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عمادة الدراسات العليا

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المنشآت برنامج تصميم وتأهيل

Effect of Using Glass Powder as Partial Cement Replacement on Physical and Mechanical Behavior of Concrete

تأثير استخدام بودرة الزجاج كاستبدال جزئي للأسمنت على السلوك الفيزيائي والميكانيكي للخرسانة

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إقـــــــــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Effect of Using Glass Powder as Partial Cement Replacement on Physical and Mechanical Behaviour of Concrete

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تأثير استخدام بودرة الزجاج كاستبدال جزئي للأسمنت على السلوك الفيزيائي والميكانيكي للخرسانة

Effect of Using Glass Powder as Partial Cement Replacement on Physical and Mechanical Behavior of Concrete

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إدارة المكتبة المركزية

أ. محمود حمد الداعور

ABSTRACT

In the case of the Gaza Strip, where the natural resources (aggregate and cement) for the concrete industry are un-existent, the need for alternative resources is vital. The recycling of waste constitutes a positive way for the concrete industry as alternative materials to replace cement and aggregates. The main objective of this research is to investigate the possibility of using glass powder in concrete as partial cement replacement and does not negatively affect the properties of the resulting concrete. In addition, the environmental benefits of the elimination of the waste glass from the landfill is another goal.

In this research, cement was replaced by waste glass powder in the range of 0%, 10%, 20% and 30% by weight; the concrete mixtures were produced, tested and compared in terms of workability, density, absorption, and mechanical tests. A new mixing method was used in mixing concrete with glass powder to improve its efficiency, which the glass powder was dissolved in water before adding to cement and aggregates. The effect of different curing temperatures (23°C, 40°C and 50°C) at ages (2, 7, 28 and 90 days) was also studied on mechanical properties and durability of concrete containing glass powder.

The output results obtained from this laboratory program showed that the workability of concrete increased as the glass powder replacement increased due to the presence of more free water in the structure, which led to having lower density and higher water absorption. but, the compressive strength of conventional mixes method decreased as the glass powder increased at an early age. Later, after 90 days, the highest compressive strength was obtained for the 20% Glass powder. In another hand, the new mixing method showed higher compressive strength than the conventional mixing method, which, Using 10%, GP in the new mixing method gave a significant increase, around 130% of the compressive strength of the control mix.

The results also indicated that concrete containing 10% glass powder at the hot temperature (40°C and 50°C) developed a strength that was 1.13, 1.20 times respectively higher than concrete cured at the reference temperature (23°C) at 3 days. It was attributed to increasing the rate of hydration and accelerating of pozzolanic activity.

Finally, this research has attempted to provide an interesting approach to introducing glass powder as a cement replacement in concrete, aiming to improve the pozzolanic activity. The Experimental results for the new mixing method verified the feasibility of this approach.

Keywords: Concrete, Glass Powder, Compressive Strength, Conventional Mixing Method, New Mixing method, curing condition.

خلاصة البحث

في حالة قطاع غزة، حيث الموارد الطبيعية (الإسمنت والركام) لصناعة الخرسانة غير موجودة، فإن الحاجة إلى موارد بديلة أمر ضروري. تشكل إعادة تدوير النفايات فرصة مهمة في صناعة الخرسانة لاستخدامها كمواد بديلة لتحل محل الأسمنت والركام. يتمثل الهدف الرئيسي لهذا البحث في إمكانية استخدام بودرة الزجاج في الخرسانة كإستبدال جزئي للأسمنت ولا يؤثر سلبًا على خواص الخرسانة الناتجة. بالإضافة إلى ذلك، الاستفادة من الفوائد البيئية من خلال تقليل كميات الزجاج في مكب النفايات.

في هذا البحث، تم استبدال الأسمنت بودرة الزجاج بالنسب 0٪ و 10٪ و 20٪ و 30٪ من وزن الاسمنت في الخرسانة؛ ثم إنتاج واختبار ومقارنة الخلطات الخرسانية من حيث القدرة التشغيلية والكثافة والامتصاص والاختبارات الميكانيكية. كما تم استخدام طريقة خلط جديدة في خلط الخرسانة ببودرة الزجاج لتحسين كفاءته، حيث تم إذابة بودرة الزجاج في الماء قبل إضافته إلى الاسمنت والركام. أيضا تم دراسة تأثير درجات حرارة المعالجة المختلفة (23، 40، 50 درجة مئوية) عند الازمنة (2، 7، 28 و90 يوم) على الخواص الميكانيكية وديمومة الخرسانة المحتوية على بودرة الزجاج.

أظهرت النتائج التي تم الحصول عليها من هذه الاختبارات أن القدرة التشغيلية للخرسانة تزداد مع زيادة محتوى بودرة الزجاج بسبب زيادة كمية المياه في الخلطة، مما أدى إلى انخفاض الكثافة وارتفاع امتصاص الماء. ونتيجة لذلك، انخفضت قوة الكسر مع زيادة بودرة الزجاج في طريقة الخلطات التقليدية في اعمار مبكرة للخرسانة. بينما بعد 90 يومًا ، تم الحصول على أعلى قوة كسر وذلك باستبدال الاسمنت ب٪ **20** زجاج. من ناحية أخرى أظهرت طريقة الخلط الجديدة قوة كسر أعلى من طريقة الخلط التقليدية. باستخدام ٪ **10** زجاج حيث أعطى زيادة كبيرة، حوالي 130 ٪ من قوة الكسر للخلطات بدون زجاج (المرجعية).

أشارت النتائج أن الخرسانة المحتوية على 10٪ من بودرة الزجاج عند درجة الحرارة الحارة (40 درجة مئوية و 50 درجة مئوية) زادت القوة ب 1.13 و 1.20 مرة أعلى من الخرسانة المعالجة عند درجة الحرارة المرجعية (23 درجة مئوية) في 3 أيام . وهذا يعود إلى زيادة معدل التفاعل وتسريع تفعيل النشاط البوزلاني للزجاج.

وأخيرا، يقدم هذا البحث طريقة مثيرة للاهتمام لإدخال بودرة الزجاج كبديل للأسمنت في الخرسانة، بهدف تحسين النشاط البوزلاني للزجاج حيث يتضح جدوى هذه الطريقة الجديدة من خلال النتائج التجريبية لها.

DEDICATION

This thesis is dedicated to:

My great father, who raised me,

My great mother, the warmest womb,

My dearest wife who sacrifice and endless support,

My beloved daughters: Fatma & Iya, whom I hope the health and happiness,

My beloved brothers and sisters, whom I hope the happy life.

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Introduction

1.1 Background

“Concrete” is a solid artificial substance with a unique advantage that participates within constructing any features of our world such as buildings, roads, bridges, underground structures, and others. “concrete” is a Latin phrase comes from concretus. The constituent materials of concrete include mainly grained particulate material “the aggregate or filler” inserted in a binder material “the cement” that set in the presence of water to fills the space among the aggregate particles and glues them together [1].

Concrete can be considered the optimum building material because of economic reasons (the cheapest construction material), its property to be cast into any shape, its ability to be fabricated anywhere and its durability.

It is well-known that cement is the principal constituent that makes concrete, but, the manufacture of Portland cement has a main negative impact, which production of one ton of Portland cement clinker make about one ton of carbon dioxide and other greenhouse gases (GHGs). Therefore, the emission of this significant amount of carbon dioxide should be alleviated by a sustainable development solution within the cement and concrete industry [2].

Prior research suggests that a real need to use new materials that can replace cement in concrete without decreasing its mechanical and durability properties and mitigation of the environmental impacts is needed.

In short, producing concrete that has cement with less clinker is the fundamental challenge of the cement industry. An extensive research was made to achieve this goal, but the most sensible solution is to blend the clinker with other materials [3]. This directly as less is required. However, this solution has some restrictions which just some materials are often wont to replace cement.

One of the most practical used materials to replace cement is “The supplementary cementitious materials SCM”, where these materials contain the needed cementitious properties to develop the mechanical properties of the concrete [4].

The main source of carbon dioxide in cement production originates from the decomposition of limestone and emits CO2 according to the following reaction:

$$CaCO_3 \rightarrow CaO + CO_2$$

Table 1.1 below shows the amount of CO_2 emitted in the atmosphere for some materials used on the planet; the table shows that cement emits a significant amount of CO_2. In addition, a huge amount of Portland cement was manufactured every year, which the "Global cement production is recorded 3.27 billion metric tons in 2010 and expected to increase to 4.83 billion metric tons in 2030"[1] , So reducing the CO2 emissions produced by cement could make a real difference to climate change.

Table (1.1): Emission of CO2 in the atmosphere for each type of material.[2]

Material	MJ/Kg	Kg of CO_2/J Kg
Cement	4.6	0.83
Concrete	0.93	0.13
Masonry	3.0	0.22
Wood	8.5	0.46
Wood, multilayer	15	0.81
Steel, virgin	35	2.8
Steel, recycled	9.5	0.43
Aluminum, virgin	218	11.46
Aluminum, recycled	28.8	1.69
Glass fiber composites	100	8.1
Glass	15.7	0.85

The fuel consumption used to produce materials for the same used represents an important parameter for the environmental impact. Concrete consumes a lower amount of fuel to fabricate

[1] Statistics and Studies from more than 22,500 Sources https://www.statista.com/statistics/219343/cement-production-worldwide/

[2] These tables were done by, ICE version 1.6a Hammond G.P. and Jones C.I 2008 Proc Instn Civil Engineers www.bath.ac.uk/mech-eng/sert/embodied/

a column of 1 m long to support 1,000 tonnes. Figure 1.1 below represents the fuel consumption needed to fabricate a column of 1 m long.

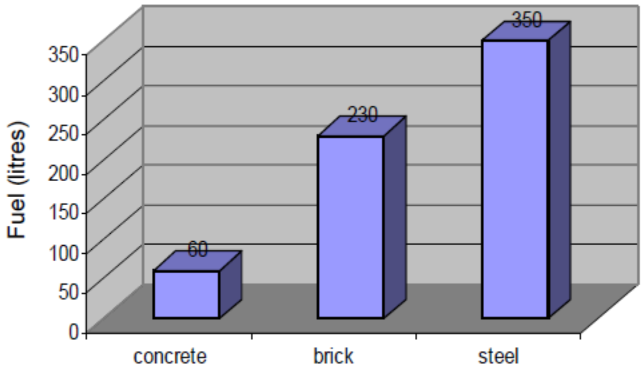


Figure (1.1): the required Energy for constructing 1 m column that supports 1000 tones.

At the end of the last century, there has been significant progress in concrete technology, mainly by the use of alternative material with cement in concrete production like the supplementary Cementing Materials (SCM). The recent researches try to learn more about concrete by the linking between chemistry and materials science with civil engineering [8-10]. The researches prove until nowadays that concrete will be the material of choice for many decades [5].

In fact, “glass powder (GP) waste is one among the foremost active research areas” that attracted many researchers in the field of civil engineering and construction materials. The glass is produced as a commercial product commonly exist with different forms such as optical components, windows, mirrors, Shopfronts, balustrades, floor panels, doors, bulbs, tubes, bottles, jars, etc. For sustainable purposes, these limited lifetime products have to be reused in order to avoid environmental issues associated with their disposal [3]. In addition, utilization of the glass in the construction sector is necessary to produce eco-friendly concrete from glass waste.

The glass powder is considered as a pozzolanic material, its reactivity is essentially governed by its size where smaller size particles react more. That refers to the fact that it is easier to be dissolved in water during mixing to form more CSH [4, 5] later in the pore solution.

Many studies are rising around the world directing the employment of waste glass in construction technology, such as [6-14]. The concept is that glass powder can be used as a cement replacement in concrete to enhance the strength characteristics to a certain extent due to its pozzolanic activity.

Therefore, this research study aims to introduce glass powder as a partial cement replacement and increasing the pozzolanic reactivity of glass within the concrete matrix, and then it highlights the positive impacts on the environment by reducing the quantities of a dumped solid waste of glassy products.

The studies revealed that extensive efforts were made to investigate the effects of using glass powder as partial cement replacement and identify the positive and negative impacts of the replacement process [6-14]. However, more research is still needed to optimize the behavior of concrete with glass powder and increasing the glass reactivity, therefore, a new approach shall be innovated to introduce glass powder within the concrete matrix and optimizing the properties of concrete with glass powder.

1.2 Problem Statement

The Gaza Strip suffers a lack of natural resources especially the principal components materials of concrete such as aggregate and cement, therefore, the need for alternative resources is vital.

In accordance with the records provided by "the Palestinian Central Bureau of Statistics (PCBS)" in 2005, 1,000 ton of the solid waste is produced daily in the Gaza Strip. It was also estimated that 0.7-1.0 kg/c/d for waste production, 0.4 kg/l for the density of waste at collection points and a growth rate was 4.0% per year [15].

Another estimation is reported that the produced solid waste was approximately 1000-1,200 ton per day in the Gaza Strip where 1.5% out of this quantity is waste glass [15, 16]. The quantity of waste glass considerably increased due to the last Israeli aggression and the upcoming reconstruction of destroyed buildings. An earlier study has shown that waste glass represents 2% of the total waste quantity in the Gaza Strip [17].

The Gaza Strip area is highly populated polity with a total area of 365 km^2, as a result, the landfills are in the very limited area available that adversely affected their individual capacity and efficiency of usage. In addition, the continuous increase of solid waste quantities without being recycled will threaten public health and bring epidemics and diseases. Therefore, developing new practical solutions that can alleviate these severe environmental concerns is very vital [15].

Figure 1.4 below represents the amount of waste produced in the Gaza Strip as a function of year.

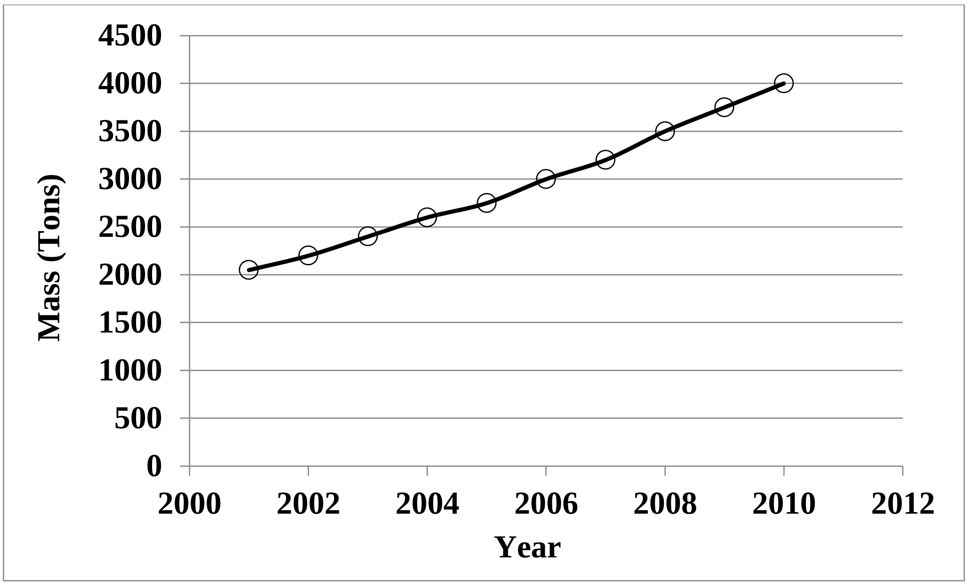


Figure (1.2): Production of waste as a function of year [3].

The recycling of waste represents an opportunity in the concrete industry as alternative materials to replace cement and aggregates. Until this moment the only replacement used in Gaza Strip is the crushed concrete as a replacement for natural aggregates. In the case of SCM, there is a small amount of slag, which comes from the recycling of steel and aluminum waste. There are two main sources for another type of SCM, the first is the Bottom Ash, which can come from the incineration of organic, paper, cartoon and wood. The glass waste represents the second SCMs, it can be grounded into a fine powder similar to cement size.

The presence of bottles and glassy products come from houses, public and private institutions increase the amount of waste on landfill.

The main idea of this research is to examine the possibility of using glass powder in concrete as a partial cement replacement and does not negatively affect the characteristics of concrete. Moreover, the environmental benefits produced by the elimination of the waste glass from the landfill is another goal.

The specific goal of this project is the use of a new method for activation of glass powder targeting improve the mechanical and the durability of concrete.

[3] Sources: Agro vision, (2010) Gaza solid waste disposal project, final report, Gaza Municipality, Palestinian National Authority.

1.3 Aim and Objectives

The overall objective of this research is to study the effect of the partial cement replacement by glass powder on both physical and mechanical characteristics of the concrete mix. This can be achieved by the following:

- Identify the influences of adding waste glass on the fresh properties of concrete mixes such as workability by the slump test and porosity by water absorption test.
- Study the influence of partial cement replacement by glass powder on hardened properties of concrete mixes including density, compressive strength, and flexural strength.
- Determine the optimum portion of glass powder to be added as a partial replacement of cement.
- Study the effect of different curing temperatures and temperature cycles on both physical and mechanical properties, and durability of concrete with glass powder.
- Study the effect of the mixing methods on the behavior of concrete, which developing a new mixing method and comparing it with the conventional mixing method.

The study used a macro-scale testing such as mechanical testing which experimental testing include crushing of waste glass, preparing samples, flexural and compressive tests and the effect of the curing temperature on mechanical properties and physical characterization.

Within the scope of the study, the study has four goals:

1. Reusing of the waste glass in the Gaza strip,
2. Obtaining a green concrete,
3. Reducing the amount of cement in concrete,
4. Putting in light the environmental issues through the use of alternative resources.

This study included three impacts;

- Engineering impact, which includes the optimization of certain properties of both fresh and hardened concrete, such as increasing strength through the use of GP.
- Environmental impact, which includes the decrease in released carbon dioxide and the amount of cement consumed as a result of less cement manufactured.
- Economical impact, which includes, for example, reducing the price of the new construction, and the relatively lower cost of glass powder when compared to cement

powder. This can be achieved by producing concrete containing waste glass with more compressive strength than the normal concrete.

1.4 Research Methodology

The scope of this project is concerned with the experimental investigation on both physical and mechanical characteristics of concrete and optimum dosage of the partial cement replacement by glass powder. The aim of the investigation is to check the behavior of concrete with the different replacement of cement by glass powder. This is achieved by conducting tests including compression and flexural strength, slump test, and water absorption test. A new mixing method was developed in order to increase the mechanical properties of new concrete.

The hypothesis of the research is that the use of very small glass powder (smaller than 75µm) in concrete mix as partial cement replacement will enhance the physical and mechanical characteristics of concrete

In this experimental investigation, the cement was replaced by waste glass powder in the range of 0%, 10%, 20% and 30% by weight for M-25 grade concrete, The concrete mixtures were produced, tested and compared in terms of workability, density, absorption and mechanical tests (flexure and compressive strength) to the conventional concrete. These tests will be carried out to evaluate the mechanical properties at 2, 7, 28 and 90 days. The effect of different curing temperatures (23°C, 40°C and 50°C) was studied. Also, the use of a new mixing method for preparing concrete and its effect on the mechanical properties and durability of concrete containing waste glass was investigated.

The following tasks were carried out in order to achieve the research objectives:

Task 1: Study of previous research in the field and statistic work on the local waste glass

This part is oriented into:

Step 1: the use of waste glass in concrete and its effect on fresh properties (workability, density, and water absorption) and hardened properties (compression and flexure) as well. Study the effect of different curing temperature and the use of the new mixing method on the mechanical properties and durability of concrete containing waste glass.

Step 2: in this part consists of fieldwork to collect more data about waste glass (quantities, volume, placement, and collection of each one etc.).

Task 2: Crush of glass and preparation of samples for testing:

This task is composed of the following:

Crushing glass into a very fine powder (smaller than 75µm).

- Casting concrete with replacement cement by glass (0%, 10%, 20% and 30%).
- Physical characterization of mixes.
- Mechanical test (compression and flexure) in order to obtain a higher value of resistance.

Task 3: Obtaining the experimental results and Analysis of both physical and mechanical properties of concrete mixes

This task explains the results of the experimental tests and summarizes the properties of concrete in order to evaluate the feasibility of inserting waste glass materials as a part of the concrete mixture. In addition, determine the parameter affecting the pozzolanic reaction of glass powder.

Task 4: Optimization of mixes to be used in industry:

This task involves researching the mixes which can be used in industry.

Task 5: Conclusions and recommendations:

The last part consists of study conclusions, recommendations, and suggestions for further research.

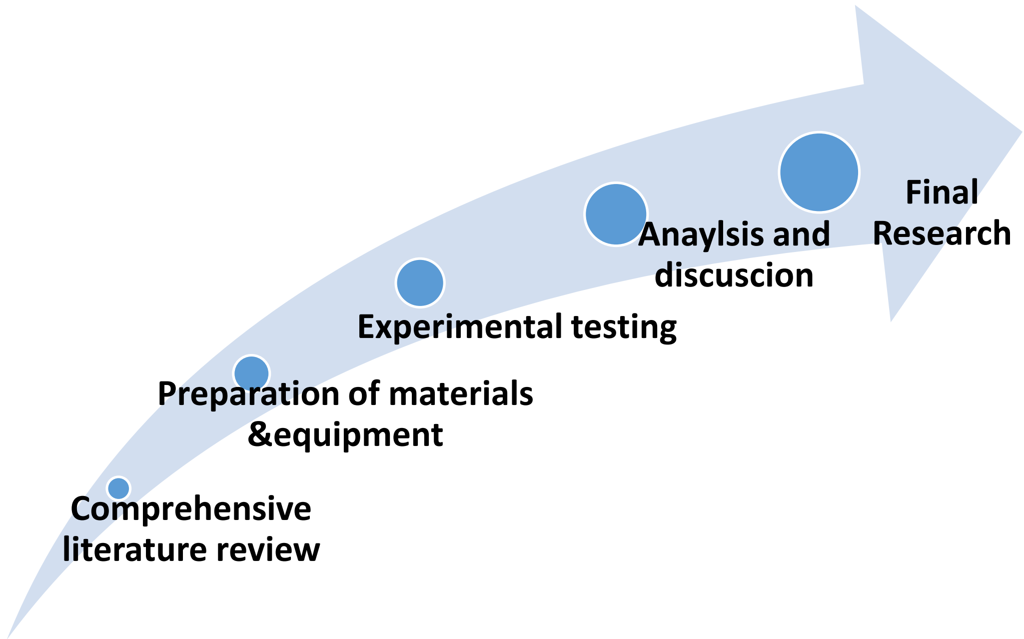


Figure (1.3): Methodology Process

1.5 Thesis Layout

This research includes five chapters as follow:

Chapter (1) Introduction

This chapter presents a brief introduction to the use of waste glass in concrete and its effect on microstructure and mechanical behavior. In addition, this chapter contains the problem studied in this research and the Methodology followed.

Chapter (2) literature Review

This chapter introduces an overall literature review for the investigation of the use of waste glass material as a cement replacement in engineering practice. The study focus on the properties of the waste glass as a cementitious material and the parameters affecting the behavior of concrete mixes at different portions of waste glass, as well, addressing the effect of different curing temperatures and mixing methods on the physical-mechanical properties and durability of concrete with waste glass

Chapter (3) Materials and Experimental Program

This chapter contains the used experimental testing program in terms of the properties of fresh and hardened concrete. The program includes many steps starting with identifying the constituents of concrete, then the design of the concrete mix, and finally conduct tests for two different mixing methods for both fresh and the hardened concrete tests.

Chapter (4) Test Results and discussion

This chapter shows the results analysis and summarizes the physical and mechanical properties of concrete, as well the followed methodology to evaluate the feasibility of the utilization of waste glass materials as a part within the concrete.

Chapter (5) Conclusion and recommendation

This chapter includes the summary of the findings of this work, the conclusions, and recommendations for future works.

Chapter 2

Literature Review

Chapter 2
Literature Review

2.1 Introduction

Concrete is a major construction material that is used all over the world. It is a composite material made from sand, gravel, cement, water, and additives. Cement plays the role of solidifying the aggregate forming the concrete. Portland cement is a mixture of various minerals (SiO_2, CaO, Al_2O_3, Fe_2O_3, and others) that are mixed with water, then left to hydrate and rapidly become hard [1].

One of the most attractive alternatives to waste disposal is waste recycling because of the limited area of landfills and due to its high cost of disposal. The utilization of waste products in concrete is an economical alternative, which concrete will become cheaper, furthermore minimizing the waste disposal cost [18].

Today a lot of research is ongoing into the replacement of Portland cement by waste materials and manufacturing products. These materials are known as Supplementary Cementitious Materials (SCM). For example, Silica fume (SF), Pulverized Fly Ash (PFA) and Ground Granulated Blast Furnace Slag (GGBS). As well, waste Glass Powder (GP) has the potential as (SCM) [12].

Recent research showed that waste glass powder could be used as a cement replacement in concrete to enhance the strength characteristics to a certain extent due to its pozzolanic activity [6-14]. Since waste glass has silica content, it exhibits pozzolanic properties. Thus, by partially replacing cement with such pozzolanic material it can meet the need for construction and environmental protection aspects.

This chapter introduces a general literature review for exploring the utilization of waste glass material as a partial cement replacement in engineering practice. The review focused on the properties of concrete containing waste glass as a cementitious material and identified the parameters affecting the behavior of concrete mixes at different portions of the waste glass.

In addition, other reviewed studies addressed the effect of different curing temperatures and mixing methods on the mechanical properties and durability of concrete containing waste glass.

2.2 Hydration process of cement

2.2.1. Introduction

“Cement” is the element responsible for the binding of the different compounds of concrete (fine and coarse aggregate) together. “Cement is a hydraulic material, this means that it depends upon a reaction with water rather than air for strength development". A chemical reaction known as hydration start immediately after adding water to cement and continues whereas water is still existent.

In the hydrous state, there are main four compounds of cement that are normally present: "alite (C3S), belite (C2S), aluminate (C3A), and ferrite phase (C4AF)". Also, other small amounts of clinker sulfate and gypsum are present [1].

2.2.2. Cement Reactions

The following are the main cement reactions including the silicates:

$$2\ C_3S + 6\ H \longrightarrow C_3S_2H_3 + 3\ CH \qquad (1)$$

$$2\ C_2S + 4\ H \longrightarrow C_3S_2H_3 + CH \qquad (2)$$

It is noticed that the above equations are neutralized, and the Ca/Si of C-S-H can show a range from 1.5 to 2 and is often around 1.8. But, it is stated that "C-S-H does not have a definite structure", which gel deposits of CH commonly trend tangentially to pore spaces and aggregates along the longitudinal axis [1].

In short, "the Calcium silicate hydrate (C-S-H) is the main binding phase and is therefore responsible for the characteristic strength of hardened concrete". As well, it is the main reaction component of the pozzolanic reaction, with 1.5-2 for a Ca/Si ratio. The increase of C-S-H and decrease of Ca(OH)2 is the main indicators for the pozzolanic reactivity of fine waste glass [5].

One of the main restrictions associated with the using of "Supplementary Cementitious Materials (SCM)" is "the alkali-silica reaction (ASR)" products which generally have a Ca/Si ratio of 0.01-1. The alkali-silica reaction and pozzolanic reaction are identified by equivalent initial materials and have the same reaction products with similar chemical compositions, in contrast, they have totally different impacts in terms of the resulting properties of concrete.

In the case of the pozzolanic reaction, high calcium, low alkali material are produced with the same properties of C-S-H, but, the ASR gel has high alkalis, low calcium, and adversely effects on strength, durability, or stability of the concrete. Over time, ASR has harmful effects on the concrete matrix due to the imbibing water and expanding to form a pressure [11].

2.2.3 Kinetics of cement hydration

The hydration of cement with water and aggregates to form concrete depends on several rates including but not limited to:

- The immersion rate throughout the phases (at the initial and later ages).
- The nucleation rate and crystal growth of hydrates.

- The diffusion rate of water and dissolved ions within the already formed hydrous materials.

In the same context, the kinetics of hydration is affected by several factors including:

- The phase of the cement composition.
- The quantity and form of gypsum within the cement.
- The particle fineness of cement, the rate of reaction increase as the fineness increase due to the increase of the surface area of cement particles.
- W/c ratio, at high w/c ratio, hydration may progress until all of the cement is consumed, whereas at low w/c the reaction may completely stop due to lack of water.
- Curing conditions: the progress of hydration can be significantly affected by relative humidity.
- Hydration temperature: the hydration rate can an increased as proportional to the increase of reaction temperature.
- The provision of chemical admixtures like set controllers and plasticizers.

2.3 Supplementary Cementitious Materials (SCM)

The term "green concrete" takes its place as an environmental product thus the use of new materials to replace cement in concrete without decreasing its mechanical and durability properties is a goal to be achieved for sustainability and must help to reduce the greenhouse effect.

The previous researchers suggested a lot of practical ways aiming to the using supplementary materials of cement, and also enhance the properties of the resulting concrete, minimize the materials cost, and further alleviate environmental concern by using streams of waste material as SCM [4, 19]. These materials contain essentially calcium, aluminates, and amorphous phases of silica, they can react within the environment of hydrating cement to provide a product which shares some of the properties of Portland cement through a secondary reaction known as the pozzolanic reaction. The most widely used SCM derived from a waste source are fly ash, GGBFS, glass powder and Silica fume [19].

The Glass revealed good pozzolanic properties or even cementitious in nature, which can be claimed that it is amorphous and contains relatively significant amounts of silicon and calcium. However, pozzolanic properties of glass positively affected when it is finer [3]. Therefore, it is concluded that glass powder (GP) can be inserted as a partial replacement for cement in concrete.

Reviewing the past investigations revealed that the pozzolanic behavior of waste glass, and most pozzolans in general, affected by fineness, chemical composition and curing conditions (relative humidity and temperature) [1-10].

2.3.1 Pozzolanic reaction

"The pozzolanic reaction is identified as the result of interactions between amorphous siliceous materials and calcium hydroxide (CH) producing calcium silicate hydrates (C–S–H)". It is acknowledged that superior long-term durability performance will be produced by the use of pozzolanic SCMs in concrete results [4, 11, 20].

$$\mathbf{SiO2 + CH \longrightarrow C\ S\ H}$$

It was concluded by a series of prior researches that glass is, in theory, a pozzolanic material due to its amorphous characteristics and its composition of silicon and calcium [5, 14, 22-26]. Replacement cement by the glass in concrete add to its value and helps its recycling [23].

Several theories have been proposed to employ waste glass, a number of these studies introduce waste glass as an aggregate replacement [27-30], others used it as a replacement of cement [3, 9, 12, 18, 31, 32] and a few studies utilization it as aggregate and cement replacement within the same mixture [4, 5, 11]

Several studies indicated that using waste glass as replacement of a coarse and fine aggregate in concrete revealed destructive results of concrete. This is claimed to the alkali-silica reaction that developed between the cement and the waste glass aggregate, this, in turn, produced a bad performance concrete, i.e. low compressive, tensile and flexural strengths [27-30].

Yet, there are some challenges to be overcome within the use of SCM, like early age lower strength in comparison to concrete without replacement. This is often due to the faster rate of the hydration of Portland cement in comparison of pozzolanic reaction [4, 21]. In addition, it is noticed that 28 days strength reduce by replacement cement, in such case of short period, this is a short-term effect because of the pozzolanic effects would not be completely valid [5].

2.3.2 Glass and Waste Glass

The glass is a widely used product on the daily-life basis in various forms. A production of glass commences with blending some materials such as silica, soda ash, and calcium carbonate at elevated temperature. Then, the process continues by cooling and solidification, without crystallization.

The main raw natural material that participates in the manufacture of Glass, are sand, silica, and limestone, In addition, recycled waste glass is another alternative used within the manufacturing process. In the case of glass recycling, the process starts with the crashing of glass product, then mixed with raw glass materials to produce new products. the compositions of glass and also the corresponding applications of different commercial forms of glass are illustrated in Table 2.1 [33].

Table (2.1): The compositions of glass and also the corresponding applications of different commercial forms of glass [33].

Glass form	Chemical Composition (by weight)	Applications
Soda-lime-silica	73% silica – 14% soda – 9% lime – 3.7% magnesia – 0.3% alumina	Glass windows – bottles – jars
Alumino-silicate	64.5% silica – 24.5% alumina – 10.5% magnesia – 0.5% soda	Fiberglass insulation – halogen bulbs
Ninety-six percent silica glass	96% Silica	Furnace sight glasses, outer windows on space vehicles
Lead (crystal)	57% silica – 31% lead oxide – 12% potassium oxide	Lead crystal tableware
Fused silica glass	ultra-pure, single component glasses ($SiO2$)	Optical fiber, used for telecommunications.
Boro-Silicate	81% Silica – 12% Boron Oxide – 4% Soda – 3% Alumina	Pyrex Cookware – Laboratory Glassware

(a) **(b)**

(c) **(d)**

Figure (2.1): Various common types of glass. a) Soda-Lime-Silica glass, b) Boro-Silicate glass Pyre, c) Lead (Crystal) glass, d) Alumino-silicate glass.

2.4 Previous Studies

The following sections summarize the previous studies in the field of the utilization of glass powder as a cement replacement in concrete.

This literature review mainly aims to present the previous works carried out to specify the effect of the glass powder on the physical properties of concrete (density, absorption), mechanical properties (compressive and flexural strength) and the effect of these properties on the durability of concrete (porosity).

2.4.1. Parameters affect the pozzolanic reaction of glass powder (size, chemical composition, curing conditions).

Several studies have investigated the parameters that influence the characteristics of concrete including waste glass as cement replacement and pozzolanic behavior of waste glass in concrete. There are several parameters from past lines of research which includes but not limited to fineness, chemical composition, curing temperature, and the pore solution present for reaction [14, 21, 22, 34, 35].

There also some restrictions which have limited the acceptance of waste glass as a common SCM, including the production of ASR gel, and the lack of pozzolanic reactivity [4].

The study of Shayan (2002) was carried out to examine the usefulness for the employment of waste glass in concrete in many forms. It concluded that positive impact in terms of concrete value adding and cost recovery produced by the use of glass powder form in concrete. It was found that cement or aggregate could be replaced by 30% GP in concrete without damaging effects at the long-term age [5].

The chemical composition of waste glasses is the most essential parameter that largely affecting the pozzolanic behavior of waste glass in concrete. It was showed that glass has a chemical composition comparable to cement and traditional SCM. Thus, glass consists mainly of silicon and calcium and is suitable as a raw material with concrete production [14, 21, 22, 34, 35].

A project by Chen, et al. [36] studied the chemical composition of glass, they identified thirty-two form of glass and indicated that the general composition of glass meets the need of the raw materials for cement production. In addition, they showed that the composition of glass relied significantly on its application, but its color or origin is not significantly affected variables [36].

Another project by Bignozzi, et al. [11]., was conducted to investigate using glass waste with various chemical composition as supplementary cementing materials. They concluded that both the pozzolanic progress and/or alkali-silica reactions are very dependable on the chemical composition of glass, which is the main responsible at developing the reactions conditions. It was also concluded that Glass waste is classified as a new source of pozzolanic addition for the production of sustainable cement [11].

The possibility of using 30% of the finely ground glass as a cement replacement was also studied by Shao, et al. [37]. Their results proved that the performance of concrete is significantly affected by the size of the ground glass. In the case of finer particle size than 38 µm of the glass, the activity of glass and corresponding compressive strength of produced concrete increased as a result of the reduction of the concrete porosity. It was also found that ground glass within concrete mix increase strength at both early and late ages in comparison to concrete with fly ash [37].

A study research was carried out to explore the effect of using crushed waste glass as an aggregate in the fresh and hardened properties of concrete, For concrete mixed with coarse waste glass as a partial replacement of coarse aggregates, the results showed that the concrete density was decreased by the increase of water to cement ratio and the corresponding 28 days compressive strength of about 385 kg/cm2 compared to 300 kg/cm2 [70].

On the other hand, It is also found that the durability characteristic will be improved by using milled waste glass as a partial replacement of cement, which properties of concrete such as sorption, chloride permeability, and freeze-thaw resistance oriented to increase. This is attributed to the removal of the deteriorated causes, filling spaces among particles, and a denser matrix of the cement paste by increasing conversion of CH to C–S–H available [3].

The influence of glass particles size was carefully explored by Soroushian [3]. They address three forms of the glass within concrete; as fine and coarse aggregate, and in powder form. Their result is agreed with prior research that using glass as aggregate at either fine or coarse forms produced harmful ASR in concrete, but in contrast, the powder form of glass could prevent the formation of ASR, this effect almost like to SCM.

Another study addressed the risk of ASR at the case of using glass particles in concrete. It noted that glass particles need to be finely crushed in order to avoid damage concrete by ASR. In contrast, using coarse particles have two main benefits that include a low crushing cost and an increase in the amount of glass that can be incorporated in the concrete [5].

Another confirmation for the damaging effect of alkali-silica reaction (ASR) was documented by Pike and Hubbard [28], their project utilize various types of glass as aggregate (quartz, opal, fiberglass, and glass) with cement. Their results are agreed with explorations of prior studies that deteriorated cracks in concrete produced because of using aggregates as cement replacement. “The immersion rate of amorphous silica is understood to be the rate-determining step throughout pozzolanic reaction” [28].

The curing temperature is considered one of the main factors which affect the rate of the pozzolanic reaction of SCM concrete [21].

The pozzolanic reaction of glass powder is largely affected by the curing temperature of the concrete specimen. which pozzolanic rate was accelerated at elevated temperature [4, 20].

The effect of curing temperature on the development of pozzolanic reactivity of glass was studied by Mirzahosseini and Riding [20], they used a very fine glass particles less than 25 μm in concrete as partial cement replacement and cured concrete at each of three temperatures 10 °C, 23 °C, and 50 °C. They concluded that the pozzolanic behavior of glass cullet is significantly affected by curing temperature.

The results also indicate the high sensitivity of glass due to a temperature which glass powder exhibit a significant pozzolanic reaction at elevated temperatures, even at early ages [20].

2.4.2. ASR (Alkali-Silica Reaction) effect

“The alkali-silica reaction (ASR) is considered one of the most deteriorated phenomena in concrete; it is identified as a chemical reaction occurs between the aggregates reactive silica and also the alkalis inside the cement paste”. The reaction result of absorbing water by the alkali-silica gel and the corresponding increase in the volume of concrete is the main responsible for the deterioration [5].

A high pressure within the cement paste and corresponding internal stress were produced by increase volume that can cause severe damage for concrete. The presence of high basic media (PH > 12) and high relative humidity are the main conditions of ASR that could increase with increasing temperature but it exhibits after a long time [27, 28].

Strength, durability, volumetric stability over time and ASR are the main indicators that determine the feasibility of using any SCM particularly waste glass, which concrete need to be protected due to the tendency for ASR of glass powder.

For instance, the following studies were conducted on the relationship of ASR and glass powder with the concrete matrix. It was found that the presence of waste glass within the concrete mix could decrease the ASR expansion in comparison to the control mix without glass. It was also confirmed that the ASR expansion gradually decreased as the particle sizes of the waste glass decreased [37]. This has also been explored in prior studies by Shi, et al. [22], the use of 20% fine grounded waste glass as a partial cement replacement in concrete showed that a significant decrease of the ASR expansion.

Another research by Johnston [29] addressed using crushed glass as aggregate with a maximum particle size of 19 mm and with high and low alkalis cement content, 0.58 and 1.13 respectively". Their results were in agreement with that of Pike and Hubbard [28] the deteriorated cracks were produced due to the alkali-silica reaction in the concrete.

The main challenge will be how the minerals of cement clinker can be affected by the alkalis in the period of alkali existence in cement clinker [23].

This has been explored in prior study by Kamali and Ghahremaninezhad [12], who studied the mechanical strength and durability behaviour of cementitious materials adjacent with two types of glass powders (with median particle size 8.4 µm) and a class F fly ash (with median particle size 8.4 µm) at different portions of cement replacement [12]. It was also found that the using of glass powders decreased alkali-silica reaction expansions of the modified cementitious materials which the lower expansion by the alkali-silica reaction was shown for mortars containing 20% GP than mortars with 20% FA. [12].

It was documented that the concrete resistance for chloride penetration can be improved by inserting waste glass especially the 20% replacement [3], another result was found that increasing the waste glass with mix may be decreased the expansion due to the ASR despite the high content of alkali [3].

Alkali-aggregate reaction and expansion can be produced due to Alkalis in the glass powder, once aggregates are alkali-reactive. ASTM C1260 stated that increasing glass powder portion leads to decrease alkali-aggregate reaction expansion, but this is limited because 50% or more glass replacement is very destructive [26].

In general, recycled glass with finer form increase its ability as a filler and enhance the pozzolanic properties to employ as a partial cement replacement, also results confirmed that fiberglass particles at replacement level can reduce the effect of ASR [26, 38].

As previously reported in the literature, cement partially replaced by glass powder may be protected from the alkali-silica reaction and its deleterious expansion. And also increasing the glass powder dosage can gradually reduce the expansion as a result of the pozzolanic reaction of the glass powder that reduced the concentration of the alkali hydroxide and also the CH of the concrete mixture [39, 40]. Furthermore, it was reported that reduction of the growth of ASR expansion below 0.1% needs at least 30% replacement of cement by glass waste [40].

A closer look to the literature on ASR expansion that molding the concrete prisms at 38 °C, 100% RH showed insignificant expansion (<0.015%) at the age of 760 days. Therefore, it is clear that ASR expansion has not taken place at that age. It also indicated that ASR expansion is largely increased by particles in the size range of 1.18–2.36 mm [42]. Similar explorations [41] showed that excessive expansion caused by glass particles of around 1.5 mm caused, whereas those <0.25 mm caused no expansion in concrete. This also was in agreement with the experimental results made by Matos and Sousa-Coutinho [43], they carried out the accelerated mortar bar test (1 M NaOH, 80 °C) and concluded that expansion did not occur with glass particles of lower than 0.30 mm.

Soroushian [3] indicated that replacing 20% of glass powder to cement could be the optimum safely percentage that exhibits a very good performance without any features of the harmful ASR expansion [3].

Sulfides, sulfates, and alkalis (which add more alkali to concrete) are deleterious chemical constituents that create a higher risk of ASR through concrete age. One of the benefits for good pozzolanic functions is mitigation both ASR and consuming the lime that minimizes the efflorescence [44].

As the authors note earlier, two differentiated process control production concrete with SCM especially glass powder. A valuable pozzolanic reaction, which produces a stable structure with good strength and durability characteristic of concrete containing glass but in a contrast the destructive ASR which swelling product that has a harmful crack and expansion.

It was concluded through the previously reviewed studies that this process can depend on many factors, mainly including "calcium content, particle size, and alkalinity, the dissolved silica will polymerize into the expansive gel, hydrate into C–S–H, or a combination of both" [45]. A mechanism by Urhan [46] indicated that ASR gel, C–S–H and a range of intermediate products can be found at any time in a concrete containing either reactive aggregate or pozzolanic material.

2.4.3. Compressive strength

The feasibility of using glass powder within the concrete matrix can be identified by many parameters, mainly the physical and mechanical properties of concrete such as compressive and flexural strength; in addition, the durability of concrete is another important parameter.

"Concrete as the main construction material", has to resist the applied loads of structures with its weight. Therefore, concrete must maintain specific mechanical properties to overcome the high stress of the weight by the construction loads. Many works were made to examine the benefits of employment waste glass powder in terms of the mechanical properties of concrete. The compressive strength of concrete is one of the main parameters affecting the amount of glass powder replacement.

The experimental results for many studies indicated that increasing percentage of the waste glass aggregate decrease both the compressive strength and flexural strength of concrete because of the reduction of adhesive strength at the glass particle surface [27-30].

In other words, a recent study by Madandoust and Ghavidel [31] was carried out to evaluate the use of the mixture containing both waste glass powder (GP) and rice husk ash (RHA) as a cement replacement. The melded mixtures were prepared with 0-20% GP (less than 40 µm of the particle size) and 0-20% RHA (range of 10-75 µm). It is found that the properties of concrete increase gradually over the age of concrete, and also the optimum percentage of replacements by GP and RHA is indicated as 10% and 5% respectively [31]. The results also showed good evidence that using both GP and RHA together in concrete did not exhibit adverse effects.

The concrete strength significantly increases in the later age, this is claimed to the increase in density of the microstructure and decrease permeability as a result to the filling effect of sub-micron sized glass particles [3].

They found that SEM crystal structure with fine glass powder exhibit low-density C–S–H gel and C–A–H crystals start to react on the 7th day, which could decrease strengthen interface binding as well as porosity [47].

For instance, a research by Khatib, et al. [48]. was made to investigate the performance of concrete containing glass powder as a partial substitution of cement [48]. They conclude that replacement level of 10% glass powder produced the maximum strength of concrete. The other proportions of GP that increase 10% glass powder revealed a reduction in strength of concrete and even is lower than that of the control. This result is in agreement with explorations made by Kumarappan [49] who indicated that using up to 10% glass powder partially replaced of cement is feasible, where compressive strength is higher than the control mix.

Similar contributions were made by Shayan and Xu [35], they used various proportions of GP (0%, 20%, and 30%) as cement replacement and then investigated the performance of glass powder in concrete under the field conditions. They concluded that the Glass powder within concrete exhibit a slower strength development up to 28 days, but at later ages of 404 days, significant increase appear within all the mixtures where the strength can reach 55 MPa for the mixture of 40 MPa target.

Moreover, Schwarz, et al. [39] studied the durability characteristics of fine glass powder modified concrete. The test results include using of (5, 10 and 20%) of waste glass as cement replacement at 3, 14, 28, 90 days. Based on the strength and hydration tests, they concluded that 10% of glass powder is the best replacement level of cement [39].

A study by Dhanaraj Mohan Patil and Sangle [18]. was carried out to identified the effect of cement replacement by glass powder on the strength characteristics, and also determine how is particles size of glass powder effect on the mechanical properties. They used two different particle size, one with a size less than 90 µm and another have particle size ranges from 90 microns to 150 µm. they concluded that on the addition of Glass powder, initially, a slower rate gain of strength revealed up to the 28th day, but it achieved the targeted design strength. It was also indicated that the maximum strength produced by 20% cement replacement by glass powder, it is higher than both the strength of the control mix and another mix with different portions of cement replacement. This corresponds with the study prepared by Hussain and Chandak [50] Who indicated that the best percentage of glass powder as a partial cement replacement is 10% which the best results in compressive and split tensile strength revealed. In addition, Shayan [5] confirmed these results and concluded that the highest compressive strength was achieved by concretes with 10% GP replacement of cement in compared to other replacements levels.

The results showed that the strength of concrete increases with decrease size of the used GP particle. It is concluded that concrete strength using particle size less than 90 µm are higher than that of a mix containing particle size ranges from 90 to 150 µm [18].

The Compressive strength of 30% glass powder replacement showed an increase in strength by 10% in comparison to that of the control mix. It also concluded that the optimum dosage of glass powder replacement in concrete is found to be 30% concentration [32].

As mentioned that many previous works studied the effect of using glass powder in concrete on the mechanical properties especially compressive strength, one of these studies carried out by Wang, et al. [47], they replaced silica-rich waste glass for cement and replaced waste glass for natural sand, then investigate the effect on the micro-observations and macro-observations of concrete [47]. They concluded that replacing cement by waste liquid crystal glass in cement mortar leads to increase the compressive strength as well as setting time, this increase is proportional to increasing glass powder content. The properties of 10–20% glass powder replacement are closest to those of the control group. Moreover, using glass as sand may increase compressive strength in compared to the control [47].

Another evidence, Soroushian [3] carried out tests using three different proportions (15, 20 and 23%) of milled waste glass (with an average particle size 13 µm) in concrete, as partial cement replacement. They observed that using milled waste glass not only increase gains in strength and durability of recycled aggregate concrete but also it protect from alkali-silica reactions. They conclude that the compressive strength of concrete increase with a replacement level of 15 and 20% waste in compared to conventional concrete without waste glass, whereas concrete with 23% waste glass replacement revealed the same compressive strength to concrete without waste glass [3].

Confirmation for the results, Vandhiyan, et al. [25] carried out experimental tests at 7, 14, 28 days for mix concrete with waste glass powder as partial replacement of cement. Their results indicated that the best result of compressive strength was for the mix with 20% glass powder up to 28 days, but the mix with 10% and 15% showed a slight increment at 14 days results.

A previous study by Vijayakumar, et al. [38] was carried out to specify the performance of concretes with glass powder (finer than 75µm) and determine the changes in compared to the performance of concretes without glass powder. The results indicated that the compressive strength increase by 19.6%, 25.3%, and 33.7% for replacement levels of glass powder in cement by 20%, 30%, and 40% respectively.

Islam, et al. [9] evaluated the flow and strength properties of mortar and concrete containing waste glass. The test results have investigated the use of (0- 25%) of waste glass as a partial replacement to cement at 7, 14, 28, 56, 90, 180 and 365 days. They indicated that replacing cement by glass powder reveals a minor increase in mortar flow. They also found that mean compressive strengths for concrete recycled glass with 10, 15 and 20% glass portion was higher than the control concrete and also the highest value among them was for 10% cement replacement. Moreover, A slight reduction (approximately 2%) of compressive strength for the 25% glass portion in compared to the control concrete [9].

Kamali and Ghahremaninezhad [12] showed that the compressive strength of concretes with (0-20%) cement replacement levels at various curing ages has a higher value the control concrete at all ages. They documented many conclusions including that the compressive strengths of concrete increase as curing age increase. Also, the compressive strengths of concrete increased as replacement levels of cement increase at later ages, finally they concluded that the optimum values of compressive strength among all percentage levels was with 20% glass powder.

In general, the pozzolanic properties of glass powder can leads to increase the density of microstructure and "improved interfacial bonding between aggregates and cement paste matrix in concrete". As a result for that, compressive strength increase as a proportion with the replacement levels of cement[12].

In short, it was shown from the above literature that an extensive research was carried out to specify the effect of the using glass powder within the concrete matrix, therefore, for the simplicity; a summary of all the reviewed researches in this field is presented in the tables below. Tables 2.1 and 2.2 also confirm the effect of smaller GP particles in the compressive strength of concrete; the smaller particles give the highest compressive strength for the concrete. Few references referred to the chemical composition of GP in order to study its effect on the compressive strength. In another hand, some of these references did not indicate the used particle size distribution of GP [30, 40, 41, 43].

Table (2.2): Summary of previous research on the optimum GP replacement in concrete.

Type of waste glass	% waste glass studied	Particle sizes studied	Optimum % waste glass	Optimum particle size	Reference
Fluorescent lamps glass (soda-lime)	30	38-150μm	30	38 μm	[37]
Glass beads (soda-lime)	20	10-700 μm	20	30-100 μm	[22]
Window plate glass (soda-lime)	0-20	1-100 μm	10	1-100 μm	[39]
Bottles (soda-lime glass)	0-23	13-25 μm	20	13-25 μm	[3]
Container (soda-lime glass)	20	20-100 μm	20	20 μm	[51]
Recycled waste glass (soda-lime)	0-20	0.1-100 μm	20	0.1-100 μm	[43]

Table 2.3: Summary of previous research on the GP replacement in concrete which gives higher compressive than the control.

GP (%)	GP size	Compressive strength increases (%)	Reference
15% and 20%	No information	The same value of the control mixes	[52]
40%	< 75µm	The same value of the control mixes	[38]
10%	< 75µm	The same value of the control mixes	[31]
10%	< 100 µm	The same value of the control mixes	[39]
20%	90 – 150 µm	The same value of the control mixes	[18]
30%	< 38 µm and < 75µm	120% 110%	[18]
20%	< 90 µm and	106%	[18]
15%	< 90 µm	123%	[25]
10%	No information	120%	[49]
10%	No information	107%	[48]
20%	< 90 µm	125%	[53]
10%	No information	105%	[50]
20%	< 90 µm	107%	[5]
20%	< 75µm	120%	[12]
10%	< 90 µm	107%	[5]
30%	< 75µm	108%	[32]

From the above Table 2.2, it was concluded that the glass has the ability as a cement replacement with acceptable function, in contrast, appropriate methods must be developed to control the undesirable effect of ASR/pozzolanic reaction [4].

From the above research, it has been concluded that initial strength values for mixes with GP is lower than the control, this is attributed to the reduction of cement content, but the strength gradually developed with time under moist-curing conditions, and finally the highest values of strength exhibits at a later age which higher than the control.

In short, prior investigations significantly studied the effect of glass powder on the mechanical properties of cementitious materials and the pozzolanic reactivity of glass powder was also evaluated.

2.4.4. Flexural test

The following studies focus on the effect of GP on the flexural strength of the concrete mix as cement replaced by different portions of GP. One of these studies was conducted by Kamali and Ghahremaninezhad [12]. Their results indicated that an "all the mechanical properties exhibit good results especially flexural and compressive strength, but the strength improvement noticeably appeared at late ages [12].

Another project carried out by Vandhiyan, et al. [25] concluded that the flexural strength has a considerable increase at 10% glass powder replacement of cement. Besides the tensile strength exhibits a marginal improvement [25]. This also proved by the work of Vijayakumar, et al. [38] they reported that the tensile strength effectively increases by the glass powder content when compared with conventional concrete. It was found that the flexural strength increases 83.07%, 99.07%, and 100% respectively [38] for each cement replacement of 20%, 30%, and 40% glass powder.

Statistical research of flexural strength was made by Soroushian [3], the results showed that the flexural strengths with high w/c ratio were significant at 56 days of age concrete with milled waste glass. The increase of flexural strength was significant in the later-age, this is attributed to improvements within "the interfacial transition zone (ITZ)" and therefore conversion of CH into C–S–H within the cementitious paste was a result to the pozzolanic reactions of milled waste glass with calcium hydroxide [3].

It was found that replacing cement with 15 and 20% waste glass is considered the optimum replacement percentage that has the highest flexural strength of concrete among other replacement levels and in compared to conventional concrete [3].

In short, the flexural strength at later age of 130 days, have a considerable increase of split tensile strength about 50% higher than at age of 28 days, this is attributed to older specimens used in the flexure tests [35].

2.4.5. Slump test

Workability is identified as the property of freshly mixed concrete that determines the ease with which it can be properly mixed, placed, consolidated and finished without pleading or segregation. The workability of fresh concrete was determined by means of the conventional slump test as per IS; 1199(1989) [38].

The use of waste glass as aggregate did not have a marked effect on the workability of concrete, but reduce the high values of the slump, air content and fresh unit weight [23] [34]. In general, Concrete with glass aggregates would require a higher content of water than conventional aggregates to reach the same workability [34].

Shayan [5] showed that the workability was reduced due to the replacement and it reduced with an increase in replacement, This is a tribute to the increase in the surface area of the glass powder and also the angular shape of the glass particles [25].

Another project by Khatib, et al. [48] studied the GP effect on the workability of concrete mix and the results revealed that there was a systematic increase in the slump as the glass powder content in the mix increases [48],[26]. The slump ranged from around 40 mm for the reference mix (i.e. 0% glass powder) to 160 mm at 40% glass powder [48].

Vijayakumar, et al. [38] also examined the workability of fresh concrete containing glass powder (finer than 75µm) with replacement levels 20%, 30%, and 40% and the results indicated that the slump values was maintained in the range of 80 mm to 100 mm [38].

In general, it was concluded that a systematic increase in the slump as the mix increases. It is also found that the density values of the concrete mixtures containing 10%, 20%, 30%, and 40% seem to be similar except the 40% GP mix has a slight drop [48].

2.4.6. Effect on Density and Absorption

The density is a parameter affecting the mechanical and the durability behavior of concrete. In other words, the density is the opposite of the water absorption and the total porosity, the concrete with higher density is a concrete with lower absorption and porosity. Reduction of water absorption and porosity can greatly enhance the long-term performance and service life of concrete in aggressive service environments. Decreased porosity also improves the compressive and flexural strengths of concrete, as a fundamental inverse relationship exists between porosity and strength of concrete [50].

Many studies were conducted to study the use of crushed waste glasses as aggregates for cement concrete and found that all concrete with glass aggregates cracked due to the formation of ASR gel[18, 22-26, 54].

It was suggested that glass powder reduces the chloride ion penetrability of the concrete, thereby reducing the risk of chloride-induced corrosion of the steel reinforcement in concrete.

The volume of permeable voids (VPV) is an important property of concrete affecting transport mechanisms through the concrete, such as ingress of aggressive gases and solutions.

The bulk density (dry), bulk density (after immersion) and volume of voids test was measured for hardened concretes with and without milled waste glass at 56 days of age [3]. Partial cement replacement with milled waste glass is discovered to produce an increase in the bulk density (dry) and therefore the bulk density (after immersion) of concrete. This might be attributed to the conversion of CH to C–S–H by the pozzolanic reaction of milled waste glass in concrete, noting that the specific gravity of the resulting C–S–H (that falls on the lower end of the 2.3–2.6 range) is somewhat higher than that of CH (2.24) [3].

Malik, et al. [55] proved that the water absorption decreased with increase in glass powder content. Soroushian [3] in their explanations on strength and durability of recycled aggregate concrete containing milled glass, as a partial replacement for cement, concluded that water absorption of concrete is observed to be significantly reduced with the addition of milled glass in both low and high w/cm ratio mixes. Other researches proved the opposite. They proved that glass powder increases the slump of concrete. Shekhawat and Aggarwal [56] showed that water absorption increased as glass powder content increased. Mabse [2013] showed that water absorption increased with the higher amount of glass powder content, while moderate substitution levels such as 5% and 20% of glass powder content achieved similar values in comparison to that of control mix.

It was observed that the higher porosity revealed in cement pastes cured at elevated temperatures arises mainly from changes in the apparent density of C-S-H. The results showed that C-S-H is highly sensitive to temperature and that its apparent density increases continuously with the curing temperature in the range 5°C to 60°C studied [54].

The significant increase means that less space is filled by the C-S-H resulting in a much higher capillary porosity which has a detrimental impact on the strength properties and durability of the high temperature cured materials [54].

The porosity of the cement pastes did not show major changes at 28 days or 91 days and varied in the range of 25–30%. It is seen that cement paste with 20% GP indicated the lowest porosity at 91 days; this can be attributed to the higher pozzolanic activity of GP compared to FA [12].

2.4.7. Effect of curing temperature

While significant literature is available on supplementary cementitious materials in concrete, such as GGBS, silica fume, fly ash and glass powder. few works have studied the effect of high-temperature curing conditions on the strength properties of concrete containing supplementary cementitious materials. Most of the research on cement paste, mortar, and concrete was conducted with the specimens hydrated at room temperature, on a level surface and during the early stages of hydration. There are some researches studied the microstructure and hydration to explain the effects of curing temperature [8].

The most pivotal parameters which affect cement or cementitious material hydration is curing temperature. It was observed that elevated temperatures can increase the rate of hydration, early strength gain, change hydration products formed, change the density of the formed products, and accelerate activation of pozzolanic activity[57, 58]. However, high temperatures can also lower ultimate strength, increase permeability and drying shrinkage, and in some cases, cause delayed ettringite formation (DEF) [57, 59].

The effect of temperature on the hydration is governed by the enhanced pozzolanic reaction. The correlation between the big porosity and the compressive strength is not perfectly clear and indicates that other factors, such as the interfacial transition zone at the aggregates in mortars, the hydrate phase assemblage and the mechanic properties of the hydration products, play an important role for the development of compressive strength [24].

The following studies investigated the effect of curing temperature on the strength & durability of the concrete mix containing GP as cement replacement. One of these studies conducted by Gallucci, et al. [54], they examined the changes to C-S-H induced by isothermal curing between 5 and 60 °C. The results show that as the temperature increases (within the range studied) the C/S ratio of C-S-H changes only slightly, with a higher degree of polymerization of silicate chains, but there is a significant decrease in its bound water content and an increase of apparent density of 25%. This increase supposes to come from a different packing of C-S-H at the nanoscale. As a consequence of these modifications, the microstructure of the cement paste is much coarser and porous, which explains the lower final strengths obtained by curing at elevated temperatures.

In addition, Deschner, et al. [24] investigated the effect of temperature on the hydration of Portland cement pastes blended with 50 wt.% of siliceous fly ash with a temperature range of 7 to 80 °C. The result showed that the temperature is very related to the OPC hydration, which leads to enhanced early compressive strength at elevated temperatures. Besides the well-known effects of temperature on the OPC hydration, a strong influence of temperature on the reactivity of fly ash is observed [24].

It was also found that the increase of the temperature from 7 to 23 °C shifts the start of the pozzolanic reaction from 90 days to 7 days. At 50 °C, the fly ash reaction starts after 1 day of hydration [24].

Another study was conducted by Yang, et al. [13], they evaluated the effects of curing temperature on the compressive strength development of High-Strength Concrete, Test results indicated that concrete at the hot temperature (40∘C) developed a strength that was 1.19 times higher than concrete cured at the reference temperature (20∘C) with w/c of 0.4 and 1.03 times for concrete with w/c of 0.28, whereas concrete at the cold temperature (5°C) showed 1.0–4.5% lower strength development.

A study by Park and Noguchi [8] was carried out to investigate the effects of mixing and curing temperature on the strength development and pore structure of fly ash blended mass concrete, indicating that The Fly ash blended mass concrete showed a significant increase in early-age strength development due to an increase in the rate of the pozzolanic reaction of fly ash. This can be attributed to the latent hydraulic properties inherent in fly ash.

Huseien, et al. [10] also studied the effect of curing temperature on properties of geopolymer mortars (GPM) containing industrial and agricultural wastes, the results revealed that mortar prepared with sodium silicate (NS) solution produced better strength at 60 °C at age of 28 days than the one cured at 27 and 90 °C.

The observed enhancement in the compressive strength and the microstructure of GPM was attributed to the creation of extra CSH with increasing calcium content [10].

Jung and Choi [7] investigated the effect of the high-temperature curing methods on the compressive strength of concrete containing high volumes of ground granulated blast-furnace slag (GGBS). Demonstrating that the high heating rate might result in an advantageous high early strength development, but a disadvantageous long-term strength development.

It also found that Incorporating GGBS into precast concrete mixes can be a very effective tool in reducing CO2 production in the cement industry and increasing the applicability of GGBS [20].

2.4.8. Relative index (reactivity of pozzolanic reaction as a function of glass powder)

The pozzolanic behavior of SCM is often determined by combining the results obtained with indirect and direct methods of analysis. As indirect methods, the compressive strength of concrete samples based on glass blended cement cured for different times and the activity index at 28 and 90 days have been measured.

Shi, et al. [22] showed that the compressive strength of mortars containing 20% fine glass powder (specific surface area = 467 m2/kg) is higher than the control mixture at 28 days based on ASTM C311 strength activity index. Additionally, they have documented that increasing the curing temperature to 65°C results in a higher strength of 20% GP mortars even at 3 days comparing to the control mortar. They analyses the pozzolanic activity index of four waste glass powders from a glass beads manufacturer: GP-fine from the screening of crushed glasses, GP-dust from a dust collector for the screening of crushed glasses, and the other two, GP-4000 and GP-6000, from the grinding of the powder and from the dust collector. Portland cement contains about 40% of particles smaller than 10µm. GP fine is too coarse for Blaine fineness measurement, while the Blaine finenesses of the GP-dust, GP-4000, and GP-6000 are 264, 467 and 582m2/kg respectively. The Portland cement has a Blaine fineness of 383m2/kg [22].

The strength activity index of those glass powders and coal fly ash at 23°C was measured, It was found that GP-fines showed the lowest pozzolanic strength activity index among the materials tested because of its coarse particles. Its pozzolanic strength activity index was around 70–74% at 7 and 28 days, which are slightly lower than the minimum of 75% as specified in ASTM C618 for pozzolanic materials. Although the particle size of GP-dust is also much coarser than the particle size of the fly ash, the pozzolanic strength activity index of the GP-dust was only slightly lower at 1–7 days, however higher at 28 days than the fly ash. It had a pozzolanic strength activity index of 82% at 7 days and 92% at 28 days [22].

From the strength aspect, GP-4000 and GP-6000 can be regarded as a good pozzolanic material. The only concern for using these materials as a cement replacement in concrete is the potential alkali-aggregate reaction when the alkali reactive aggregate is used [22].

Matos and Sousa-Coutinho [43] examined the use of different percentages of waste glass powder (10 and 20%) as a partial replacement to cement to produce concrete. The experimental results indicated that the compressive strength decreased as the percentage of the waste glass increased. And the strength activity index for the 10% concrete and the 20% concrete was 97% and 103% respectively compared to the concrete without waste glass.

Shao, et al. [37] measured the strength of the lime–glass mixtures as the pozzolanic index for three glass powders: 150,75 and 38µm ground glass. The strength results indicated that the 38µm glass satisfied the minimum strength requirement at the 7-day test, and attained an increase in strength after an additional 21 days of curing in water. The strength of the mixture with 150µm glass was far below the limit as a result of the size of the glass was too coarse to function as a pozzolan. The 75-mm glass performed marginally. Its 7-day strength was slightly lower than the threshold value, whereas additional 21-day curing in water increased the strength to a satisfactory level [37].

2.4.9. Effect of Mixing Methods on the behaviour of concrete containing GP

One important factor which influences the composition and properties of the resulting C–S–H in concrete is the mixing method and the adjacent concentrations of the reactants [21].

To develop concrete materials containing glass powder SCM, it is important to know the correct proportioning and materials processing procedures that result in optimum mechanical, durability, and environmental performance [21]. To provide a better understanding of the pozzolanic reaction of glass powder (GP) with calcium hydroxide (CH), Past studies [1–12] have used arbitrary dosages of glass powder and curing methods and evaluated their impact on concrete properties.

The stoichiometry of the pozzolanic reaction is dependent on the availability of dissolved CH and GP, and as such, can change over time. At early ages, CH dissolves more rapidly than GP, and the resulting C–S–H has a higher Ca/Si and lower crystallinity. Over time, as more GP dissolves into pore solution (especially as CH is depleted), C–S–H with lower Ca/ Si and better crystallinity forms [69].

The pozzolanic reaction of glass grains leads to a significant increase in sodium concentration in pore solution. The sodium concentration in pore solution for a hydrating blend with GPF reaches 730 mmol/l at 120 d, which is even higher than that of alkali solution (0.6 M NaOH) for acceleration ASR expansion. Concentrations of aluminum, sulfate, and silicon also increase notably with time for the blend with fine glass powder [69].

A study by Park and Noguchi [8] was carried out to investigate the effects of mixing and curing temperature on the strength development and pore structure of fly ash blended mass concrete [8]. Conventional mixing method was used to prepare the concrete mix, which the concrete was mixed in a twin shaft-type mixer (200 L). After first mixing the mortar for 50 sec., the coarse aggregate was added and the resulting concrete was mixed for another 90 seconds. The mixing was conducted in the summer and in the winter to provide the two types of weather conditions. The results showed that the fly ash blended mass concrete showed a significant increase in early-age strength development due to an increase in the rate of the pozzolanic reaction of fly ash. This can be attributed to the latent hydraulic properties inherent in fly ash [8].

A study was made by Shayan and Xu [35], they used various proportions of GP (0%, 20%, and 30%) as cement replacement and then investigated the performance of glass powder in concrete under the field conditions. The results showed that the strength of cores drilled from the slab was lower than that of the cast cylinder, which has been attributed to less efficient curing under field conditions than laboratory fog curing and also to less effective compaction of the slabs compared to the cylinders. They concluded that the Glass powder within concrete exhibit a slower strength development up to 28 days, but at later ages of 404 days, significant increase appear within all the mixtures where the strength can reach 55 MPa for the mixture of 40 MPa target.

2.5 Concluding Remarks

The previous studies suggested that a lot of efforts have been done for determining the effect of using waste glass materials as a part of the concrete mix, but all of them are attempting to confirm the possibility of replacement process and identify the relevant specifications and parameters affecting the properties of concrete containing waste glass. This research aims to develop a new mixing method aiming to optimize the behavior of concrete by increasing the reactivity of glass powder.

Chapter 3

Materials and Experimental Program

Chapter 3

Materials and Experimental program

3.1 Introduction

This chapter discusses the characteristics of the constituent materials used to produce the concrete at different proportions of glass powder as a partial replacement of cement as well as the experimental program linked to this research.

The effect of used proportions of glass powder, curing temperature and mixing procedures on the concrete compressive and flexural strength together with workability, porosity and density were studied.

Several constituent materials used in the tests to produce concrete with glass powder and its properties such as unit weight, specific gravity, and grain size distribution are discussed.

The tests of the fresh and hardened concrete properties were prepared according to testing procedure specifications from the American Standard of Testing Materials (ASTM). Compression and flexure tests were used to investigate the concrete hardened properties. In addition, slump and water absorption tests were used to check concrete fresh properties.

A new mixing method was used in mixing concrete with glass powder; it consists of mixing the glass powder with water before adding to the concrete in order to dissolve the SiO_2, CaO and NaO ions which compose the glass powder. The compressive strength of concrete prepared by the new mixing method was compared to the conventional method.

For this target, the optimal portion of Glass powder was mainly obtained based on the concrete compressive strength that was considered as one of the most important properties of concrete and a major indicator of general quality control. In addition, the strength activity index is defined as indicative of the pozzolanic action of the raw or natural pozzolans. Then, mechanical properties were investigated using concretes made with these optimal proportions.

The tests procedures, details and equipment used to assess concrete properties are illustrated in the following sections.

3.2 Characterizations of Constituent Materials

This section presents the properties of all the components used in the various concrete mixes. Concrete is a structural material that contains some simple elements but when mixed with water would form a rock-like material. Concrete mix is comprised of coarse aggregates usually gravel, fine aggregates usually sand, cement, water, and any necessary additives.

Most of the materials used in this research were local materials. Moreover, the cost of this is acceptable in economic view.

The Ingredients of the concrete mixes are described in details with their properties as follow:

3.2.1. Cement

Cement is the adhesive or glue element in concrete, which when set binds particles of aggregate (fine, coarse) together. Cement is a hydraulic material, this means that it depends upon a reaction with water rather than air for strength development. When water is added to cement, a chemical reaction called hydration commences immediately and continues while water is still present.

The used cement for the production of concrete mixes is the Ordinary Portland Cement CEM II (Nesher CEMII AM SVL 42.5 N). This type of cement is one of the most common types of cement used in the Gaza Strip.

The physical properties of cement according to manufacturer datasheet are shown in Table (3.1).

Table (3.1): Physical Properties of Cement According to Manufacturer Data Sheet[4].

Properties		Cement	ASTM C150-07 Requirements
Fineness (cm^2/gm.)		3500	Min. 2800
Setting Time, Vicat Test (hr: min)	Initial	2 hr 5 min	≥ 45 min
	Final	5 hr	≤ 375 min
Mortar Compressive Strength (MPa)	2 days	25	>10
	28 days	58	>42.5

Throughout the testing program, the amount of cement was replaced by dosage of glass powder with 10%, 20%, and 30%.

3.2.2. Aggregates

Aggregates are a general definition of particulate material used in construction. Including Basalt, quartz sand and quartz powder etc.

Sources of aggregate can be grouped into two main categories, rock fragments Igneous, Sedimentary or Metamorphic. In addition, recycling of concrete.

The aggregate used in all mixtures throughout the experimental testing program for this research study was obtained from a local concrete factory. Three types of coarse aggregate are used in

[4] Online Database by Nesher Israel Cement Enterprises, https://www.nesher.co.il/en/product/cem-ii-42-5-nam-slv/

this research, the natural crushed limestone of 20 mm nominal maximum size was used as coarse aggregate in the mix proportions.

Figure 3.1 shows samples of various types of natural aggregate (fine, medium and coarse) were used for composing the concrete mixes.

(a) **(b)** **(c)**

Figure (3.1) Sample of the natural coarse aggregate for concrete mix, a) coarse aggregate, b) medium size aggregate, c) fine aggregate

The sieve analysis of representative samples for the naturally originated aggregates to be used in the concrete mix was obtained according to ASTM C136 / C136 M-14 [60] and using the standard U.S. sieves. Figure 3.2 shows the particle size distribution curves for the three types of aggregate (fine, medium and coarse) and the sand used in the concrete mix.

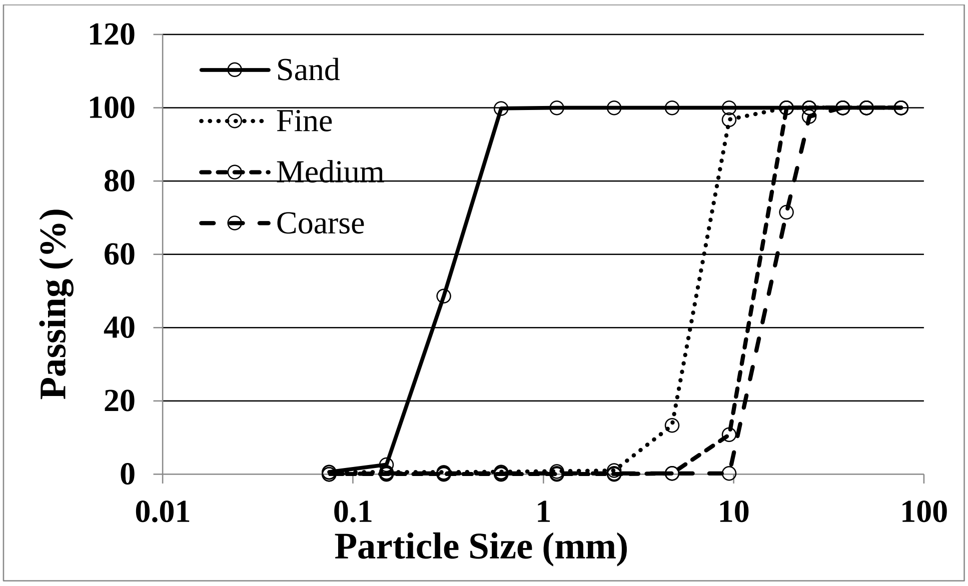


Figure (3.2): Grain size distribution curves of sand, fine, medium and coarse aggregates respectively.

Figure 3.3 shows the cumulative particle size distribution of the aggregates mix. The curve shows that the aggregates used are well graded and the cumulative Particle size distribution (PSD) is located within the maximum and the minimum limits of ASTM C136 / C136 M-14 [60].

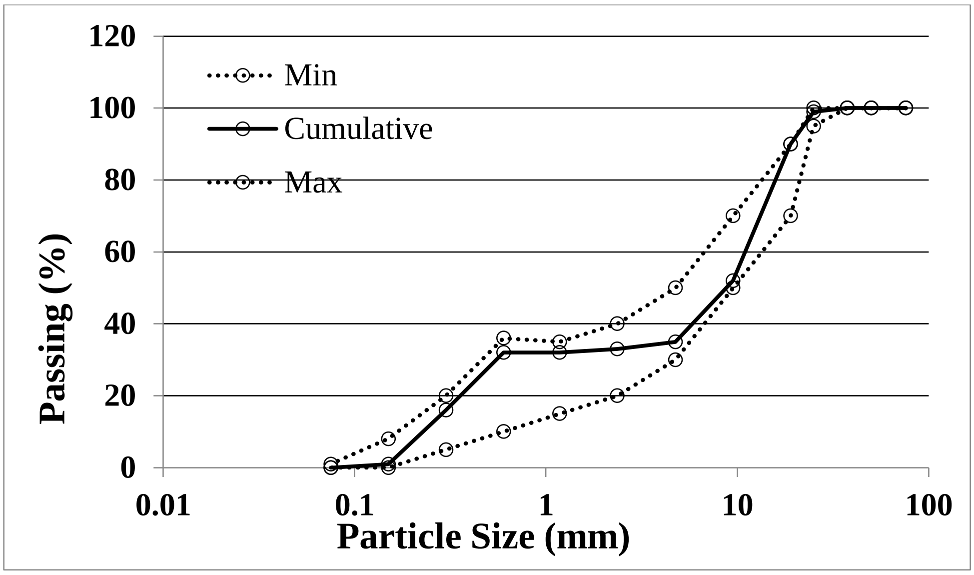


Figure (3.3): Cumulative Particle size distribution of aggregate according to ASTM (C136).

3.2.3. Waste Glass

The Glass is widely used in manufactured products such as glass sheets, bottles, glassware, vacuum tubing, etc. The amount of crushed waste glass was collected from a local landfill site in Gaza strip, where the waste glass represents between 2 to 3% of the total amount of municipal solid waste (2000 ton/day) [17 and 62]. The glass was cleaned out of the dirt materials and impurities, and then crushed into powder and sieved to get particle sizes smaller than 75 µm as shown in Figures 3.4. Figure 3.4 shows the used glass powder particles throughout this experimental study.

Figure (3.4): Glass powder particles (less than 75 µm).

Table 3.2 shows the chemical composition of the glass powder and CEMII cement as realized by XRF measurement according to ASTM D5357-03 [61]. The composition of the glass powder shows a small amount of cement due to the impurities coming from the crushing machine and its environment, a small amount of cement is traces and it is very negligible to be considered [6].

Table (3.2): chemical composition of the glass powder and CEMII cement [6].

Composition by mass %	GP	CEMII
CaO	18.55	66.69
SiO_2	64.94	18.84
Al_2O_3	1.81	6.3
Fe_2O_3	1.97	3.72
SO_3	0	2.66
P_2O_5	0	0.70*
MgO	3,12	0.61*
K_2O	0.44	0.5
Na_2O	9.16	0

Figure 3.5 shows the particle size distribution (PSD) of the cement (CEM II) and the Glass Powder (GP) according to ASTM C136 / C136 M-14 [60]. The figure shows that CEMII has a finer particle size than GP [6].

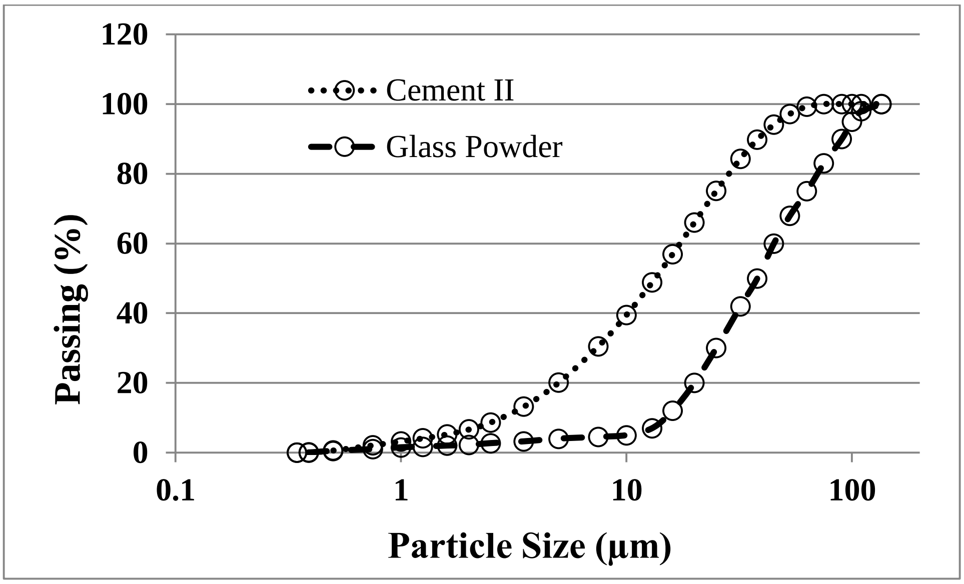


Figure (3.5): Particle size distribution of cement and glass powder [6].

3.2.4 Water

Tap water was used in all concrete mixtures and in the curing of all the tests specimens. The water source was used from the Soil and Materials Laboratory at IUG.

3.3 Mixing Design Procedure

The design of concrete mix includes many steps, first of all, is to determine the performance pattern required according to concrete specifications, then to select and quantify the constituent material in the mix by weight, also the preparation of design test composition and its proportions is another step, and the step before the last is to apply experimental tests related to fresh and hardened concrete properties, finally, is to verify the test results.

For the testing program in this research, a series of 336 standard compressive tests were conducted with variable controlling factors: waste glass content, curing temperature and method of mixing. The compressive strength cubes are divided into four parts, 192 cubes prepared for the conventional mixing method, 92 cubes for the new mixing method, and 24 cubes prepared for each of the cycles No 2 & No 3.

The reference testing samples for comparison purposes were the B 250 Portland Cement Type II mix with no waste glass content, and all the tests were done for 2, 7, 28 and 90 days compressive strength accompanied by a slump test for each case sample. Tables 3.5 and 3.6 summarize the entire testing plan conducted within this research and note that each group in this list comprises three samples for conducting the compressive strength and one for the slump tests.

The main idea behind subdividing each testing group into 3 samples is to ensure the optimum level of credibility for the output data points and to create a real margin of excluding extremely odd data points so as to reach a higher level of the representative database for the analysis phase.

Then, the testing program continued for determining the flexural strength for the two optimal concrete mixes. An extra series of 44 tests were conducted for each group of glass powder replacement.

3.3.1. Constituent material

This is an important starting step for determining the mass of waste glass powder to be included in the concrete mix according to the assigned portion of waste glass powder for each testing trial. Table 3.4 lists all the raw components of the concrete mixes with the specific gravities used in the testing program.

Table (3.3): Specific Gravities of Concrete Mix Raw Components for B 250

Component	Specific Gravity Gs
Cement	3.15
Coarse crashed Aggregate	2.70
Medium crashed Aggregate	2.65
Fine crashed Aggregate	2.60
Waste Glass	2.50
Sand	2.60
Water	1.00
Air Content	0.00

3.3.2. Concrete Job Mixes

Throughout the laboratory program of this research, the mix properties of the standard B-250 concrete job mix without any waste glass content was used as a reference for testing as illustrated in Table 3.5, and then for determining the various job mixes listed in Table 3.6 with varying the contents of waste glass powder.

This is an important starting step for determining the mass of waste glass powder to be included in the concrete mix according to the assigned portion of glass powder for each testing trial.

Concrete was cast with a water to cement ratio of 0.56**.** The mix design was elaborated in order to have a control mix with a compressive strength of 25MPa (B250). Three percentages of cement replacement by glass powder were used (10, 20 and 30%), as shown in Table 3.6.

Table (3.4): Concrete Job Mix for B 250 with w/c = 0.56 and Glass Powder = zero

Material description	**Size/type**	**Condition**	**Weight kg/m³**	**Volume (m³)**	**Material Source**
Cement	CEM II	Dry	**300**	0.13	CEM II -AM-SLV 42.5 N
Coarse. Aggregate (Foulia)	25 mm	Air dry	**660**	0.28	Crushed Limestone
Medium. Aggregate (Adasia)	20 mm	Air dry	**250**	0.11	Crushed Limestone
Fine. Aggregate (Simsim)	10 mm	Air dry	**350**	0.15	Crushed Limestone
Fine sand	0.1-0.6 mm	Natural wet	**600**	0.25	Gaza Dune Sand
Free water	Tap	Liquid	**215**	0.09	Tap water-Gaza
Glass powder % from cement	0.075 µm	Dry	**0**	0.00	Grain size less than 75 micro meter
Total			**2375**	1.00	

It should be mentioned that these job mixes were as per the approved standards and specifications of ASTM C136 and ASTM C 33-03.

Table (3.5): Mix proportions of concrete with GP.

Mix	**Cement**	**GP**	**Water**	**Sand**	**FA**	**MA**	**CA**	**W/C**
0% GP	300	0	215	600	350	250	660	0.56
10% GP	270	30	215	600	350	250	660	0.63
20% GP	240	60	215	600	350	250	660	0.71
30% GP	210	90	215	600	350	250	660	0.81

3.4 Experimental tests

3.4.1 Fresh concrete tests:

A. Slump test:

The slump test was made according to ASTM C143 / C143 M-00 [62]. Tests were done on fresh concrete as a function of cement replacement by glass powder in order to study the effect the workability effect of GP replacement.

B. Density:

The Density of concrete samples was determined according to ASTM C642-13 [63]. The density was calculated directly by dividing the mass of the concrete sample by its volume ($\rho=\frac{M}{V}$).

C. Water Absorption:

Water absorption of concrete samples was determined according to ASTM C642, [63]. Where the mass of the wet and the dry mass of the samples obtained after drying the sample in the oven at 105 °C for 24 hours. The absorption was calculated as follows:

$$\textbf{Absorption} = \frac{\mathbf{Mass_{Wet} - Mass_{Dry}}}{\mathbf{Mass_{Wet}}}$$

3.4.2 Hardened concrete tests:

A. Compressive strength tests:

Scope:

The test method covers the determination of the compressive strength of cubic concrete specimens. It consists of applying a compressive axial load to molded cubes at a rate (1 MPa/s) which is within a prescribed range until failure occurs. The compressive strength is calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen.

Test Procedure:

The Compression tests were conducted according to ASTM C39 / C39M-18 [64] at the age of 2, 7, 28 and 90 days using 10*10*10 cm cubes. Three samples were tested for each mix and the average was reported as well as the standard deviation which was found in most cases less than 3%. Figure 3.6 shows the crushed compressive testing cube after failure.

Figure (3.6): crushed compressive testing cube after failure.

Conventional mixing method:

According to ASTM C192 / C192M-16a [65], the cement, glass powder and aggregate were mixed for 2 minutes in order to obtain a homogenous mix. The water was slowly added over 2 minutes. Then, the mixer was stopped for 4 minutes. The last step of mixing was done for 2 minutes. The slump test was directly carried out and concrete cubes (10*10*10 cm) and concrete prisms (10×10×50 cm) were prepared for the compressive and flexure tests respectively. The samples were kept in a moist condition for 24 h and then after demolding the specimens were placed in curing tank. After a specified period of curing, strength test of the specimens was conducted shortly after taking those out from storage water.

New mixing method:

To investigate the effect of immersion of GP in the water, GP was first mixed with the amount of water determined as w/c = 0.72 for 8 hours. This step has the role to hydrolysis the glass powder in order to produce SiO_2, CaO, and Na_2O which can participate in the formation of CSH. Then, the water was slowly added to the dry concrete ingredients.

B. Flexural strength tests:

Scope:

The flexural test measures the force required to bend a beam under three-point loading conditions.

Procedures:

The test method followed the ASTM C78 / C78M-18 [66], where the 10×10×50 cm hardened concrete specimen lies on two 45 cm apart supporting spans. Then, the load is applied to the center using the loading nose at three points bending at a specified rate till failure. Figure 5 shows the crushed sample (prism).

Figure (3.7): Crushed concrete cubes and prisms.

C. Activity index calculation:

Pu [67] proposed the following mathematical method to calculate and analyze the activity of any addition or cement replacement material:

$$\text{Relative Index or Activity Index} = 1 - \frac{\text{Compressive Strength of Control mix} * \text{GP percentage}}{\text{Compressive Strength of GP mix} * 100}$$

The activity index can have:

1. A negative value, which indicates no activity for GP and a decrease of the compressive strength.
2. Zero no change in activity and the compressive strength is the same.
3. A Positive value, which indicates a reactivity of GP and the GP replacement have a positive effect on the compressive strength.

3.5 Testing program

The experimental program followed the following tasks:

Task 1: It consists of crushing waste glass in order to obtain a very fine powder smaller than 75µm. it is known that coarse glass can potentially deteriorate concrete by the risk of ASR.

Task 2: Casting concrete mixes with different amount of glass powder in order to test the effect of glass powder replacement on fresh and hardened concrete mechanically (in flexure and in compression tests) as shown in the below table 3.6.

1. **Physical characterization of mixes.**

   The mix design for this study comprises a PC concrete and glass powder mixes with replacement percentages of 0%, 10%, 20%, and 30% GP respectively. Grades 25 concrete is aimed at the design, as the B 250 grade is the most commonly encountered concrete grades in the Gaza strip.

2. **Cycles of curing temperature.**

   The experimental program was conducted at three different curing condition in term of the curing temperature at 23°C, 40°C and 50°C and the duration of curing (cycles), the cycles are illustrated as follow:

   A. General Cycle 1:

- The general cycle was conducted with a total number of 192 cubes; these cubes are divided into three equal groups as shown in figure 3.8. The first group of cubes was cast and cured under a temperature of 23 °C for ages of 2, 7 and 28. As well, the second and third groups were cast and cured under a temperature of 40 °C and 50 °C respectively.
- Four cubes were cast and cured under a temperature of 23 °C, three of these were tested for compressive test and the fourth cube was prepared for the absorption test in order to evaluate the porosity of the concrete.
- For each GP mixes with replacement percentage, twelve cubes were cast and cured at each temperature of 40 °C and 50 °C respectively. cubes were tested at the age of 2, 7 and 28 days.

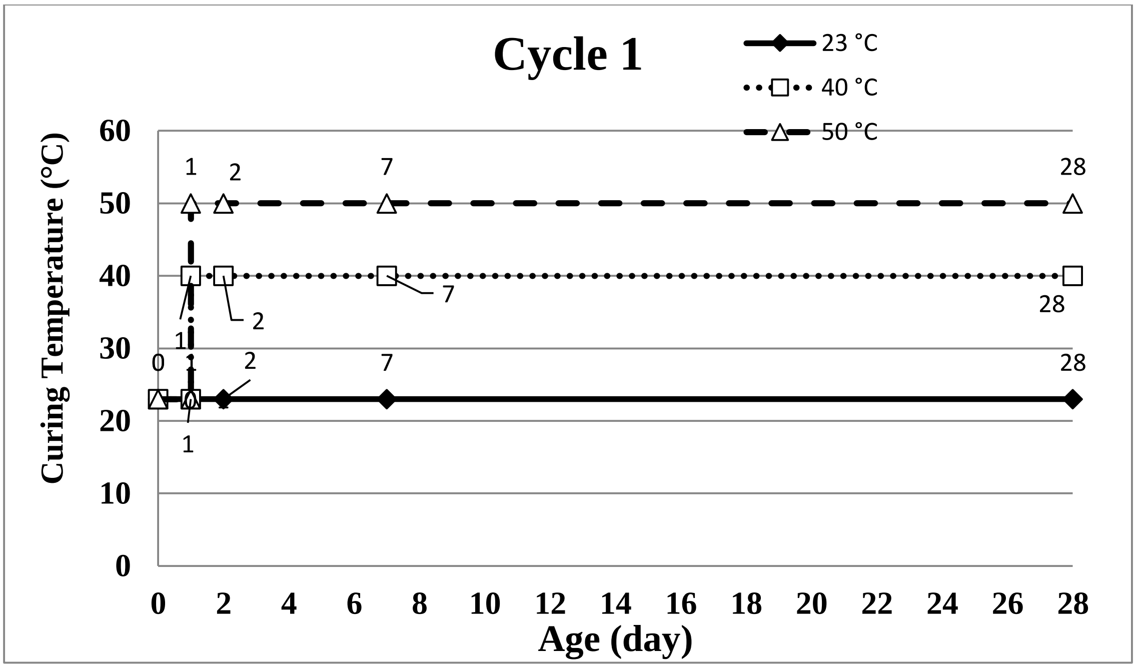


Figure (3.8): Curing Temperatures during 28 days for cycle No. 1.

B. The cycle No 2

The cycle No 2 composed of curing cubes under a temperature of 40 °C at each of the ages 2 and 7 days as shown in figure 3.9, and then they were removed to cure under the temperature of 23 °C in order to be tested at 28 days compressive strength.

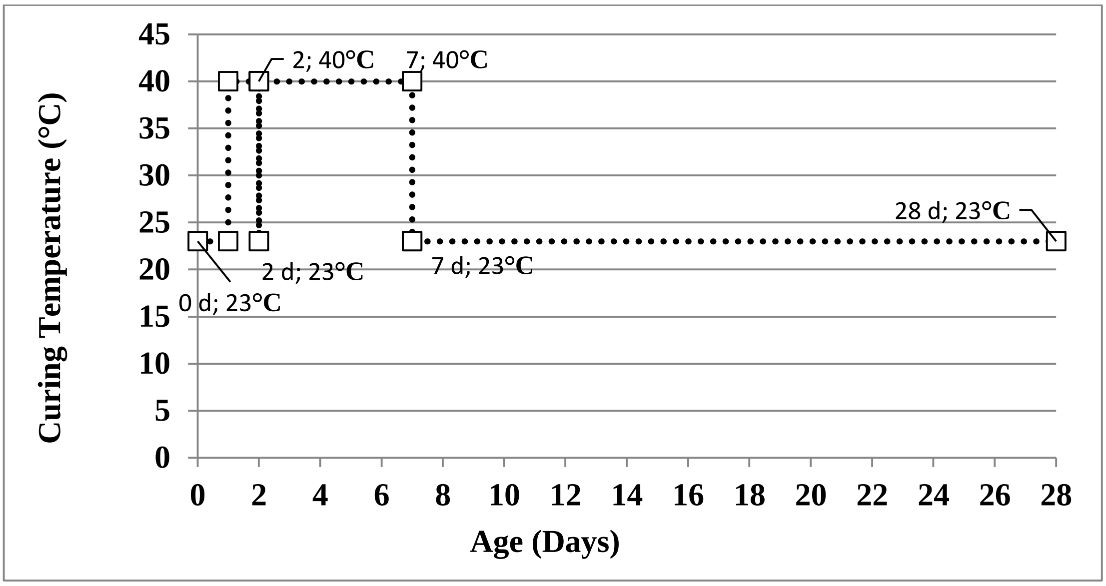


Figure (3.9): Curing Temperatures during 28 days for cycle No. 2.

C. The cycle No 3

The cycle No 3 composed of curing cubes under a temperature of 50 °C at each of the ages 2 and 7 days as shown in figure 3.10, and then they were removed to cure under the temperature of 23 °C in order to be tested at 28 days compressive strength.

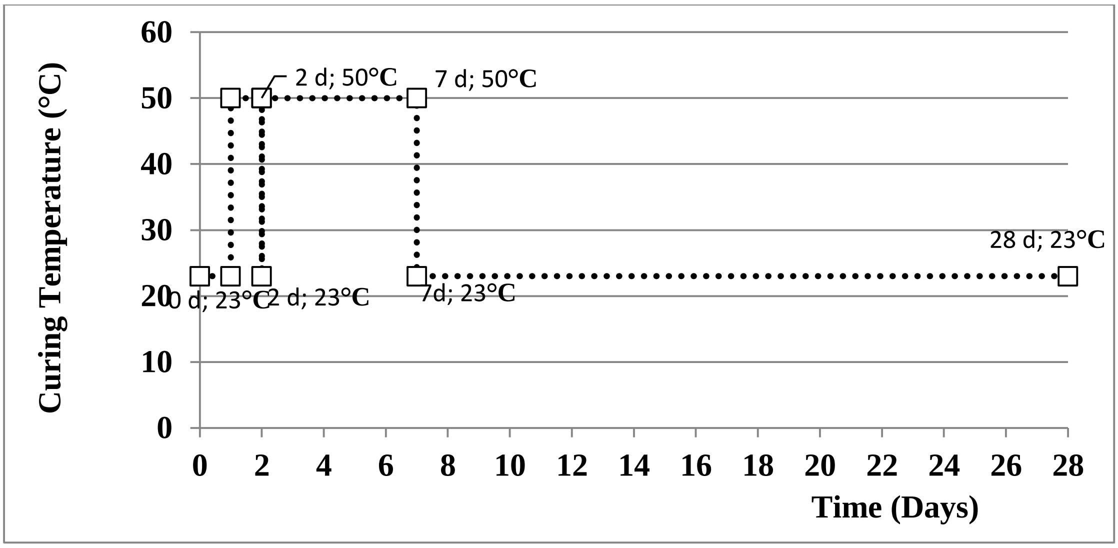


Figure (3.10): Curing Temperatures during 28 days for cycle No. 3.

3. Mechanical test (compression and flexure).

- For each GP mix with replacement percentage, four cubes were cast and cured under a temperature of 23°C, three of these were tested for compressive strength at each of the following test ages: 2, 7, 28 and 90 days. The fourth cube is to be conducted for the absorption test in order to evaluate the porosity of the concrete.
- For each GP mix with replacement percentage, thirty-two cubes were cast and cured under a temperature of 40 °C and 50 °C respectively. Three of these will be tested at the age of 2, 7 28 and 90 days using the compressive test and the fourth will be used to evaluate the absorption test.
- Other prisms were cast in order to be tested in flexure

4. Mixing methods:

- Two concrete mixing methods were used in preparing the concrete mix, the first method is the conventional method, which the cement, glass powder and aggregate were mixed in order to obtain a homogenous mix; then the water is slowly added to the mixture. The second mixing method consists of dissolving the glass powder particles in water before mixing with the dry aggregate and cement in order to increase the pozzolanic reaction in concrete.
- A new mixing method proposed to introduce and study the effect of glass powder as a partial cement replacement.

5. Mixing procedures and sample preparation:

- According to ASTM C192 / C192M-16a [62], the cement and aggregates were mixed for two minutes in order to obtain a homogenous distribution of cement, sand, and aggregates. Six dissolution times were conducted 0, 1, 2 3, 6 and 12 hours for studying the effect of dissolution time on the different properties of concrete. The water is to be added slowly over 2 minutes time to the mix. Then, the mixer should be stopped for 4 minutes. The last step of mixing was done for 2 minutes time. Once the mixing was finished, the slump test was carried out directly.
- Concrete cubes (10*10*10 cm) were prepared for the compressive test. The cubes were filled with fresh concrete and then compacted by rod method in accordance to the standard, after preparing the specimens, cubes were covered in a moist condition for 24 h and then after demolding the specimens were placed in curing tank. After a specified

period of curing, strength test of the specimens was conducted shortly after taking those out from storage water.

- The new mixing method consists of dissolving the glass powder particle in the water before mixing with the dry aggregate and the cement.

Task 3: Optimization of the quantities of each replacement in order to have the highest strength.

Table (3.6): Experimental program

Curing Temperature ©		23 °C				40 °C				50 °C			
Glass powder /Cement Percentage by weight		0%	10%	20%	30 %	0%	10%	20%	30%	0%	10%	20%	30%
Compressive strength tests	2 days	X	X	X	X	X	X	X	X	X	X	X	X
	7 days	X	X	X	X	X	X	X	X	X	X	X	X
	28 days	X	X	X	X	X	X	X	X	X	X	X	X
	90 days	X	X	X	X	X	X	X	X	X	X	X	X
Flexure test	2 days	X	X	X	X	X	X	X	X	X	X	X	X
	7 days	X	X	X	X	X	X	X	X	X	X	X	X
	28 days	X	X	X	X	X	X	X	X	X	X	X	X
Absorption test	2 days	X	X	X	X	X	X	X	X	X	X	X	X
	7 days	X	X	X	X	X	X	X	X	X	X	X	X
	28 days	X	X	X	X	X	X	X	X	X	X	X	X
	90 days	X	X	X	X	X	X	X	X	X	X	X	X

Chapter 4

Laboratory Testing Results and Data Analysis

Chapter 4

Laboratory Testing Results and Data Analysis

4.1 Introduction

This chapter explains the results and summarizes the essentials of mechanical properties of concrete analysis and the methodology followed to highlight the usefulness of considering waste glass materials as a main component within the concrete mix. Proper treatment of uncertainties within the data analysis process required understanding the sources of errors for determining the final output results.

It is worthy to mention that for the sake of simplicity, this chapter discusses the results of the main variables that may actually influence the hardened properties of concrete mixes such as density, compressive strength, and flexural strength. Firstly, this research studies the effect of replacement cement by different portions of glass powder on concrete mixes, as well determine the optimum waste glass content to be added as a partial replacement of cement, Furthermore, the effect of different curing temperature on the mechanical properties and durability of concrete containing waste glass, finally study the effect of the new mixing method on the mechanical properties of concrete.

4.2 Testing program results

According to the experimental testing program set previously, the experimental tests include mainly the fresh and hardened concrete properties tests, which were applied in the coincidence of ASTM Standards. The following sections will analysis comprehensively all obtained experimental results. Which the experimental results and analysis were obtained for Slump test to check concrete fresh properties, In addition, compression strength test, flexure strength test, and water absorption test to investigate the concrete hardened properties.

The results of experimental testing were obtained for concrete prepared by the conventional mixing method and the new mixing method.

4.3 Effect of partial cement replacement by GP on physical and mechanical properties of the concrete mix:

The results of experimental testing were obtained for concrete prepared by the conventional mixing method and the new mixing method.

4.3.1 Dissolution of glass powder in the water before mixing with the concrete:

The dissolution of glass powder on the water leads to release Na and Ca ions in the water, table 4.1 shows the number of free ions on the water for 10% GP. The amount of Ca ions is less than the amount of Na ions; this comes from the less mobility of Ca than Na to be dissolved from the glass particles. These free ions can actively participate in the hydration process of the cement by increasing the amount of CSH.

Table (4.1): Amount of Ca and Na ions release on the water**.**

Mix	**Ca ions**	**Na ions**	**PPM**
10%	23.0 mmol/L	96.3 mmol/L	1460

4.3.2 Workability of concrete:

The final output results for different sample groups regarding slump values for fresh concrete are listed in table 4.2, Moreover; the effect of glass powder content on the workability of the fresh concrete is shown in figure 4.1. The slump test was also conducted after 15 minutes to measure the slump loss from the time of original batching.

Table (4.2): workability values of concrete with several waste glass powder contents

	Slump test (cm)	
GP group	**0 min**	**15 min**
0%	11	9
10%	14	12
20%	17	16
30%	20	18
10% new mixing method	17	15

The results show that the workability increases gradually by the increase of glass powder content. The increase of workability agrees with the finding reported by Khatib, et al. [48] and Shi and Zheng [26]. The increase in workability can be attributed to the presence of more free water in the mix as the amount of the glass powder increases, which the ratio of water to cement content increase linearly as a function of GP content as shown in figure 4.2. The slump after 15 minutes decreased due to the use of free water in the formation of hydrate products.

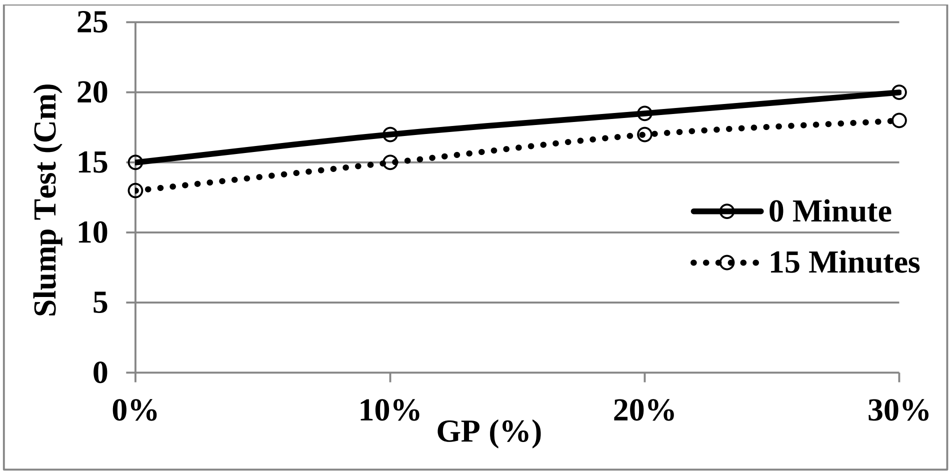


Figure (4.1): Slump test results as a function of GP replacement at 0 and 15 minutes.

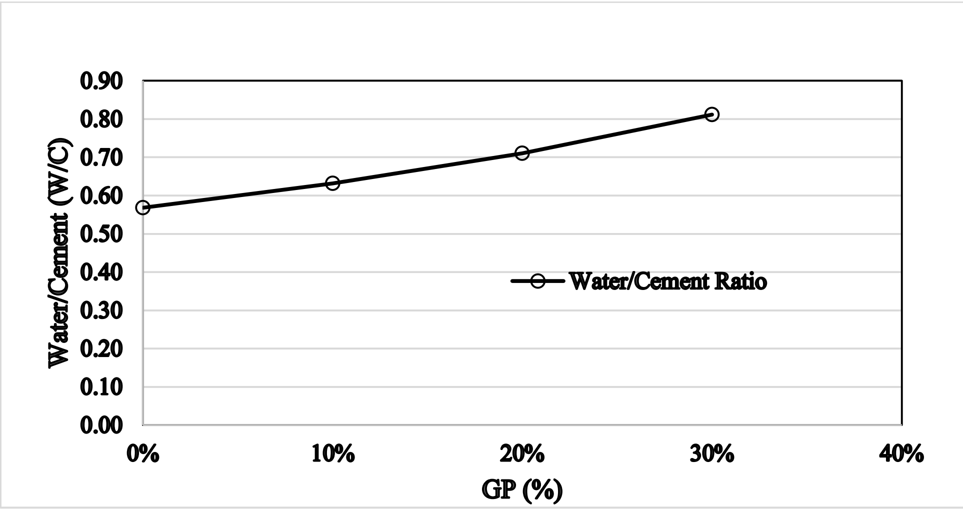


Figure (4.2): Water/ cement ratio as a function of GP replacement.

The slump of concrete made with the new mixing method showed a minor increase in the slump. It didn't report as it is negligible.

4.3.3 Density

The final output results for different sample groups regarding mass densities for hardened concrete are listed in table 4.3.

Table (4.3): Mass densities of concrete with several waste glass powder contents using the conventional method and new mixing method.

Type of Mixing	GP group	Density (kg/m^3) at 23°C		
		2 days	7 days	28 days
Conventional Method	0%	2392	2400	2410
	10%	2385	2395	2403
	20%	2380	2391	2396
	30%	2376	2385	2390
New Mixing Method	10% new mixing	2398	2415	2420
	30 % new mixing	2394	2400	2408

A. The density of concrete prepared with a conventional mix

The density of concrete mixes as a function of the GP replacement and age is shown in figure 4.3. The results showed two trends. First, an increase in the density as a function of age which comes from the formation of more hydrate products which lead to a decrease of the porosity. Second, a decrease in the density as a function of GP replacement which comes from the loss of the excess of free water as well as the reduction of the cement content which has higher specific gravity. The 30% GP mix showed the lowest density. Later, the density shows a higher value at 10, 20% GP mixes, it suggested that the pozzolanic reaction between glass powder and the cement becomes higher and leads to form more hydrate products. The optimum is located at 20% GP mix.

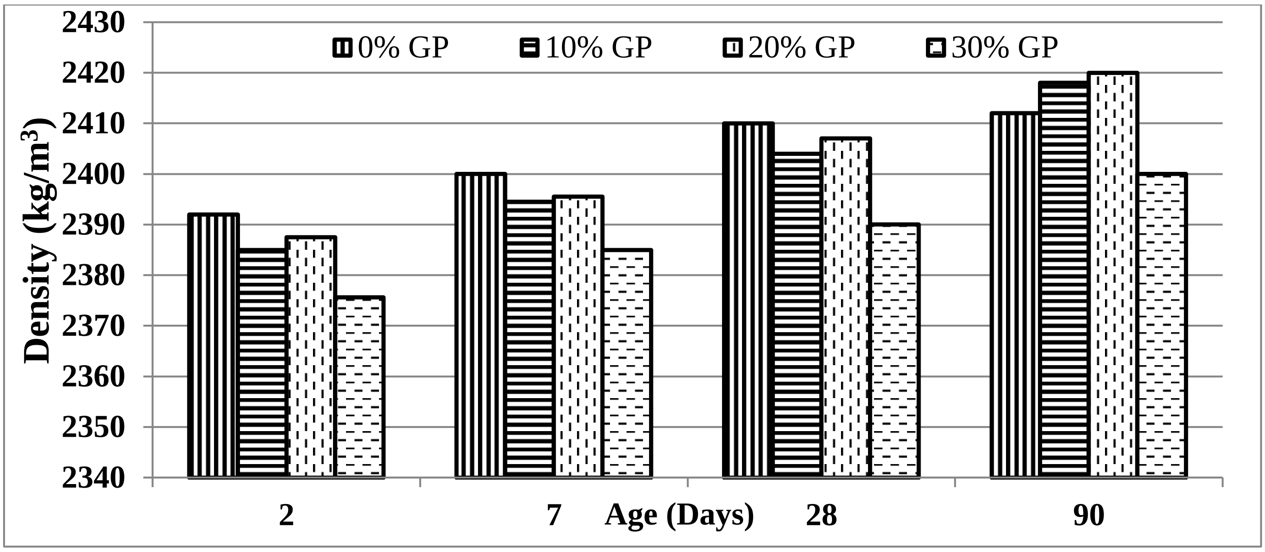


Figure (4.3): Density of concrete mixes as a function of GP replacement and age prepared with conventional mixing method.

B. The density of concrete prepared with new mixing mix:

The density of concrete mixes as a function of GP replacement and age using the new mixing method is presented in figure 4.4. The results showed higher density at 10% GP using the new mixing method than the other mixes. At 30% GP with the new mixing method, the density was similar to the control mix at all ages. This result indicates that the new mixing method gives higher density due to the more hydrate products which can be emerged from the inclusion of the glass powder's free ions in the formation of the CSH gel rather than CH. The immersion of glass powder in water attests a positive effect in the formation of denser hydrate product due to the pozzolanic reaction.

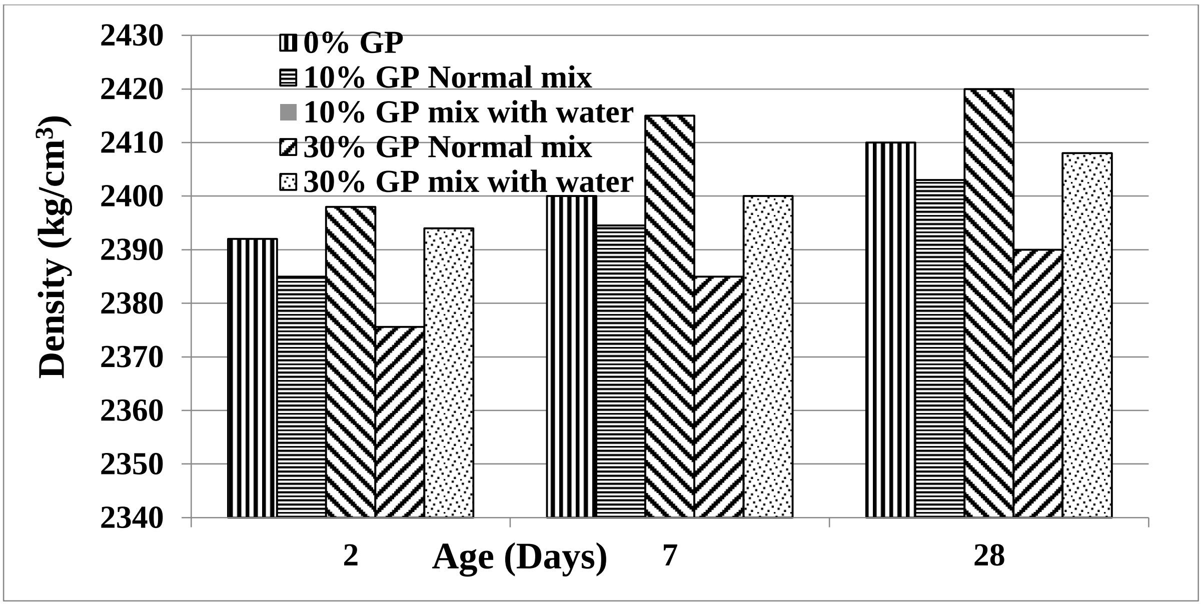


Figure (4.4): Density of concrete mixes as a function of GP replacement and age prepared with new mixing method.

4.3.4 Compressive strength tests:

A. The compressive strength of concrete using the conventional mixing method:

The compressive strength values as a function of GP replacement and age are shown in figure 4.5 and tables 4.4& 4.5. A decrease in the compressive strength is observed as the amount of the GP increased until 28 days. Later, at 90 days, an increase in the compressive strength was obtained at 10% and 20% GP.

At 2, 7 and 28 days, the compressive strengths of 10% and 20% GP mixes were very close to the control mix, but the strength of the 30% GP mix showed a sudden reduction.

At 90 days, both the 10% and 20% GP mixes showed higher compressive strength than the control mix. This increase can be attributed to the pozzolanic reaction which takes place at later ages, which affect the interfacial transition zone between the cement paste and the aggregate and the pores are more refined in the interfacial transition zone, this result was confirmed by Du [68]. Previous work showed that the 20% GP mix improve the pozzolanic reaction by the consumption of CH and the formation of CSH [6]. These also agree with the findings reported by Soroushian. [3] and Dhanaraj Mohan Patil and Sangle [18].

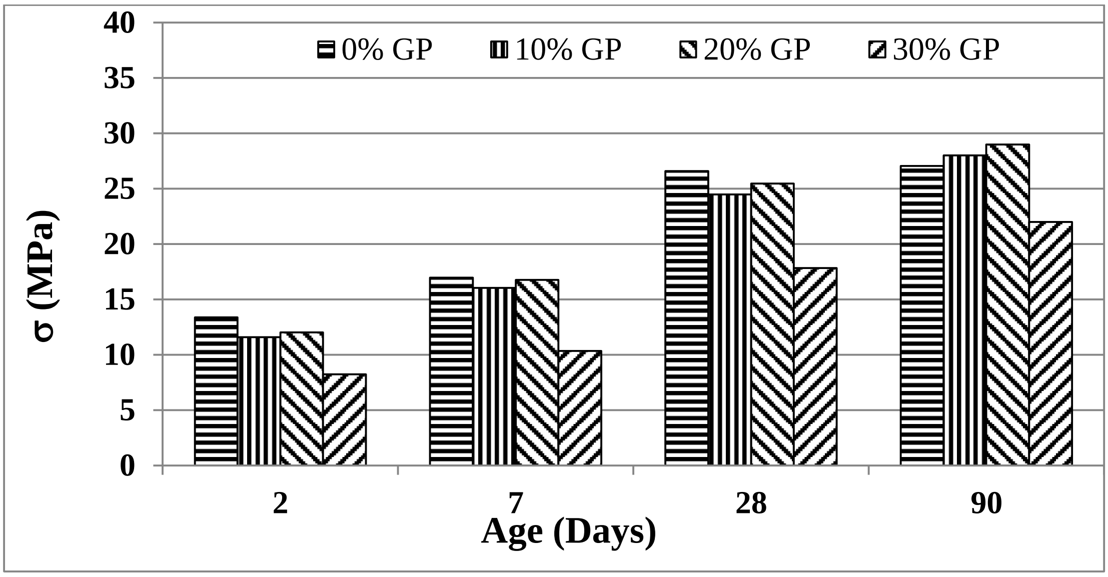


Figure (4.5): Compressive strength of concrete as a function of GP replacement and age using conventional mixing method.

Table (4.4): Compressive strength of concrete with several waste glass powder contents using the conventional method and new mixing method.

	Compressive Strength (kg/mm^2)					
	Conventional mixing method				**New mixing method**	
Curing Duration (days)	0 %	10%	20%	30%	10 new mixing	30 new mixing
2	13.38	11.58	12.02	8.24	17	14.75
7	16.96	16.03	16.75	10.35	20.15	18.02
28	26.58	24.47	25.45	17.84	28.25	20.93
90	27.05	28	29	22	34.32	25

Table (4.5): the normalized compressive strength (according to the control mix) with several waste glass powder contents using the conventional method and the new mixing method.

	Normalized Compressive Strength Percentage (%)				
	Conventional mixing method			**New mixing method**	
Curing Duration (days)	10	20	30	10 new mixing	30 new mixing
2	86.57	89.90	61.60	127.10	110.28
7	94.54	98.76	61.04	118.84	106.28
28	92.06	95.74	67.09	106.28	78.74
90	103.51	107.20	81.33	126.87	92.42

Figure 4.6 shows the normalized compressive strength (according to the control mix) as a function of GP replacement and age. At 90 days, the 20% GP mix showed a slight increase, around 7%, higher than the control mix, while 10% GP mix showed a smaller increase of around 3.5%. The 30% GP mix showed 20% decrease.

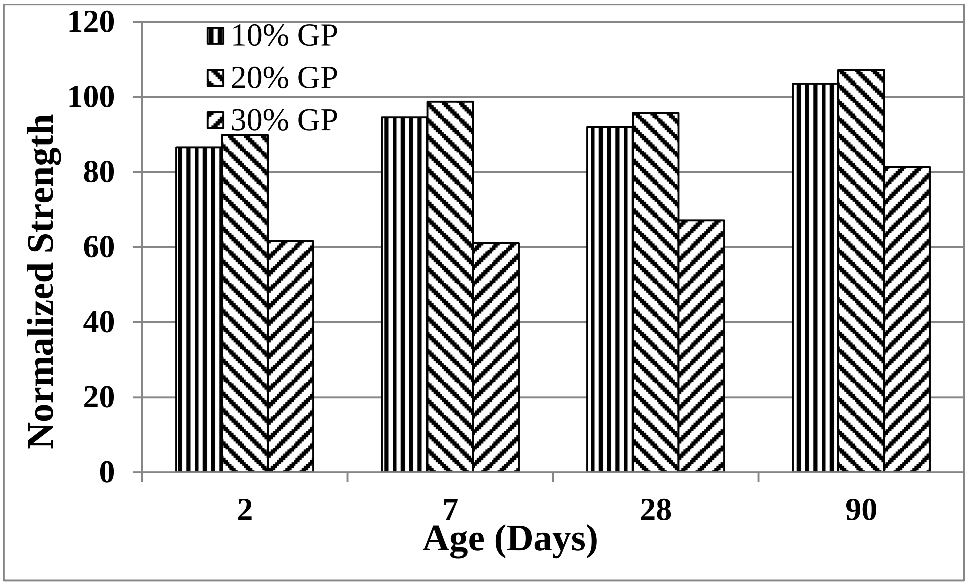


Figure (4.6): Normalized compressive strength of concrete as a function of GP replacement and age.

B. The compressive strength of concrete prepared with the new mixing method:

The effect of 10% and 30% GP replacement on the compressive strength using the new mixing method are presented in figure 4.7. The results showed a significant increase in the compressive strength of the various mixes using the new method. The highest compressive strength was obtained at 10% GP replacement.

The dissolution of glass powder leads to improve the compressive strength at an early age (at 2 and 7 days) which comes from the formation of more free ions in the water before mixing as shown in table 4.1. Later at 90 days the compressive strength is higher due to the progress of the pozzolanic reaction like what has happened with the conventional mixing method, see Figure. 4.5. It suggests that the increase of the compressive strength at an early age can be related to the pozzolanic reaction and the packing filling effect of the glass powder, while later it is related only to the pozzolanic reaction.

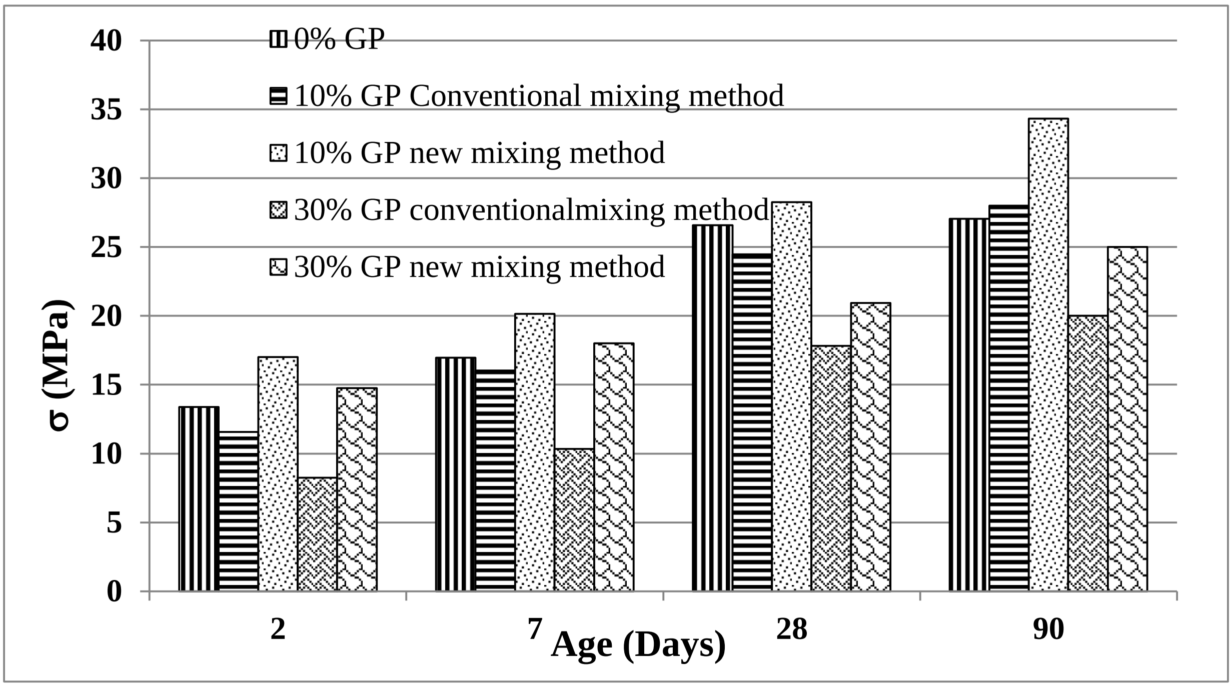


Figure (4.7): Compressive strength at 10 and 30% GP replacement with different mixing methods.

Figure 4.8 shows the normalized compressive strength (relative to the control mix) of concrete following the new mixing method as a function of age and GP replacement. The results showed that both the 10% and 30% GP mixes, using new mixing method, resulted in the highest compressive strength compared to the conventional mixing method at early ages (2 and 7 days)., which the 10% GP showed the highest compressive strength.

It is noted that the 30% GP mix prepared by new mixing has a higher compressive strength than the conventional mixing method at early ages (2 and 7 days). However, the decrease in the compressive strength at 30% GP, using the new mixing, can be attributed to the presence of more free water compared to the 10% GP and the limited percentage of dissolved free ions as the GP/w ratio increases. In order to verify the results, mixing the same concrete with higher w/c ratios should be conducted in future research work.

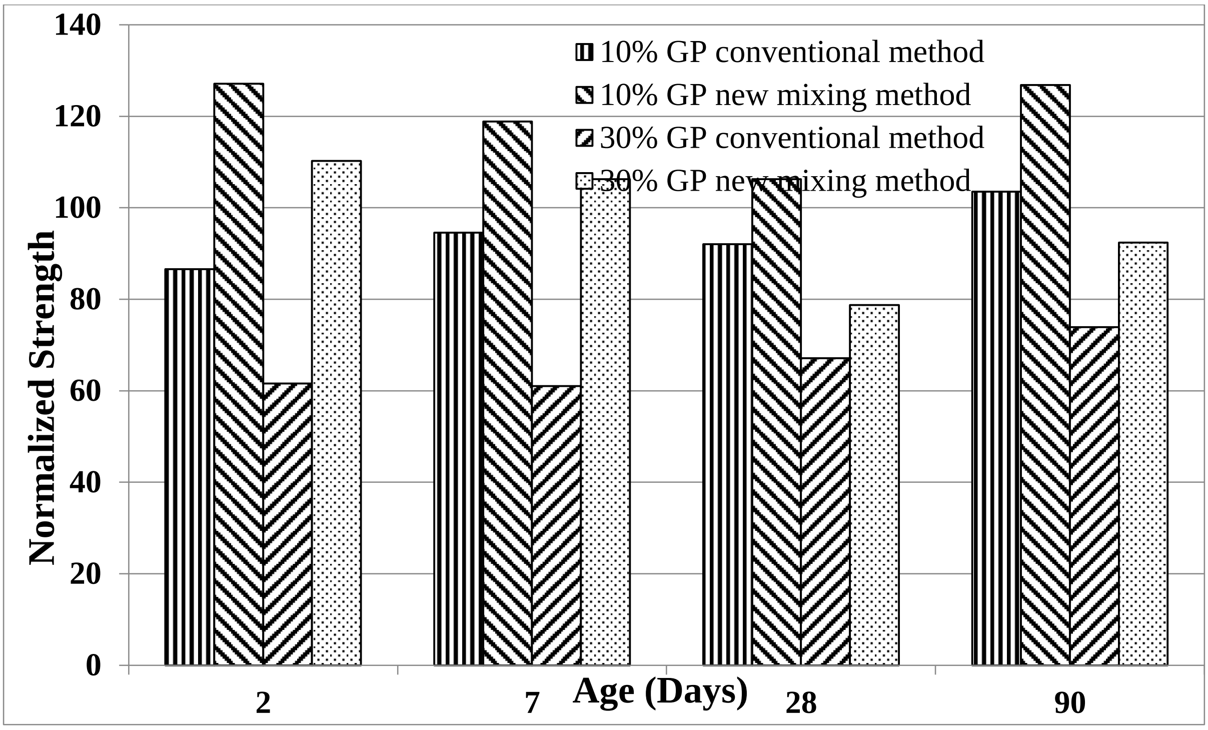


Figure (4.8): Normalized compressive strength of concrete using the new mixing method as a function of age and GP replacement.

In order to understand the effect of the new mixing method on the compressive strength, figure 4.9 shows the normalized compressive strength of 10% GP mix using the new mixing method and the conventional mixing method as a function of age. The curves show an increase in the compressive strength due to the new mixing method in comparison to the conventional mixing method.

At an early age, 2 days, the new mixing method showed higher compressive strength than the control mix (27%) and the conventional mixing method (40.5%). This increase is attributed to the effect of the immersion of the GP particle in the water before mixing with the concrete. That procedure can lead to the formation of free ions of SiO2 and CaO in the water before mixing with cement in order to form more hydrate products, especially the formation of CSH at an early age. Then, the curves show a decrease at 7 days' time in the difference between the new mixing method and both of the conventional and the control ones, which can be the result of the participation of all free ions in the reaction.

The lowest difference was observed at 28 days' age, and that supposes that the increase of the compressive strength at this age is emerging mainly from the hydration of cement.

Later at 90 days' time, the GP particles which are not dissolved and present in the structure will participate on the formation of the new CSH, therefore, increase of the compressive strength, which is confirmed by Shi and Zheng [26] & Elaqra and Rustom [6].

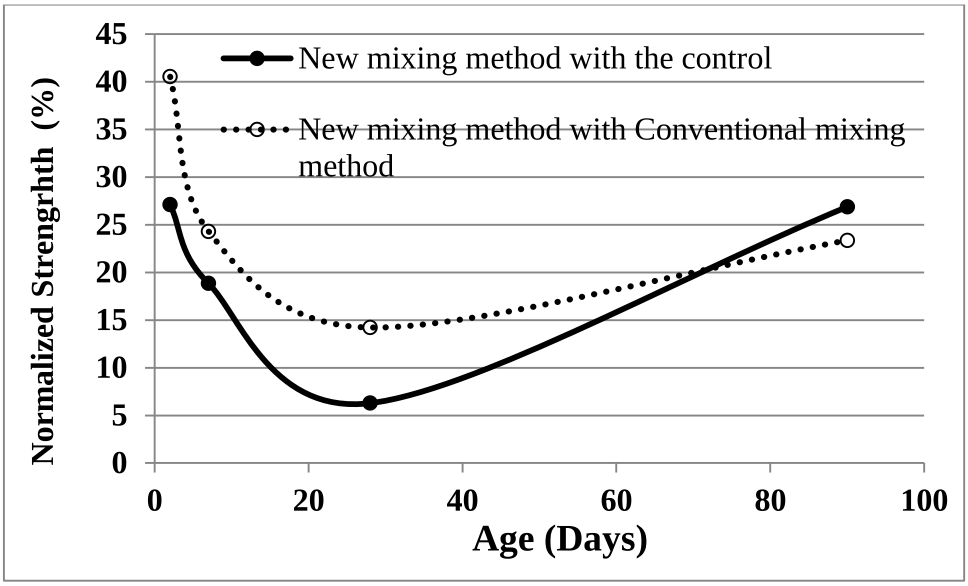


Figure (4.9): Normalized Compressive strength of 10% GP mix using the new and conventional mixing methods.

Figure 4.10 shows the normalized compressive strength of 30% GP mix with new mixing method and the conventional mixing method as a function of age. The same result was obtained for 30% GP mix using the new mixing method at 10% GP.

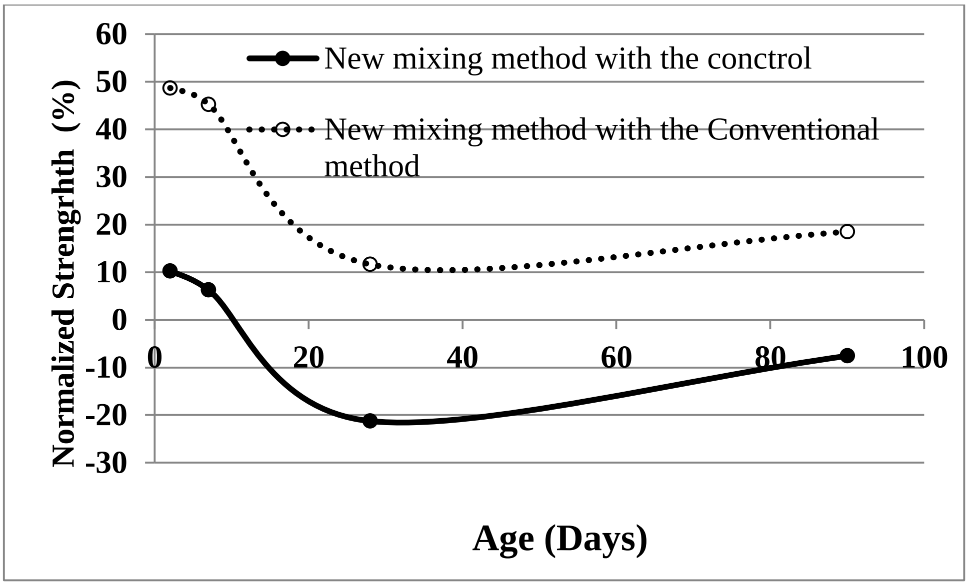


Figure (4.10): Compressive strength of 30% GP mix using the new and conventional mixing methods.

C. Relative Index Calculation

Figure 4.11 illustrates the relative index for GP mixes using the conventional mixing method as a function of age. Both the 10% and 20% GP mixes indicate higher values at 7 days followed by decreasing rates at 28 days, and then rising rates at 90 days. This behavior indicates higher reactivity at 7 days which can come due to the participation of free glass powder's ions in the formation of denser CSH. Later at 90 days, the reactivity became higher due to the participation of ions present in the pore solution, where the pozzolanic reaction of glass powder increases the concentration of Na2O and SiO2 and decreases the CaO concentration. The dissolved Si_2O ions produce CSH, which develops a rim around the glass powder particles [54].

The 30% GP mix indicates the lowest value after 7 days' time, which then increased to reach the same level as the 10% GP mix. This can be attributed to the dissolution of the glass powder and the formation of more CSH.

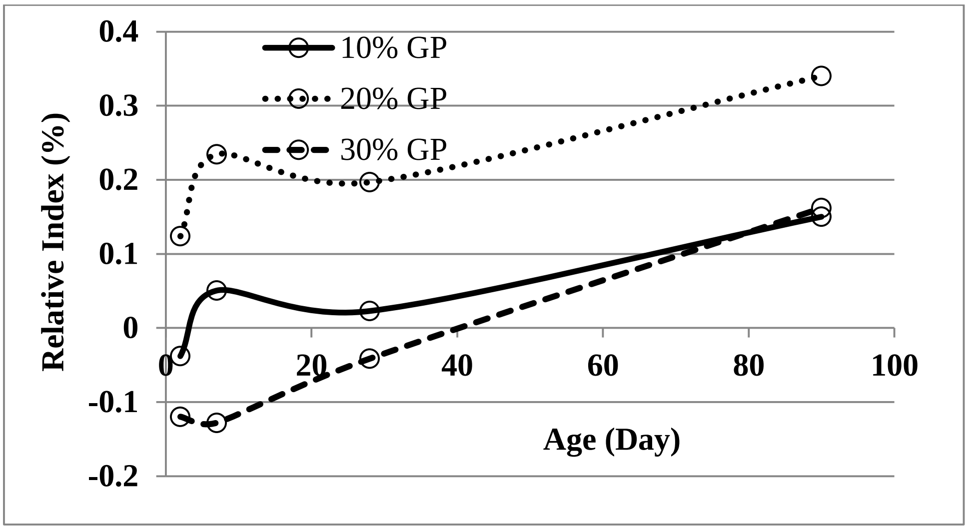


Figure (4.11): Relative index as a function of GP replacement and age.

Figure 4.12 shows the relative index of GP mixes which was prepared using the new mixing method as a function of age. The 30% GP mix indicates higher relative index than the 10% GP mix. At an early age, both mixes showed a higher value than that at a later age. It is suggested that the immersion of GP in water can lead to the creation of free ions of SiO2, Na2O, and CaO in water before mixing with cement, so the free ions will be ready to react with cement and form more CSH.

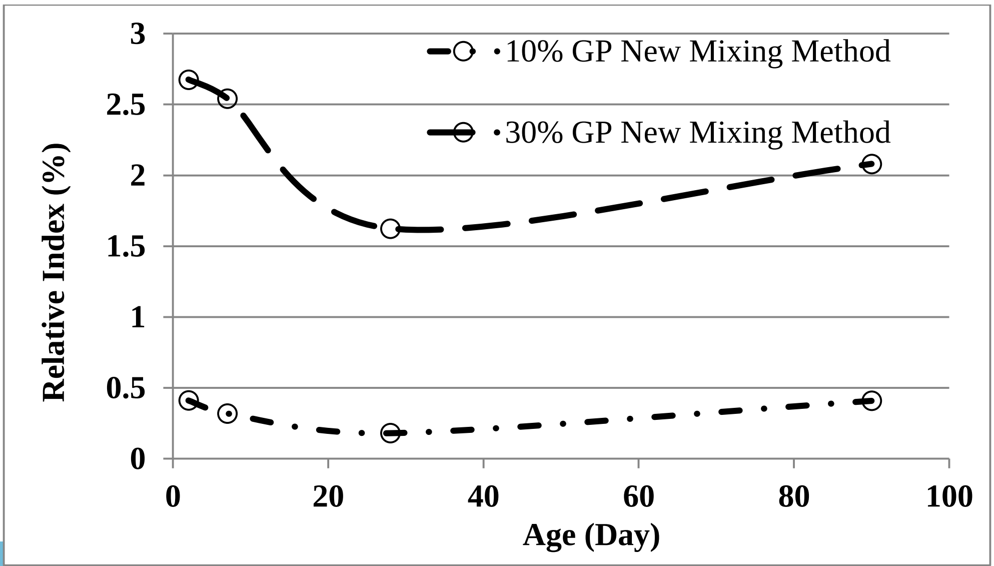


Figure (4.12): Relative index as a function of GP replacement of new mixing method and age.

4.3.5 Flexural Strength Tests:

Figure 4.13 shows the flexural strength as a function of GP replacement at the age of 28 days. The results showed that as the amount of GP increases, the flexure strength decreases. The 10% GP mix indicates a flexure strength that was similar to that of the control mix. but the lowest flexure strength was obtained at 30% GP. This is in agreement with the conclusion of Vandhiyan et al. [25]. The flexure strength indicates the presence of porosity sizes in the structure, thus the 10% mix has a finer pore size than the control.

The flexure strength of concrete made with new mixing method reveals an increase up to 5.5 MPa, which represents about 20% of the flexure strength of the 10% GP mix prepared with conventional mixing method. The increase in the flexure strength can be correlated to the increase of the binding of the interfacial transition zone between the cement paste and the aggregates and the refinement of the porosity.

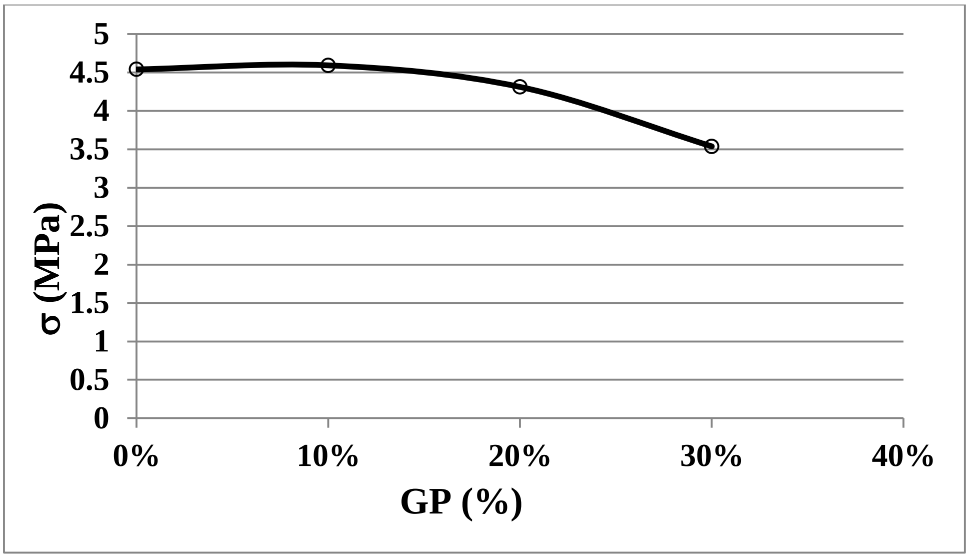


Figure (4.13): Flexure strength as a function of GP replacement at 28 days.

Table (4.6): Flexural strength of concrete with several waste glass powder contents using conventional method.

	Flexural test (MPa)	
GP percentage	**Failure load (KN)**	**28 – Days Flexure strength (MPa)**
0%	6.73	4.50
10%	6.80	4.60
20%	6.39	4.30
30%	5.24	3.50

Relative Index Calculation:

Figure 4.14 shows the relative index for flexure's strength as a function of GP replacement of mixes at 28 days' age. The 20% GP mix indicates the highest value of a relative index which proves that the 20% GP replacement has the highest reactivity for glass powder.

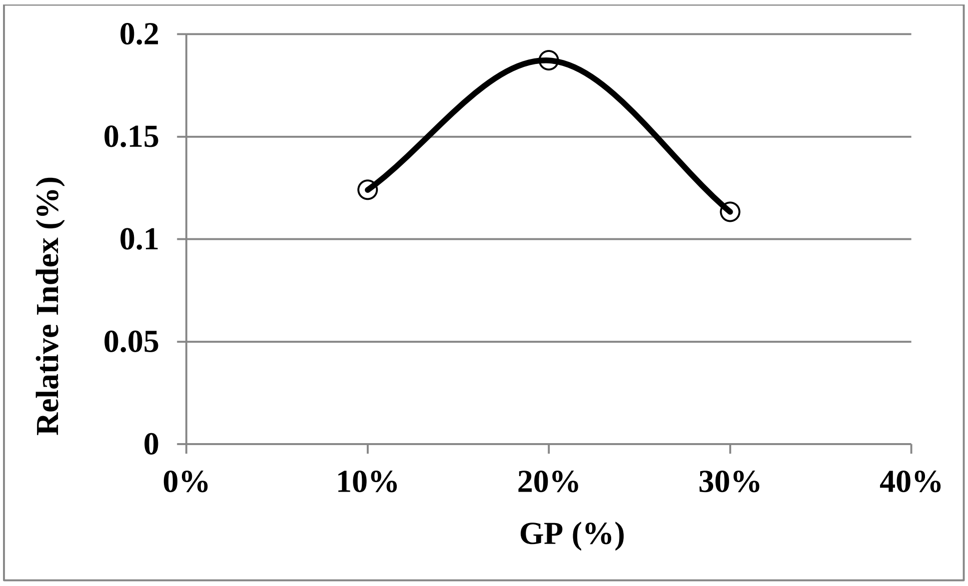


Figure (4.14): Relative index for flexure strength as a function of GP replacement at 28 days.

4.3.6 Water absorption:

A. Water absorption of concrete prepared with the conventional method:

Figure 4.15 represents the effect of GP replacement cement on water absorption of the concrete mixes at different ages. The results showed a decrease of the absorption as a function of age and GP replacement. The decrease of water absorption agrees with the conclusions of Malik, et al. [55]. The inadequate water absorption of the glass powder surface influences the total absorption of mixes prepared with GP. The decrease of the absorption is in correlation with the increase of the density of mixes as a function of age, see Figure 4.3 & Figure 4.5. The absorption is directly related to the progress of the hydration process as a function of age, therefore, a decrease of the porosity of the samples.

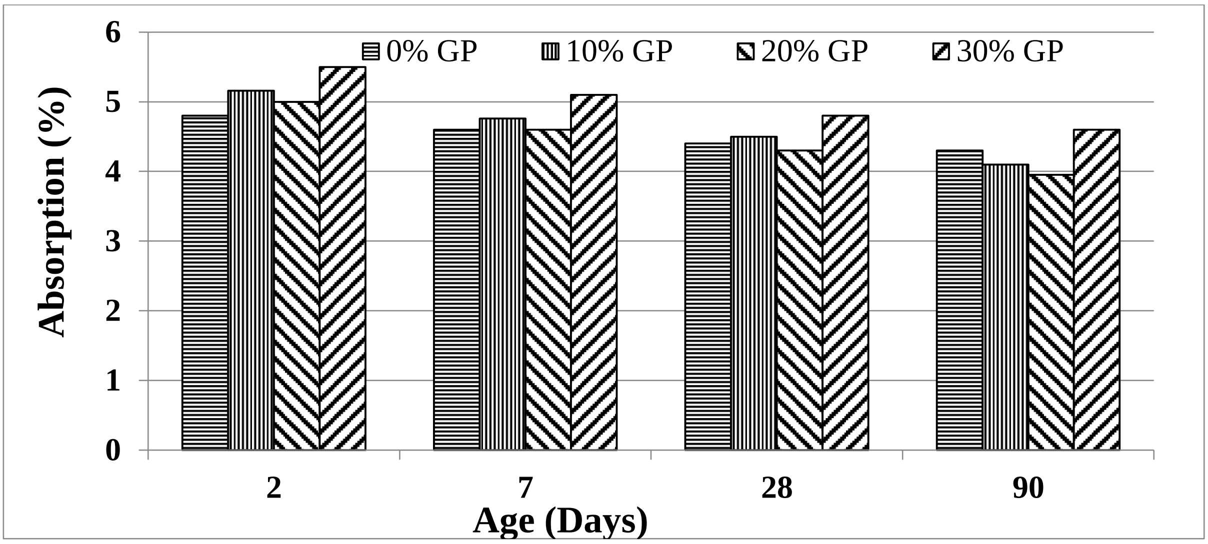


Figure (4.15): Absorption of concrete as a function of GP replacement and age.

Table (4.7): Water absorption of concrete with several waste glass powder contents using the conventional method and new mixing method.

Type of mixing	GP Group	Absorption 23°C		
		2 days	7 days	28 days
Conventional Mixing	0%	6.7	5.1	4.6
	10%	5.16	4.8	4.3
	20%	4.98	4.5	3.9
	30%	4.4	4	3.6

New Mixing method	10% new mixing	4.3	3.9	3.4
	30% new mixing	4.1	3.7	3.1

B. Water absorption of concrete prepared with new mixing method:

Figure 4.16 represents the effect of the new mixing method on the water absorption of concrete for the 10% and 30% GP mixes. The results showed a significant decrease relevant to the absorption of mixes prepared by the new mixing method in regard to the conventional mixing method. The 10% GP of the new mixing method shows a decrease in the absorption of the 10% GP of the conventional mixing method, a similar result was obtained for the 30% GP mix prepared by new mixing method. The decrease of the absorption is in correlation with the increase of the density of mixes prepared by the new mixing method and the refinement of the pore structure as mention by Du [68].

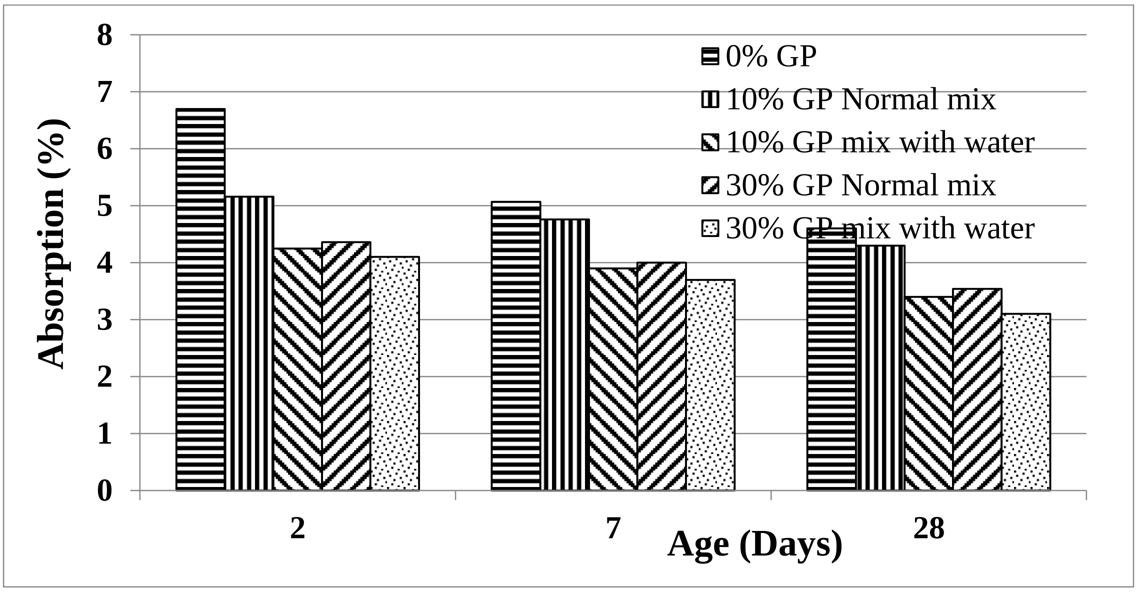


Figure (4.16): Absorption of concrete as a function of age and mix methods.

The density and the absorption results support the trend observed in the compressive strength results for the mixes prepared by the new mixing method. The mixes with higher density lead to form fewer porosities and as a result less water absorption and higher compressive strength. These results are originated from the participation of the glass powder free ions in the formation of denser CSH than CH due to the pozzolanic reactivity of the glass powder.

4.4 Effect of Curing Temperature on physical and mechanical properties of concrete mixes:

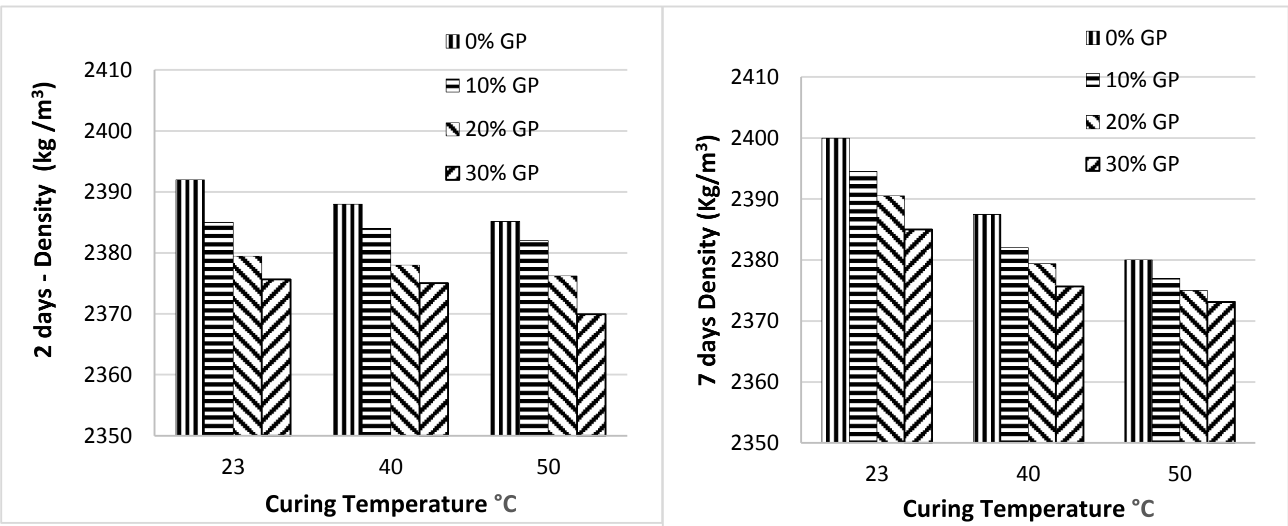
The following section presents the final output results which address the effect of different curing temperature 23°C, 40°C and 50°C on the physical and mechanical properties of concrete containing different admixtures of GP as partial cement replacement.

The experimental results have discussed the effect of curing temperature on fresh properties of concrete such as densities, water absorption, As well, hardened concrete such as compressive strength. The results were obtained for concrete prepared by the conventional mixing method and the new mixing method.

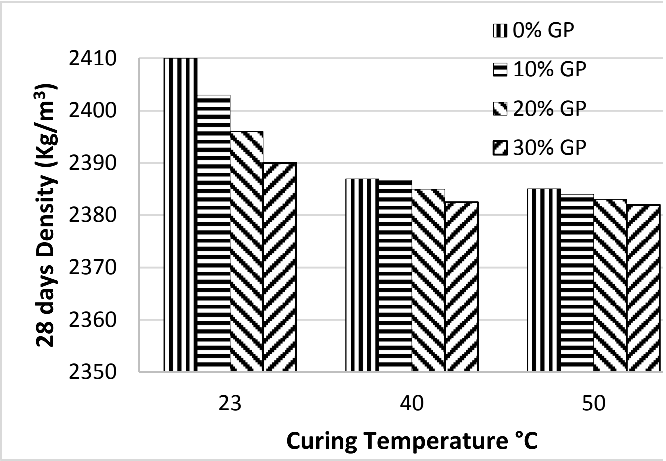
4.4.1 Density:

A. The density of concrete made with the conventional mixing method:

Figure 4.17 shows the density of concrete mixes as a function of GP replacement, age and curing temperature. The results showed three trends, as the age of samples increases the density increases, which result from the formation of more hydrate thus denser structure. The effect of GP content is the second trend; the density decreases with the increase of GP content at 2 and 7 days (Figure 6a and 6b). Later at 28 days, the density of control mix and GP replacement are similar at elevated temperature (40°C and 50°C) see figure 6 c, where cement has to reach a high hydration degree, while at 23°C the mixes need more time to reach the same hydration degree. The effect of curing temperature represents the third trend, as the temperature increases the density decreases due to the decrease of the content of ettringite which leads to higher (capillary) porosity at 50°C [8].



(a) (b)



(c)

Figure (4.17): Density of concrete mix as a function of GP content and ages at: (a) 2 days, (b) 7 days, (c) 28 days.

4.4.2 Compressive strength test:

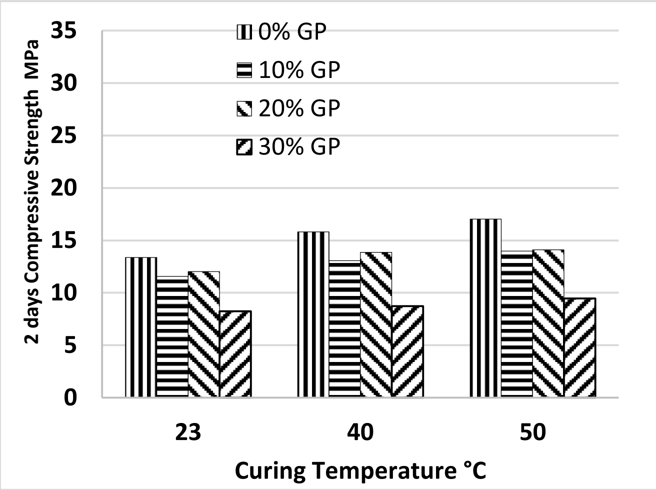
A. The compressive strength of concrete made with conventional mixing method:

Figure 4.18 shows the compressive strength as a function of GP replacement, curing temperature and the age of mixes prepared by the conventional mixing method.

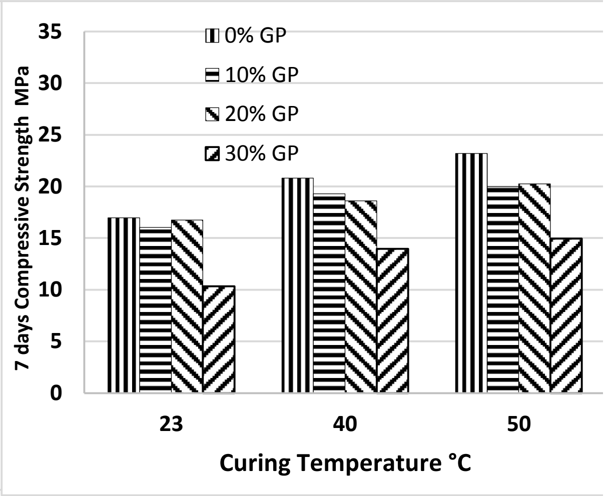
The lowest value was obtained for the mix with 30% GP at all ages and curing conditions which are an adequate relationship with the density, lower density gives lower compressive strength due to the presence of higher porosity.

The compressive strength behavior at an early age (2 and 7 days) is differing with later behavior at 28 days. All mixes show a higher compressive strength at elevated temperature (40°C and 50°C) than at 23°C at the same age. The 10% and 20% GP mixes showed the same compressive strength as the control mix while 20%GP mixes show higher compressive strength than 10% GP mix.

The behavior at 28 days showed higher compressive strength at 40°C (especially for 20% GP mix) than other curing temperature. The decrease of compressive strength at 50°C can be related to the decrease of the content of ettringite which leads to higher (capillary) porosity [8].



(a)



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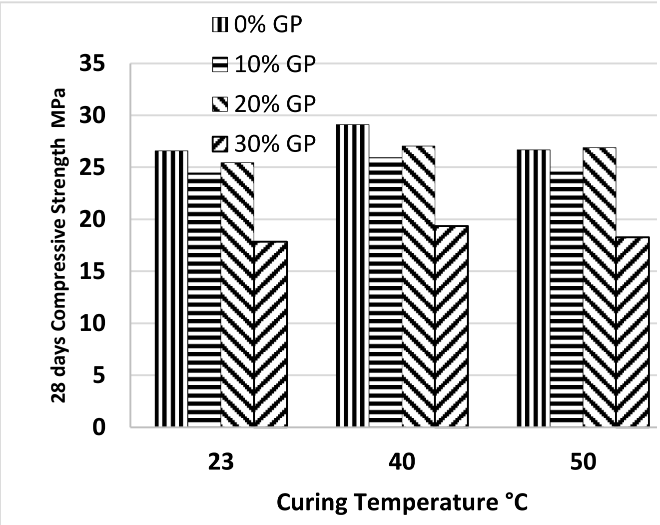


(c)

Figure (4.18): Compressive strength of concrete as a function of GP replacement, curing temperature and age of conventional mixing method at (a) 2 days, (b) 7 days, (c) 28 days.

B. The compressive strength of the new mixing method:

Compressive strength of concrete made with the new mixing method at 23°C was discussed in the part 1 which summarize as: At an early age (2 days) the new mixing method shows higher compressive strength than the control mix (27%) and the conventional mixing method (40.5%) as shown in figure 4.7. This increase is attributed to the effect of the immersion of the GP particle with water before mixing with the concrete, which increases the immersion of free ions of SiO_2 and CaO in the water before mixing with cement thus the free ions is ready to react with the cement. The dissolution of the GP particles leads to form more hydrate products, especially the formation of CSH at an early age. Then the curves show a decrease at 7 days in the difference between the new mixing method and both the conventional and the control which can be the result of the participation of all free ions in the reaction.

The lowest difference was observed at 28 days, it supposes that at this age the increase of the compressive strength is coming mainly from the hydration of cement.

Later at 90 days, the remaining GP particles that were not dissolved and present in the structure will participate on the formation of the new CSH thus increase of the compressive strength, which is confirmed by the work of Shi and Zheng [26]& Elaqra and Rustom [6].

Figure 4.19 shows the compressive strength as a function of age, type of mixing and GP replacement at 40°C. The result showed that 10% GP new mixing method showed the highest compressive strength at 2, 7 and 28 days. The increases are coming from the effect of the dissolution of the GP particle with water before mixing with the concrete, which increases the dissolution of free ions od SiO_2 and CaO in the water before mixing with the cement. The dissolution of the GP particle leads to form more hydrate products especially the formation of CSH.

The compressive strength at 28 days for 10% GP new mixing method showed an increase of 115% than the control mix at the same conditions and 130% than 10%% GP conventional mixing method. The compressive strength of mixes cured at 40°C is slightly higher than at 23°C.

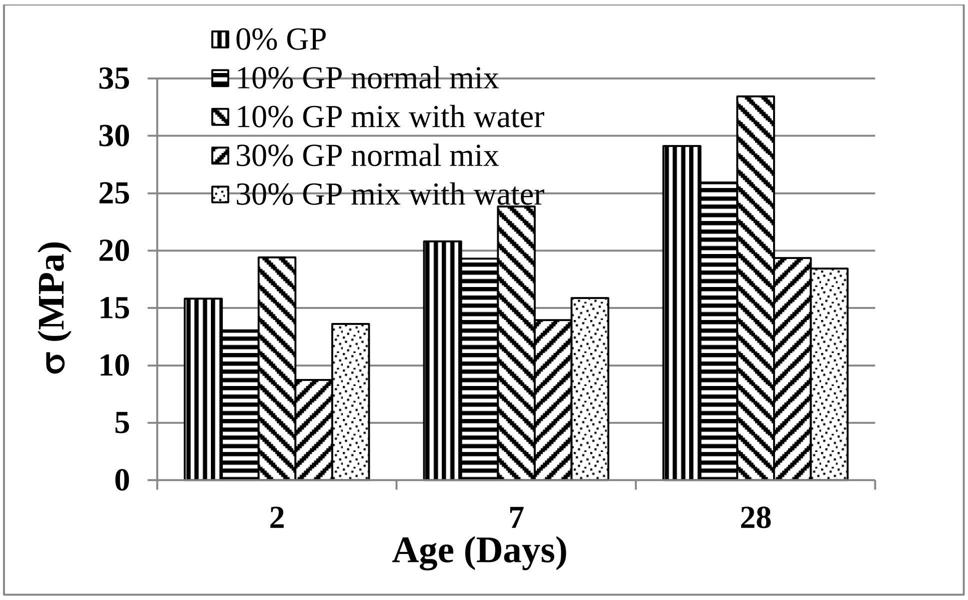


Figure (4.19): Compressive strength as a function of age and type of mixing at 40°C.

Figure 4.20 shows the difference in compressive strength between the new mixing method and the control and the conventional mixing method of 10% GP as a function of age. The highest difference was obtained for the new mixing method and the conventional mixing method, which come from the participation of free ions in the formation of hydrate products. The difference is higher at an early age (at 2 days) then it decreases as the age increases. Later at 28 days, the increase of the difference can be attributed to the later pozzolanic reaction between the rest of ions and glass powder with the cement.

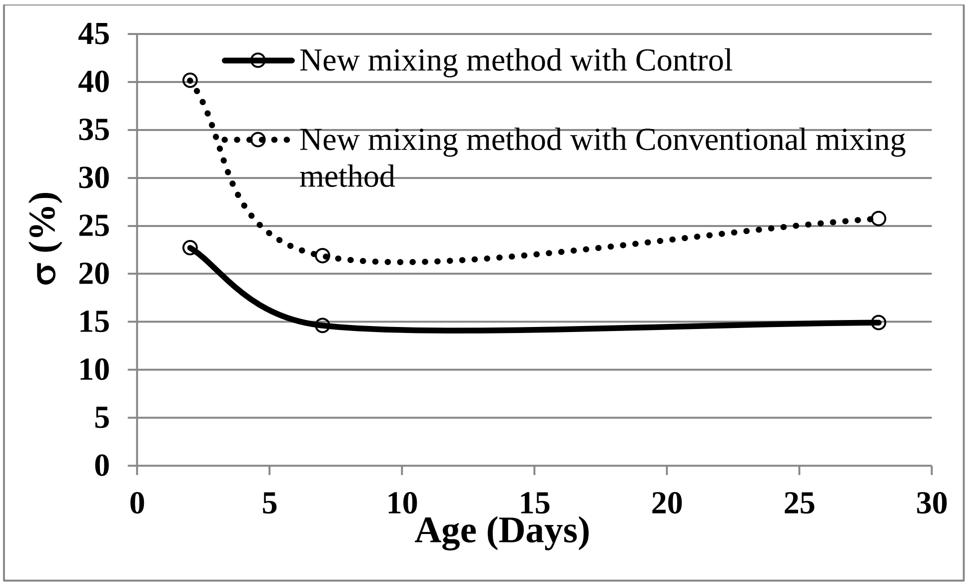


Figure (4.20): Normalized Compressive strength of 10% GP mix with new mixing method and conventional as a function of age at 40°C.

Figure 4.21 shows the normalized compressive strength as a function of the mixing method, GP replacement, and age at 50°C. The same behavior was observed as for mixes cured at 40°C, the highest compressive strength was obtained for 10% GP new mixing method. The compressive strength is lower at 50°C than at 40°C, which is related to the decrease of the content of ettringite at higher temperature lead to higher (capillary) porosity [8].

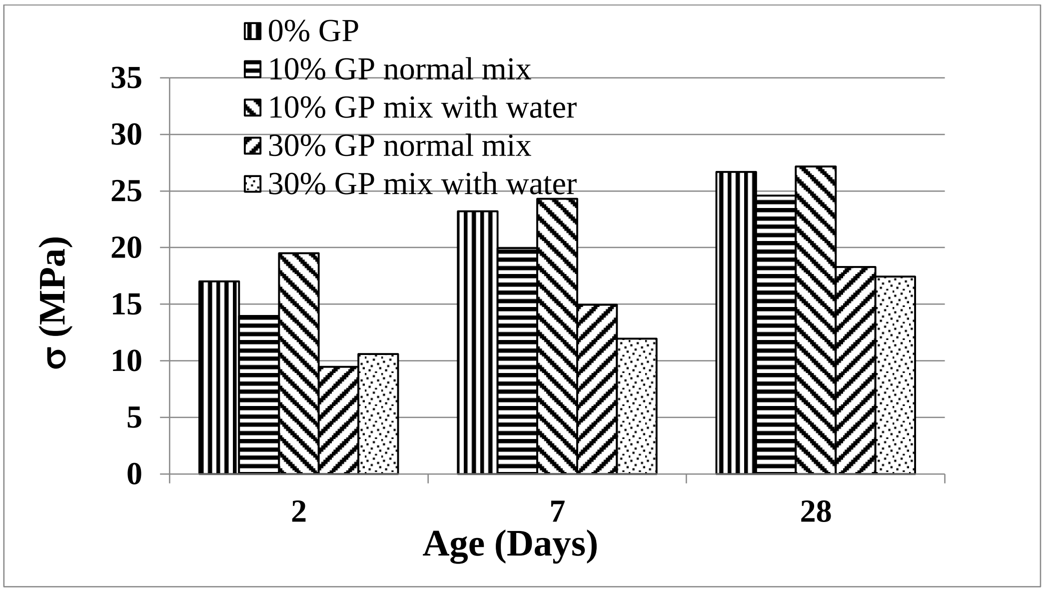


Figure (4.21): Compressive strength as a function of age and type of mixing at 50°C.

Figure 4.22 shows the compressive strength for control and 10% GP new mixing and conventional method as a function of age and curing temperature. Compressive strength at 2 and

7 days showed that both curing temperatures are higher than at 23°C; this is related to the acceleration of the hydration process. Curing mixes at 50°C showed higher compressive strength than 40°C. Later at 28 days, the highest compressive strength was obtained for mixes cured at 40°C, the 10% GP new mixing method showed the highest compressive strength (115%). Then the compressive strength decreases for mixes at 50°C is related to the formation of more porosity in the structure.

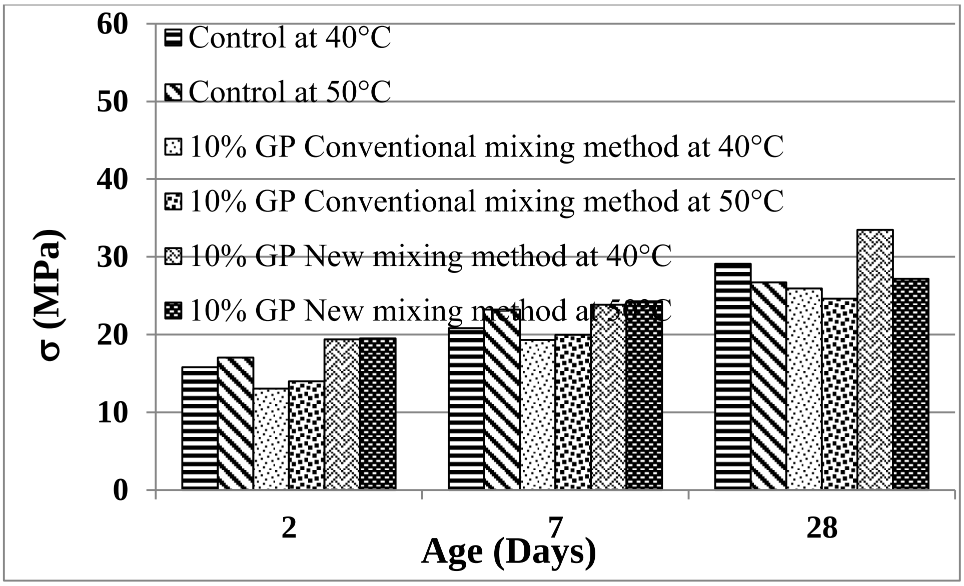
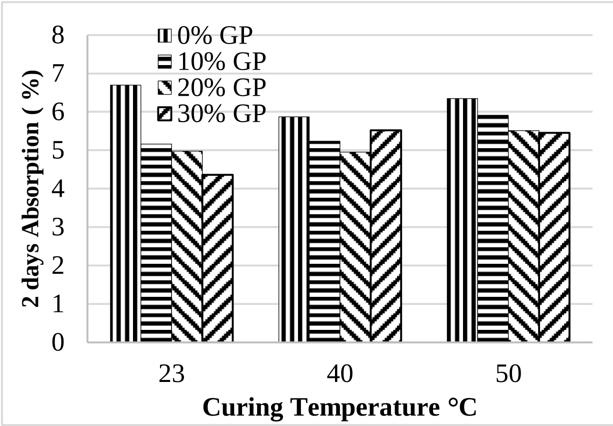


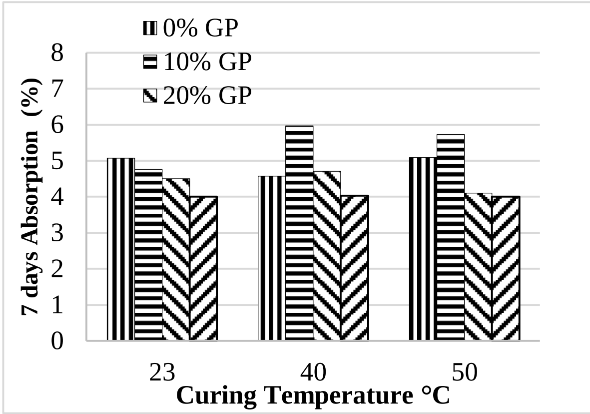
Figure (4.22): Compressive strength for control and 10% GP new mixing and conventional method as a function of age and curing temperature.

4.4.3. Absorption

Figure 4.23 represents the effect of GP replacement cement on the water absorption of concrete mix at 23°C, 40°C and 50°C respectively. The results showed a decrease of the absorption as a function of age and GP replacement. The decrease of the absorption is in correlation with the increase of the density of mixes as a function of age, see figure 6. The absorption is directly related to the progress of the hydration process as a function of age thus a decrease of the porosity of the samples.



(a)



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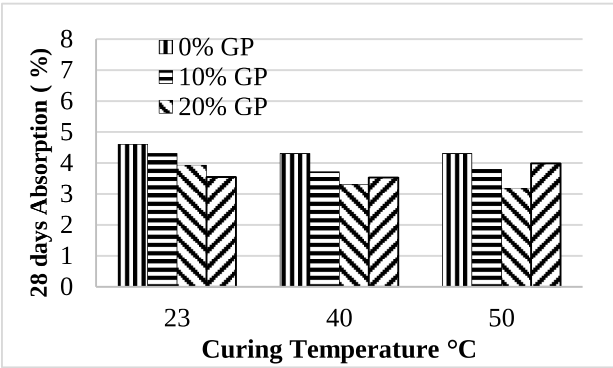


(c)

Figure (4.23): Absorption of concrete as a function of GP replacement and curing Temperature at (a) 3 days, (b) 7 days, (c) 28 days.

4.4.4 Effect of Curing Temperature cycles on concrete mixes containing GP

A. Cycle No 1

As illustrated in chapter 3, the cycle No. 1 of curing temperature composed of three groups of curing temperature, the first group of cubes were cast and cured under a temperature of 23 °C, as well, the second and third groups were cast and cured under temperature of 40 °C and 50 °C respectively, then testing compressive strength at each of the following test ages: 2, 7, 28 and 90 days.

The cycle No 1 of curing temperature was discussed as illustrated in the previous sections but, the comparative analysis between the three different cycles of curing temperature are presented hereafter in the following sections. In addition, each cycle as a function of curing temperature duration is presented as follow:

B. The cycle No 2

The cubes were cured under a temperature of 40 °C at each of the ages 2 and 7 days, and then they were removed to be cured under the temperature of 23 °C in order to be tested at 28 days compressive strength.

Figure 4.24 represents the effect of a curing temperature of 40 °C on the compressive strength of the concrete mix when cured at the following ages 2, 7 and 28 days respectively. The results showed an increase of compressive strength as a function of the duration of curing temperature, which the compressive strength of cubes cured for 28 days at 40 °C showed a higher than cubes cured for only 3 or 7 days at 40 °C then cured at 23 °C.

The increase of the compressive strength of cubes cured for 28 days at 40 °C is in correlation with the increase of the density of mixes as a function of age. The curing temperature is directly related to the progress of the hydration process as a function of age.

The lowest value was obtained for the mix with 30% GP at all ages and curing conditions which are an inadequate relationship with the density, lower density gives lower compressive strength due to the presence of higher porosity.

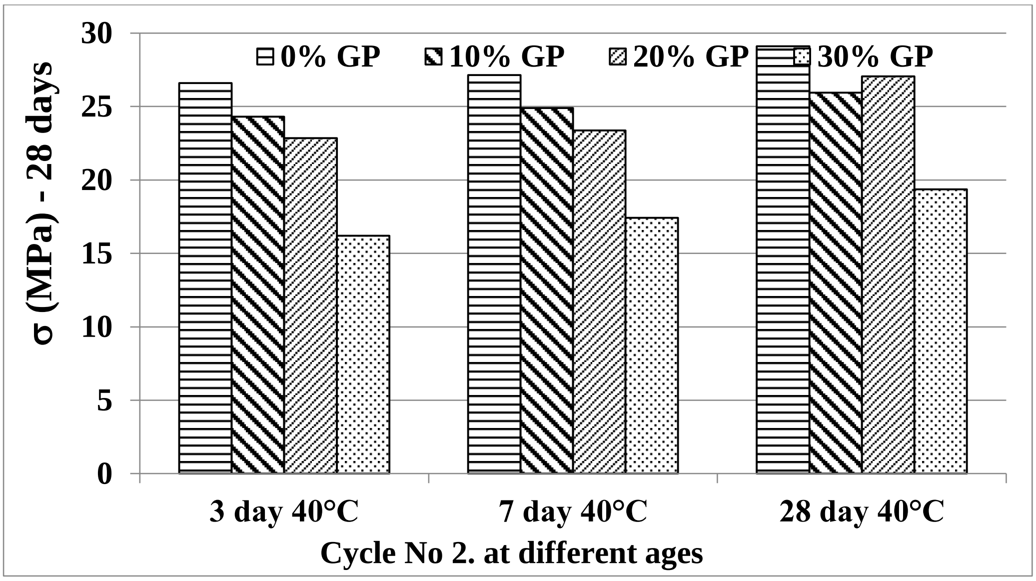


Figure (4.24): 28-day Compressive strength of concrete as a function of GP replacement for cycle No 2 of curing Temperature.

C. The cycle No 3

The cubes cured under a temperature of 50 °C at each of the ages 2 and 7 days, and then they will be removed to be cured under the temperature of 23 °C in order to be tested at 28 days compressive strength.

Figure 4.25 represents the effect of a curing temperature of 50 °C on the compressive strength of the concrete mix when cured at the following ages 2, 7 and 28 days respectively. The results showed that the compressive strength of cubes cured for 7 days at 50 °C showed a higher than cubes cured for 3 or 28 days at 50 °C. The increase of the compressive strength of cubes cured at 50 °C is in correlation with the increase of the density of mixes as a function of age. The curing temperature is directly related to the progress of the hydration process as a function of age.

After 28 days of curing at 50 °C, the results showed that the compressive strength of cubes cured for 28 days at 50 °C lower than the compressive strength of cubes cured for 7 days at 50°C (especially for 0 and 10% GP mix). The decrease of compressive strength can be related to the decrease in the content of ettringite, which leads to higher (capillary) porosity (7).

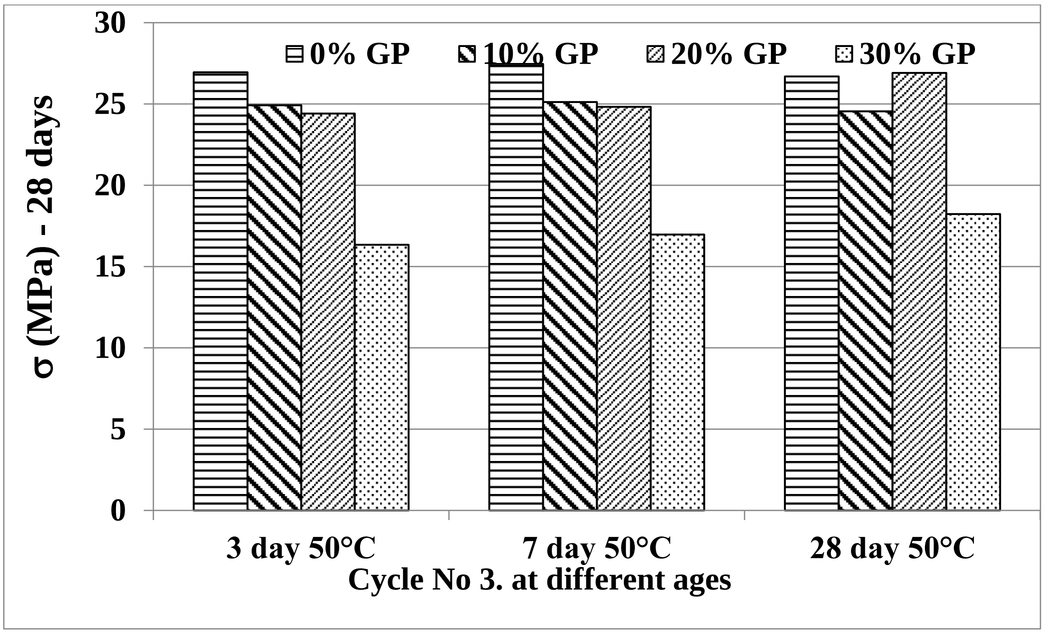
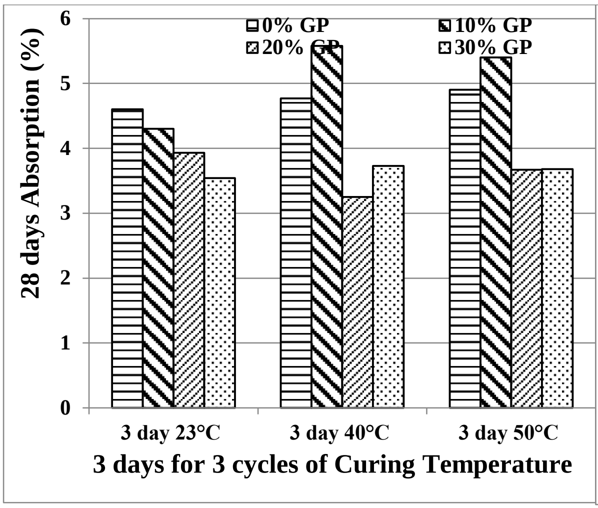
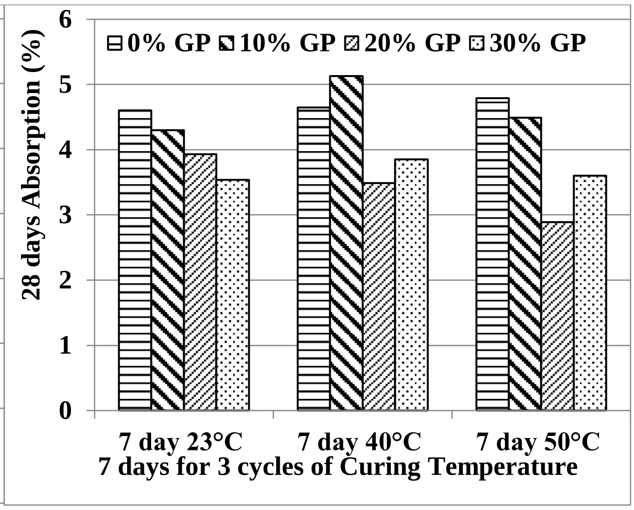


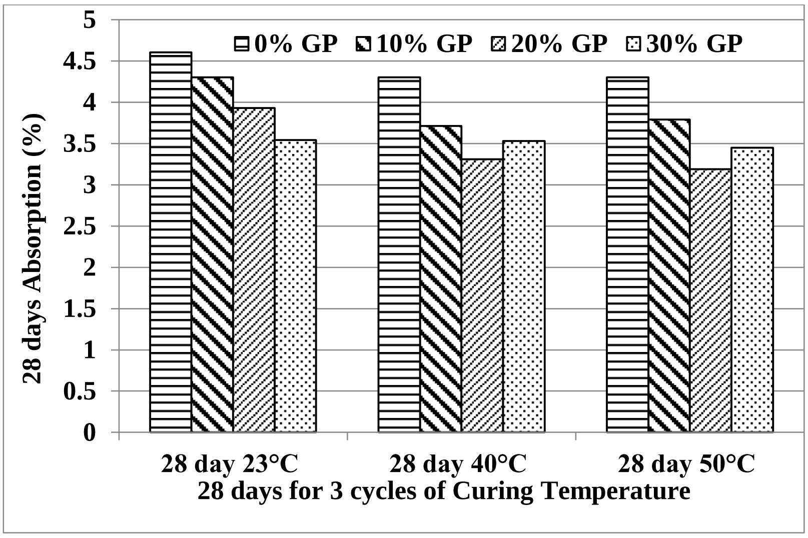
Figure (4.25): 28-day Compressive strength of concrete as a function of GP replacement for cycle No 3 of curing Temperature.

Figure 4.26 & Figure 4.27 represent 28 days absorption and mass densities of concrete for three different cycles of curing Temperature at the following ages 2, 7 and 28 days respectively.



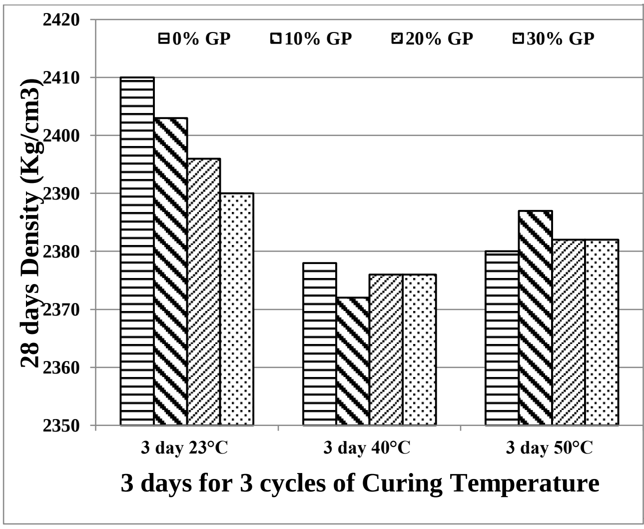


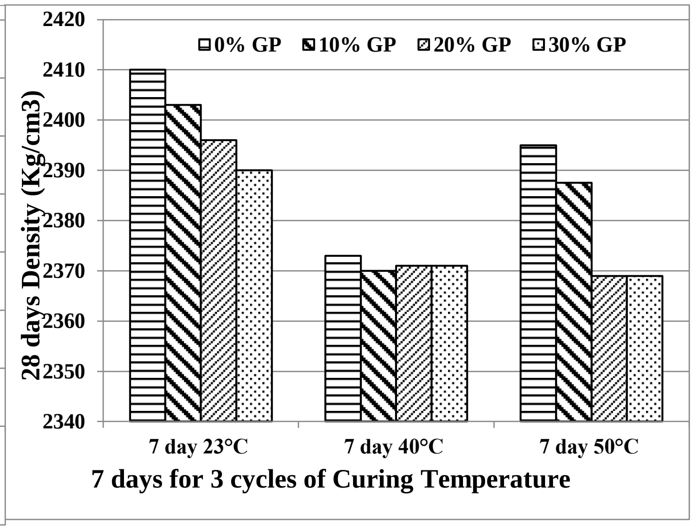
(a) **(b)**



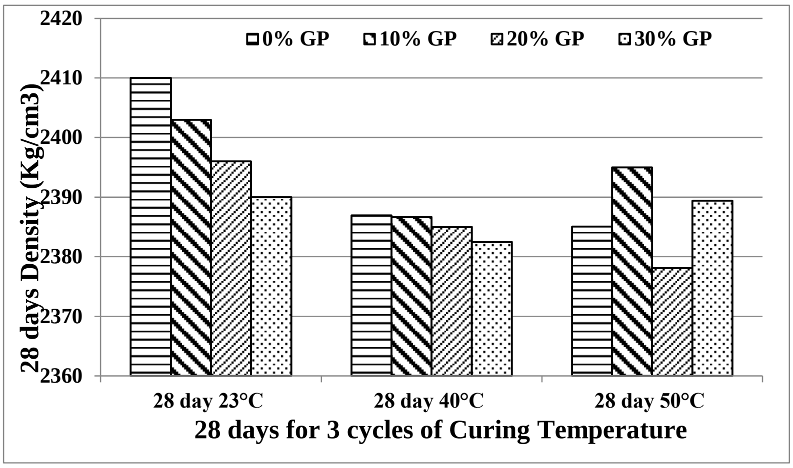
(c)

Figure (4.26): 28-day Absorption of concrete as a function of GP replacement and cycles of curing Temperature at (a) 3 days, (b) 7 days, (c) 28 days.





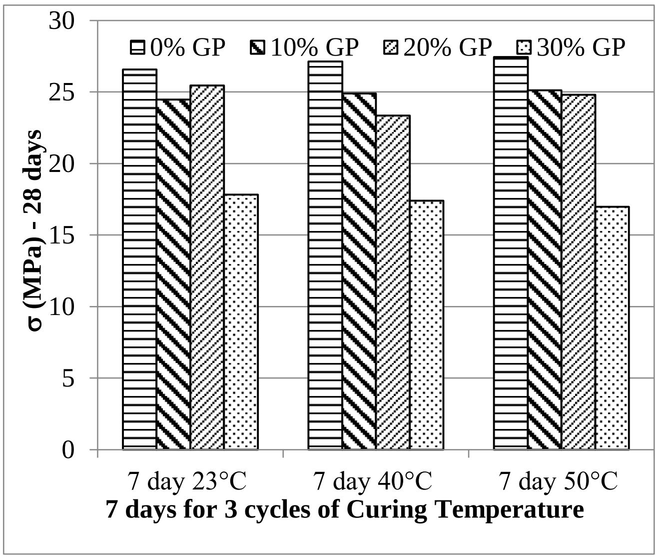
(a) (b)



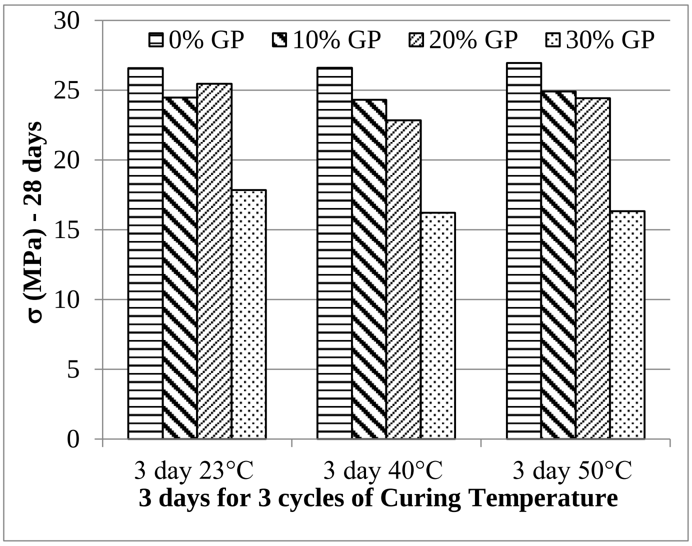
(c)

Figure (4.27): 28-day density of concrete as a function of GP replacement and cycles of curing Temperature at (a) 3 days, (b) 7 days, (c) 28 days.

Figure 4.28 represents 28 days Compressive strength of concrete as a function of GP replacement and cycles of curing Temperature at the following ages 2, 7 and 28 days respectively. The results showed a slight difference between the three cycles of cubes cured at different temperature for 3 or 7 days, but the compressive strength of cubes cured for 28 days at 40 °C higher than the compressive strength of cubes cured for 28 days at 23°C or 50°C.



(a)



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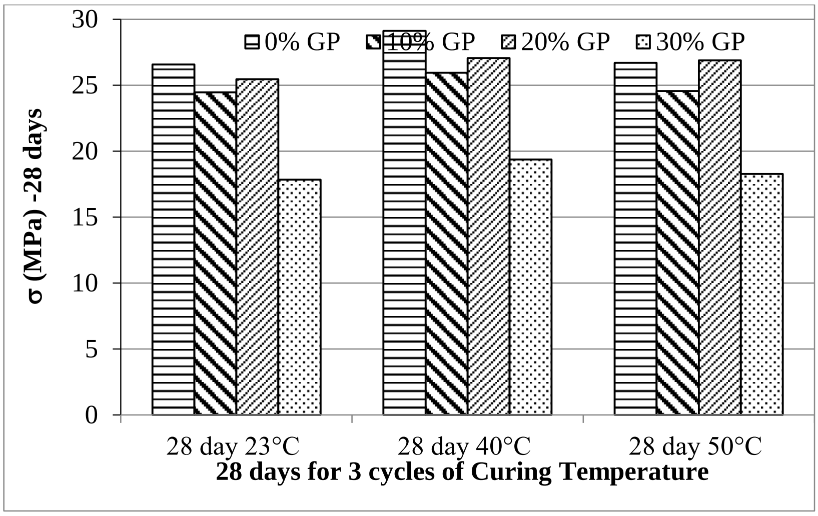

(c)

Figure (4.28): 28-day Compressive strength of concrete as a function of GP replacement and cycles of curing Temperature at (a) 3 days, (b) 7 days, (c) 28 days.

Chapter 5

Conclusions and Recommendations

Chapter 5

Conclusions and Recommendations

5.1 Summary

The primary objective of this research was to study the effect of waste glass content on the properties of concrete mixes when added as a partial replacement of cement. This objective was achieved through the following:

- Identify the effects of adding waste glass on concrete mixes such as workability by the slump test and porosity by water absorption test.
- Study the influence of the partial cement replacement by glass powder on hardened properties of concrete mixes such as density, compressive strength, and flexural strength.
- Determine the optimum glass powder content to be added as a partial replacement of cement.
- Study the effect of different curing temperature and method of mixing on the physical and mechanical properties of concrete containing glass powder.
- Study the effect of the new mixing method on the physical and mechanical properties of concrete.

These goals were reached by conducting a standard series of a slump, water absorption, mass density, compressive strength, and flexural strength tests. The output results obtained from this laboratory program showed reliable data points and promising further research horizons.

5.2 Conclusions

The following conclusions can be highlighted from the result of this research and can be illustrated as follows:

5.2.1 Effect of waste glass on properties of concrete

- As a general outcome, it was noticed that the increase of glass powder amount in concrete influences the fresh and hardened concrete properties. The workability increases as the amount of GP increases in the concrete while the density of the concrete decreases. This can be attributed to the increase in the amount of free water in the mix which comes from the decrease in the amount of cement in concrete and the need for less water to hydrate the cement. The mixes with a higher amount of GP showed low porosity and lower absorption rates.

- The conventional mixing method showed that the optimum of the compressive strength is found at 20% GP mix, the increase of the compressive strength is more significant later at 90 later. The progress of the pozzolanic reaction can be the origin of this increase rather than the packing filling effect
- The output results demonstrated that the new mixing method is a good approach to form denser hydrate products due to the pozzolanic reactivity of glass powder. However and in spite of the promising results, a comprehensive study is still needed to evaluate the behavior related to density and pore structure using MIP or SEM observations, in order to correlate the total porosity with the mechanical behavior.
- The high value of the compressive strength at 2 days prove that the dissolution of glass particles leads to form free ions which participate in the hydration process and the formation of the denser interfacial transition zone and finer porosity. This increase can demonstrate the participation of pozzolanic effect reaction and the packing filling effect on the densification of the interfacial transition zone, while later at 90 days it originates from the pozzolanic reaction.
- Although the design of concrete structures is based on the 28 days compressive strength, the effect of glass powder in concrete, as a cement replacement, shows higher compressive strength at 90 days and above. The 10% and 20% GP mixes showed higher compressive strength than the control mix at 90 days. The optimum percentage was obtained at 20% GP replacement. The 10% and 20% GP mixes showed almost the same values of flexure strength as the control mix. The new mixing method leads to higher flexure strength which comes from the pozzolanic reaction and the packing filling effect of the glass powder particles
- It was noticed that a significant increase in the compressive strength using the new mixing method was obtained. This can be attributed to the immersion of the GP particles in water before mixing. Some numerical analysis methods were employed to conclude that the 10% GP showed a significant increase, around 130% of the compressive strength of the control mix at an early age, 2 days, and at 90 days compared to the conventional mixing method. This increase indicates that the pozzolanic reaction, which takes place in the process of cement hydration, leads to the formation of more CSH than that in the control mix. An extensive study by XRD and SEM could confirm the results obtained. It is suggested that the presence of SiO_2 and CaO ions in water will increase the chance of forming CSH rather than CH at early and later ages. The use of the relative index represented a good method to evaluate the reactivity of glass powder.

- This research provides an interesting approach to introduce glass powder as a cement replacement in concrete, aiming to improve the pozzolanic activity. The Experimental results for the new mixing method regarding density, compressive strength and water absorption verified the feasibility of this approach.

5.2.2 Effect of Curing Temperature.

- It was concluded that the density of mixes showed a higher value for control than the GP mixes due to the presence of free water in the structure which leads to form more porosity after its departure. Curing at elevated temperature proved the early hydration process thus the compressive strength of mixes, the higher curing temperature (50°C) had a negative effect on the compressive strength due to the formation of more porosity in the structure which has been showed in the absorption of mixes cured at 50°C.
- The output results revealed that the new mixing method proved the compressive strength of mixes at an early age due to the participation of free ions in the formation of more CSH. Mixes cured at 50°C showed lower compressive strength than the mixes cured at 23°C and 40°C due to the formation of more pores in the structure.

5.3 Recommendations for Further Research

It is suggested for future works for extending this research to a wider perspective in order to be able to recognize more parameters and different combinations of parameters governing the effect on the behavior and engineering properties of fresh and hardened concrete containing different types and sizes of waste glass materials. This new research work is aiming to examine the results of this study, considering this phase as a threshold for exploring the facts in a more powerful and accurate manner.

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