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RECYCLING OF WASTE GRANODIORITE POWDER AS A PARTIAL CEMENT REPLACEMENT MATERIAL IN ORDINARY CONCRETE

ABSTRACT

In this study, the effect of using waste granodiorite powder (WGP) as a cement replacement material in percentages ranging from 1 to 9% on various physical and mechanical properties of ordinary concrete was investigated. The resistance of produced concretes with WGP to the high temperature effects on the 28 days compressive strength were studied as well. Granodiorite is one of the well-known igneous rocks that have been used in previous research as a replacement for coarse or fine aggregates due to the hardness of its grains. However, rare studies have investigated its powder as a partial cement replacement material. Results showed the ability of investigated WGP with high surface area to act as a supplementary cementitious material that contributed to enhance the results of mechanical and physical properties of concrete. At traditional room temperature, the optimal replacement percentage was 7%, where the 28 days compressive and tensile strengths were improved by 28.3% and 17.3%, respectively. The optimal replacement ratio varied between 7 and 9% in the case of high temperatures, according to exposure time and temperature degree. Statistical and sensitivity analysis was conducted on 66 available compressive strength value represents all variables before and after elevated temperature exposure. While the regression equation showed good R^2 value of 85.3%, sensitivity analysis indicated that compressive strength value is most sensitive to temperature, followed by WGP ratio and exposure time, with importance values of 56, 26, and 18 %, respectively. Results showed also that the setting times and consistency was decreased with increasing the replacement ratio with WGP, while the workability was slightly improved up to 5% replacement ratio. Furthermore, microstructure analysis showed that WGP can help to densify the concrete matrix due to its small size and ability to fill the interstitial voids in the concrete matrix.

Keywords: *granodiorite; igneous rocks; waste concrete; supplementary cementing materials; waste granodiorite powder*

INTRODUCTION

The demand for construction projects is constantly growing; thus, the production of building materials also increases. Concrete is the most widely used building material in the construction sector worldwide [1]. Excessive consumption and limited availability of raw materials on the one

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hand, and the problem of increasing the amounts of industrial and construction waste and the lack of waste landfills on the other hand, led to the development of studies related to the recycling of these wastes in the production of building materials, especially concrete [2]. Recycling waste in concrete production contributes to preserve the environment by reducing the consumption of large amounts of energy required for cement production, effective management of the available natural resources, and reducing greenhouse gas emissions, mainly carbon dioxide (CO_2), into the atmosphere. Mineral additives are commonly used today in cement industry [3]. Searching for ways to reduce energy consumption and CO_2 emissions will only reinforce this tendency.

Quarrying activities and producing of construction raw materials typically generate large quantities of wastes in the form of useless rock masses of different sizes and shapes. These useless rock materials may have a similar mineralogical composition especially if collected from a same source. Besides its environmental hazards, transporting this waste to landfills or collection centers is expensive. Many types of waste have been successfully used in concrete to reduce environmental hazards [4]. In general, the manufacture of rocks used in the construction sector, such as granite, granodiorite, marble...etc., has contributed to significant environmental problems due to the generation of large quantities of wastes in the various stages of mining and processing operations [5]. Leaving these wastes directly in the environment often causes serious environmental problems. Therefore, many countries are working on developing innovative ways to reuse these mineralogical wastes to reduce its environmental risks, with the possibility of achieving added economic value from the recycling process. Several studies have recently focused on examining the possibility of reusing these wastes in various industries, especially concerning construction materials such as concrete [6]. Waste recycling has many advantages: firstly, the consumption of virgin natural resources of economic value is reduced, and secondly, wastes are is disposed of in a safe, effective, and environmentally friendly manner. Worldwide, work is being done to recycle waste materials in many industrial fields. In the concrete industry, the value and impact of using wastes in the production of concrete can be measured by studying the extent of their impact on the performance of concrete with its various indicators such as mechanical properties, workability, durability, …etc. It is usually sought to reduce the amount of expensive or limited components with cheap substitute materials to achieve the greatest possible economic value. From the environmental side, when industrial waste is recycled, greenhouse gas emissions are reduced, and production waste from other industries is reused, so less material is thrown into landfills, and more natural resources are preserved. The cement industry produces large amounts of CO_2 because of clinker calcination, so the use of alternative materials added after the clinker grinding process contributes to reducing the emission of CO_2 [7].

In the current study, authors seek to recycle waste granodiorite powder (WGP) in the concrete industry by using it as a partial alternative material for cement to act as a supplementary cementing material (SCM). Granodiorite, a member of the granitic igneous rock family, is widely utilized in various applications. Its most prominent uses include decorative purposes, as well as flooring and wall coverings. The wasted losses of cutting and polishing operations represent approximately 10% of the weight of granitic rocks, including granodiorite [8]. Usually, these losses are not utilized. On the contrary, they represent an environmental problem due to disposing of them in large landfills.

Hence, recycling losses resulting from granodiorite cutting operations will positively impact the environment, with the expectation that it will positively impact the different properties of concrete.

Igneous rocks like granodiorite are formed due to the cooling and solidification processes of magma or volcanic lava. The nomenclature of the igneous rock depends on whether this rock has cooled inside the Earth (plutonic igneous rock) or on the surface of the Earth after the eruption of magma from the vent of the volcano (an extrusive or volcanic igneous rock) [9]. For example, a plutonic felsic rock is called granite, while a volcanic felsic rock is called rhyolite. Granite and rhyolite have the same mineral composition, but the grain size and formation method give each a different appearance. Regarding chemical composition, magma can be classified into felsic, intermediate, mafic, and ultramafic. Felsic magma contains higher ratios of silicon (Si), sodium (Na), and potassium (K), while on the other side, mafic and ultramafic magma is characterized by the presence of high ratios of magnesium (Mg) and iron (Fe) [10]. Felsic magma rocks have the lowest density and highest viscosity among igneous rocks. From the atomic and crystalline composition side, five major mineral groups control the igneous rocks' nature and classification. Quartz and its polymorphs (Q), alkali feldspar (A), plagioclase (P), feldspathoids (F), and mafic minerals (M) represent these five groups where the sum of them (% volume) must always close at 100% [11]. In construction engineering, many types of igneous rocks are used in various applications such as floor and wall covering works, decorative uses, aggregates (whether coarse or fine aggregates) in concrete industry, or even as a replacement material for cement. Granite is one of the most famous and widely used igneous rocks in concrete production. Granite is one of the most famous, durable, and widely used igneous rocks in concrete production. The distinctive properties and hard performance of granitic rocks in cementitious mixtures makes crushed granite a popular choice in many studies, where it's used as a substitute for various sized aggregates (both coarse and fine) after being processed to standard dimensions [12]. In addition, crushed granite powder or granite dust resulting from rock cutting and polishing operations has been used in various studies as a substitute for cement. The chemical composition of granite dust contains a high percentage of silicon and aluminum oxides, which are known for their ability to activate the cement hydration process and give concrete more strength by increasing the percentage of calcium silicate hydrates (C-S-H) gel [13].

Basalt, classified as a mafic extrusive igneous rock, is one of the most popular igneous rocks used as aggregates in concrete production. It has become common in many experimental studies on the different types of concrete that the coarse aggregate used in the control mixture is Basalt [14]. Moreover, basalt powder waste, whether produced by grinding large basalt particles or collected as a by-product of the production of mineral-asphalt mixtures, was tested as a substitute to sand in concrete and mortar in various studies [14-16]. Results indicate an improvement in compressive strength by about 25% when cement sand is replaced by 30% of fine basalt aggregate [14]. The basalt powder's filler effect also can improve concrete's flexural strength [15]. Using basalt powder can also enhance various properties of concrete, such as abrasion resistance, water permeability, and freeze-thaw effects [16].

Gabbro is a solid, dense, and homogeneous igneous rock similar in composition to Basalt (consisting of plagioclase, olivine, and clinopyroxene) [17]. Gabbro is an intrusive igneous rock that cools slowly and has coarse-grained crystals, unlike Basalt, which is classified as an intrusive igneous rock that cools quickly and has fine-grained crystals. Gabbro is mostly used as a coarse aggregate in concrete and is often used in the production of high-strength concrete [18].

Rhyolite is another igneous felsic extrusive rock with many construction engineering uses. It is rich in silicon oxide content (SiO_2 > 69%) and exists in many colors, so it is commonly used in decoration works and facade coverings. Rhyolite powder was proven to have a pozzolanic activity similar to fly ash, making it very suitable as a partial replacement material for cement in the concrete industry [19]. Rhyolite has also been used in many studies as a coarse or fine aggregate, as it has a suitable specific gravity (2.2 – 2.8) and a low absorption rate value (about 1%) [20].

Andesite is a type of rock from igneous origin that is intermediate in composition between Basalt and rhyolite. It is typically gray to black and mainly composed of plagioclase feldspar and one or more mafic minerals such as biotite, hornblende, or pyroxene. It is widely used in construction and as a decorative stone due to its durability and attractive appearance [21]. Some studies have shown that andesite powder positively affects the mechanical properties of concrete when partially replacing cement. Uzun &Terzi (2012) [22] found that andesite waste can replace up to 20% of the fine aggregate fraction in asphaltic concrete and improve its mechanical properties, including stability, flow, and Marshall Quotient. In accordance, the results of Davraz et al. (2018) [23] showed that the compressive strength of the concrete increased by up to 11% when 15% of andesite waste powder was added, the flexural strength of the concrete increased by up to 14% when 20% of andesite waste powder was added, and the split tensile strength of the concrete increased by up to 9% when 10% of andesite waste powder was added.

Other types of igneous rocks have low density and high porosity, such as pumice (0.5-1.5 gm/cm^3) and perlite (0.3-1.2 gm/cm^3). These types are usually used in the production of lightweight concrete and its powder can be used as mineral additives to enhance bonding properties of the repairing cementitious mortar [24].

Granodiorite as the same is an igneous plutonic rock with intermediate composition. According to the International Union of Geological Sciences (IUGS) classification, the igneous rock can be classified as a granodiorite if quartz ratio represents 20 to 60% of the felsic minerals and plagioclase ratio is 65 to 90% of all feldspars. Granodiorite is one of the most common rocks in the world. It is commonly found in continental crust and can form in a variety of tectonic settings, including subduction zones, collisional orogens, and continental rifts. The texture of granodiorite is hypidiomorphic-granular with grayish-white color. Generally, the color of granodiorite is darker than granite because of its higher plagioclase ratio in composition. Granodiorite is resistant to weathering and erosion, making it a popular choice for construction projects that require durable building materials. The hardness of granodiorite is 6 on Moh's hardness scale. Consequently, the use of crushed granodiorite as an alternative to natural aggregates in concrete, especially the coarse ones, has been tried in several previous studies. Glinicki et al. (2016) [25] studied the effect of cement type on various durability properties of concrete made with crushed granodiorite and limestone coarse aggregates. After curing age of 28 days, specimens prepared with granodiorite obtained higher values of compressive strength compared to those prepared with limestone, in four out of six mixtures of different types of cement, with improving ratios ranging from 3 to 21 %. Smarzewski & Barnat-Hunek. (2017) [26] used granite and granodiorite as coarse aggregates in their study that aimed to assess the effects of hybrid fibers on the microstructure and mechanical behavior of ultra-high performance concrete (UHPC). Specimens of granodiorite aggregates and 1% steel fibers exhibited the optimal resistance of both compressive and tensile stresses. Bodnárová et al. (2020) [27] examined the potential for using crushed and mined aggregates to improve the wear abrasion resistance of concrete. The obtained results emphasized that crushed aggregates (granodiorite and amphibolite) have higher compressive, tensile, and flexural strength at the early and late ages. Góra & Piasta. (2020) [28] tried crushed granodiorites, as one of different thirteen aggregates type, to evaluate the impact of aggregate mechanical resistance on ordinary and high strength concrete behavior. It's observed that the obtained results of mechanical properties for granodiorite mixes were better in the high strength concrete specimens than those of the ordinary concrete. In general, it can be said that the results of concrete samples with granodiorite aggregates lie in an intermediate zone between the different types of aggregates. With the exception of the higher strength values of basalt and dolomite specimens, the strength values of granodiorite specimens achieved better results than concretes that contained granite, quartz and gravel in their composition.

Because of the similarity in terms of hardness, shape and nature of use between the granitic rocks, researchers should be more interested in studying the possibility of using granodiorite powder as a SCM that can replace cement in concrete mixtures. Despite being a well-known type of rock and having already been used in many studies as a partial or complete replacement for coarse and fine aggregates, limited studies have utilized granodiorite in the form of powder in concrete mixes. From these studies is Lagerblad et al. (2014) [29] where they investigated the suitability of using various fine powders from crushed rocks in concrete production. Authors highlighted that the powders of different rock like granite, granodiorite, and gabbro can be used as a filler material in concrete. Meziani et al. (2018) [30] studied the effects of replacing cement with various powders including granodiorite on the transport properties and service life of cement mortar. Results revealed that the permeability is decreased and the diffusion coefficient increases with porosity in the case of using granodiorite powder as a cement replacement material. In this research, authors investigate the possibility of using WGP in the production of cement and concrete, by studying the effect of replacing different proportions of cement with granodiorite powder and evaluating the effect on the mechanical, physical and microstructural properties of concrete.

MATERIALS

Cement

In the current study, Ordinary Portland cement (OPC), CEM I 42.5 N produced by Misr Beni Suef company (Beni Suef city, Egypt) complies with the ASTM C 150 [31] was used. Physical and mechanical properties of the used cement are given in Tables 1 and 2.

Table 1. *Properties of used cement*

Physical properties					Soundness (mm)	Mortar compressive strength (MPa)		
Color	Specific gravity	Initial setting time (min)	Final setting time (min)	Surface area(cm^2/g)		3 days	7 days	28 days
Grey	3.15	162	295	3520	1	26.5	33.4	42.8

Table 2. *Chemical composition of used cement (% mass)*

SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	C_3A	P_2O_5	Cl	TiO_2	LOI*
20.32	61.8	3.3	1.72	2.31	2.82	0.42	3.54	0.17	0.1	0.38	3.05

* LOI: Loss on Ignition at 1000 ˚C

Aggregate

Natural siliceous sand with fineness modulus of 2.42 was used in this research as fine aggregate, whereas crushed dolomite with a nominal maximum size of 19 mm was used as coarse aggregate. The grading of both fine and coarse aggregate satisfies the ASTM C33-03[32] grading limits as shown in Figure 1. Physical properties of the used aggregates are provided in Table 3.

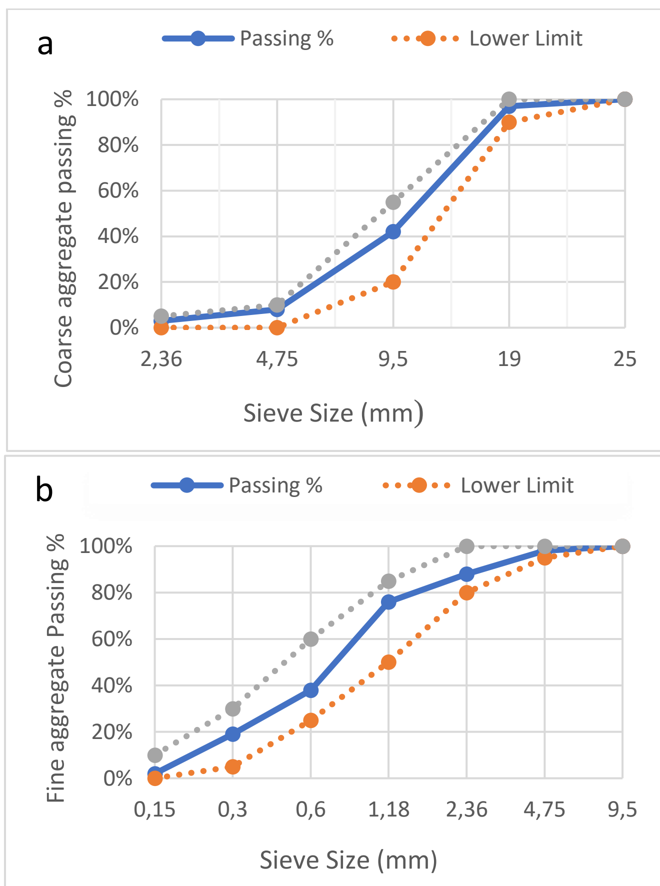


Fig. 1. Grading with standards limits for a) coarse aggregates, and b) fine aggregates

***Table 3.** Physical properties of the used aggregates*

	Specific gravity	Bulk density (kg/m^3)	Voids (%)	Absorption (%)	Clay and fine materials (%)	Crushing Value (%)	Fineness modulus
Coarse Aggregate	2.66	1668	36	0.5	1	22	--
Fine Aggregate	2.54	1728	33	0.9	1.2	--	2.42

Water

Clean and fresh water that meet the requirements of Egyptian code for design and execution of concrete structures was used for both mixing and curing of concrete specimens.

Superplasticizer

Superplasticizer (S.P) have a commercial name of (GLENIUM ACE 30) with density 1.25 kg\L produced by chemicals company (BASF) in Egypt was used. For all mixes, a fixed ratio of 1.5% by water weight was used in the mixing process, as the recommended percentage by the manufacturer ranged from 1% to 3%. The used superplasticizer, works as a high range water reducer of modified polycarboxylates, meets the requirements of standard specifications for chemical admixtures ASTM C494 (types F) [33].

Waste granodiorite powder

The Egyptian granodiorite is widely present with high quantities in various zones such as Abo Marw in Aswan, Samut area in the south eastern desert, Abu Ziran in the central eastern desert Abu Kharif area in the northern eastern desert, scattered in many other locations in red sea mountains, and Sinai. In this study, granodiorite waste (in large particles size as shown in figure 2) were obtained from one of the ornamental stone industry factories located at Shaq El- Thu'ban zone in Egypt as a by-product resulting from granodiorite stone cutting and shaping processes. Then, granodiorite particles were ground for five minutes using a vibratory pulverizer machine (ring mill) with two rings and a puck inside (20.32 cm diameter) grinding bowel. The grinding machine has high efficiency in rapidly reducing the wet or dry samples of minerals, rocks, soil, or similar materials to a final +400 mesh within one minute. The grinding machine is not highly energy intensive where it operates at traditional electrical voltage 220 volts and does not require a long grinding duration to achieve the desired fineness. The obtained granodiorite powder was then dried in an oven in the laboratory at 120 ◦C for two hours to remove the moisture to ensure a constant W/C ratio for concrete mixes. At the final stage, granodiorite powder was re-vibrated for two minutes to remove any agglomeration from the powder, then mechanically sieved through sieve No. 200 to get particles less than 75 microns ready for use as a cement replacement material. Compared to recycling granodiorite dust generated from its cutting and finishing processes, grinding large waste pieces offers several advantages. These include homogeneity, consistency in physical and chemical properties, and uniform particle size of the resulting powder. Waste granodiorite's final appearance and particle size distribution are shown in Figures 2 and 3. The physical properties of the used WGP are presented in Table 4, while the chemical composition obtained via X-ray fluorescence (XRF) analysis is presented in Table 5. Results of the mineral oxides composition of WGP clear the presence of a high ratio of silicon oxide (SiO2) and a suitable ratio of alumina (Al_2O_3), which are known for their pozzolanic activity that helps cementitious compositions to gain more mechanical strength [34]. Figure 4 displays the peaks from the X-ray diffraction (XRD) analysis. These peaks which represents the mineral composition of the investigated sample are consistent with the results of the chemical analysis. Quartz is the dominant mineral in the rock sample, followed by a relatively higher proportion of albite, a sodium-rich plagioclase feldspar. Biotite is present in smaller quantities, and trace amounts of accessory minerals like calcite and actinolite were also detected.

Fig. 2. Granodiorite powder preparation process

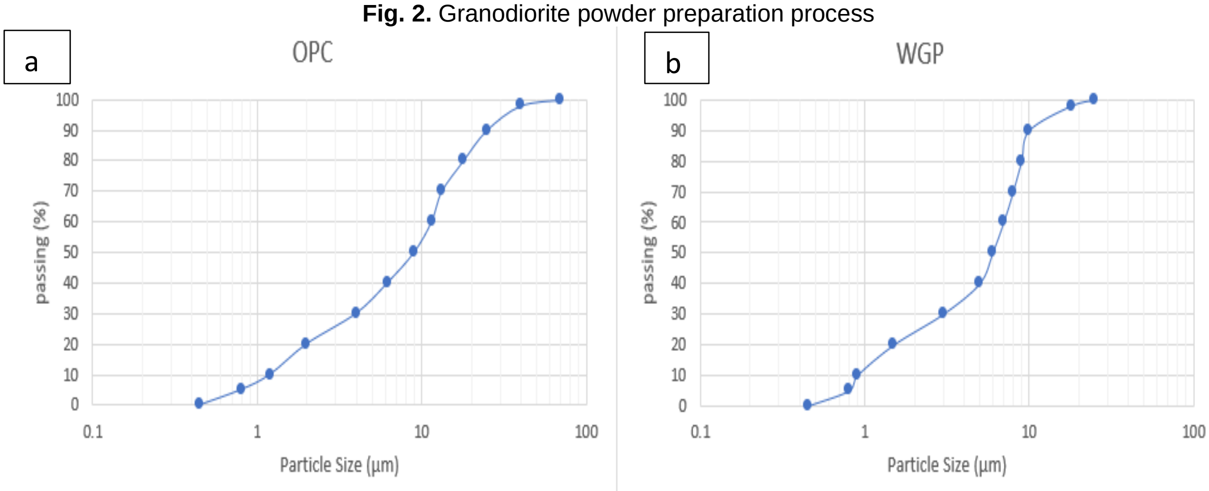


Fig. 3. Particle size distribution of a) OPC and b) WGP

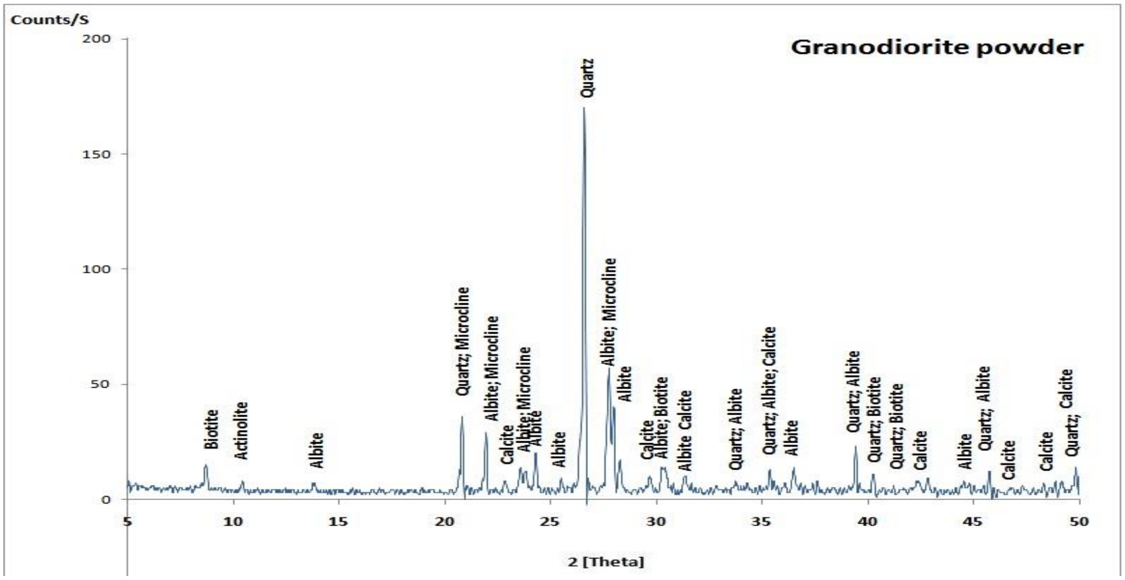


Fig. 4. XRD patterns of granodiorite powder

Table 4. *Physical properties of WGP*

Property	Color	Specific gravity	Surface Area (cm^2/gm)
	Gray	2.7	13350

Table 5. *Chemical composition of WGP (% mass)*

SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	P_2O_5	Cl	TiO_2	LOI*
64.6	5.48	15.8	5.21	1.58	1.37	3.55	0.06	0.31	0.04	0.69	1.02

* LOI: Loss on Ignition at 1000 ˚C

Petrographic description of the used WGP

The petrographic description refers to the detailed description of the properties and features of rocks through the analysis of rock samples using a petrographic microscope. This includes a description of the rock's microscopic texture, mineralogy, and compositions. The petrographic description aims to characterize and identify the rock type by observing the thin sections under the microscope. The description helps identify, interpret rock origin, and determine rock suitability for specific uses [35]. The thin-section photomicrograph reveals that the studied granodiorite sample is composed essentially of twinned lamellar plagioclase crystals associated with quartz crystals that were noticed as anhedral, medium to coarse-grained monocrystalline to polycrystalline crystals represented by wavy extinction and interference color. Moreover, subhedral medium to coarse brownish crystals of biotite mineral was presented, besides traces of subhedral greenish brown prismatic crystals with one set of cleavage were altered to chlorite. Microscopically, the evidence for slight alteration is represented by scattered dark brown patches, most likely clay minerals. Figure 5 shows the petrographic description of the used granodiorite rock.

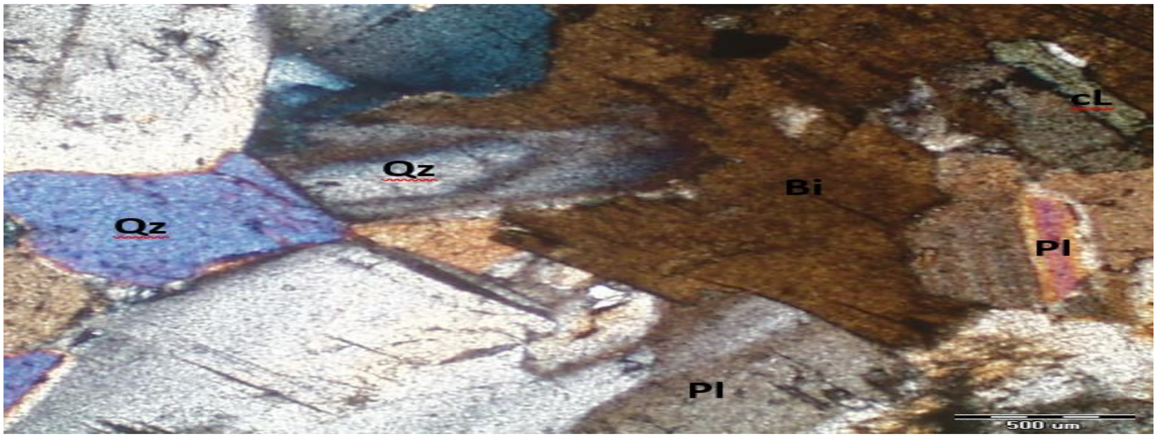


Fig. 5. Petrographic description of used granodiorite sample. Pl: Plagioclase, Bi: Biotite Qz:Quartz, Bi:Biotite, Cl:Clorite

Under the microscope, granodiorite typically exhibits a hypidiomorphic-granular texture, meaning that the mineral grains have a roughly equal size and are interlocking, but do not show a regular geometric shape. The plagioclase feldspar may show polysynthetic twinning, which is a repeating pattern of parallel lines that is caused by the crystal structure of the mineral. The quartz grains may show undulose extinction, which is a wavy appearance under cross-polarized light caused by deformation of the crystal lattice. Biotite and hornblende may show pleochroism, which is a variation in color under different viewing angles due to differences in the orientation of the crystal structure. Generally, the petrographic description of granodiorite includes a coarse-grained texture with prominent plagioclase and potassium feldspar crystals, smaller quartz grains, and scattered biotite and/or hornblende. These characteristics can help identify and distinguish granodiorite from other types of rock.

EXPERIMENTAL PROGRAM

Preliminary test on mortar

To determine the range at which the best substitution ratio of cement with WGP lies, a preliminary test was conducted to assess the effect of substitution ratios ranging from 2% to 12% of this material on the compressive strength of 7x7x7 cm mortar cubes at 28 days of curing. One cubic meter of the reference mix of mortar was composed of 400 kg of cement, 1450 kg of dry natural siliceous sand, and 200 liters of water. The results shown in Figure 6 indicate that the optimal ratio for adding WGP lies between 6% and 10%, with the best substitution ratio being 8%, showing an improvement of 15.6% compared to the control mix. Additionally, the preliminary results show that addition ratios above 10% may have a negative effect on the compressive strength of the mortar cubes, as the strength decreased compared to the control mix at 12% substitution ratio. Based on these findings, the substitution ratios used in the concrete mixes were modified to be 1%, 3%, 5%, 7%, and 9%.

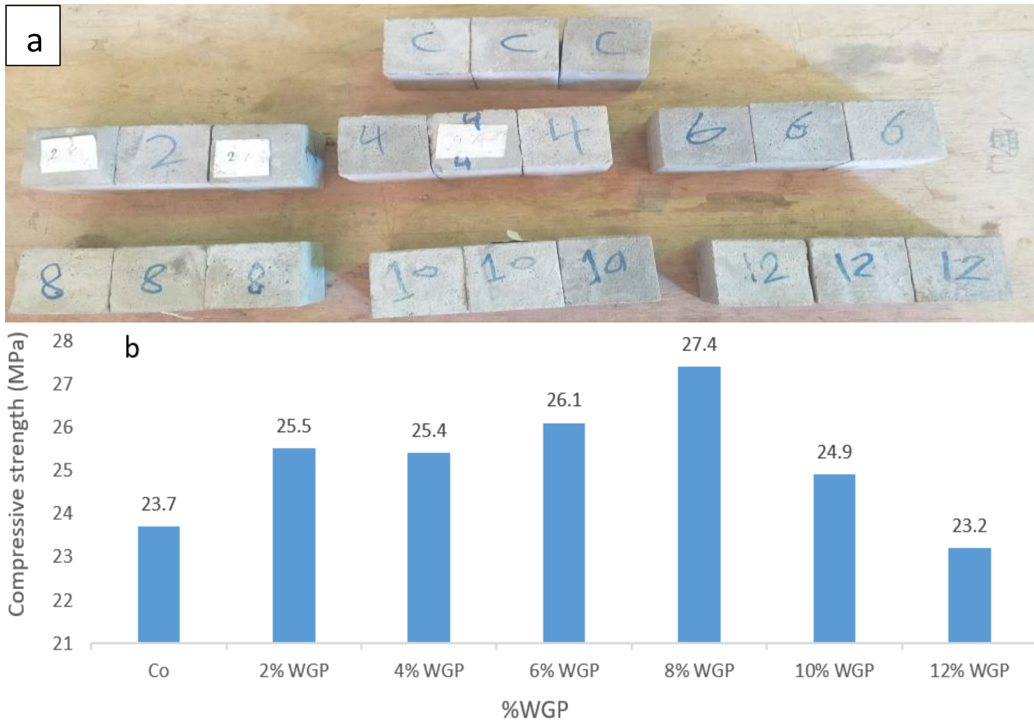


Fig. 6. a) Mortar cubes, and b) the mortar cubes compressive strength values at 28 days

Mix design

To capture the effect of using WGP as a cement replacement on the mechanical properties of concrete (compressive strength- tensile strength), five increasing replacement ratios (1%, 3%, 5%, 7%, and 9%) were tried. The control mix was designed according to the criteria of ACI 211.1 method [36]. Ingredients weights used for one cubic meter (1 m^3) of the concrete control mix were 350, 1135, 755 and 140 kg for cement, coarse aggregate, fine aggregate and water content, respectively as cleared in Table 6. Water to cement (W/C) ratio is 0.4, while a superplasticizer dosage of 1.5% of water weight was adopted for all mixes.

Table 6. *Concrete mix design (kg/m3)*

Mix	Symbol	Cement (kg)	Aggregate (kg)		Water (lit)	S.P (kg)	Waste Granodiorite Powder (kg)
			coarse	fine			
Control mix	C0	350	1135	755	140	2.1	----
1% WGP	G1	346.5	1135	755	140	2.1	3.5
3% WGP	G3	339.5	1135	755	140	2.1	10.5
5% WGP	G5	332.5	1135	755	140	2.1	17.5
7% WGP	G7	325.5	1135	755	140	2.1	24.5
9% WGP	G9	318.5	1135	755	140	2.1	31.5

Specimens preparation and curing.

Steel molds of different models with dimensions 10x10x10 cm cubes and 10 cm diameter x 20 cm height cylinders were prepared to be poured with concrete to determine the effect of different cement substitution ratios with WGP on the compressive and tensile strength. For the mixing procedure of the different mixtures, coarse and fine aggregates were firstly mixed for one minute, then cement, and WGP were incorporated and mixed for two minutes. At the final stage, the designed water quantities containing the liquid chemical additive were added to the mixture and mechanically mixed for additional two minutes. After the mixing and pouring, the compaction process begins with an electric vibrator to obtain good compaction, and then the surface samples are smoothed. After 24 hours of casting, concrete specimens were demolded and cured in a clean water tank with a temperature degree of 25 ± 2˚C and relative humidity higher than 95% until the scheduled testing times.

3.4. Tests setup

Various physical properties of fresh concrete and cement paste can be studied to understand the later properties of the produced hardened concrete. In this study, workability (expressed by the slump values of the standard slump cone test), setting times, as well as the standard consistency of all mixes designed with WGP and the control mix have been investigated. Slump cone test was conducted (following the guidelines outlined in ASTM C143/C143M [37]) to assess the workability of concrete for all the designed mixes. This test was performed using standard slump cone of 10 cm top diameter, 20 cm base diameter, and 30 cm height, as shown in Figure 10. Setting times refers to the durations needed by the cement paste to attain a certain degree of rigidity, while the standard consistency represents the water quantity needed for the modified cement paste to get certain degree of stiffness. The initial and final setting times in addition to the consistency percentages for all designed mixes were evaluated utilizing a Vicat needle apparatus, and following guidelines highlighted in (ASTM C 187 and ASTM C 191) [38,39].

As previously stated, concrete cubes with a size of 10 x 10 x 10 cm were used to measure the compressive strength of the various concrete mixtures incorporating WGP. For each mixture, specimens were tested to detect compressive strength values at 7, 28, and 90 days of curing ages. The final compressive strength value represents the average of three specimens tested under the same conditions. Uniaxial loading instrument with capacity of 3000 kN was used to specify the compressive strength values of all concrete specimens. The same instrument was also used to measure the splitting tensile strength of a 10 cm diameter x 20 cm height cylindrical concrete samples at 28 days of curing age. The splitting tensile strength of the concrete cylinders was obtained by applying the compressive force along the length of the specimens, where the final result represents the average of three tested cylinders under the same conditions. At the testing date after 28 days of curing, concrete cylinders were horizontally placed in the testing machine and then the sample was applied by continuous loading till the failure. To study the residual compressive strength of WGP concrete specimens after elevated temperatures exposure, an electric furnace, available at the physics labs in Fayoum university, was used for that purpose. The used furnace has a maximum temperature degree of 1000°C. The chamber size is approximately 23 x 18 x 23 cm, which is suitable to put four concrete cubes in each heating cycle. The chamber is made of high-temperature resistant materials insulated by a secondary layer for heat retention and safety.

Microstructural analysis for the various concrete specimens were performed via using Scanning Electron Microscope (SEM), Energy dispersive X-ray spectroscopy (EDX), XRD, and Thermogravimetric Analysis (TGA). SEM analysis is commonly used to have a sight on the internal microscopic composition of mortar or concrete samples with the aim of interpreting the mechanical resistance results and linking them to the internal composition of the concrete element in terms of cracks presence and dimensions, voids size, C – S – H gel formations, the distribution of nanomaterials additives if they are added to the mixture, etc. Dried concrete samples with dimensions of approximately 1 x 1 x 1 cm taken from the core of the concrete cubes were prepared to perform the SEM analysis. Concrete samples were scanned using narrow electron beam by focusing on spotted area for X-ray photons production by interacting with silicon detector for electric pulses generation.

EDX is a technique for analyzing the elemental composition of a material. It involves using an electron microscope to generate X-rays from the sample being analyzed. The X-rays emitted by the sample contain information about the elements present in the material. The X-rays are detected and analyzed using a detector to determine the energy of the X-rays, which is related to the atomic number of the element that produced them. By measuring the energy of the X-rays, EDX analysis can identify the elemental composition of the material being studied.

XRD is an important technique that used to identify the main elements and crystalline or amorphous states of the scanned materials. In crystalline materials, particles are orderly arranged, but in amorphous materials they obtain random arrangement. In cement and concrete industry, XRD analysis are commonly used to study the properties and microstructural phase of cement, crushed concrete powder, cement paste samples, or even the additives such as nanomaterials and pozzolanic additives powders. In the current study, WGP was scanned via XRD device in order to confirm the its chemical composition results, and to ensure the expected amorphous state of its particles. In addition, 2 samples of the control and 7% WGP concrete samples were crushed (up to uniform powder size passing from 75-micron sieve) and scanned via XRD device to discuss and explain the obtained mechanical strength results.

Besides the evaluation of concrete’s thermal stability, TGA can be used to assess the hydration reaction by estimating the amount of water chemically bound within the concrete's hydrated cement paste. A lower amount of calcium hydroxide (CH) measured through TGA indicates a more complete hydration reaction, which generally translates to better strength and durability of the concrete. TGA helps in pinpointing the different phases present in the concrete, like portlandite, calcite, calcium-aluminate-hydrate (C-A-H), and C-S-H, that help to understand the concrete's structure and strength. TGA was conducted in this experimental study for the control and 7% WGP concrete specimens to observe the variations that can help to understand the associated effects of using WGP at its optimum ratio as a cement replacement material, and to explain the linked obtained mechanical properties values.

RESULTS AND DISCUSSION

Fresh concrete workability

Workability of concrete refers to the ease with which the concrete mixture can be mixed, transported, placed, and compacted without segregation or bleeding. It is an important property of concrete as it directly affects the quality of the produced concrete. The obtained slump results are presented in Figure 7. It is worth noting that the slump value depends on many affecting factors such as the W/C ratio, cement type, the proportion and size of aggregates, the use of admixtures, and the temperature and the relative humidity of the surrounding environment. All the mentioned factors were fixed, while the only varying factor was WGP ratio. Results shows a minor effect of the various replacement ratios of WGP with cement on the workability of concrete. Slight increase of the slump values with %WGP increasement, where the higher slump was recorded for the 5% WGP replacement with cement at 7.8 cm with 8.3% increasement relative to the control mix. This increase can be explained by finer particle size of granodiorite powder compared to cement, where granodiorite powder fills up the voids and provides better particle packing, which allows the water to be better distributed throughout the concrete and make the concrete more flowable. In a study by Ying et al. (2012) [40], increasing proportions of granitic powder with a chemical composition close to the WGP used in the current study were used as a cement replacement. It was noted that the slump value increased with increasing replacement ratio of granitic powder with cement up to a maximum of 40%. %. Prokopski et al (2020) [41], also confirmed the effectiveness of granite powder in improving the performance of concrete, but at lower rates than those achieved by Ying. Overall, the results of granite powder incorporation into concrete cannot be completely extrapolated to granodiorite in terms of improving the workability of concrete, due to the aforementioned differences between the two materials.

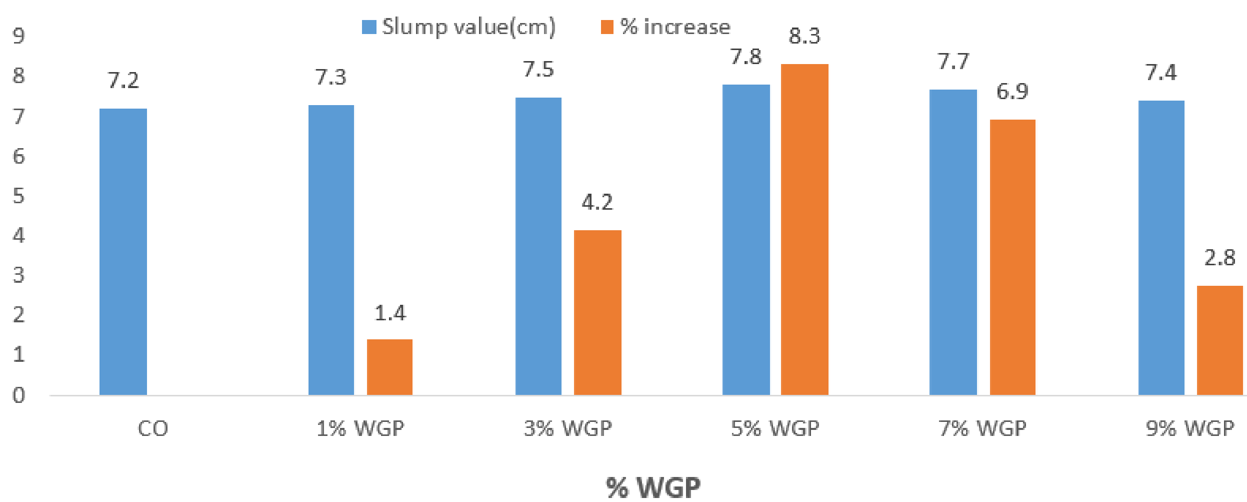
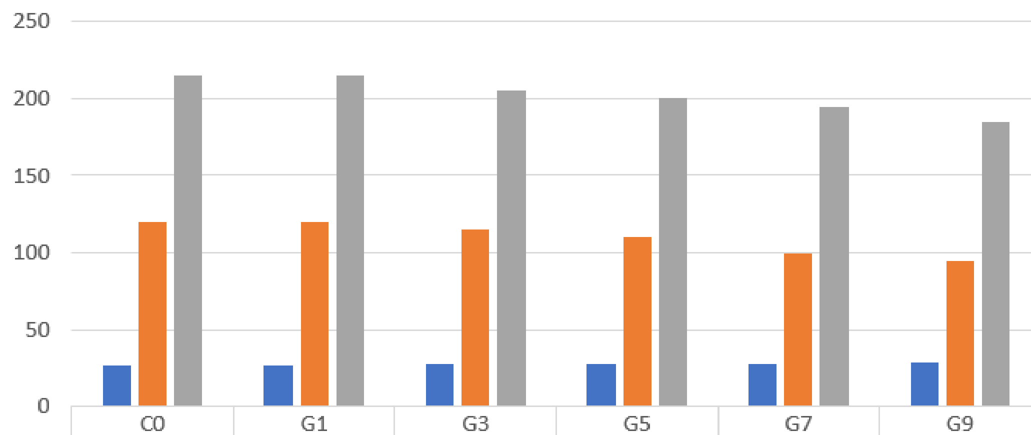


Fig. 7. Slump values and the relative variance to the control mix

Setting times and standard consistency

Figure 8 demonstrates the values of initial and final setting times, alongside with the standard consistency percentages for a total of five samples representing all designed mixes in addition to the control mix. The results showed decreased setting times with increasing the replacement values of WGP with concrete. This observation aligns with the assumption that WGP may function as supplementary cementitious material (SCM) that facilitate the continuity and activation of hydration reactions, thereby accelerating the development of strength within the cementitious paste. Findings from literature studies have demonstrated analogous outcomes when utilizing granite powder with a chemical composition comparable to that of WGP powder [6]. These studies attributed the decrease in setting time to the high pozzolanic reactivity, high surface area, and the filling effect which promotes the formation of hydration phases. Regarding the consistency values, higher percentages were obtained upon incorporating WGP into the cement paste. This could be linked to the heightened water absorption capacity, which can be ascribed to the substantial specific surface area and the angular, rough surface texture of WGP particles [6,42]. Similar results were observed with employing granite powder that have similar amorphous particle shapes and high surface area, where additional water quantities were necessitated for wetting [43].



	C0	G1	G3	G5	G7	G9
Consistency (%)	26.5	27	27.5	27.5	28	28.5
Initial Setting Time(mins)	120	120	115	110	100	95
Final Setting Time(mins)	215	215	205	200	195	185

Fig. 8. Setting times and standard consistency %

Compressive strength of concrete

Compressive strength at ambient temperature.

Figure 9 & Table 7 illustrates the compressive strength values and its improving rates for the tested concrete cubes at curing ages of 7, 28 and 90 days; respectively. The control mix exhibited a compressive strength of 21.2, 27.9 and 30.8 MPa at 7, 28 and 90 days, respectively. The results indicate varying degrees of improvement in compressive strength values for all samples where cement was partially replaced with WGP at the different curing ages. This improvement can be explained by the pozzolanic nature and the chemical composition of WGP, which contains high amounts of silica and alumina oxides. The pozzolanic reaction between the silica and alumina content in the WGP and the calcium hydroxide released during cement hydration can lead to an increase in the compressive strength value. This reaction forms additional C-S-H gel, which contributes to denser and more durable concrete with improved strength properties. The optimum improvement values were recorded at the replacement level of 7% WGP, where the compressive strength values gained additional strength by 25.9%,28.3%, and 27.9% of their control values, at the ages of 7, 28 and 90 days, respectively.

The results align with several previous studies in the general direction of improving concrete compressive strength by partially replacing cement with granite powder (with similar chemical composition to the WGP used in the current study), albeit with variations regarding the optimum replacement ratio. In a study by Abd Elmoaty (2013) [44], the optimal cement replacement ratio with granite powder was found to be 5%, resulting in an 8.2% improvement in compressive strength. The optimal replacement ratio in mortar mixes was found to be 7.5%. According to Ghorbani et al (2018) [45], the highest compressive strength among all the concrete mixes was observed in specimens containing 10% granite powder, which increased the strength by 10%, 10.5%, and 12% after 7, 28, and 91 days of testing, respectively. The ability of granite powder to improve the compressive strength of UHPC under various curing conditions was also confirmed by Zhang et al (2019) [46]. The optimal replacement ratios for compressive and tensile strength found to be 5%, 10%, and 15% for UHPC cured under standard, warm water, and autoclaved curing conditions, respectively. It is worth mentioning that the optimal replacement ratio of WGP with cement can be influenced by several factors, including the nature of the WGP itself such as its chemical composition, particle size distribution, specific surface area, and the proportions of other oxides present in its composition. In addition, other factors such as the type of cement, its grade, and chemical composition also play a role in determining the optimal replacement ratio. Other factors such as the water-cement ratio, curing conditions, and the intended purpose of the concrete production can also contribute to changing the optimal replacement ratio of cement with WGP. Therefore, it is necessary to conduct practical studies that take into account these variables to determine the optimal replacement ratio that suits the intended purpose of the concrete production. For example, if the goal is to minimize the use of cement to reduce emissions associated with its production, the replacement ratio can be increased until the point at which the mechanical properties values are equal to their reference (control) values.

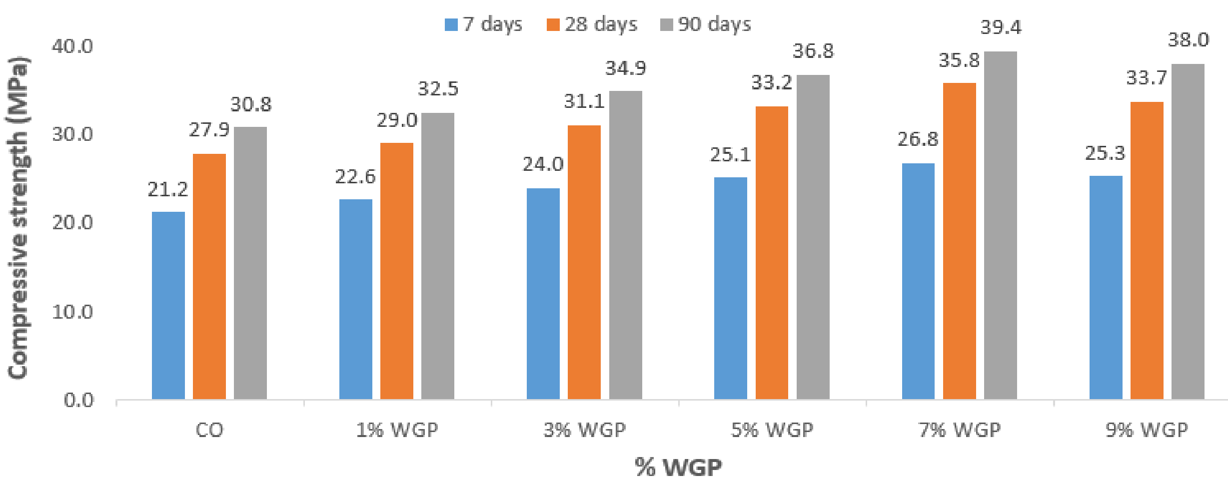


Fig. 9. Compressive strength at the different ages

Table 7. *Compressive strength improving rates at the various curing ages*

Mix	Compressive strength improvement rates %		
	7 days	28 days	90 days
1% WGP	6.3	3.9	5.7
3% WGP	12.8	11.5	13.3
5% WGP	18.4	19	19.6
7% WGP	25.9	28.3	27.9
9% WGP	18.9	20.8	23.4

Compressive strength after 28 days at elevated temperatures.

Table 8 shows the results of the residual compressive strength of the various mixes after elevated temperature exposure under different exposure temperatures (200,400,600,800, and 900 ^{0}C) and exposure times (60 &120 minutes). Results confirmed the significant influence of high temperatures exposure on the values of compressive strength of concrete. Even though low temperatures up to 400°C had little impact on reduction of compressive strength, with some enhancement noted at 200°C, subjecting concrete cubes to the high temperatures at 800°C and 900 ^{0}C for one and two hours resulted in extreme strength reduction. Specifically, the control mix lost about 49.1% and 54.1% of its original 28 days compressive strength value after two hours of exposure to 800°C and 900^{0}C degrees, respectively. This decrease in strength with increasing temperatures can be attributed to a number of accompanying physicochemical effects. Although heightened temperatures might initially speed up the hydration process (as noted for the 200^{0}C exposed specimens), they can lead to an early halt in hydration during subsequent stages, leading to diminished strength development. As temperatures surpass certain level, the liberation of chemically bonded water from cement hydration byproducts like C-S-H and CH induces microcracking as the cement paste begins to dehydrate [47]. Moreover, variations in thermal expansion between the aggregate and cement paste can generate tensile stresses and cracking within the interfacial transition zone due to disparate rates of thermal expansion. Additionally, the dehydration and decomposition of cement minerals prompt structural alterations in the cement matrix, leading to heightened porosity and friability. The conversion of CH into CaO also generates microcracks. At extremely high temperatures exceeding 550°C, the formation of pressurizing gases through chemical reactions can induce extensive cracking within the cementitious binder network, significantly diminishing its ability to bear loads under compression. This substantial decline in strength, sometimes reaching half of its original value, can frequently result in structural failure and even collapse in certain instances. In this study, incorporating of WGP into the concrete mixtures could effectively improve its residual compressive strength with various rates regarding the cement replacement ratio and high temperature exposure conditions. Table 9 shows the recorded increase percentage in the residual compressive strength values for all WGP mixes in the various temperature exposure conditions compared to its initial value in the control which led to a 45% greater improvement than the control mix when exposed to 800°C for two hours mixture. In most cases, the optimum replacement ratio was at 7% which led to a 53.5% increase in the residual compressive strength value compared to the control mix when exposed to 800°C for 120 minutes. At the most extreme conditions at 900 ^{0}C for 120 minutes, 7% WGP contributed to reduce the significant decline in compressive strength from 54.1% to 34%. In some mixes the replacement ratio of 9% WGP with cement obtained the optimal results. Materials acts as a SCM, as suggested for WGP, can improve concrete's ability to withstand the deleterious effects of elevated temperatures through various mechanisms [48]. The pozzolanic reaction between materials like WGP and CH generates supplementary CSH and calcium alumino-silicate hydrates within the cement matrix. This secondary CSH gel has the capacity to occupy the pores and voids within the concrete structure, leading to a more compact microstructure. This increased density of the microstructure strengthens the concrete's resilience to heat and reduces permeability. When subjected to thermal stress, the additional hydration products effectively mitigate crack formation. These combined effects resulting from the addition of supplementary cementitious materials lead to improved resistance to spalling and higher RCS values for concretes exposed to elevated temperatures [49]. Figure 10 shows some of the optical observations for concrete surface of the control and optimum WGP replacement mixes at the high temperatures after 120 minutes exposure time. For the control mixture, some clicking and voids appear when exposed to a temperature of 400°C, evolving into superficial cracks with minor separations and mass loss as the temperature rises to 600°C. The severity and depth of cracks increase at 800°C. At 900°C, significant separations of the surface concrete mass occur, accompanied by near-collapse of the concrete cover and substantial mass loss, resulting in reduced strength. These thermal effects were less pronounced in the case of the optimal replacement ratio mixture with 7% WGP, where the surface of the concrete cubes was nearly void-free at a temperature of 400°C, increasing more significantly along with minor surface cracks at 600°C. Superficial cracks increased slightly in terms of number and length at 800°C, although they were not as deep as in the control mixture. Finally, exposure to a temperature of 900°C caused the network of cracks to expand and resulted in some loss of mass, but to a lesser extent than in the control mixture.

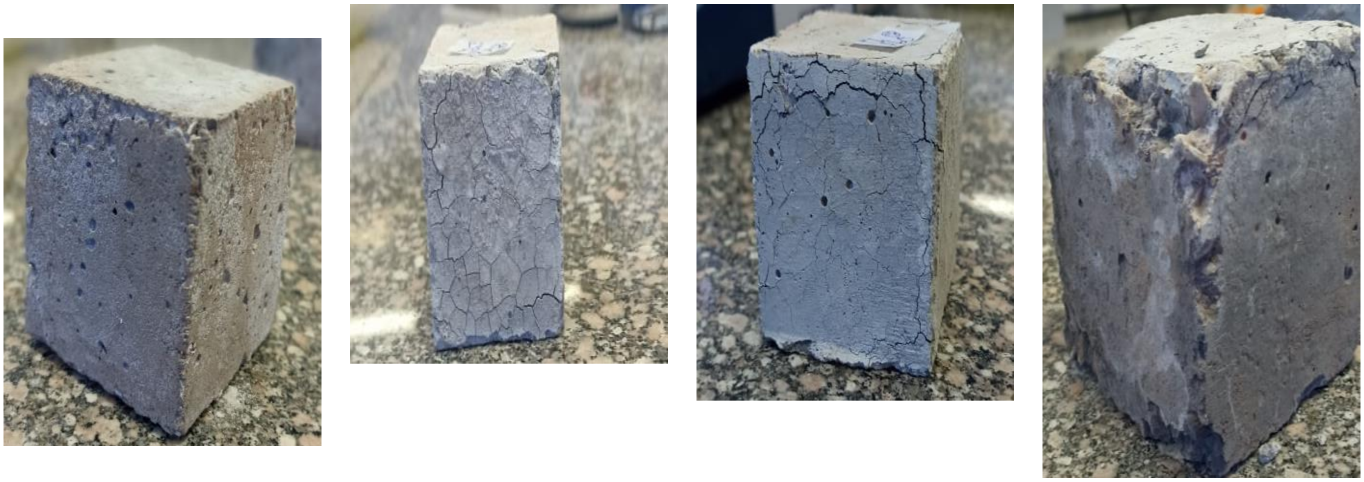
Table 8. *Compressive strength at various temperature conditions*

Mixture	Compressive strength at 28 days (MPa)									
	60 minutes exposure time					120 minutes exposure time				
	200ºC	400ºC	600ºC	800ºC	900ºC	200ºC	400ºC	600ºC	800ºC	900ºC
Control	28.5	27.7	24.7	17.6	14.8	28.2	27.1	22.9	14.2	12.8
1% WGP	29.5	28.9	26.1	18.3	15.3	30.2	27.8	24.0	14.7	13.6
3% WGP	30.8	29.8	26.8	18.9	16.8	31.7	28.9	24.9	16.0	14.4
5% WGP	33.8	33.2	28.5	22.5	19.1	33.0	32.0	26.7	20.1	16.7
7% WGP	36.5	35.8	31.1	24.3	20.8	36.7	34.7	29.0	21.8	18.4
9% WGP	33.4	32.7	31.4	24.7	20.2	32.9	32.1	29.5	21.0	17.5

Table 9. *Residual compressive strength improvements for the various WGP mixes and exposure conditions*

Mixture	Improvement rates of residual compressive strength %									
	60 minutes exposure time					120 minutes exposure time				
	200ºC	400ºC	600ºC	800ºC	900ºC	200ºC	400ºC	600ºC	800ºC	900ºC
1% WGP	3.5	4.3	5.7	4.0	3.4	7.1	2.6	4.8	3.5	6.3
3% WGP	8.1	7.6	8.5	7.4	13.5	12.4	6.6	8.7	12.7	12.5
5% WGP	18.6	19.9	15.4	27.8	29.1	17.0	18.1	16.6	41.5	30.5
7% WGP	28.1	29.2	25.9	38.1	40.5	30.1	28.0	26.6	53.5	43.8
9% WGP	17.2	18.1	27.1	40.3	36.5	16.7	18.5	28.8	47.9	36.7

400⁰C 600⁰C 800⁰C 900⁰C



(a) Control mixture

(b) The optimum mixture at 7% WGP replacement

Fig. 10. Optical observations for concrete surface at the various temperature degrees after 120 minutes exposure time

Table 10. *Standard deviation, maximum, minimum, and average amount of compressive strength results*

Variables	Abbreviation	Sum	Minimum	Maximum	Average	Standard deviation
Input Variable						
Temperature degree (C°)	Temp	66	25	900	529.54	293.94
Exposure time (hour)	Time	66	0	2	1.36	0.647
Waste granodiorite Powder (%)	WGP	66	0	9	4.16	3.21
Output Variable						
Compressive Strength (MPa)	CS	66	12.8	36.7	25.86	6.81

Based on the results of the experimental work provided in Tables 7&8, statistical analysis of variance (ANOVA), regression analysis, in addition to sensitivity analysis was conducted on the available experimental data. ANOVA is a powerful tool that helps us understand the meaning of mathematical models and the effects they describe [50]. It works by breaking down the total variation in an experiment's data. The standard deviation, maximum, minimum, and average amount of rough data of the compressive strength results in this study are presented in Table 10. Regression analysis results are provided in Table 11 and Figure 11. ANOVA analysis results are illustrated in Table 12.

Table 11. *Regression analysis results*

Observations	Multiple R	R^2	Adjusted R^2	Standard Error	Regression equation for CS prediction
66	0.924	0.854	0.846	2.667	CS=-0.02Temp+0.49Time+0.757WGP+32.68

Table 12. *ANOVA analysis results for CS model*

Source	Degrees of fredom	Sum of square	Mean square	F- value
Model	3	13361325	4453775	206.0522
Error	4	5619845	21614.79	F- value
Total	7	18981170		2.639

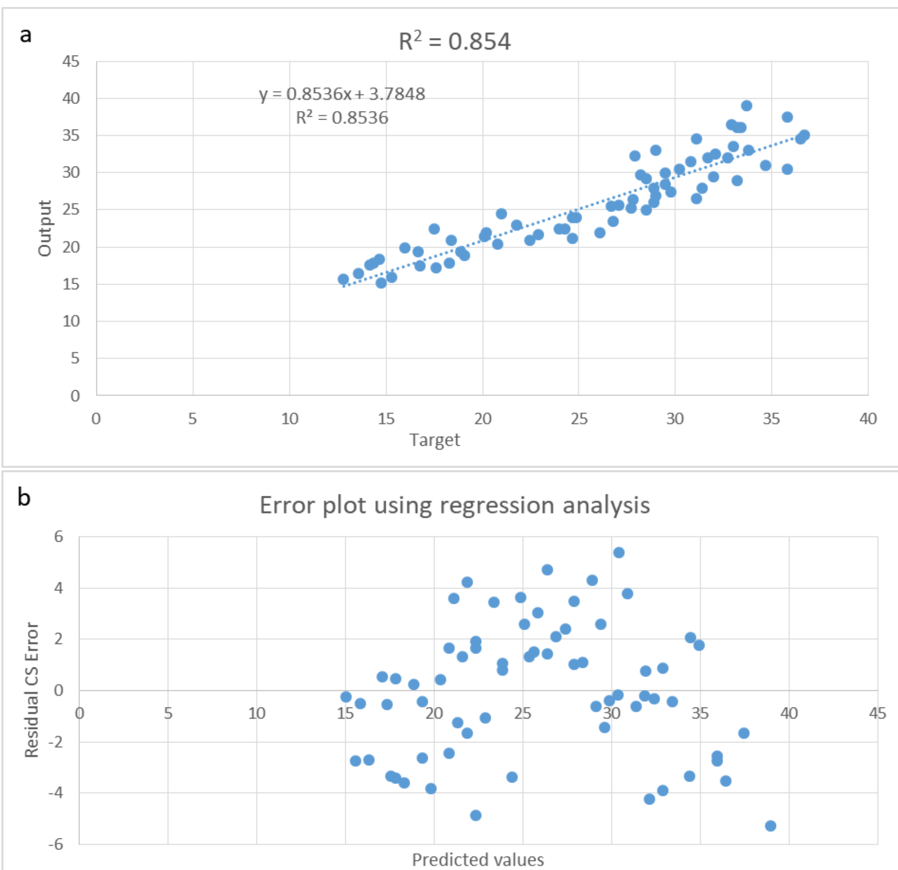


Fig. 11. a) Regression Plot for the actual and predicted values, b) Residual error plot

To study the impact of each of the three input variables (replacement ratio, temperature degree, and exposure duration) on the compressive strength value, sensitivity tests were conducted using a neural network model in SPSS software. Sensitivity analysis aims to investigate how uncertainties in the output of a mathematical model or system can be attributed to different sources of uncertainty in its inputs [51]. By reassessing outcomes using different assumptions, the influence of various variables can be identified, offering an effective approach to comprehending the fundamental relationships between input and output variables in a model. Figure 12 illustrates the effect of each parameter on the compressive strength value. The analysis indicates that temperature degree is the most significant factor impacting the compressive strength value followed by WGP replacement ratio and exposure duration, recepectively.

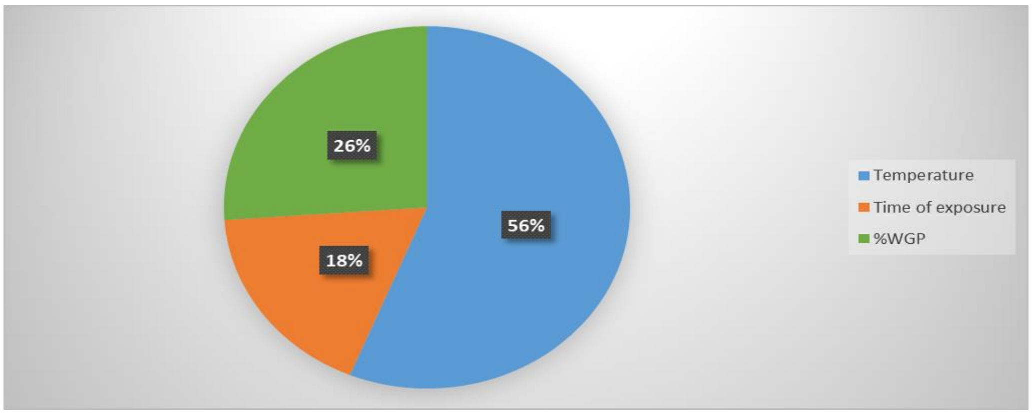


Fig. 12. Sensitivity analysis of the input and output factors affecting the compressive strength

Tensile strength of concrete

Results of the effect of replacing cement with various ratios of WGP on the concrete tensile strength measured using the split cylinder (Brazilian) test are shown in Figure 13. Each result represents the average value of three cylinders. The results demonstrate the ability of WGP to reasonably enhance the tensile strength of concrete, with similar way to the compressive strength of concrete in which the optimal replacement ratio was found to be 7%. This ratio contributed to improving the tensile strength of concrete cylinders by approximately 17.3% at the age of 28 days. It is also noted that the improvement ratios of the WGP-supported concrete tensile strength are higher at the early age of 7 days compared to relatively later ages, as cleared in Table 13. The ability of granite powder (with a chemical composition similar to that of WGP) to improve the tensile strength of concrete has been confirmed in several previous studies. Abd Elmoaty (2013) [44] conclude that replacing cement with 5.0% granite dust slightly improves the tensile strength of concrete compared to the control mix. However, concrete mixes with granite dust replacement levels greater than 5.0% exhibit lower tensile strength than the control mix. Ghorbani et al (2018) [45] demonstrated that the replacement ratio of 10% is the optimal to improve the tensile strength of concrete subjected to adverse exposure conditions. Allam et al (2016) [52] reported that incorporation of 5% fine granite waste as a partial cement replacement increased the splitting tensile strength of the concrete by 20% compared to the control mix. However, increasing the cement replacement ratio to 10% resulted in a splitting tensile strength value similar to that of the control mix.

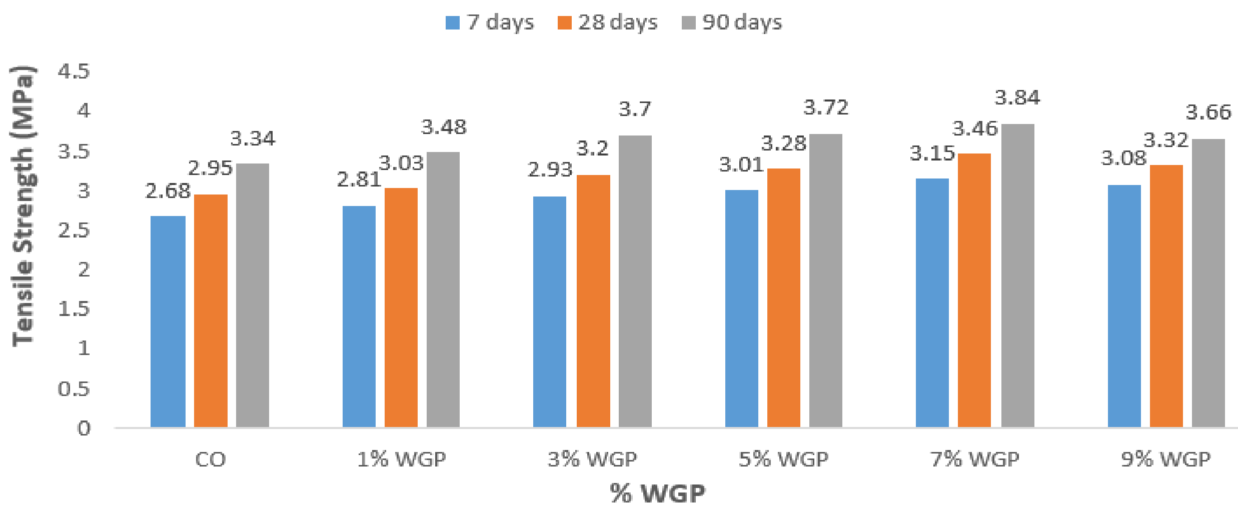


Fig. 13. Tensile strength at the different ages

Table 13. *Tensile strength improving rates at the various curing ages*

Mix	Compressive strength improvement rates %		
	7 days	28 days	90 days
1% WGP	4.9	2.7	4.2
3% WGP	9.7	8.5	9
5% WGP	12.3	11.2	11.4
7% WGP	17.5	17.3	15.3
9% WGP	14.9	12.5	10.2

XRD results

Figure 11 illustrates the XRD patterns of the investigated WGP. As shown from the figure; Quartz (SiO_2), Albite (Na(Al Si_3 O_8)), and Biotite (K Fe Mg_2 (Al Si_3 O_{10})(OH $)_2$), have been traced and detected. The results obtained from XRD test of the WGP sample closely match the chemical composition results of the chemical composition results obtained via the XRF test, confirming that quartz and albite minerals are the main mineral content of the WGP. Besides minor amount of biotite mineral with traces of accessory minerals as calcite and actinolite are also detected. The XRD patterns of composite cement pastes for the control mix and the optimum replacement ratio of WGP at 7% and are also cleared in Figure (14). Varying intensity values of various peaks of CSH, portlandite $Ca(OH)_2$, Albite, Quartz, Calcium Silicate Hydrate ($Ca_{1.5}$ Si $O_{3.5}$ x H_2O), and Biotite are shown in the mentioned figures. The XRD pattern of cement paste with 7% WGP paste indicates a significant increase in the CSH peaks. This increase in CSH content can be attributed to the high SiO_2 content in WGP, which participates in a hydration reaction with CH to produce additional CSH. This reaction is reflected in the higher intensity of the CSH peaks. The resulting higher CSH content leads to an improvement in the mechanical properties of concrete, particularly in compressive strength. Furthermore, the presence of high silica content in WGP is responsible for a remarkable increase in quartz content in the investigated sample. A similar observation was highlighted by Abd Elmoaty (2013) [44], where the increase in the proportion of quartz observed in the XRD test results was attributed to the high SiO_2 content in the granite used in his study, as close to the case with the WGP used in the current study.

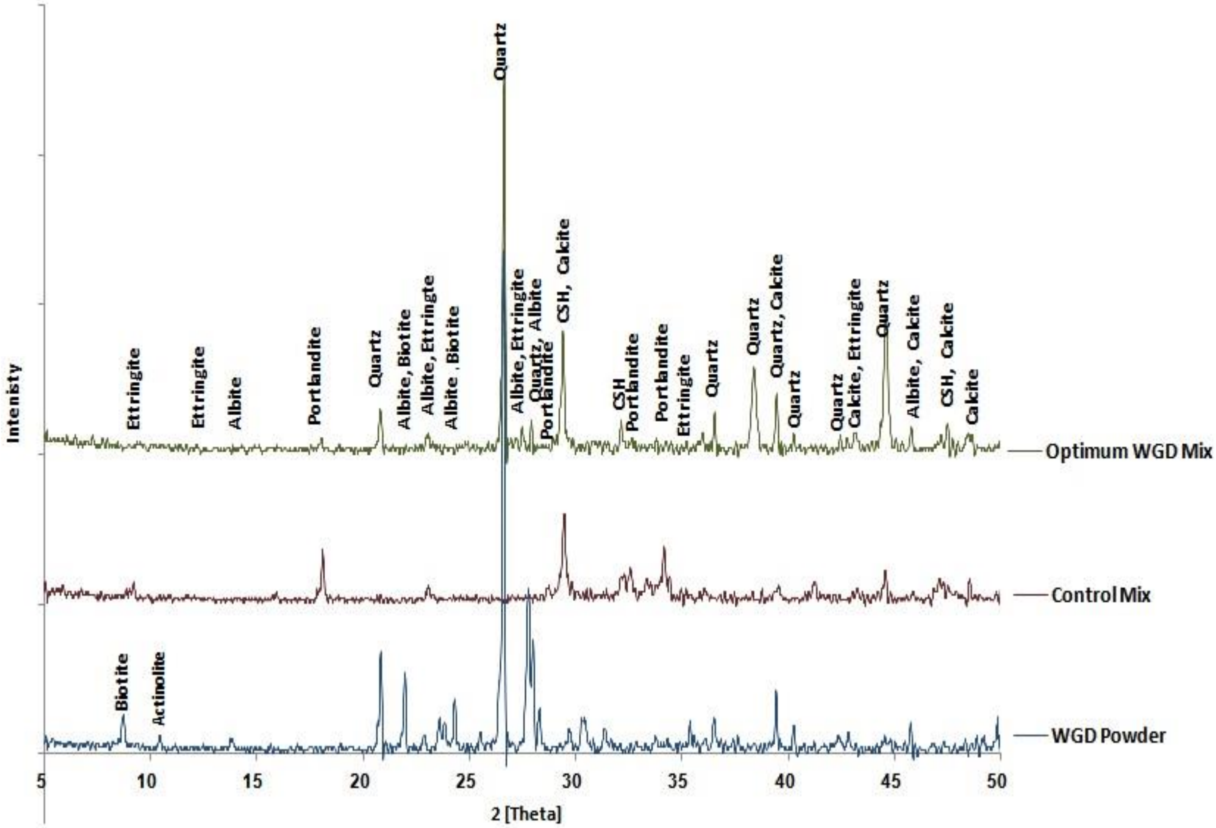


Fig. 14. XRD patterns of the WGD powder, Control Mix and Optimum WGD Mix

SEM imaging

SEM analysis was performed for two samples represents the control and the optimum WGP mixes. As shown in Figure 15, it can be observed that the control mix displays a highly porous microstructure and a heterogeneous matrix with irregular, detrimental pores, indicating poor quality concrete. The presence and size of large, wide pores throughout the bulk matrix are obvious. Furthermore, the cracks in the matrix are thick and wide. Additionally, large CH crystals are unevenly distributed throughout the matrix, with plate-shaped CH crystals appearing as hydration products in the concrete, as seen in the micrograph. Figure 16 illustrates a highly condensed microstructure observed in the optimum blend containing 7% WGP. In contrast, the concrete specimen with WGP exhibits an abundance of C-S-H in the form of needle-like structures, with no visible CH or ettringite crystals, and no signs of cracks or pores. The WGP plays a crucial role in maintaining the continuity of the hydration process, which leads to the formation of additional gel calcium silicate hydrate.

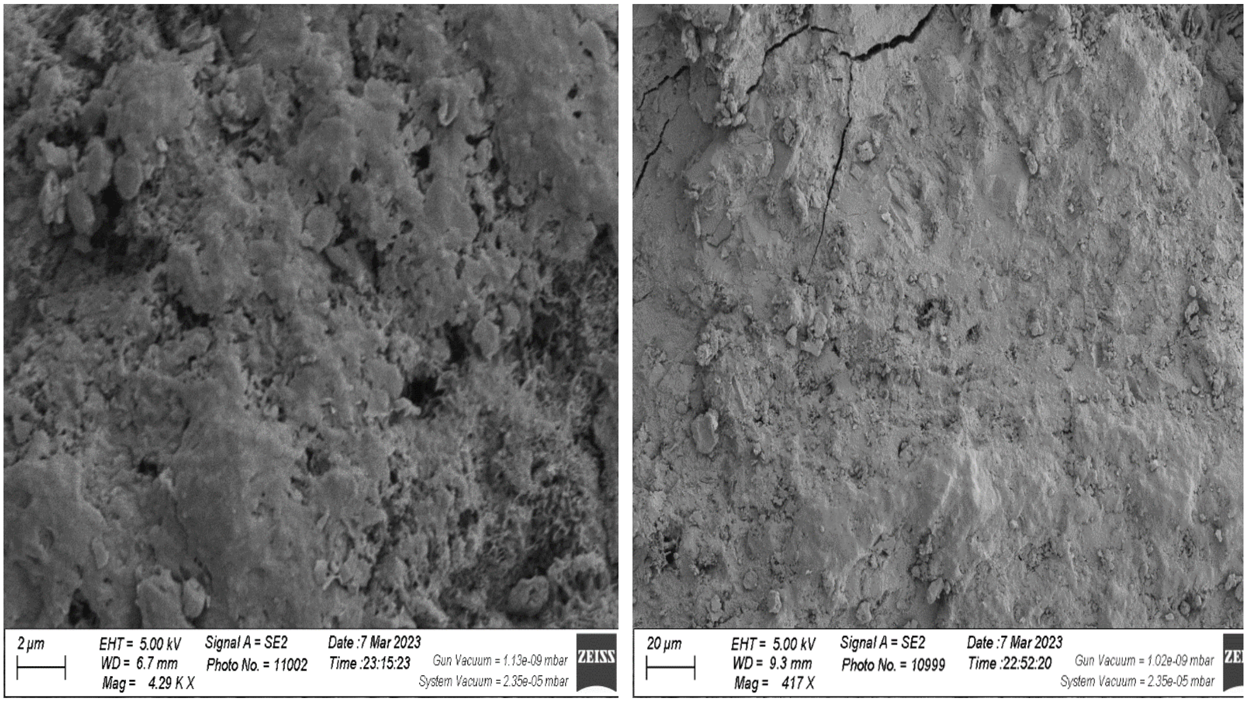


Fig.15. SEM images of the control mix

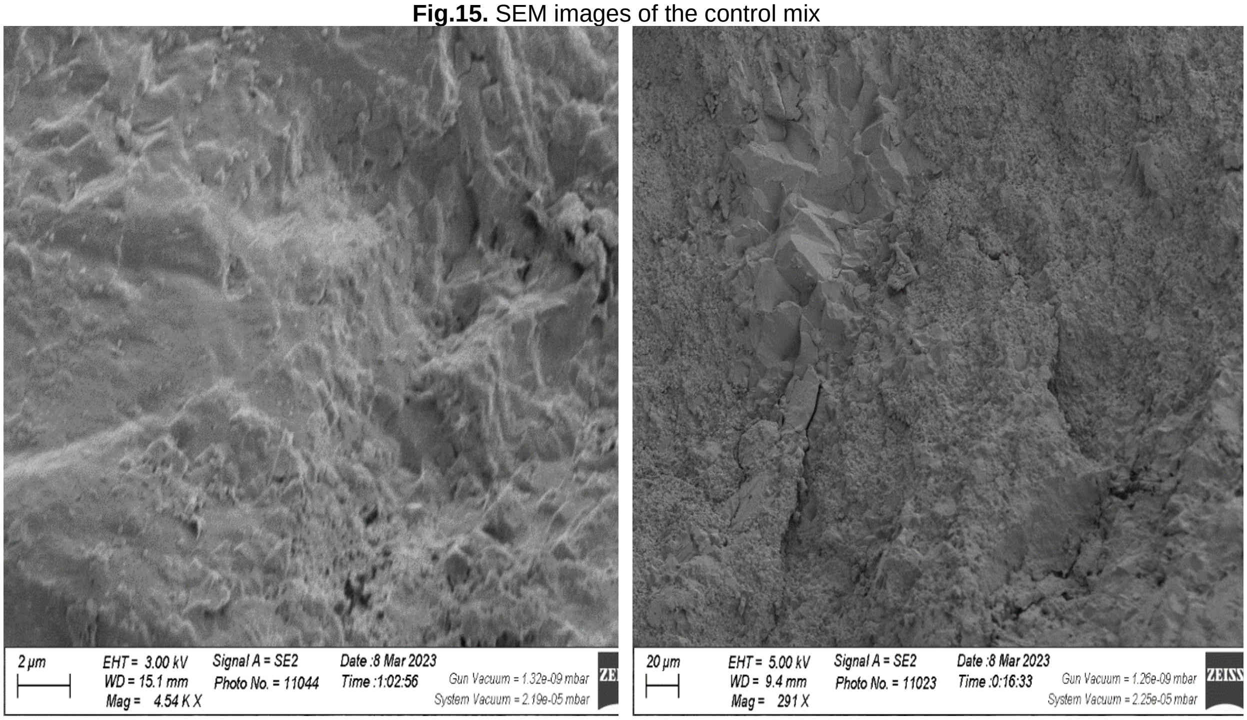
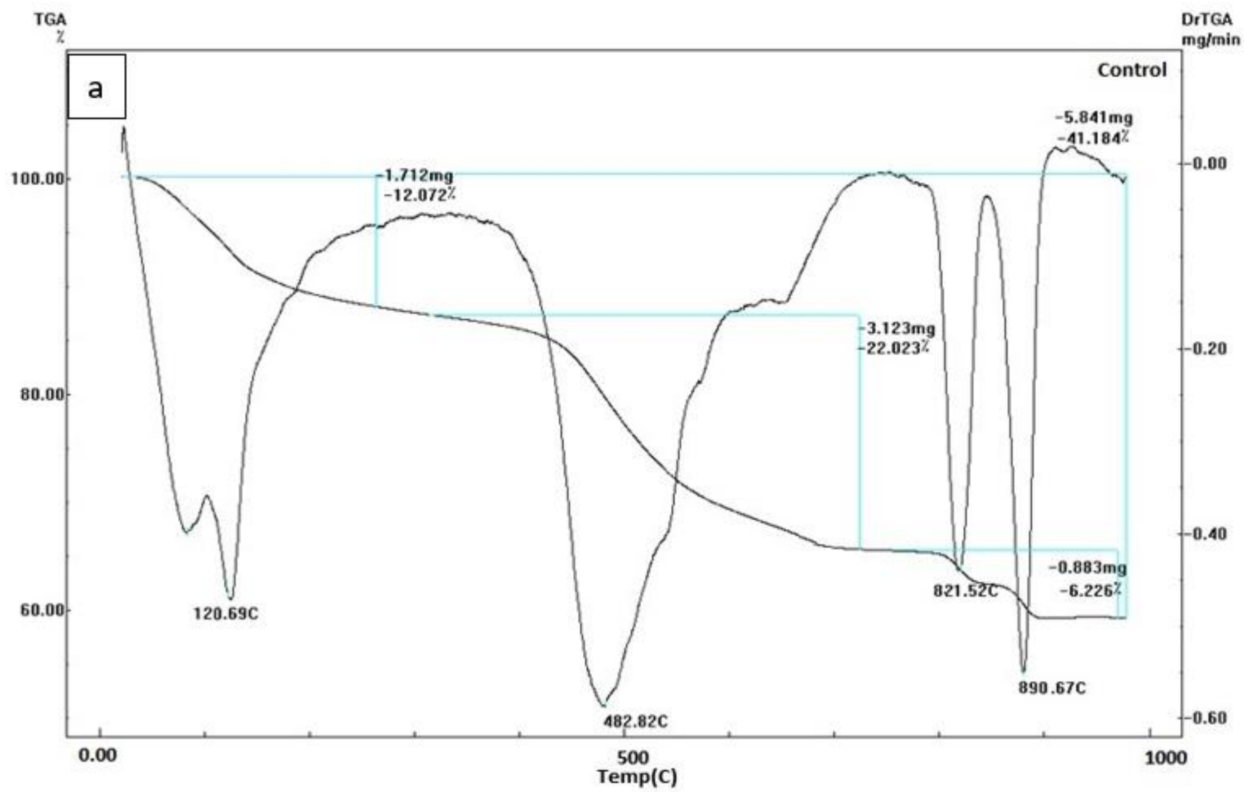
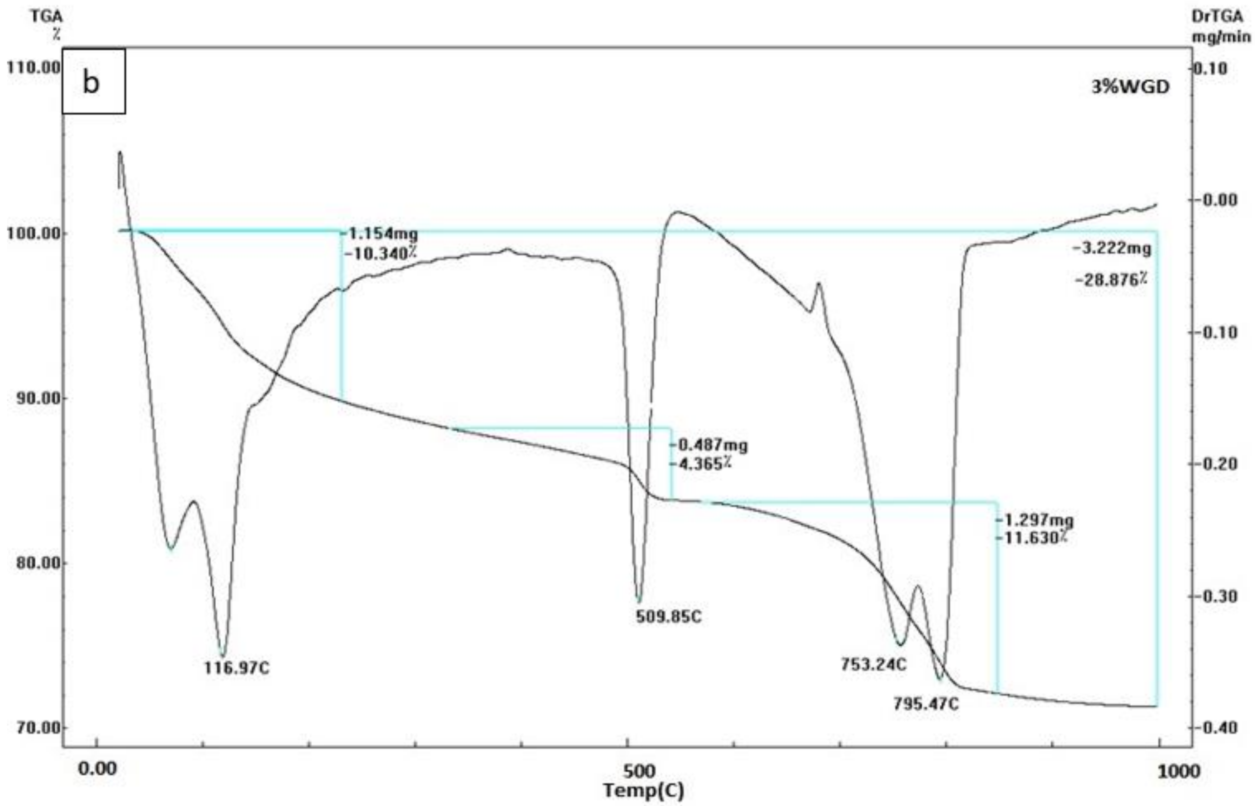


Fig.16. SEM images of 7% WGP mix

TGA analysis results

The test was performed by increasing the temperature from 22 to 1000^{0}C in order to quantify the hydration products (more specifically the Portlandite). The mass loss was measured to approximately 15 mg samples placed in an aluminum crucible and exposed under an inert atmosphere of Nitrogen. The temperatures ranged from 22 to 1000^{0}C at a heating rate of 20 C/min. A blank curve, obtained under the same conditions with the same empty aluminum crucible, was systematically subtracted. Figure 17 shows the TGA-DTA thermogrames of the hydrated sample of concrete with only OPC as a control sample, 3%WGD and 7%WGD to clarify the amounts of hydrated products and the consumed portlandite mineral with increasing of cement replacement with waste Granodiorite powder. The thermogrames illustrate endotherms approximately at 110-130°C, 480-510°C and 740-890°C. The decomposition of calcium silicate and calcium aluminate hydrates was clarified by the first endothermic peak. The second endothermic peak represents the dehydroxylation of portlandite ($Ca(OH)_2$). In addition, the last endothermic is due to the decomposition of calcium carbonate ($CaCO_3$). It can be noticed that, the peak area of $Ca(OH)_2$ is relatively higher in the control sample than other mixes with replacement percentages 3% and 7%WGD. This means that there is a type of reaction consumes the produced portlandite and enhances the hydration phases with increasing cement replacement up to 7%.





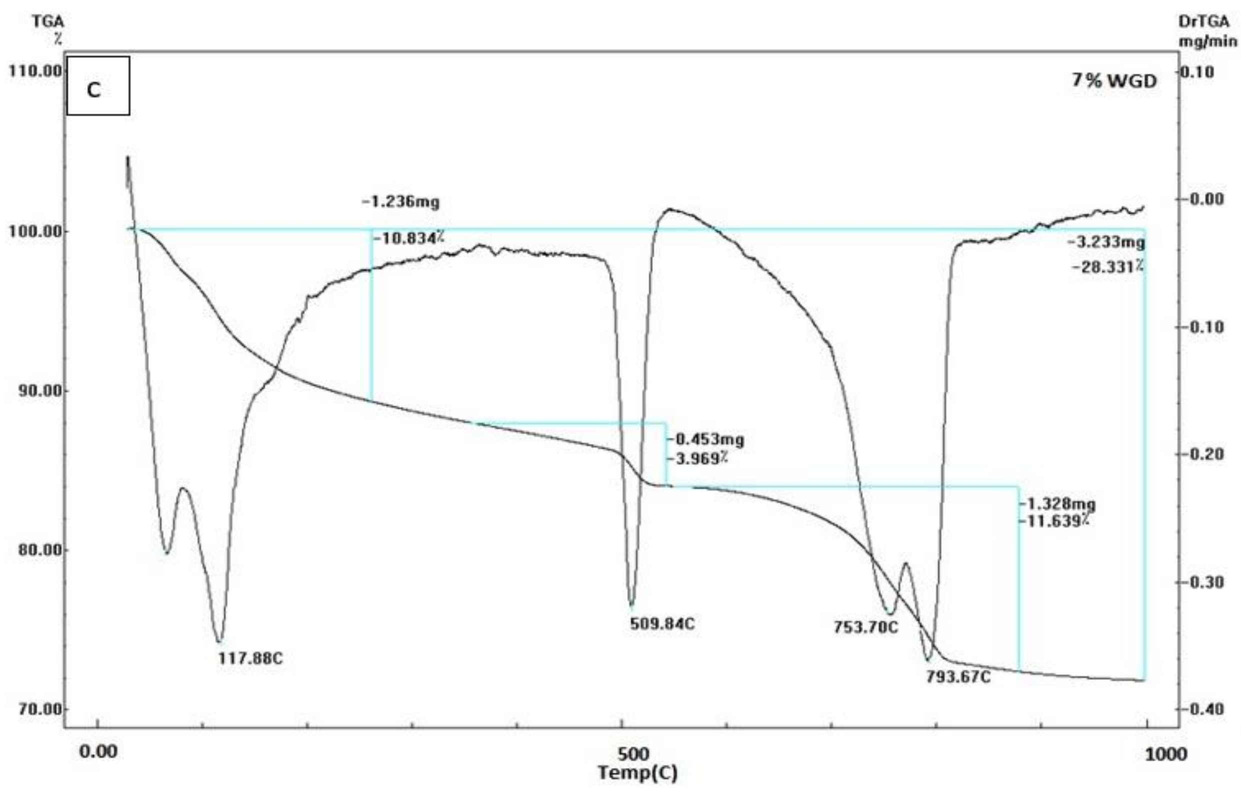


Fig. 17. Thermogravimetric analysis TGA / DTG for the mixes a) control, b) 3%WGP, c) 7% WGP

EDX analysis results

EDX analysis is a widely used technique to investigate the chemical composition of various materials and compare the weight percentage of different elements. In the field of concrete research, the Ca/Si ratio is a crucial factor that affects the strength development of different concrete samples. The ratio refers to the ratio of the mass of CaO to the mass of SiO_2 in the cement used to make the concrete. The Ca/Si ratio of the C-S-H gels present in concrete can indicate the degree of polymerization of the C-S-H. In general, a higher Ca/Si ratio in the cement used to make the concrete can lead to a higher compressive strength of the resulting concrete. This is because a higher Ca/Si ratio typically results in a higher degree of cement hydration, which can lead to a denser and stronger concrete matrix. However, the relationship between the Ca/Si ratio and compressive strength is not always straightforward, and other factors such as the type and amount of aggregate used, the water-cement ratio, and the curing conditions can also influence the strength of the concrete. In certain cases, an inverse relationship between the Ca/Si ratio and compressive strength of concrete may be observed. This can occur when the Ca/Si ratio is too high, leading to an excess of calcium oxide in the cement. If the Ca/Si ratio is too high, it can lead to the formation of excessive amounts of $Ca(OH)_2$ during the cement hydration process. This can cause the concrete to be more porous and weaker, resulting in a lower compressive strength.

The present study investigated the main constituents of hydration products in various concrete specimens. Specifically, the O, Ca, Si and Al peaks were examined, as detailed in Table 14 in terms of weight percent. Notably, Table 15 indicates that the Ca/Si ratio of concrete specimens ranged from 6.7 to 3.6, corresponding to (CO, 3%WGP, 9%WGP, and 7%WGP), respectively. Additionally, Table 15 illustrates also that the Ca/Al ratio of concrete specimens ranged from 32.6 to 15, corresponding to (CO, 3%WGP, 9%WGP, and 7%WGP), respectively

Table 14. *EDX results for different concrete mixes*

Element	Co	3%WGP	7%WGP	9%WGP
	(Weight %)			
O K	37.92	40.12	44.48	41.95
Ca K	44.36	36.75	28.92	32.82
Si K	6.59	7.12	7.98	7.63
Al K	1.36	1.52	1.92	1.73
Fe K	1.68	1.78	1.96	1.88
Mg K	0.28	0.39	0.66	0.49
Na K	1.87	1.56	0.72	1.35
C K	5.92	10.75	13.35	12.14

Table 15. *Ca/Si ratio for different concrete mixes*

Mix	Co	3%WGP	7%WGP	9%WGP
Ca/Si ratio	6.7	5.1	3.6	4.3
Ca/Al ratio	32.6	24.1	15	18.9

From the results, it can be deduced that the order in Ca/Si ratio and Ca/Al ratio follows the trend of Co > 3%WGP > 9%WGP > 7%WGP. Therefore, the findings obtained via EDX analysis verified that a lower Ca/Si ratio resulted in a higher compressive strength. The EDX analysis thus confirmed the relationship between the examined constituents and the compressive strength of the concrete. This could be explained by the Pozzolanic effect of WGP that led to Pozzolanic reactions resulted in in some reduction of the Ca/Si ratio compared to cement hydration alone. The pozzolanic action of WGP reduces the CH and lowers the Ca/Si ratio of the C–S–H phase in the concrete. When cement hydrates, calcium hydroxide is formed as a product which exists in the pore solution but does not contribute significantly to concrete strength. WGP acts as a pozzolan that can react with the calcium hydroxide to form additional C–S–H gel. By consuming some of the calcium hydroxide through this reaction, the metakaolin reduces the amount of "free" calcium hydroxide in the concrete microstructure. The C–S–H gel formed from the pozzolanic reaction of WGP has a lower Ca:Si ratio compared to the C–S–H gel formed solely from cement hydration. This indicates that it contains less calcium and more silicon in its structure, allowing it to pack together more efficiently and contribute more strength to the concrete. Results are in a good agreement with several studies like Kim et al. (2013) [53], where they studied the nano-mechanical properties of synthetic C-S-H samples with different Ca/Si ratios ranging from 1.5 to 0.5. They found that the silicate polymerization increased and higher mean chain length of silicate polymers was calculated with decreasing C/S ratio. They also observed some distinct differences in the nano-mechanical properties of the synthetic C-S-H samples depending on their C/S ratios. The sample with the lowest Ca/Si ratio of 0.5 exhibited the highest nano-hardness and elastic modulus. Kavitha et al. (2015) [54] concluded that the pozzolanic reaction of metakaolin (MK) reduces the amount of CH and lowers the Ca/Si ratio in the C-S-H gel in the concrete. The C-S-H gel that is formed by the pozzolanic reaction of metakaolin has a lower Ca/Si compared to the C-S-H gel formed from cement hydration alone. This lower Ca/Si ratio C-S-H gel can pack together more efficiently and contribute more strength gaining of concrete. Thus, by both reducing the calcium hydroxide content and forming a lower Ca/Si ratio C–S–H gel, the pozzolanic action of metakaolin improves the microstructure and properties of the concrete. Abouelnour et al. (2024) [6] highlighted that EDX analysis validated a reduced Ca/Si ratio correlated with enhanced mechanical characteristics, notably in compressive strength. Furthermore, they elucidated that a lower Ca/Al ratio results in an augmentation of alumina content, counterbalanced by a reduction in portlandite content, consequently promoting the formation of C-A-H.

CONCLUSIONS

Through this current study, the authors aimed to investigate the effect of using WGP as a partial replacement material for cement on some physical, mechanical and microstructural properties of concrete. Unlike many other types of igneous rocks, researchers have not focused on experimenting with the use of granodiorite powder as an alternative material to cement in the concrete industry. Therefore, this current study could serve as a starting point for a series of research studies that aim to expand the investigation of the effect of replacing cement with granodiorite powder on the remaining properties of concrete. It’s worth mentioning that the results and conclusions obtained from the current study are subject to limitations imposed by the investigated variables. This includes the type of concrete (ordinary concrete), class of the employed cement (CEM I 42.5 N), the investigated replacement ratios (up to 9%), and the inherent physicochemical properties of the utilized granodiorite rock. Further investigations are required to explore a broader range of variables, enabling a more comprehensive understanding of the advantages and drawbacks associated with the utilization of granodiorite powders or analogous powders derived from rocks with comparable compositions as partial cement replacement materials.

The main conclusions of this current study can be summarized in the following points:

- Replacing cement with WGP improved the compressive strength of concrete at all replacement ratios and different ages of testing. The optimal replacement ratio was found to be 7%, which resulted in an increase in compressive strength by 25.9%, 28.3%, and 27.9% at ages of 7, 28, and 90 days, respectively.
- Regarding the tensile strength, the test results showed a similar behavior in terms of performance improvement, but with lower improvement ratios than the compressive strength case. The optimal replacement ratio led to an increase in tensile strength by 17.5%, 17.3%, and 15.3% at ages of 7, 28, and 90 days, respectively.
- WGP incorporation into concrete mixtures improved its residual compressive strength after elevated temperatures exposure at the various conditions of replacement ratios and exposure durations. As example, replacing cement with 7% WGP could improve the residual compressive strength values by 55.3 and 43.8% after 120 minutes of exposure to temperature degrees of 800^0C and 900^0C, respectively.
- As the replacement ratio of WGP with cement increased up to 5%, a slight improvement in the workability of fresh concrete was observed, as reflected in the slump test results. The mixture prepared with the mentioned replacement ratio recorded an increase in the slump rate of concrete by 8.3%.
- The microstructure of a concrete sample was studied at the optimal replacement ratio of WGP and compared to the control mix through SEM analyses. The results showed that incorporation of WGP into concrete mixture helped to reduce the microstructural voids and cracks in the concrete, and aided in increasing the production rate of the C-S-H compound, which leads to enhancing the strength of concrete.
- XRD test results showed a close convergence with the chemical composition results of the WGP, indicating the presence of a high content of SiO_2. Furthermore, WGP was found to contribute to an increase in the CSH content in the sample, which in turn contributes to an increase in the concrete's resistance to mechanical loads, particularly compressive strength.
- Results from EDX revealed that the pozzolanic effect of WGP addition resulted in lower Ca/Si ratios in the concrete, leading to higher mechanical strengths. The highest compressive and tensile strengths were recorded at the lowest Ca/Si ratio of 3.6.
- TGA results showed that the reaction of WGP in the cement paste matrix consumes more of the produced portlandite and enhances the hydration phases with increasing cement replacement ratio up to 7%.
- Statistical measures provided insights into the influencing variables on the compressive strength with or without elevated temperature exposure. All variable parameters of

temperature degree ratio, WGP ratio, and exposure time are effective with different rates on the final compressive strength value as proved via the ANOVA, regression, and sensitivity analysis.

- The promising results of this study could provide a basis for further investigating the effects of using granodiorite powder on other concrete properties, including flexural strength as well as durability indicators like resistance to chemical effects and performance under extreme weather conditions. These investigations could evaluate multiple replacement ratios and particle sizes of granodiorite powder, like nanosized particles.

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