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**EFFECT OF BLAST FURNACE SLAG AND PUMICE ON THE  
PROPERTIES OF CEMENT MORTARS**

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**BY  
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EFFECT OF BLAST FURNACE SLAG AND PUMICE ON THE PROPERTIES OF  
CEMENT MORTARS

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August 2022

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## **ABSTRACT**

### **EFFECT OF BLAST FURNACE SLAG AND PUMICE ON THE PROPERTIES OF CEMENT MORTARS**

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Master of Science in Civil Engineering

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In this study, the effect of ground granulated blast furnace slag (GGBFS) and pumice powder (PP) substitution on the properties of fresh and hardened mortar was investigated. 480 samples were prepared for ten different mixtures with GGBFS and PT substitutes, and two different cures (laboratory and temperature-humidity controlled room) were applied to the samples. The spreading properties of the mixtures were tested to determine the effect of GGBFS and PP on the fresh mortar properties. The physical properties such as unit volume, water absorption, porosity, and mechanical properties such as flexural and compressive strength of the hardened mortar samples, which were cured for 3, 7, 28, and 90 days, were investigated. It was observed that the P0C20 samples containing 50% GGBFS and 0% PP showed high spreading, and the substitution of GGBFS and PP decreased the physical property values compared to the reference sample. The specimens cured in a temperature-humidity controlled condition showed higher mechanical properties than the laboratory cured specimens. It was determined that the GGBFS and PP substitution had a negative effect on the early age strength, but the compressive and flexural strengths of the 90-day samples with 35% GGBFS replacement were increased.

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**Keywords:** Portland cement, Pumice, Slag, Compressive and flexural strength

## ÖZET

# YÜKSEK FIRIN CÜRUFU VE POMZANIN ÇİMENTO HARÇLARININ ÖZELLİKLERİNE ETKİSİ

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Bu çalışmada, öğütülmüş yüksek fırın cürufu (YFC) ve pomza tozu (PT) ikamesinin taze ve sertleşmiş harç özelliklerine etkisi araştırılmıştır. YFC ve PT ikameli on farklı karışım için 480 numune hazırlanmış, numunelere iki farklı kür (laboratuvar ve ısı-nem kontrollü oda) uygulanmıştır. YFC ve PT'nin taze harç özelliklerini üzerindeki etkisini belirlemek amacıyla karışımların yayılma özellikleri test edilmiştir. 3, 7, 28 ve 90 gün süreyle kür uygulanan sertleşmiş harç numunelerin birim hacim, su emme, gözeneklilik gibi fiziksel, eğilme, basınç gibi mekanik özellikleri incelenmiştir. %50 YFC ve %0 PT içeren P0C20 numunelerinin yüksek yayılma gösterdiği, YFC ve PT ikamesinin referans numuneye göre fiziksel özellik değerlerini düşürdüğü görülmüştür. Isı-nem kontrollü ortamda kürlen numuneler, laboratuvar kürü uygulanan numunelere göre daha yüksek mekanik özellikler göstermiştir. YFC ve PT ikamesinin erken yaş dayanımlarını olumsuz etkilediği, ancak %35 GYFC ikameli 90 günlük numunelerin basınç ve eğilme dayanımlarında artış belirlenmiştir.

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**Anahtar Kelimeler:** Portland çimentosu, Pomza, Yüksek fırın cürufu, Basınç ve eğilme dayanımı

## **PREFACE AND ACKNOWLEDGEMENTS**

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**Raghda Shihab Ahmed ALKHATEEB**

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## LIST OF SYMBOLS

|            |                                     |
|------------|-------------------------------------|
| A          | Cross section area                  |
| B          | Average width of sample at fracture |
| D          | Average depth of sample at fracture |
| L          | Span length                         |
| P          | Maximum applied load                |
| W1         | Saturated-surface dry sample weight |
| W2         | Immersion sample weight             |
| W3         | Oven-dried sample weight            |
| $\rho$     | Density of water                    |
| $\sigma_c$ | Compressive stress                  |

## LIST OF ABBREVIATIONS

|                 |                                      |
|-----------------|--------------------------------------|
| AEC             | Air-entraining cement                |
| B               | Binder                               |
| BFS             | Blast furnace slag                   |
| BFSC            | Blast furnace slag cement            |
| CC              | Colored cement                       |
| CO <sub>2</sub> | Carbon dioxide                       |
| DP              | Dolomite powder                      |
| FA              | Fly ash                              |
| GGBFS           | Ground granulated blast furnace slag |
| GM              | Glass microspheres                   |
| HAC             | High alumina cement                  |
| HPC             | Hydrophobic cement                   |
| HSC             | High strength concrete               |
| ITZ             | Interfacial transition zone          |
| LHC             | Low heat cement                      |
| LPWT            | Liquid paraffin wax treatment        |
| LS              | Lignosulphonate                      |
| OPC             | Ordinary portland cement             |
| PÇ              | Portland çimentosu                   |
| PC              | Portland cement                      |
| PCE             | Polycarboxylate                      |
| PNS             | Polynaphthanele sulfonate            |
| PP              | Pumice powder                        |
| PRM             | Paste replacement methodology        |
| PT              | Pomza tozu                           |
| PZC             | Pozzolanic cement                    |
| QSC             | Quick-setting cement                 |
| RHC             | Hardening cement                     |
| RPC             | Reactive powder concrete             |
| SAA             | Surface area per unit mass           |
| SCC             | Self compact concrete                |
| SCM             | Self compact mortar                  |
| SG              | Specific gravity                     |
| SMF             | Sulphonated melamine formaldehyde    |
| SNF             | Sulphonated naphthalene formaldehyde |
| SP              | Superplasticizer                     |
| SRC             | Sulfate-resistant cement             |
| UHPC            | Ultra high performance concrete      |
| W               | Water                                |

|     |                     |
|-----|---------------------|
| WC  | White cement        |
| WGP | Waste glass powder  |
| YFC | Yüksek fırın cürufu |



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## 1. INTRODUCTION

### 1.1 Background

Cement is the one of main construction materials in the world, increasing the building and construction industry throughout the world led to an increasing demand to consume more cement and concrete. A huge amount of energy between 30-70% of total energy in the world is consumed by industrial fields, while cement production processes take a large part of this consumption. Cement production required a hugely energy-intensive process in case to ensure the calcination that required high thermal energy (the furnace's temperature may be reached around 1500 °C (Ige *et al.* 2021, Kabay *et al.* 2021). Cement industrial processing involves about 50% of carbon dioxide emission (Hasanbeigi *et al.* 2012). This carbonation in the raw materials of Portland cement leads to the construction of a different concrete microstructure that effects on mechanical and durability properties of the resulting concrete. Furthermore, causing a decrease in the pH value of pore solution increases the corrosion and effects by lowering pore space because of the increase of  $\text{CaCO}_3$  value in front of the  $\text{Ca(OH)}_2$  compound (Andrade and Sanjuán 2021).

Researchers are presently searching for creative ways and solutions for cement productions issues because of a high rate of population, fast consumption of energy resources, and problems of getting rid of waste. When considering waste as one of the sources of raw materials, recycling the waste material has big support around the world and helps many countries to improve and develop using energy in an effective way (Cetin 2015, Ige *et al.* 2021). One way of reducing this effect and decreasing carbon pollution is by using mixed cement, which means Portland cement is replaced partially with cementitious materials, like fly ash, which is a waste of coal-fired plants, and granulated blast furnace slag, which is a waste of metals productions, and pumice powder, which is milled pumice rock (Kabay *et al.* 2021, Turner and Collins 2013).

Utilizing pozzolanic materials as alternative materials instead of clinkers such as (fly ash and silica fume), inert like (calcium carbonate filler), or latent hydraulic like (blast-furnace slag), those replacement materials help to decrease the clinker amounts in the

cement by about 50%. Some studies mention that portion of clinker replacement in all resulted cement is reached 25% around the world (Sousa and Bogas 2021).

Pumice is a rock volcanic in nature spread in many parts of the world. Pumice characterizes as a lightweight aggregate that is light, strong, and suitable to be utilized in lightweight concrete production. Pumice is a porous rock and due to its desired characteristics became one of the important alternatives to cement and aggregate materials in the civil industry field (Karthika *et al.* 2020).

According to ASTM C 125-16 the Blast Furnace Slag (BFS) is known as a non-metallic by-product, contains oxides like calcium alumina silicate and calcium silicate, appeared in a molten state with iron in a furnace, and is widely applied in the construction field. Steel slag is estimated to form (10-15)% of steel raw production. This could be an environmental threat as a result of its disposal in nature without curing. Currently, great efforts were given to resolve this issue. One of these solutions is to Ground slag into coarse and fine aggregate and reuse slag waste as supplementary cementitious materials in concrete and mortar production (Gencel *et al.* 2021, Kadhim *et al.* 2020).

In general, there are two ways taken to achieve cement contents replacement, first, if the particle sizes of the mixing replacement material are the same or close to the size of cement particle size, in this case, the cement replacement method is preferred, else the aggregate replacement is preferred. When inspecting and studying those two ways of replacement, clearly can be seen that the aggregate replacement way could be more competitive because this way does not affect compressing strength as the cement replacement way does (Kabay *et al.* 2021). Alternative materials are materials that completely or partially replace cement to enhance mortar or concrete properties or reduce the cost or environmental effect. For example, if 130 kg/m<sup>3</sup> of ground granulated blast furnace slag was used in a mixture, the amount of cement content will be reduced from 300 to 200 kg/m<sup>3</sup> (Claisse 2016).

## 1.2 Thesis Objectives

Cement is one of the most employed building materials in the whole world, production of cement is enlarging significantly because of the widening of infrastructure and civil industries (Chen *et al.* 2010). The most accompanying problems of cement production are environmental issues like huge energy consumption, CO<sub>2</sub> emissions, and greenhouse gases. In this issue, many serious attempts have been taken to prevent and decrease the negative effect. In this context, going to employ cement replacement taking advantage of pozzolanic materials as a partial alternative to cement in order to reduce using cement, as result reflecting positively on the environment (Safari *et al.* 2020). Whoever, in order to reduce cement consumption and improve mortar properties and produce self-compacting mortars, many researchers have investigated cement substitutes materials such as (fly ash, dust rust, recycled concrete, ceramic waste, silica fume, slag, pumice, etc.). As well as, they studied their environmental effect and the properties of final mortar and concrete and succeed to produce self-compacting mortar with interesting properties (Kabay *et al.* 2021, Lim *et al.* 2012, Raval *et al.* 2013, Zeyad *et al.* 2019).

In this context, the aims of this study could be briefly listed as the following;

- a) Aimed to investigate the effect of applying ground granulate blast furnace slag and pumice powders as a partial replacement for Portland cement in order to prepare self-compacting mortar, which reduce the use of cement in mortar production and that reflect on helping to reduces the environmental problems.
- b) Study the fresh properties of prepared (slag/pumice powder/Portland Cement) mortars.
- c) Study the mechanical properties of hardened slag and pumice mortars in comparison with reference mortar.
- d) Investigate the effect of two different curing regimes; in room temperature water and in a controlled room with fixed humidity and temperature.

### **1.3 Thesis Outline**

This thesis is constructed from five chapters. The sections and contents are illustrated briefly as follows:

Chapter 1: Chapter one consists of a general introduction and background of the work-study. General information about cement, mortar, concrete, cement alternative materials, as well as general background about materials used in this study like powder pumice and ground granulate blast furnace slag. In addition, illustrated the study objectives and thesis aims.

Chapter 2: Literature Review will be listed and illustrated. The previous studies and works that relate to the influences of applying alternative materials as a partial cement replacement on the fresh and hardened mortar properties, as well as, an overview of the mortar materials, curing regimes, and water to cement ratio.

Chapter 3: This chapter consists of full details of this experimental study. Full information about the used materials such as cement, PP, GGBFS, sand, and superplasticizer (SP). Additionally, illustrated the mixing procedure and mixture proportions, as well as, the adopted tests in this study.

Chapter 4: This chapter will be discussed the results obtained from adopted tests. in this part of the thesis, presented (data table of the flow test, obtained values of flexural and compressive strength test). In addition, illustrate the (water absorption, specific weight, porosity) tests results. Moreover, a full discussion of the investigation test results was illustrated.

Chapter 5: The conclusion of the obtained results will be summarized in this chapter.

## **2. LITERATURE REVIEW**

Many studies in the civil industry have adopted the development of mortar and concrete, and they succeeded to applied cement replacement materials in the early mixture and achieved impressive results in this field. In this chapter, recent works will be listed and a brief explanation of the material selection impact and methods and results will be given.

### **2.1 Affecting Impacts on Mortar Properties**

#### **2.1.1 Materials selection impacts**

Preparing mortar must satisfy the requirement of flowability and workability. Generally, the main mortar raw content is cement, aggregate, and water in addition to the admixtures. In this context, the properties of fresh and hardened mortar are affected directly by the selection, quality, and proportion of those materials. Choosing the proper materials for preparing mortars is the main key that rules producing mortar with the optimum performance (Kingsley 2003).

##### **2.1.1.1 Cement**

Cement is a powder matter made of clay and calcined lime as the main contents. Clay supported silica, iron oxide, and alumina while calcium oxide was provided by calcined lime. Turkey is one of the main producers of cement. Turkish construction companies have a 2% in the global of building and construction market. Chemical composition of cement collected from variant regions in turkey as an average value is shown in (Table 2.1) below. In Turkey, cement are fabricate and produced under the TS EN 197-1 standard, depending on this standard the major types of cement produced in Turkey are categorize as below (Cevik *et al.* 2011):

- Portland slag cement
- Portland silica fume cement
- Portland pozzolanic cement
- Portland fly ash cement
- Portland-limestone cement
- Blast furnace slag cement
- Pozzolanic cement
- Composite Cement

**Table 2.1** Chemical composition of cement, collected from variant regions in Turkey (Cevik *et al.* 2011)

| Compound                       | Mean      | Compound                       | Mean       |
|--------------------------------|-----------|--------------------------------|------------|
| Na <sub>2</sub> O              | 1.23%     | TiO <sub>2</sub>               | 0.39 (ppm) |
| MgO                            | 1.70%     | V <sub>2</sub> O <sub>5</sub>  | 185 (ppm)  |
| Al <sub>2</sub> O <sub>3</sub> | 11.9%     | Fe <sub>2</sub> O <sub>3</sub> | 2.59%      |
| SiO <sub>2</sub>               | 35.1%     | NiO (ppm)                      | 63 (ppm)   |
| SO <sub>3</sub>                | 4.16%     | CuO                            | 39 (ppm)   |
| K <sub>2</sub> O               | 0.99%     | ZnO                            | 87 (ppm)   |
| CaO                            | 42.0%     | Rb                             | 36 (ppm)   |
| SrO                            | 785 (ppm) | ZrO <sub>3</sub>               | 124 (ppm)  |
| BaO                            | 789 (ppm) | La <sub>2</sub> O <sub>3</sub> | 58 (ppm)   |
| CeO <sub>2</sub>               | 90 (ppm)  | PbO                            | 26 (ppm)   |
| ETha                           | 10 (ppm)  | eUa                            | 4 (ppm)    |

The main object of cement is a binder in the first place, and its major function is to bind materials together, among all types of cement the PC is one of the most important and commonly used in the construction field types of cement. It is mixed with either sand or water to create mortar or with aggregate, sand, and water to make concrete. Due to the high level of energy consumption and environmental pollution during cement production, the demand to reduce using cement are increased throughout the whole world, which makes using alternative materials take priority in the civil industry field (Markos Makebo 2019).

### 2.1.1.2 Ground granulated blast furnace slag

Ground granulated blast furnace slag (GGBFS) is forming as a byproduct of raw iron making, emerges, and floats after heating of iron ore. After then, the hot melted slag passes either, through the granulation process by cooling it in a water jet with high pressure and then finely milling. In this case, amorphous slag will result and this type of slag shows good hydraulic properties and is suitable as a cement replacement (Claisse, 2016), or passes through a foaming process by which the slag is cooled in the air by mixing with water. In this case, a crystalline substance of slag will be formed, which is more favored to use as aggregate replacement in concrete productions (Ates *et al.* 2021, Khalid *et al.* 2019).

Slag powder has the same main PC constituents: lime, alumina, magnesia, and alumina, but may differ in concentrations. Due to these reasons, slag is interesting and more reliable for applying to concrete as a cement replacement (Khalid *et al.* 2019). In addition, the mortar and concrete, which contains slag powder, have high chemical aggression resistance. slag has the advantage of being its hydration is staying for a long time, slag mortar and slag concrete are Featuring being their age resistance higher than ordinary concrete that giving the advantage of manufacturing long-life concrete (Ates *et al.* 2021).

Depending on the replacement level, the direct replacement of cement with slag may reduce the short-term strength, but increase the long-term strength. The same strength of ordinary PC was obtained after 28 days when 50% of the cement was replaced by slag, but 60% of the 28 days strength was obtained after 7 days, conversely to 80-90% of ordinary PC. However, slag concrete is restricted by one condition, which is that must be cured well.

On the other hand, excellent durability will be obtained. slag is favored for sulphate resisting cement replacement except for very aggressive sulphate also it causes lowering the chloride transport because of lowering the diffusion and raising of chloride linking (Claisse 2016).

Many researchers have studied the influence of applying GGBFS as cement replacement in Mortars and concrete production. The strength, compressive stress, and porosity of GGBFS mortar and concrete were investigated. The observable feature of mortar and concrete containing GGBFS is the rate of hydration in comparison with ordinary mortars and concrete, therefore, they required a longer curing time.

Kenai *et al.* (2021) examines the ways to overcome the negative effect of applying slag in cement and mortars production on strengths development. Three different fineness of slag was ground and used. They studied the durability, compressive strength, water absorption, and autogenous shrinkage of prepared Self-Compacting Mortars (SCM) containing GGBFS. In this context prepared seven mixes, proportions of control mix fixed at 1:1.8:0.38 (cement:sand:water) and for other mixes the cement replaced partially with (15 and 30)% of different slag fineness of (350, 420, and 500) m<sup>2</sup>/kg, while the other constituents unchanged. The results showed plastic viscosity, yield stress, and durability of SCM were reduced with finer slag content. The results indicated also at early curing ages of slag mortars a reduction in compressive strength occurs. However, the long-term slag mortar shows higher compressive strength than the control mortar. Generally, with finer slag contents there is an increase in autogenous shrinking and a decrease in total shrinking of Mortar contain slag.

Atiyah *et al.* (2020) used blast furnace slag in nanoscale and studied the effect of applying Nano slag as an additive to the self-compacting mortar with portions of (1, 2, 3, 4, 5)% by weight. After (7, 28, and 90) days, the results showed the increases of density, tensile, flexural, and compressive strength as additives content increases, while the water absorption and porosity of prepared mortar decrease.

Lozano-Lunar *et al.* (2019), evaluated the durability of self-compacting mortar including two kinds of electric arc blast furnace slag that are classified as risky waste. The filler powder with variant volume content portions (25, 50, and 100)% was replaced. Their results relayed that up to 25% of furnace slag replacement was given interesting results. They demonstrated that electric arc furnace slag is suitable for application as a secondary raw material for cement replacement.

Nguyen *et al.* (2018), used dolomite powder (DP) to produce self-compacting concrete (SCC) having 50% cement and 50% of GGBFS, low calcium coal fly ash (FA) and explored the enhancement of engineering performance of resulted (SCC). Results recorded that there are no effective effects for GGBF/OPC pastes setting properties when partially replaced GGBF with DP, in contrast to the FA/OPC and FA/GGBF/OPC that shows impressive enhancement. In addition, they produced self-compacting mortar containing partially DP-replaced pozzolanic materials. Compressive strength and flowability of the produced SCMs show significant enhancement at 30% DP content, and results recorded optimum compressive strength after 7 days.

Liu & Wang (2017), studied the influence of applying GGBFS and steel slag with ratios 1:1 and 3:2 of GGBFS/steel slag. The use of mixed binder in a large concrete structure under sulfate attack is investigated by evaluating the increase in the adiabatic temperature, hydration heat, elastic modulus, compressive strength, sulfate attack resistance, and chloride ion permeability. Their results show the mixed binder hydration heat decreases observably of cement replacement 50% portion at 45 °C, the adiabatic temperature of concrete contain (GGBFS/steel slag) add mixture decreases observable, the results record that elastic modulus decrease with using add mixture, while long-aged compressive strength record satisfactory results. However, the used admixture increases the concrete resistance against sulfate attack and chloride ion permeability.

Zhao *et al.* (2015) prepared Self Compacting Concrete (SCC) containing GGBFS and FA of (20, 30, and 40)% and investigated the fresh mechanical, porosity, and durability properties of SCC. Their results showed that initial slump flow increased with the presence of FA and GGBFS but reduced the wet density and slump flow rate of SCC, while prolonged mortar-setting times. Also applying FA and GGBFS as cement replacements lowered SCC mechanical properties and increased porosity in the short term. Although the GGBFS-FA SCC showed higher carbonation depth than the reference SCC, the GGB, FA SCC has more effective against chloride ion migration and drying shrinking.

Lim *et al.* (2012) investigated the effects of applying GGBFS on fresh and hardened mortar properties. They suggested a maximum limit of GGBFS content be at 50% to make the optimum improvement in long-term compressive strength. Their results also indicated that the prepared mortar workability and final bleeding value decrease with the increase of GGBFS content.

### **2.1.1.3 Pumice**

Pumice is a porous light siliceous volcanic rock resulting from volcanic explosives. It is found in many places around the world, especially near volcanoes, about a quarter of world pumice mining is extracted from turkey reached to 4 million metric tons yearly, giving the opportunity to use this material in various construction activities (Kockal & Camurlu 2020). Pumice structure contains a large number of voids that give a sponge-like shape. Has a low density of about  $(0.35-0.65) \text{ g/cm}^3$  and high water holding capacity (20-30)% and its main contents are  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  (Kong *et al.* 2021). Relying on its  $\text{SiO}_2$  and  $\text{CaO/MgO}$  contents, Pumice shows acidic or basic behavior. Basaltic pumice, also known as scoria, has a dark appearance and has a higher specific weight than acidic pumice  $(1.2-2) \text{ g/cm}^3$ . On the other hand, the most familiar type is acidic pumice, which featured silisium, potassium, and sodium contents, and has a white to gray-white color (Degirmenci and Yilmaz, 2011).

Pumice is interesting as a cement replacement material due to its pozzolanic properties and uses in concrete production either as a powder or as an aggregate form (Mehrabi *et al.* 2021). Pumice aggregate is helping to produce lightweight concrete. Structures with pumice concrete are 2-3 times lighter than ordinary concrete with observable thermal and sound insulation, and the pozzolanic compositions of pumice enhance the durability and strength of pumice mortar and concrete, also its porous structure causing of raise the freezing and decreasing the thawing of mortar and concrete (Ulus *et al.* 2016).

Many researchers mention that using pumice powder as cement replacement met with criteria of light concrete, and reported that using pumice aggregate reached 100%. However low compressive strength and elastic modulus were obtained in contrast to

ordinary concrete but higher permeability and initial surface absorption were remarked (Anwar Hossain 2004).

Rahman *et al.* (2022) evaluated the durability and mechanical properties, as well as the microstructure of mortar containing high contents up to 40% of cement replacement pumice. The evaluating test results after 90 days of curing indicate that the mortar samples containing 20% pumice had 9.8% higher compressive stress and 36% lower porosity in comparison to control mortar samples. Results also showed that utilizing pumice increases acid attack resistance obviously. Additionally, Microstructure analysis confirmed the pumice pozzolanic reactivity that was reflected in the enhancement of durability and mechanical performance of pumice mortars.

Kabay *et al.* (2021) utilized the paste replacement methodology (PRM) to investigate the effective application of PP and glass microspheres (GM) as fillers in cement mortar. Cement was replaced by (0, 10, and 20)% of PP and GM by volume. They conducted several tests to determine fresh and hardened mortar properties. Results showed that in comparison to the reference mix the PRM methods showed promising results to maintain the compressive strength, water absorption, and lowering the voids content at all tests ages. Results concluded that up to 20% of PP and GM could be replaced by the PRM method without changing compressive strength.

Liu *et al.* (2019) utilized porous pumice to replace river sand by (10, 20, and 30)% in preparing Ultra-High Performance Concrete (UHPC) and investigated the autogenous shrinkage and microstructure of UHPC. Results indicated that the autogenous shrinkage of UHPC containing wetting pumice reduced significantly without lowering mechanical properties. The microstructure inspections revealed that the interfacial transition zone (ITZ) between pumice and UHPC paste enhanced significantly.

Zeyad *et al.* (2019) prepared high strength concrete (HSC) containing (0, 10, 20, 30)% content of volcanic pumice as complementary cementitious material. The efficiency of utilizing pumice was investigated as a basis of pozzolanic reactivity for improving strength and durability. Results revealed that pumice contributes obviously to strengths

and transport properties enhancement were the optimum of 180 curing day flexural, compressive, and tensile strengths of pumice HSC (10.5, 78.9, and 6.22) respectively.

Karataş *et al.* (2017) prepared eight groups of SCMs containing grounded pumice powder as a mineral additive with variant pumice contents (5, 10, 20, 25, 30, and 35)% by binder weight. Seventy-two samples (40 \* 40 \* 160) mm with curing ages of (3, 28, and 90) days were designed to achieve tensile and compressive investigation. In addition, 24 cubic samples of 50 mm at 28 days of curing age were also prepared in order to perform (sorptivity, porosity, density, and water absorption) tests. The results reflect that the mortars containing pumice between (10-25)% show the optimum strength in comparison with the stander sample, and 15% pumice mortar has the best pozzolanic reaction at 28 and 90 days of curing. Whoever, a decrease in water absorption, porosity, and sorptivity was observed when applying (10-20)% PP as a cement alternative.

Uluslu *et al.* (2016) studied the effect of adding pumice with (10, 20, 25, 30, and 40) % on blended cement paste and mortar properties. The cement blended with fineness pumice was prepared by inter grinding Portland cement clinker, gypsum, and pumice. The produced samples were tested to investigate particle size distribution, setting times, chemical analysis, soundness, bending and compressive strengths, autoclave expansion, drying shrinkage, and sulfate resistance. In addition to microstructure characterization. Results showed that the pumice blended cement mortar had compressive strengths lower than Portland cement of up to 360 days aged. While, the inclusion of pumice-blended cement enhances durability, shrinkage, sulfate expansion, and autoclave expansion.

#### **2.1.1.4 Superplasticizer (SP)**

SP is a water-reducing admixture surface-active material added to fresh and hardened concrete to provide better workability. SP is an effective dispersing agent that modifies the surface charge of cement particles. Still understanding and evaluating the influences of SPs in concrete preparation is complicated. Even for systems that are non-reactive like ceramic suspensions, which become a subject of ongoing research. Different factors of SPs obviously affect the flowability of fresh concrete such as its molecular weight,

functional groups, dosage, and structure. Moreover, the fineness, phase and chemical composition, sulfate content of cement, and alkali are essential characteristics that play an important role in controlling the compatibility between SPs and cement.

Ibrahim & Meawad (2022) claimed that there is a research gap and their study tries to fill and gain complete knowledge about the compatibility of SP and ordinary Portland cement and the replacement cementitious material. they prepared different mixtures using cement replacements like waste glass powder (WGP) and Polynaphthene sulfonate (PNS) or Polycarboxylate (PCL) as SPs. Their tests recorded that when PNS or PCL is applied as a SP with the presence of WGP, a significant effect occurs on the flowability and flowability retention time. Their results concluded that the zeta potential measurement and the adsorption behavior change described the compatibility of mixed cement and SP.

Vanga *et al.* (2020) studied in detail the effect of using a variant dosage of SP on durability and mechanical properties of produced self-compacting concrete. They attempt many tests to evaluate the fresh concrete rheological properties and hardened concrete mechanical properties. Their results stated that the compressive strengths decrease with a higher dosage of SP. In addition, the diameter of slump flow and Hf/Hi ratio increases with increases in SP dosage. While plastic viscosity, V-funnel flow time, and yield stress recorded lower values with higher dosages of SP.

There is an experimental investigation conducted by (Cheah *et al.* 2019) to study the improvability of concrete containing high levels of cement alternative with the polycarboxylate-based SP, to make used cement replacement system, and at high replacement level suitable for practical usage. The study claimed that the optimum dosage of SP used is 1.0% of binder weight which is compatible with making the optimum replacement percentage become 60% of cement.

Other research deals with the effect of SP types on the performance of concrete. where (Manomi *et al.* 2018) in their study investigated the influence of four different types of SP namely (Lignosulphonate (LS), Polycarboxylate (PCE), Sulphonated Melamine Formaldehyde (SMF), and Sulphonated Naphthalene Formaldehyde (SNF) on the

durability and mechanical properties of concrete containing fly ash as partial cement replacement. Moreover, the SP dosage for all four groups of produced concrete coincides with saturation dosage. Their results conclusion stated that the PCE-based SP is more effective in the durability and mechanical properties.

Antoni *et al.* (2017) in their study used different brands of SPs to prepare mortar by applying two different cement types. Their study evaluated the influence of SP type and dosage on setting time, flowability, and compressive strength. The evaluating results conclude that the flowability increase with increasing SP dosage in the mixture. However, the optimum value of SP dosage differs among the different brands and for each water/binder ratio. Nevertheless, over dosage of SP leads to segregation and bleeding and lowers the compressive strength. In addition, results stated that using ordinary Portland cement required a larger SP dosage than Portland pozzolanic cement in order to gain the same value of flowability. Their results also conduct that a longer setting time of mortar mixtures was observed for all different used SP brands.

### **2.1.2 Water to binder ratio**

The water to binder ratio (w/b) has a direct influence on the properties of mortars and concrete, many researchers stated that the ratio of w/b has directly proportional to porosity. Moreover, the permeable thereby of mortar and concrete will be less, leading to a high value of strength and improved durability. In this context, the recommendation of ACI 318 (2011) is the ratio of w/b must be not greater than 0.45 for concrete that is subject to normal to severe freezing and thawing cycles or exposed to acidic chemicals with highly deicing (Antoni *et al.* 2017).

In short-term curing concrete, the chemical reaction of water and the cement particles results in hydrates that include C-S-H and  $\text{Ca(OH)}_2$ , and generate various pore distributions of porosity. This process is the main route of water and gas. Many researchers studied the relationship between w/b and porosity but these studies for normal concrete with an appropriate w/b ratio. However, this fact is not always suitable, on construction sites, for easy concrete placing and passing between the spacing of steel, the

water is added often. This process can be useful for easy finish ability and workability. Nevertheless, this advantage comes at the expense of aggregates segregation and degradation of durability and strength of concrete (Kim *et al.* 2014).

There is an abundance of information about the effect of the water to cement ratio on compressive stress. With a higher w/c ratio, the compress strength decreases. According to Abram's law, there is an importance of the w/c ratio on concrete strength. Which stated, that there is an inverse proportion between the w/c ratio and compressive stress. While still, insufficient information about the influence of the w/c ratio on mortar stress (Rao 2001, Schulze 1999).

Elnemr (2020) experimental work conducted an investigation and after 28 curing days as assigned by ACI standard, the effect of w/b ratio on hardened mortar properties. they Used generated empirical equations to evaluate mortar strength mixed with 15% silica fume as cement replacement and also varying sand portions (1:3, 1:4, 1:5, and 1:6) and different w/b ratios that ranged from (0.4-0.8) and variant. They conclude that the optimum w/b ratio for workable mortar is mainly dependent on cement to sand portions.

The evaluation of additional water on performance of durability was investigated by (Kim *et al.* 2014). Where prepared samples of cement mortar with 0.45 water-binder ratio for control case and up to 0.60 w/b ratios for comparison mixtures. Durability tests such as (chloride diffusion, saturation, strength, air permeability, and moisture diffusion) were achieved. In addition, changed porosity, pore size distribution, additional water content, and total porosity were analyzed. The test results conclude that in comparison with the control mixture, increasing the water to binder ratio leads to rising the porosity to 150%. additionally, adding water content up to 0.60 (133% increase of w/b ratio) caused increasing in water loss by 139%, 150% in porosity, 157% in coefficient of chloride diffusion, 192% air permeability, 266 in the coefficient of moisture diffusion and 259% in moisture sorptivity.

### 2.1.3 Curing regimes

Concrete and mortar curing terms mean cement hydration, which is an exothermic reaction that occurs between water and cement. As long as the mix includes water and in case of availability of suitable temperature conditions the hydration of cement can continue for many years at decreasing rate. Hardened mortar and concrete are curing usually achieved by water ponding (Sajedi and Razak 2011). The importance of curing mortar and concrete comes from the fact that it is necessary to gain durability and strength. In general, the curing process ensures the availability of water for hydration and provides suitable conditions, i.e., temperature and relative humidity in order to ensure hydration reactions which lead to forming hydrated compounds that fill voids.

Curing duration is one of the most important features of proper curing processing, achieving adequate hydration of mortar and concrete depending basically on three factors;

- Chemical and mineral compositions
- Fineness cement
- The cementitious material

ACI recommended the curing duration of structural concrete as 7 days of moist curing. While 14 days if the cement contains cementitious materials like fly ash and slag that is due to owning a slow hydration reaction of supplementary materials and calcium hydroxide, this type of reaction required always the presence of water in order to form cement compounds (Federowicz *et al.* 2020, Sajedi and Razak 2011).

Previous literature stated that curing duration, conditions, and curing type significantly affect the mortar and concrete properties. Development of some properties especially after placement, like strength, highly depends on the cement hydration. Adequate curing can support the favorable moisture content and a proper temperature in hardened mortar and concrete during their short-term ages resulting that the required properties may develop (Mardani Aghabaglou *et al.* 2020, Qureshi and Ghosh 2013).

Affecting of different curing media on mortar mechanical properties were dealt with in a study conducted by (Benli *et al.* 2017). Where investigated the mechanical properties of self-compacting mortars cured in four different media (tap water treatment, wet sack treatment, air treatment, and liquid paraffin wax treatment with variant treatment periods (3, 7, 28, 56, and 180) days. Two types of mixtures were produced, A binary mixture consisting of fly ash and silica fume replaced PC with (10, 20, and 30)% fly ash and (6, 0, and 14)% silica fume. the other prepared mixture was a triple mixture consisting of cement alternatives up to 30% of cement as 10% fly ash with (6, 10, 14)% of silica, and 20% fly ash with (6, and 10)% silica fume and C/W ratio ranged between (0.37 to 0.48.). Fresh and hardening results mortars behaviors were evaluated. Results indicated that the optimum value of compressive stress was at day 180 of binary mix mortar containing 10% fly ash cured at water media and of ternary mix mortar containing 10% FA + 6% SF cured at the wet sack. Results indicated that the best flexural strength value also at day 180 for 10% silica fume mortar cured at LPWT media, whoever, the lower result of the sorptivity coefficient was at 10% fly ash mortar of 0.4 water/binder ratio.

Early curing effect on the development of concrete strengths was investigated by Hiremath and Yaragal 2017, where their study includes preparing reactive powder concrete (RPC) cured under four different curing regimes which are hot air, ambient air, hot water bath, and accelerated. Test results record that, between the variant four curing regimes, the hot water bath recorded a higher value of strength. While the combined curing showed a significant improvement in compressive strength, about 63% 180 MPa in comparison with stander curing that recorded about 110 MPa.

Another experimental study achieved by (Sri Rama Chand *et al.* 2016) evaluated the self-curing effect on mortars' properties. The study includes preparing two kinds of mortars, the first type was with a 1:1 s:c and w/b ratio of 0.34 and the other with a 1:3 s:c and w/b ratio of 0.5. Three different curing conditions (self, wet, and without) curing have been experimented with. The Prepared mortars contain (0, 0.1, 0.5)% of 4000 and 200 polyethylene glycol. The Suitable flow properties according to specifications were evaluated by adopting V funnel and Mini-slump flow tests. Additionally, compressive strength, acid durability, sorptivity, and water retention tests on produced mortars were

also investigated. Results conclude that curing agents in certain content enhance the strength and durability characterizations of self-curing self-compacting mortars.



### **3. MATERIAL AND METHODS**

For investigating the characterization of Pumice-slag/self-compacting mortar and evaluating the mechanical properties, many experimental works were achieved. In this chapter full detail about materials and preparation, curing type, the mixture concentration, samples design, and the tests adopted in this work will be given.

#### **3.1 Materials**

The purpose of this work is to study the effect of using slag and pumice as cement replacements in producing self-compacting mortar. The properties of fresh and hardened mortar were investigated, in this context Portland cement, slag, and pumice as a binder, the ordinary sand as aggregate in addition to tap water and additive was also attempted in preparation methods.

##### **3.1.1 Cement (PC)**

In this research ordinary Portland cement type CEM I 42.5R that met the TS EN 197-1:2012 standard was attempted. Having specific surface area and specific gravity of 3560 m<sup>2</sup>/g and 3.08 g/cm<sup>3</sup> respectively. Mechanical, physical, and chemical properties are illustrated in Table 3.1 below, Figure 3.1 shows the used Portland cement.



**Figure 3.1** Cement type CEM I 42.5R

**Table 3.1** Physical and chemical properties of CEM I 42.5R

| CEM I 42.5R                          |                         | TS EN 197-1 |          |
|--------------------------------------|-------------------------|-------------|----------|
| Physical Properties                  | Values                  | Minimum     | Maximum  |
| Specific Surface                     | 3560 cm <sup>2</sup> /g | -           | -        |
| Specific Weight                      | 3.08 g/cm <sup>3</sup>  | -           | -        |
| Normal Consistency Water Requirement | 28%                     | -           | -        |
| Initial Setting time                 | 135 min                 | 60 min      | -        |
| Final Setting time                   | 220 min                 | -           | -        |
| Volume Expansion                     | 0 mm                    | -           | 10 mm    |
| 2 day Compressive Strength           | 31 MPa                  | 20 MPa      | -        |
| 7 day Compressive Strength           | 42.1 MPa                | -           | -        |
| 28 day Compressive Strength          | 53.1 MPa                | 42.5 MPa    | 62.5 MPa |
| Chemical Properties                  | Values                  | Minimum     | Maximum  |
| MgO                                  | 1.73%                   | -           | -        |
| SO <sub>2</sub>                      | 3.16%                   | -           | -        |
| Cl <sup>-</sup>                      | 0.0485%                 | -           | 0.1%     |
| Insoluble Residue                    | 0.79%                   | -           | 5%       |
| Ignition Loss                        | 3.33%                   | -           | 5%       |

### 3.1.2 Ground granulated blast furnace slag (GGBFS)

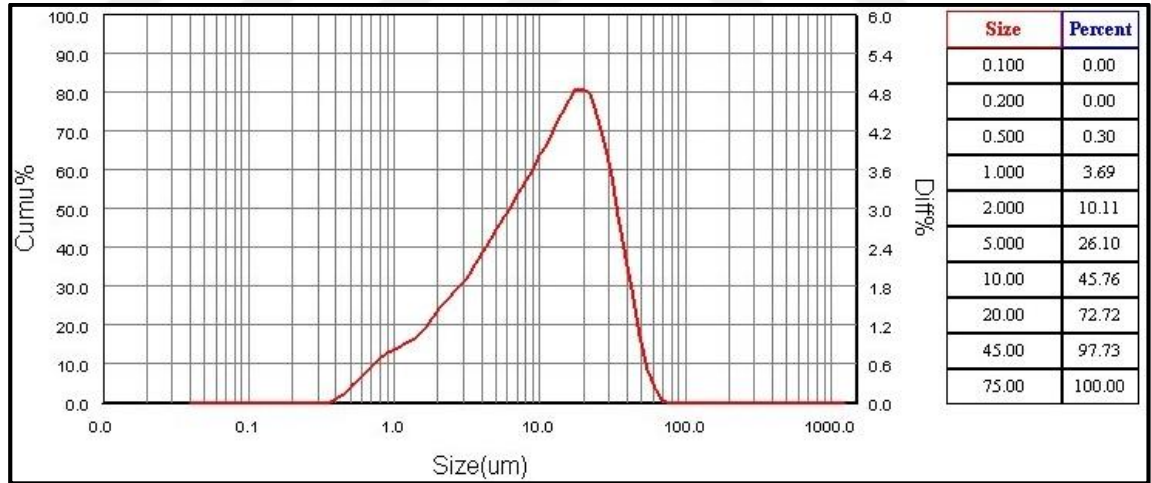
The ground granulated blast furnace slag (GGBFS) was supported from (Zonguldak-Ereğli) steel and iron factory in turkey (Erdemir and Oyak Bolu Cement) as a by-product waste was applied as partial cement replacement in this study. GGBFS has a specific gravity of  $2.95 \text{ g/cm}^3$  and powder fineness of  $4989 \text{ cm}^2/\text{g}$ . The index of pozzolanic activity is 54.2 for 7 days and 72.5 for 28 days. The physical and chemical properties of slag as received from the factory are shown in Table 3.2. Figure 3.2 is showing the used GGBFS in this work. The particle size grading of GGBFS is shown in Figure 3.3.



**Figure 3.2** The used GGBFS

**Table 3.2** Chemical and physical specification of GGBFS

| Component                             | %      | TS EN 197-1 Standard          | Test Method   |
|---------------------------------------|--------|-------------------------------|---------------|
| SO <sub>3</sub>                       | 0.19   | Max 2.5%                      | TS EN 196-2   |
| MgO                                   | 5.75   | Max 18                        | TS EN 196-2   |
| Cl <sup>-</sup>                       | 0.0185 | Max 0.1                       | TS EN 196-2   |
| S (Sulfide)                           | 0.54   | Max 2.0                       | TS EN 196-2   |
| Na <sub>2</sub> O                     | 0.56   | -                             | TS EN 196-2   |
| K <sub>2</sub> O                      | 0.28   | -                             | TS EN 196-2   |
| Na <sub>2</sub> O equivalent          | 0.74   | -                             | TS EN 196-2   |
| Moisture                              | 0.06   | Max 1.0                       | TS EN 15167-1 |
| <b>Physical Properties</b>            |        |                               |               |
| Specific surface (g/cm <sup>2</sup> ) | 4989   | Min 2750 (g/cm <sup>2</sup> ) | TS EN 196-6   |
| Specific weight (g/cm <sup>3</sup> )  | 2.95   | -                             | TS EN 196-6   |
| <b>Mineralogical Properties</b>       |        |                               |               |
| LOI                                   | 0.09   | Max 3.0                       | TS EN 196-2   |
| Glass content                         | 100    | -                             | TS EN 196-2   |

**Figure 3.3** Grading of GGBFS particle size

### 3.1.3 Pumice

The used waste pumice in this research work was supported by the factory of Nevşehir. Pumice has passed through crushing and grinding processes to achieve pumice powder. Specific surface and specific gravities are 308.6 m<sup>2</sup>/kg and 2.4 g/cm<sup>3</sup> respectively. The

used pumice powder is shown in Figure 3.4, and particle size grading is shown in Figure 3.5.



**Figure 3.4** The used pumice powder

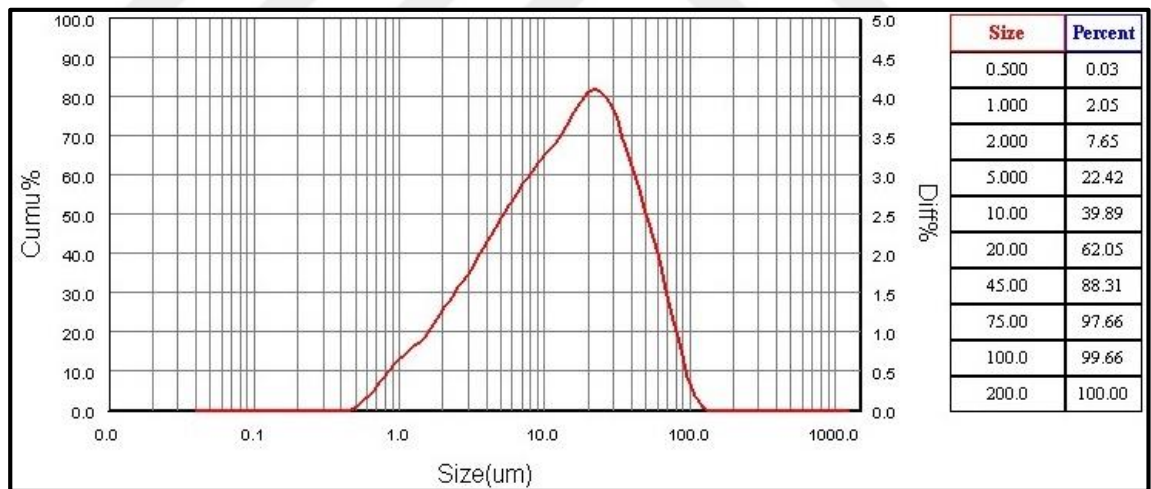


**Figure 3.5** Pumice particle size grading

#### 3.1.4 Aggregate

The aggregate used in this work is natural or river sand, which is a residual of eroded rock particles. River or nature sand has various particles size in its natural according to wearing level. It extracts from the riverbed and is rich in inorganic matters, mineral contents, and

clay that has an effect on mortar and concrete properties. Figure 3.6 below shows the natural river sand.



**Figure 3.6** The used sand

### 3.1.5 Superplasticizer (SP)

The SP used in this work is supported by CHRYSO Lab Bet 8109. SP is a polycarboxylate-based polymer water-soluble and it is a third-generation liquefied. The as-received Lab Bet 9109 specifications are shown in Table 3.3 below.

**Table 3.3** SP specification

|                      |                                 |
|----------------------|---------------------------------|
| <b>Color</b>         | Brown                           |
| <b>Density</b>       | $1.075 \pm 0.02 \text{ g/cm}^3$ |
| <b>pH</b>            | $> \%0.1$                       |
| <b>Active Matter</b> | Polycarboxylate                 |

### **3.1.6 Water**

Normal tap water was used for both mixtures preparation and for the curing process; the water of the laboratory meets the TS-EN standard requirements.

## **3.2 Methods**

### **3.2.1 Mixing procedure design and contents proportions**

In this study, nine trial mixtures were prepared including different portions of cement replacements, in addition to one mix of reference (Table 3.4). For each mixture, 48 samples were prepared, and as result, produced 480 samples for all mixtures.

Reference mixture includes using the standard contents of ordinary mortar: Portland cement as a binder, sand as an aggregate, addition to water, and SP.

For trial mixtures, were implied the pumice and slag as cement replacements with variant portions ranging from 20-65% of cement.

Binder to aggregate ratio fixed to 1:2 and water to binder was 23% for all mixtures, SP adding ranged from 12 g-16 g. Table 3.4 below shows the contents and proportions of the mixture.

All mixtures were cured at two different curing regimes for 3, 7, 28, and 90 curing aged, the first curing type is water at room temperature, the second, hot water at 90 °C for 24 hours, then at curing room at 31 °C and 70% relative humidity.

**Table 3.4** Mixtures contents proportions

| Samples No. | Pumice (%) | Slag (%) | Sand:Binder | Water (%) | SP (g) |
|-------------|------------|----------|-------------|-----------|--------|
| 1           | 0          | 0        | 1:2         | 0.23      | 14     |
| 2           | 0          | 0.2      | 1:2         | 0.23      | 14     |
| 3           | 0.1        | 0.2      | 1:2         | 0.23      | 12     |
| 4           | 0.15       | 0.2      | 1:2         | 0.23      | 12     |
| 5           | 0          | 0.35     | 1:2         | 0.23      | 14     |
| 6           | 0.1        | 0.35     | 1:2         | 0.23      | 13     |
| 7           | 0.15       | 0.35     | 1:2         | 0.23      | 16     |
| 8           | 0          | 0.5      | 1:2         | 0.23      | 14     |
| 9           | 0.1        | 0.5      | 1:2         | 0.23      | 15     |
| 10          | 0.15       | 0.5      | 1:2         | 0.23      | 15     |

### 3.2.2 Material preparation

For producing self-compact mortar containing cement replacements like pumice and slag, in addition to sand, pre-treatment processing was achieved for these materials in order to be ready to use.

Pumice, slag, and sand undergo drying in the oven (Figure 3.7) for 24 hours at 100 °C in order to remove any possible moisture.

The dried pumice then passes through a milling process using a steel ball machine CHRYSO-CEM 3 shown in Figure 3.8 below for 120 minutes.



**Figure 3.7** The used oven



**Figure 3.8** Steel ball-grinding machine CHRYSO-CEM 3

### 3.2.3 Mixing sequences

The mixing procedure was achieved using a mixer (Figure 3.9a), also materials were scaled using a supersensitive scale (Figure 3.9b).

The mixing sequence procedure of all ten mixtures was achieved according to the following steps;

1. Dry sand was placed in the mixer and the amount was determined by relying on the binder proportion, mixing for 1 minute,
2. Adding 30% of water content according to determining water/binder proportion,
3. Mixing for further 5 minutes to obtain wet sand mixed,
4. Adding the binder (cement or cement/slag/pumice), mixing for further 5 minutes,
5. Adding 50% of SP and other 30% of water gradually, mixing for further 5 minutes,
6. Finally, add the remaining amount of water and SP and continue mixing for a further ten minutes.



(a)

(b)

**Figure 3.9** (a) The supersensitive scale, (b) The mixer used in mixing contents

#### 3.2.4 Samples preparation

In this work, 480 samples for all ten mixtures were prepared, where for each mixture 48 samples were produced, and the fresh mortar was casted in a rectangular mold with (40x40x160) mm dimensions. Fresh mortar was poured into the molds without pressing

and covered with a suitable glass cover for 24 hours in order to prevent water loss. Figure 3.10a and b shows the mold used and prepared samples.



**Figure 3.10** (a) The mold used in molding, (b) The prepared sample

### 3.2.5 Curing regimes

Two types of curing were adopted, curing by immersion of the samples into room temperature water (Figure 3.11), and the other by heating the sample in the oven (Figure 3.5) at 100 °C for 24 hours and then in a controlled room with 30 °C and 70% humidity fixed environment as shown in Figure 3.12 below. The samples of every mixture were divided into two groups, where 24 samples were cured with room temperature water curing, and 24 were cured in the controlled temperature and humidity room. All samples for both two curing regimes were cured for four different age durations (3, 7, 28, and 90) days, and after completing each curing duration, the final samples underwent evaluation.



**Figure 3.11** Room temperature curing basin



**Figure 3.12** Controlled curing room

### 3.3 Evaluation Tests

Fresh and hardened prepared mortars underwent many evaluation tests in order to study and compare the obtaining results. In this section, apparatus and tests methods of (flow test, compressive and flexural stress tests, porosity, absorption, and specific weight) will be illustrated.

#### 3.3.1 Flow test

In order to study the effect of employing cement replacements on fresh SCM flow, directly after mixing workability was inspected. Depending on TS EN 12350-8 standard, a flow test was achieved (Figure 3.13) below. TS EN 12350-8 is a European standard that identifies the method of examining the flow rate and followability of SCC and SCM without any obstacles.



**Figure 3.13** (a) Flow test apparatus, (b) Flow tested fresh mortar

#### 3.3.2 Flexural and compressive tests

Evaluating compressive and flexural stress was performed using UTCM-3742 double chamber Automatic Flexure/Compression testing machine Figure 3.14 below. UTCM-3742 is designed for reliable and suitable testing of mortar mold samples. UTCM-3742

conforms to the following standards EN (196-1, 1015-11), ASTM (C 109, C348, C349), and BS (3892-1, 4551-1) in the technical properties context. In addition, this machine meets the specifications of CE norms for the safety and health of the user.



**Figure 3.14** The UTCM-3742 double chamber automatic flexure/compression apparatus

For calculations of flexural stress of center-point loading according to standers ASTM C109 mentioned above, rectangular samples were adopted for achieving tests. The flexural test was calculated using the following Equation (3.1):

$$\text{Module of rupture} = \frac{3Pl}{2bd^2} \quad (3.1)$$

Where;

Module of rupture (MPa)

$P$  = maximum applied load (N)

$l$  = span length (mm)

$b$  = average width of sample at fracture (mm)

$d$  = average depth of sample at fracture (mm)

For compressive strength, the following Equation (3.2) is used in calculating the values:

$$\text{Compressive strength } (\sigma_c) = \frac{P}{A} \quad (3.2)$$

Where;

$\sigma_c$  in (Mpa)

$P$  = applied load (N)

$A$  = cross section area (mm<sup>2</sup>).

Flexural and compressive tested samples are shown in Figure 3.15 below.

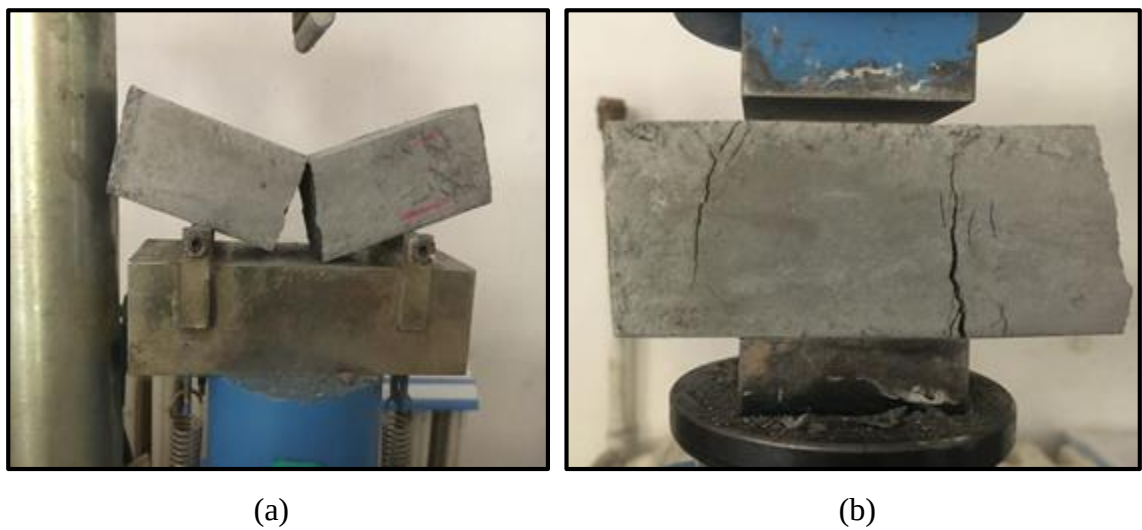


**Figure 3.15** (a) Flexural tested sample, (b) Compressive tested sample

### 3.3.3 Physical properties

Evaluating Porosity, Absorption, and bulk density values were determined by testing the samples for all ten mixtures in the following steps:

1. The supposed testing samples were dried at 100 °C for 24 hours and then cooled at room temperature for 1-3 hours.
2. Immersion of the samples in room temperature water for 24 hours and then removed the samples and wiped with an absorbent cloth to obtain the saturated-surface dry weight.
3. Placed samples in a water submersible-wired basket to obtain immersion weight.
4. Dried the samples at 100 °C for 24 hours and then cooled at room temperature for approximately 3 hours and obtained the dry weight of the samples.

The values were calculated by employing the following Equations (3.3), (3.4), and (3.5) below, according to ASTM C 64224 stander:

$$\text{Dry Bulk density (g/cm}^3\text{)} = \left( \frac{W_3}{W_1 - W_2} \right) \times \rho \quad (3.3)$$

$$\text{Porosity (\%)} = \frac{(W_1 - W_3)}{(W_1 - W_2)} \times 100\% \quad (3.4)$$

$$\text{Absorption (\%)} = \frac{W_1 - W_3}{W_3} \times 100\% \quad (3.5)$$

Where  $W_1$  is the saturated-surface dry sample weight (g),  $W_2$  immersion sample weight (g),  $W_3$  oven-dried sample weight (g), and  $\rho$  is the density of water = 1 g/cm<sup>3</sup>.

## 4. RESULTS AND DISCUSSIONS

In this chapter, the obtained results from tests of fresh and hardened mortar: (flow test, water absorption, porosity, bulk density, and compressive and flexural strength) will be illustrated.

### 4.1 Fresh Mortar Properties

The results of flow tests of the different mortar mixtures are shown in Table 4.1 below.

**Table 4.1** Flow test results of mortar mixtures

| Sample No. | Sample Code | Cement % | Pumice % | Slag % | Sand/Binder | Water % | Flow (cm) |
|------------|-------------|----------|----------|--------|-------------|---------|-----------|
| 1          | REF         | 100      | 0        | 0      | 1.2         | 23      | 21        |
| 2          | P0C20       | 80       | 0        | 20     | 1.2         | 23      | 22.5      |
| 3          | P10C20      | 70       | 10       | 20     | 1.2         | 23      | 21        |
| 4          | P15C20      | 75       | 15       | 20     | 1.2         | 23      | 20        |
| 5          | P0C35       | 65       | 0        | 35     | 1.2         | 23      | 25        |
| 6          | P10C35      | 55       | 10       | 35     | 1.2         | 23      | 23.5      |
| 7          | P15C35      | 50       | 15       | 35     | 1.2         | 23      | 22        |
| 8          | P0C50       | 50       | 0        | 50     | 1.2         | 23      | 26        |
| 9          | P10C50      | 40       | 10       | 50     | 1.2         | 23      | 24        |
| 10         | P15C50      | 35       | 15       | 50     | 1.2         | 23      | 22        |

Table 4.1 clarifies the flow test results were ranged between 21 cm and 26 cm, according to illustrated results the lowest flow result was for the P15C20 mix which contained 15% PP and 20% of GGBFS as cement replacement, while the highest flow result was for the P0C50 mix which contained 50% of GGBF as cement alternative. As stated by (Wang *et al.* 2021) the flow value is increasing as the including of slag increases. Figures 4.1 and 4.2 below show the effect of GGBFS and PP on the flow results.

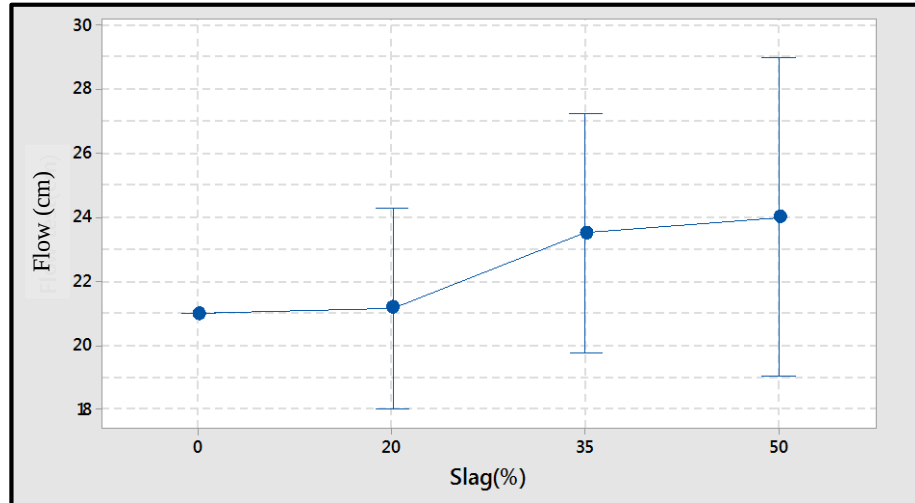


**Figure 4.1** Effect of GGBFS on flow test

As shown in Figure 4.1 the increase of GGBFS content in mortars mixtures from 0% to 20% to 35%, and then to 50% led to obtaining average flow values as (21, 21.16, 23.5, 24) cm respectively. This means the included GGBFS in the mortar mixture caused increased flow test results and enhance the workability. That agrees with previous research, the workability of mortar is related to many factors like replacement level amount, partial size, the reactivity of admixtures, and specific surface. The surface characterization of the GGBFS grains and the good intergranular slip and the limited water absorption may describe this increase in workability (Kenai *et al.* 2021). Another study (Madallah *et al.* 2020) showed an enhancement of mortar workability with an increasing GGBFS proportion, that due to the reason cementation materials like GGBFS are distributed regularly and that improve flow property. The GGBFS contents higher than 50% of replacement level lead to increasing of slump flow, additionally, the higher specific surface area of GGBFS led to enhancement of mortar workability, this can be described as the GGBS particles filling the voids in the mixture (Shi *et al.* 2004).

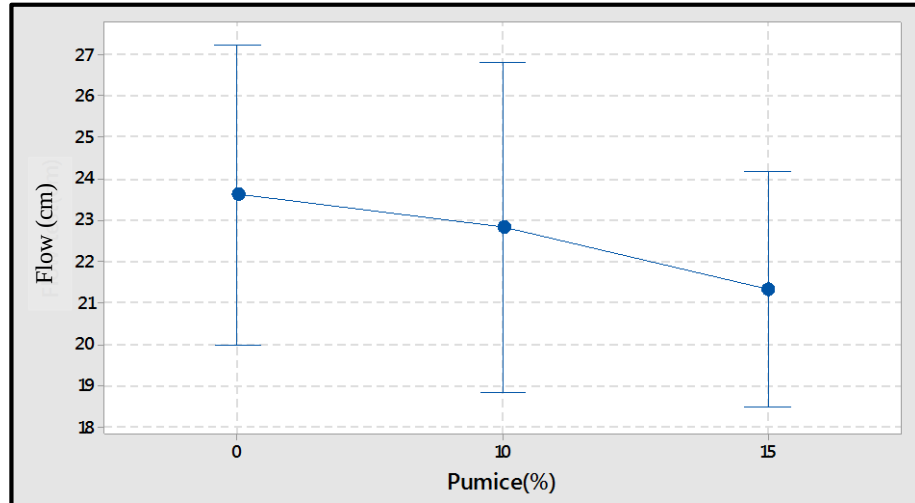


**Figure 4.2** Effect of PP on flow test

Figure 4.2 shows the effect of PP on flow tests, as shown, the increase of PP contents caused decreasing in the flow values. The increase of PP percentage from 0% to 10% and then to 15% led to a lowering in the average flow results from 23.6 cm to 22.7 cm and then to 21.3 cm respectively. In other meaning, while the PP contents level raised from 0% to 15% the flow results decreased 9%. This result is because PP has a high water absorption in the early mixing stage which may cause agglomeration of cement and limited the slump (Anwar Hossain 2004). Other research reported that mortar-containing pumice required high SP dosages than reference mortar reaching 85-100%, this related to the high surface area and the porous structure of PP particles (Ghasemi *et al.* 2019). The same behavior was noticed in the literature of (Samimi *et al.* 2018) when applied PP as PC replacement more SP dosage was required to obtain the same reference mix flow values, as the increasing of substitution proportions decreased the mortar slump flow. Other research work (Karatas 2017) recorded fluctuated workability results when including PP. The slumps flow result does not show a linear path. However, the slump value at low content of PP (5 and 10)% and high content (30 and 35)% is lower than the reference mixture results, due to the PP particles showing an irregular shape and also due to spongy structure led to a decrease the values of mortar slump.

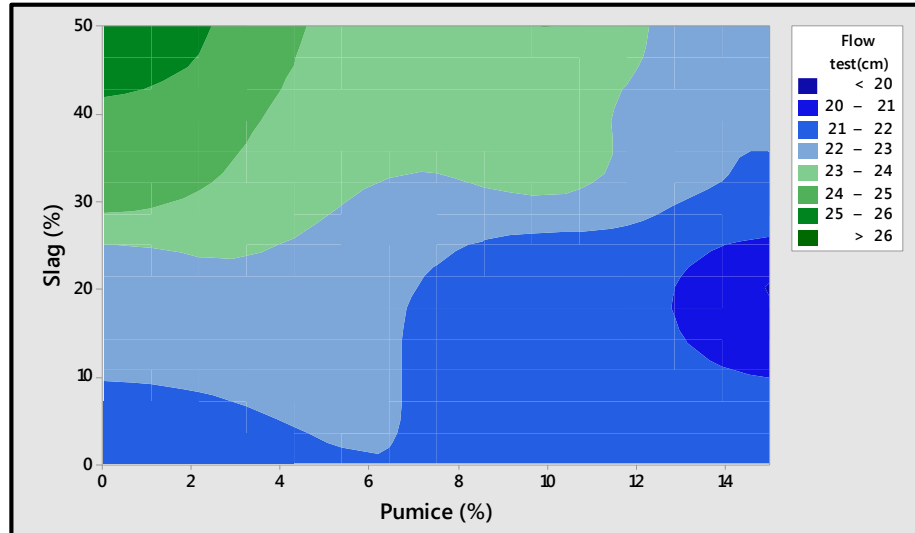


**Figure 4.3** Effect of GGBFS and PP on flow results value

Figure 4.3 illustrates the effect of both GGBFS and PP on flow values. From the Figure above, can clearly notice the maximum value of flow was obtained at 50% GGBFS and 0% PP while the minimum values obtained at 20% GGBFS and 15% PP.

## 4.2 Physical Properties

The results of bulk density, porosity, and absorption, after 90 days of curing, for samples with and without PP and GGBFS, and cured in water at room temperature and in the controlled room, are illustrated in Figures (4.4, 4.5, and 4.6) below. Achieving the above tests after 90 days of curing attributed to that this treatment duration is sufficient time for the pozzolanic reaction to take place adequately and nearly completed, so the influence of adding PP and GGBFS clearly appears (Lim *et al.* 2012, Wang *et al.* 2021).

### 4.2.1 Bulk density

From Figure 4.4 below, the results of bulk density for the mixtures cured in normal water and in the controlled room showed almost the same values for both curing types. However, the maximum value was for reference samples, which were (2.19 and 2.18) g/cm<sup>3</sup> and cured in normal water and in the controlled room. While the minimum value

of bulk density result belongs to the P15C50 sample that contains 15% PP and 50% BBFS, which were (2.117 and 2.12) g/cm<sup>3</sup> and cured in normal water and in the controlled room.

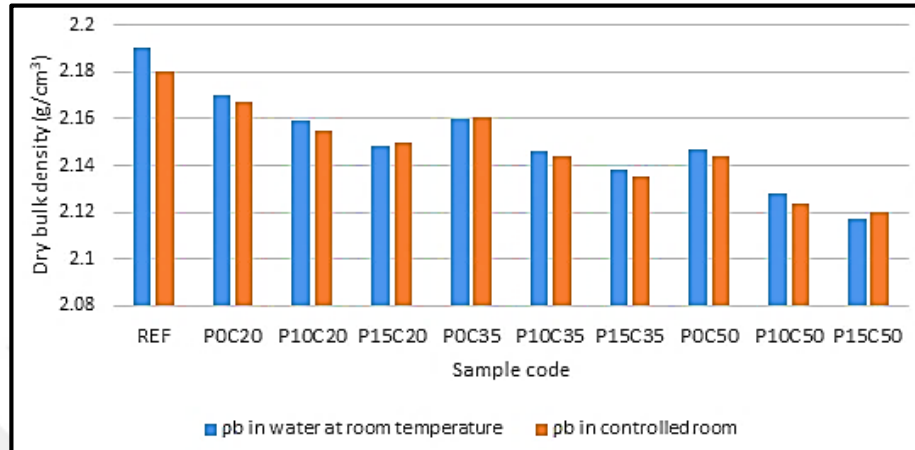


**Figure 4.4** Dry bulk density of mixture with and without GGBFS and PP

Figures 4.5 and 4.6 below describe the influence of including GGBFS on the dry bulk density; can notice from the Figures, the dry bulk density decreases with the increase of GGBFS. For samples that cured in normal water at room temperature (Figure 4.5), as with increased GGBFS content from 0% to 20 and to 35% and then reached to 50% the dry bulk density decreases from 2.195 g/cm<sup>3</sup> to (2.159, 2.148, and then to 2.13) g/cm<sup>3</sup> respectively. In addition, for samples cured in the controlled room (Figure 4.6), the bulk density of samples also decreases from 2.18 g/cm<sup>3</sup> to (2.157, 2.146, and then to 2.129) g/cm<sup>3</sup>, with the same increased level of GGBFS.

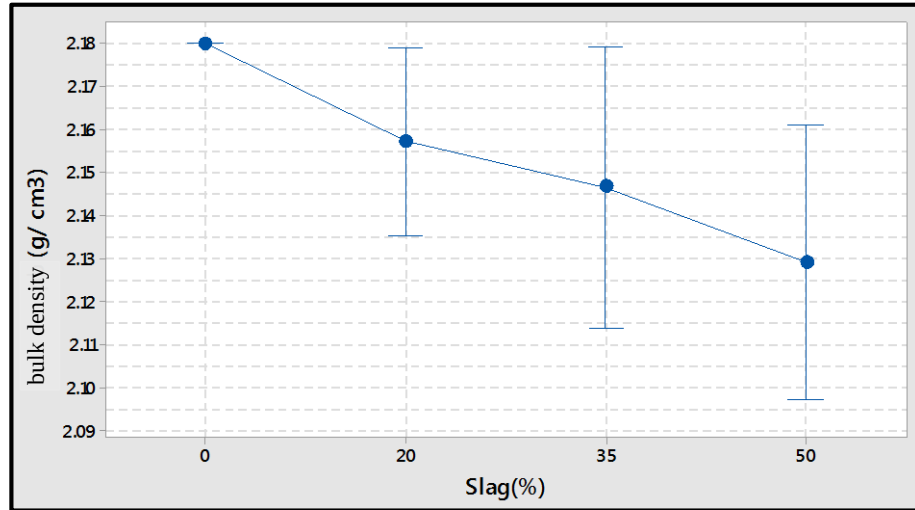


**Figure 4.5** Effect of GGBFS on dry bulk density of mixture cured in water at room temperature

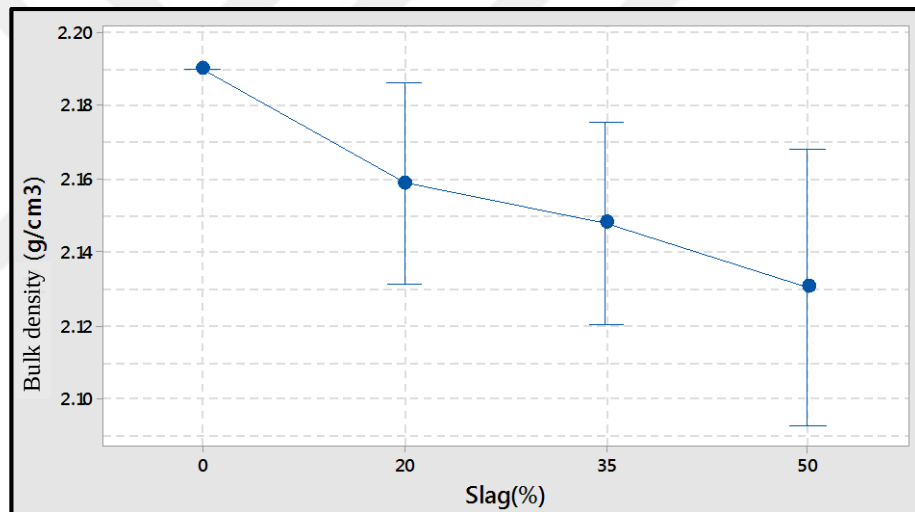


**Figure 4.6** Effect of GGBFS on dry bulk density of mixture cured in the controlled room

Moreover, as for the inclusion of pumice and its influence on the bulk density, Figures 4.7 and 4.8 illustrate the behavior of bulk density with increasing PP and for both curing types. however, for samples cured in water at room temperature, from (Figure 4.7), as can be observed, the bulk density follows decreasing behavior with increasing of PP from 0% to 10% and then to 15%. were bulk density shown decreasing from 2.166 g/cm<sup>3</sup> to 2.144 g/cm<sup>3</sup>, and then to 2.134 g/cm<sup>3</sup> respectively. Additionally, for samples cured in the controlled room (Figure 4.8), and with the same pumice increasing level, bulk density was (2.163, 2.141, and 2.135) g/cm<sup>3</sup>, respectively. The reason for decreasing density with

GGBFS and PP increases is that the PP and GGBFS have a low density in comparison to other contents. Also due to the porous and the rough structure of slag and pumice (Karatas 2017). In addition, (Gao *et al.* 2005) observed that utilizing slag cement led to reducing in the size and content of  $\text{Ca}(\text{OH})_2$  crystals in the interfacial transition zone. Moreover, other literature observed decreasing in density with longer curing time, in this context (Saridemir and Bulut 2021), obtained a lower mortar density with a longer curing period where the reduction ranged between 1.40% and 3.74%.

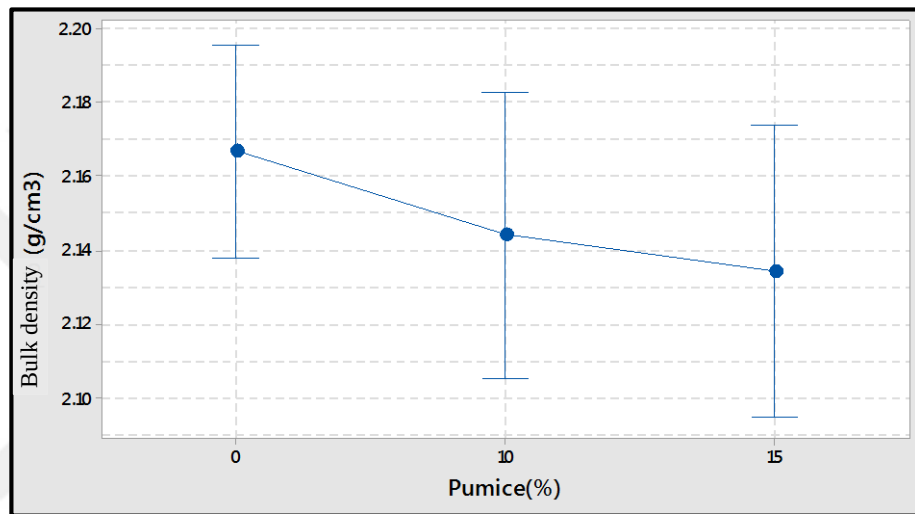


**Figure 4.7** Effect of PP on dry bulk density of samples cured in water at room temperature

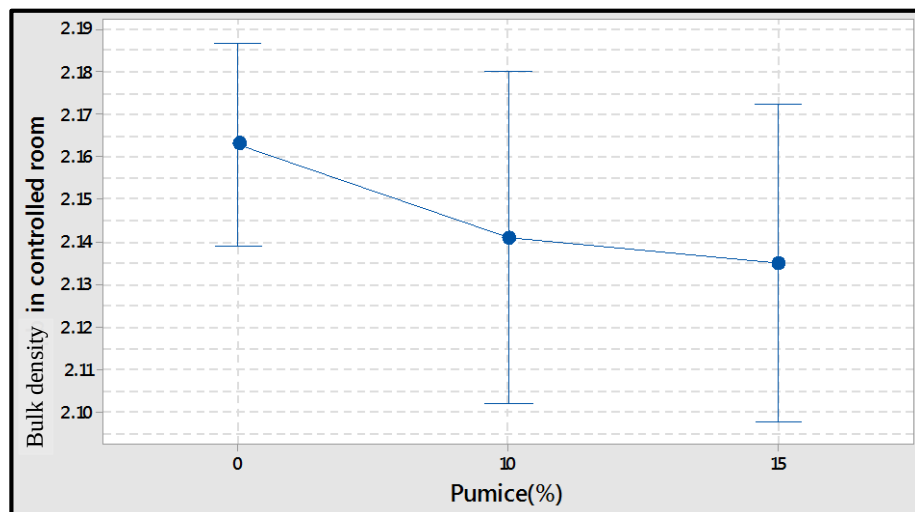


**Figure 4.8** Effect of PP on dry bulk density of mixture cured in the controlled room

#### 4.2.2 Porosity

Figure 4.9 below shows the porosity results of samples with and without GGBFS and PP and cured in water at room temperature and in the controlled room. The porosity values were affected by the inclusion of GGBFS and PP, as shown from the Figures; the higher porosity was for references mixtures and was 1.24% for both curing media. While the lowest porosity for both curing media was 0.93% and 0.9% for the P15C50 mixture that contains 50% GGBFS and 15% PP.

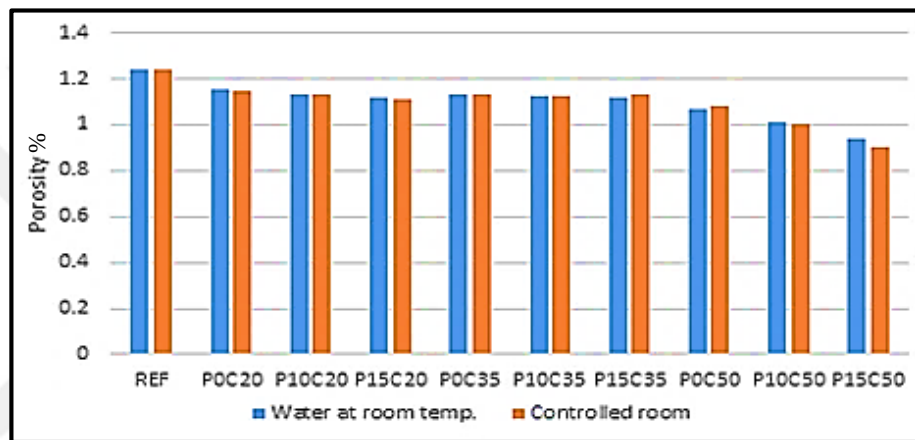


**Figure 4.9** The porosity of mixture with and without GGBFS and PP

Figures 4.10 and 4.11 below illustrate the porosity of samples after curing in water at room temperature and in the controlled room. The results of porosity (for cured in normal water) ranged from 1.24% for the reference sample as maximum porosity, and 1% for samples containing 50% GGBFS as minimum porosity, while the porosity of samples with (20 and 35)% GGBFS was (1.134 and 1.122)%. In addition, for samples cured in the controlled room, the maximum porosity was 1.24% also belongs to the reference sample, and the minimum porosity was 0.99% for the sample containing 50% GGBFS, moreover, the porosity of samples containing (20 and 35)% GGBFS were (1.129 and 1.127)%.

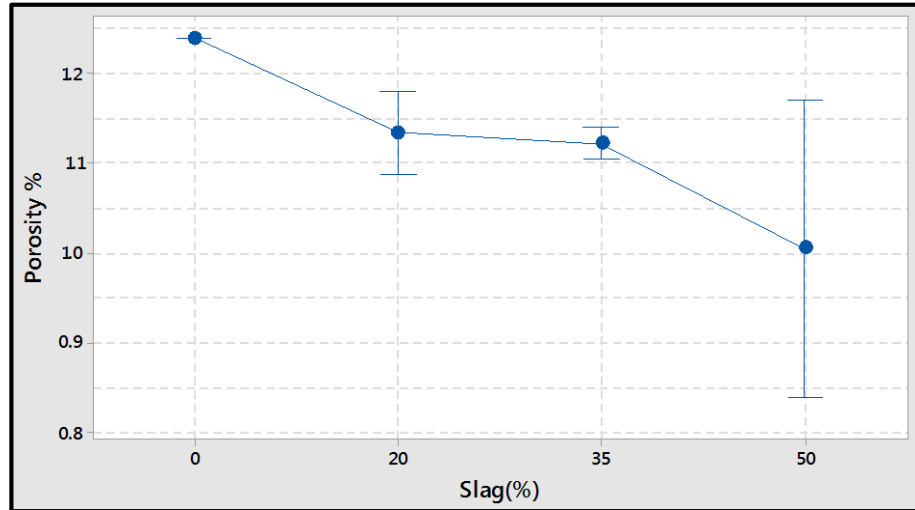


**Figure 4.10** Effect of GGBFS on samples porosity cured in water at room temperature

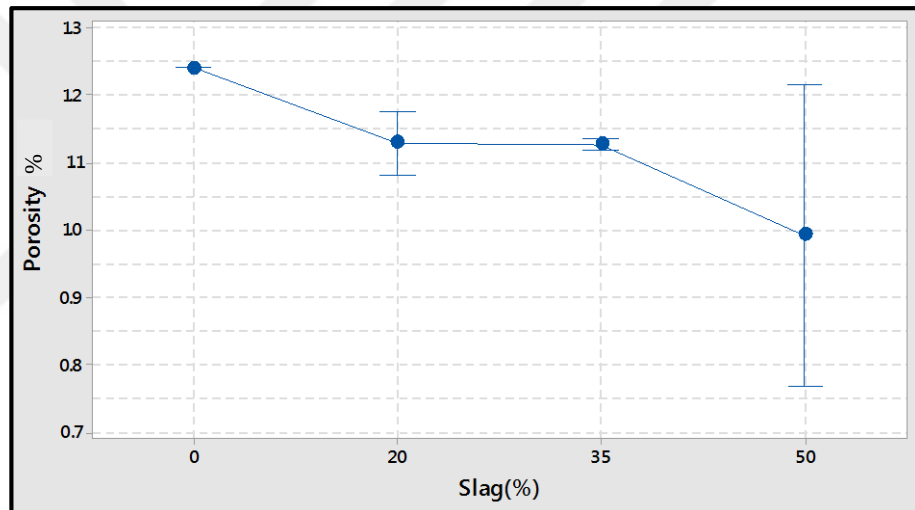


**Figure 4.11** Effect of GGBFS on porosity of mixture cured in the controlled room

In the same context, the effect of pumice on the porosity of samples cured in both curing types is illustrated in Figures 4.12 and 4.13. Can be noticed that as the PP content increase the porosity decrease. for samples cured in normal water, the maximum porosity was for reference samples as 1.148%, and then slightly decreased to 1.088% and then to 1.056% as the pumice content increased to 10% and then to 15% respectively. Moreover, for samples cured in the controlled room, the same effect on porosity was observed. As the porosity decreased from 1.149% to 1.08% and then to 1.046% as the PP content increased from 0% to 10% and then 15% respectively. This may be attributed to two reasons, the first, for the fact that the GGBFS and PP contain finer particles than ordinary Portland

cement, which then form C-S-H and C-S-A-H bonds that fill the microstructure pores (Sadagopan 2021) this is in line with the explanation of (Kabay *et al.* 2015) were obtained the same finding. The second reason, the pozzolanic reactions of GGBFS and PP, lead to creating a denser structure (Giosuè *et al.* 2018).

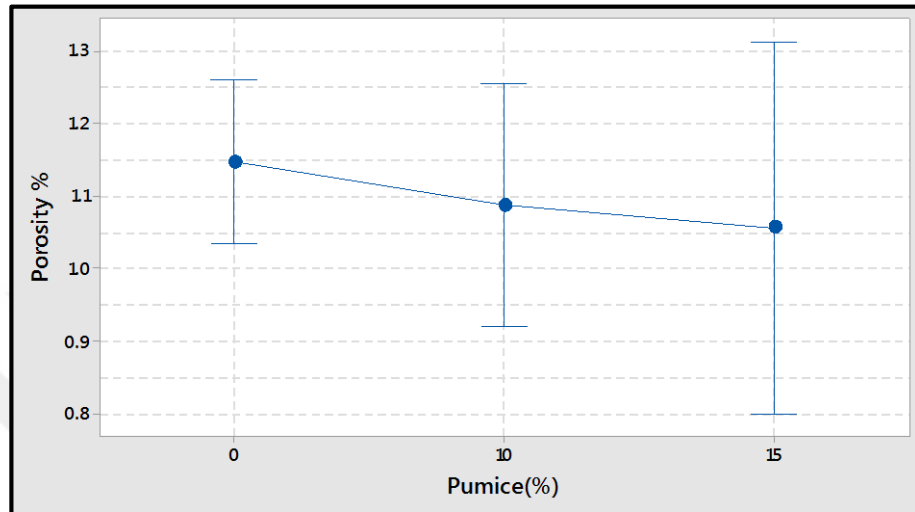


**Figure 4.12** Effect of PP on porosity of mixture cured in water at room temperature

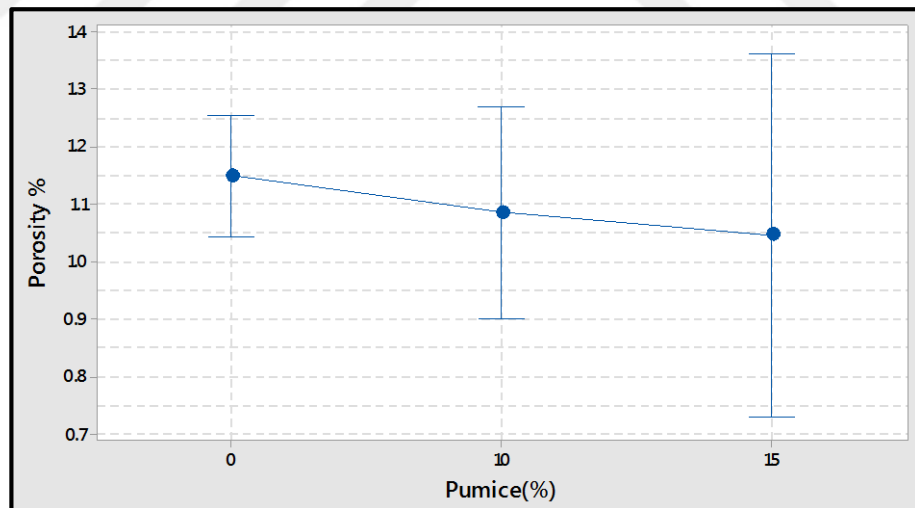


**Figure 4.13** Effect of PP on porosity of mixture cured in the controlled room

#### 4.2.3 Water absorption

Figure 4.14 below illustrates the water absorption of samples containing GGBFS and PP in addition to the reference sample and cured in water at room temperature and in the

controlled room. As observed from the Figure, the inclusion of GGBFS and PP decreases the porosity. Whoever, the maximum absorption was for the reference sample that recorded 1.4% and 1.41% absorption; for both curing media respectively, while the minimum belong to the P15C50 sample with 15% PP and 50% GGBFS and recorded absorption of 0.39 % and 0.33% for both curing media respectively.

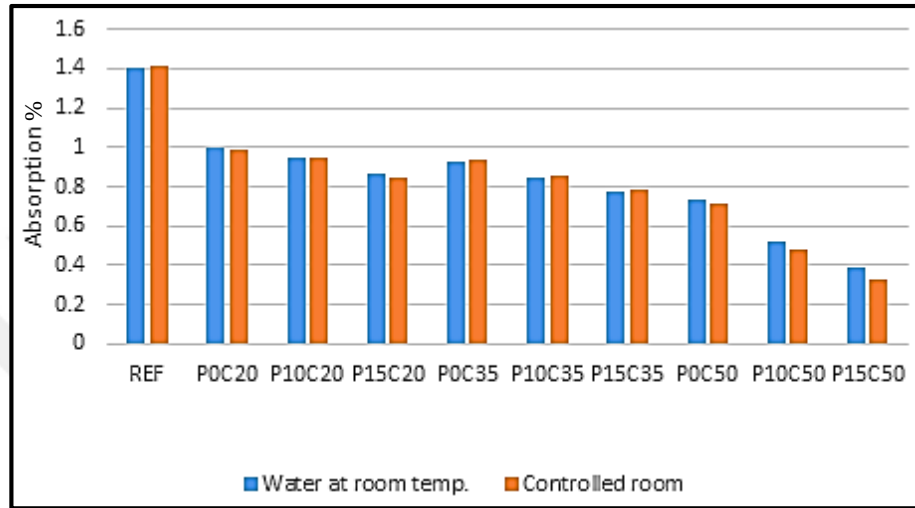


**Figure 4.14** Absorption of mixture with and without GGBFS and PP

As seen from Figures 4.15 and 4.16 below, the water absorption of samples cured in water at room temperature and in the controlled room decreases with the increase of GGBFS content. however, the water absorption of samples cured in water at room temperature decreased from 1.4% to 0.93% and 0.85% and then to 0.54% as the content of GGBFS increased from 0 to 20% and 35 and then to 50%, respectively. Moreover, for samples cured in the controlled room, the water absorption also decreases from 1.41% to 0.92% and 0.85%, and then to 0.50% with the same GGBFS increasing level.

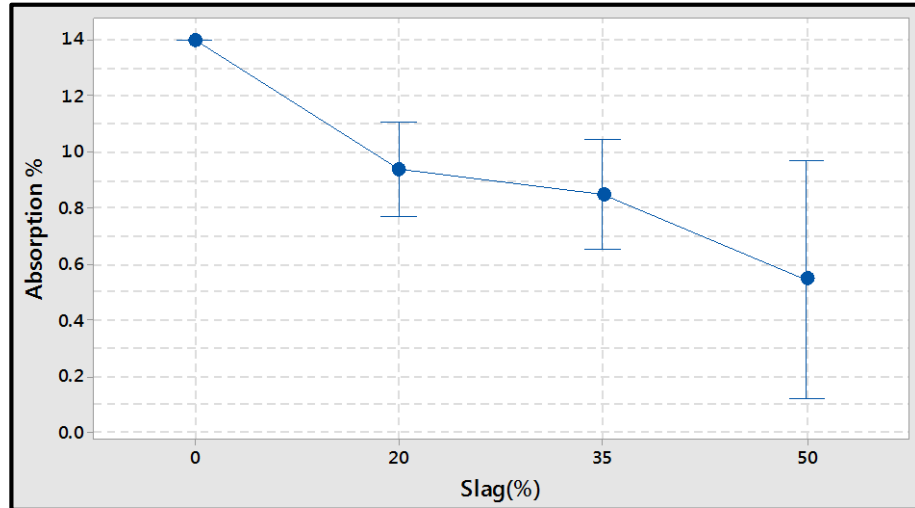


**Figure 4.15** Effect of GGBFS on samples absorption cured in water at room temperature

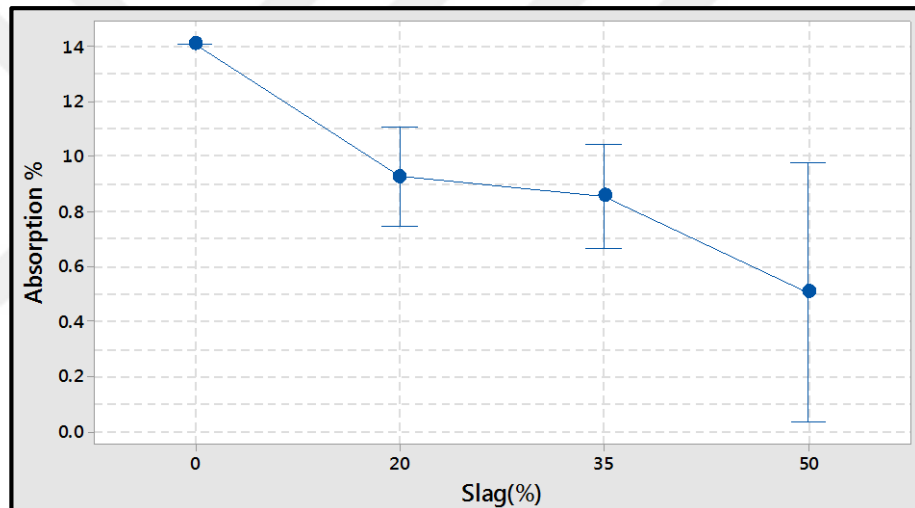


**Figure 4.16** Effect of GGBFS on absorption of mixture cured in controlled room

In the same context, the effect of the inclusion of PP on the water absorption of samples cured in both curing types is shown in Figures 4.17 and 4.18 below. From the Figures, the water absorption slightly decreases with increasing the pumice content. From Figure 4.17 for samples cured in water at room temperature, the absorption decreases from 1.01% to 0.77% with increasing of PP content from 0% to 10% and then decreases to 0.67% with PP content reaching 15%. Moreover, the same water absorption behavior was observed for samples cured in the controlled room, Figure 4.18, where the absorption decreased from 1.01% to 0.76% and then to 0.65% with the same PP content increasing level. This may relate to the same porosity decreasing reasons, as the pozzolanic reaction

of PP and GGBFS forming hydrate products that fill the pore and gap, also as the pumice powder and slag form denser content inside mortar structure (Giosuè *et al.* 2018, Kabay *et al.* 2015, Sadagopan 2021). A similar finding was achieved by (Atiyah *et al.* 2020), were observed a decrease in water absorption and porosity of mortars with increasing slag content also with longer curing time. Another research work achieved by (Rahman *et al.* 2022), obtained a decreasing behavior of porosity as the PP content increased, also with a long term curing period.

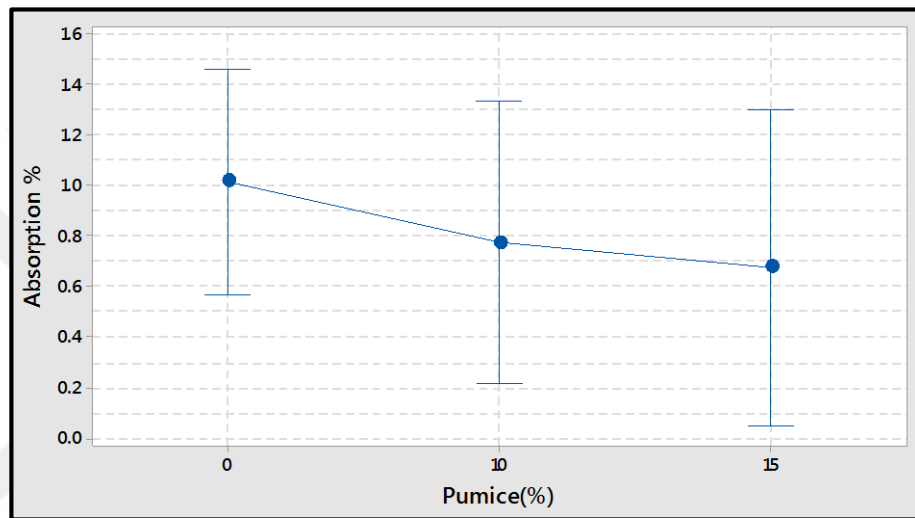


**Figure 4.17** Effect of PP on absorption of mixture cured in water at room temperature

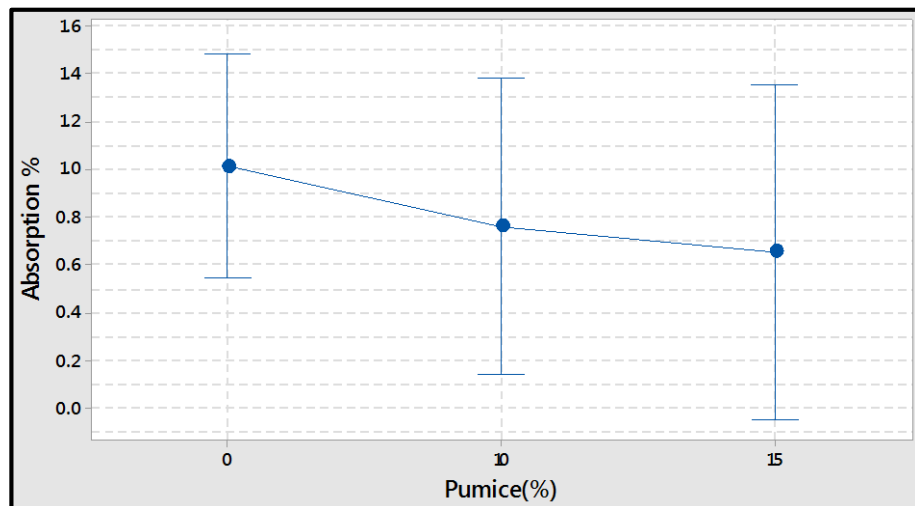


**Figure 4.18** Effect of PP on absorption of mixture cured in the controlled room

### 4.3 Compressive Strength

One of the most valuable properties of hardened mortar and concrete is compressive strength. Moreover, the compressive strength may indicate the overall performance of mortar and concrete. The compressive test results of mixtures samples containing GGBFS and PP and curing in room temperature water and in controlled heat and humidity curing room for (3, 7, 28, and 90) days are illustrated in Figures 4.19 and 4.20 respectively.

Figure 4.19 below that shows the compressive strength of samples cured in room temperature water for variant curing periods, is clearly shown that the reference mixture shows the maximum compressive strength value of 46.3 MPa after 3 days of curing age, while the lowest value is 25.66 MPa was for P15C50 mixture which contains 15% PP and 50% GGBFS. After 7 days of curing duration, the compressive strength values slightly increased than of 3 days curing age, and still, the highest value belongs to the reference mixture without any cement replacement which recorded 50.56 MPa, and the lowest compressive stress 33.3 MPa also belongs to P15C50 mixtures. After 28 curing days, even the compressive strength values obviously increased than of 3 days curing aged, the highest and lower value still belong to reference and P15C50 mixtures of 55.51 and 39.65 MPa. Compressive strength after 90 days curing age, recorded an obvious increase than of 3 days period and the highest value for P15C20 and P15C35 of 82.16 MPa and lowest compressive strength was for also P15C50 of 66.66 MPa. In addition, results demonstrate that all mixtures samples showed an increase in compressive strength with a long curing duration.

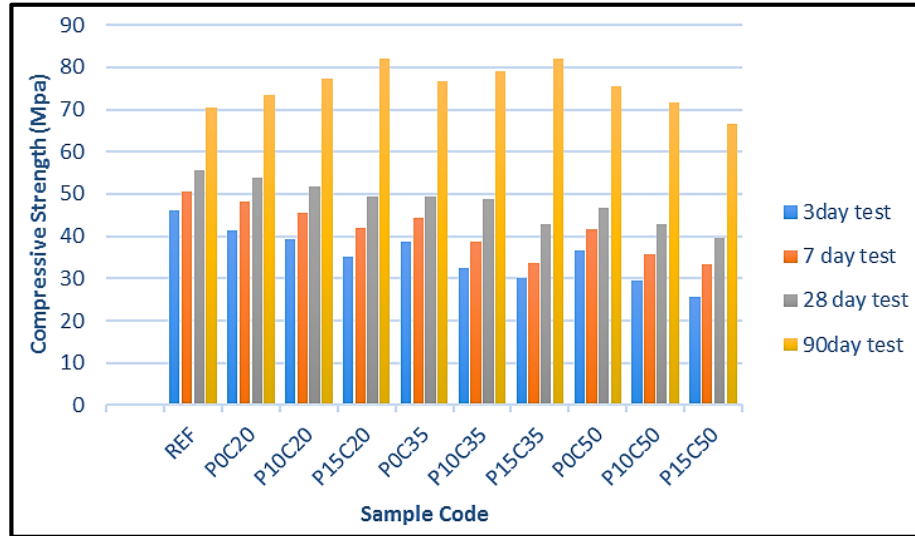


**Figure 4.19** Compressive strength of samples cured in room temperature water

Figure 4.20 shows the compressive strength results of samples cured in a controlled room with fixed temperature and humidity for different curing periods. From the Figure below can clearly be noticed that after 3 days of curing age the reference mixture has the highest compressive strength value of 52.3 MPa, and the lowest compressive strength is 36.7 MPa was for the P15C50 mixture which contains 15% PP and 50% GGBFS. Moreover, after 7 days of aging duration, still, the highest compressive strength value belongs to the reference mixture without any cement replacement, which was 56.31 MPa, and the lowest compressive stress 41.83 MPa also belongs to the P15C50 mixture. After 28 curing days, the maximum and minimum values still belong to plain and P15C50 mixtures, which were 61.97 and 41.53 MPa respectively. Obviously can see the compressive strength after 90 days of curing showed an obvious increase than of 3 days aging duration where the highest value for the P15C20 mix recorded 84.55 MPa and the lowest compressive strength was for the P15C50 mix that recorded 67.22 MPa.

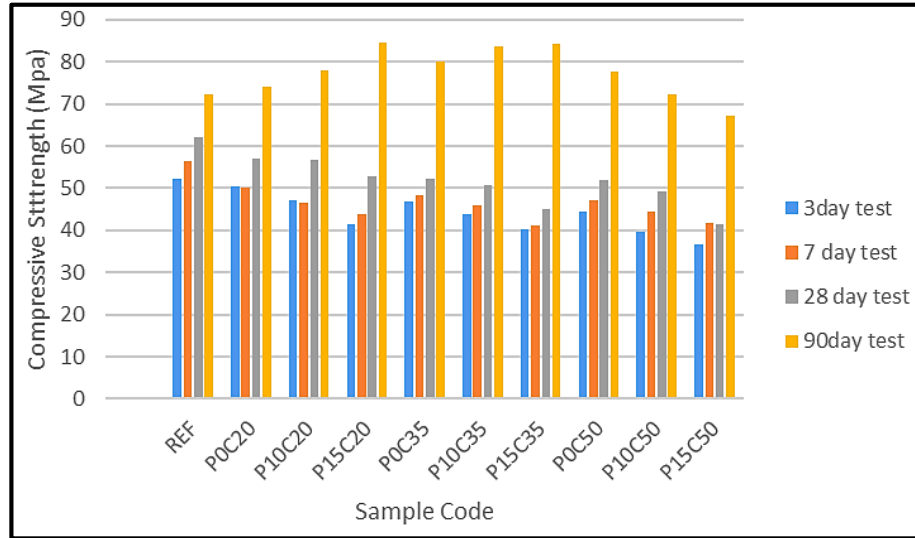


**Figure 4.20** Compressive strength of samples cured in controlled room

Generally, and in comparison, of both compressive strength results of mixtures cured in room temperature water and in the controlled room, the results obtained from the curing in the controlled room showed higher strength values than samples cured in room temperature water. This relates to the reason for forming high hydrated contents under the heating process also heating accelerates the pozzolanic activities and the inner voids and pores will be filled by hydrated materials (Hiremath and Yaragal 2017).

#### 4.3.1 Effect of GGBFS on compressive strength

Figures 4.21, 4.22, 4.23, and 4.24 illustrate the effect of GGBFS on the compressive strength after (3, 7, 28, 90) days of both types of curing.

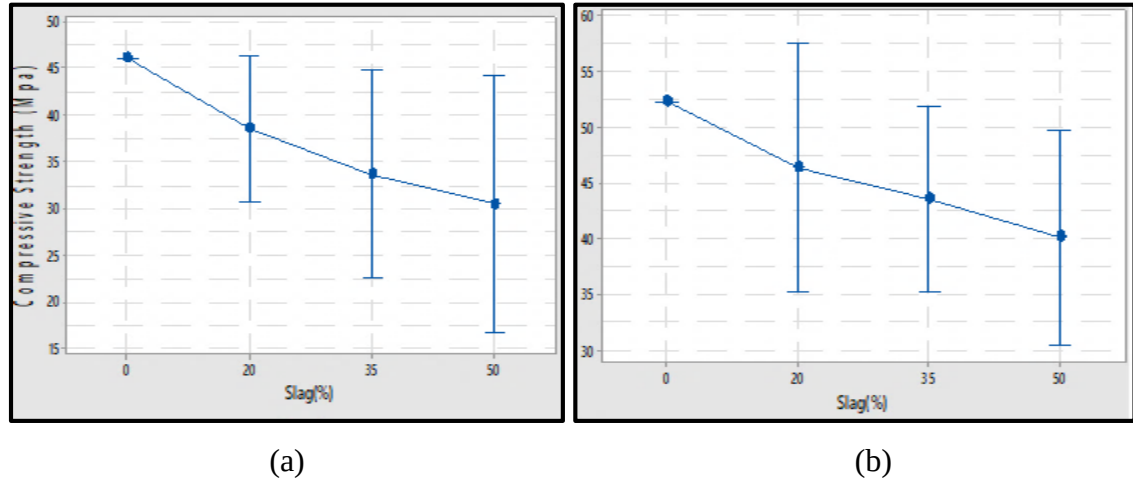


**Figure 4.21** Effect of GGBFS on compressive strength after 3 days of cured in: (a) water at room temperature, (b) controlled room

From Figure 4.21 can be examined the relationship between slag powder and compressive strength of 3 days curing in both of curing types. From the Figure above can clearly notice that the values of compressive strength decrease with increasing GGBFS contents levels. Whereat 0% GGBFS the compressive stress value was 52.3 and 46.2 MPa of both two curing types, which is the highest value. Moreover, when the GGBFS proportions increase to 20%, 35%, and then 50% the compressive strength decreases to (46.35, 43.6, and 40.18) MPa respectively for mixtures cured in a controlled room, and (38.62, 33.73, and 30.54) MPa respectively for samples cured in water at room temperature. this fact is related to the GGBFS Although it is a pozzolanic material but has a lower CaO content in comparison to ordinary pozzolanic cement which has >60%. However, as the GGBFS replacement levels increase, the Cao percentage decreases in the mixture leading to reducing the hydrated products, in results limiting the short-term compressive strength (Lim *et al.* 2012). Another reason is that the pozzolanic activities of GGBFS are relatively slow in comparison to ordinary pozzolanic cement, thus the mixtures without cement replacement; show a higher compressive stress development in the short term (Kenai *et al.* 2021). This is in line with other literature (Liu and Wang 2017) whereas the GGBFS mixture show disadvantage in early age curing (3 or 7) days but the compressive strength for a mixture containing GGBFS continues developing and achieving more strength with long-term aging than the plain mixture.

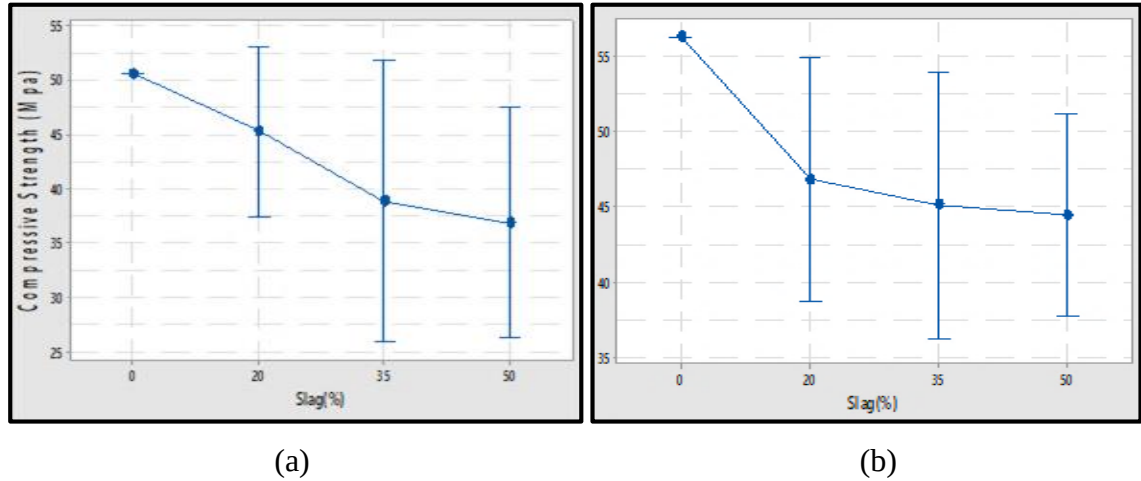


**Figure 4.22** Effect of GGBFS on compressive strength after 7 days of curing in: (a) water at room temperature, (b) controlled room

Figure 4.22 clarifies the GGBFS content effect on the development of compressive strength after 7 days of curing in room temperature water (Figure 4.22a) and in the controlled room (Figure 4.22b). From the Figure above and for after 3 days curing duration, the increase of GGBFS proportion caused to lowering the compressive strength values. Where for 0% GGBFS content the compressive strength recorded (50.56 and 56.31) MPa for room temperature water and controlled room of curing media, respectively. Moreover, as the GGBFS contents increase to 20 and 35 and then to the maximum content of 50%, and in both curing types, the compressive strength development is still slow in comparison to 0% GGBFS content. Where recorded (45.27, 38.88, and 36.85) MPa respectively for samples cured in room temperature water and for samples cured in the controlled room (46.86, 45.16, and 44.49) MPa respectively. As mentioned before the development of compressive strength in early curing duration, is relatively slow due to the GGBFS content which lowers hydrated products (Kenai *et al.* 2021, Liu and Wang 2017).

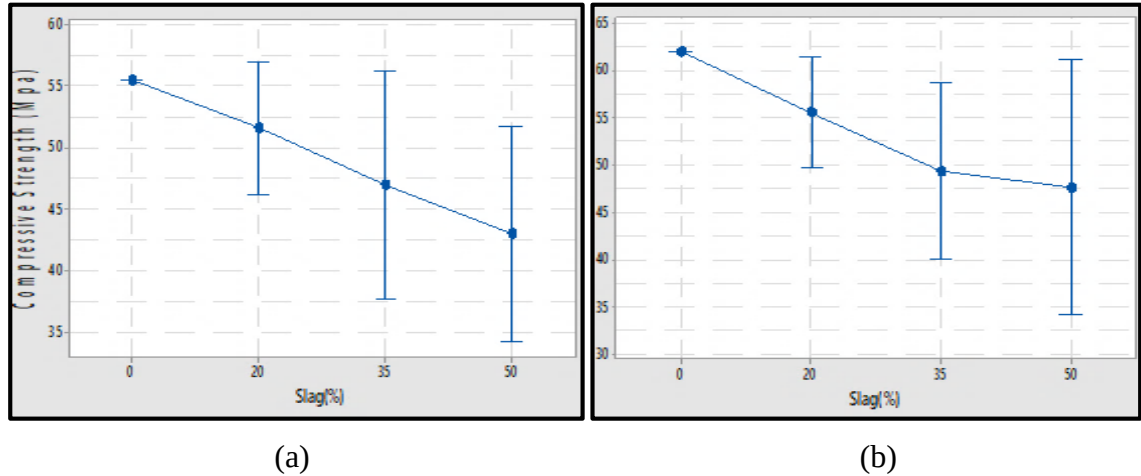


**Figure 4.23** Effect of GGBFS on compressive strength after 28 curing days in: (a) water at room temperature, (b) controlled room

Figure 4.23 shows the Effect of GGBFS contents on the development of compressive stress after 28 curing days in water at room temperature (Figure 4.23a) and in the controlled room (Figure 4.23b). As seen from the Figure, also increasing GGBFS content caused a lowering of the compressive strength. Whereas The Maximum value belonged to the mixture without GGBFS contents, which are (55.51 and 61.97) MPa for samples cured in water at room temperature and in a controlled room respectively. Moreover, the decrease continues as GGBFS content increased where the compressive stress recorded (51.61, 47, 43.03) MPa and (55.54, 49.37, 47.6) MPa for samples having (20, 35, 50)% GGBFS proportions and that cured in water at room temperature and in the controlled room, respectively. As mentioned before, there is a slow compressive strength development at the early curing term (up to 28 days), and additionally, it also relates to the fact that the GGBFS contains a glassy content, and they have a slow reaction with water need a long time, and in other words long curing period above 28 days (Lim *et al.* 2012).

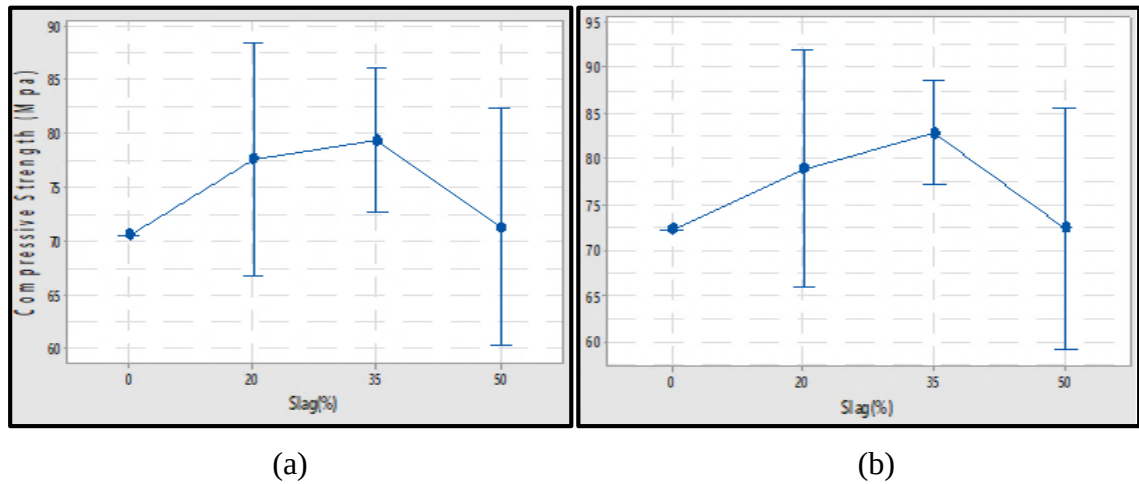


**Figure 4.24** Effect of GGBFS on compressive strength after 90 curing days in: (a) water at room temperature, (b) controlled room

Figures 4.24a and b above illustrate the effect of (after 90 days of curing) GGBFS contents on the development of compressive strength of samples cured in normal water at room temperature and in the controlled room. As clearly shown in the Figure above, the compressive strength development does not follow a linear behavior with increasing GGBFS contents, the values fluctuate between 79.73 MPa and 82.80 MPa for samples having 35% GGBFS that were cured in water at room temperature and in controlled room respectively, which are the maximum recorded compressive strength values. While the lowest value belongs to the reference mixture, which was 70.58 MPa for the sample cured in normal water and 72.25 MPa for the sample cured in a controlled room. This can be explained by the curing period that longer than 28 days is enough time for the glassy compound in GGBFS to react with water and gain hydroxyl ion from Portland cement hydrated products, and breaking the glassy parcels of GGBFS (Lim *et al.* 2012). Another reason is that the pozzolanic reaction in this stage of the curing period becomes advanced and nearly completed (Wang *et al.* 2021). In addition, because of the activity of pozzolanic reactions (reaction of  $\text{SiO}_2$  in GGBFS with  $\text{CaOH}_2$  in cement), creating more C-S-H gel in the mixture. Moreover, hydration will be filled the gaps and pores and lead to improvement in strength (Lim *et al.* 2012, Madallah *et al.* 2020). Samples that contained 20% GGBFS recorded values higher than the reference mixture where 77.62 MPa for sample cured in water at room temperature and 78.88 for sample cured in a controlled room. Other literature (Uysal *et al.* 2012) and (Boukendakdji *et al.* 2012) also reported similar results when adding GGBS as cement replacement which caused a

lowering of the compressive strength in short term, while giving an enhancement at the long curing period. However, as the GGBFS contents increased to 50% the compressive strength values reduced again to slightly above the reference value for samples cured in room temperature water and in the controlled room, where values were (71.32 and 72.4) MPa respectively. In this context, (Madallah *et al.* 2020) stated that the optimum content of slag incorporation end at 40%, and no more improvement of strength above this proportion. Another (Liu and Wang 2017) research gained slightly different compressive stress for concrete contained 50% GGBFS than plain concrete.

#### **4.3.2 Effect of PP on compressive strength**

Figures 4.25, 4.26, 4.27, and 4.28 illustrated the effect of PP contents on compressive stress development of samples cured for (3, 7, 28, and 90) days in the two different curing media.

Figure (4.25a and b) below illustrates the relationship of PP contents with the development of compressive strength for samples cured for 3 days in two different curing types. From the Figure, can notice that the increase in PP proportion decreases the compressive strength. Where the samples with (0, 10, and 15)% PP recorded compressive strength (40.72, 33.67, and 30.32) respectively for samples cured in water at room temperature, and (48.43, 43.55, and 39.43) MPa respectively, for samples cured in the controlled room. This can be explained as the pumice powder having slow pozzolanic activities, unlike ordinary Portland cement (Ghasemi *et al.* 2019).

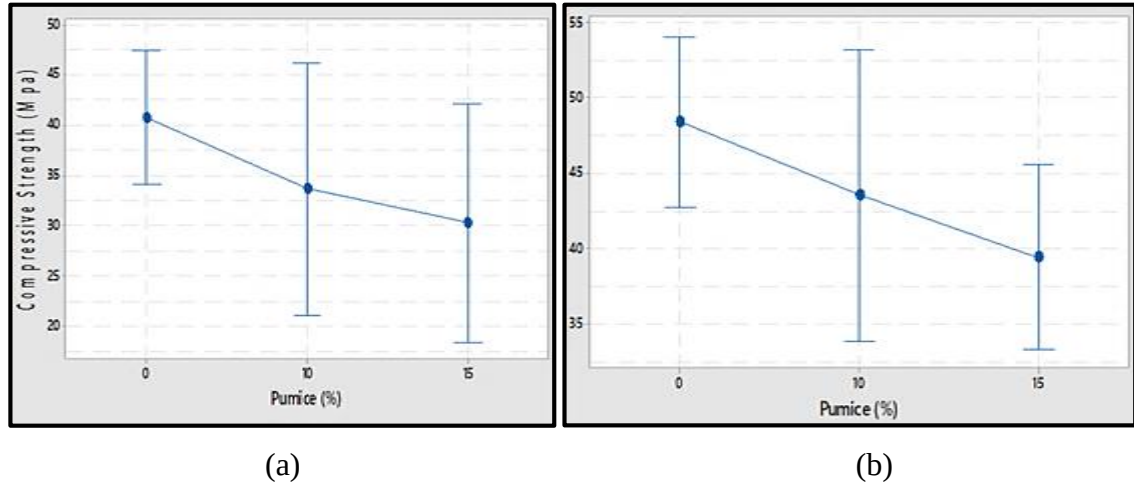


**Figure 4.25** Effect of PP on compressive strength after 3 curing days in: (a) water at room temperature, (b) controlled room

Effect of pumice powder proportion on compressive strength after 7 and 28 days illustrated in Figures 4.26 and 4.27 and in both curing media, (a) in room temperature water, (b) in the controlled room. As shown from the Figures below, after 7 and 28 curing days, the increased PP contents caused decreasing the compressive strength. After 7 days of treatment, samples with (0, 10, and 15)% PP achieved strength results (46.16, 39.98, and 36.33) MPa respectively, of curing in water at room temperature, and (50.51, 45.67, and 42.27) MPa respectively for samples cured in the controlled room. Moreover, after 28 days, the same compressive strength decreasing behavior was observed as PP content increased. Where samples cured in water at room temperature achieved strength (51.34, 47.78, and 43.91) MPa respectively, and for samples cured in the controlled room (55.83, 52.22, and 46.50) MPa respectively. Karatas 2017 and Hossain 2004 remarked that at the early curing stage the effect of adding pumice powder on compressive strength is negative. Due to the chemical effect as the pozzolanic reactions did not take place yet, in addition to the physical effect, as the fillers were not formed in a proper amount, and this disadvantage in the early aging term.

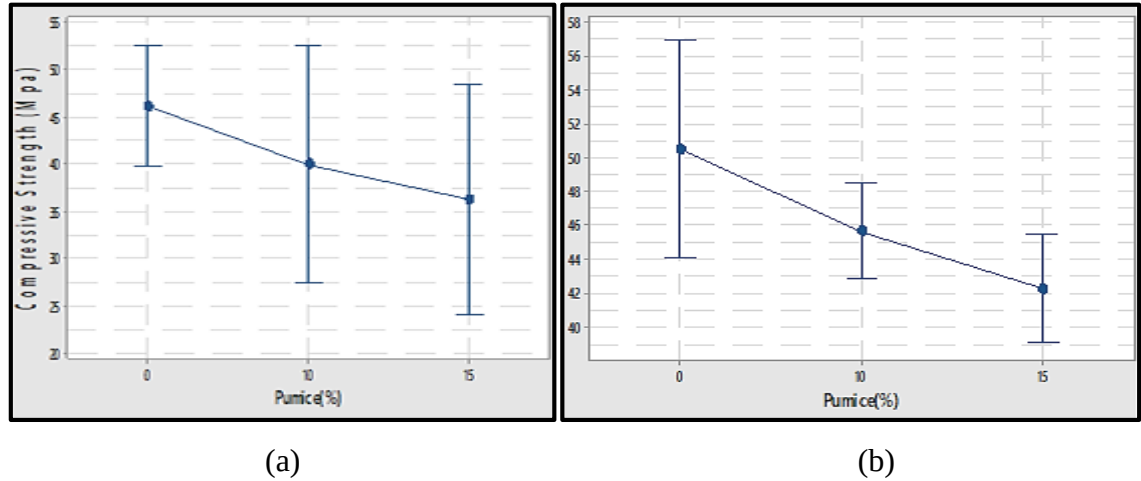


**Figure 4.26** Effect of PP on compressive strength after 7 curing days in: (a) water at room temperature, (b) controlled room

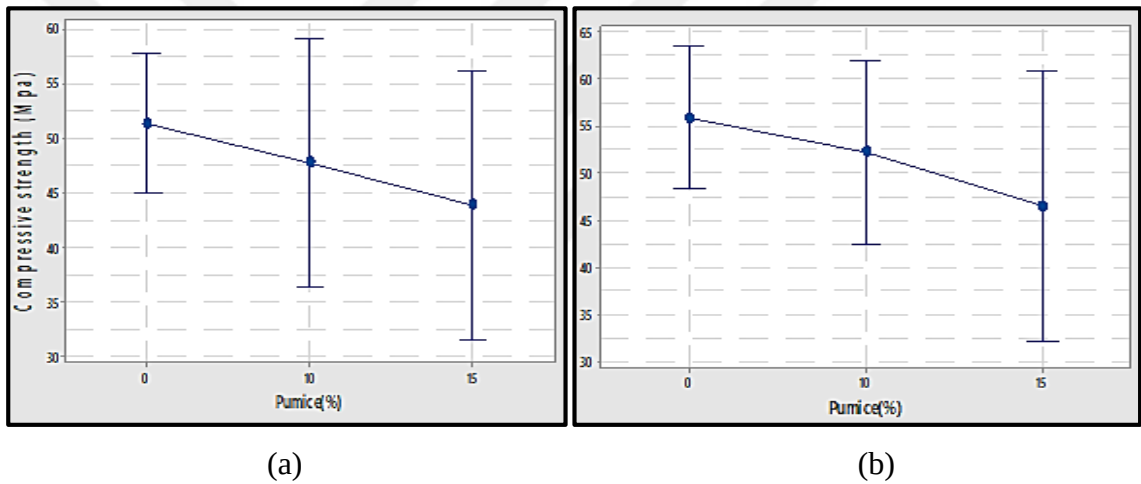


**Figure 4.27** Effect of PP on compressive strength after 28 days of curing in: (a) water at room temperature, (b) controlled room

Additionally, for 90 days of aging, as shown in Figure 4.28 below, an enhancement was observed as pumice powder inclusion increased. Whereat at (0, 10, and then 15) PP content achieved strength (74.09, 76.05, and 76.99) MPa respectively for those treated in water at room temperature, and for samples treated in the controlled room were (76.12, 77.95, and 78.72) MPa respectively. This increase in compressive strength can be explained as the 90 days of curing being enough for pozzolanic activities to take place and forming the filler to fill the gap and pores that reflected positively on improving the strength (Ghasemi *et al.* 2019, Granata 2015). Moreover, as stated by (Kabay *et al.* 2015) in their research work the compressive strength of concrete that contains PP, increases

gradually as the curing duration is extended, and the improvement will be observable after 28 days of curing. And that agrees with other literature (Rahman *et al.* 2022) stated that the mortars samples that contain pumice powder gained strength with time, attribute that the pumice helped the portlandite to be consumed during hydration, leading to improving the secondary binder of gels, and as a result, more strength for samples.

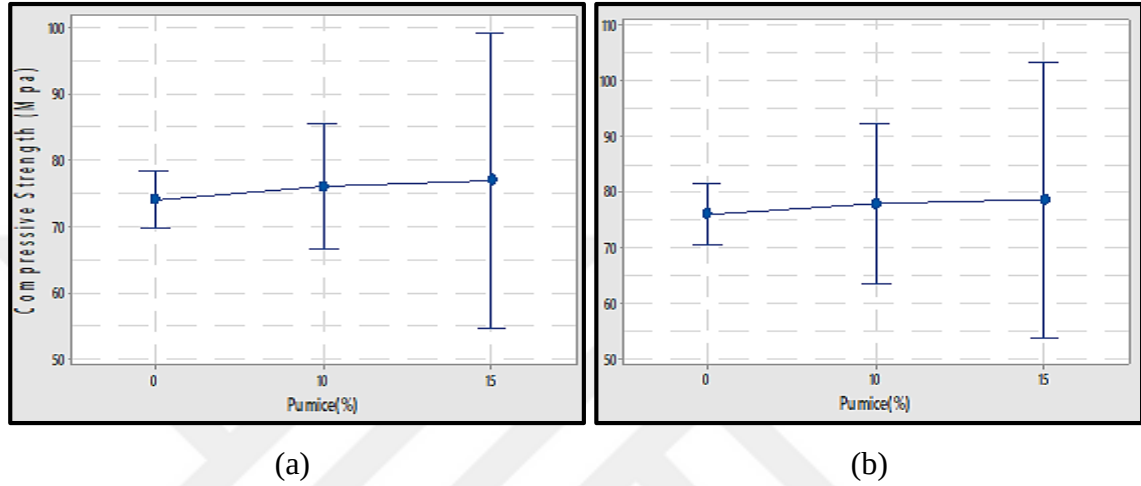


**Figure 4.28** Effect of PP on compressive strength after 90 curing days in: (a) water at room temperature, (b) controlled room

#### 4.4 Flexural Strength

Another important mechanical property was investigated in this research work. Figures 4.29 and 4.30 represented the flexural strength results for samples containing PP and GGBFS in addition to plain samples, which were cured in water at room temperature and in the controlled room of fixed humidity and temperature for (3, 7, 28, and 90) days curing period.

As shown in Figure 4.29 below, after 3 days of curing, the contribution of PP and GGBFS led to a decrease in the flexural values, where the maximum result belongs to the reference mixture of 3.14 MPa while the lowest result was 2.14 MPa for the P15C50 mixture that contains 15% PP and 50% GGBFS. For the 7 and 28 curing periods the maximum flexural result belongs to plain mixtures of (4.40 and 4.61) Mpa respectively. While the minimum values were (3.57, and 3.9) MPa for samples containing 15% PP and 50% GGBFS and

cured for (7, and 28) days respectively. Moreover, for 90 aging days, the maximum flexural strength value belongs to the sample with 15% PP and 20% GGBFS and the sample with 15% PP and 35% GGBFS, which recorded 5.61 MPa. While minimum value was for the mixture that included 15% PP and 50% GGBFS which achieved 5.06 MPa.



**Figure 4.29** Flexural strength for samples cured in water at room temperature

Figure 4.30 below describes the flexural results of samples cured in the controlled room. As shown after (3, 7, and 27) days the maximum values were for the reference mixture as (4.48, 4.65, and 4.88) MPa respectively, while the minimum values were for P15C50 samples as (3.75, 3.98, and 4.07) MPa respectively. Moreover, results of flexural strength that were achieved after 90 days of treatment show that the highest result was for the P15C20 sample with 15% PP and 20% GGBFS as 5.7 MPa and the lowest value belong to the sample with 15% PP and 50% GGBFs as 5.08 MPa.

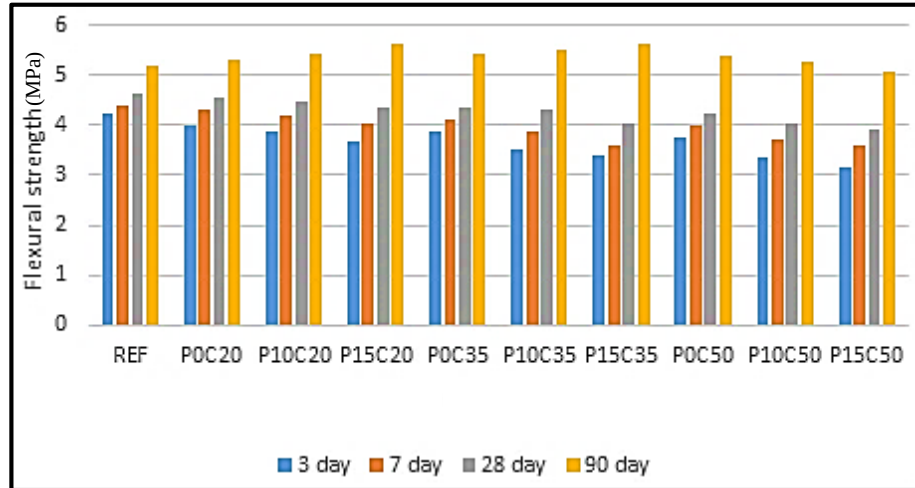


**Figure 4.30** Flexural strength for samples cured in the controlled room

#### 4.4.1 Effect of GGBFS on flexural strength

The effect of contributing GGBFS on flexural strength after (3, 7, 28, and 90) days of curing in water at room temperature and in the controlled room is illustrated in Figures 4.31, 4.32, 4.33, and 4.34 below.

As seen in Figures 4.31 and 4.32a and b, the influence of GGBFS after 3 and 7 of aging in water at room temperature and also in the controlled room on flexural strength behavior is similar to its effect on compressive strength in the short term. In another word, the increasing GGBFS contribution as a cement replacement limited the flexural strength in early curing. Where average flexural after 3 days of curing in water at room temperature was recorded (4.24, 3.85, 3.59, and 3.41) MPa, while in the controlled room was (4.48, 4.21, 4.09, and 3.92) MPa for (0, 20, 35, and 50)% of GGBFS. Moreover, the mean of flexural strength after 7 days was (4.4, 4.16, 3.86, and 3.75) MPa for cured in water at room temperature, and was (4.65, 4.25, 4.18, and 4.12) for cured in the controlled room, with (0, 20, 35, and 50)% of GGBFS contents respectively. Lim *et al.* 2012 and Wang *et al.* 2021 in their research works reported that at early curing, there is a decrease in flexural strength as GGBFS increases.

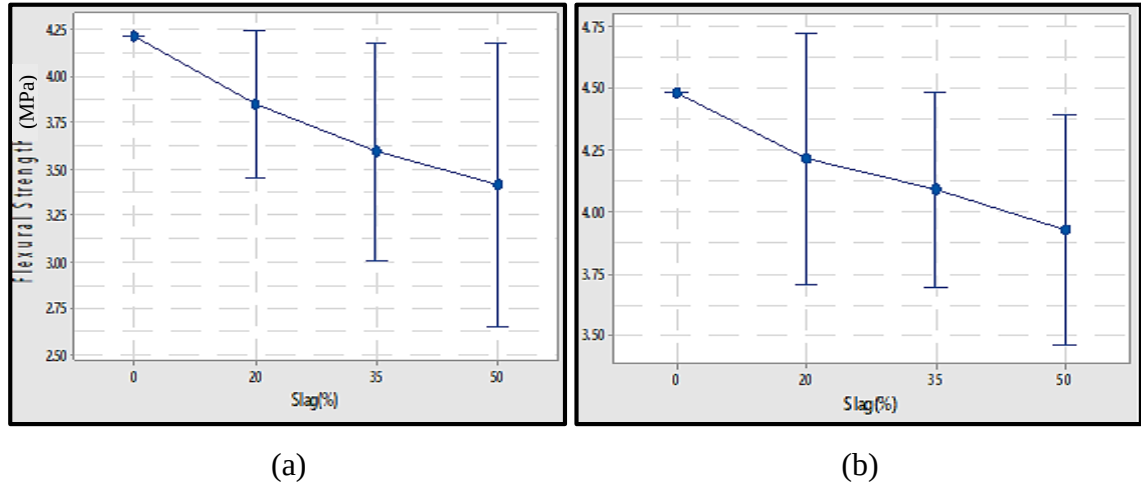


**Figure 4.31** Effect of GGBFS on flexural strength after 3 days of curing in: (a) water at room temperature, (b) controlled room

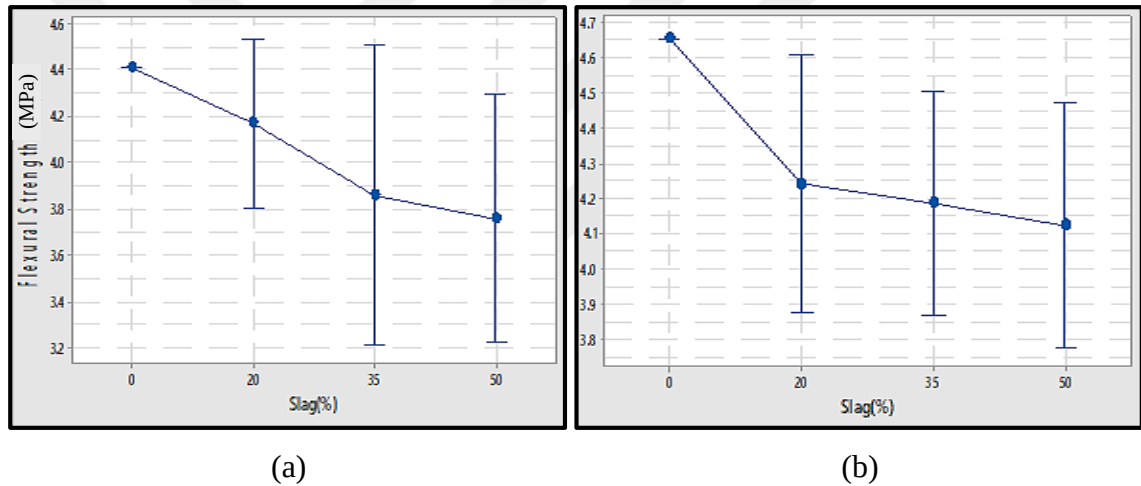


**Figure 4.32** Effect of GGBFS on flexural strength after 3 days of curing in: (a) water at room temperature, (b) controlled room

Figure 4.33 below describes the relationship of flexural with GGBS content after 28 days of curing. Can notice that as the GGBFS content increases the flexural strength still decreases. Where for (0, 20, 35, and 50)% GGBFS content, and for both curing media (normal water and control room), the corresponding flexural strength was (4.61, 4.45, 4.24, and 4.06) MPa and (4.88, 4.62, 4.35, and 4.29) MPa respectively. This can attribute to the pozzolanic reaction that did not take place yet at this stage of curing (Lim *et al.* 2012, Wang *et al.* 2021).

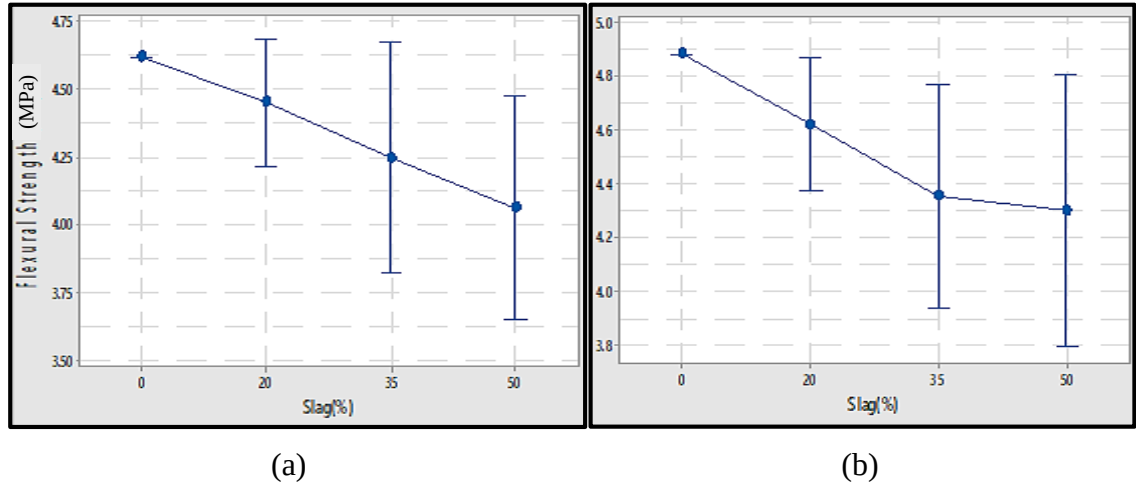


**Figure 4.33** Effect of GGBFS on flexural strength after 28 curing days in: (a) water at room temperature, (b) controlled room

After 90 days of curing in water at room temperature and in the controlled room (Figure 4.34 a and b), can clearly notice that the contribution of GGBFS led to enhancing Flexural strength up to 30% of GGBFS content. Where the value of flexural strength for mixtures cured in room temperature water, increases from 5.20 MPa at 0% slag and then to 5.46 MPa at 20% slag and reaches the maximum value of 5.52 at 30% slag. In addition, for mixtures cured in the controlled room, the flexure strength values were 5.27 MPa at 0% slag and 5.50 MPa at 20% slag, and then 5.64 MPa as the highest value at 30% of slag. This may relate to the GGBFS having a relatively slow pozzolanic activity unlike ordinary Portland cement and that may describe the negative effect at early curing term and its positive influence at long curing period (Mei *et al.* 2020). Also, demonstrate that the decreasing of flexural strength at early curing due to the activity of GGBFS is not stimulated enough (Zhu *et al.* 2012). Whoever, at 50% of slag content and in both curing types, the flexural strength recorded (5.23 and 5.27) MPa respectively, nevertheless, still slightly higher than values for reference mixtures. This meets with the results obtained by Karri *et al.* 2015 where achieved the optimum flexural strength at 40% slag and the value decreased as slag content become 50%. Another research (Mei *et al.* 2020) also observed that the flexural strength of mortar containing GGBFS starts to decrease with slag proportion at a higher level.

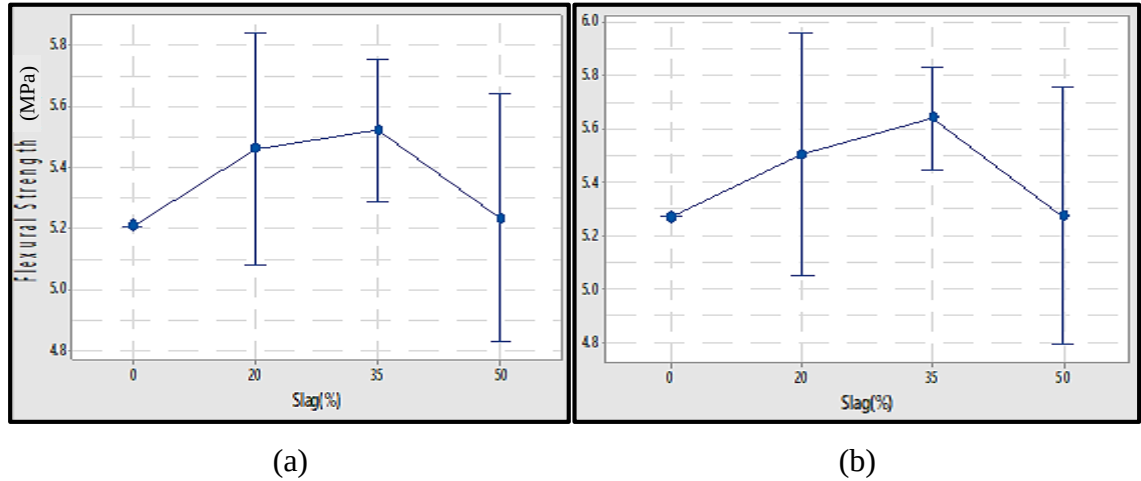


**Figure 4.34** Effect of GGBFS on flexural strength after 90 curing days in: (a) water at room temperature, (b) controlled room

#### 4.4.2 Effect of PP on flexural strength

The effect of PP on flexural strength after (3, 7, 28, and 90) days are illustrated in Figures (4.35, 4.36, 4.37, and 4.38) respectively.

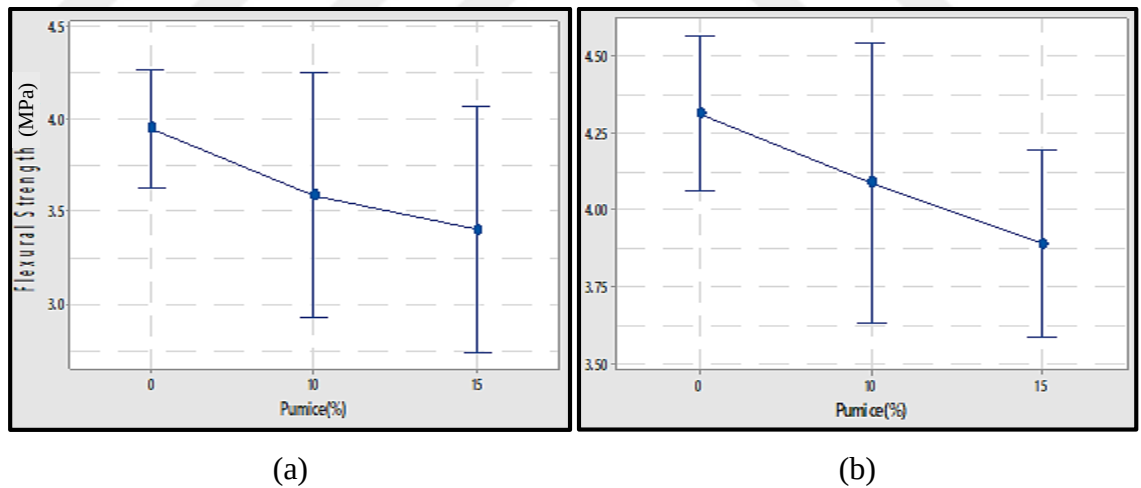


**Figure 4.35** Effect of PP on flexural strength after 3 curing days in: (a) water at room temperature, (b) controlled room

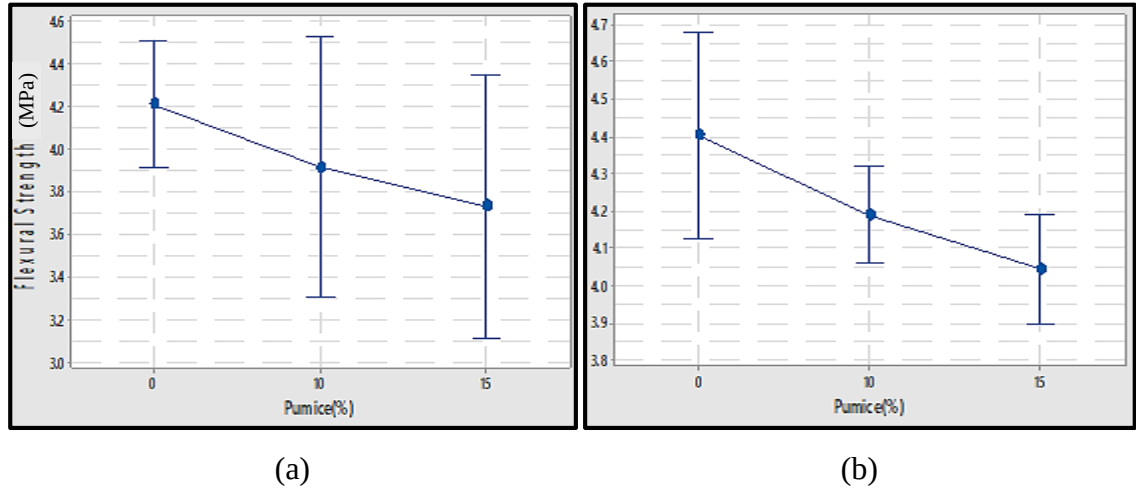


**Figure 4.36** Effect of PP on flexural strength after 7 curing days in: (a) water at room temperature, (b) controlled room

As shown in Figures 4.35 and 4.36 above, and at early aging (for 3 and 7) days, the effect of the contribution of PP led to a decrease in the Flexural strength in both curing media. Where the flexural strength values at 3 days of curing and at (0, 10, and 15)% of PP were (3.95, 3.59, and 3.4) MPa respectively in the normal water curing media and were (4.31, 4.08, and 3.89) MPa in the controlled room curing media respectively. Moreover, after 7 days of treatment, the flexure strengths were (4.2, 3.91, and 3.73) MPa respectively in normal water curing media, and in the controlled room, recorded (4.4, 4.18, and 4.04) MPa respectively. That is attributed to the pozzolanic activity of PP that cannot adequately appear its influence at the early curing (Karatas 2017, Ulusu *et al.* 2016) also provide this fact.

After 28 days of curing, (Figure 4.37a and b), and in both two curing types, flexural strength shows the same behavior of decreasing with the increase of PP contents, this is related to that the 28 days of aging is still not enough period to stimulate the pozzolanic activity of PP as confirmed by Karatas 2017 and Zeyad *et al.* 2019.

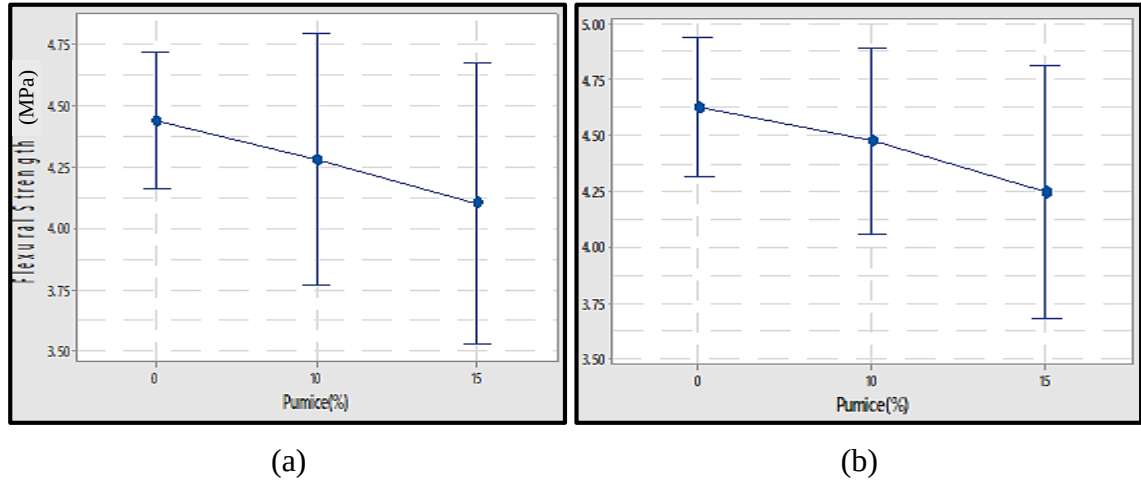
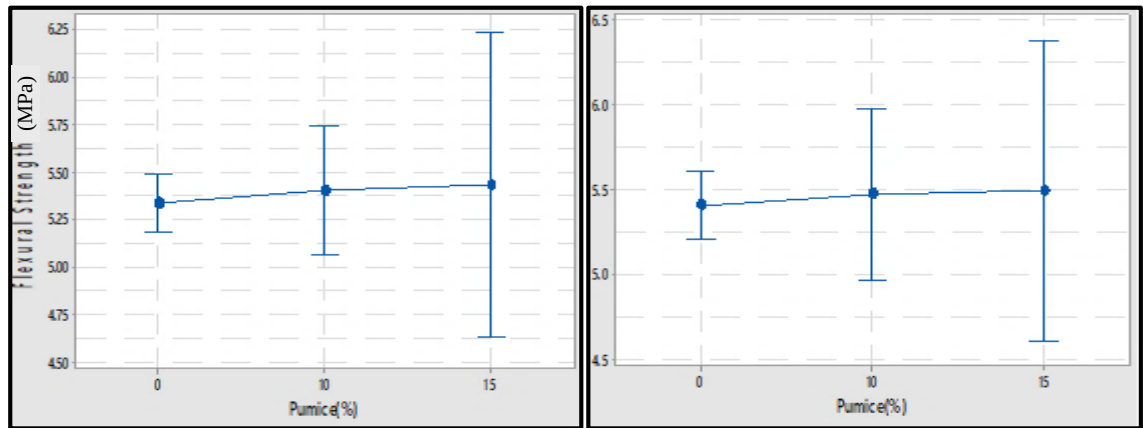


**Figure 4.37** Effect of PP on flexural strength after 28 curing days in: (a) water at room temperature, (b) controlled room

In addition, for 90 days of curing as shown in (Figure 4.38a and b) below, the positive effect PP on Flexural strength appears, as with increasing of PP content the flexural strength recorded higher values in comparison with the reference mixture. Where the flexural strength at (0, 10, and 15)% PP was (5.33, 5.40, and 5.43) MPa respectively, for cured in room temperature water, and was (5.4, 5.47, and 5.49) MPa respectively, for cured in the controlled room. This may attribute to the pumice powder having pozzolanic features and has the possibility of reacting with calcium hydroxide and forming an additional hydrate-silicate-calcium. However, this activity did not appear sufficiently at an early treating age (3, 7, and 28) days it needs a longer time, In other words, more than 28 days to take place, then the positive influence starts to appear on mechanical properties (Giosuè *et al.* 2018). In the same context, (Karatat 2017) obtained the highest value of flexural strength results after 90 days of curing, and with 15% of pumice powder as cement replacement.



(a)

(b)

**Figure 4.38** Effect of PP on flexural strength after 90 curing days in: (a) water at room temperature, (b) controlled room

## 5. CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

According to the results obtained from the experimental investigation of (GGBFS and PP/Mortars) cured in two different curing types, the conclusions may be drawn as in the following:

The influence of GGBFS and PP on the mortar fresh properties is as follows:

1. The increases in GGBFS content increased the flow values of all fresh mortar mixtures.
2. The effect of adding PP to the mixtures was negative on flow values.
3. Maximum flow value was 26 cm for the mixture with 50% GGBFS and 0% PP.
4. The minimum flow value belonged to the mixture that contains 15% GGBFS and 20% PP and was 20 cm.

The effect of the inclusion of GGBFS and PP on bulk density and porosity as well as the water absorption of the resulting mortar can be concluded as follows:

1. Utilizing GGBFS and PP as cement replacement led to the resulting mortar having lower bulk density, porosity, and water absorption in comparison to reference mortar.
2. In both curing types, the bulk density decreased as the content of GGBFS and PP increased.
3. The maximum bulk density was for the reference mixture in both curing media, where recorded (2.19 and 2.18) g/cm<sup>3</sup> in water at room temperature and in the controlled room respectively.
4. The maximum bulk density was for the reference mixture, in both curing media, where recorded (2.19 and 2.18) g/cm<sup>3</sup> in water at room temperature and in the controlled room respectively. While the minimum value for the mixture contained

15% PP and 50% GGBFS, which were (2.117 and 2.12) g/cm<sup>3</sup> for both curing types respectively.

5. Adding GGBFS and PP decreases the porosity and water absorption of mortar.
6. Maximum porosity was for reference mortar of 1.24% in water at room temperature and in the controlled room, and the minimum value was for the mixture with 50% GGBFS and 15% PP which showed porosity of 0.93% and 0.9% in the both curing types respectively.
7. Maximum water absorption belonged to the reference mixture and in water at room temperature and in the controlled room with 1.4% and 1.41%, and the minimum was for 50% GGBFS and 15% PP mixture, which showed water absorption of 0.39% and 0.33, in both curing types respectively.

The effect of adding GGBFS and PP content as cement replacement on compressive and flexural strength can summarize as follows:

1. In both curing types, the inclusion of GGBFS and PP as cement replacement has a negative influence on compressive and flexural strength at the early curing stage, while giving positive values in the long term, in another word, after 28 days of aging. that due to pozzolanic reaction in long-term curing becomes advanced and nearly completed (Wang et al. 2021). Moreover, the activity of pozzolanic reactions creates more C-S-H gel in the mixture. in addition, the pores and gaps will be filled by hydration and enhance the strength (Lim et al. 2012, Madallah et al. 2020). This met with other literature (Uysal et al. 2012) and (Boukendakdji et al. 2012) when applied GGBS as cement replacement, caused a decreasing of the compressive strength in short term, while giving an improvement at the long curing period. In same context, similar results were obtained by (Karatas 2017), when including 15% of pumice powder as cement replacement, recording the optimum flexural strength results after 90 days of treatment.
2. The mixtures that were treated in the control room showed higher compressive and flexural values than mixtures that were treated in water at room temperature, and at all curing periods.
3. The values of compressive and flexural strength increased with longer mortar age.

4. The observable enhancement of compressive strength was at 90 days of curing, where the mixture with 15% PP and 20% GGBFS as well as the mixture with 15% PP and 35 % GGBFS and cured in room temperature water showed a compressive value of 82.16 MPa as maximum compressive value. Moreover, for curing in the controlled room the maximum compressive strength was for the mixture with 15% PP and 20% BBGFS. However, a further increase of GGBFS content above 35% led to a decrease again in the compressive strength.
5. The maximum flexural strength was observed at 90 days of aging in both curing types, for room temperature curing media, the mixture with 15% PP and 20% GGBFS and the mixture with 15% PP and 35% GGBFS, showed a flexural value of 5.61 MPa. In addition, for controlled room curing media, the maximum flexural strength was 5.7 MPa. For the mixture with 15% PP and 20% GGBFS. Whoever, and as in the compressive strength, the optimum GGBFS content was 35% and further increasing caused a decrease in flexural strength again.

## **5.2 Recommendations**

Many suggestions and future work can be listed as follows:

- Study the effect of cement type on Mortar properties.
- Utilizing other types of curing such as curing in the furnace or curing in the air at ambient temperature.
- Study of mortar mechanical properties at long-term longer than 90 days of aging.
- By utilizing the same replacement materials, a study on GGBFS and PP/Mortar durability such as (fire and chemical resistance, high-temperature performance, permeability, strength development mechanism), should be achieved.
- Achieving an investigation on properties like (creep, shrinkage, stress-strain behavior in (compression and tension), and modulus of static and dynamic).
- Adding another type of pozzolanic material besides GGBFS and PP and investigating their influence on resulting mortar performance.

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| MSc           | Çankırı Karatekin University<br>Graduate School of Natural and Applied<br>Sciences Department of Chemical<br>Engineering, Çankırı, Turkey | 2019-Present |
| Undergraduate | Almuthana University<br>Faculty of Engineering<br>Department of Civil Engineering,<br>Almuthana, Iraq                                     | 2010-2014    |

### Work Experience

| Year      | Institution/Adress                                | Position         |
|-----------|---------------------------------------------------|------------------|
| 2015-2016 | Almuthana Technical Institute,<br>Almuthana, Iraq | Research Asst.   |
| 2017-2018 | Project of Almuthana Stadium,<br>Almuthana, Iraq  | Project Engineer |