due to increased air voids and weak adhesion between concrete matrix and PET granules.
- Long-term drying shrinkage of concrete increased with increasing PET aggregate percentage due to lower elastic modulus and increased porosity of concrete, albeit shrinkage increase was less noticeable for 10% PET concrete.
- Incorporation of 10% PET granules had no effect on water absorption and apparent volume of permeable voids of concrete because of even dispersion of PET aggregates in concrete at low replacement ratio. The performance deteriorated with increasing PET percentage due to uneven dispersion of PET aggregates at high replacement ratio.

- Concrete containing 10% PET granules displayed improved resistance to chloride penetration because of electrical resistance of PET aggregates relative to sand. Although performance reduced with increasing PET content, the reduction was insignificant for concrete containing 30% PET granules. The increased porosity of concrete with higher PET content contributed to increased chloride penetration.
- Current shrinkage models based on the ACI-209 (ACI-209, 1992), AS 3600 (AS3600, 2018), B3 (Bazant and Murphy, 1995), and Eurocode 2 (Eurocode 2, 2004) standards underestimated experimental findings. A shrinkage model was proposed by considering the percentage of PET granule aggregates in concrete mix, and the results corresponded well with experimental findings.

Declaration and competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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5.2. Links and implications

The experimental results showed that increasing percentage of PET granules in the mixture reduced ASR expansion based on the 21-day mortar bar and one-year concrete prism tests. The inclusion of 10% PET granules marginally reduced creep rate of concrete, decreasing by 1% compared to the control concrete. Incorporating 10% PET granules improved chloride resistance of concrete, whereas 30% PET granule had almost no effect on chloride penetration of concrete. Furthermore, the incorporation of 10% PET granule aggregate showed no impact on water absorption and apparent volume permeable voids of concrete. The test results revealed that incorporating PET granules increased one-year shrinkage of concrete, albeit the increase was negligible for the concrete with 10% PET content. In addition, a shrinkage model was proposed for concrete containing PET aggregate, and the results agreed well with the experimental findings.

The significant findings of the study are presented in the **Chapter 6**, along with the recommendations for future study to further explore the benefits of this novel material. The findings of the studies presented in the following chapter could serve as a guide for future research into the properties of concrete incorporating PET aggregate.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

The use of waste materials in concrete manufacturing has become a sustainable approach to reduce environmental pollution. To date, several research have been conducted on the feasibility of waste materials in concrete fabrication, with plastic, glass and construction demolition waste being areas of interest. However, relatively few studies have investigated the properties of concrete containing recycled PET. Furthermore, most of these studies have focused on using PET waste as fibre reinforcement in concrete, while only limited literature is available on concrete containing PET waste as a replacement for constituents of concrete (fine or coarse aggregates). Previous research on the use of PET aggregates in concrete showed that shape and size of PET waste had considerable impact on concrete properties. The incorporation of PET aggregates in the form of fibre, flake, shredded with different sizes were investigated in the past and the results were variable. However, there is a lack of knowledge base on the effect of PET granules as aggregate replacement on the characteristics of concrete. Incorporating PET granules as fine aggregate replacement in concrete manufacturing could be beneficial due to their shape and dimensions comparable to sand, mitigating the impact of varying grading on concrete properties. Therefore, the present study focused on examining the characteristics of concrete incorporating PET waste in the form of granules as partial fine aggregate replacement. This study was conducted in the following three stages:

- Investigation on workability and mechanical properties including density, compressive strength, tensile strength, elastic modulus and flexural strength together with microscopic analysis. In addition, the crack mouth opening displacement of the PET concrete beams were examined using DIC system.
- Evaluation of bond behaviour between steel reinforcement and PET concrete mixtures, porosity analysis of PET concrete mixtures, and flexural and cracking behaviour of RC beams containing PET aggregates. Additionally, finite element modelling was performed to numerically simulate the flexural behaviour of the RC beams containing PET granules.
- Examination of long-term performance of concrete incorporating PET granule aggregates, including ASR expansion, creep strain, shrinkage strain, rapid

chloride penetration, water absorption and apparent volume of permeable voids.

The key findings achieved from the comprehensive studies included herein are presented below:

6.1. The effect of PET granules on mechanical property of concrete

The **objective 1** of the study was addressed by investigating the workability and strength parameters of concrete incorporating PET granules as partial replacement for fine aggregate (0%, 10%, 30%, and 50% by volume) to establish the effect of PET granule aggregate on the mechanical properties of concrete. The compressive strength, tensile strength and elastic modulus tests were conducted on cylindrical specimens (100 mm diameter and 200 mm height), while the flexural strength and crack mouth opening displacement tests were conducted on the concrete beams (150 mm x 150 mm x 700 mm). The variation of normalised parameters for previous studies was examined and compared with those of this study. The microscopic analysis was conducted on the concrete composites. Furthermore, the applicability of AS3600 (AS3600, 2018) and ACI (ACI Code, 2022) standards in predicting the strength parameters of the concrete with PET granule content was evaluated. The conclusions related to this study are summarised as follows:

- Incorporating 10% PET granules had no effect on the workability of concrete. Although the workability of concrete decreased with increasing PET granules percentage, the reduction was insignificant because of the relatively comparable shape and size of PET granules compared to sand.
- The inclusion of 10% PET granules slightly improved compressive strength of concrete. While compressive strength decreased with increasing PET percentage to 30% and 50%, the concrete with 30% PET content met the target compressive strength for Grade 32 concrete.
- The elastic modulus decreased with increasing PET granules in concrete. However, the reduction was less noticeable for concrete with 10% PET content. The presence of 10% PET marginally improved tensile strength of concrete and performance started to deteriorate with further increase of PET percentage.

- The incorporation of PET granules up to 30% replacement ratio improved the flexural strength and toughness of the concrete beams and performance started to decline with increasing PET proportion in concrete. PET granule aggregate had positive impact on post peak performance of the beams. However, the improvement was more apparent for concrete with 10% PET content.
- Incorporating 10% PET granules significantly improved the post-crack behaviour. Although the ultimate bearing capacity of the specimens with 30% and 50% PET were lower than control specimen, both specimens demonstrated improved post-crack performance due to the flexible nature of PET granules compared to sand.
- The SEM images exhibited even distribution of PET granules in the concrete with 10% PET content, while increasing percentage of PET granules to 30% and 50% resulted in uneven distribution and larger interfacial transition zone (ITZ). The findings of this study on mechanical properties of concrete containing PET granules demonstrated considerably better performance compared to the previous studies due to the shape and size of PET granules.
- The experimental results of strength parameters agreed well with predictions of AS3600 (AS3600, 2018) and ACI (ACI Code, 2022). Moreover, the inclusion of PET granules to Grade 32 concrete mix demonstrated substantial reduction in environmental pollution.

From the above findings, incorporating PET granule aggregate improved post peak performance of concrete. Moreover, the concrete incorporating 10% PET granules as fine aggregate replacement demonstrated the optimum performance on mechanical properties of concrete. The Australian and American design guidelines were found to be reliable in predicting the strength parameters of concrete containing PET granules. The impact of PET granule aggregate based concrete on the performance of structural members was investigated in the next stage.

6.2. The effect of PET granules on the behaviour of concrete beams

The flexural and cracking behaviour of RC beams with PET granule content were investigated. Furthermore, the bond strength between concrete containing PET granules and steel reinforcement was evaluated. The microstructural analysis was conducted to examine average diameter and area of the pores in the concrete mixtures. This addressed the **objective 2** of the study. The mix design was for grade 30 concrete and PET granules were used as a partial replacement (0%, 10%, 30%, and 50%) by volume of sand. The flexural and cracking behaviour were investigated on the RC beams measuring 100 mm width x 250 mm depth x 1400 mm length. The RC beams were under reinforced by design with 10 mm deformed bar as flexural reinforcement and 6 mm plain bar as transverse reinforcement. Theoretical evaluation was conducted on cracking and flexural moment of the RC beams and compared with the experimental results. Finite element modelling was conducted to simulate the load-deflection behaviour of RC beams with PET granule content. Lastly, the pull-out test was carried out on the cylindrical samples (100 mm in diameter and 200 mm in height) and 12 mm deformed bar embedded in centre of each sample. The following conclusions can be drawn from this study:

- The inclusion of 10% PET granules had positive impact on flexural capacity of the RC beam and the performance declined as the amount of PET granules in concrete increased. However, the presence of PET granules at all replacement level improved ductility behaviour of the RC beams because of the flexibility of PET aggregate.
- Incorporating PET granules at all replacement ratios enhanced the RC beam deflection associated with peak load, with the optimum performance was achieved for the beam with 10% PET content.
- Incorporating PET granules at all replacement levels improved cracking moment and crack width of RC beams because of the plastic nature of PET aggregates, which improved the matrix structure of concrete by delaying crack initiation and resisting crack propagation. Prediction values of ACI 318 (ACI Code, 2022) and AS3600 (AS3600, 2018) standards for cracking and flexural moments of the RC beams were in good agreement with the experimental results. The results of finite element models matched reasonably well with the experimental findings.
- Incorporating 10% PET granules slightly improved the bond strength of concrete with reinforcement due to the uniform distribution and flexibility of PET granules. The performance deteriorated with increasing PET percentage in concrete because of the improper distribution of PET granules and larger

ITZ with increasing PET replacement ratio. A model for predicting bond strength of concrete containing PET aggregate was developed and the results were in good agreement with the experimental results of the present and previous studies.

- The concrete specimen with 10% PET granules demonstrated lower porosity with smaller average diameter and area of the pores, while higher porosity was found for the specimens with higher PET content.

From this study, it can be concluded that 10% PET granules had positive impact on bond behaviour, as well as flexural strength and cracking behaviour of RC beam. The equations of ACI 318 (ACI Code, 2022) and AS3600 (AS3600, 2018) standards for predicting cracking and flexural moments of RC beams were applicable for the RC beams containing PET granule aggregates. The load-deflection behaviour of RC beams with PET granule content may be effectively simulated using finite element modelling. It is important to investigate the durability properties of concrete incorporating PET granule aggregates if this innovative material is to be used in structural applications.

6.3. Long-term performance of concrete incorporating PET granules

The **objective 3** of the study was addressed by investigating the durability characteristics of concrete containing PET granules as a volumetric replacement (0%, 10%, 30%, and 50%) for fine aggregate. A series of tests were conducted, including alkali silica reactivity (ASR) of 21-day mortar bar and one-year concrete prism tests, 90-day creep test, 90-day rapid chloride penetration test (RCPT), one-year shrinkage test, 90-day apparent volume of permeable voids (AVPV) and water absorption tests. The SEM and Fourier-transform infrared spectroscopy (FTIR) analysis was conducted on the PET granules to examine its reaction in an alkaline environment. Moreover, the experimental shrinkage results were compared with the predictions of four commonly used shrinkage models. Based on the experimental findings, the following conclusions can be drawn:

- The increase of PET replacement ratio resulted in reduced ASR expansion of mortar bars and concrete prisms because of the reduced pressure associated with ASR gel trapped in the air voids. The SEM and FTIR observations showed that PET granules had no chemical reaction in alkaline environment.

- Incorporating 10% PET granules slightly improved the creep rate of concrete due to the homogenous composition of PET concrete at low replacement level. The performance started to degrade with increasing PET replacement ratio because of the poor bond between PET granules and concrete matrix at high replacement level.
- The inclusion of 10% PET granules had minimal impact on one-year shrinkage strain of concrete. However, the shrinkage strain increased with increasing PET granules percentage in concrete because of the higher porosity and lower elastic modulus of concrete with higher PET content.
- The incorporation of 10% PET granules had no impact on water absorption and AVPV of concrete due to the uniform distribution of PET granules in the mix, and performance started to deteriorate as the amount of PET granules in the concrete increased because of the uneven distribution of PET aggregates at high replacement ratio.
- Incorporating 10% PET granules improved resistance to chloride penetration of concrete due to the electric resistance of PET granules compared to sand. While 30% PET granules had negligible impact on chloride penetration, the performance declined for the specimen with 50% PET content because of the higher porosity of the 50% PET concrete.
- The predictions of shrinkage models based on the ACI-209 (ACI-209, 1992), AS 3600 (AS3600, 2018), B3 (Bazant & Murphy, 1995), and Eurocode 2 (Eurocode2, 2004) standards underestimated the experimental findings. Therefore, A shrinkage model was developed for concrete with PET aggregate and the results matched reasonably well with experimental findings.

The above study demonstrated that increasing PET granule aggregates considerably affected durability properties of concrete. The 10% PET concrete achieved the optimum performance for creep strain, rapid chloride penetration, water absorption and AVPV properties, while having almost no impact on shrinkage strain. However, increasing PET aggregates had positive impact on alkali-silica reactivity by decreasing ASR expansion of mortar and concrete mix.

6.4. Contribution of the study

The findings of this study provided an in-depth understanding of the behaviour of sustainable concrete incorporating recycled PET granules as partial fine aggregate replacement. This study included several experimental studies, theoretical models, as well as numerical simulations that are valuable for engineers and designers to efficiently use this novel product in the construction industry for various applications. It can be inferred that incorporating PET granules in concrete would be of tremendous ecological and energy saving advantages in recycling industry as no additional treatment or colour removal is required, unlike other conventional recycling applications, and it also helps preserve natural sand. Furthermore, concrete incorporating PET aggregate is a sustainable material for circular solutions as it could be recycled and reused in road pavements once its life cycle ends. The significant contributions of this study are as follows:

- Addressing the knowledge gap on the effect of PET waste in the form of granule on mechanical and long term durability characteristics of concrete, and identifying the optimum percentage of PET granules as fine aggregate replacement
- Understanding the flexural and cracking performance of the RC beams with PET aggregate content, as well as bond strength between steel reinforcement and concrete containing varying PET granule content.
- Developing theoretical models to accurately predict bond behaviour and shrinkage strain of concrete with PET granule aggregates.
- Numerical model that can reasonably closely simulate load-deflection behaviour of reinforced concrete beams incorporating PET granule aggregates.
- Contributing significantly to the plastic waste management, where incorporating PET granules in normal concrete manufacturing, even as 10% replacement for fine aggregate, could potentially preserve 115 kg sand per m^3 concrete mix while diverting 5700 waste PET bottles (500 mL) from landfills.

6.5. Future research opportunities

This study extensively investigated the impact of PET granules as a partial replacement for fine aggregate on the characteristics of concrete. Based on the findings of this study, areas that need further investigation to better understand the practicality of PET concrete as a sustainable material are as follows:

- While the impact of PET granules on normal strength concrete up to 50% replacement for fine aggregate is investigated, a study on the effect of PET granules as fine aggregate replacement on lightweight concrete is important to understand lightweight properties of this novel material.
- The flexural performance of reinforced concrete beams containing PET granules as partial replacement for fine aggregate was examined in this study. However, research on the impact of PET granule on other structural applications, such as large-scale RC columns, RC beam-column connection subject to reversed cyclic loading should be conducted to fully understand structural behaviour of concrete containing PET granule aggregates.
- Increasing percentage of PET granules in concrete reduced the overall performance of normal strength concrete. An investigation on the properties of PET concrete using other substitutes, such as fly ash and silica fume, as a partial replacement for cement can be implemented to potentially improve the performance of concrete with higher PET content.
- The effect of PET granule aggregate on the flexural behaviour of RC beam under static bending load was examined in this study. However, higher cycle loading is expected in real-world applications such as bridges due to the effect of moving loads. As a result, it is critical to evaluate the dynamic behaviour and fatigue effect on the flexural performance of RC beam containing PET granule aggregate.

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APPENDIX A: CONFERENCE PAPER

Kangavar, M. E., Lokuge, W., Manalo, A., Karunasena, W., (2023). Stress-Strain Behaviour and Strength Parameters of Concrete Incorporating Recycled Polyethylene Terephthalate (PET) Granules as Fine Aggregate Replacement. *Proceedings of the 31st Biennial National Conference of the Concrete Institute of Australia (Concrete 2023)*, 10-13 September, Perth, Australia. (Accepted).

Stress-Strain Behavior and Strength Parameters of Concrete Incorporating Recycled Polyethylene Terephthalate (PET) Granules as Fine Aggregate Replacement

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Abstract: Plastic waste is regarded as a significant contributor to the environment pollution. This study examines the behavior of sustainable concrete incorporating recycled PET granules. The primary variables were the percentage of PET granules by volume of fine aggregate (0%, 10%, 30%, 50%). Important characteristics including workability, density, compressive strength, elastic modulus, tensile strength, and flexural strength were assessed along with stress-strain behavior. In addition, the stress-strain relationship of the experimental results was compared to the previously proposed analytical models. The findings indicate that volumetric replacement of fine aggregate with 10% PET granules had positive impact on the strength parameters. It was further revealed that incorporating PET granules improved the strain behavior of the concrete, although the improvement was more pronounced with 10% replacement ratio. Moreover, the stress-strain curves of the experimental data demonstrated good agreement with those of the proposed analytical models. Overall, the partial substitution of fine aggregates with 10% PET granules has demonstrated encouraging outcomes for promoting sustainable construction material.

Keywords: plastic waste, PET granules, mechanical properties, stress-strain behavior, sustainability.

1. Introduction

Plastic waste management has become a significant environment challenge across the world. Polyethylene terephthalate (PET), widely used in plastic bottles, is the fifth most produced plastic waste in the world, contributing significantly to negative environmental effects in landfills (1). The consumption of PET bottles is growing substantially due to their light weight and easy transportation (2). In 2021, 583 billion waste PET bottles were generated globally (3). The use of waste materials in concrete fabrication has been the subject of previous research, with waste glass, plastic, steel, and demolition concrete being of particular interest. One of the possible methods for recycling PET waste in the construction industry is its use in concrete in the form of granule. Granules are untreated raw materials from plastic recycling industry. The use of PET granules could be beneficial as it saves cost and effort needed to turn them into fibers or strips while also fulfilling the aim of recycling waste plastics rather than disposing them in landfills. Previous studies have used PET waste as reinforcement or substitute for natural aggregates in concrete (4). The potential use of PET waste as natural aggregate substitute reduces landfills and natural resource depletion, resulting in a more sustainable environment (5). Frigione (6) studied the effect of partially replacing fine aggregates (1-5%) in the concrete with PET particles (300 μm - 2.36 mm). It was found that compressive and tensile strength of concrete with 5% PET slightly reduced by 2% and 2.4%, respectively, compared to control, while 5% PET particle had almost no impact on workability of concrete. Saikia and de Brito (7) used PET flakes as a partial (5-15%)

volumetric replacement of fine and coarse aggregates in the concrete mixture. They noted that increasing size and content of PET flakes were correlated with decreases in all mechanical properties proportional to the amount of PET replacement. In general, there was a more substantial decrease in the mechanical properties of those specimens with PET replacing coarse aggregates (CA). Compressive strength declined by 66% for the specimens containing 15% PET replacing CA compared to 15% for the specimens containing 15% replacing fine aggregates (FA). The split tensile strength was seen to decrease by 54% for the specimens containing 15% PET as replacement for CA compared to 14% for the specimens containing 15% PET replacing FA. Workability was seen to decrease slightly by 6% for the specimens containing 15% PET replacing CA and 4% for the specimens containing 15% PET replacing FA. Another study by Rahmani et al. (2) tested the fresh and dry unit weight of concrete specimens containing PET particles as a partial replacement of fine sand by volume (5%-15%) for 14 and 28 days. The size of sand and PET particles were smaller than 7 mm. However, the PET particles were predominantly distributed between 4.75 mm and 2.36 mm, with no significant variation in sand dispersion between 0 and 4.75 mm. Both the fresh and dry unit weight were found to be lower for PET concrete in comparison to conventional concrete, a result that was attributed to the lower overall density of PET particles (464 kg/m^3) compared to the river sand (1728.9 kg/m^3). A similar study by Lee et al. (8) evaluated the compressive strength and workability of concrete containing 10%-30% volumetric replacement of coarse aggregate with PET flakes. As a key difference from other studies, the PET flakes were initially treated with hydrogen peroxide (H_2O_2) and calcium hypochlorite ($Ca(ClO)_2$) before addition to concrete. Following the trials, slump was seen to decrease, whereas compressive strength was increased, with the ($Ca(ClO)_2$) treated specimens showing greater improvement over those treated with H_2O_2. The authors concluded that chemical treatment had improved the bonding between the plastic and cement paste, as a result of surface oxidation leading to improved hydrophilicity of the PET particles.

While the use of PET waste in concrete fabrication has previously been investigated, the results have been variable. Furthermore, there has been a significant variability in the size, shape and texture of the PET waste used, with fibers, flakes and shredded shapes being most commonly used. In contrast, the use of PET granules has not given significant attention. This study aims to examine the impact of PET granules as partial fine aggregate substitute on stress-strain behavior and mechanical characteristics of concrete.

2. Experimental program

2.1 Materials and concrete mix design

Ordinary Portland cement was used in this study. The coarse aggregate had nominal sizes of 7 mm and 10 mm. A granulator machine was used to produce PET granules. The particle size distribution (PSD) of sand and PET granules as fine aggregate component are presented in Table 1. The PSD of PET granules were generated relatively comparable to sand in order to minimize the effect of varying grading on characteristics of concrete. The concrete mix with water/cement ratio of 0.45 was designed for a characteristic strength of 32 MPa at 28 days. PET granules were used as a volumetric substitute for sand (10%, 30%, and 50%). All the mixtures had the same quantity of coarse aggregates, cement, and water, with values of 1320 kg, 440 kg, and 210 L , per m^3, respectively. Table 2 presents the amount of fine aggregate per m^3 for each mix.

Table 1. PSD of Sand and PET Granules.

Sieve(mm)	Percentage passing (%)	
	Sand	PET granules
4.75	100	100
2.36	96.8	90
1.18	87.74	79
0.6	69.3	58
0.3	27.52	25
0.15	3.93	0

Table 2. Fine Aggregate Quantity.

Mixture	Fine aggregate (kg/m^3)	
	Sand	PET granules
Control	710	-
10% PET	648	59
30% PET	492	176
50% PET	388	245

2.2 Instrumentation and test procedure

The Slump test was performed to evaluate workability of the concrete mixtures according to AS 1012.3.1 (9). The density, compressive strength, elastic modulus, and indirect tensile strength tests were conducted on cylindrical specimens (100 mm diameter and 200 mm height) according to AS 1012.5 (10), AS 1012.9.1 (11), AS 1012.17 (12), and AS 1012.10 (13), respectively. A strain gauge was attached to the mid-height of compressive strength test specimens in order to determine axial stress-strain behavior. The flexural strength test was performed on the concrete beams (150 mm x 150 mm x 700 mm) according to AS 1012.11 (14). Two specimens were cast for each concrete mix to increase reliability of the results.

3. Results and discussion

Workability of the specimen with 10% PET content was identical to the control specimen with the value of 97 mm. However, the slump value for the specimens with 30% and 50% PET content decreased to 93 mm and 90 mm, respectively. While prior studies (2, 15) reported a decrease in concrete workability with increasing PET percentage, the performance deterioration was less pronounced in this study. This behavior might be explained by the sub-rounded shape of PET granules and their comparable dimensions to sand. Table 3 presents the experimental test results on hardened concrete.

3.1 Density

Density of the concrete mixes was inversely proportional to the increase of PET granules in concrete mix, where the value for the specimens with 10%, 30%, and 50% PET content decreased by 3%, 12%, and 22%, respectively, compared to the control. This conclusion is consistent with previous studies (16, 17).

Table 3. Experimental Test Results.

Mixture	Density (kg/m^3)	*Sd	Compressive strength (MPa)	*Sd	Tensile strength (MPa)	*Sd	Elastic modulus (MPa)	*Sd	Flexural strength (MPa)	*Sd
Control	2410	12.5	31	1.5	3.8	0.8	24.4	1.5	3.9	0.4
10% PET	2340	16.4	33	1.7	4	0.5	24	1.6	4.2	0.6
30% PET	2120	19	30.5	1.3	3.7	0.2	20	1.2	3.97	0.5
50% PET	1845	24.8	25	1.2	3	0.3	18	1.8	3.2	0.3

*Sd: Standard deviation

3.2 Compressive strength

The compressive strength of the specimen with 10% PET content was slightly increased by 7% compared to the control, while 30% PET granules had almost no impact on compressive strength, decreasing by 1.5% relative to the control. However, the reduction was more noticeable for the specimen with 50% replacement ratio, decreasing by 20% compared to the control. While previous study (2) agreed on improving compressive strength up to 5% replacement ratio, the improvement in this study was at a higher replacement ratio than previous study which could be due to the size and shape of PET granules, as well as uniform dispersion of PET granules at a low replacement ratio. The performance deterioration with increasing PET granules in concrete might be explained by uneven distribution of PET granules, resulting in more porosity in the concrete mix (18).

3.3 Indirect tensile strength

The tensile strength of the specimen with 10% replacement rate increased by 5% compared to the control, whereas the value for the specimen with 30% PET content reduced by 2.5% compared to the control. However, the reduction was more pronounced for the specimen incorporating 50% PET granules, as evidenced by a 21% decrease compared to the control specimen. This conclusion is in line with the findings of Azhdarpour et al. (17). However, the performance was higher in this study, which could be attributed to the relatively comparable size and shape of PET granules to sand, and uniform distribution of PET granules at low replacement ratio (7).

3.4 Elastic modulus

The elastic modulus of the specimen with 10% PET level was close to the control with only 1.5% decrease. However, the elastic modulus of the specimens with 30% and 50% decreased by 17% and 24%, respectively, relative to that of the control. Although other studies (2, 6) also found a reduction of elastic modulus with increasing PET content, the reduction in this study was less noticeable, particularly for the specimen containing 10% PET granules. The gradual reduction in elastic modulus could be related to the decrease in concrete density as PET proportion in concrete increases (19).

3.5 Flexural strength

The inclusion of 10% and 30% PET granules in concrete mix improved the flexural strength, demonstrating 9% and 2% increase respectively, over the control specimen. In contrary, the value for the specimen with 50% replacement ratio decreased by 7% compared to the control specimen. The performance improvement of the concrete up to 30% replacement level might be related to the flexibility of PET granules compared to sand, and lower elastic modulus of the specimens with PET content, suggesting ductile behavior of the specimen with PET granules compared to the control. The performance reduction for the specimen with 50% PET granules might be due to the lower density of PET granules compared to sand, resulting in improper distribution at high replacement level (4).

3.6 Stress-strain behavior

Figure 1 depicts the stress-strain behavior of the specimens under compression test. It was observed that the slope of ascending branch (before peak stress) for the specimen with 10% PET content was relatively comparable to the control. However, the peak stress and corresponding strain of the 10% PET concrete with the values of 33 MPa and 0.0019 (mm/mm) were slightly higher than the control with the values of 31 MPa and 0.0017 (mm/mm), respectively. In the descending branch (after peak stress), the specimen containing 10% PET granules displayed gradual reduction of stress with increasing strain up to 0.0026 (mm/mm) before failure, whereas the control specimen failed with a sudden drop of stress at the peak stress. While the specimens with 30% and 50% PET granules failed at lower compressive stress than the control, the compressive strain at failure for both specimens were higher than the control with values of 0.0024 (mm/mm) and 0.0022 (mm/mm), respectively. Therefore, the inclusion of PET granules in concrete mix improved the post-peak behavior, indicating higher ductility of the specimens with PET granules compared to control. This behavior could be attributed to the flexibility of PET granules, which transfers applied stress to natural aggregates, acting as reinforcement by delaying failure (5).

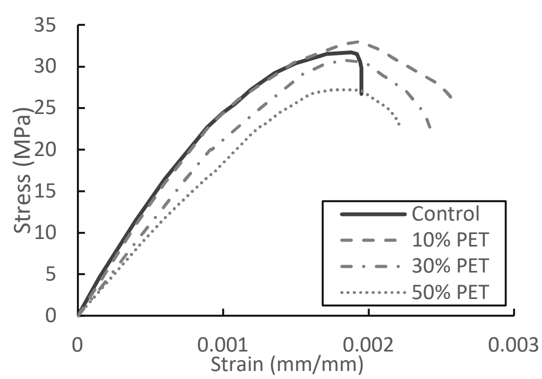

Figure1. Stress-strain behaviour of the concrete mixtures.

3.7 Comparison of experimental stress-strain curves with theoretical models

The experimental stress-strain curves were compared to those obtained from two commonly used analytical models proposed by Carreira and Chu (20) (Eqs.1 and 2) and Popovic (21) (Eqs.3 and 4). Where $f^{'}$ and ε are stress (MPa) and strain (mm/mm) of concrete mixtures, respectively. $f_c^{'}$ is the maximum stress (MPa), and $\varepsilon_c^{'}$ is the strain associated with the maximum stress (mm/mm). E_0 is the modulus of elasticity at origin. Figure 2 depicts the stress-strain curves of experimental and analytical models. The ratio of experimental strain at peak stress to the predicted values using Carreira and Chu model (20) were found to be 1.02, 1.08, 1.12 and 1.14 for the control, 10% PET, 30% PET, and 50% PET specimens, respectively, whereas the ratios using Popovic model (21) were 0.98, 0.94, 0.92, 0.92, respectively. Although the predictions of Carreira and Chu model (20) were more conservative than those obtained by Popovics model (21), the stress- strain curves of both models were in good agreement with the experimental curves.

Carreira and Chu model (20):

$$f' = \frac{f_c' \beta (\varepsilon/\varepsilon_c')}{\beta - (\varepsilon/\varepsilon_c')^{\beta}} \quad (1)$$

$$\beta = \frac{1}{1 - \left(\frac{f_c'}{E_0 \varepsilon_c'}\right)} \quad (2)$$

Popovics model (21):

$$f' = f_c' \frac{\varepsilon}{\varepsilon_0} \frac{n}{n - 1 + (\varepsilon/\varepsilon_0)^{n}} \quad (3)$$

$$n = 0.4 \text{ x } 10^{-3} f_c' + 1.0 \quad (4)$$

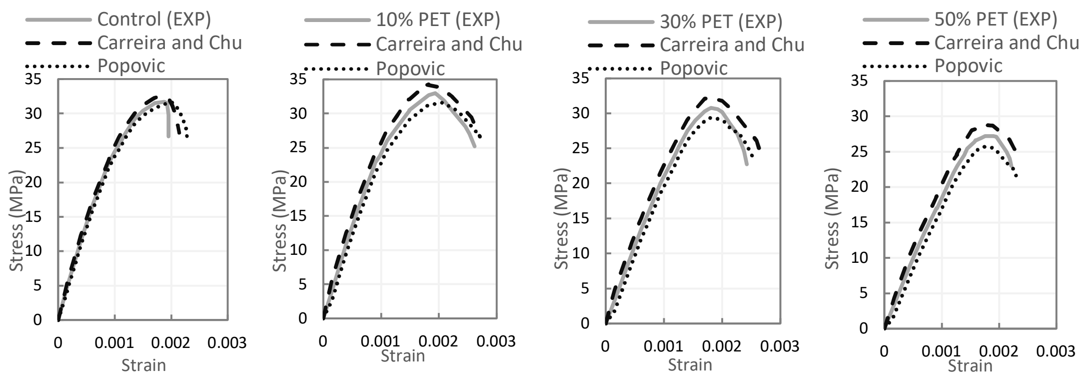

Figure 2. Comparison of experimental stress-strain behavior with Carreira and Chu (1985) and Popovics (1973) models.

4. Conclusion

- The inclusion of 10% PET granules had no effect on workability of concrete, and the performance declined gradually with the further replacement ratio. The density of concrete was inversely proportional to the amount of PET granules.
- The concrete incorporating 10% PET granules achieved the optimum compressive strength. While compressive strength decreased with increasing PET content in concrete mix, the specimen with 30% PET content met the target compressive strength of 32 MPa. The inclusion of 10% PET granules slightly improved the tensile strength of concrete. However, the performance declined as the replacement level increased.
- The elastic modulus decreased as the amount of PET granules in the mix increased, albeit the reduction was insignificant for the concrete containing 10% PET granules. Flexural strength of concrete increased with increasing PET granules up to 30% replacement ratio and then started to decrease as the replacement percentage increased.
- The incorporation of 10% PET granules improved the stress-strain behavior of concrete. Although the performance deteriorated with increasing PET granules in the mix, the 30% and 50% PET still had positive impact on the post peak behavior (ascending branch), Indicating higher ductility of concrete containing PET granules.
- Both Carreira and Chu (20), and Popovics models (21) were able to predict the experimental stress-strain curves with reasonable degree of accuracy, suggesting the applicability of both models for the concrete containing PET granules.

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