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OPTIMIZATION OF WATER TREATMENT PLANT SLUDGE AND SLAG-BASED GEOPOLYMER CONCRETE TO PRODUCE AN ENVIRONMENTALLY FRIENDLY ALTERNATIVE TO TRADITIONAL CONCRETE

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ABSTRACT

Annually, 635 million cubic meters of water treatment plant sludge (WTPS) is produced in Egypt and is treated as waste and disposed back to the Nile River. Alternative disposable routes, such as using WTPS as a binder in construction applications, are under consideration. Also, industrial by-products such as ground granulated blast furnace slag (GGBFS), fly ash, and other aluminosilicate sources are commonly used as binders for geopolymers, which are explored as potential replacements for cement due to their lower carbon dioxide emissions, with reduction of approximately 800 kg/ton compared to traditional cement production. Utilizing WTPS and GGBFS as binders for geopolymer concrete provides an economical and environmentally friendly alternative to cement. This study investigates the optimum geopolymer concrete mix using a combination of WTPS and GGBFS as a binder to investigate their mechanical properties to be used for construction applications. Various mixing ratios of GGBFS to WTPS (50:50 and 25:75) were studied. The activator solution consisted of sodium silicate (Na2SiO3) and sodium hydroxide (NaOH), with a solution modulus of 1.0 for all developed mixes. The Na_2O to binder ratio varied between 10%, 12%, and 14% for each GGBFS-WTPS ratio. Workability was assessed using the slump test, while compressive strength was determined using cubic specimens from each developed mix. The optimum geopolymer concrete mix was identified as having a 50:50 WTPS to GGBFS ratio, with the optimum Na_2O to binder ratio of 10%. The optimum mix gave a slump value of 22 cm and a 28-day compressive strength of 36.7 MPa.

KEYWORDS: Ground granulated blast-furnace slag; Solution modulus; Na_2O to binder ratio; Slump test; compressive strength test.

تحسين الخرسانة الجيوبوليمرية القائمة على الحمأة والخبث في محطات معالجة المياه لإنتاج بديل صديق للبيئة للخرسانة التقليدية

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الملخص

يُنتج في مصر سنويًا ٦٣٥ مليون متر مكعب من رواسب محطات معالجة المياه (WTPS)، وتُعالج كنفايات وتُعاد إلى نهر النيل. ويجري حاليًا دراسة طرق بديلة للتخلص منها، مثل استخدام WTPS كمادة رابطة في تطبيقات البناء. كما تُستخدم المنتجات الثانوية الصناعية، مثل خبث فرن الصهر الحبيبي المطحون (GGBFS)، والرماد المتطاير، ومصادر ألومينوسيليكات أخرى، بشكل شائع كمواد رابطة للجيوبوليمرات، والتي تُستكشف كبدائل محتملة للأسمنت نظرًا لانخفاض انبعاثات ثاني أكسيد الكربون فيها، مع انخفاض يُقارب ٨٠٠ كجم/طن مقارنةً بإنتاج الأسمنت التقليدي. يوفر استخدام WTPS وGGBFS كمواد رابطة للخرسانة الجيوبوليمرية بديلاً اقتصاديًا وصديقًا للبيئة للأسمنت. تبحث هذه الدراسة في مزيج الخرسانة الجيوبوليمرية الأمثل باستخدام مزيج من WTPS وGGBFS كمادة رابطة، وذلك لدراسة خصائصها الميكانيكية التي يمكن استخدامها في تطبيقات البناء. دُرست نسب خلط مختلفة من GGBFS إلى WTPS (٥٠:٥٠ و٧٥:٢٥). تكوّن محلول المنشط من سيليكات الصوديوم (Na_2SiO_3) وهيدروكسيد الصوديوم (NaOH)، بمعامل حل ١,٠ لجميع الخلطات المُطوّرة. تراوحت نسبة Na_2O إلى المادة الرابطة بين ١٠٪ و١٢٪ و١٤٪ لكل نسبة من GGBFS إلى WTPS. قُيّمت قابلية التشغيل باستخدام اختبار الانكماش، بينما حُدّدت قوة الضغط باستخدام عينات مكعبة من كل خلطة مُطوّرة. حُدّدت خلطة خرسانة الجيوبوليمر الأمثل بنسبة ٥٠:٥٠ من WTPS إلى GGBFS، مع نسبة Na_2O إلى المادة الرابطة المثلى ١٠٪. أعطى الخلط الأمثل قيمة انكماش ٢٢ سم وقوة ضغط ٣٦,٧ ميجا باسكال لمدة ٢٨ يومًا.

الكلمات المتاحية : خبث الفرن العالي الحبيبي المطحون؛ معامل الانحلال؛ نسبة Na_2O إلى المادة الرابطة؛ اختبار الانكماش؛ اختبار قوة الضغط.

1. INTRODUCTION

Nowadays, there is an increasing demand to find alternatives to cement for various construction applications, driven by the negative environmental impact of cement production. The cement industry contributes approximately 8% of global carbon dioxide (CO_2) emissions [1]. This concern has led to exploring geopolymers as an alternative to ordinary Portland cement (OPC). The production process of geopolymers emits significantly less CO_2 compared to OPC, with a reduction of around 800 kg per ton [2]. Additionally, shifting to geopolymers offers enhanced mechanical properties and durability for construction applications. Geopolymers provide high compressive strength, making them suitable for structural applications [3]. Moreover, geopolymers utilizing industrial by-products such as ground granulated blast-furnace slag (GGBFS), fly ash, rice husk, water treatment plant sludge (WTPS), and other aluminosilicate materials help in waste management and reducing landfill usage [4 & 5]. Other substitutes for cements are for example rice husk, metakoline, bentonite and glauconite [6]. Also, some research has tested substituting fine aggregate with pretreated rubber to help in waste management [7].

In Egypt, a vast amount of WTPS is produced annually, and this WTPS is considered waste and is discharged back into the Nile River. However, WTPS is rich in silica, aluminum, and iron hydroxide, making it a suitable precursor for geopolymers. Utilizing WTPS in geopolymer production offers an environmentally friendly disposal method that aligns with multiple Sustainable Development Goals (SDGs) [8]. Using WTPS as an alternative binder to cement demonstrates promising mechanical properties. WTPS has been utilized as a substitute for cement mortar, concrete, and fine aggregates [9-15]. Haider et al. (2013) replaced 6% of cement with WTPS and found that this significantly enhanced compressive strength [11]. Another by-product used in geopolymer production is GGBFS. GGBFS has been used to replace OPC and sand, yielding superior mechanical properties [16-20]. Didamony et al. (2014) replaced 5% of cement with GGBFS and WTPS, concluding that this was the optimum replacement percentage for achieving good mechanical properties [12]. Geraldo et al. (2017) used WTPS as a precursor with an activator solution, replacing metakaolin to produce a geopolymer. They recorded a compressive strength of 28 MPa for a mix with 15% WTPS replacement [13]. Hagemann et al. (2019) activated WTPS by drying, calcining at 700°C for 1 hour, and grinding for 1 hour, achieving a compressive strength of 80 MPa for a 15% replacement of activated WTPS for cement [14]. Oliveira et al. (2024) have studied the replacement of cement with WTPS in self-compacting mortars. The research concluded that the replacement of cement with 2.5% and 10% WTPS increased the compressive strength by 27.3% and 30%, respectively [15]. Abdelhalim et al. (2025) studied the activation of WTPS through calcination at different temperatures (500-800˚C) with different durations (30-90 minutes). A Chapelle test was conducted for the different WTPS powder samples to obtain the optimum calcination temperature and duration. Then, the findings of the Chapelle test were verified through chemical and mechanical tests carried out on mortar specimens prepared by the activated WTPS.

This previous research concluded that the optimum calcination regime was calcining the WTPS powder at 650˚C for 90 minutes. This research has determined the compressive strength of different mixing ratios of the activated WTPS and GGBFS on a mortar scale using alkaline activator of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) with different solution modulus (Ms) values and constant Na_2O to binder ratio of 12%. The compressive strength test carried on mortar specimens concluded that a mixing ratio of (50:50) of WTPS:GGBFS gave around 21 MPa, while the mixing ratio (100:0) of WTPS:GGBFS gave around 12 MPa. Also, this study concluded that the optimum Ms value is 1.0. In addition, the authors studied the energy and economic feasibility of using activated WTPS instead of cement. It was concluded that WTPS provides an economic and energy-efficient alternative to cement, as the production of WTPS requires 92% less energy and costs almost 50% less than cement production [21]. Amer et al. (2021) studied the activation of hybrid cement, which was a mix of high ratios of slag with a lower ratio (up to 30%) of OPC. In this study, OPC and GGBFS were used as binders in various percentages with an alkaline activator made of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The parameters studied included the slag-to-cement ratio, solution modulus (Ms), Na_2O ratio, and water-to-binder ratio. The mixes were cured at ambient temperature, and compressive strength and workability tests were conducted. The highest compressive strength was recorded for the mix with 100% GGBFS. The authors concluded that the optimum W/B ratio was 0.45, the optimum Ms ratio was 1.0, and the optimum Na_2O ratio was 10% [18]. Also, Sawant et al. (2023) have replaced cement with GGBFS at 10%, 20%, and 30% and tested the compressive strength at different ages. The authors did not use an activator solution in this study. The authors have concluded that the optimum compressive strength was 40.57 MPa at 20% replacement percentage [19]. Cheruvu et al. (2024) investigated the replacement of cement with GGBFS at different percentages and concluded that a 30% replacement value was the optimum with a 28-day compressive strength of 56.89 MPa [20].

According to the presented literature review, the use of WTPS and GGBFS in producing construction materials offers superior properties compared to OPC. However, there is limited research assessing the mechanical properties of WTPS-based geopolymer concrete. This study is the second phase of the previous research that studied the different activation regimes for WTPS and justified the findings through testing mortar specimens. This paper aims to determine the optimum concrete mix for WTPS-based geopolymer incorporating GGBFS. The incorporation of

GGBFS is to develop concrete mixes of high mechanical properties. This involves mixing WTPS with GGBFS in various ratios. The activator solution used consists of sodium silicate and sodium hydroxide. The research tested the Na_2O to binder ratio and maintained the solution modulus equal to 1.0 for all of the tested mixes. The mixing ratios, solution modulus, and the different Na_2O to binder ratios were selected according to past research of Abdelhalim et al. (2025) and Amer et al. (2021) [18&21]. Slump and compressive strength tests were conducted to evaluate the workability and mechanical characteristics of the developed geopolymer concrete mixes.

2. MATERIALS AND METHODS

2.1. Raw materials

GGBFS and WTPS were the binders used in this study. The GGBFS was obtained from a local producer in Egypt, while the WTPS was delivered from the 6th of October water treatment plant in Giza, Egypt. The WTPS was first dewatered in a drying oven at 90°C for 24 hours. It was then ground in ball mills until reaching a specific surface area of 6750 cm^2/g, as measured by the Blaine test, ASTM C204-07 [22]. The raw powdered WTPS was then activated to function as a binder by calcining it in a heating oven at 650°C for 90 minutes. The preparation method of WTPS powder used in this study was based on the findings of a recently published study by the same research project and authors [21]. **Fig. 1** and **Fig. 2** show the WTPS powder after treatment and the GGBFS powder. The chemical composition of the GGBFS and treated WTPS used in this study is presented in **Table 1**. The specific gravity of GGBFS and WTPS was 2.8 and 2.64, respectively. The specific gravity of the WTPS was determined according to ASTM C188-17 [23]. Natural sand, with a fineness modulus of 2.56, was used as the fine aggregate in this study. The coarse aggregates used had a specific gravity of 2.63.

Fig. 1: WTPS-treated powder

Fig. 2: GGBFS powder

The activator solution used in this study was a mixture of Na_2SiO_3 and NaOH, both sourced from a local producer in Egypt. The Na_2SiO_3 was in liquid form, while the NaOH was in flake form. The chemical composition of the NaOH and Na_2SiO_3 used was 60.25% Na_2O, 39.75% H_2O, and 31.0% SiO_2, 12.0% Na_2O, and 57.0% H_2O, respectively.

Table 1: Chemical composition of the GGBFS and treated WTPS (mass %).

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	TiO_2	Mn_2O_3
GGBFS	41.66	13.96	1.49	34.53	5.53	0.97	0.49	---	0.58	0.35
WTPS	59.20	18.00	8.68	5.72	1.67	1.08	0.56	0.77	1.47	---

2.2. Mixing Matrix

This study aims to determine the optimum concrete mix for WTPS-based geopolymer incorporating GGBFS. Concrete mixes with different GGBFS to WTPS ratios were tested, and for each ratio, various Na_2O to binder ratio values were evaluated. The two GGBFS: WTPS ratios tested were 25:75 and 50:50. These ratios were chosen because the 0:100 ratio gave very low compressive strength, while the 50:50 gave good compressive strength. The solution modulus (Ms) for all developed mixes was kept constant at 1.0. The different Na_2O to binder ratio values studied were 10%, 12%, and 14%. Based on these parameters, six different mixes were developed, as presented in **Table 2**. For all these mixes, the binder content and water-to-binder ratio were kept constant at 500 kg/m^3 and 0.45, respectively. The mix proportions of these six mixes are presented in **Table 3**.

Table 2: Mixing matrix.

Mix Code	GGBFS: WTPS	Ms	Na_2O
Mix 1	25:75	1.0	10
Mix 2	25:75	1.0	12
Mix 3	25:75	1.0	14
Mix 4	50:50	1.0	10
Mix 5	50:50	1.0	12
Mix 6	50:50	1.0	14

Table 3: Mixing proportions of all developed mixes by weight (per 1 m3).

Mix Code	GGBFS (kg)	WTPS (kg)	Na_2SiO_3 (kg)	NaOH (kg)	Water (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)
Mix 1	125	375	161	51	113	488	999
Mix 2	125	375	194	61	90	485	993
Mix 3	125	375	225	71	68	482	987
Mix 4	250	250	161	51	113	490	1004
Mix 5	250	250	194	61	90	487	988
Mix 6	250	250	226	71	68	484	992

2.3. Mixing Protocol

First of all, the cube molds that were used in this study were painted with oil and placed on a vibrating table. To prepare the six concrete mixes, the activator solution was first prepared. The activator solution was prepared by dissolving the NaOH flakes in potable water, after which the Na_2SiO_3 was added to the mixture. The solution was left to cool to a temperature between 30-35°C before being added to the tested concrete mixes. The dry materials, WTPS, GGBFS, fine aggregates, and coarse aggregates were added to the mixing drum and mixed for one minute. Then, the activator solution was added gradually while mixing, and all the components were left to mix for one minute. The concrete was poured into each mold and vibrated for one minute. The surfaces of the cubes were leveled, and then the molds were moved into a secure area to cure at ambient temperature until testing age at 7 days and 28 days. While pouring the concrete into the molds, the slump test was carried out by pouring the concrete in the slump cone and determining the slump value. **Fig. 3** shows a schematic diagram that illustrates the steps of the following mixing protocol.

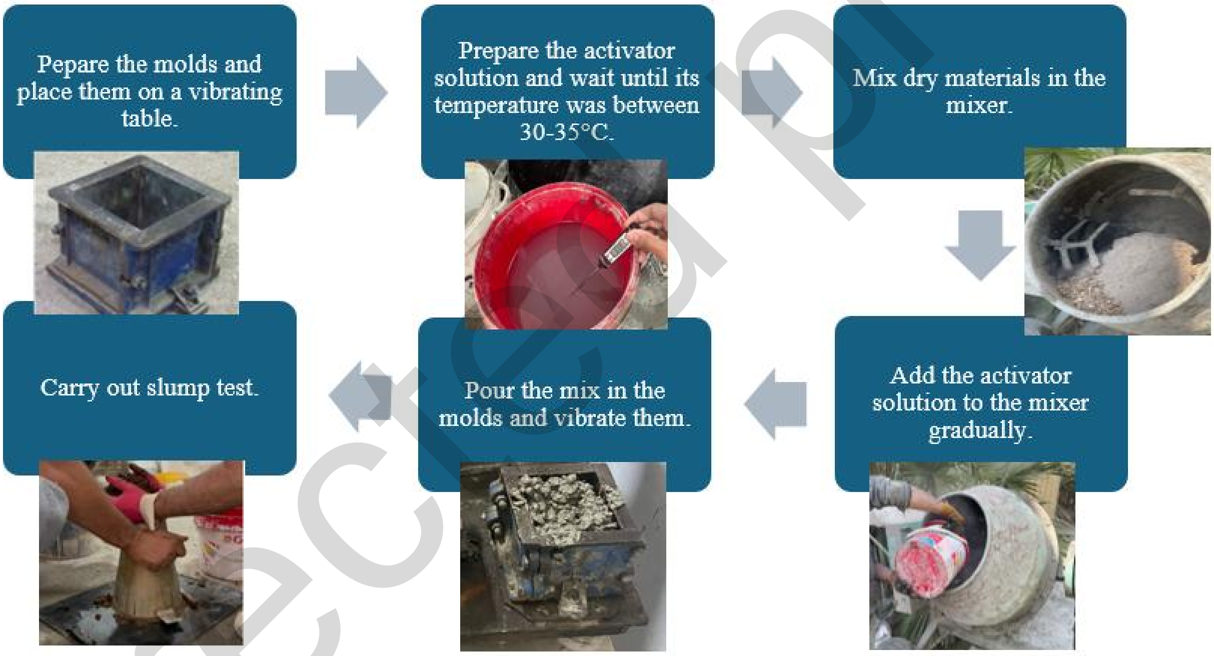

Fig. 3: Steps of the followed mixing protocol

2.4. Test Method

To determine the optimum mix from all developed GGBFS/WTPS-based geopolymer concrete mixes, a compressive strength test and a slump test were conducted on all mixes to assess their mechanical performance and workability, respectively.

The slump test was conducted according to ASTM C 143 [24] to assess the workability and fluidity of the developed geopolymer concrete mixes. The test involved filling the standard slump cone in three layers, with each layer being rodded 25 times using the standard tamping rod. Afterward, the slump cone was lifted straight up without any side motions. The shape of the failure was then assessed, and the slump was measured using a measuring tape.

The compressive strength test was conducted on all mixes according to BS EN 12390-3 [25] to assess their mechanical performance. The compressive strength of each mix was determined at 7 and 28 days. Three cubic specimens were prepared for each testing age to be tested under compression. The test specimen dimensions were 10×10×10 cm. The specimens were cast in steel molds by BS EN 12390-1 [26]. The specimens were removed from the molds after 24 hours and left to cure in the lab at an ambient temperature of 25 ± 2 °C until the testing age. The average compressive strength of the three specimens was calculated at each tested age and used for comparison.

3. RESULTS AND DISCUSSION

3.1. Slump Test

The slump value for each of the six developed mixes was measured immediately after the mixing process was completed. The results are presented in **Fig. 4,** while **Fig. 5** shows the obtained slump shape for each tested mix.

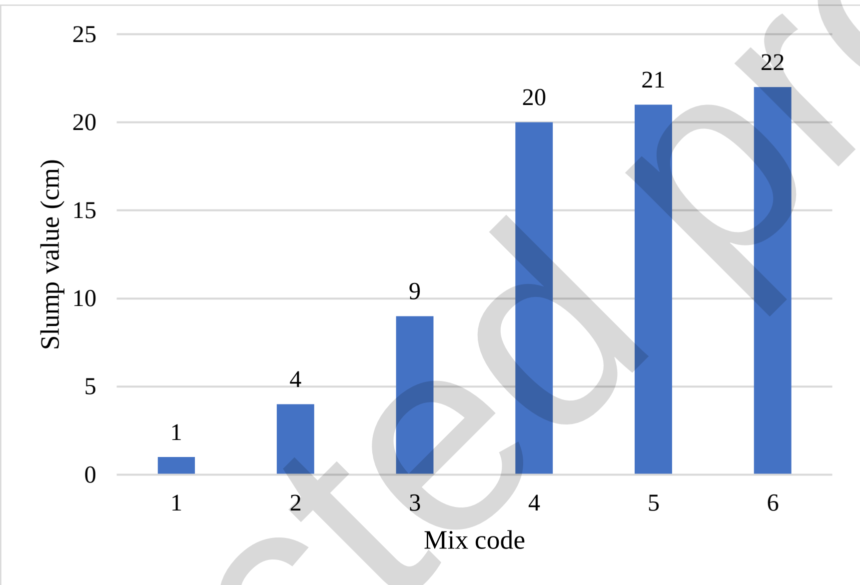

Fig. 4: Slump test values for the six mixes.

When comparing mixes 1, 2, and 3 to mixes 4, 5, and 6, it was observed that increasing the GGBFS percentage from 25% to 50% resulted in better slump values**,** with mixes 4, 5, and 6 recording 20, 21, and 22 cm, respectively. This indicated sequentially better workability compared to mixes 1, 2, and 3, which recorded slump values of 1, 4, and 9 cm, respectively. The observed trend of slump results for the six developed mixes is presented in **Fig. 4.** The increase in the GGBFS ratio from 25% to 50% significantly enhanced workability due to the higher percentage of SiO_2 in the WTPS. This sequentially caused a faster geopolymerization rate and consequently lowered workability. Gado et al. (2020) confirmed that the presence of silicon ions in the matrix caused the alkaline solution to become viscous, thereby decreasing workability [27].

For mixes 4, 5, and 6, with a GGBFS: WTPS ratio of 50:50, increasing the Na_2O to binder ratio at a constant Ms value of 1.0 did not significantly affect the slump, which provided good workability for GGBFS-based alkali-activated concrete. This confirmed the findings of Amer et al. (2021) and Tong et al. (2018) [18 & 28]. The slight improvement in slump values upon increasing the Na_2O to binder ratio was due to the increase in Si ions, which extended the activation process time and subsequently improved the workability of the concrete [29].

For mixes No. 1, 2, and 3 with a GGBFS: WTPS ratio of 25:75, the slump improved with increasing the Na_2O to binder ratio, confirming the findings of Meesala et al. (2019) [30].

Increasing the Na_2O to binder ratio sequentially increases the Si ions, which reduces the alkalinity of the activator, allowing for a longer activation process and resulting in better workability. Heshmat et al. (2023) concluded that when the SiO_4 ions surpass the Ca ion saturation level, there was a reduction in the alkalinity of the activator, sequentially retarding the hydration process and allowing for better workability [29].

Mix No. 1 Mix No. 2

Mix No. 3 Mix No. 4

Mix No. 5 Mix No. 6

Fig. 5: The Obtained Slump Shape of All Tested Mixes.

3.2. Compressive Strength Test

The compressive strength of each developed mix was determined at 7 and 28 days. For each testing age, three specimens were tested for all mixes, and their average compressive strength was calculated. The results for all tested mixes are presented in **Fig. 6.**

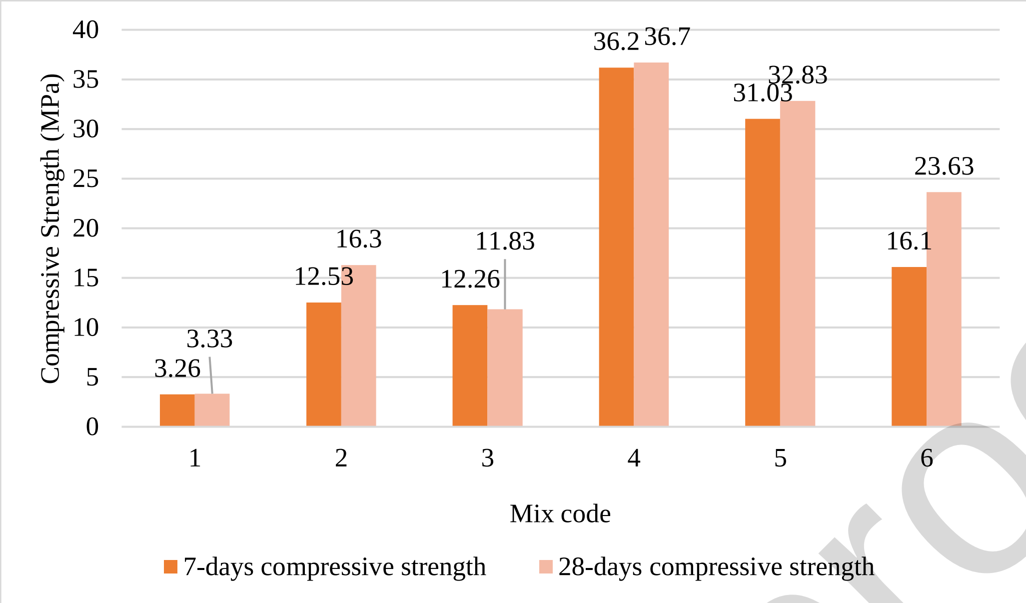

Fig. 6: The Obtained Compressive Strength of All Tested Mixes.

Upon comparing the results of the 7-day compressive strength test for mixes 1, 2, and 3 to mixes 4, 5, and 6, it can be concluded that increasing the GGBFS percentage from 25% to 50% significantly increased the compressive strength, as shown in **Fig. 6.** This was due to the high calcium amount found in the GGBFS, allowing for the formation of more calcium silicate gel [29]. This allowed the formation of C-S-H and hydrated sodium aluminum silicate gel (C-A-S-H) in addition to silico-aluminates gel type (N-A-S-H), where N is the alkaline cation formed in the WTPS-based alkali-activated concrete provided higher compressive strength [31-35]. This confirmed the conclusion of Meesala et al. (2019) and Rafeet et al. (2019), where the authors concluded that upon increasing the slag percentage when mixing with FA, the compressive strength was enhanced [30&33]. **Fig. 6** shows the 7-day compressive strength results of the six tested mixes.

The concrete mixes, 1,2, and 3, showed an increasing trend for compressive strength upon increasing the Na_2O to binder ratio. Increasing the Na_2O to binder ratio from 10% to 12% or 14% showed a jump in compressive strength from 3.26 MPa to 12.53 and 12.26 MPa, respectively, as shown in **Fig. 6.** This indicated that upon increasing the alkaline solution, an increase in hydration products took place, and sequentially, the compressive strength results were higher, and this confirmed the findings of Amer et al. (2021) [18]. The rise of the Na_2O to binder ratio from 12% to 14% had almost no significant effect on compressive strength, and this was shown in **Fig. 6.** This could be due to increasing the alkaline liquid-to-binder ratio, which caused a loss in strength. This was the finding of Meesala et al. (2019) for Fly ash geopolymer concrete [30].

Mixes 4 and 5 recorded almost the same compressive strength with a slight decrease upon increasing the Na_2O to binder ratio from 10% to 12%, 36.2 MPa, and 31.03 MPa, respectively. **Fig. 6** shows the compressive strength values for mixes 4 and 5. The best compressive strength was recorded by the mix of Na_2O to binder ratio equals 10%, and this confirmed the findings of Amer et al. (2021) when the authors used GGBFS and OPC in geopolymer concrete [18]. Upon increasing the Na_2O to binder ratio more than 12%, in mix number 6, a dramatic decrease in the compressive strength took place. The decreasing trend in the compressive strength upon increasing the Na_2O to binder ratio is shown in **Fig. 6.** This may be due to the increase in the concentration of the alkalis, which negatively affected the condensation process of the silicate species. Also, this could be due to increasing the alkaline liquid-to-binder ratio, which caused a loss in strength. This was the finding of Meesala et al. (2019) for fly ash geopolymer concrete [30].

For the 28-day compressive strength test results, upon comparing the results of mixes 1, 2, and 3 to the results of mixes 4, 5, and 6, it can be observed that mixes 4, 5 and 6 of 28 days compressive strength: 36.7, 32.83 and 23.63 MPa, respectively, recorded higher compressive strength than the mixes 1, 2 and 3 of 28 days compressive strength 3.33, 16.3 and 11.83 MPa, respectively, by almost 200%. The values of the 28-day compressive strength are shown in **Fig. 6** for the six mixes. It can be concluded that the increase in the GGBFS percentage significantly increased the compressive strength. This was due to the high calcium amount found in the GGBFS, allowing for the formation of more calcium silicate gel. This allowed the formation of C-S-H and hydrated sodium aluminum silicate gel (C-A-S-H) in addition to silico-aluminates gel type (N-A-S-H), where N is the alkaline cation formed in the WTPS-based alkali-activated concrete provided higher compressive strength [31-35]. This confirmed the conclusion of Meesala et al (2019) and Rafeet et al. (2019), where the authors concluded that upon increasing the slag percentage when mixing with FA, the compressive strength was enhanced [30&33].

Mixes 1, 2, and 3 had an increasing trend in the 28-day compressive strength upon increasing the Na_2O to binder ratio, as shown in **Fig. 6.** At a 10% Na_2O to binder ratio, the compressive strength was very low, recording 3.26 MPa. By increasing the Na_2O to binder ratio to 12%, the compressive strength was almost multiplied by 5, recording 16.3 MPa. Upon increasing the Na_2O to binder ratio further, reaching 14%, the compressive strength slightly decreased, recording a compressive strength of 11.83 MPa. Mix number 1 recorded very low compressive strength on the 28th day because of its very low workability, which caused segregation. The increase in the Na_2O to binder ratio to 12% caused an increase in the NaOH, which significantly impacted hydrolysis, dissolution, and condensation processes during the geopolymer synthesis [30]. At Na_2O to binder ratio equals 14%, the increase in the alkali concentration negatively impacted the silicate species condensation process and sequentially lowered strength [30].

Upon comparing the 7-day and 28-day compressive strength for Mixes 1, 2, and 3, it can be seen that the Na_2O to binder ratio of 10% showed no enhancement in the compressive strength, remaining around 3 MPa. While at Na_2O to binder ratio of 12%, the 28-day compressive strength was higher than the 7-day compressive strength by almost 30%. For the Na_2O to binder ratio of 14%, there was almost no significant change between the 7-day and 28-day compressive strength; the value of compressive strength remained around 12 MPa. It can be concluded that with less than a 12% Na_2O to binder ratio, the activation effect of the activator solution was very low, and by increasing the Na_2O to binder ratio to 12%, more reaction took place, and the compressive strength increased. This happened because mix number 1 was very stiff during pouring, causing significant segregation, which demonstrated the very low compressive strength recorded on the 7th day and the 28th day. This means that the hydration process was very short, and no further hydration took place. The increase in the Na_2O to binder ratio to 12% causes an increase in the NaOH, which significantly impacted hydrolysis, dissolution, and condensation processes during the geopolymer synthesis [30]. However, upon increasing the Na_2O to binder ratio more than 12%, no change between the 7-day and 28-day compressive strength took place, meaning that the optimum Na_2O to binder ratio for the activation was 12%.

For mixes 4, 5, and 6, a decreasing trend for the 28-day compressive strength took place. At an Na_2O to binder ratio of 10% and 12%, the compressive strength was almost the same, and by increasing the Na_2O to binder ratio to 14%, the 28-day compressive strength dropped to 23.63

MPa. The 28-day compressive strength test results are presented in **Fig. 6.** The 7- and 28-day compressive strength had almost the same trend. This was attributed to the increase in the alkali's concentration, which negatively impacted the silicate species condensation process and sequentially lowered the strength [30]. Also, this was because increasing the alkaline liquid to binder ratio caused a loss in strength. This was the finding of Meesala et al. (2019) for fly ash geopolymer concrete [30].

The 28-day compressive strength of mixes 4 and 5 was nearly identical to the 7-day compressive strength. For mix number 6, the compressive strength increased from 16.1 MPa at 7 days to 23.63 MPa at 28 days. For the 10% and 12% Na_2O to binder ratio, the 7-day compressive strength was 98% and 94% of the 28-day compressive strength, and this confirmed the findings of past research. This means that most of the hydration process took place early [18]. At a 14% Na_2O to binder ratio, the increase between the 7-day and 28-day compressive strength was 31%. This meant that the hydration process took a longer time when increasing the alkalinity of the mix.

CONCLUSIONS

This study aimed to determine the optimum concrete mix for WTPS-based geopolymer incorporating GGBFS. This was done by designing a testing matrix of different GGBFS to WTPS mixing ratios and Na2O to binder ratios. Based on the results obtained and the discussion carried out, the following conclusions can be drawn:

- Utilizing WTPS powder as a binder in geopolymer concrete can effectively produce concrete mixes with desirable workability and compressive strength for construction applications instead of disposing of it as waste material.
- Increasing the percentage of WTPS replaced with GGBFS in WTPS-based geopolymer concrete significantly improves the workability of the mixes. The highest slump value obtained from mixes with a GGBFS: WTPS ratio of 25:75 was 9 cm, while the highest slump value obtained from mixes with a GGBFS: WTPS ratio of 50:50 was 22 cm.
- The effect of increasing the Na_2O to binder ratio on improving workability is more pronounced at lower ratios of WTPS replacement with GGBFS. For a GGBFS: WTPS ratio of 25:75, the slump value increased from 1.0 to 9.0 cm, with an increase in the Na_2O ratio from 10% to 14%. Meanwhile, for a GGBFS: WTPS ratio of 50:50, the slump value increased from 20.0 to 22.0 cm.
- Increasing the percentage of WTPS replaced with GGBFS in WTPS-based geopolymer concrete significantly improves the compressive strength of the mixes. The highest compressive strength value obtained from mixes with a GGBFS: WTPS ratio of 25:75 was 16.3 MPa, while the highest compressive strength value obtained from mixes with a GGBFS: WTPS ratio of 50:50 was 36.7 MPa
- For the mixes with a GGBFS: WTPS ratio of 25:75, increasing Na_2O to binder ratio till 12% significantly increases the compressive strength, while beyond 12%, the compressive strength decreased.
- For the mixes with a GGBFS: WTPS ratio of 50:50, the optimum Na_2O to binder ratio was 10%, and beyond 10%, the compressive strength significantly decreased.

It is recommended for future research to carry out more mechanical tests, flexural strength test, and modulus of elasticity test on larger-scale specimens, such as reinforced beams, to assess more mechanical behavior for the WTPS-based geopolymer concrete incorporating GGBFS.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article**.**

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