EFFECT OF INCROPRATING OF FLY ASH, WASTE GLASS POWDER AND NANO SILICA ON THE PROPERTIES OF CONCRETE

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ABSTRACT

This study evaluates the effect of incorporating of fly ash, waste glass powder or nano silica as a replacement for cement on the workability, compressive and flexural strength also rate of absorption (sorptivity) of concrete. The study followed the design of experiments (DoE) approach to test concrete mixes based on the response surface method (RSM). The experimental program included testing eight concrete mixes including reference mix with three investigated variables include fly ash, waste glass powder and nano silica at the replacement levels for cement of (30, 15 and 2) % respectively. The results show that the nano silica has a significant improvement of mechanical properties of concrete mixes, and the glass powder has a positive effect on the studied properties of the developed concrete mixes. While using fly ash presented less effect on the properties of studied concrete mixes. Besides, the target compressive strength at 28 days was achieved by incorporating fly ash, nano silica, waste of glass powder indicating the potential of using materials in the concrete mixes.

Keywords: Fly ash, waste glass powder, nanosilica, design of experiments

NOMENCLATURE

DoE	Design of experiments
RSM	Response surface method
F	Fly ash
G	Waste glass powder
N	Nano silica

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INTRODUCTION

The need for concrete industry is growing daily as concrete became a prime building material. However, the production of concrete has impacts on the environment because of the manufacturing of Portland cement being responsible for very high CO_2 emissions and energy consumption (Imbabi et al., 2012). Therefore, one of the priorities of the scientific community is the development of sustainability for the concrete industry. Thus, the manufacturing of concrete must consider not only adequate strength and durability properties but also the environmentally friendly and economically aspects for the resulting concrete (Russell et al., 2018). So far, the use of variety of existing waste, industrial by-products materials and the mineral additives to partially or completely substitute cement in different kinds of concrete is an optimistic way for lowering the adverse environmental impacts from the concrete industry. These materials include rice hush ash, waste paper ash, waste wood ash, recycled concrete, glass, plastics, fly ah, silica fume, powdered granulated blast furnace slag, and metakaolin (Owaid et al., 2021). Fly ash is an industrial by-product generated by the combustion of coal in the thermoelectric plants; it is highly active pozzolan material due to high levels of silica, alumina, and iron oxide. The chemical and physical properties of fly ash can differ depending on the circumstances of combustion process of coal and the coal composition (Ribeiro et al., 2014). According to ASTM C618 (ASTM, 2017), fly ash is classified into two types: class F fly ash, and class C fly ash, which both types used as supplementary cementitious materials (SCMs) in the production of concrete (Akbulut et al., 2024). Enormous researchers have focused on the feasibility of using fly ash as a partial substitute to concrete components in production of different types of concrete (Wang et al., 2003; Hefni et al., 2018, sun et al., 2019; Muhsin et al., 2021; Harith et al., 2023). Glass, meanwhile, is the most of the man-made inventions that is produced in different forms and widely used through glass products such as bottles for drinks, windows for cars and buildings, glassware, screens and candles. The manufacturing of glass products is increased constantly, but these products have a short life, and this, in turn, increases the waste glass in the landfill. Hence, such waste needs to be reused to avoid the environmental problems (Jiang et al., 2022).

Therefore, the implementation of waste glass powder in concrete production will produce important contributions for lowering the environmental issues (Zeybek et al., 2022). Extensive studies regarding the effect of this substitute on the properties of concrete have been carried out (Park et al., 2004; Aliabdo et al., 2016; Shruthi et al., 2015; and Lu et al., 2018). With regard to the use of nanosilica (N), and according to previous studies (Said at al., 2012; Du et al., 2014 ; Torabian et al., 2016; Mohammed et al., 2016 ; Behzadian and Shahrajabian 2019; Lavergne et al., 2019; Shahrokhinasab et al.,2021), it has become one of the most common options to be utilized in nano additives in either mortar or concrete to improve the mechanical and durability properties due to its ultrafine particle size and high reactivity.

The main objective of this study is to examine the impact of fly ash, waste glass powder and nano-silica experimentally when these materials utilized as a replacement of cement in concrete, and thereby to evaluate the engineering properties of produced concrete.

EXPERIMENT PROGRAM AND METHODOLOGY

The experimental program involved developing concrete mixes based on replacing a proportion of cement with fly ash, waste glass and nano silica. The number of experiments has been designed by using design of experiment (DOE) method using the response surface method (RSN) as a basis. In this study, A central composite design technique (CCD) is used in response surface methodology (RSM), it is a successful experimental design that is employed to produce appropriate combination of related variables with a small number of experiments. The CCD is used to determine the interaction between such variables, and to determine the optimal response within experimental data. (Branchu et al., 1999). The (CCD) structure for a k factor three-level experimental design require $2^k + 2k + c$ design points, where k is the number of studied variables, with 2k factorial points representing all combinations of coded values, which are in the corners of a cube; plus 2k axial points at a distance $\pm \alpha$ from the origin, which are in the center of each face of the cube; and c center points with all levels set to coded level 0, which are in the center of the cube where 2k is the factorial points that reflect all possible combinations of coded values $x = \pm 1$, and k is the number of variables under study.
The three studied variables assessed for this experiment and their coded levels; maximum (+1), minimum (-1), are shown in Table 1. This model works with mixtures that have a water-to-binder ratio of 0.4 that are mixed, cast, and allowed to cure naturally. Fly ash (F), waste glass powder (G) and nano silica (N) and were respectively added by three doses of (0 to 30%), (0 to 15%) and (0-2%) nano silica dosages of by the total mass of the binder. In this study, eight points were produced to study the effect of the implemented three variables as given in Table 1.

Table 1. Variables and their coding values

Variables	Coded values	
	-1	+1
Fly ash, kg/m^3 (0 to 30%)	0	133
Nano silica, kg/m^3 (0 to 2%)	0	8.8
Waste glass powder, kg/m^3(0 to 15%)	0	66.5

Materials

In this study, the materials used to prepare the reference and the other studied mixes were ordinary Portland cement CEM II/A-L-42.5R complied to the specification of C150/C150M, (ASTM International C150/C150M-, 2017), fly ash (F) class C conformed to the standard specification of C618 (ASTM International C618, 2017), nano silica (N) and waste glass powder (G). Natural fine aggregate (FA), and coarse aggregate (CA) of maximum size equal to 20 mm were also used. The fine and coarse aggregates are conformed to the standard specification of C33-07 (ASTM C33-07). The chemical composition and physical properties of ordinary Portland cement, fly ash (F), nano silica (N), waste glass powder (G) are detailed in Table 2. Besides, in this study, a high - performance water reducing admixture was used in the prepared mixes, which is known commercially as (Hyperplast PC200), a high - performance super plasticizer (SP) and conforming with C494 (ASTM C494-15).

Table 2. Physical characteristics and chemical analysis of the binder component

Chemical composition	**Cement**	**Fly ash (F)**	**Nano silica(N)**	**Waste glass powder (G)**
SiO_2 (%)	19.30	33.48	99.8	65
Al_2O_3 (%)	4.29	11.88	-	1.25
Fe_2O_3 (%)	2.27	19.33	-	0.15
CaO (%)	61.09	24.23	-	15
MgO (%)	2.37	0.0027	-	2.15
SO3 (%)	2.90	5	-	-
Loss on ignition L.O.I	0.9	1.2	-	-
I.R insoluble residue	1	-	-	-
Physical properties				
Specific gravity	3.160	2.15	2.2	2.55
Specific surface area cm^2/ g	3350	3600	200000	2850

- Properties of cement provided from the manufacture factor
- Properties of fly ash tested in the construction materials laboratory in the science and technology ministry.
- Properties of Nano silica provided from manufacture factor
- The properties of waste glass powder were tested in the environmental laboratory at the civil engineering college and the engineering laboratory in the ceramic department.

Preparation of specimens, curing and testing

Eight concrete mixes were produced as shown in Table 3 to examine the effect of incorporating of fly ash (F), nano silica (N) and waste glass powder (G) on the slump, compressive strength, flexural strength and sorptivity of such produced concrete in comparison to the properties of reference mix. The design strength of the developed concrete mixes was 35 MPa, these mixes included eight studied mixes, the symbol of each mix (ID) is composed of a number that refer to the percent of such materials (F, N and G) and the letter that refers to incorporation materials within the mixes (Table 3). The total dosage of the amount of binder in each mixture and the w/b ratio are 444.4 kg/m^3 and 0.4, respectively. The partial replacements of F, N and G were (30, 2 and 15) % by the total content of cement respectively, the proportions of mixes are presented in Table 3. The mixing procedure was completed in compliance with ASTM C192-16, using a concrete mixer with capacity of 0.025 m^3. The water was added gradually after mixing the dry materials. After three minutes of mixing, the concrete was let to rest for two minutes before being mixed once again for three minutes. The concrete samples in fresh state were poured into molds then vibrated them on a vibrating platform. These samples were then demolded after a day and placed in a water tank until the testing age. The workability of the slump test, which was conducted in compliance with ASTM C143/C143M-05a, was used to evaluate the fresh concrete mixtures. To evaluate the compressive and flexural strengths, sets of three cubes of 150 mm and two prisms of (100*100*400) mm was cast and tasted for each mix at ages 7 and 28 days. The compressive strength test was done according to (BS EN 12390-3), and the flexural strength test was done according to (ASTM C78-02). Regarding the water absorption of the developed silica concrete mixes, the rate of water absorption (sorptivity) was calculated on 100 mm cubes according to C1585 (ASTM C1585).

Table 3. The combination of set points (coding) and the proportion of mixes for cubic meter mix.

Mix id	Coding (F, N, G)	Fly ash, kg	Nano -silica kg	Glass powder, kg	Cement Kg	Water L	SP L	Sand kg	Gravel kg
0F0N0G	-1, -1, -1	0	0	0	444.4	178	2.5	696.8	1037
30F0N0G	1, -1, -1	133	0	0	311.4	178	2.5	696.8	1037
0F2N0G	-1, 1, -1	0	8.8	0	435.6	178	2.5	696.8	1037
30F2N15G	1, 1, 1	133	8.8	66.5	236.1	178	2.5	696.8	1037
30F2N0G	1, 1, -1	133	8.8	0	302.6	178	2.5	696.8	1037
0F2N15G	-1 ,1, 1	0	8.8	66.5	369.1	178	2.5	696.8	1037
30F0N15G	1, -1, 1	133	0	66.5	244.9	178	2.5	696.8	1037
0F0N15G	-1, -1, 1	0	0	66.5	377.9	178	2.5	696.8	1037

RESULTS AND DISCUSSION

Slump test

The slump test has been done to evaluate the workability of the tested concrete mixes in the fresh state. As mentioned earlier, during the production of these concrete mixes, the amounts of water/binder ratio, water, and the SP were kept constant to assess the effect of the utilizing of (F, N and G) on the consistency and hardened properties of the concrete mixes. In the reference mix (0F0N0G), the target slump was (10 ± 3) cm. Fig. 1 presents the result values of slump test of the tested concrete mixes. Fig 1 shows that out of all the combinations that were tested, the fly ash mix (30F0N0G) showed higher value of slump, and this mix showed an increase in the slump value by 38.5% in comparison to the reference mix 0F0N0G. This is because of the morphological effect and strong lubrication effects of (F) particles due to their spherical shape and small size (Wang et al., 2003). This behavior was also reported by Harith et al., (2023) who, stated that the Particles of fly ash can fill in the gaps between cement particles, lowering the need for water for lubrication of the mix ingredients. Besides, the results demonstrated that by using the waste glass powder (G) to produce the glass powder mix (0F0N15G), there was a reduction in the slump value by 15 % in comparison with the 0F0N0G mix. Although the specific surface area of glass powder is generally lower than that of ordinary Portland cement, the reduction in workability is mainly attributed to the angular and irregular shape of the ground glass particles, which increases inter-particle friction and restricts the flow of the fresh mix. In addition, glass powder lacks the lubricating properties typically provided by cement paste, as it does not participate in early hydration reactions. This further contributes to the observed decrease in slump, despite the relatively lower surface area. These findings are consistent with the observations reported by Shao et al. (2000) and Taha and Nounu (2009), who noted that the use of recycled glass particles tends to reduce workability due to their physical texture and inert nature at early ages, besides, this reduction is due to reaction of G into the concrete mix, which does not start immediately, and this means that more water is needed in the fresh state of concrete to keep the same consistency (Guignone et al., 2020). Whereas using F combined with G to produce mix 30F0N15G mix, there was an increase in the slump value by 7.7% in comparison to the reference mix.

On the other hand, it can be seen that nano silica had a negative effect on the slump of nano-silica concrete mixes. For instance, the slump values for 0F2N0G, 0F2N15G, 30F2N0G, and 30F2N15G mixes were decreased by 69 %, 69 %, 62 % and 31 % respectively in comparison to 0F0N0G mix. It is clear that the slump's values dropped due to the absorption of the mix water by the nano silica particles, and thereby, increasing the viscosity of fresh such concrete and decreasing slump. This observation is in agreement with previous research on using of nano-silica (Harith et al., 2023, Lavergne et al. 2019).

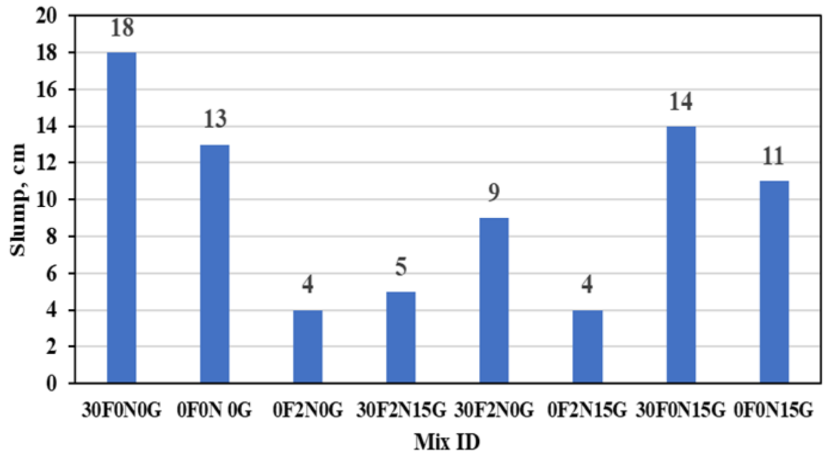

Fig. 1**.** The slump values of the concrete mixes

Concrete's mechanical characteristics

Table 4 provides a summary of the concrete specimens' compressive and flexural strength data, at ages of 7, 28 days. The experimental results of the compressive strengths varied from 18.91 to 33.40 MPa and 35.70 to 47.31 MPa at 7 and 28 respectively. Whereas the results for flexural strength varied from 1.82 to 3.16 MPa and 2.93 to 4.10 MPa at 7 and 28 days respectively. Also, from the experimental results it can observed that for all mixes the development for both compressive and flexural strengths continue with the age of tested specimens.

Table 4. Mechanical properties test results for tested concrete mixes.

Mix id	Compressive strength, MPa		Flexural strength, MPa	
	7days	28days	7 days	28days
0F0N0G	28.90	42.50	2.75	3.28
30F0N0G	20.03	37.80	1.82	2.93
0F2N0G	33.40	47.31	3.16	4.10
30F2N15G	20.31	35.75	2.45	3.62
30F2N0G	21.80	37.92	2.32	3.41
0F2N15G	30.50	45.40	2.45	3.80
30F0N15G	18.91	35.70	2.25	3.45
0F0N15G	23.20	37.81	2.43	3.60

Compressive strength

The compressive strength results of concrete samples were measured at 7 and 28 days (see Fig. 2). As seen in Fig. 2, the decrease in compressive strength at 7 days for the fly ash mix 30F0N0G and glass powder mix 0F0N15G were 31% and 20% in contrast to the reference mix's compressive strength 0F0N0G. This reduction occurred because fly ash has a slow reactivity at early ages, and glass powder has a low percentage of silica since it is made from grinded glass bottles rather than pure glass; thus, its reactivity requires more time to develop. The nano-silica mixes 0F2N0G and 0F2N15G showed increase in compressive strength, which the increases were respectively 16% and 6% higher than that of 0F0N0G mix. The improvement in compressive strength can be attributed to the accelerating effect of nano silica on the early hydration of cement paste (Torabian et al., 2016). Figure 2 illustrates the compressive strengths of various mixtures 30F0N15G, 30F2N0G, and 30F2N15G decreased by about 35%, 25%, and 30%, respectively, compared with 0F0N0G mix. Also, it can be seen that the lowest compressive strength was for the mix without nano silica (30F0N15G), and the effect of the inclusion of nano-silica in these mixes is more pronounced.

Overall, at 28 days, the target compressive strength of 35 MPa was achieved for all tested samples, indicating the potential of these materials as an alternative to cement for developing concrete mixtures .The compressive strength of fly ash mix 30F0N0G was found to be almost similar to that of glass powder mix 0F0N15G, The decrease of compressive strength for these mixes were 11% in comparison to that of 0F0N0G. Compared to the 0F0N0G mix, the nanosilica silica mix 0F2N0G and nano silica glass powder mix 0F2N15G showed a rise in compressive strength by 11% and 7% respectively. This can be attributed to the pozzolanic response of nano silica and glass powder as these materials improve the internal structure of mixes. While the compressive strength for the mixture 30F20N0G, 30F0N15G and 30F2N15G mix were lower by 11%, 16%, 16% respectively.

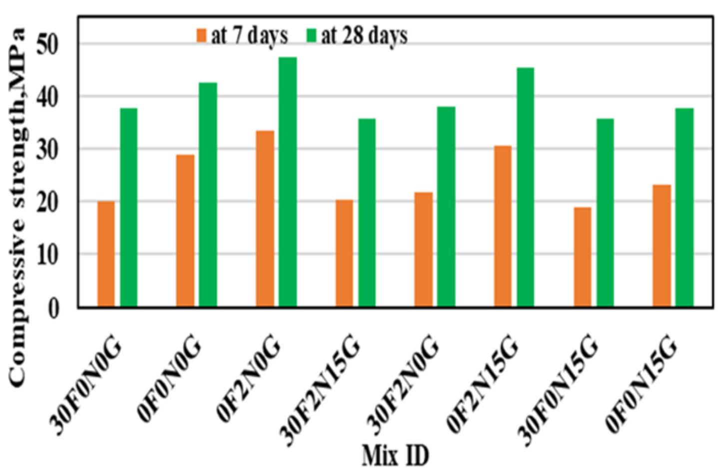

Fig 2. The compressive strength test results at 7 and 28 days.

Flexural strength

The flexural strength results at 7 and 28 days are given in Table 4. and Fig. 3. It is apparent that the fly ash mix's flexural strength 30F0N0G and glass powder mix 0F0N15G reduced by about 34% and 12% in comparison to 0F0N0G mix. Whereas, the nano silica mix 0F2N0G displayed the higher value of flexural strength, which increases by about 15% compared with 0F0N0G mix. The flexural strength for the mixes 30F2N0G, 0F2N15G, 30F0N15G and 30F2N15G decrease by 16%, 11%, 18% and 15% at 28 days respectively in comparison to 0F0N0G mix. According to Table 4, the flexural strength values were consistently lower than the compressive strength values, which aligns with the typical mechanical behavior of cementations materials. This difference can be attributed to the partial replacement of cement with waste-derived materials that possess lower binding capacity and slower pozzolanic reactivity. As a result, the development of strength, particularly flexural strength, may be delayed beyond 28 days due to the gradual formation of calcium silicate hydrate (C–S–H) gels.

All of the studied concrete mixes showed improvements in flexural strength after 28 days of age as compared to 0F0N0G mix, excluding the 30F0N0G mix that has the lower flexural strength values, where substituting cement with 30% of fly ash results in decrease in flexural strength by 11%. Whereas, the glass powder mix 0F0N15G had increase in flexural strength by about 10 % in comparison to 0F0N0G mix, this could be attribute to the pozzolanic behavior of glass powder because it has a significant proportion of amorphous silica in it (Park et al., 2004). Nano silica on the other hand had a positive effect on the flexural strength tested concrete mixes, the flexural strength of 0F2N0G increased by 25% in comparison to that of 0F0N0G mix. The flexural strength for mixes 30F2N0G, 0F2N15G, 30F0N15G and 30F2N15G increase by 4%, 16%, 5% and 10% due to the promoted cohesion amongst the contact region of the binder paste and aggregate that was achieved by nanoparticles (Behzadian and Shahrajabian, 2019).

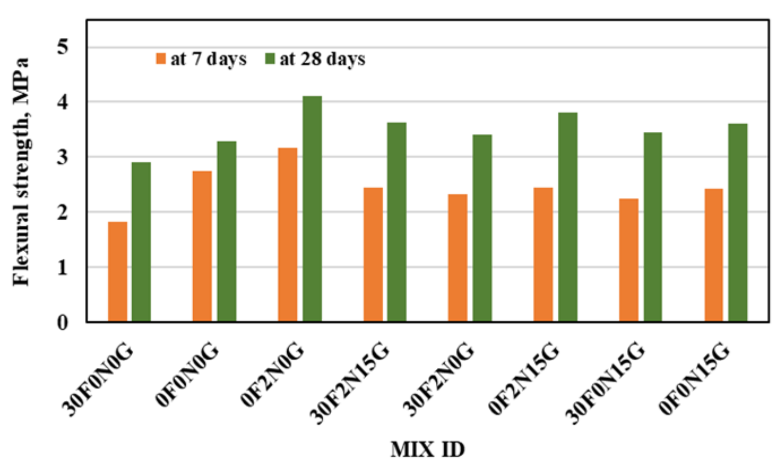

Fig 3. The flexural strength test results at 7 and 28 days of the concrete mixes.

Sorptivity

In the sustainable development, the durability of concrete is recognized as the most principal property, serves as a measure of the ability to resist aggressive conditions, and it is often relied on the pore structure and permeability of concrete. The water absorption test was used in this investigation as a gauge of concrete durability. The experimental results of water absorption at Table 5 provides 28 days. According to the data, the tested concrete mixes' water absorption is significantly lower than that of the reference mix. The water absorption for the nano-silica mix 0F2N0G decreased by 43% in comparison to that of 0F0N0G. This could be because of the improved of concrete microstructure and using nanosilica decrease the capillary of concrete (Du et al., 2014). The reduction in the water absorption for fly ash mix 30F0N0G and glass powder mix 0F0N15G were 28% and 20%, respectively, compared to that of the 0F0N0G mix. Whereas, the water absorption for the mixes 30F0N15G, 30F2N0G, and 30F2N15G decreased by 49%, 60% and 65%, respectively. This can be attributed to the effect of combination of fly ash, nanosilica and glass powder, which can effectively reduce the absorption of concrete by creating a denser and more refined microstructure through enhanced pozzolanic activity and improved packing density (Behzadian and Shahrajabian, 2019).

Table 5: The sorptivity test results for the concrete mixes

Mix id	**Sorptivity at 28 days mm/√min**	**The reduction of sorptivity %**
0F0N0G	0.1	-
30F0N0G	0.072	28
0F2N0G	0.057	43
30F2N15G	0.035	65
30F2N0G	0.04	60
0F2N15G	0.042	58
30F0N15G	0.051	49
0F0N15G	0.08	20

CONCLUSIONS

Based on the results of this experimental investigation, the following conclusions were drawn:

1. The slump results of concrete mixes reveal that the fly ash mix 30F0N0G exhibited an increase in the slump by 38.5%, whereas the glass powder showed decreasing in the slump by 15% in comparison to that of reference mix 0F0N0G. Comparing to

the slump of reference mix 0F0N0G, the nano silica concrete mixes showed a significant reduction in the slump values.

2. At age of 28 days, all the tested concrete mixes achieved the target compressive strength of 35 MPa, which indicated potential of the fly ash, nanosilica and waste glass powder as a cement substitute for the developed mixes.
3. The mechanical property data demonstrate that adding nanosilica to concrete mixtures improves their compressive and flexural strengths. Additionally, whether added to the 0F0N15G mix or the nano silica concrete mix, the glass powder improves the mechanical qualities. The age of the concrete effects how the mechanical qualities of fly ash mixtures evolve.
4. The results show a significant reduction of water absorption for tested concrete mixes, comparison to that for the reference mix where the reduction ration of water absorption ranged from 20% to 65%.

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