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Investigating the Effect of Rubber Powder and Nano Silica on the Durability and Strength Characteristics of Geopolymeric Concretes

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ABSTRACT

In this research, the effect of adding different percentages of nano-silica and rubber powder on the compressive strength of the geopolymeric concrete specimens is investigated. The set of performed tests includes the compressive and tensile strength tests of the geopolymeric concretes. Due to the high rate of consumed concrete and the daily increase of the need for cement production, it is essential to consider environmental defects of this material and present new replacement products to move towards sustainable development. Low shrinkage, high compressive, and tensile strengths are among the main properties of produced concrete. Also, the application of nanoparticles, due to their specific physical and chemical properties, in many respects, are very good candidates for producing novel materials with unique capabilities. Hence, the use of nano-silica as one of the nanotechnology products which could play the role of a very active artificial pozzolan in concrete has been under the focus of attention. Replacement of the rubber powder in the construction industry, due to the irresolvability of this type of wastes and also its specific structure such as improved ductility, reduced density, and improved resistance against concrete cracking, has been practiced today. The aim of this research is to implement the two mentioned materials as additives in the concrete mix design and to investigate their effect on the increase of the compressive and tensile strengths in concrete. The results of this research have shown that the use of nano-silica powder and rubber powder results in the increase of the compressive strength of concrete up to 1.45 times that of the control specimen using the nano-silica powder and 1.35 times that of the control specimen using the rubber powder.

Keywords: Nano silica, Geopolymere, rubber powder.

1. INTRODUCTION

In this type of concrete, the use of rubber powder has resulted in the production of environmentally friendly concrete. Application of the geopolymer instead of Portland cement as the main connection between concrete components leads to a reduced amount of carbon dioxide in nature. On the other hand, rubber powder as an additive could help with reducing environmental pollution. The rubber geopolymeric concrete (RGC) with 10% and 20% rubber has replaced natural aggregates, and its impact on the increased strength of concrete is investigated. The effect of GCs on the concrete performance has been investigated by the slump flow, density, compressive, tensile, and flexural strength tests at the 7 and 28-day ages. Aly et al. [1] in 2019 have examined the effect of various percentages of rubber crumbs as partial replacement of geopolymeric material. In this research, the recycled plastics with volumetric percentages of (0%, 10%, 20%, and 30%) have been added to the aggregates, and their effect on the hardened concrete properties (compressive, tensile, and flexural strengths) and also resistance against impact in geopolymeric concrete have been investigated. Abd-Elaal [2] has dealt with refined rubber powder and its application in concrete. In that research, a new approach for refining the rubber crumbs by heat treatment at 200 temperature prior to its use in concrete is presented and investigated. The required time of heating, rubber size, and rubber contents were the variables in the research. Scanning Electron Microscope (SEM) investigation was performed on the specimens treated with heat rubber particles and also Crumb Rubber Concrete (CRC) specimens. The results showed promising advancements with respect to the previous findings in terms of the concrete performance so that a combination of rubber content equal to 20% of aggregate weight resulted in increased compressive strength of concrete by 60.3%. Murugan [3] in 2015 investigated the application of the rubber powder in concrete. The main advantages of using rubber crumbs in concrete are reduced density, resistance against impact and increased concrete strength and ductility, and a produced concrete with enhanced sound insulation property. Crumbed rubber is made by the grinding of waste rubbers. The size of crumbed rubber particles ranges from 0.075mm to more than 4.75mm, which is similar to that of fine-grained aggregates. The weight percentage of rubber powder was 5-25% of aggregates (river sand and gravel) weight in made concrete. The test results showed that the addition of rubber powder leads to increased density, compressive strength, and tensile static modulus. Naito et al. [4] have investigated the effect of rubber powder on the concrete. Replacement of powdered rubber per 0.75 aggregate has been investigated in this research. Also, the addition of the powdered rubber leads to reduced unit weight of concrete and increased compressive and tensile strengths and modulus of elasticity in concrete. Furthermore, flexural strength increases with the addition of rubber powder. Xu et al., 2020 [5] have investigated the strength of concrete beams by the addition of rubber powder. The aim of that study was to present a guide for examining the rubber powder presence in concrete. For instance, it was found that the effect of rubber powder on the increase of the tri-axial compressive strength is negligible [6]. Also, the application of Nano silica powder has been observed in the previous research. For example, the effect of adding Nano-SiO_2 (NS) on the geopolymeric material characteristics has been examined through measuring the physicomechanical and morphological characteristics of the hardened specimens by Khater et al. in 2016. The investigated materials in this research include alumino-silicate, water-cooled slag, albite, kaolin, and metakaolin. The materials were prepared by the water to sodium silicate ratio within the range 0.244-.320, and the results showed that the compressive strength of geopolymeric mixture with Nano-silica composition has the highest value. Çevik et al. [7] in 2018 investigated the effect of using Nano-silica on the geopolymeric compound made of Nano-silica and fly ash and examined the strength and chemical durability of this type of concrete. In this research, four types of geopolymeric and ordinary Portland cement (OPC) concrete were tested in solutions of sulfuric acid (H_2SO_4), magnesium sulfate ($MgSO_4$), seawater (NaCl) with concentrations of 5%, 5%, and 3.5%, respectively. Change in the weight of concrete was used as a measure for durability. In order to assess the mechanical performance in the chemical environments, the compressive, tensile, and flexural strength tests also were conducted on the specimens. The results showed that FAGPC concretes in the vicinity of chemical attacks due to the low content of calcium have a better performance with respect to OPC concrete. Ami Ghanei et al., 2019 [8] investigated the use of Nano-silica and fibers in the mortar. The results of that research showed that the compressive and flexural strengths of the mortar reduced with the increase of Metakaolin amount, whereas Nano-silica had a positive effect on the concrete strength. Finally, the research results were investigated using numerical and experimental methods. Sikander et al. (2019) [9] investigated the use of Nano-silica in geopolymers. In their research, the mechanical performance of concrete, such as the compressive strength and split tensile strength, and measured tensile modulus, were investigated. Furthermore, rapid chloride permeability, water absorption, and porosity tests were examined. Ravithage et al. (2019) [10] investigated the effect of Nano-silica and GGBS on the strength of geopolymer concretes. In their research, they investigated the role of aluminum silicate as an activator in the geopolymeric concrete. In addition, the compressive strength of concrete at 3, 7, and 28 –day ages were examined [11]. Also use of Nano-silica in some other studies like that of Rashad in 2019 [12], Çevik in 2018 [13], and Naskar in 2016 [14] show that these Nanoparticles could lead to an increase in the concrete strength. The above-mentioned studies demonstrate that the application of Nano-silica in geopolymeric concrete is a novel topic that has recently been considered in some research works. In addition, the use of the rubber powder in the ordinary and geopolymeric concretes, due to its characteristics, is a topic that recently has come under the focus of attention. But the simultaneous application of both rubber powder and Nano-silica is a topic that has not been referred to in the research works. In the present research, the simultaneous effect of applying both materials in concrete is investigated, and their role in increase or decrease of the compressive and tensile strengths has been examined.

2. MATERIALS AND METHODS

In the present research, use has been made of the rubber powder and Nano-silica as additives. Concrete or geopolymeric mortar could not be made without a precursor and activator substance. Selection of the proper precursor is among the most important stages of making polymeric concrete. Metakaolin, blast-furnace slag, fly ash, and Nano-silica are among the precursors. Selection of the activation method is made with respect to selected precursor matter. The activator solution acts by solving the precursor and lets it to be reconstructed as an inorganic polymeric matter. For the polymerization reaction, the alkaline activator solution was gently and continuously poured on the precursor. The mixing process was performed using the mechanical mixers till reaching a full homogenous paste. The proper time for mixing the alkaline with slag precursor was 15 minutes using a magnetic mixer with a speed of 120 rounds per minute. Also, the Nano-silica compound first was manually dry-mixed for 4 hours using a jar mill and then was mixed for 30 minutes by a mixer. Finally, a gel is produced, which was hardened by time, and its viscosity increased. The obtained homogeneous mixture, before become hardened, was placed in molds with proper dimensions for curing and then tested by the compressive strength test. In this research, for the alkaline activation of the initial raw materials, use was made of sodium hydroxide and potassium hydroxide. For this purpose, both sodium hydroxide and potassium hydroxide were prepared in the form of fins and solved in distilled water to attain solutions of 6, 8, and 10 molars. Sodium silicate, which is a solution made of NaO2 and SiO2 has been used with 2.33 molarity.

2.1. INTRODUCING THE USED MATERIALS

Rubber powder: During a process, the waste vehicle tires or those damaged which could not be repaired are recycled. These tires are among the high volume wastes in the world and are very problematic. The main issue with them is their long durability and large volumes of produced wastes. By clinching old tires and filling them with soil, and covering them with concrete, some forms of tiny houses could be built. The waste tires also could have different applications in civil engineering and building construction, such as the roof cover or insulators, cover of playgrounds for children, filling embankment dams, or inner layer of dams [15,16].

Figure 1. Rubber powder

2.1.1. Nano-Silica

Nanotechnology in recent years has been the cause of widespread advancements in human knowledge, and various scientists from a variety of fields have taken advantage of this technology. Nanoparticles, due to their special physical and chemical characteristics, have been used in many fields for making new materials with unique properties. Hence, the use of Nano-silica as a product of Nanotechnology that could play the role of a very active artificial pozzolan in concrete has been under the focus of attention. Nano-silica is a compound product with spherical particles in a wide spectrum range of 1 –50 Nanometers. The application of Nano-silica compound in concrete, Portland cement, and other materials has been successful in the laboratory [17]. Nano-silica reduces porosity in the hydrated cement by filling the void spaces between larger particles in the Nanoscale. Furthermore, Nano-silica provides for the pozzolanic activities in the materials and fly ash, which results in an increased rate of strengthening. Also, it has the potential of reducing the problems associated with the low strength of pozzolanic materials [18]. Nano-silica was purchased from Nanomavad Co. (Hydroshimi Trading Co.)

Figure 2. Nano-silica powder

2.1.2. Slag Powder

Use of the slag powder mixed with cement in the concrete making, produces secondary gel during reaction with the calcium hydroxide produced by cement hydration. By increase of the concrete age, the gel leads to improved durability and strength characteristics of concrete and while reducing the actual cost enhances the concrete resistance against the aggression of corrosive elements. This product is recommended for large volume concrete placing in hot climate areas. In the present research, the mentioned product is used as a replacement for cement in the geopolymeric concrete mixes to increase the concrete strength. The slag powder used in this research was purchased from Asiatak Company. Table 1 depicts the purchased slag properties.

Table 1. Used Slag characteristics

Mass percentage											
Material name	**Cao**	**SiO2**	**Al2O3**	**Fe2O3**	**SO3**	**MgO**	**Na2O**	**K2O**	**TiO2**	**MnO**	**L.O.I**
Slag	36.75	37.21	11.56	1.01	0.97	8.52	0.61	0.70	1.23	0.99	0.02

Figure 3. Slag Powder

The aggregates used in this project were prepared from the southwestern parts of Tehran. The fine-grained materials (sand) were of a natural type, and the coarse-grained materials (gravel) were of broken type. Also, for improving the compatibility between the grain distribution curve and ASTM C33 fine concrete aggregate, the distribution curve was somehow modified by adding fine-grained sands (0-1mm) to the ordinary size sands.

2.1.3. Cement

Cement is a binder that has the capability of binding the particles and creating an integrated and strong body. It is made of a composition of lime, clay, silica, and mineral oxides at 1400-1500. The produced material after heating is called clinker. By grinding the cement clinker and combining it with a proper amount of gypsum one could produce cement with different types. Also, by adding pozzolans to cement clinker and gypsum, the pozzolanic cement is produced. The size of clinker grains is 5-20mm, and its color is dark green.

2.1.4. Sodium Silicate

Sodium silicate is white color water-soluble powder and produces an alkaline chemical environment. Silicates are among the most known mineral compounds which are used for the manufacturing of glass, tile, and ceramic products [19]. Table 2 depicts the characteristics of the purchased sodium silicate.

Table 2. Properties of different industrial grades of sodium silicate

Environment	**Acid**	**Neutral**	**Alkaline**	
Ph -range	1 to less than 7	7	Greater than 7 to 14	
Density –(At 20 ℃)	Max 1.69	Min 1.59	Min 1.38	Min 1.26
Non-solubility	Max 0.2%	Max 0.2%	Max 0.2%	Max 0.2%
Na2O	17-18%	14-15%	9-20%	6-7%
SiO2	36-38%	34-36%	28-30%	23-25%
Ferrous dioxide	Max 0.05%	Max 0.05%	Max 0.03%	Max 0.03%

2.1.5. Sodium Hydroxide

Sodium hydroxide is a mineral compound with the chemical formula of NaOH. This material is a solid ionic compound with white color, which is composed of Sodium cation (Na+) and hydroxide anion (OH-). This compound, when contacted with the hand skin, could cause severe chemical burns. Sodium hydroxide is highly soluble in water and could easily absorb the moisture and carbon dioxide in the atmosphere [19].

Table 3. Chemical properties of sodium hydroxide

Solubility	density	Molar mass	Chemical formula
Water-alcohol-methanol	2.13 g/cm³	39.997 g/mol	NaOH

2.2. MIX DESIGN OF THE RESEARCH SPECIMENS

In the present research, 6 different mix designs are incorporated wherein the percentages of Nano-silica, and rubber powder are variable. Table 4 shows the mixed designs of the prepared specimens. In the table, group 1 is the control specimen, and groups 2-7 represent the 7 geopolymeric concrete specimens made of Nano clay and Nano-silica.

Table 4. Mix design of the geopolymeric concretes made in the laboratory

Material	sand	gravel	Slag	Sodium Silicate	Sodium hydroxide	Rubber powder	Nano-silica
GR_0	750	1000	450	150	75	0	0
GR_1	750	1000	450	150	75	3	0
Gr_ 2	750	1000	450	150	75	5	0
Gr_ 3	750	1000	450	150	75	10	0
Gr_4	750	1000	450	150	75	0	1
Gr_ 5	750	1000	450	150	75	0	2
Gr_ 6	750	1000	450	150	75	0	3
Gr_7	750	1000	450	150	75	5	3
Gr_8	750	1000	450	150	75	5	2

2.3. CONDUCTED TESTS

2.3.1. Compressive Strength

The concrete compressive strength is the result of determining the concrete compressive strength test. The amount of exerted load per one square centimeter on the specimen with a specific age and at the moment of specimen failure is defined as the compressive strength of concrete. To perform this test, first using a scale, the specimen weight is measured, and incorporating a caliper, the length, width, and height are measured. The load is precisely exerted upon the center of the specimen. The apparatus should be calibrated according to ASTMC39 standard prior to the start of tests. The loading rate could affect the test results. The loading rate is assumed to equal to 20 sec/MPA in all the specimens, and the applied load is taken equal to 1350 kg/cm2. The load is gradually increased till full failure of the specimens [20].

Figure 4. Determination of the compressive strength of concrete

2.3.2. Tensile Strength

A tensile strength test is performed in order to determine the uniaxial tensile strength of concrete, known as the Brazilian Test. In fact, tensile stress is applied on the rock, and another stress with a value of maximum 3 times that of the principal tensile stress is applied as compression. In this way, tensile failure occurs at the uniaxial tensile stress [21].

Figure 5. Determination of the tensile strength of concrete

2.3.3. Durability test in the sulfate environment

The durability test in the sulfate environment (figure 6) is designed to examine the durability of concrete specimens after 21 days of curing in the saturated limewater with sodium sulfate solution of 8%. The effect of submergence of concrete in the sulfate solutions for 28 days is measured by the change in the compressive strength according to BS 1881-116 Standard.

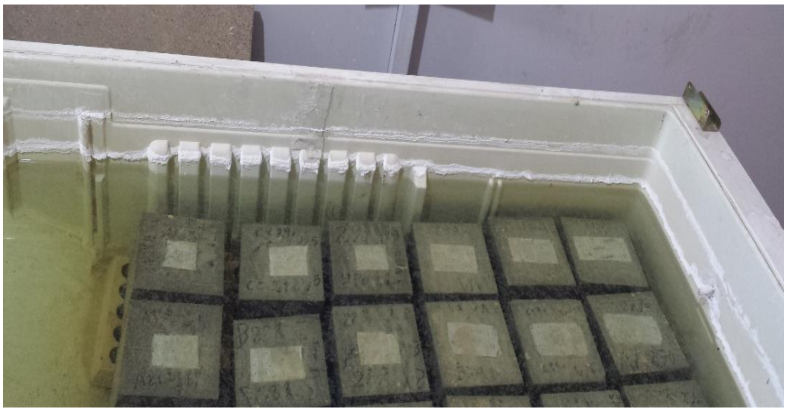

Figure 6. Sodium sulfate basin

3.4. PREPARATION OF THE GEOPOLYMERS AND RESEARCH OBJECTIVE

In the geopolymeric concrete made of the slag, for the mass of alkaline solution to the mass of basic material ratio, the values within range 0.45 are selected. The duration of mixing is 5 minutes, and curing is performed under a wet sack for 24 hours after placing it in the mold. In various performed tests, it is observed that the use of different amounts of sodium hydroxide leads to scattered values of the compressive strength for concrete specimens. Also, change in the ratio of sodium hydroxide to sodium silicate results in change in the compressive strength values in concrete specimens and their consistency limit [21,22].

4. RESULTS AND DISCUSSION

In this section, the results of the compressive and tensile strengths of geopolymeric concretes are examined, and an investigation of the effect of additives on the concrete behavior is performed. As is seen, in all the figures, adding Nano clay and Nano-silica at 3 wt% of concrete exhibited the highest compressive and tensile strengths, whereas corrosion of the geopolymeric specimens in the acid environment is significantly reduced. In the future, an attempt is made to explain the causes of these phenomena by discussing the results of this research. The results presented in diagrams no. 6-8 correspond to the average values of all the prepared specimens in the laboratory at 7 and 28-day ages, separately. Per each group, 3 to 5 specimens are made for controlling the validity of the results and reliability purposes.

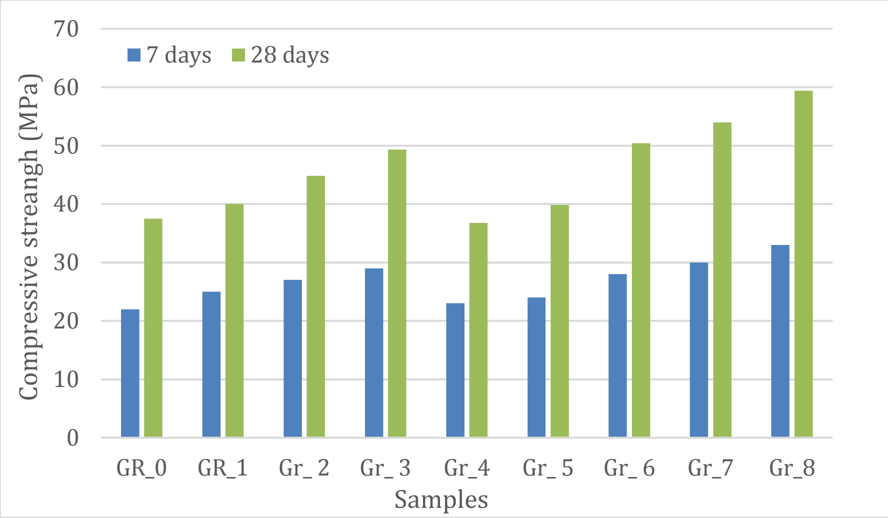

Figure 7. Compressive strength of concrete

Figure 7 shows the results of the compressive strength test of the specimens made using the rubber powder and Nano-silica. Application of the rubber powder and Nano-silica in the concrete specimens leads to the increased compressive strength of the concrete with respect to the control specimen. The concrete strength is investigated at the two ages of 7 and 28 days, and the results are drawn numerically on the diagram. Among the specimens made of Nano-silica, the 7-day concrete reaches its maximum strength per addition of 3% Nano-silica, which increases the concrete strength by 1.30 times. Also, per addition of 2% Nano-silica, the 7-day strength of concrete increases by 1.20 times, and finally, by addition of 1% Nano-silica, the concrete strength increases by 1.10 times. The effect of Nano-silica on the 28-day strength of concrete has also been investigated, and the results showed that the maximum strength belongs to the specimens with 3% Nano-silica in the concrete. Using 3% Nano-silica, the strength of concrete specimens increases by 1.4 times that of the control specimens. Using 2% Nano-silica, the strength of concrete specimens increase by 1.25 times that of the control specimens. Also, when using 1% Nano-silica in the concrete specimens, the concrete strength reaches 1.15 times that of the control specimens, which indicates that the application of Nano-silica could improve the concrete performance. In continuation, the results of concrete specimens made of the rubber powder are investigated, indicating increased strength of concrete through the use of rubber powder in concrete. Specimens GR-4 to GR-6, show the compressive strength values corresponding to the use of rubber powder in concrete. A comparison between the results of Nano-silica and rubber powder reveals that the use of Nano-silica has resulted in a higher increase in the concrete strength. However, the use of the rubber powder by 10% of the aggregate weight results in maximum compressive strength of concrete. This value for the 7-day age specimens is 1.27 times that of the control specimens, and for the 28-day age, specimens is 1.39 times that of the control specimens. Also, the use of rubber powder at 3% and 5%, results in an increase in the compressive strength of concrete. The addition of 3% rubber powder increases the compressive concrete strength by 1.11 times that of the control specimens at 28- day age, and for the 7-day age specimens, this value reaches 1.09% of the control specimens. Simultaneous use of the rubber powder and Nano-silica results in maximum strength of concrete.

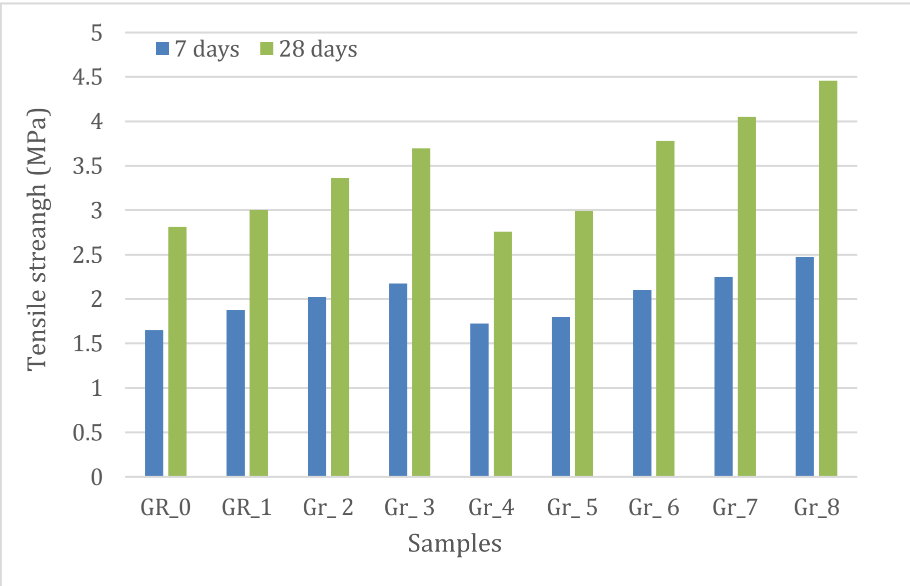

Figure 8. Tensile strength of concrete

Figure 8 shows the results of the tensile strength of the geopolymeric specimens. The use of the rubber powder and Nano-silica in concrete specimens leads to an increase in the compressive and tensile strengths of concrete with respect to the control specimen. Among the made specimens with Nano-silica, the 7-day age concrete experiences maximum tensile strength by adding 3% Nano-silica where the concrete strength reaches 1.27 times that of the control specimen. Also, per addition of 2% Nano-silica, the 28-day strength of concrete reaches 1.18 times that of the control specimen, and finally, per addition of 1% Nano-silica, the concrete strength reaches 1.06 times that of the control specimen. The effect of Nano-silica on the 7-day strength of the concrete also has been investigated, and the results have revealed that the maximum strength belonged to the specimens wherein 3% Nano-silica was used in making the concrete. In these specimens, the strength of concrete specimens per 3% use of Nano-silica reaches 1.35 times that of the control specimen. In the case of using 2% Nano-silica, the strength of concrete specimens reaches 1.27 times that of the control specimen, and finally, using 1% Nano-silica in the concrete specimens causes 1.13 times increase of the strength with respect to the control specimen. These results show that the use of Nano-silica could improve concrete performance. In continuation, the results of using rubber powder in concrete specimens are investigated. Application of the rubber powder causes an increase of the concrete strength. Using the rubber powder by 10% of the aggregate weight leads to a maximum compressive strength of concrete. This value for the 7-day age specimens is 1.25 times that of the control specimens, and for the 28-day age, specimens is 1.34 times that of the control specimens.

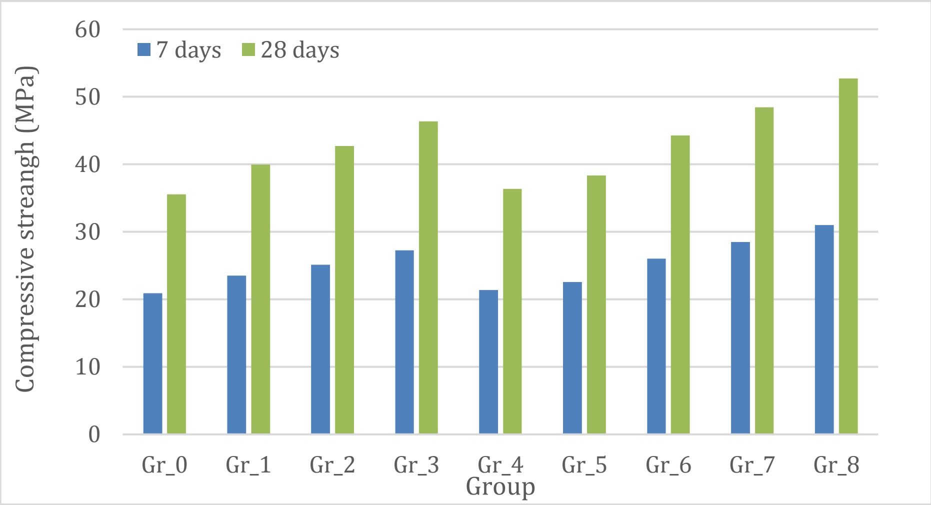

Figure 9. Compressive strength of the concrete after placing in the basin

Figure 9 shows the changes in the compressive strength of concrete at the 7 and 28-day ages after being placed in the sodium sulfate solution. As seen in the figure, placing concrete in the sodium sulfate solution leads to a decrease of the concrete compressive strength by about 10%. This reduction in the strength observed among different specimens is almost constant. Nevertheless, in the specimens that 3% Nano-silica is added to them, strength reduction reaches about 8%. In fact, the higher the compressive strength of specimens, the higher is their resistance against sulfate. As the natural or artificial pozzolans can have a positive effect upon increased compressive strength of concrete, by reducing the percentage of Nano-silica in the alkaline concrete, the resistance of the specimens against sodium sulfate is increased, and their strength is reduced. The use of Nano-silica in the concrete mix reduces the porosity of the concrete and improves its durability against sulfate attack. Thus it could be concluded that by increasing the percentage of Nano-silica instead of the rubber powder present in the sodium silicate, the reduction in strength is mitigated, and by replacing the rubber powder with silica fume, the reduction in the strength is increased.

4.1. Permeability Test

In this test, the resistance of the cubical concrete specimens with 15cm dimensions against water is tested under 5Bars pressure. For this experiment, the prepared specimens up to 51 and 110-day ages were cured in the saturated limewater solution and then were tested. The results of water permeability are presented in diagram No. 10. Generally, the use of natural pozzolans has been effective in improving the resistance of concrete against water penetration. Filling of void spaces due to the formation of secondary silicate gels by the pozzolanic activity could be the best reason for this phenomenon. As seen in diagrams no. 4-6, replacing cement with the slag and Nano-silica reduces water absorption in concrete. This decreasing trend becomes more visible by replacing a higher percentage of cement with Nano-silica. The addition of the rubber powder to the geopolymeric concretes leads to decreased water absorption by concrete, but this reduction is less visible with respect to the specimens containing Nano-silica.

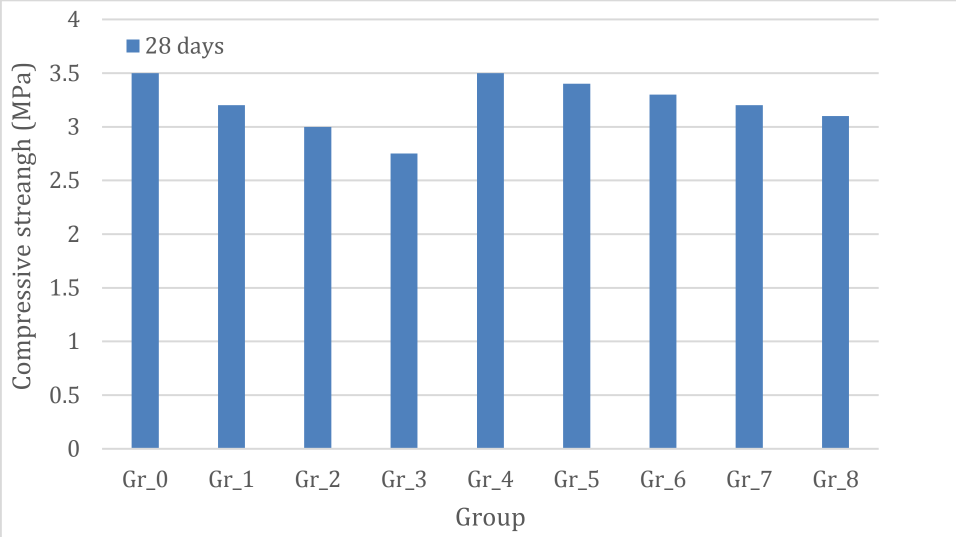

Figure 10. Water absorption percentage of the concrete specimens

4. CONCLUSION

The present research was performed in order to investigate the presence of Nano-silica and rubber powder in concrete to enhance the compressive and tensile strengths of concrete. The results showed that the simultaneous application of these two materials could help with improving the compressive and tensile strengths. The overall results showed that by an increase in the percentage of rubber powder in the concrete, the compressive strength increases, and by adding Nano-silica, this increase in strength is improved. By adding 2 and 3% Nano-silica to the specimens containing rubber powder, it is observed that the compressive strength increases with respect to the specimens containing rubber powder. The reason for this improvement of strength is attributed to filling of the Nanopores by Nanomaterials in the cement paste. Partial replacement of aggregates with rubber powder, results in the reduction of density by up to 6%, which is due to the smaller density of the rubber powder with respect to that of the aggregates.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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