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FLEXURAL BEHAVIOR OF GEOPOLYMER REINFORCED CONCRETE BEAM INCORPORATING PET WASTES

A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Civil Engineering
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Prepared By
Noor Munther Shakir
B.Sc. civil engineering, 2005

Thesis Supervisors: **Prof. Dr. Abbas Oda Dawood**

بِسۡمِ ٱللَّهِ ٱلرَّحۡمَٰنِ ٱلرَّحِيمِ

لَا يُكَلِّفُ ٱللَّهُ نَفۡسًا إِلَّا وُسۡعَهَاۚ لَهَا مَا كَسَبَتۡ وَعَلَيۡهَا مَا ٱكۡتَسَبَتۡۗ رَبَّنَا
لَا تُؤَاخِذۡنَآ إِن نَّسِينَآ أَوۡ أَخۡطَأۡنَاۚ رَبَّنَا وَلَا تَحۡمِلۡ عَلَيۡنَآ إِصۡرًا كَمَا حَمَلۡتَهُۥ
عَلَى ٱلَّذِينَ مِن قَبۡلِنَاۚ رَبَّنَا وَلَا تُحَمِّلۡنَا مَا لَا طَاقَةَ لَنَا بِهِۦۖ وَٱعۡفُ عَنَّا وَٱغۡفِرۡ
لَنَا وَٱرۡحَمۡنَآۚ أَنتَ مَوۡلَىٰنَا فَٱنصُرۡنَا عَلَى ٱلۡقَوۡمِ ٱلۡكَٰفِرِينَ ٢٨٦ .

[سورة البقرة, ٢٨٦].

صدق الله العظيم

ABSTRACT

Geopolymer concrete is an eco-friendly alternative to traditional Portland cement concrete, made using industrial by-products like fly ash or slag activated with alkaline solutions. This research investigates its mechanical and physical properties as a substitute for regular Portland cement concrete, with partial replacement of natural sand by waste polyethylene terephthalate (PET). The study highlights the environmental benefits, including a 1.5% to 2% reduction in CO_2 emissions, by incorporating GGBFS as a partial or complete replacement for Portland cement, thus lowering the overall carbon dioxide emissions associated with cement production. The study is divided into two main sections:

Section 1: Mechanical and Physical Properties of Concrete

Physical tests were conducted to measure density and absorption, while mechanical tests were performed for flexure, splitting, compression, elastic modulus, axial strain, and energy absorption. Various weight percentages (5%, 10%, 15%, 20%, and 30%) of PET waste particles were used to partially replace the fine aggregate (sand), keeping all other ratios constant. Additionally, ultrasonic pulse velocity was measured. Specimens were observed over periods of 7, 28, and 90 days. The test results indicated that the presence of PET particles altered the mechanical and physical characteristics of the produced concrete. While the absorption rate increased by 58.04% for 30% substitution, density and ultrasonic pulse velocity decreased steadily as PET ratios rose. Furthermore, specimens with partial substitution ratios ranging from 5% to 15% showed increases in compressive strength (11.04%, 3.64%), tensile strength (3.46%, 11.07%), and flexural strength (10.26%, 8.45%) compared to the reference specimens. Axial strain and energy absorption increased with PET substitution percentages ranging from 5% to 30%, while the elastic modulus declined as PET concentration rose. Strength parameters dropped for PET content exceeding 15%.

In summary, the strength-related values of geopolymer concrete were positively impacted by using PET particles in place of sand, provided the replacement ratio was 10%.

Section 2: Mechanical Properties of Reinforced Geopolymer Concrete Beams

This section examines the structural behavior of reinforced geopolymer concrete beams when PET waste is used as a partial substitute for fine aggregate. Five concrete beams (150 x 200 x 1400 mm) with comparable steel reinforcement (one beam for each PET percentage) were tested. The effect of PET waste on the structural behavior of the beams was assessed using the following: ultimate load failure, ultimate deflection, energy absorption, stiffness, ductility index, crack investigation (including first crack load and crack pattern), and comparison with reference beams. The findings revealed that the ultimate failure load, ultimate deflection, ductility index, initial stiffness, and energy absorption increased as the PET waste content in the reinforced geopolymer concrete beams increased (7.76%, 92.52%, 92.59%, 29.33%, and 298.46%, respectively, for 30% substitution). Conversely, a 44.07% decrease in secant stiffness was observed. Additionally, as the amount of PET waste in concrete beams increased, so did the load at which the first crack appeared and the spacing between cracks. However, the quantity and depth of cracks decreased.

SUPERVISOR CERTIFICATION

I certify that the preparation of this thesis entitled " **FLEXURAL BEHAVIOR OF GEOPOLYMER REINFORCED CONCRETE BEAM INCORPORATING PET WASTES**" was presented by "**Noor Munther Shakir**", and prepared under my supervision at University of Misan, Department of Civil Engineering, College of Engineering, as a partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Structural Engineering).

Signature:

Prof. Dr. Abbas Oda Dawood

Date:

In view of the available recommendations, I forward this thesis for discussion by the examining committee.

Signature:

Assist Prof. Dr. Murtada Abass Abd Ali

(Head of Civil Eng. Department)

Date:

EXAMINING COMMITTEE'S REPORT

We certify that we, the examining committee, have read the thesis titled **(FLEXURAL BEHAVIOR OF GEOPOLYMER REINFORCED CONCRETE BEAM INCORPORATING PET WASTES)** which is being submitted by (**Noor Munther Shakir**), and examined the student in its content and in what is concerned with it, and that in our opinion, it meets the standard of a thesis for the degree of Master of Science in Civil Engineering (Structures).

Signature:
Name: **Prof. Dr. Abbas Oda Dawood**
(Supervisor)
Date: / /202

Signature:

Name:	Name:
(Chairman)	(Member)
Date: / /202	Date: / /202

Signature:
Name:
(Member)
Date: / /202

Approval of the College of Engineering:
Signature:
Name: Prof. Dr. Abbas Oda Dawood
Dean, College of Engineering
Date: / /202

DEDICATION

Whoever says, “I got it,” gets it

The journey was not a short one, nor should it have been,

the dream wasn't close and the road wasn't easy,

but I did it and I got it

Alhamdulillah, thanks and gratitude to Allah, thanks to whom I am today looking at a long-awaited dream that has become a reality that I am proud of.

To my strength after God, my first and eternal supporter “my husband”, I dedicate this achievement, which without your sacrifices would not have existed, grateful that God has chosen you from among humans as the best support.

To the ones who supported me without limits and gave me freely

”Mom and Dad“

To whom it was said;

(قَالَ سَنَشُدُّ عَضُدَكَ بِأَخِيكَ)

“Brothers” may Allah keep you as a steady rib

To those who believed in me and stood behind me like a shadow

”My daughters“

These words are an expression of my gratitude and appreciation to all of you, you are the ones who added real meaning to my life, I pray to God to protect you and take care of you.

ACKNOWLEDGEMENTS

Praise be to God who helped me to complete this scientific research, and I extend my sincere thanks and appreciation to my supervisor, Prof. Dr**. Abbas Oda Dawood**, who had the biggest role in guiding and guiding me during the stages of research. His support was not limited to the academic aspect only, but was a source of encouragement and inspiration on the personal and scientific levels.

I thank him for his time, efforts and patience in following my progress and teaching me how to deal with research challenges in a spirit of perseverance and critical thinking. His sound advice and meticulous guidance were the impetus that propelled me towards this achievement.

I am grateful to him, and I ask Allah to bless his knowledge and work

Finally, I extend my sincere thanks and appreciation to everyone who helped me from near or far in overcoming the difficulties, patience and great effort, even with a kind word and sincere prayer.

Researcher

Noor Munther Shakir

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Fr: modulus of rupture (MPa)

L: span length(mm)

b: average width of the specimen (mm)

d: average depth of specimen (mm)

σ: Stress

e: Strain

Pu: maximum load applied (kN)

Δy: yield deflection (mm)

Δu: maximum deflection (mm)

a/d: where (a) the distance between each point load and support mm, while(d) the effective depth mm.

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BR	Basalt Rock
BS	British standard
CAGR	Compound Annual Growth Rate
CAO	Oxo calcium
FA	Fly Ash
FNS	Ferronickel Slag
GCI	Global Change Institute
GGBFS	Ground Granulated Blast Furnace Slag
GPC	Geopolymer Concrete
HPC	High Performance Concrete
KOH	Potassium hydroxide
NA_2SIO	Sodium silicate
NAOH	Sodium hydroxide
OC	Ordinary Concrete

OPC	Ordinary Portland Cement
PET	Polyethylene Terephthalate
PC-RHA	Portland Cement- Rice Husk Ash
RGPC	Reinforced Geopolymer Concrete
RPCC	Reinforced Portland Cement Concrete
SP	Super Plasticizer
UHGPC	Ultra-High-Performance Geopolymer Concrete
UHPC	Ultra High-Performance Concrete
W/C	Water to cement ratio

CHAPTER ONE

INTRODUCTION

CHAPTER ONE: INTRODUCTION

1.1General

The rapid growth in the construction sector has led to a significant increase in carbon dioxide emissions, primarily released during the production of cement from raw materials. The widespread use of concrete in construction has further amplified the global demand for raw materials, resulting in the excessive consumption of natural resources. Cement production worldwide is estimated to exceed 2.8 billion tons, contributing 5% to 6% of total global carbon dioxide emissions. Similarly, the use of other raw materials, such as fine and coarse aggregates, is also at its peak. There is an urgent need for alternative materials that possess similar physical and chemical properties. Concrete has been used in construction for thousands of years, playing a crucial role in the development of engineering structures such as houses, bridges, and other infrastructure. The search for sustainable alternatives to traditional concrete materials is essential to reduce the environmental impact of construction activities. Sustainable alternatives, such as green concrete and geopolymer concrete, offer promising solutions. These materials not only reduce carbon emissions but also promote the use of industrial by-products and recycled materials, contributing to a more sustainable and eco-friendly construction industry [1-6]. The parameters of the alternative materials have an amazing effect at the houses of exposed concrete to severe temperatures [7-10]. Several research [11-14] had been done to increase the thermal stability of concrete uncovered to severe temperatures with the aid of incorporating fillers, nanoparticles, fibers and polymer sodium alginate [15,18].

1.2 Geopolymer concrete

Polymer concrete is a type of concrete in which natural aggregates, such as sand and gravel, are bonded using a polymer binder. This binder serves as an additive or alternative to traditional cement [19] Fig. (1-1). Compared with regular concrete, polymeric concrete has more mechanical properties, chemical resistance and ductility [20,21]. According to the (ACI 548.3R), polymer is the only binding agent observed in PC concrete [22].

However, GGBFS and Fly ash can be use with the aggregates to increase mechanical properties and decrease creation expenses. GPC can reach approximately eighty percent of its 28-day compressive strength, with a most compressive power of 100 MPa [20,23]. The strength of geopolymer concrete made with fly ash ranges from 15 to 50 MPa, while GGBFS geopolymer concrete from 25 to 70 MPa. Durability tests for geopolymer concrete, including alkali-silica reaction, acid attack, and sulphate attack, displayed positive outcomes up to 84 days when compared to concrete made with Ordinally Portland Cement (OPC) [24] using fly ash to create geopolymer concrete is a superior option compared to traditional OPC concrete as it offers greater initial strength, durability, cost efficiency, and reduced carbon emissions. Simultaneously, it reduces the amount of waste produced [25]. Utilizing Sewage Sludge Ash with elevated CaO levels (23.8–32.9%) and a ratio CaO/SiO2 (1.39–2.03) results in increased compressive strength of mortar more than OC [37] Polymer concrete has more sturdiness than OC [26-28] The compressive strength of Portland Cement- Rice Husk Ash (PC-RHA) was slightly less than that of Portland Cement (PC). Nonetheless, the compressive strength of PC-RHA with 10% RHA replacement surpassed that of PC at 60 and 90 days. This happens as the pozzolanic reaction starts after 28 days, decreasing CH levels and enhancing density [29].

Understanding the concrete behavior subjected to varying temperatures is considered important to achieve the safety and lifespan objectives for which homes are built. Concrete research normally uses three distinct temperature stages: low temperature (0 °C), medium temperature (0-50 °C), and excessive a high temperature (50 °C) [30]. Based on exposure conditions, preceding research has evaluated the thermal response of concrete to temperatures underneath 200°C, underneath 600°C, and beneath a 1000°C [31-39]. Generally, 600°C is selected because the inner temperature of concrete factors will no longer exceed 600°C in a short period of time [40]. Because the raw fabric is almost attaining it restrict and cannot be abundantly used. Research is underway to replace cement, aggregates with waste products from various industries. GGBFS and Fly ash have demonstrated to be the fine choice to partially or completely replaced cement. [41- 44].

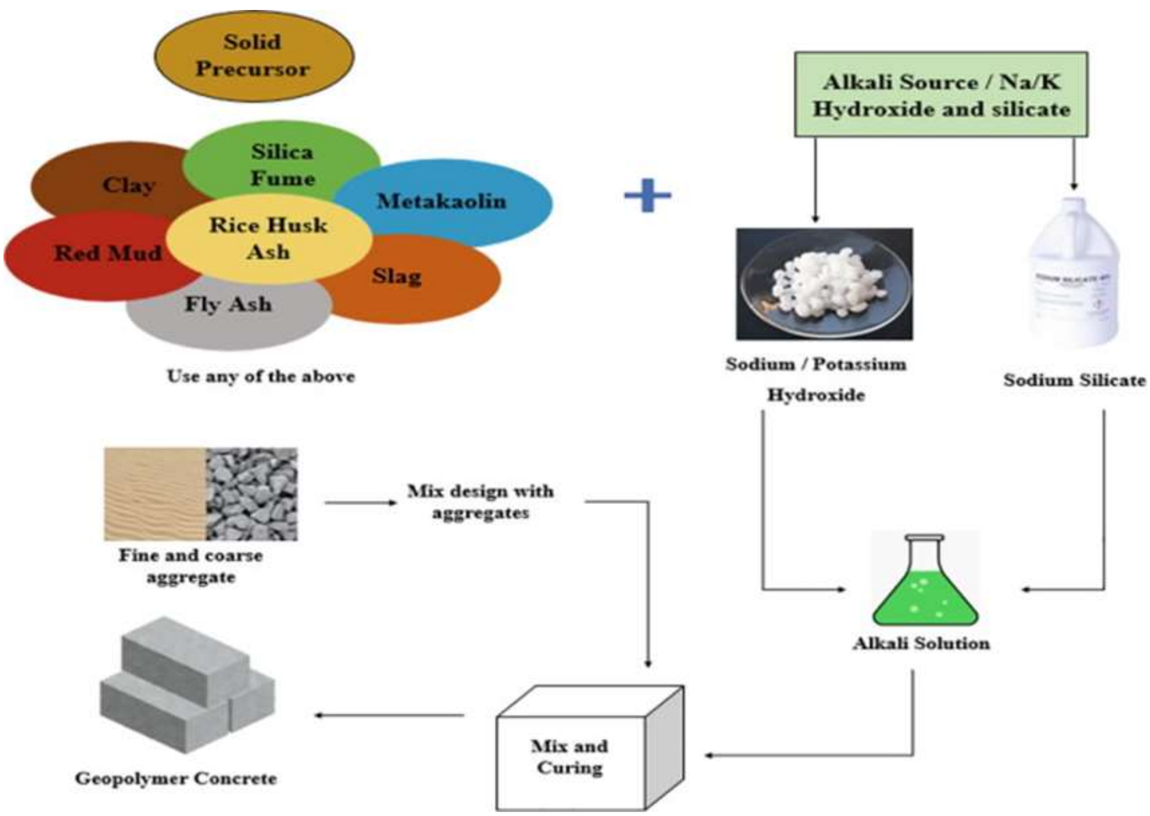

Fig. (1-1) Geopolymer concrete [25]

1.3 The Geopolymer Concrete Benefits

Geopolymer concrete has many blessings in comparison to traditional concrete because it's far versatile in infinite ways. Below are the geopolymer concrete benefits:It lasts much longer than normal concrete and desires minimum preservation. Therefore, saving considerable sums of money that could have to be used for upkeep. Geopolymer concrete has a long lifespan because of its capacity to undergo for heaps of years. Greater sustainable than traditional concrete. Geopolymer concrete has proven its effectiveness in resisting corrosion and fire. It displayed strong resistance to compressive and tension it fast reaches its maximum strength. This concrete has a decrease shrinkage as compared to regular concrete. Incorporating ground granulated blast furnace slag (GGBFS) as a partial or complete replacement for Portland cement helps reduce overall CO_2 emissions by 1.5% to 2%. The production of Portland cement is a major contributor to carbon dioxide emissions. By substituting GGBFS for Portland cement, the demand for Portland cement is significantly reduced, thereby effectively lowering the overall carbon dioxide emissions associated with cement production. Geopolymer concrete gives a new method for advancing sustainable improvement [44].

1.4 Synthesis of Geopolymer Cement

Geopolymers are usually produced via combining supply substances containing alumino-silicate with alkaline solutions Materials such as kaolinite, clays, zeolite, fly ash, silica fume, slag, and rice-husk ash, crimson dust are utilized. The typical alkaline for geopolymerization entails a mixture of (NaOH, KOH) and sodium silicate. Geopolymers are created while source substances like solid fly ash (FA) are blended utilizing solutions of alkali of the right concentration and sodium silicate. Zhuang et al. [45] mentioned that the polymerization interaction of fly ash should involve the following approaches Fig. (1-2). At times, the solid alkali activator is ground along with source materials (such as FA) of specific composition, producing a fine grain resembling cement. This is later combined with a suitable quantity of water during its application [46,47].

Fig. (1-2) Geopolymerization processes using fly ash [54]

1.5 PET Waste

Plastic production was first invented in the 1860s and advanced for industrial use by the 1920s. By the 1940s, it became one of the fastest-growing global industries. Between 1950 and 2012, the replacement of materials like steel and glass with plastic led to a significant increase in production. The average annual growth rate of plastic production rose from 1.7 million tons to nearly 300 million tons by 2015. Global annual production reached around 393 million tons in 2017. Asia led in plastic production, accounting for 45.6% of global output in 2013, with China producing nearly a quarter of the world's plastic. By 2025, the global population is expected to exceed 9.5 billion, with over 97% of the growth occurring in Africa and Asia. [48-49].

A percentage of plastic among 22%and 43% represents a wasted useful resource worldwide and destroys societies and the environment by way of causing pollution, further to the environmental harm induced to marine ecosystems by using plastics. Every year, around 10 to twenty million tons of plastic emerge as within the oceans [48]. According to an editorial written via the BBC in 2018. Three billion tonnes of plastic had been produced thus far, of which 9% is recycled, 12% is burned and the last seventy 9% is waste accumulated within the environment and in landfills. These articles additionally kingdom that if contemporary manufacturing maintains and waste is poorly managed, 12 billion metric lots will emerge as in landfills or the surroundings via 2050 [50]. PET is developed in North America initially inside the mid-Nineteen Forties with the aid of DuPont chemists searching out new synthetic fibers. In the early 1970s, the era for blowing PET into bottles turned into developed. The PET bottle become patented in 1973 [51]. PET is a clean, light and robust plastic, that is frequently used for packaging liquids and meals, mainly smooth beverages, juices and water. Plastic waste makes up 5 to 15% of the burden of municipal waste, it makes up 20 to 30% of the volume [52]. The manufacturing of PET bottles has caused a massive growth in the international consumption of PET. The PET bottle enterprise grew at a CAGR of 4.3% between 2009 and 2013. The common global consumption of PET bottles is ready 20 million heaps, with an annual growth of 12 to 15%. At the equal time, the recycling price of PET bottles is low [53]. PET intake ruled beverage packaging production, same to 79% of overall world production in 2017 [63]. The prosperity of the manner of producing water and soft beverages bottled with plastic bottles has been considerable in Iraq specifically inside the closing decade.

The record at the state of the environment in Iraq in 2017, the quantity of solid waste generated per character in keeping with day is estimated at 0.3 kg/individual/day and in a few areas, it reaches 1 kg/man or woman/day depending on the standard of dwelling. There are not any government factories for recycling waste, similarly to increasing consumption of PET resin thru gentle drink bottles and water. Unluckily, large portions are thrown into open areas, streets, forests, parks and rivers. Maysan province is the town of Amarah, placed in southeastern Iraq, about 370 km south of Baghdad. Its area is approximately 55.2 km_2, its place is equivalent to 3% of the total vicinity of Maysan province and 0.01% of the place of Iraq [55]. The destiny imaginative and prescient of Amarah City and reading the population increase rate, that is based totally on forecast statistics Table (1.1) below. It should be mentioned that growth charges have numerous over the years and their stability at regular growth charges of 3.4%, due to the relative improvement inside the living conditions of individuals [55].

Table1.1 Number of population growth rate for the city of Amara for the duration (1977-2016) [55]

Years	City Population(people)	Growth rate
1977	106348	-
1987	195014	6.2
1997	272286	3.3
2016	515041	3.4

The relationships between growth and annual stable waste lets in us to calculate the quantity of solid waste produced in step with character in step with year. Based on that, we can calculate the quantity of solid waste produced within the future, even if most effective roughly, and find early answers to deal with and eliminate it. Several researches have evaluated using PET and polystyrene in structural and light-weight concrete mixes to reduce the world's waste. Strength of compressive, density, tensile strength, elastic modulus, and strength of flexural, are some of the features examined for these types of concrete.

1.6 Research Objectives

The present research focuses on the use of GGBFS as a replacement for Portland cement and polyethylene terephthalate (PET) waste in geopolymer concrete as a partial substitute for fine aggregate mixtures. Adding GGBFS and PET waste to concrete achieves two main benefits. The first is the economic benefit of reducing raw material costs, and the second is the environmental benefit of addressing some of the solid waste problems caused by waste materials. The environmental impact is significant, as it helps reduce overall CO_2 emissions and promotes the use of industrial by-products, contributing to a more sustainable and eco-friendly construction industry. While research goals focus on the following issues:

1-Replace ordinary Portland cement with geopolymer material.

2-There are a variety of admixture percentages available to evaluate the effect of the volume of recycled PET on the GPC when it is utilized partially replace sand in a geopolymer concrete mix.

3- Evaluate the effect of geopolymer material and additional PET particles on the mechanical and physical characteristics of geopolymer concrete mixtures.

4- The impact of geopolymer materials and additional PET particles on the mechanical and physical properties of reinforced geopolymer concrete beams.

1.7 Thesis Layout

The first chapter: Provides a summary of the importance of geopolymer concrete (GPC) and methods to address its weaknesses. It includes statistics on the local growth of plastic waste, definitions and clarifications of the properties of geopolymer materials and polyethylene terephthalates, and global statistics on waste plastic bottles. Additionally, it presents data on the population and population growth in the Maysan Governorate.

The second chapter: A review of outcomes from earlier research and research and the impact of geopolymer material and PET plastic waste on the properties and behavior of concrete mixtures. Some studies were reviewing the use of geopolymer materials as a replacement for OPC and partially replacement for PET waste as a fine aggregate to the mixture.

The third chapter: The characteristics of the materials, equipment, tests and mixture percen tages used in the research are presented. Work steps, sample details,
preparationand processing method, tests performed on these samples and concrete sample tests.

The fourth chapter: The results and relationships obtained in this study are discussed, and a discussion of these results is also presented.

The fifth chapter: The important conclusions reached by outcomes of the tests carried out during this study, as well as some recommendations and recommendations documenting this work and ways to obtain them for scientific benefit in future studies.

CHAPTER TWO

LITERATURE REVIEW

CHAPTER TWO: LITERATURE REVIEW

2.1 General

The purpose of this literature review is to identify the need for a suitable substitute for concrete made with OPC using a report on the environmental effects of cement production. It will provide background information on current geopolymer cement production, current GPC production methods and materials, as well as the chemical reactions required for GPC.

2.2 What is Geopolymer Concrete?

Geopolymer concrete (GPC) is made by blending aluminosilicate oxides with inorganic alkali polysilicates to form polymeric silicate-oxygen alkali bonds (Si-O-Al), which are essential for the bonding process [56-58]. Aluminosilicate oxides like fly ash, collected from coal-fired power plants. Coal is ground into a fine powder and burned in a boiler to generate steam for electricity. During this process, minerals in the coal bond together to form spheres with a glassy alumina-silicate structure. These spheres are collected by precipitation downstream of the boiler [59-60]. The classes are generally differentiated by the CaO content of the FA the different calcium percentages based on mass. Class F have CaO less than 8% while Class C have CaO more than 8%. In most of the articles reviewed [61-64]. GGBFS is another type of aluminosilicate oxides it is produced by heating iron or coke in a blast furnace, collecting the molten materials, and quickly cooling them. The resulting slag, composed of aluminates and silicates from coke and ore ash, is then ground for use in concrete mixes [60]. Alkali polysilicates required to complete the polymerization process are typically solutions of Na_2SiO_3 and NaOH. The higher the NaOH content, the higher the resulting compressive strength [62].

2.3 Literature Review

2.3.1 Geopolymer Materials

In 2012, Dattatreya et al. [63] Based on the study conducted on GPC T-beams (flange dimensions: 270 mm x 75 mm, web dimensions: 75 mm x 300 mm, length: 2200 mm) cured at room temperature, the structural behavior of the geopolymer concrete beams (RGPC) closely resembles that of reinforced cement concrete beams. The study found that RGPC beams perform adequately as structural components, making them suitable for use in the construction of multistoried buildings, bridges, dams, and other structures.

In 2012, Supraja et al. [64] GGBFS replaces Portland cement with varying molarities (3, 5, 7, and 9) in different curing methods (sunlight curing and oven curing at 50°C). The study found that compressive strength increases with higher molarity of sodium hydroxide. After three days of curing, the increase in compressive strength is not significant. Specimens cured in an oven exhibit superior compressive strength compared to those cured in direct sunlight, although sunlight curing is more convenient.

In 2013, H. Gokulram [65] Two types of structures were used: one with 100% substitution of cement by fly ash (FA) and ground granulated blast furnace slag (GGBFS), and another with 100% substitution of natural sand by manufactured sand. Mixtures were produced using an alkaline liquid to binder ratio of 0.45 for mixes 1, 2, and 3, and 0.55 for mixes 4 and 5. Polypropylene fibers were added to the mix at a quantity of 0.25% by weight of concrete. The mechanical characteristics of the specimens were studied after 28 days of ambient curing and 24 hours of heat curing. The mix with 100% GGBFS showed better flexural, splitting tensile, and compressive strength in both curing methods compared to the mix with 100% FA. The use of polypropylene fiber in geopolymer synthesis improves environmental benefits and addresses issues of excessive shrinkage and brittleness.

In 2013, Neetu Singh et al. [66] Class F fly ash (FA) with alkali activator fluid (sodium silicate and sodium hydroxide) was used. The highest compressive strength was achieved at a curing temperature of 120°C for 72 hours. The freshly created geopolymer was subsequently exposed to durability tests under chemical environments, specifically examining the impact of salts containing acid sulfate and chloride, and compared with ordinary Portland cement (OPC). Precast geopolymer cubes were immersed in different solutions for varying durations (30, 60, and 90 days). It was found that fly ash-based geopolymer concrete has excellent resistance to sulfate and acid attacks compared to conventional concrete. The mechanisms of attack by sulfuric acid and sulfates differ between geopolymer concrete (GPC) and OPC. Conventional concretes, like OPC, are generally not resistant to prolonged exposure to high concentrations of these solutions due to the decalcification of calcium silicate hydrate (C-S-H), which weakens the concrete structure. No damage was observed on the surface of test samples following their exposure to sodium sulfate solution for up to 90 days. There was no significant change in the mass and compressive strength of the specimens after a 90-day exposure period. Heat-cured GPC has excellent resistance to chloride attack, making it suitable for use in seawater environments.

In 2014, Adams Joe et al. [67] A total of ten mixes, including cubes and cylinders, were analyzed. GGBFS and steel fibers were combined with a water-to-binder ratio of 0.35, along with the use of CONPLAST SP-430. Flexural, tensile splitting, compressive, and pull-out tests were conducted on the cylinders, cubes, and prisms. GGBFS demonstrated the ability to improve the durability characteristics of high-performance concrete (HPC) compared to a standard mix. The blend with substitution rates of 10%, 20%, 30%, 40%, and 50% GGBFS, along with 1% steel fiber, exhibited superior strength and durability. It was found that replacing 40% of cement with GGBFS and steel fibers was effective as in Fig. (2-1). The addition of fibers significantly enhanced the toughness of the concrete compared to regular concrete.

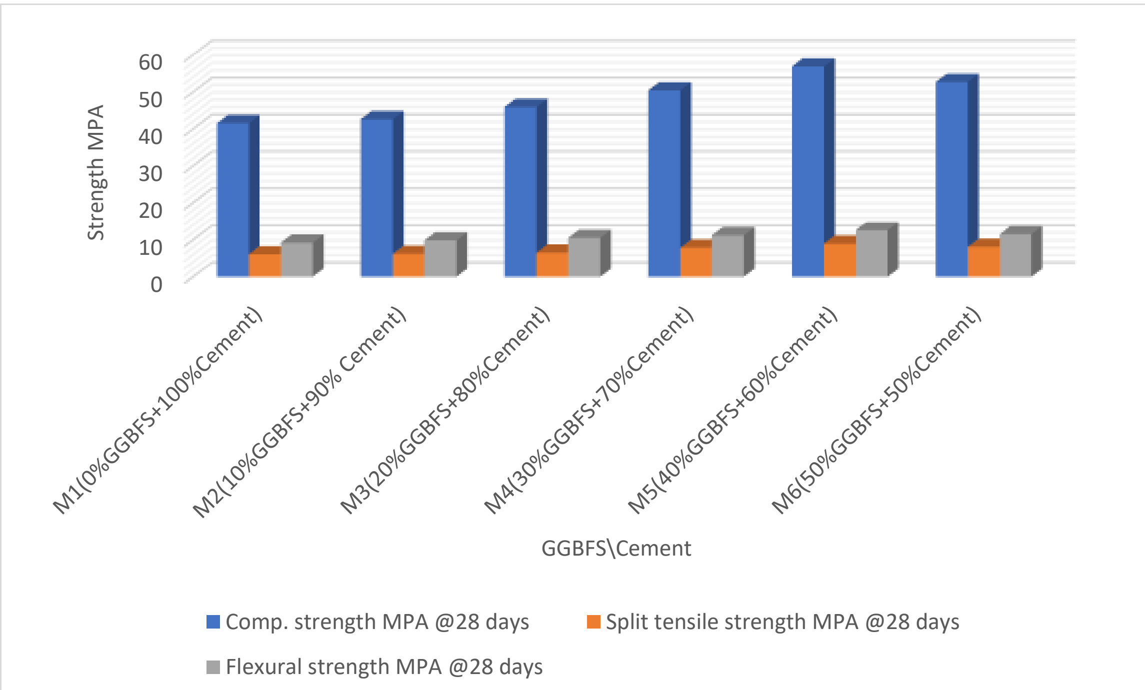

Fig. (2-1) Strengths of mixes [67]

In 2014, Ambily et al. [68] This study discusses the formulation of ultra-high-performance geopolymer concrete (UHPGPC) that can be cured at ambient temperatures. The UHPGPC mixtures included four blends containing fibers and one blend without fibers. The highest average compressive strengths achieved were 175 MPa for UHPGPC with steel fibers and 124 MPa for UHPGPC without fibers. From the load–deflection curve plotted for the UHPGPC prismatic specimens; it can be observed that the plane concrete failed abruptly at the end of linearity as in

Fig. (2-2). Utilizing industrial waste to manufacture this material and avoiding traditional curing processes for UHPC will enhance sustainability and enable on-site casting of UHPC.

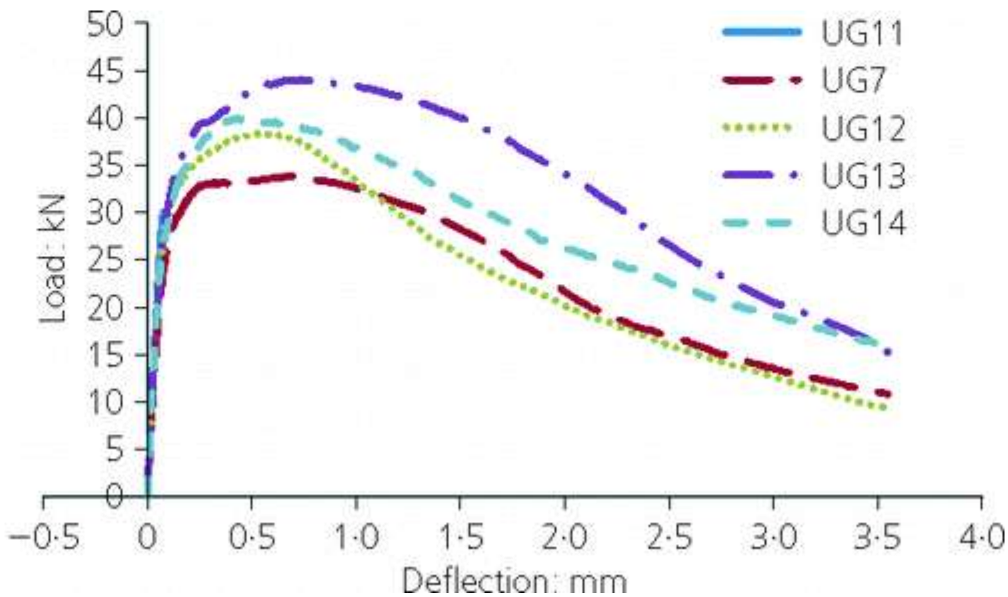

Fig. (2-2) Load–deflection for UHPGPCs with (UG7, UG12–UG14) and without (UG11) fibre [68]

In 2016, Singh et al. [69] In this study, fly ash and ground granulated blast furnace slag (GGBFS) were used in equal amounts (50% each). Polyethylene terephthalate (PET) fiber was incorporated into the geopolymer concrete at varying percentages (0.25% and 0.5% by weight of the cubes). The geopolymer concrete containing PET fiber was cured under outdoor conditions. Split tensile and compression tests were conducted on the cubes. The study included nine standard geopolymer concrete cubes, three geopolymer cubes with 0.5% PET fiber, and six geopolymer cubes with 0.25% PET fiber for the compression test. For the split tensile test, six geopolymer concrete cylinders with normal filler and six geopolymer cylinders with 0.25% PET fiber were cast. After 7 days, the compressive strength of the geopolymer concrete containing 0.5% PET fiber increased by 7.3%, while the compressive strength of the concrete with 0.25% PET fiber increased by 9.03%. After twenty-eight days, the compressive strength of the geopolymer concrete with 0.25% PET fiber increased by 12.07%. The tensile splitting strength of the geopolymer concrete with 0.25% PET fiber increased by 6.08% after seven days and by 9.56% after twenty-eight days compared to the samples without PET fiber.The experimental study found that adding PET fiber to geopolymer concrete prevents cracks during loading and delays the spread of cracks.

In 2019, Sharma et al. [70] In this study, geopolymer concrete was formulated using equal amounts of ground granulated blast furnace slag (GGBFS) and fly ash (FA) (50% each). Polyethylene terephthalate (PET) fibers were incorporated at varying percentages (2%, 3%, and 4%) to observe the mechanical and durability characteristics. The geopolymer concrete containing PET fibers was cured using two techniques: oven curing (24 hours at 60°C) and ambient curing. The dimensions of the PET fibers were 90 mm in length and 2 mm in breadth. The prepared samples were examined at 7 and 28 days. The results showed slight improvements in tensile, flexural, and compressive strengths. Throughout the loading process, the PET fibers acted as crack preventers, delaying the spread of cracks.

In 2020 Al-dujaili et al. [71] Investigated the influence of different alkaline activators (Na and K) on the mechanical and thermal behaviors of metakaolin-based geopolymer. The aim is to identify the mixes and process parameters that produce geopolymer paste with high compressive strength, low porosity, and optimal setting times. The results show that using a combination of K-ions and Na-ions significantly improves the compressive strength of the geopolymer compared to using Na-ions alone. Additionally, the setting time is reduced for geopolymers with silica content below 3.8 when K-ions are used. The bulk density of geopolymers also decreases with the addition of K-ions.

In 2021 Ahmed et al. [72] Reviews the compressive strength of sustainable geopolymer concrete composites, emphasizing the environmental benefits of using geopolymer concrete as an alternative to traditional Portland cement. The review examines various parameters that influence compressive strength, including the chemical composition of binder materials, the ratio of alkaline liquid to binder, extra water content, superplasticizer dosages, and curing conditions as in Fig. (2-3). Analyzing a dataset of 800 samples, the study identifies curing temperature, sodium silicate content, and alkaline solution to binder ratio as the most significant parameters affecting the compressive strength of fly ash-based geopolymer concrete composites.

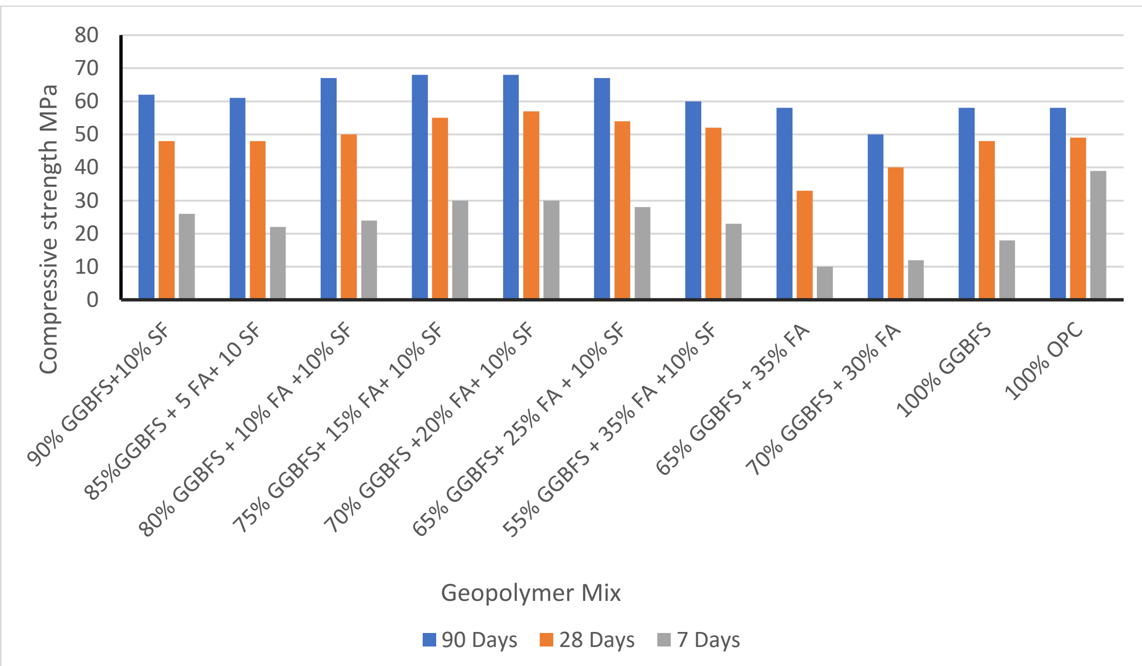

Fig. (2-3) Compressive strength of geopolymer mixes [72]

In 2021 Samer Medljy [73] This study investigates the use of ground granulated blast furnace slag (GGBFS) and class F fly ash as binding materials in geopolymer concrete, with steel fibre reinforcement added at different volume fractions to promote the use of structural geopolymer concrete made with 100% recycled concrete aggregates (RCA). The mechanical behavior of steel fibre-reinforced RCA geopolymer concrete was extensively tested for compressive strength, splitting tensile strength, and modulus of elasticity. Flexural performance was described using flexural strength, toughness, deflection, and residual strength. Durability properties were assessed by measuring bulk electric resistivity, water absorption, sorptivity, and abrasion resistance. Experimental findings revealed that 100% RCA slag-based and slag-fly ash blended geopolymer concrete with a 2% steel fibre volume fraction exhibited superior mechanical performance and comparable durability properties to those of the plain natural aggregate (NA)-based control mix.

In 2023, Nguyen et al. [74] Numerous trials had been carried out consisting GGBFS–FNS (50% GGBFS and 50% FNS) combination chances, numerous chemical admixtures curing in room temperature. The research assessed physical and durability properties, shrinkage, compressive strength and setting time. Conventional admixtures had no impact on the setting times of GGBFS–FNS geopolymer pastes. Increasing the water/solid ratio extended the setting time, while increased GGBFS content reduced it. The geopolymer mortars achieved compressive strengths over 30 MPa after 28 days as in Fig. (2-4). The water absorber admixture significantly reduced shrinkage up to 480 days. Increasing Na_2O/binder by adding NaOH pellets improved compressive strength, meeting marine environment requirements. The water absorber admixture also reduced shrinkage and improved chloride diffusion resistance. All things considered the geopolymers showed promise being eco-friendly fabric for engineering applications particularly in harsh settings.

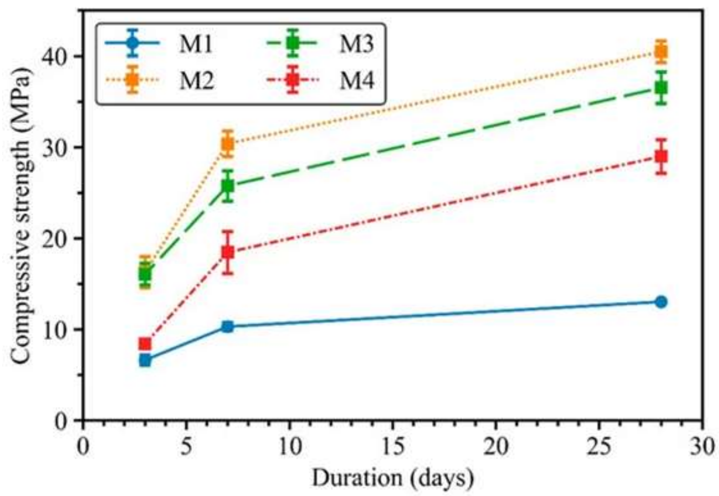

Fig. (2-4) Compressive strength of geopolymer mortar mixes [74]

In 2024 Abed et al. [75] Examined the effects of different ratios of ground granulated blast furnace slag/fly ash (GGBFS/FA) and sodium silicate/sodium hydroxide (SS/SH) on the properties of mechanochemically activated geopolymer (MAG) paste. Mechanochemical activation reduced rheological characteristics and setting time, with an 11% increase in strength compared to conventional activation. Increased GGBFS content improved rheological characteristics and mechanical properties. Higher SS/SH ratios negatively impacted rheological characteristics and mechanical properties. Setting time decreased with higher GGBFS content but increased with higher SS/SH ratios. Microstructural analysis revealed additional unreactive particles in both conventionally activated geopolymer and MAG paste containing 50% GGBFS.

2.3.2 Recycled PET Waste as a Fine Aggregate

In 2014, Prabhu et al. [76] Used PET bottle as a partial substitution of fine aggregate with fiber was carried out. The percentages of replacement were 0.5%, 1.0%, and 1.5% by volume. Three dimensions of fiber were regarded in this investigation (50*3) mm, (100*3) mm, and (150*3) mm with mixing proportion of 1: 1.48: 2.54 and w/c of 0.45. The flexure strength and compressive tests were conducted at ages of three, seven and twenty-eight days. (100*3) mm of fiber dimension had been given higher strength, and 1.0 % replacement of sand by volume was an optimum percentage of both tensile and compressive strength.

In 2015, Khanna et al. [77] Fine aggregate replacement in the concrete mixture. The PET waste used to partially replace the sand were 10%,20%,30% and 40% (by volume). Fly ash was utilized in part substitution of 5%,10% and 15% by weight for cement. The water to cement was 0:45. Super plasticizer ratio was for each mix 0.01. concluded that the compressive strength increased to its maximum when the fly ash content is 10% and PET waste plastic is partially substituted even 30% by volume of fibers.

In 2016, Azhdarpour et al. [78] PET waste fragments in percentages of (5, 10, 15, 20, 25, and 30) % were demonstrated as a partial substituted for fine aggregates. There were two kinds of plastic fragments used. With a diameter of 0.05–2 mm (Pf) the second gradation fragment was finer than the first which had a diameter of 2–4. 9 mm (Pc). That adding PET waste particles in place of 5% and 10% of fine aggregates increased the concretes flexural strength and increased its compressive strength to 39% and 76% respectively. Additionally, they discovered that substitutions exceeding 10% reduced bending, resistance but the 30% substitution rate exhibited behavior more akin to creep in concrete.

In 2021, Dawood et al. [79] The tests results presented that the presence of PET particles changed the physical and mechanical properties of produced concretes. Physical properties (density and ultra sound velocity) gradually decreased as PET ratios increased, while an increase in absorption rate was observed. Furthermore, for strength-related properties, the results showed that the specimens containing partial substitution ratios ranging within 5 %–12.5 % displayed 26.8 %–43.64 %, 18.6 %–26.9 %, and 18.1 %–30.2 % increments in the compressive, tensile, and flexural strengths, respectively, compared with the reference specimens. The findings also revealed an increase in energy absorption and axial strain of the specimens with 5%–20 % replacement percentages, while the modulus of elasticity decreased as the PET content increased. The results further indicated that the strength parameters decrease when the PET content exceeds 15 %.

2.4 Summery

Cement reduction in building materials is a major focus for academics, aiming to reduce carbon dioxide emissions by replacing some of the cement component with ecological binders.

- Industrial waste, such as GGBFS and fly ash, can be utilized in building materials to address the increase in waste from agriculture and industry.
- RGPC and RPCC beams have nearly identical load deflection characteristics.
- Substituting fly ash with GGBFS in GPC reduces water absorption, resulting in increased strength in a short amount of time.
- Replacing 40% of cement in High-Performance Concrete with GGBFS achieves optimal compressive strength.
- Increasing the molarity of sodium hydroxide enhances compressive strength.
- Oven-cured specimens yield higher compressive strength compared to sunlight-cured specimens.
- GPC beams have a slightly greater maximum load-carrying capacity than conventional OPCC beams.

- RGPC and RPCC beams exhibit similar crack width, spacing, and quantity of cracks for a given load.
- Fly ash geopolymer concrete shows excellent resistance to acid and sulphate attack compared to traditional concrete.
- Heat-cured GPC has high resistance to chloride attack, making it suitable for seawater locations.
- Adding PET fiber to geopolymer concrete prevents cracks during loading and delays crack propagation.
- Increasing PET plastic waste decreases the flexural and compressive strengths of the concrete.
- Incorporating shredded waste PET particles into concrete can help design seismically sound buildings.

The study addresses the need for sustainable and eco-friendly building materials by utilizing industrial waste and ecological binders. It aims to reduce carbon dioxide emissions and improve the mechanical and durability properties of concrete. The findings contribute to the development of geopolymer concrete with enhanced performance and resistance to environmental factors, making it suitable for various construction applications.

CHAPTER THREE

EXPERIMENTAL WORK

CHAPTER THREE: EXPERIMENTAL WORK

3.1 Experimental Program

The experimental work is divided into two primary sections. The first section involves the utilization of various geopolymer materials with different molarities and curing conditions in a geopolymer concrete mixture. The second section focuses on replacing a portion of the fine aggregates in the geopolymer concrete mixture with varying percentages of used PET bottles. This research utilizes various materials including geopolymer materials (GGBFS, Fly Ash), Sodium Silicate (S.S.), Sodium Hydroxide (NaOH), fine and coarse aggregate, reverses osmose water, and plastic PET bottle waste. Additionally, superplasticizer is utilized to enhance the mixtures workability.

3.1.1 Fly Ash

When making geopolymer concrete from fly ash generally works out more economically than Portland cement and improves the mixes workability and durability. Additionally, by recycling hazardous waste rather than letting it end up in a landfill this formula lowers the quantity of CO_2 emissions produced while in the process of production cement [98]. The composition of these substances is confirmed to (ASTM C618, 2002) [99], as illustrated in Table 3.1and 3.2.

3.1.2 Ground Granular Blast Furnace Slag (GGBFS1)

The exponential growth of urbanization and industrialization has made the recycling and management of industrial byproducts a significant challenge. Ground granulated blast furnace slag (GGBFS), a byproduct of the iron and steel industries, is highly reactive and beneficial in enhancing the properties of cement paste, mortar, and concrete. GGBFS improves strength, durability, and workability, and increases resistance to chemical attacks. It also reduces the heat of hydration, making it advantageous for large-scale concrete pours. Additionally, using GGBFS in cementitious materials promotes sustainability by recycling industrial byproducts and reducing the carbon footprint of traditional cement production [100]. These substances chemical makeup has been verified (ASTM C989,2010) [101], as illustrated in Table 3.3 and 3.4.

Table3.1 Physical properties of FA

Physical properties of FA	Content Range
PH	8-10
Fineness as surface area mm_2/g	12-18
Specific gravity	2.7
Particle size	0.03-0.12
Density (Kg/m^3)	1700 (bulk)
Color	Gray

Table 3.2 Chemical Compositions of FA

Chemical Compositions of FA	Content %
SIO_2	88.15
AL_2O_3	4.24
CaO	1.82
Fe_2O_3	1.6
Na_2O	0.08
MgO	0.18
K_2O	0.51
SO_3	0.02
TiO_2	0.04
L.O.I	3.23

Table 3.3 Physical properties of GGBS

Physical properties of GGBFS	Content Range
PH	11.5-12.5
Fineness as surface area mm^2/g	450
Specific gravity	2.98
Particle size	13.8
Density (Kg/m^3)	1000-1200(loose)
Color	Off-white

Table 3.4 Chemical compositions of GGBFS

Chemical Compositions of GGBFS	Content %
SIO_2	35.9
AL_2O_3	8.4
CaO	37.9
Fe_2O_3	0.6
Na_2O	0.3
MgO	8.9
K_2O	0.7
SO_3	0.7
TiO_2	1.9
L.O.I	0.9

3.1.3 Fine Aggregate

In this study, natural sand was utilized as a fine aggregate. The sand characteristics were in accordance with Iraqi Specification No. 45/2019, Zone [102]. This specification outlines that the fine aggregate should be clean, hard, durable, and free from any deleterious materials that could affect the concrete's performance. The particle size distribution of the sand should conform to the grading limits specified in Zone 2, ensuring a well-graded material that enhances the workability, strength, and durability of the geopolymer concrete. The use of natural sand with these specifications ensures that the concrete mix achieves optimal mechanical and durability properties, as in Table (3.5), (3.6) and Fig. (3-4). To calculate the fineness modulus of fine aggregates, a representative sample of the fine aggregate is first obtained and weighed before sieving. A sieve analysis is then conducted using a series of standard sieves with progressively smaller openings. The sample is passed through the sieves, shaking them to separate the particles. The weight of the material retained on each sieve is recorded, and the cumulative percentage retained on each sieve is calculated. Finally, the cumulative percentages are added and divided by 100 to obtain the fineness modulus. This value provides an indication of the aggregate's particle size distribution and is used in concrete mix design to ensure desired performance characteristics.

Table3.5 Physical properties of fine aggregate

Physical Properties	Test results
Specific gravity	2.56
Sulfate content %	0.13
Absorption %	0.75

Table 3.6 Sieve analysis of fine aggregate

Sieve size (mm)	Passing (%)	Requirements Gradation (IQS)	Retained %
9.5	100	100	0
4.75	98.2	100-90	1.8
2.36	90.8	100-75	9.2
1.18	73.3	90-55	26.7
0.6	52.3	59-35	47.7
0.3	15.1	30-8	84.9
0.15	4.2	10-0	95.8

3.1.4 Coarse Aggregate

Coarse aggregate has a maximum size of 19. 5mm.The grading of coarse aggregate according to the Iraqi Specification No. 45/2019[102] as in Table 3.7.

Table3.7 Sieve analysis of coarse aggregate

Sieve size (mm)	Passing (%)	Requirements Gradation
25	100	100
19	98.5	90-100
9.5	63.9	40-70
4.75	2.7	0-15
2.36	0.2	0-5

3.1.5 Sodium Hydroxide

Sodium hydroxide (NaOH) is an extremely caustic metallic base and a strong sodium alkali. It appears as a white solid and is commonly sold in the form of flakes. This compound is highly reactive and is widely used in various industrial and chemical processes, including the manufacture of paper, textiles, and detergents, as well as in water treatment and chemical synthesis. Its caustic nature necessitates careful handling and storage to avoid potential harm or damage. Fig. (3-1) as well as in prepared solutions in various concentrations.

Fig. (3-1) NaOH Flakes

3.1.6 Sodium Silicate

Sodium silicate is the formula Na_2SiO_3. Also referred to as liquid glass or water glass.[103]. Fig. (3-2).

$$Na_2CO_3 + SiO_2 \rightarrow Na_2SiO_3 + CO_2 \quad 3\text{-}1$$

Table3.8 The characteristics of sodium silicate

characteristics of sodium silicate	Content range
Specific gravity	1.534-1.551
Na_2O % by mass	13.1-13.7
SiO_2% by mass	32-33
Viscosity: (CPS) 20°	600-1200
Density-20 Baum	51±0.5

Fig. (3-2) Sodium Silicate Solution

3.1.7 Water

The Osmosis recycled (R.O) water was utilized for casting was used for the study.

3.1.8 Super Plasticizer (TOPFLOW SP 603)

In this study Super plasticizer (TOPFLOW SP 603) was utilized as admixture to improve the workability. which is agreed with ASTM C494 Types A, B, D, F and G [104], according to the technical international specification shown in Table 3.9.

Table 3.9 Technical description of TOPFLOW SP 603

description of TOPFLOW SP 603	Content discerption
Chemical Base polymer	Modified polycarxylates based
Appearance/colors liquid	Dark Brown/Black Liquid
Flash Point	N/A
Specific gravity @25º C ±2C	1.21
Dosage	0.5 to 3.0 liter per 100 kg of cementitious material

3.1.9 Alkaline Activator

The alkali solution is made by blending sodium hydroxide anhydrous flakes form and deionized water with sodium silicate solution available commercially.The sodium silicate solution is commercially available. In this thesis, sodium silicate solution had a percentage of SiO_2 to Na_2O by mass 2.44. The proportions by mass of ingredients, are SiO_2 =32 %, Na_2O = 13.1 %, and water = 54.9 %. The NaOH solution is mixed to the Na_2SiO_3 solution after it has been prepared. For use in the cast GPC, the alkaline solvent should be prepared by combining all solutions for at least 24 hours [105].

3.1.10 PET Plastic Waste as Sand Replacement

PET bottle waste is the plastic type that used in the current research. PET bottles with different sizes and colors were particles passing the sieve No. 4 from the factories and Choppers or Al-Naseri gropes, (Sama Pack) branch from Baghdad city, Altajiat region, which are specialized in recycling PET waste exclusively as in Fig. (3-3). A sieve analysis was carried out for PET particles and found that it approximates to the sieve analysis based on the Iraqi specification No.45/1984 zone 2[102] see Table (3.10). The specific gravity of PET particles is 1380 kg/m³[79].

Fig. (3- 3) The PET wastes shape

Table 3.10 PET waste particle classification

Sieve size (mm)	PET passing %	IQS limit %
10	100	100
4.75	95.2	90-100
2.36	80.34	75-100
1.18	50.52	55-90
0.60	30.5	35-59
0.3	0.6	8-30
0.15	0.21	0-10

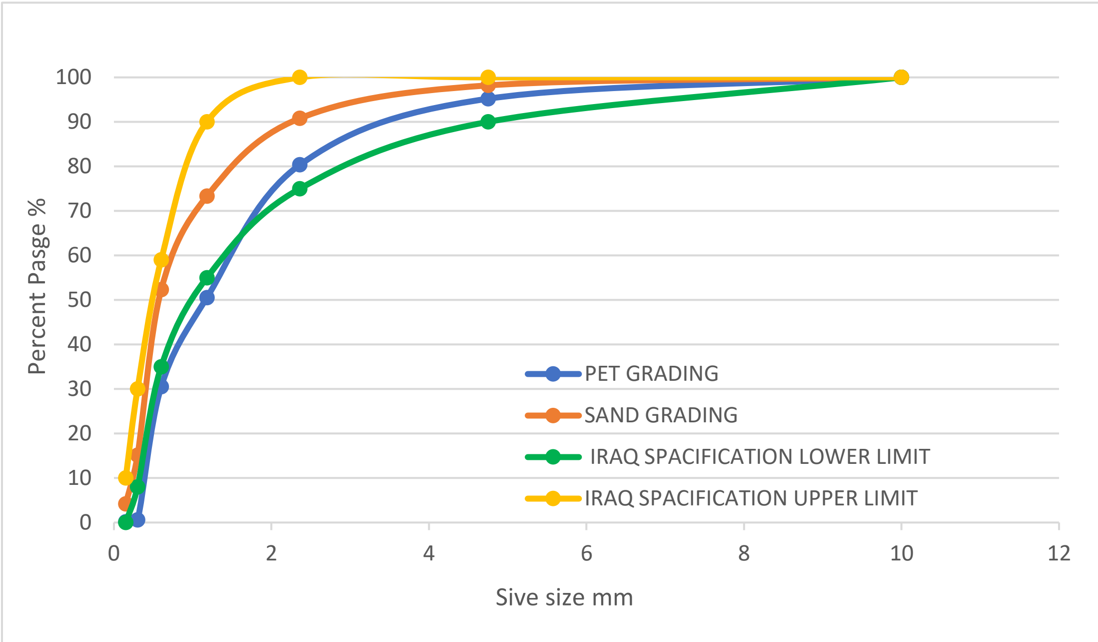

Fig. (3- 4) Grading curve for original PET waste and fine aggregate

3.1.11 Steel Reinforcement

The deformed steel bars of 12 mm used for tension reinforcement, 10 mm diameter for shear reinforcement, and 10 mm used as a stirrup in the reinforcement of shear specimens. The properties of reinforcing bars are shown in Table 3.11. The results were found to comply with the requirements of ASTMA615/A615M-20[118].

Table 3.11 Properties of steel reinforcement

Bar type	Bar diameter (mm)	Bar area (mm^2)	Yield strength fy (MPa)	Tensile strength fu (MPa)	Yield Strain
Longitudinal steel bars & stirrups	10	78.5	515	624	0.00258
Longitudinal steel bars	12	113.04	493	583	0.00247

3.2 Details of Experiments (Selection Geopolymer Material)

3.2.1 Fly Ash

The mix design for the geopolymer concrete included a ratio of 1:1.5:3 for fly ash: fine aggregate: coarse aggregate, respectively. The water-to-cementitious material ratio was maintained at 0.125 for the mixtures. See Table 3.12.

Table 3.12 Summarizes the mix design (FA)

Fly ash(kg/m³)	NaOH (kg/m³)	S.S (kg/m³)	water (kg/m³)	Fine agg. (kg/m³)	Coarse agg. (kg/m³)	s.p (kg/m³)
400	23	110	50	650	1200	12

Alkaline liquid is prepared by mixing sodium silicate solutions and sodium hydroxide at least for 24 hours [105]. The sodium hydroxide with flake formed of 99 % purity, is commercially available. NaOH needs to be dissolved in distilled water to create a solution with a specific concentration before geopolymer casting. Depending on the various ratios of caustic soda flake to water a molar concentration may be produced. Sodium hydroxide concentration usually varied from (5–16) in molarity. The percentage used is (10) Molar. Properties for using sodium hydroxide in the mixture were according to (ASTM.E291, 2009).[106]. The sodium silicate solution is commercially available. The same mixing method was used for GPC, depending on previous research by researchers who confirmed that the same technique could be used for regular concrete in manufacturing geopolymer [105]. The dry components are added to the mixer for three minutes in order to mix well. The alkali solution was mixed with the water and the superplasticizer and left for two minutes. Then, the solution was added to the dry mixture, and the mix continued [117]. After that, the blend is introduced into the molds and compacted manually to be closer to field pouring conditions to get rid of air/voids were cured in ambient temperature [86], in the laboratory for a period up to 28 days after casting, After the curing period the samples underwent tests. See Fig. (3-5)

Fig. (3 -5) Samples of Fly Ash Cubes

The mixing for geopolymer concrete specimens was performed using a mixer. The mixtures were cast in (150*150*150) mm cubes molds. Compressive strength measurement of cubes was carried out according to the British standard (BS 1881 part 116-83) [107]. This test was done in the College of Engineering, Basrah University, using a compression machine with a capacity of (2000 kN). Three cubes were tested for each age. The samples were tested at (seven and twenty-eight) days after casting. The test continued until the failure of the GPC specimens. Table (3-13).

3.2.2 GGBFS 1

The mix design for the geopolymer concrete included a ratio of 1:1.5:3 for ground granulated blast furnace slag (GGBFS): fine aggregate: coarse aggregate, respectively. The water-to-cementitious material ratio was maintained at 0.182 for the mixtures. See Table 3.14

Table 3.13 Results of the compression and density at age "7 and 28" days for the FA cubes for the pre-trial experiment work

compression MPa (7 days)	Density kg/m³ (7days)	compression MPa (28 days)	Density kg/m³ (28days)
14.6	2253.3	18.27	2205
14.9	2266	19.8	2234
16.8	2253	22.4	2236

Table 3.14 Summarizes the mix design (GGBFS1)

GGBFS (kg/m³)	NaOH (kg/m³)	S.S (kg/m³)	Water (kg/m³)	Fine agg. (kg/m³)	Coarse agg. (kg/m³)	s.p (kg/m³)
400	19	200	73	650	1200	12

Alkaline liquid is prepared by mixing sodium hydroxide solutions and sodium silicate at least for 24 hours [105]. The percentage used is (8) Molar. Properties for using sodium hydroxide solution in the mixture were according to (ASTM.E291, 2009) [106]. The same mixing and curing method were used as in 3.9.1. After 4 days the curing period the specimens were tested Fig. (3-6).

The mixing for geopolymer concrete specimens was performed using a mixer. The mixtures were cast in (150*150*150) mm cubes molds. Compressive strength measurement of cubes was carried out according to the British standard (BS 1881 part 116-83) [107]. This test was done in the College of Engineering, Basrah University, using a compression machine with a capacity of (2000 kN). Three cubes were tested for each age. Three cubes were tested for each age. The specimens were tested at (7,14 and 28) days after casting. The test continued until the failure of the GPC specimens. See Table (3-15).

Fig. (3-6) Samples of GGBFS1 Cubes

Table 3.15 Results of the compression and density at age "7,14 and 28" days for the (GGBFS1) cubes for the pre-trial experiment work

Compression MPa (7 days)	Density kg/m³ (7days)	Compression MPa (14 days)	Density kg/m³ (14days)	Compression MPa (14 days)	Density kg/m³ (28days)
23.4	2339	24.7	2337	26.8	2330
24.1	2342	25.2	2340	27.0	2338
25.1	2348	25.7	2345	27.2	2341

3.2.3 GGBFS 2

The mix design ratio for mixture was same to 3.10.2. The water to cementitious ratio was 0.125 for mixes. See Table 3.16. Alkaline liquid is prepared by mixing sodium hydroxide solutions and sodium silicate at least for 24 hours [105]. The percentage is (10) Molar. Properties for using sodium hydroxide in the mixture were according to (ASTM.E291, 2009) [106]. The same mixing method was used as in 3.9.1. After the curing period (in the oven 65°C [108,109] in two layers for 24 hours after casting) the specimens were tested. See Fig. (3-7).

Table 3.16 Summarizes the mix design (GGBFS2)

GGBFS (kg/m³)	NaOH (kg/m³)	S.S (kg/m³)	Water (kg/m³)	Fine agg. (kg/m³)	Coarse agg. (kg/m³)	s.p (kg/m³)
400	23	110	50	650	1200	12

Fig. (3-7) Samples of GGBFS2 Cubes

The mixing for geopolymer concrete specimens was performed using a mixer. The mixtures were cast in (150*150*150) mm cubes molds. Compressive strength measurement of cubes was carried out according to the British standard (BS 1881 part 116-83) [107] testing method on a Universal Testing Machine. Three cubes were tested for each age. The samples were tested at (7,14 and 28) days after casting. The test continued until the failure of the GPC samples. Table (3-17) , Fig. (3-8) and Fig. (3-9).

Table 3.17 Results of the compression and density at age of " 7,14 and 28" days for the (GGBFS2) cubes for the pre-trial experiment work

Compression MPa (7 days)	Density kg/m³ (7days)	Compression MPa (14 days)	Density kg/m³ (14days)	Compression MPa (14 days)	Density kg/m³ (28days)
38.2	2368	44.4	2359	50.6	2350
45.1	2343	47.5	2340	52.3	2330
48.0	2351	51.1	2348	53.3	2344

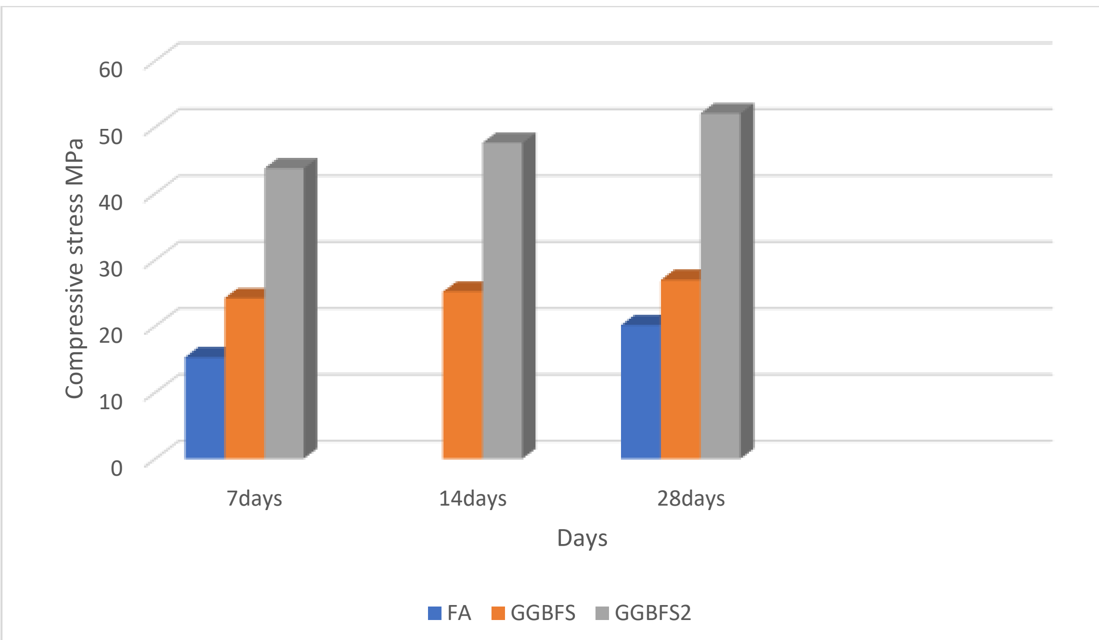

Fig. (3-8) Compression strength to geopolymer concrete cubes for the pre-trial experiment work

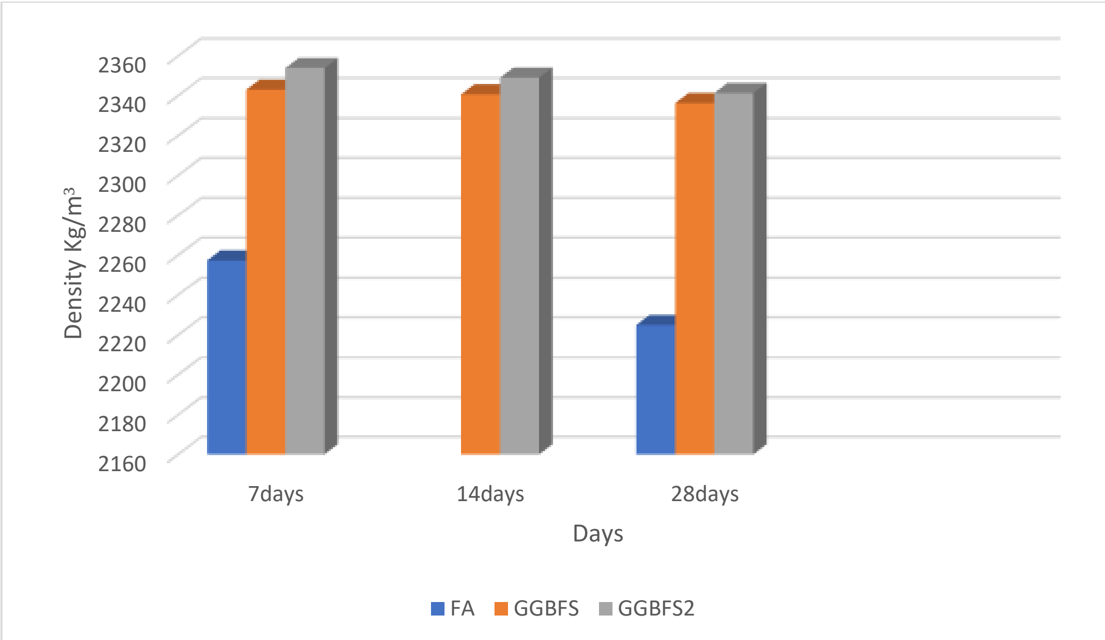

Fig. (3-9) Density to geopolymer concrete cubes for the pre-trial experiment work

3.3 Experimental Work of Partial Sand Replacement with PET Waste Particles

Experimental work involves studying the result of utilizing waste PET resulting from cutting and chopping plastic bottles of water and soft drinks on GPC physical and mechanical characteristics, besides studying its effects on the behavior of RGPC beams when it uses in concrete mixtures.

3.3.1 Concrete Mixture

In this investigation, the mix proportion is 1: 1.5: 3 as a concrete mix by weight. The weights of GGBFS, sand and gravel for each cubic meter in this mixture are (400, 650, and1200) kg, respectively. The water-cementitious ratio was 0.125 with admixture (Superplasticizer) percent of 0.3% to improve workability. This study replaced some of the sand with five percentages of PET waste (5%, 10%, 15%, 20%, and 30%), additionally in relation to the reference mixture without PET 0%.

Table (3.18) showed all quantities and substate percentages in the mixtures. The scope of this work includes the use geopolymer material (GGBFS) and one kind of waste made of plastic which is PET plastic bottles waste as a sand replacement. Accordingly, this section will focus on the proportion of the mixture and the replacement percentages used in the mixture, see Table (3-18).

Table 3.18 Concrete mixture proportion with all PET replacement

Material(kg/m³)	PET%					
	0%	5%	10%	15%	20%	30%
GGBFS	400	400	400	400	400	400
NaOH	23	23	23	23	23	23
S.S.	110	110	110	110	110	110
Sand	650	617.5	585	552.5	520	455
Gravel	1200	1200	1200	1200	1200	1200
Water	50	50	50	50	50	50
PET	0	32.5	65	97.5	130	195
S.P.	12	12	12	12	12	12

3.3.2 Mixing Procedure

The mixtures were mixed by a 240L electric mixer in the structural laboratories at the Faculty of Engineering, Basrah University, based on what follows steps:

1- All the ingredients of each mixture were weighed and placed in a clean area.

2- Wash and dry PET, gravel and sand before use in a mixture.

3- Prepare and clean the mixer and ensure continuous operation during the mixing period.

4- Initially, a specified percentage of the PET waste particles are added to the supplementary amount of sand so that their final weight is equal to the weight of the fine aggregate in the GPC mixture and placed in the mixer.

5- Gravel, sand and GGBFS were added in to mixer, then they mix for two minutes for homogeneity.

6- After homogenization of the mixture, alkaline solution and super plasticizer. Along are added with extra water to dry mix and the same is mixed thoroughly for four minutes to get homogeneous mix.

3.3.3 Casting and Curing Procedure

The procedures are included lubricating the internal sides of the molds and fixing the reinforcing cages inside them, then casting the geopolymer concrete into the molds in three layers, and using the vibrator, take into consideration the leveling of the upper outer surface of each mold. All geopolymer concrete beams are extracted from the molds after one day and they are then demolded and kept in lab temperature till required age is reached. After prescribed age, the mechanical properties are determined. The other specimens (cubes, cylinders, and prisms) treatment with same way. Fig. (3-10) shows the preparing and casting for beams and specimens.

Fig. (3-10) Beams and specimens

3.4 Mechanical and Physical Characteristics of Concrete Partially Substituted with PET Waste for Sand

This section of the current research investigates the impact of PET plastic impact on the physical and mechanical characteristics of geopolymer concrete mixture. For each percentage of PET waste, nine (150*150*150) mm cubes, nine cylinders measuring (150*300) mm, and six prisms measuring (100*100*400) mm. These were used to calculate density, compressive strength, elastic modulus, splitting tensile strength, absorption, conductivity, and flexural strength.

3.4.1 Reinforced Beam Specimens Containing PET Waste in Place of Sand

This part of study is focused on the impact of using PET bottles waste as a sand replacement on the behavior of structural beam specimens. Five beams with dimensions (150 *200 *1400) mm were used for testing the PET waste utilized as a partial sand substitute, one for each substituted percentage, besides the reference beam (without PET). All geopolymer concrete beams are casting using iron formwork.

The steel molds were with movable iron base and fixed sides connected with each other by weld, the beams are simply supported. This detail was used in all reinforced geopolymer concrete beams which contained PET particles percentages as a partial substituted of sand. Two points loads separated by a distance of 440 mm and two supports with a clear span of 1400 mm were used in this study, see Fig. (3-11). The concrete beams were loaded in such a way to prevent a shear failure in the beams section, where the distance between each point load and support (a) was of 380mm while the effective depth (d) of beam section was of 150mm. So, the ratio of (a) to (d) was equal to 2.5, which indicates that the section of the beams with stand shear force. The ACI318-25 [110] is followed in the design of the flexural beam reinforcement to ensure that the compression zone of the beam section fails in flexure, with controlled failure in tension zone, and designed for shear reinforcement to guarantee that the beam section hold out shear force, according to ACI 318- 95 [110]. All beams were reinforced by two bars at the tension zone with12 mm and two 10 mm bars at the compression zone. Stirrups with a 10 mm diameter and a 60 mm c/c spacing are used at shear span with a 100 mm c/c spacing in the middle [119]. as illustrated in Fig. (3-11).

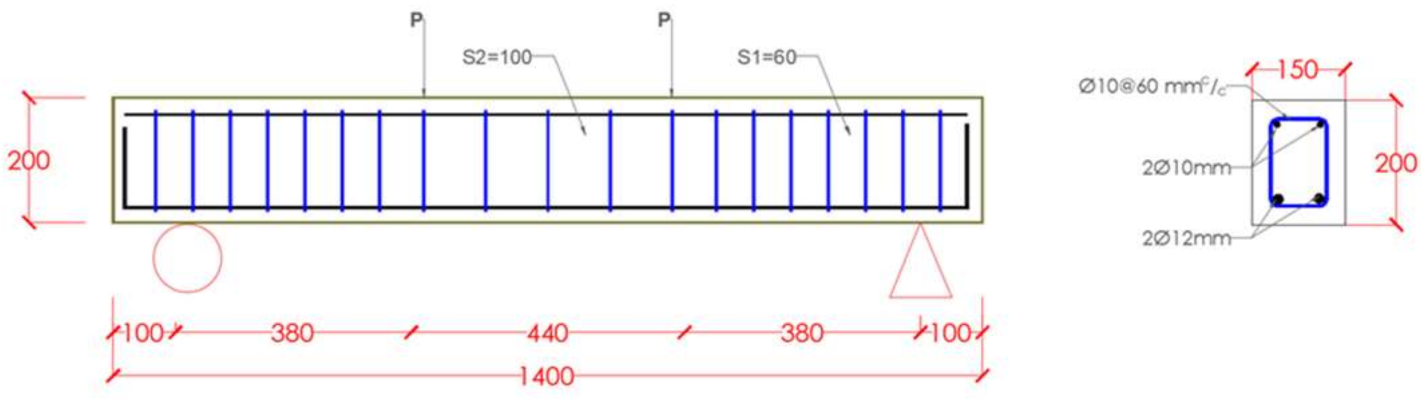

Fig. (3-11) Dimensions and details of beam specimen

3.5 Tests on Concrete Mixtures

3.5.1 Fresh Concrete Tests

3.5.1.1 Slump test

The concrete is deemed suitable and consistent when it demonstrates workability, maintains homogeneity during casting, manages without segregation, and can be compacted without requiring extra effort. This ensures that the concrete mix can flow and fill the formwork effectively, producing a uniform and cohesive structure that maintains its integrity throughout the construction process, leading to higher quality and durability of the final product. Slump test is prescribed according to ASTM C143 [111] as in Fig. (3-12).

Fig. (3-12) Slump test

3.5.2 Hardened Mechanical Tests

3.5.2.1 Compression Strength

This test was done by using cubical specimens with dimension (150*150*150) mm according to the British standard BS 1881 part 116-83 [107]. A compressive machine of 3000 kN capacity was used herein as in Fig. (3-13).

Fig. (3-13) Compression machine test

3.5.2.2 Splitting Tensile Strength

Cylinders samples with dimensions of (150*300) mm for splitting tensile strength. The Civil Engineering labs were used in the Engineering College, Basrah University according to ASTM-C496 [112] standard. The Universal Testing Machine (200 ton) is used see Fig. (3-14).

Fig. (3-14) The Universal testing machine

3.5.2.3 Flexural Strength Test

Prism specimens with dimensions (100*100*400) mm were used to examine concrete flexural strength test according to the ASTM-C78[113]. This test was done in the College of Engineering, Basrah University, by using The Universal Testing Machine (200 ton) as shown in Fig. (3-15). To calculate the flexural strength the following Eq.3.1 is utilized.

$$Fr=PL/bd^2 \qquad 3\text{-}2$$

where:

Fr: modulus of rupture (MPa)

P: maximum applied load (N)

L: span length (mm)

b: average width of the specimen (mm)

d: average depth of specimen (mm)

Fig. (3-15) Flexural Strength Test

3.5.2.4 Absorption Test

Cubes samples with dimensions (150*150*150) mm were used according to ASTM C642 [114]. The specimens are initially dried in an oven at a temperature of 100°C for 72 hours, as illustrated in Fig. (3-16). Following this drying period, the specimens are weighed to obtain their dry weight. Subsequently, the dried specimens are submerged in water for a duration of 24 hours. After immersion, the specimens are weighed again to determine their wet weight. The percentage of water absorption is then calculated based on the relationship between the dry and wet weights, providing insights into the material's porosity and absorption characteristics.

Absorption rate = 100*(weight after submerged- weight before submerged)/ weight before submerged.

Fig. (3-16) Drying the specimens of absorption test in the oven

3.5.2.5 Conductivity

In this study the concrete conductivity is measured by ultrasonic pulse velocity through concrete cube according to ASTM C597 [115]. Cubes samples with dimensions of (150*150*150) mm and ultrasonic pulse velocity apparatus see Fig (3-17). The UPV test is performed by using PUNDIT PC 1012 with an accuracy of 0.1 micro second, direct methods from two directions.

Fig. (3-17) Ultrasonic device and test method

3.5.2.6 Energy Absorption and Modulus of Elasticity Tests

Six cylinders with dimensions (150 x 300) mm were used to test energy absorption and elastic modulus (toughness) after attached to strain gauge. This test was set up by using a 200-ton compression machine and data acquisition device as in Fig. (3-18). Elasticity modulus and toughness tests are done according to ASTM C469 / C469M – 14 [116].

Fig. (3-18) Modulus of elasticity and energy absorption tests

3.5.2.7 Density Tests

The density is measured before compression test for each cubical specimen.

3.6 Testing of concrete beams

3.6.1 Testing Machine

In the structural Laboratories of the University of Basrah, an automatic compression machine with a capacity of 200 ton and was used to test beam. Also, it can be controlled manually. The applied loads were in successive increments of about 5 kN until reaching to the failure load. Observations were noted after every load increase, such as the strain value, deflection and first crack and draw crack patterns.

3.6.2 Dial Gauges

In order to calculate the deflections for all beams at every load stage, two dial gauges were used in the 1400mm beams. The first one was placed under the mid-span of beam and the second placed at 1/4 – span of beams as in Fig. (3-19). The dial gauges accuracy was of 0.01mm with a maximum reading of 10 cm for mid and 1/4 – span gauge.

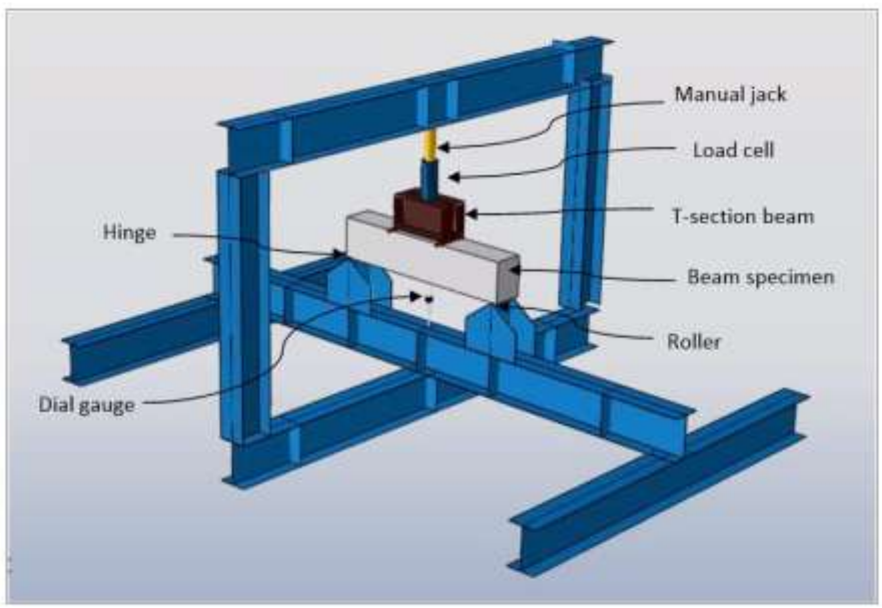

Fig. (3-19) Dail gauges used in tests

3.7 Test Variable

3.7.1 Mechanical and Physical Properties of Geopolymer Concrete with PET Waste

The sand replacement percentages with PET waste are the main test variable in this part. Five replacement proportions of PET waste are used 5%,10%, 15% ,20% and 30% along with reference mix without PET (0%). For each percentage the following properties were determined; slump, density, compressive strength, elastic modulus of elasticity, splitting tensile strength, absorption, conductivity, flexural strength, energy absorption, strain and ductility.

3.7.2 Reinforced Concrete Beams with PET as a Sand Replacement

In this part, five beams were tested with different PET percentage, i.e. each beam has been one PET percentage and the PET percentages are 5%, 10%,15%, 20% and 30% in addition, reference beam. These percentages are variables used as sand replacement weight percentages. Its detail is as shown in the Table (3-19).

Table 3.19 Beams details

No.	Beam remark	Dimension mm	Weight percentage of PET as sand replacement	Reinforcement
1	B 0% R	1400*200*150	0%	Steel Rebar
2	B 5%	1400*200*150	5%	Steel Rebar
3	B10%	1400*200*150	10%	Steel Rebar
4	B15%	1400*200*150	15%	Steel Rebar
5	B20%	1400*200*150	20%	Steel Rebar
6	B30%	1400*200*150	30%	Steel Rebar

CHAPTER FOUR

RESULTS AND DISCUSSIONS

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 General

In this chapter, the results and discussion are presented for the fresh and hardened geopolymer concrete. The slump result test is pointed out herein for fresh GPC. While for hardened GPC some results testes are presented in this chapter such as: compressive, splitting, flexural shear, modulus of elasticity. In addition, ultrasonic pulse velocity, absorption and density tests. Six mixes design are presented herein, five mixtures with natural sand is partially substituted with PET and one mixture is reference. Also, the structural behavior results of the semi-full-scale beam for each replacement ratio was presented. These results included the ultimate load, the ultimate deflection, ductility, energy absorption, number of cracks, the load when the initial crack appears and spacing between cracks, with drawing relationships for each parameter.

4.2 Tested Specimens

The experimental results are divided into two parts. The first part is included mechanical and physical tests results of partial replacing of sand with PET waste bottle particles in GPC mixture. The behavior of RGC beams was examined in the second section in relation to PET wastes used as a partially substitute for sand. Properties both physical and mechanical tests for concrete included the use of 150 specimens that were as follows 54 cubes with dimensions (150 *150 * 150) mm, 54 cylinders with dimensions (150 * 300) mm, 36 prisms with dimensions (100 * 100 * 400) mm. Structural behavior tests (the section about replacing fine aggregate with PET waste) included six semi-full scale GPC beams with measurements of (150 * 200 * 1400) mm.

4.3 Outcomes of The Mechanical and Physical Characteristics

This section presents the results of both hardened and fresh geopolymer concrete (GPC) properties, as well as GPC with varying proportions of PET used as a replacement for sand in the mixture. The properties were evaluated at the ages of (7, 28, and 90)days, which include:

1- Workability of mixes.

2- Density.

3- Compressive strength.

4- Splitting tensile strength.

5- Flexural strength.

6- Conductivity

7- Energy absorption and elastic modulus.

8- Absorption test

4.3.1 Fresh Concrete Test (Workability)

After mixing process slump test was taken immediately to ensure the workability requirements of mixes with 0.125 water-cementitious ratio. Each mix that contains variable percentages of PET particles was tested by slump cone test. The outcomes were shown slump is decreased when the percent of PET is increased as in Table (4-1) and Fig. (4-1). Reduced slump is associated with a number of causes, including the irregular PET shape bottle waste particles with sharp and irregular edges, causing an increase in particles surface area, and another reason is that the PET plastic particles are reduced the homogeneity of the mixtures by isolating the mixture components from each other, i.e. more heterogeneity with the increasing of PET. In order to resolve this issue had been used super plasticizer [79].

Table 4-1 Results of slump for PET percentages as sand replacement

No.	PET/Sand Percentages	Slump test (mm)	Workability Classification	Limit of ENV 206 [42]	Reduction in slump %
1	0%	170	High workability	>160 mm	-
2	5%	150	Medium workability	100-150 mm	11.7
3	10%	140	Medium workability	100-150 mm	17.6
4	15%	120	Medium workability	100-150 mm	29.4
5	20%	100	Medium workability	100-150 mm	41.1
6	30%	80	Low workability	50-90 mm	52.9

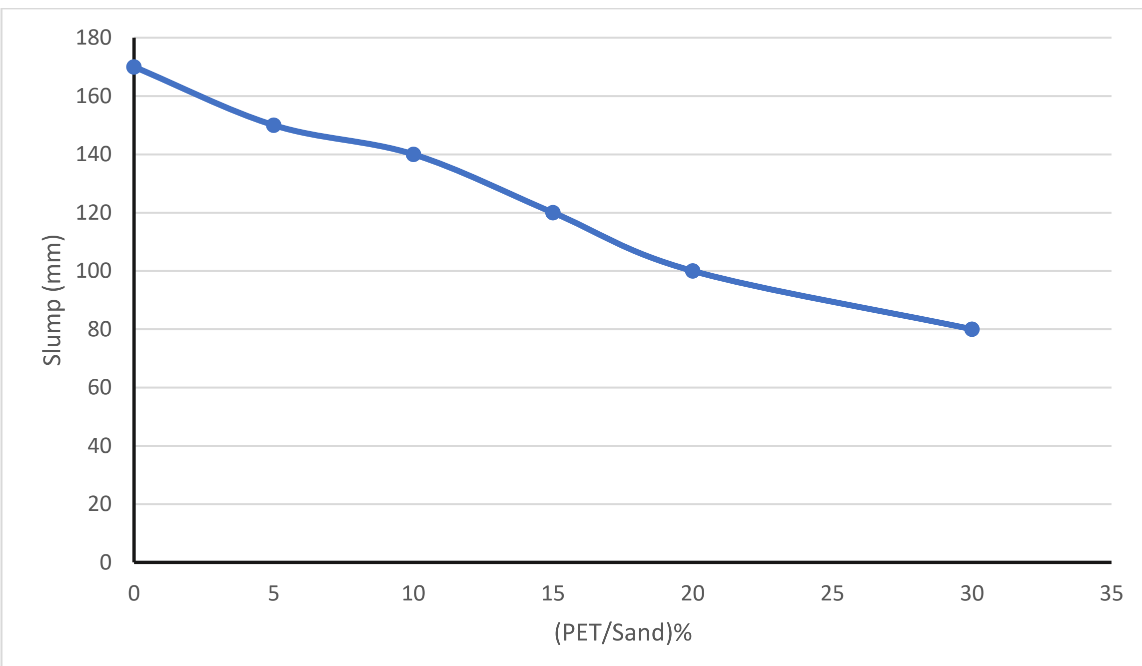

Fig. (4-1) Slump for PET percentages as a sand replacement

4.3.2 Hardened Concrete Tests

4.3.3 Compressive Strength

The compressive strength considers among its most crucial attributes that reflect GPC performance. It represents the ability of GPC to resist axial forces (compression or tension). Nine GPC cubes were casted having measurements of (150*150*150) mm for each weight percentage of PET, they were tested for compression as three cubes at 7 days, three at 28 days, and two for 90 days. The compressive strength results are shown in Table (4-2) and Fig. (4-2). It is observed through the results that the replacement percentage which ranging between 5% and 15% achieved a rise in strength when compressed when comparing to the compression of the reference cubes outcomes. The percentage 20% and 30% decreased in compression resistance by 17.86% and 28.88 % respectively from the reference cubes. However, the compressive strengths of specimens for ages 28 and 90 days are close, where the replacement percentages of 5 % -15% representing the higher values of compressive strength (52.2 and 48.28) MPa respectively at 90 days, the PET percentages ranged between 5%-15% are influenced to the grading of aggregates and contributed a little of voids, i.e. PET particles are improved grading of aggregates, and an increase in compressive strength occurs within this range. see Fig. (4-2). The structure of particles of the PET is affected on the failure mode when the applied load is reached ultimate load, i.e. the internal stresses are converted from shear stresses to tensile stresses that led to boost the strength of concrete. Furthermore, the plastic materials exhibit greater elongation from aggregate particles (sand) resulting in loading transformation prior to failure. More precisely, the GPC without any PET waste fragments is brittle material therefore the failure point is appeared at lower applied load than specimens with PET waste. In contrast, the compressive strength is decreased when the fragments of PET waste are more than 15 %, see Fig. (4-2). Smooth surface of PET fragments is influenced on bond strength between cementitious paste and PET particles negatively. In contrast, specimens containing higher percentages of PET waste (20% and 30%) exhibited a more pronounced transition zone between the PET particles and the cementitious paste. This transition zone, being weaker, resulted in the specimens having reduced compressive strength. Essentially, the increased presence of PET waste particles compromised the overall structural integrity of the concrete, making it less able to withstand compression loads effectively [79]. By contrasting the method of failure for percentages containing PET with reference cubes, it is noted that the cubes containing PET are not crushed suddenly. In contrast the cracks were appeared without crushing or separation when applied loading up to failure, but the references specimens were failed suddenly under loading to achieve failure loading, see Fig. (4-3). This indicates the ductility provided by the presence PET plastic waste.

Table 4.2 Results of compressive strength for PET percentages as sand replacement

PET waste (%)	Average compressive strength(fcu) MPa			Changing in compressive Strength (%) (90 Days)	7/28 Ratio	28/90 Ratio	7/90 Ratio
	7Days	28Days	90 Dyas				
0%	43.05	46.36	47.01	-	0.92	0.98	0.91
5%	45.66	51.04	52.20	+11.04	0.89	0.977	0.87
10%	50.39	52.25	53.37	+13.52	0.96	0.979	0.94
15%	44.62	47.38	48.28	+3.64	0.94	0.98	0.92
20%	33.13	37.55	38.61	-17.86	0.88	0.97	0.85
30%	26.61	32.87	33.43	-28.88	0.80	0.98	0.79

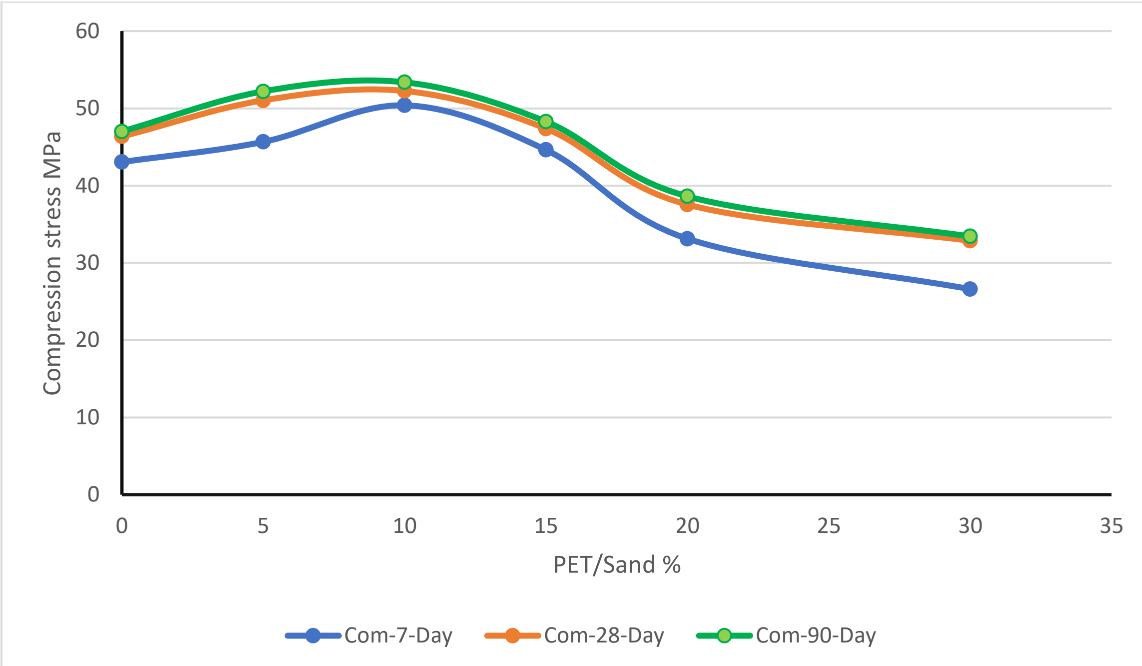

Fig. (4-2) Compressive strength curves for PET percentages as a sand replacement

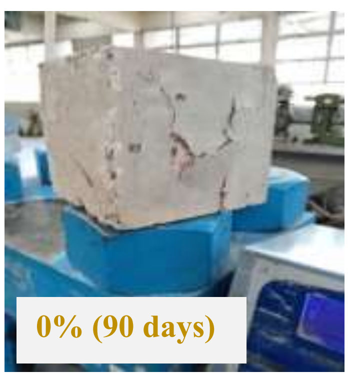

Fig. (4-3) Concrete cubes failure modes for PET percentages as a sand replacement

4.3.4 Split Tensile Strength

Nine cylinders with dimensions (300 *150) mm were casted for each PET percentage for splitting tensile test. Three of them were tested at 7 days, three at 28 days, two at 90 days. The results are shown in Table (4-3) and Fig. (4-4).

Comparing the concretes splitting tensile strength the outcomes were in comparison to the reference specimens that using PET in place of sand between 5% to 15% increased the strength. The specimens with PET percentage of 10% is more than references specimens which yielded tensile strength greater than reference mix by 23.87%.

Whereas, the tensile splitting strength is decreased by 8.30%, and 12.45%, when the replacement percentage is 20% and 30% respectively. Thus, the tensile splitting strength increases by increasing the replacement of sand with PET waste in range 5% - 15%, see Fig. (4-4). The growing splitting tensile stress as a result of sharpness of the PET particles and increased ductility which is caused to reduce slipping when it compared to sand particles, while the specimens more than 15 % PET replacement have been decreased in splitting tensile stress.

Can explain this behavior cause to a lot of number of particles may be collected in one place and stick together and there is no absorption of water on the smooth surfaces of PET waste led to reduce the hydration of cementitious past; therefore, the interaction zone between cementitious pastes and aggregates are lost in bonding at higher PET percentages 15% [79]. The reference cylinder failure mode is suddenly crushed and divided completely into two parts, while there is no separation in the PET waste cylinder specimens, but there is surface crack develop and spread on the sample see Fig. (4-5) which indicate that the PET waste provided ductility.

However, in contrast the crack pattern is more clearness for the specimens with PET than the references specimens before failure state, and the specimens are did not divided two parts when achieved ultimate loading.

Table 4-3 Result of tensile splitting strength for PET percentages as a sand replacement

PET waste (%)	Average Split tensile (fs) MPa			Changing in Split tensile (%) (90 Days)	7/28 Ratio	28/90 Ratio	7/90 Ratio
	7Days	28Days	90 Dyas				
0%	2.46	2.86	2.89	-	0.86	0.98	0.85
5%	2.72	2.96	2.99	+3.46	0.91	0.98	0.90
10%	3.21	3.44	3.58	+23.87	0.93	0.96	0.89
15%	2.90	3.12	3.21	+11.07	0.92	0.97	0.90
20%	2.50	2.61	2.65	-8.30	0.95	0.98	0.94
30%	2.45	2.51	2.53	-12.45	0.97	0.99	0.96

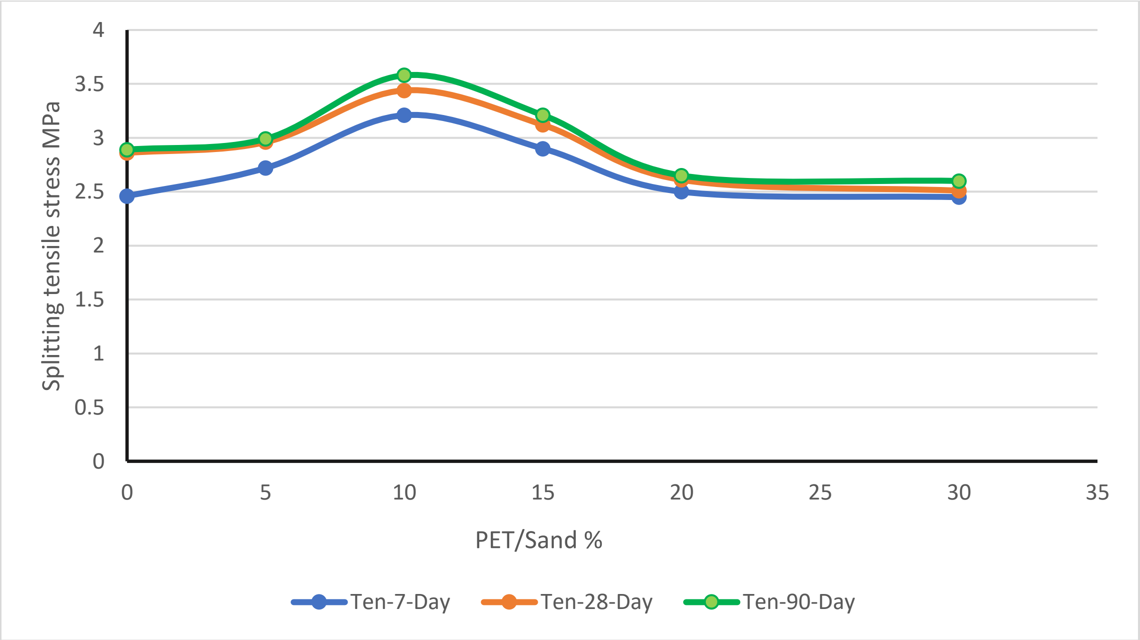

Fig. (4-4) Split tensile strength result for PET percentages as a sand replacement

Fig. (4-5) Concrete cylinders failure modes for PET percentages as a sand replacement

4.3.5 Strength of Flexural

Strength of Flexural test was performed by casting six prisms with dimensions (100*100*400) mm for each PET substitution of sand. Three prisms were tested at 7 days and the other three were tested at 28 days. The results of strength of flexural test were showed in Table (4-4) and Fig. (4-6). The outcomes demonstrated that a substitute partially of sand by PET with percentages ranging 5%-15%, achieved a rise in strength of flexural and decreased for the specimens with 20% and 30% PET in contrast to the reference specimens. The percentage of substituted 10% achieved the highest flexural strength with a rise in 14.28% when that compared to the reference GPC followed by the percentages 5%, and 15% with an increment of 10.26%, and 8.45%, respectively, and the replacement percentage 20% and 30% showed a slight decrease from the reference GPC by 0.6% and 1.81%. The GPC is brittle material, and have low tensile strength. Therefore, using PET particles improve the ductile behavior. Compared to fine aggregates like sand PET waste particles are more damned. The flexural strength has increased for the samples with PET percentages of 5%, 10%, and 15% by 10.26%, 14.28%, and 8.45%compared to the reference mix, respectively. Since the elastic modulus falls as the amount of PET particles increases, that means the concrete specimens are more deformable before failure loading. However, the proportion of PET particles more that 15 % leads to decrease of flexural strength [79]. This decline cause to the particles of PET is formed groups in the concrete specimens, i.e. increase the possibility of collecting a considerable quantity of these particles together in one region. These groups lead to produce weakness zones into GPC. The prisms failure modes as in Fig. (4-7), in which the flexural failure for reference prism (no PET wastes added) cause complete fracture of the prism and divided it for two separate parts. While, although the prism that contain PET waste are failed, there is no movement in fracture path and the specimens are stilled appear as one part. Thus, the PET waste has significant impact regarding the bending characteristics for beams. It reduces spreading and development of cracks which very important property to minimize cracks width and protect the reinforcement.

Table 4-4 Flexural strength results for PET percentages as a sand replacement

PET waste (%)	Average flexural strength (fr) MPa		Changing in flexural strength (%) (28 Days)	7/28 Ratio
	7Days	28Days		
0%	4.27	4.97	--	0.85
5%	5.19	5.48	+10.26	0.94
10%	5.49	5.68	+14.28	0.96
15%	5.09	5.39	+8.45	0.94
20%	4.83	4.94	-0.60	0.97
30%	4.39	4.88	-1.81	0.89

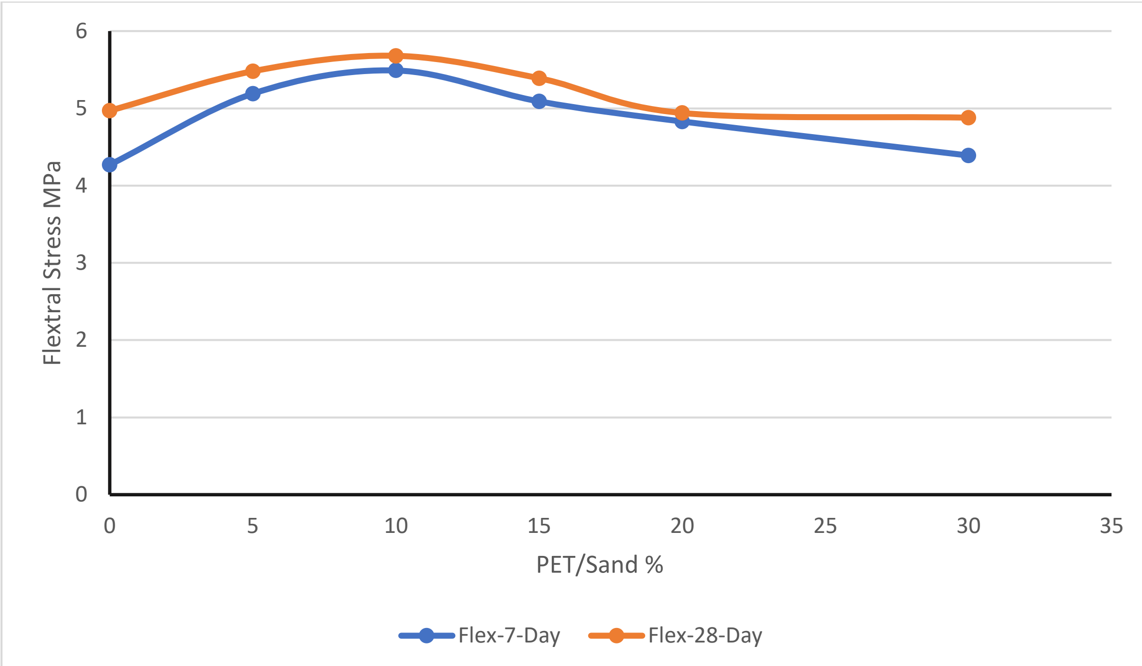

Fig. (4-6) Flexural strength results for PET percentages as a sand replacement

Fig. (4-7) Prisms failure modes for PET percentages as a sand replacement

4.3.6 Density

All cubes' specimens were used to measure dry density measurement before compression strength testing. Dry density was calculated at age 7, 28, and 90 days as the same as the compression test. The results are showed that the density decreases as the PET particles ratio in concrete increase PET see Table (4-5) and Fig. (4-8). At age of 90 days the density of reference specimens is 2375.12 kg/m3, then its slightly decreased upon a rise in the replacement ratio. The 5% PET replacement ratio was recorded density of 2369.4 kg/m3with decreasing of 0.24% compared to reference specimens. Conversely though, the increasing of PET replacement percentage to 30%, achieved concrete density of 1983.42 kg/m³ with decreasing of 16.49% compared to reference mix. a low particle density of PET which equal 1380kg/m3 is principal cause of the decreasing concrete density [79]. The reduction in density contributes to the production of lightweight GPC.

Table 4-5 Density results for PET percentages as a sand replacement

PET waste (%)	Density kg/m³			Changing in Density (%) (90 Days)
	7Days	28Days	90 Days	
0%	2363.66	2391.60	2375.12	-
5%	2352.19	2333.2	2369.4	-0.24
10%	2305.15	2315.57	2314.60	-2.55
15%	2247.25	2225.35	2228.95	-6.15
20%	2193.98	2209.66	2182.44	-8.11
30%	1963.92	1979.02	1983.42	-16.49

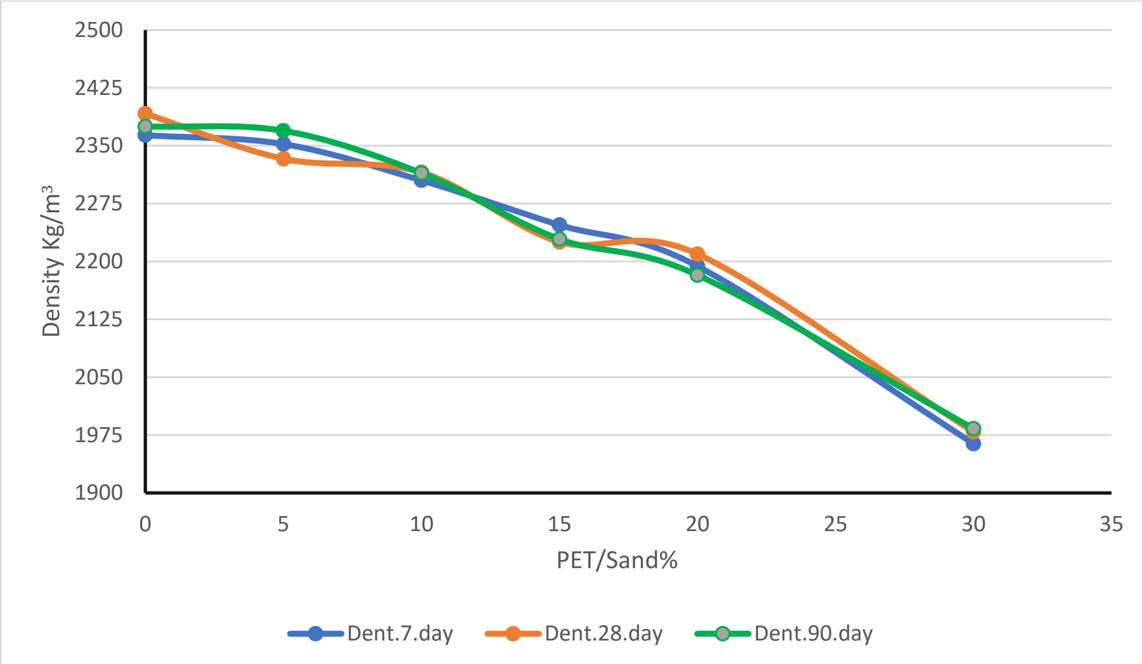

Fig. (4-8) Density for PET percentages as a sand replacement

4.3.7 Absorption Test

Six GPC cubes were used to conducting an absorption test, in which one cube was used for every proportion of PET particles. The cubes were dried in the oven for 72 hours and collected its dry weight and then submerged in water for a full day (24 hours) to find its wet weight according to ASTM C642 [50]. The results were seeing Table (4-6) and Fig. (4-9). The outcomes revealed that the absorption ratio increase as the PET waste/sand increase. The reference cube records an absorption ratio of (0.76%), then the absorption ratio increases gradually with increasing PET waste /sand ratio. The PET percentages of 5%, 10%,15%,20% and 30% had an absorption ratio of 0.79%, 0.85%, 0.89%, 0.96%, and 1.20% i.e., more than the mixture used as a reference by 3.94%, 11.84%, 17.10%, 26.31%, and 58.04% respectively. The rise in the proportion of waste PET in the aggregate means an increase in its particles that collect in irregular shapes, sharp edges and large surface areas compared to sand particles, forming voids and gaps between them. As the proportion of PET waste increases, the number of voids also rises. These voids, when filled with water post-curing, lead to an increased absorption rate [79].

Table 4-6 Absorption results for PET percentages as a sand replacement

PET waste (%)	Dry weight (D.W) kg	Wet weight (W.W) kg	W.W- D.W Kg	%Absorption Ratio	% Changing
0%	7.944	8.005	0.061	0.76	-
5%	7.914	7.977	0.063	0.79	3.94
10%	7.755	7.821	0.066	0.85	11.84
15%	7.526	7.593	0.067	0.89	17.10
20%	7.333	7.404	0.071	0.96	26.31
30%	6.577	6.656	0.079	1.20	58.04

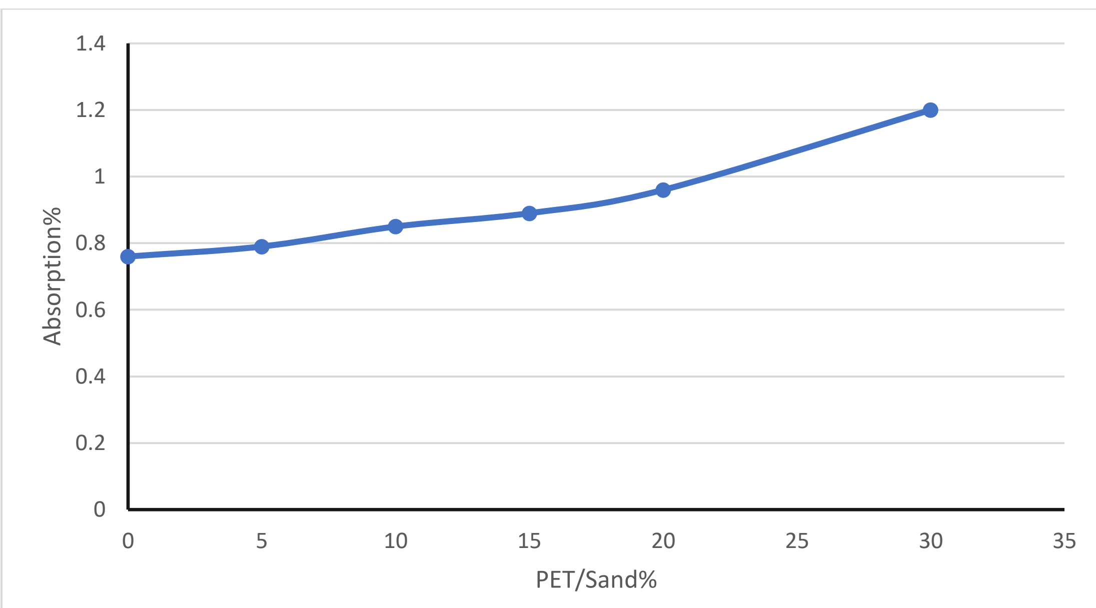

Fig. (4-9) The absorption curve for PET percentages as a sand replacement

4.3.8 Conductivity Test

Conductivity was measured through ultrasonic pulse velocity. Six GPC cubes were tested. One cube for each percentage of PET waste. The test was carried out directly for two directions. The results are in Table (4-7) and Fig. (4-10). The results are showed a slight decreased in the pulse velocity as a PET percentage particle increase. Reference specimens recorded a pulse velocity estimated at 4697 mm/µs, while the velocity through specimens with a replacement ratio of 5% was estimated at 4644 mm /µs, with a decrease of 1.21% compared to the reference specimens. The proportion has increased of PET replacement in specimens lead to gradually decreasing in pulse velocity, due to PET have relatively low connectivity characteristics, in which the percentages 10%,15%, 20% and 30% are recorded a pulse velocity of 4594,4384,4326 and 4317 mm/µs, namely less by 2.19%, 6.66%, 7.89%, and 8.09% than the reference mixture respectively. The pulse velocity and density in a symmetric trend are decreased with increasing of the waste from PET percentage in GPC where, the 30% replacement percentage is recorded an 8.09% and 16.49% decreasing in pulse velocity and density compared to the reference specimens respectively while, the 20% replacement percentages were recorded 8.11% and 7.89% decreasing in density and pulse velocity compared to reference specimens. This leads to the conclusion that PET waste particles have low conductivity too.

Table 4-7 Ultrasonic test for PET percentages as a sand replacement

PET waste (%)	Ultrasonic velocity reading (mm/micro sec.)		Average velocity (mm/µs.)	% Changing
	Axis 1	Axis 2		
0%	4701	4694	4697	-
5%	4658	4630	4644	-1.12
10%	4587	4601	4594	-2.19
15%	4420	4348	4384	-6.66
20%	4329	4323	4326	-7.89
30%	4310	4325	4317	-8.09

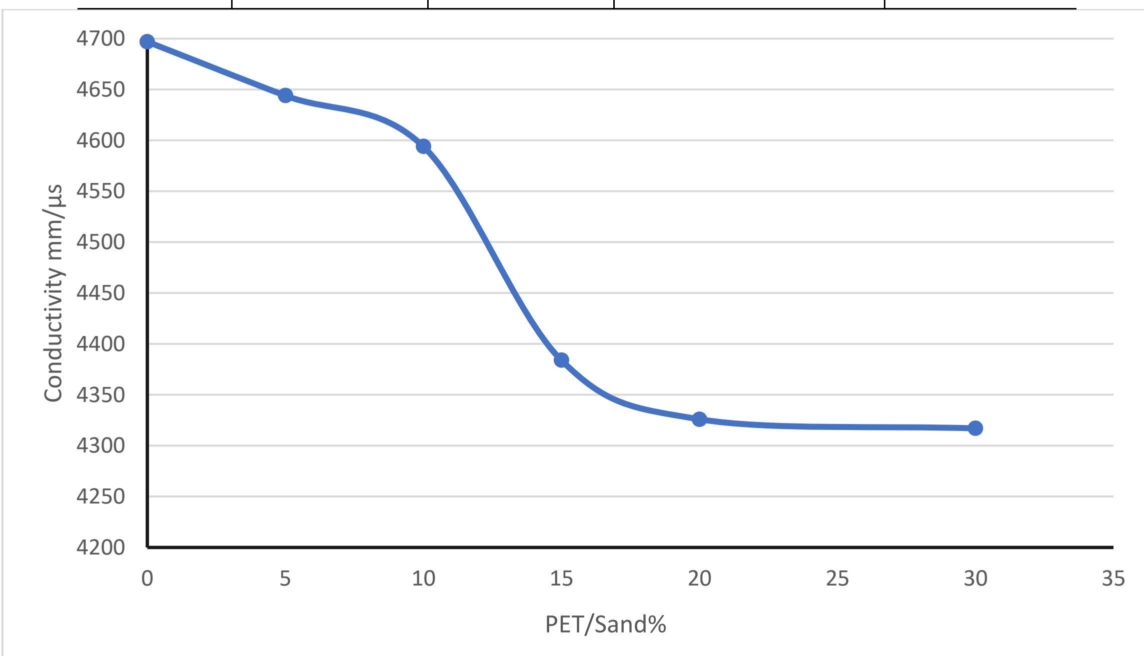

Fig. (4-10) Conductivity curve for PET percentages as a sand replacement

4.3.9 Energy Absorption and Elastic Modulus

Energy absorption measures how much energy a material can absorb before it fails or deforms significantly. It is calculated as the area under the stress-strain curve from a tensile or compression test. A larger area indicates better toughness and resistance to impacts or sudden loads. Elastic modulus is calculated according to ASTM C-469 [21] from stress -strain curve Fig. (4-12). Six cylinders with dimensions (150*300) mm have been tested to determine the elastic modulus and energy absorption one for each replacement percentage. This was done by gluing a strain gauge at mid-depth of cylinder specimen and connected it to the data acquisition device, then tested it in a 200-ton capacity compression machine Fig. (4-11).

The relations of elastic modulus and energy absorption with the ratio of substitution are shown in Table (4-8) and Figs. (4-13), (4-14) respectively**.** The results and relations obviously are showed that the elastic decreases with the increasing in terms of PET percentage plastic particles. The reference cylinders recorded an elastic modulus of 32492.12 MPa, and then the elastic modulus started to decrease as the substitution ratio increased, and a gradual rise in strain was also observed. Where the cylinders with replacement rate of 5% was achieved an elastic modulus of 29437.77 MPa, with a decrease of 9.40% compared to the reference cylinders.

It was noted that the elastic for cylinders with substitution ratios of 10%, 15%, 20% and 30% were decreased with each increase in the ratios of PET particles, and yielded a value of (27711.40,27640.76, 26294.51 and 24112.45) MPa respectively with a decrease of (14.71%,14.93%,19.07% and 25.78%) respectively with compared to the reference cylinders. Fig. (4-11) showed test method and specimens. The results are showed that the value of energy absorption (Toughness) rises with increasing replacement proportion of PET particles in fine aggregates as in Table (4-8) and Fig. (4-14). Where the reference specimens documented the absorption of energy of 0.02076 kN.mm and then gradually increased, as the replacement percentages increased, the percentages 5%, and 10% have achieved energy absorption of 0.0272and 0.03124kN.mm with an increase of 31.35%, and 50.48% compared to the reference mixture, respectively. While the replacement percentages 15%,20%, and 30% recorded energy absorption of 0.0347,0.03202, and 0.03193 kN.mm with an increasing of 67.29%,54.23% and 35.80% respectively. The experimental results clearly demonstrate an increase in stresses and strains corresponding to higher replacement percentages of PET waste in the geopolymer concrete compared to the reference cylinders. As the proportion of PET waste increases, the material shows greater flexibility and energy absorption capacity, leading to enhanced ductility and structural performance. The specimens with higher PET content exhibited improved load-bearing capacity, better distribution of stresses, and reduced likelihood of large cracks forming. These factors collectively contribute to the superior behavior of the geopolymer concrete with PET waste, indicating its potential for use in various structural applications.

Fig. (4-11) Energy absorption and elastic modulus test

Table 4-8 Energy absorption and elastic modulus for PET percentages as a sand replacement

PET waste (%)	Elastic modulus		Energy absorption	
	Value MPa	% Changing	Value E-2 kN.mm	%Changing
0%	32492.12	-	2.076	-
5%	29437.77	-9.40	2.727	31.35
10%	27711.40	-14.71	3.124	50.48
15%	27640.76	-14.93	3.473	67.29
20%	26294.51	-19.07	3.202	54.23
30%	24112.45	-25.78	3.193	35.80

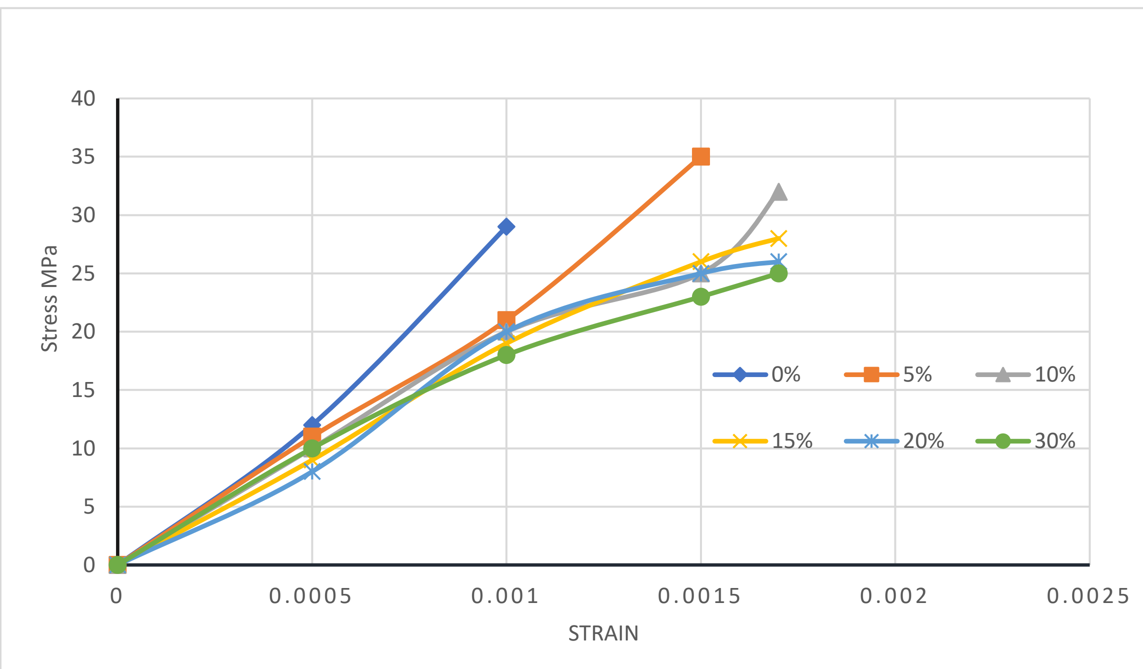

Fig. (4-12) Stress- strain relationship for every percentage

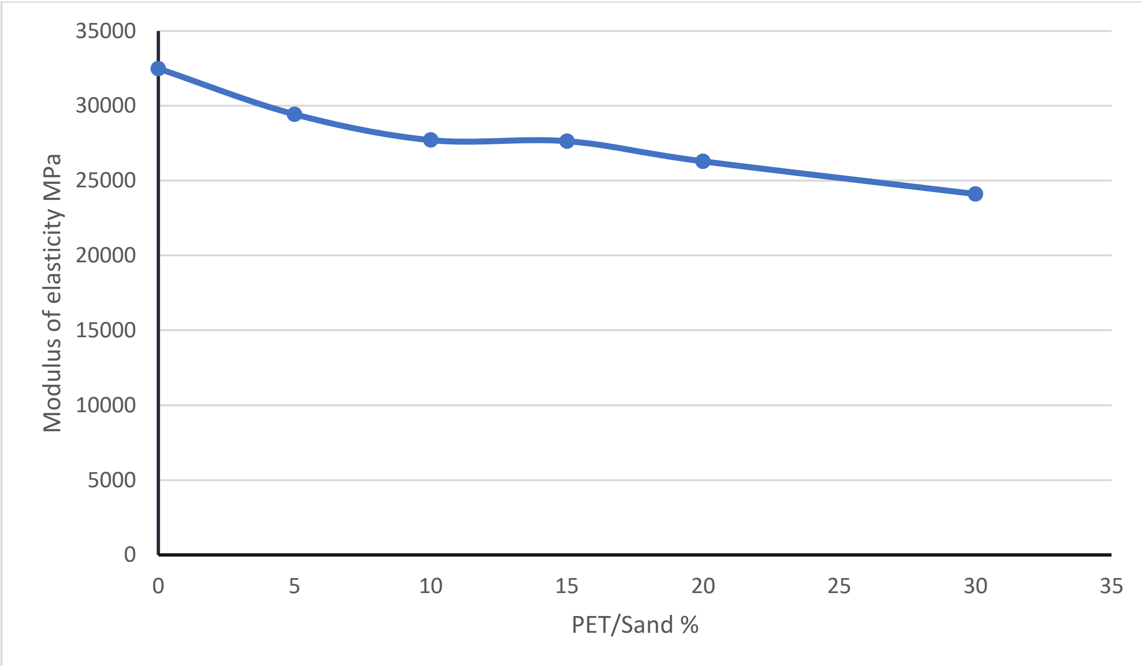

Fig. (4-13) Modulus of elasticity to (PET/Sand) relation

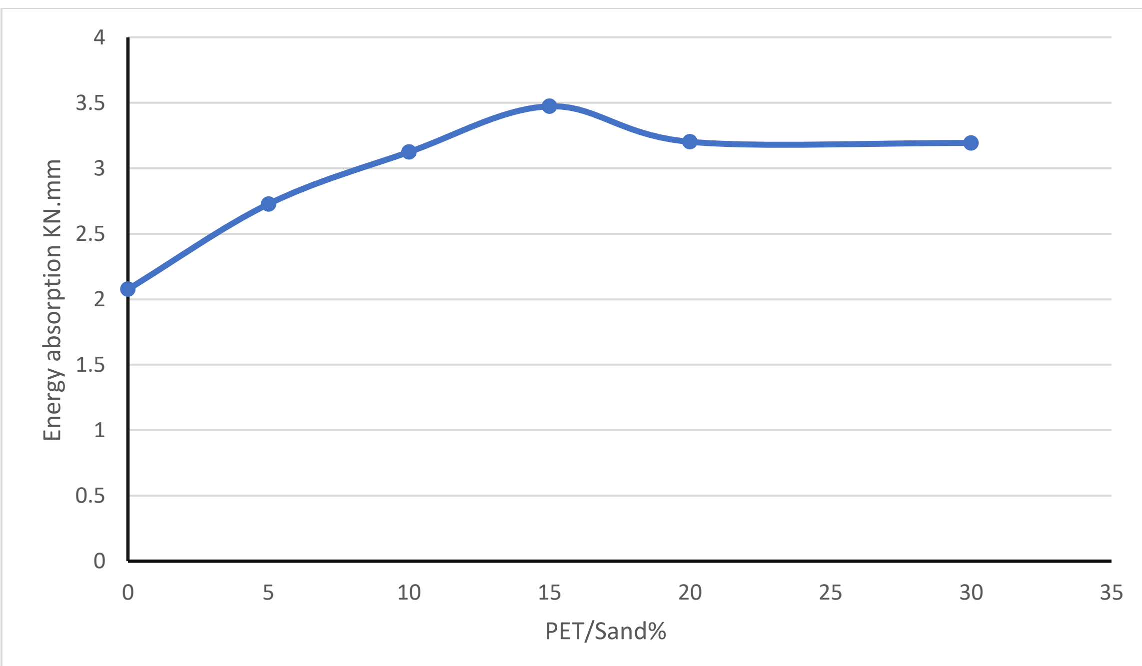

Fig. (4-14) Energy absorption to (PET/Sand) relation

4.3.10 Axial Strains and Ductility Index

With PET waste particles present the GPC exhibits a shift from brittle to more flexible and ductile behavior as evidenced by a rise in the ductility index (ductility is a material's ability to deform under tensile stress. It is a measure of how much a material can be stretched or elongated before it breaks.

Ductility is an important property for materials used in construction and manufacturing, as it indicates the ability to withstand deformation without fracturing). and axial strain at failure load as the amount of PET in the geopolymer concrete increases as in Table (4-9) and Figs. (4-15) and (4-16). The stress-strain curve was drawn for each substitution ratio sees Fig. (4-12).

The reference specimens achieved axial strain at a failure load of 1.39E-3 and ductility of 1.23.Then, the axial strain and ductility started to increase gradually, with the rise of the substituted in the GPC, where the replacement percentages 5%, 10%, 15%,20%, and 30% was recorded an axial strain of (1.85, 2.31, 2.42, 2.45, and 2.59) $*10^{-3}$ with increment of 33.09%, 66.18%, 74.10%, 76.25%, and 86.33%compared to reference specimens, respectively. While its achieved ductility index of 1.34, 1.67, 1.88, 2.01, and 2.3 with increment of 8.94%, 35.77%, 52.84%, 63.41%, and 86.99% compared to reference specimens, respectively. This behavior is due to high flexibility of PET particles**.**

Table 4-9 Axial strain & ductility index for PET percentages as a sand replacement

PET waste (%)	Axial strain		Ductility	
	Value *10-3	% Changing	Value	%Changing
0%	1.39	-	1.23	-
5%	1.85	33.09	1.34	8.94
10%	2.31	66.18	1.67	35.77
15%	2.42	74.10	1.88	52.84
20%	2.45	76.25	2.01	63.41
30%	2.59	86.33	2.3	86.99

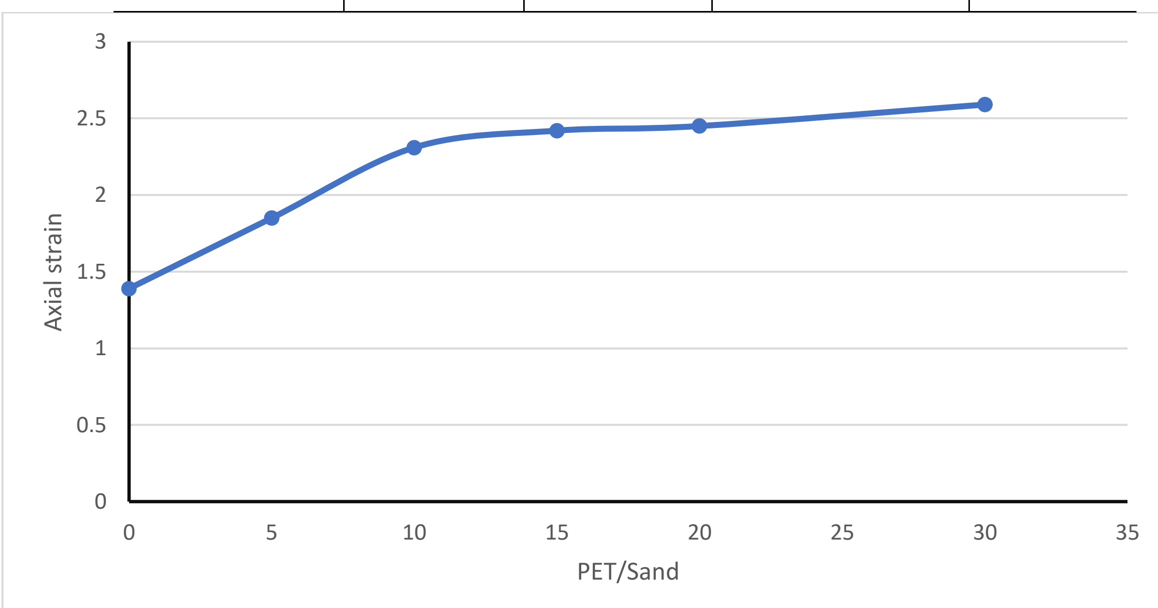

Fig. (4-15) Axial strain to (PET/Sand) relation

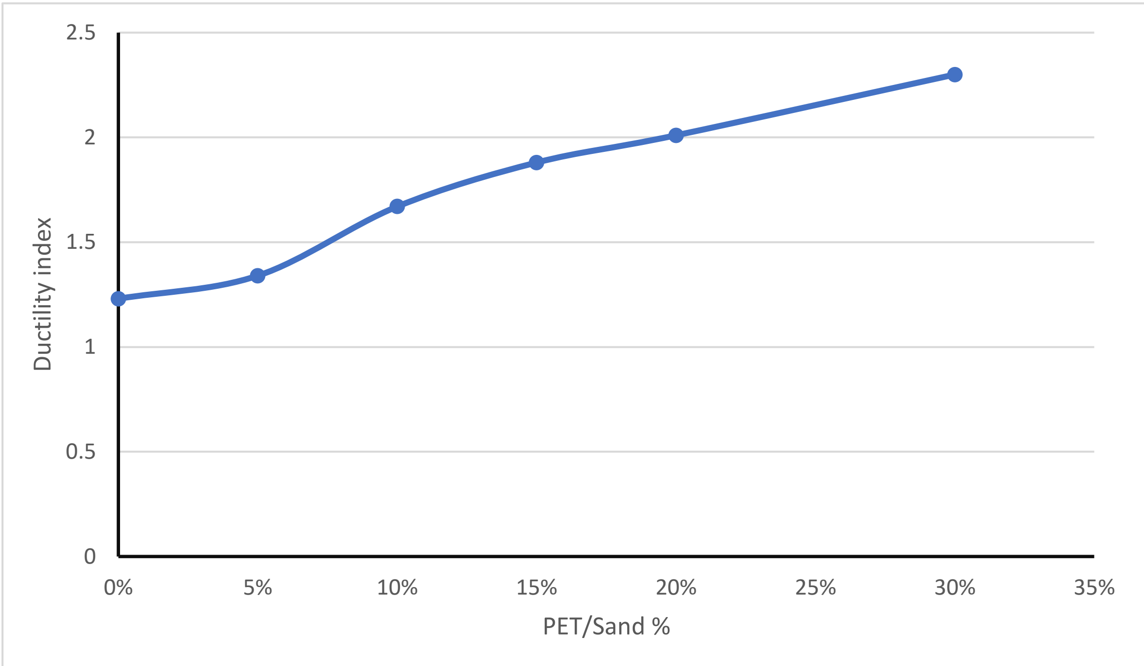

Fig. (4-16) Ductility index to (PET/Sand) relation

4.4 Part Two: Structural Behavior of Beams Containing PET As a Partially Sand Replacement

4.4.1 Beam Ultimate Load

The ultimate loads for all Reinforced Geopolymer Concrete beams are recording and presented in Table (4- 10). All beams are having the same detail of steel reinforcement. The only difference is the amount of PET plastic waste is utilized as a substitute for a portion of sand. The water to cementitious ratio used of the GPC mixture for all beams is 0.125. The reference beams ultimate failure load B 0% R (without PET) is 170.97 kN, the beams B 5% which have a 5% PET plastic waste as sand replacement was182.29 kN. While the RGPC beams B 10% PET replacement ratio was 184.39kN. As for the concrete beam B 15% with PET waste content of 15% as a sand replacement, it observed that the maximum failure load was 185.81 kN with increasing by 8.67%

compared to the reference beam. Furthermore, the beam B 20% which replaced 20% of the sand with PET waste was 183.01 kN, whereas, the ultimate of specimens B 30% which recorded failure load of 184.25 with increment of 7.76%, compared to the reference beam. The beam B15% achieved the best failure load characteristic the increase in load with higher PET content can be attributed to improved bonding, microstructural enhancements, and increased ductility, resulting in a more resilient concrete capable of withstanding greater loads before failure. as in Fig. (4-17).

Table 4-10 Ultimate load for beams specimens containing PET as a sand replacement

Beam remark	Axial strain F cu	Fcu*0.85=fc'	Pu KN	Ductility Pu/Pu (Reference beam) *100	Change in ultimate load
B 0% R	47.01	39.95	170.97	100	-
B5%	52.20	44.37	182.29	106.62	6.62
B10%	53.37	45.36	184.39	107.84	7.84
B 15%	48.28	41.03	185.81	108.67	8.67
B 20%	38.61	32.81	183.01	107.04	7.04
B 30%	33.43	28.41	184.25	107.76	7.76

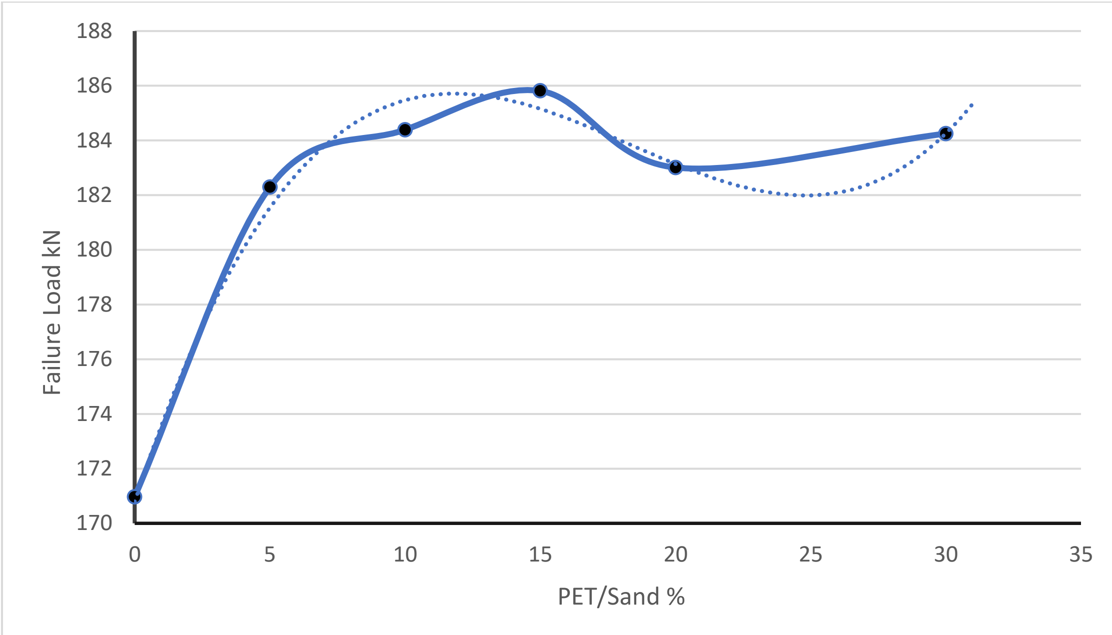

Fig. (4-17) Ultimate load to (PET/Sand) relation curve for beams specimens containing PET as a sand replacement

4.4.2 Load-Deflections Behavior

Table (4-11) presents the deflection of all RGC beams. Load-deflections at (mid-span) curves were graphed as in Figs. (4-18) and (4-19). The results are showed that the reference beam B0% had the max deflection of 28.1 mm, lower than all other beams with PET plastic waste used to partially replace the sand.

The results also showed a gradual increasing in the maximum deflection as the PET replacement rate increases in the geopolymer concrete beams, where the RGPC beam B5% is recorded a max deflection of 33.8mm with a rise of 20.28% compared to the reference beam. There is increasing of the maximum deflection with increasing PET waste, RGPC beams B10%, B15%, B20% and B 30% yielded a maximum deflection of 37.4, 50.8, 52.7, and 54.1mm with a rise of 33.09%, 80.78%, 87.54%, and 92.52 % compared to the reference beam respectively. The behavior of

RGPC beams through the upward max deflection path, which increases with the rise of PET particles in RGPC beams, is a clear indication that the PET waste has changed the behavior of GPC from brittle to another more flexible behavior. Indicating a longer fraction time and prior to failure an early warning are also indicated by it. Reduced susceptibility to impulsive loads earthquakes and dynamic loads is a crucial property of concrete.

Increasing the PET content in RGPC beams alters the crack pattern by reducing the number of cracks and making them finer and more uniformly distributed. This occurs because the enhanced ductility and energy absorption capacity of the concrete with PET content allows it to deform more evenly under load, minimizing the formation of large, concentrated cracks. Consequently, the cracks that do form are less severe and spread out over a larger area, improving the overall integrity and durability of the structure as in 4.4.6.2.

Table 4-11 Maximum deflection for beams specimens containing PET as a sand replacement

Beam remark	Ultimate Load Pu (kN)	Maximum deflection Δu (mm)	Δu/Δu (Reference beam) *100	Change in deflection
B 0% R	170.97	28.1	100	0
B5%	182.29	33.8	120.28	20.28
B10%	184.39	37.4	133.09	33.09
B 15%	185.81	50.8	180.78	80.78
B 20%	183.01	52.7	187.54	87.54
B 30%	184.25	54.1	192.52	92.52

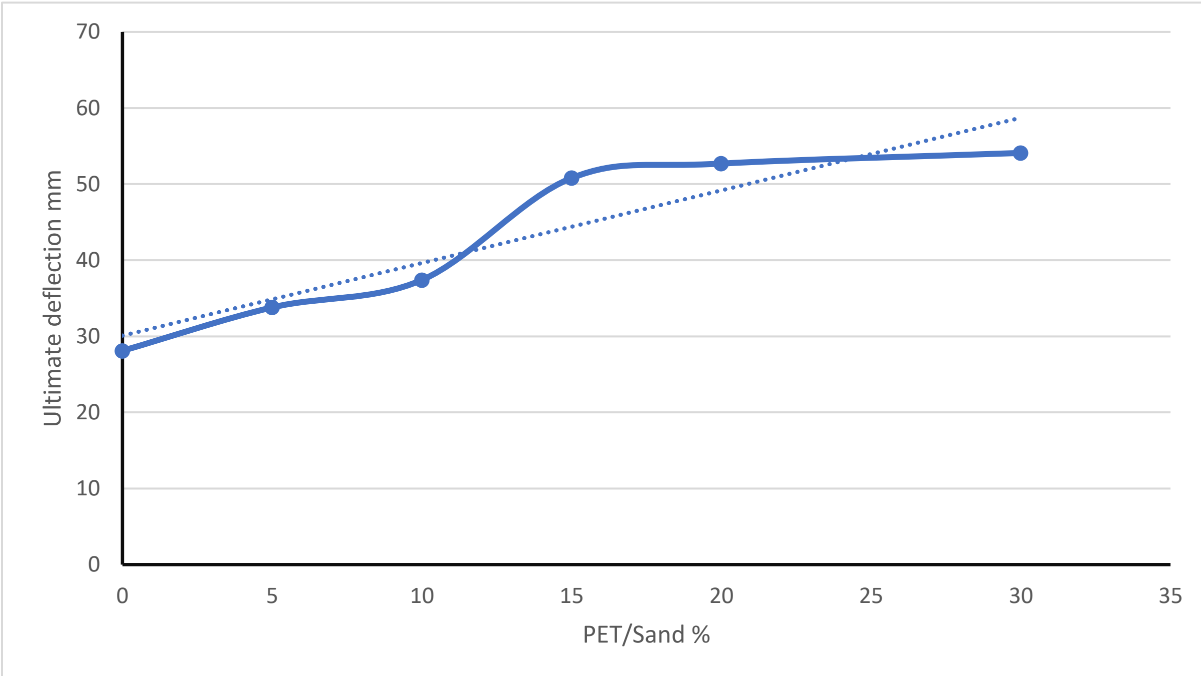

Fig. (4-18) Relation between maximum deflection to (PET/Sand) for beams specimens

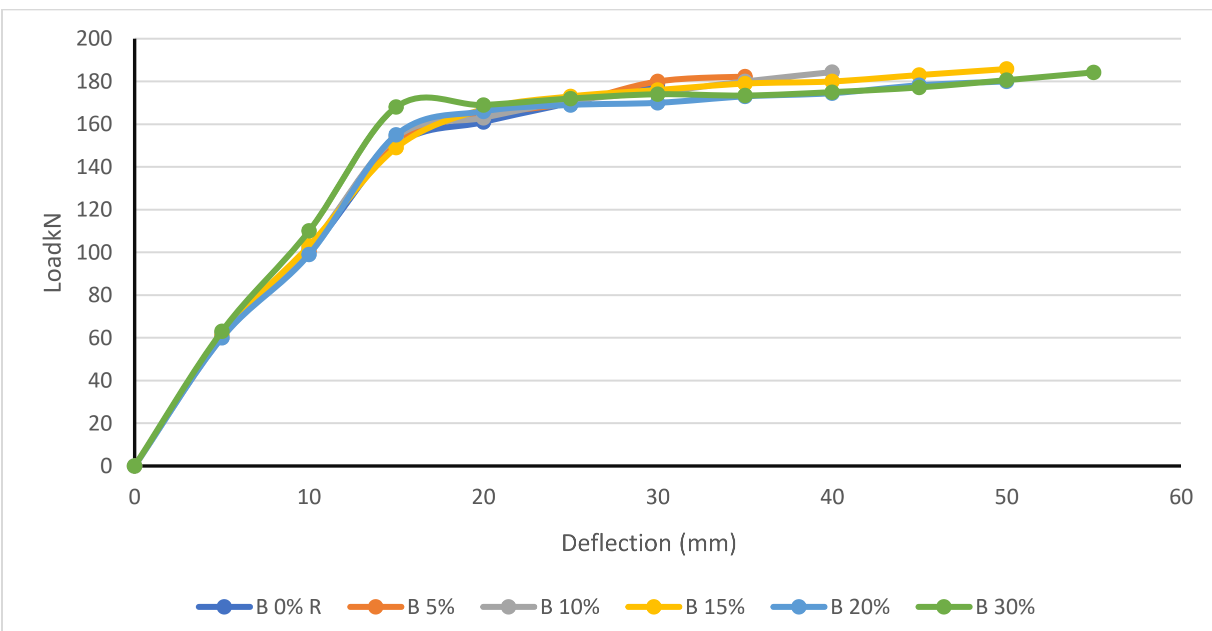

Fig. (4-19) Load to deflection curve for beams specimens

4.4.3 Ductility Index

Ductility refers to the capacity of RGPC (Reinforced Geopolymer Concrete) members to undergo substantial deformation before reaching failure. This property indicates the material's ability to absorb and dissipate energy, which enhances its performance under loading conditions and contributes to its overall structural resilience. The ductility index (μ) is accessible through the load-deflection curve, which equal, The proportion of maximum deflection (Δu) to the yield deflection (Δy). Table (4-12) shows the ductility for all geopolymer concrete beams. It is noticed from the Table (4-12) and Fig. (4-20) that the maximum deflection curve and the ductility index have a very similar trajectory, even the increase rates of ductility and the percentages of maximum deflection are compatibility as opposed to the reference samples. As the proportion of PET waste of in the geopolymer concrete increases ductility starts to progressively rise, where the beams B5%, B10%, B15%, B20%, and B30% recorded a ductility of 4.22, 4.79, 6.35, 6.67, and 6.76 with increment of 20.22%, 36.46%, 80.91%, 90.02%, and 92.59% compared to the reference beam respectively. As the proportion of PET waste in the geopolymer concrete increases, the maximum deflection also increases. This change in behavior affects the crack pattern by leading to fewer but finer cracks that are more evenly distributed. The increased PET content enhances concrete's flexibility and ductility, allowing it to deform uniformly and reducing the risk of large, concentrated cracks. The PET fibers create multiple micro-cracks that absorb and dissipate energy efficiently, resulting in a more distributed cracking pattern. This improves the concrete's durability and performance under load, enhances its resistance to external stresses, and prolongs its service life while reducing maintenance costs as in 4.4.6.2.

Table 4-12 Ductility index for beams specimens containing PET as a sand replacement

Beam remark	Ultimate Load Pu (kN)	Maximum deflection Δu (mm)	Yield deflection (Δy) mm	Ductility index	Changing in ductility
B 0% R	170.97	28.1	8	3.51	-
B5%	182.29	33.8	8	4.22	20.22
B10%	184.39	37.4	7.8	4.79	36.46
B 15%	185.81	50.8	7	6.35	80.91
B 20%	183.01	52.7	7	6.67	90.02
B 30%	184.25	54.1	8	6.76	92.59

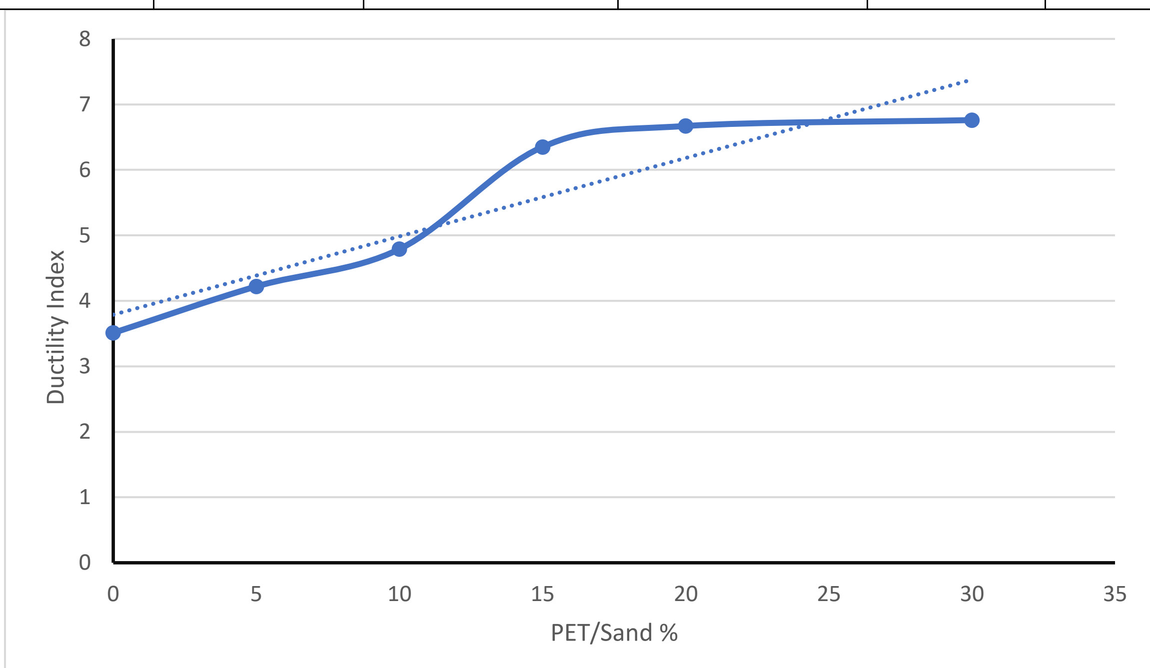

Fig. (4-20) Ductility index-(pet/sand) relation for beams containing PET as a sand replacement

4.4.4 Stiffness

Stiffness at the beginning and stiffness throughout the whole range are (effective stiffness) was calculated based on the load-deflection curve by dividing the maximum load applied (Pu) either on the yield deflection (Δy) in the case of initial stiffness or on the maximum deflection (Δu) in the case of secant stiffness. Below are the Eq. (4-1 and 4-2) that were used:

$$\text{Initial stiffness} = \frac{Pu}{\Delta y} \qquad \text{4-1}$$

$$\text{Secant stiffness} = \frac{Pu}{\Delta u} \qquad \text{4-2}$$

Stiffness calculation is carried out according to Mustafa S. Abdulraheem study [55] as in Fig. (4-21). The results that are presented in Table (4-13) the initial stiffness of the reference RGPC beam B 0% and the beams B 5%, B10%, B15%, B20%, and B 30% are recorded initial stiffness of (40.70, 43.40, 46.09, 46.45, 49.46, and52.64) kN/mm respectively, with an average increasing of 6.63%, 13.24%, 14.12%, 21.52%, and 29.33% compared to the reference beam, respectively. Therefore, the initial stiffness rises as PET waste increases but that a small rise in PET waste has no effect on it as in Fig. (4-22). The observed variations in the modulus of elasticity between concrete cylinders and reinforced beams can be attributed to the impact of fibers and additives on the structural behavior of the material. In concrete cylinders, the addition of fibers like PET may result in a reduced overall stiffness due to the non-uniform distribution of fibers and their limited effect on the sample's volume. Conversely, in reinforced beams, the same fibers enhance ductile behavior by effectively distributing stress and reducing the likelihood of large cracks. The fibers improve material cohesion and its ability to withstand repeated loads, thereby increasing the ductility of the beams. The difference in size, shape, and fiber distribution in the samples explains the discrepancies in the modulus of elasticity between concrete cylinders and reinforced beams. In the geopolymer concrete beams secant stiffness decreases as PET waste increases as demonstrated in Table (4-13) and Fig. (4-23). A secant stiffness of 6.08 kN/mm was recorded for reference beam B 0% R. However, as the level of PET material in the concrete beams increased the secant stiffness gradually began to decrease. where the beams B5%, B10%, B15%, B 20% and B30% were achieved a secant stiffness of (5.39, 4.93, 3.65, 3.47, and 3.40) kN/mm through a ratio of reduction of 11.34%, 18.91%, 39.96%, 42.92%, and 44.07% compared to the exemplar used for reference respectively. The inclusion of PET waste content in reinforced geopolymer concrete beams typically leads to an increase in initial stiffness while causing a reduction in secant stiffness. The initial stiffness is enhanced due to the improved bonding and cohesion provided by the PET fibers, which contribute to the material's resistance to deformation under initial loading. However, the secant stiffness decreases as the PET content rises, reflecting a reduction in the material's ability to sustain higher loads over time. This behavior can be attributed to the changes in the microstructure and the distribution of stresses within the concrete matrix, influenced by the presence of PET fibers.

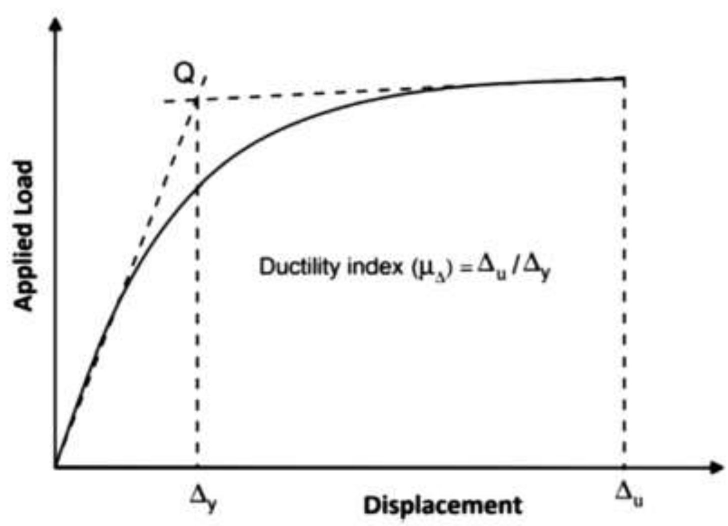

Fig. (4-21) The calculation method of Secant and Initial stiffness [55]

Table 4-13 Secant and Initial stiffness results for beams containing PET as a sand replacement

Beam remark	PET/Sand %	Initial stiffness kN/m	Changing in stiffness *100	Secant stiffness kN/mm	Changing in Secant stiffness *100
B 0% R	0%	40.70	-	6.08	-
B5%	5%	43.40	6.63	5.39	-11.34
B10%	10%	46.09	13.24	4.93	-18.91
B 15%	15%	46.45	14.12	3.65	-39.96
B 20%	20%	49.46	21.52	3.47	-42.92
B 30%	30%	52.64	29.33	3.40	-44.07

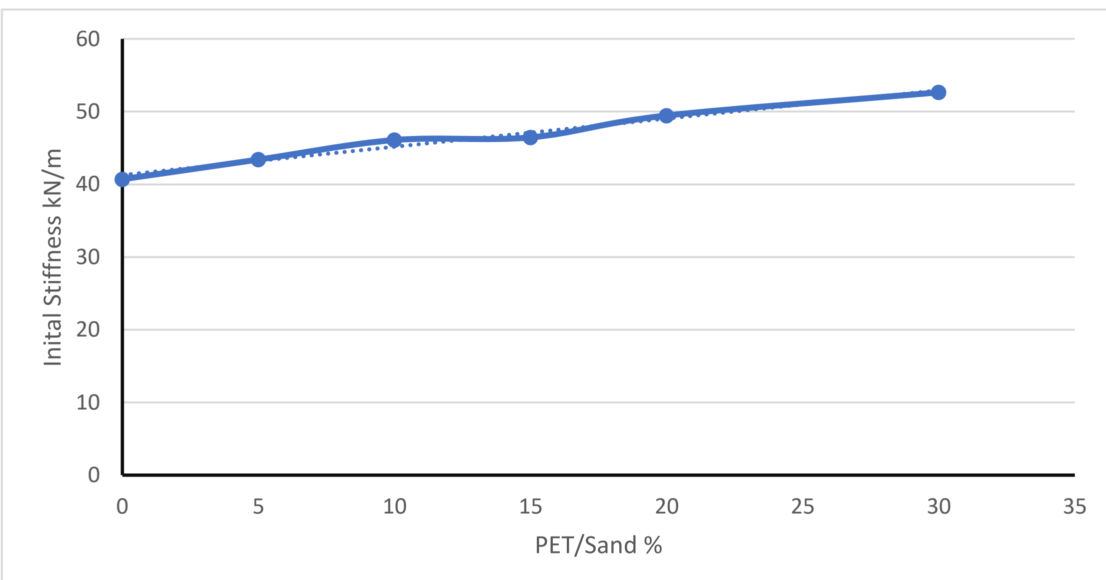

Fig. (4-22) Relation between Initial stiffness to (PET/Sand) for beams specimens containing PET as a sand replacement

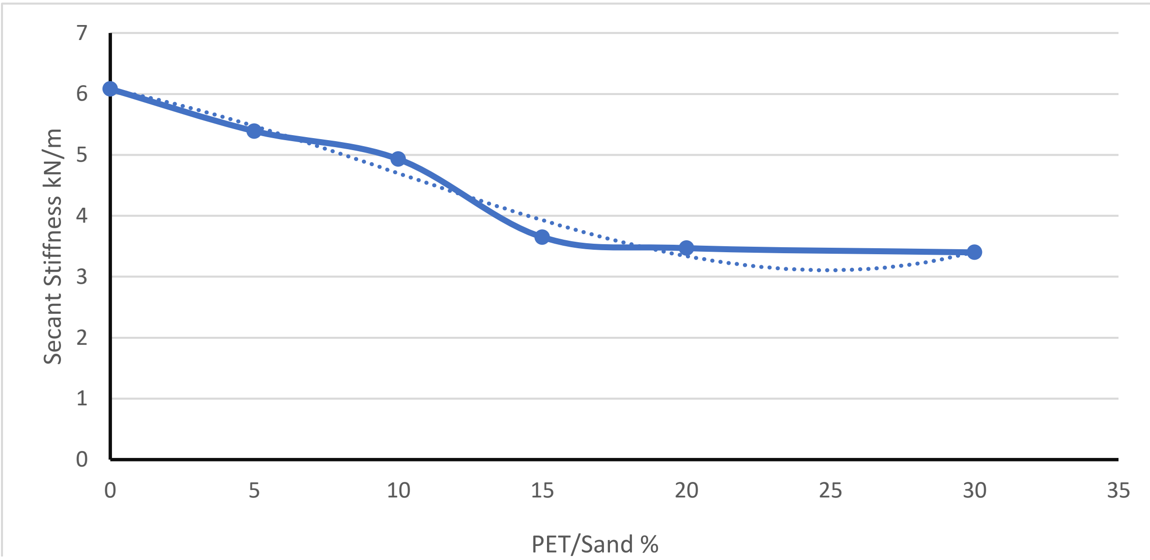

Fig. (4-23): Relation between Secant stiffness to (PET/Sand) for beams specimens containing PET as a sand replacement

4.4.5 Energy Absorption

The energy absorption, or toughness, is calculated by determining the area under the load-deflection curve. This area represents the material's ability to absorb energy before failure, providing an indication of its overall toughness and resilience under loading conditions. Table (4-14) presented the energy absorption outcomes (toughness) for every RGPC beam which demonstrated a significant rise in energy absorption because particle waste made of PET presence. Reference beam recorded energy absorption of 298.21 kN.mm. The energy absorption enhanced as the proportion of PET waste rose, where beams B5%, B10%, B15%, B 20% and B30% achieved an energy absorption of 472.40, 541.16 ,945.72, 1053.98, and 1188.25 kN.mm, i.e. larger than reference beam by 58.41%, 81.46% ,217.13% ,253.43%, and 298.46%, respectively. The relation between energy absorption and PET waste percentages was showed in Fig. (4-24).

Table 4-14 Energy absorption results for beams specimens containing PET as a sand replacement

Beam remark	PET/Sand %	Energy absorption kN.mm	Changing in toughness *100
B 0% R	0%	298.21	-
B5%	5%	472.40	58.41
B10%	10%	541.16	81.46
B 15%	15%	945.72	217.13
B 20%	20%	1053.98	253.43
B 30%	30%	1188.25	298.46

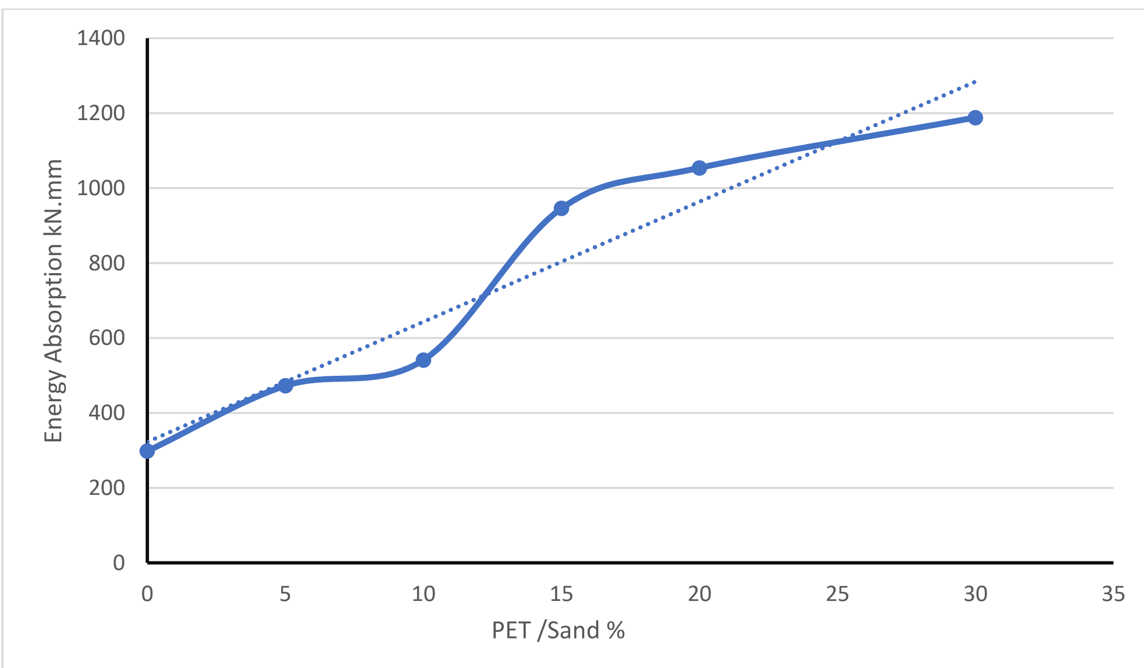

Fig. (4-24) Relation between Absorption of energy to (PET/Sand) curve for beams specimens containing PET as a sand replacement

4.4.6 Cracking

The crack investigation is accomplished according to the following topics:

A. First cracking load.

B. Crack pattern.

4.4.6.1 Initial Cracking Load (Pcr) For Beams

The initial crack loads for all RGPC beams were recorded and presented in Table (4-15), and Fig. (4-25). Table (4-15) shown that as the proportion of PET waste in the RGPC increases the point at which the initial crack appears in the beam used for reference increases gradually starting at load 24.9 kN.The first crack of the beam B5% was appeared at load 38.5 kN with an increase of 54.61% compared to the reference beam, as opposed to the initial crack of the beams B10%, B15%, B20%, and B30% appeared at loads 43.1, 44.9, 46.3, and 47.4 kN ,i.e. larger than reference beam by 73.09%, 80.32%, 85.94%, and 90.36%, respectively. This characteristic of RGPC that include PET as a sand replacement, is important in some applications that not allowed for GPC crack like concrete storage tanks and sewage manholes.

4.4.6.2 Pattern Crakes

The patterns crack for all beams at failure were showed in Fig. (4-27). Also, the first load in which the crack started to appear is shown. The patterns of the cracks in the beams are different and emerged in various forms. In all beams with PET plastic waste present in the GPC mixture in varying proportions the cracks start in the mid-span in the area of tension and spread until they reached the compression zone. The number and depth of cracks are decreases in terms of the PET substituted rises in the RGPC beams, while the spaces between cracks increase as in Table (4-16). B 0% R has been recorded the maximum number of 13 cracks and maximum crack depth of 200 mm with ratio to the cross-section depth of 100%, while it is achieved the lowest spacing between the cracks of 80mm.The number and depth of cracking began to decrease and spacing increase as the PET wastes content increased in beams. The beams B 5%, B10%, B15%, B 20% and B 30% recorded a number of cracks 12, 12, 7, 6, and 5, with depth of 194, 181, 154.7, 142.1, and 146mm with ratio of 97%,90.5%,77.3%,71%, and 73% compared to the depth of cross section, while the spaces between cracks was of 87.1, 93.4,112, 121.2, and 124 mm, respectively. The observed results align with the ductility index, showing that an increase in the PET content in RGPC (Reinforced Geopolymer Concrete) beams results in a reduced number of cracks due to enhanced ductility, improved energy absorption, and a refined microstructure. These improvements lead to a more even stress distribution within the material. The increase in PET (Polyethylene Terephthalate) content in RGPC beams enhances their ductility through several mechanisms. Firstly, PET fibers improve the material's ability to absorb and dissipate energy, allowing it to withstand larger deformations before failure. Secondly, the fibers facilitate a more uniform distribution of stress throughout the concrete matrix, which reduces the likelihood of localized failures and the formation of large cracks. Additionally, the inclusion of PET fibers contributes to a refined microstructure, making the concrete more cohesive and less susceptible to brittle fractures. Collectively, these factors significantly enhance the ductility of RGPC beams, enabling them to perform more effectively under dynamic and repeated loading conditions are showed in Fig. (4-26).

Table 4-15 First cracking load results for beams specimens containing PET as a sand replacement

Beam remark	Pcr (kN)	Ultimate Load Pu (kN)	Pcr/Pu *100	Pcr/Pcr (Reference beam) *100	Changing in first cracking load
B 0% R	24.9	170.97	14.56	100	-
B5%	38.5	182.29	21.12	154.61	54.61
B10%	43.1	184.39	23.37	173.09	73.09
B 15%	44.9	185.81	24.16	180.32	80.32
B 20%	46.3	183.01	25.29	185.94	85.94
B 30%	47.4	184.25	25.72	190.36	90.36

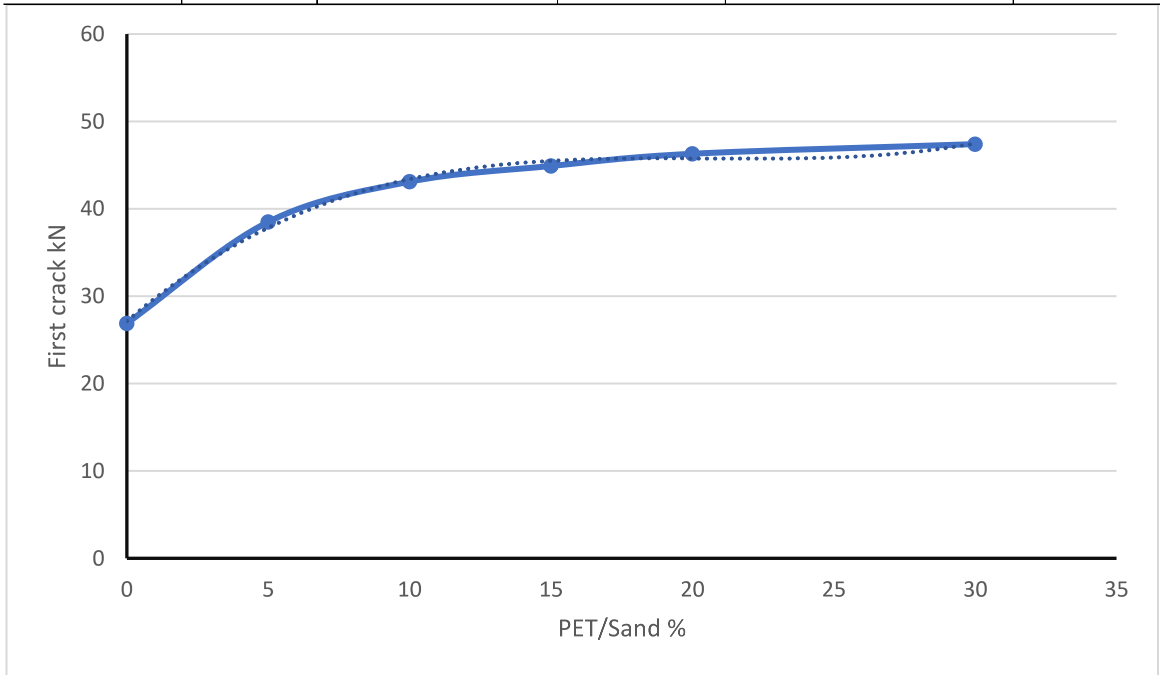

Fig. (4-25) Relation between Initial crack to (PET/Sand) curve for beams specimens containing PET as a sand replacement

Table 4-16 Number and average depth of crack and average spacing between them for beams containing PET as a sand replacement

Beam remark	Pet/sand	No. of crack	Average spacing between crack (mm)	Average depth of crack(mm)	Crack depth/ section depth*100
B 0% R	0%	13	80	200	100
B5%	5%	12	87.1	194	97
B10%	10%	12	93.4	181	90.5
B 15%	15%	7	112	154.7	77.3
B 20%	20%	6	121.2	142.1	71
B 30%	30%	5	124	146	73

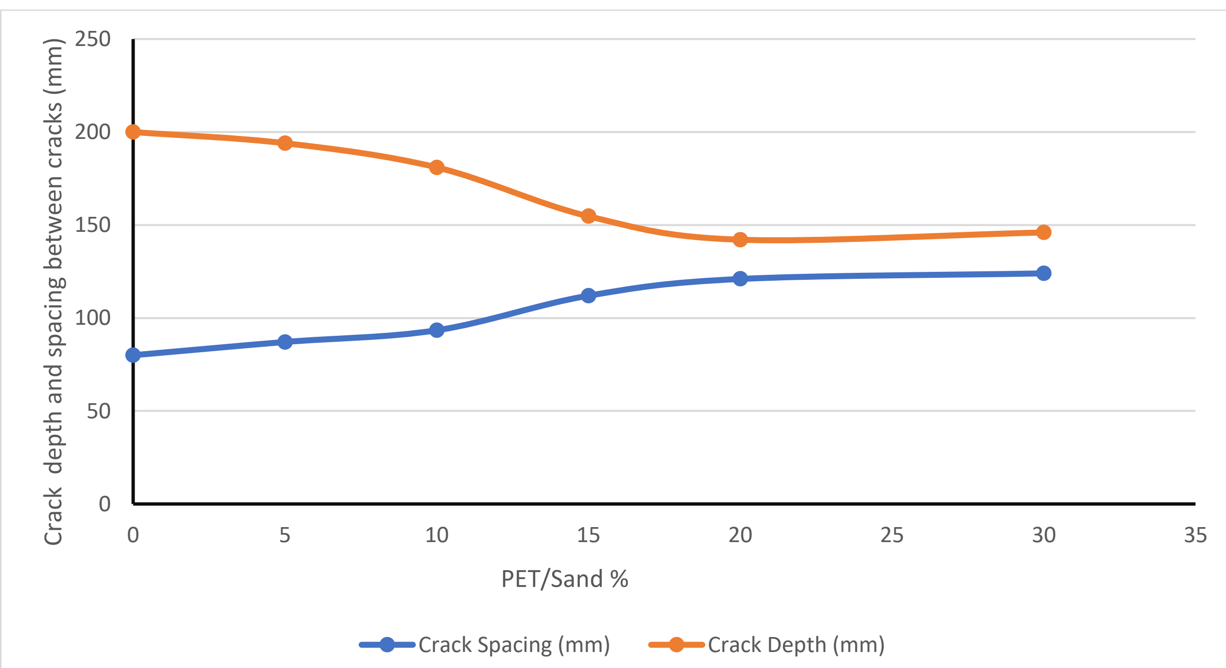

Fig. (4-26) Crack depth and spacing of crack for beams containing PET as a sand replacement

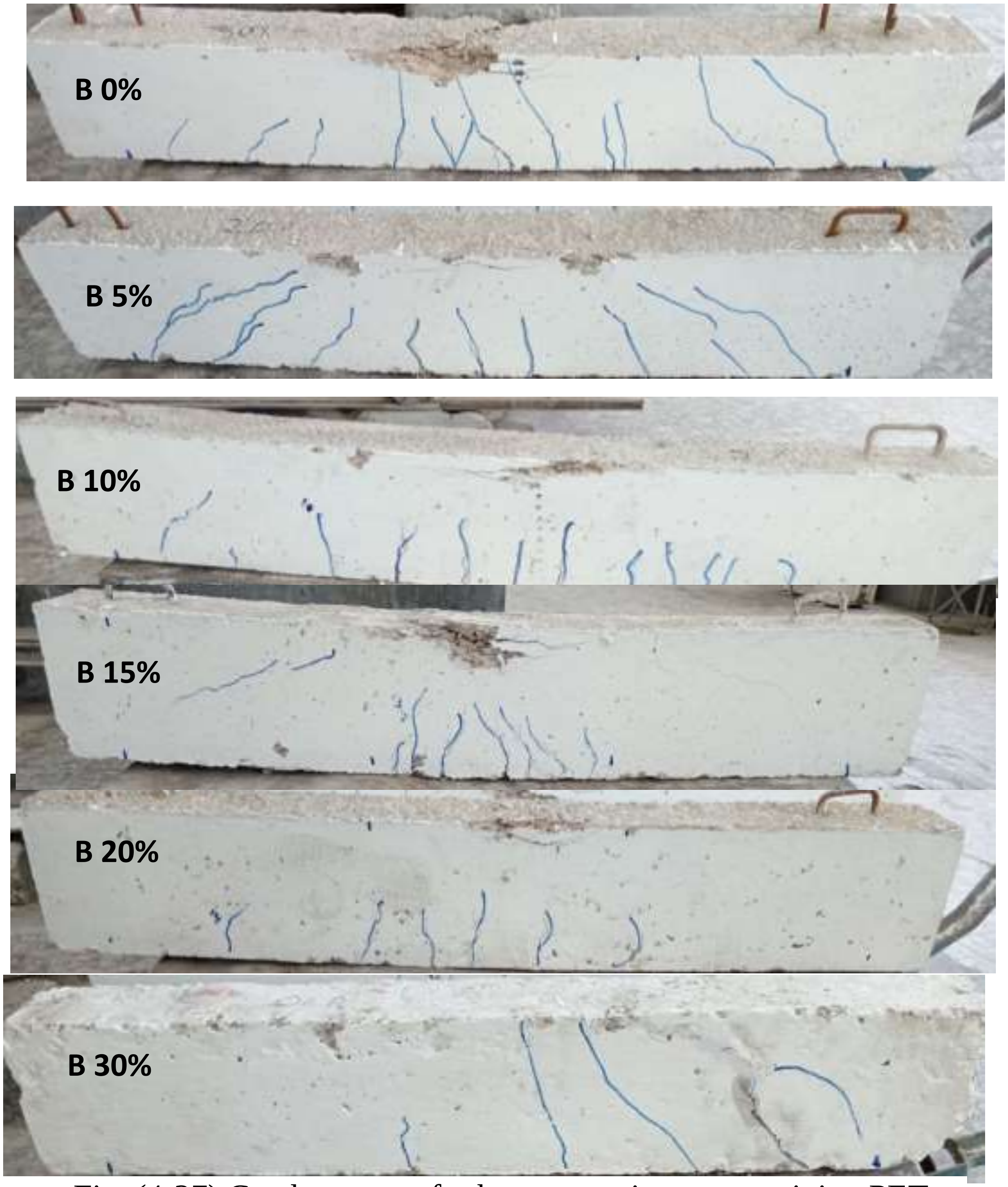

Fig. (4-27) Cracks pattern for beams specimens containing PET as a sand replacement

CHAPTER FIVE

CONCLUSIONS

AND RECOMMENDATIONS

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 General

In this chapter, the primary conclusions derived from the experimental work are presented. Based on the nature of the results, the conclusions are categorized into two main themes:

1-Mechanical and physical properties of Geopolymer Concrete (GPC) incorporating PET waste as a partial replacement for sand.

2-Structural behavior of Reinforced Geopolymer Concrete (RGPC) beams containing PET waste particles as a partial replacement for sand.

5.2 Conclusions

5.2.1 Mechanical as Well as Physical Attributes

1-The workability decreases as the percentage of PET waste in the geopolymer concrete mixture increases at constant w/c. The reference mixture recorded the highest workability, while the PET percentages 5%,10%, 15%,20%, and 30%were recorded a reduction of 11.7% ,17.6%,29.4%,41.1% and 52.9% compared to reference mixture respectively.

2- The compressive, splitting tensile and flexural strengths, are increased as the PET percentages as a sand replacement in GPC increased up to 15% were the replacement percentages 5% ,10% and 15% achieved compressive, tensile, and flexural strength greater than the reference specimens by (11.04% ,3.46% ,10.26%), (13.52% ,23.87% ,14.28%), and (3.46%,11.07%,8.45%) respectively. The 20% and 30% PET percentage showed reduction in compressive, tensile, and flexural strength by (17.86%,8.30%,0.6%) and (28.88%, 12.45% ,1.81%) and compared to the reference specimens.

3-The density and conductivity of GPC are decreases when the PET replacement percentage increased. Reference specimens recorded a highest density and conductivity, while the density and conductivity of PET percentages 5%,10% ,15%,20% and 30% are less than reference specimens by (0.24%,1.12%), (2.55%,2.19%), (6.15%,6.66%), (8.11%,7.89%), (16.49%,8.09), respectively.

4-The absorption increased as the PET replacement percentage increased. The reference specimens recorded the lowest absorption rate, while PET percentages 5%, 10%,15%, 20% and 30%achieved an absorption rate greater than reference specimens by 3.94%, 11.84%, 17.10%, 26.31%, and 58.04% respectively.

5- The axial strain increased and modulus of elasticity decreased as the PET replacement percentage increased. The PET percentages 5%,10%,15%, 20% and 30%yielded axial strain increment of 33.09%, 66.18%, 74.10%, 76.25%, and 86.33%compared to reference specimens respectively. The PET percentages 5% and 30% recorded an elastic modulus less than reference specimens by 9.40% and 25.78% respectively.

6-The energy absorption increases as PET content in concrete increased, but with varying proportions, The PET percentages 5%,10%, 15%,20%, and 30% showed absorbed energy rising than reference specimens by 31.35%, 50.48%, 67.29%, 54.23%, and 35.80%respectively.

7-Ductility index increased with the increasing PET waste content in GPC specimens, where the specimens containing replacement percentages (5%,10%, 15%, 20% and 30% recorded an increment in ductility index of (8.94%,35.77%, 52.84%, 63.41%, and 86.99% in contrast to the reference specimens respectively.

8- The failure mode observed in the various tested specimens indicated that the reference specimens were completely destroyed and fragmented into parts. In contrast, the specimens containing PET replacement particles maintained their structural integrity without disintegration and the failure was limited to the small crack's appearance, numbers and as the replacement percentage rose lengths decreased

5.2.2 Structural Behavior of Reinforcement Steel Geopolymer Concrete Beams

Structural behavior of reinforcement steel geopolymer concrete beams containing PET waste particles as a partial substituted to sand was studied via five reinforced concrete specimens and the following conclusions were obtained

1- The ultimate failure load for all RGPC beams, both with and without PET, showed variations in performance. The beams containing 5%, 10%, 15%, 20%, and 30% PET demonstrated incremental improvements in their load-bearing capacity. Specifically, the beams exhibited increases in failure load by approximately 6.62%, 7.84%, 8.67%, 7.04%, and 7.76%, respectively, compared to the reference specimens. This indicates that incorporating PET plastic waste can enhance the structural performance of RGPC beams.

2- As the proportion of PET waste increased in the RGC beams, both the maximum deflection and ductility index showed corresponding increases. Specifically, beams with 5%, 10%, 15%, 20%, and 30% PET content exhibited significant improvements in these parameters compared to the control beam. These enhancements indicate that incorporating PET waste contributes to the overall flexibility and energy absorption capacity of the beams, leading to better structural performance.

3- The energy absorption in RGC beams significantly increased with higher PET replacement percentages. The beams with 5%, 10%, 15%, 20%, and 30% PET content exhibited greater energy absorption than the control beam, with increases of approximately 58.41%, 81.46%, 217.13%, 253.43%, and 298.46%, respectively. This demonstrates that incorporating PET waste enhances the material's ability to absorb energy under load.

4- The initial stiffness of the beams increased slightly with higher percentages of PET content, with increments of 6.63%, 13.24%, 14.12%, 21.52%, and 29.33% compared to the control beam. However, the secant stiffness decreased as the PET content increased. The reductions in secant stiffness were 11.34%, 18.91%, 39.96%, 42.92%, and 44.07% for the beams with PET content, compared to the reference specimens.

5- The load at which the first crack appeared in RGC beams increased gradually with higher PET content. Specifically, beams with 5%, 10%, 15%, 20%, and 30% PET content experienced their first cracks at load increments of 54.61%, 73.09%, 80.32%, 85.94%, and 90.36%, respectively, compared to the reference beam. This indicates that incorporating PET waste improves the load-bearing capacity before cracking occurs.

6-The numbers and depths of cracks decrease slightly, while the spaces between cracks increase, as the PET content increases in the RGPC beams. It's observed the cracks be less in number, length and spread when PET percentage increased.

7-The PET fiber act as a crack arrester for the concrete during the loading. It helps
to delay the propagation of crack.

8- In light of the findings that were discussed and shown in the earlier sections. the potential for using geopolymer as a building material in engineering fields and it can produce geopolymer with success.

5.3 Recommendations

The following recommendations are suggested for future studies:

1- Investigate the strength parameters at elevated temperatures to study high-temperature-resistant geopolymer concrete.

2-Examine other concrete properties, such as abrasion resistance and acid resistance.

3-Explore different proportions of replacement materials and test the same mix combinations with varying NaOH molarity levels.

4-Assess the environmental and economic impacts of using GPC, focusing on cost and sustainability to raise awareness and promote its application.

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الملخص

الخرسانة الجيوبوليمرية هي بديل صديق للبيئة للخرسانة الأسمنتية البورتلاندية التقليدية، تُصنع باستخدام منتجات ثانوية صناعية مثل الرماد المتطاير أو الخبث المنشط بالمحاليل القلوية. يبحث هذا البحث في خواصها الميكانيكية والفيزيائية كبديل للخرسانة البورتلاندية العادية، مع استبدال جزئي للرمل الطبيعي بنفايات البولي إيثيلين تيريفثاليت .(PET) وتسلط الدراسة الضوء على الفوائد البيئية، بما في ذلك خفض انبعاثات ثاني أكسيد الكربون بنسبة 1.5% إلى 2% من خلال دمج البولي إيثيلين تيريفثالات البولي إيثيلين كبديل جزئي أو كامل للأسمنت البورتلاندي، وبالتالي خفض انبعاثات ثاني أكسيد الكربون الإجمالية المرتبطة بإنتاج الأسمنت. تنقسم الدراسة إلى قسمين رئيسيين:

القسم 1: الخواص الميكانيكية والفيزيائية للخرسانة

تم إجراء الاختبارات الفيزيائية لقياس الكثافة والامتصاص، في حين تم إجراء الاختبارات الميكانيكية لقياس الانثناء والانشطار والضغط ومعامل المرونة والإجهاد المحوري وامتصاص الطاقة. تم استخدام نسب وزنية مختلفة (5% و10% و15% و20% و30%) من جزيئات نفايات PET لتحل محل الركام الناعم (الرمل) جزئيًا، مع الحفاظ على ثبات جميع النسب الأخرى. بالإضافة إلى ذلك، تم قياس سرعة النبض بالموجات فوق الصوتية. تمت ملاحظة العينات على مدار فترات 7 و28 و90 يومًا. أشارت نتائج الاختبار إلى أن وجود جزيئات PET غيّر من الخصائص الميكانيكية والفيزيائية للخرسانة المنتجة. في حين أن معدل الامتصاص زاد بنسبة 58.04% عند الإحلال بنسبة 30%، انخفضت الكثافة وسرعة النبض بالموجات فوق الصوتية بشكل مطرد مع ارتفاع نسب .PET علاوة على ذلك، أظهرت العينات ذات نسب الاستبدال الجزئي التي تتراوح بين 5% إلى 15% زيادات في قوة الانضغاط (11.04%، 3.64%)، وقوة الشد (3.46%، 11.07%)، وقوة الانثناء (10.26%، 8.45%) مقارنةً بالعينات المرجعية. زاد الإجهاد المحوري وامتصاص

الطاقة مع زيادة نسب استبدال PET التي تتراوح من 5% إلى 30%، في حين انخفض معامل المرونة مع ارتفاع تركيز .PET انخفضت معاملات القوة عند تجاوز محتوى PET نسبة 15%. وباختصار، تأثرت القيم المتعلقة بقوة الخرسانة الجيوبوليمرية بشكل إيجابي باستخدام جزيئات PET بدلًا من الرمل، بشرط أن تكون نسبة الإحلال 10%.

القسم 2: الخواص الميكانيكية لعوارض الخرسانة الجيوبوليمرية المسلحة

يفحص هذا القسم السلوك الإنشائي لعوارض الخرسانة الجيوبوليمرية المسلحة عند استخدام مخلفات البوليمر المقوى كبديل جزئي للركام الناعم. تم اختبار خمس عوارض خرسانية (150 × 200 × 1400 مم) مع تسليح فولاذي مماثل (عارضة واحدة لكل نسبة من مخلفات البوليمر الجيوبوليمرية). تم تقييم تأثير مخلفات PET على السلوك الإنشائي للعوارض باستخدام ما يلي: فشل الحمل النهائي، والانحراف النهائي، وامتصاص الطاقة، والصلابة، ومؤشر الليونة، والتحقيق في الشقوق (بما في ذلك حمل الشق الأول ونمط الشق)، والمقارنة مع العوارض المرجعية. كشفت النتائج أن حمولة الفشل النهائية، والانحراف النهائي، ومؤشر الليونة، والصلابة الأولية، وامتصاص الطاقة زادت مع زيادة محتوى نفايات PET في العوارض الخرسانية الجيوبوليمرية المسلحة (7.76%، 92.52%، 92.59%، 29.33%، 298.46% و298.46% على التوالي في حالة الإحلال بنسبة 30%). وعلى العكس من ذلك، لوحظ انخفاض بنسبة 44.07% في الصلابة القاطعة. بالإضافة إلى ذلك، كلما زادت كمية نفايات PET في العوارض الخرسانية، زاد الحمل الذي يظهر عنده أول تشقق والتباعد بين الشقوق. ومع ذلك، انخفضت كمية الشقوق وعمقها.

جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة ميسان/كلية الهندسة
قسم الهندسة المدنية

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رسالة مقدمة في استيفاء جزئي لمتطلبات الحصول على درجة

ماجستير العلوم في الهندسة المدنية

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بواسطة

نور منذر شاكر

B.Sc. civil engineering, 2005

المشرف على الرسالة: **أ.د. عباس عودة داود**