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Effect of various NaOH molarities and various filling materials on the behavior of fly ash based geopolymer composites

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HIGHLIGHTS

- Crushed limestone and waste foundry sand were employed in the fabricated matrix.
- Using 10% of waste foundry sand as a partial replacement enhanced the mechanical strength properties.
- The mixes showed a reliable performance under freezing-thawing cycles and less than 1 gm under abrasion.

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ABSTRACT

Among the recent research interests in the construction section, Geopolymers, represent a rising trend due to their significant performance in terms of strength and long term properties. In this research, an attempt was conducted to examine the effect of using different filling materials and the effect of different NaOH concentrations on the properties of the resulted composites. Strength properties, physical properties, abrasion resistance, and freezing-thawing behavior were tested along with a microstructural characterization that included scanning electron microscopy (SEM) and X-ray diffraction (XRD). In general, the effect of including crushed limestone and waste foundry sand was beneficial in terms of the general properties of the fabricated specimens. Also, the microstructural analyses showed a compact matrix that could be considered in line with the obtained results from the other tests.

1. Introduction

Portland cement, as one of the most important binders in the construction industry, represents the backbone material for many applications. The increasing need for this material is attributed to the rising trend of construction all over the world. The cement production process, however, is not classified among the eco-friendly production processes. The CO_2 emissions which are caused by the cement production form a serious reason of environmental problems [1]. For such reasons, using systems that are based on alternatives such as waste materials and industrial by-products is the most effective potential to reduce the aforementioned environmental impacts. Geopolymers are based on alternatives and require no cementitious components in their production process. Recently, the research interest in such binding systems has increased due to the satisfactory properties that they can exhibit. Related to the fact that silica-alumina rich materials could be used successfully in fabricating geopolymer composites, industrial by-products such as fly ash represent a reactive precursor in this field [2–4]. Fly ash-based geopolymers were the main title of many research attempts due to the cheap availability of fly ash and good performance in terms of strength and durability [5–10]. In the same concern, various research attempts were conducted to evaluate the effect of using different aggregates and different activators. Temuujin et al. [11] fabricated geopolymer composites with different aggregate content and tested their strength and physical properties. They found out that both aggregate content and chemical activator details are strongly connected. To be more specific, with the same amount of chemical activator, the increasing filler content negatively affected the performance of the manufactured composites. They also suggested an optimization procedure for their investigation to achieve a better understanding of the relationship between chemical activators and aggregate content.

Josepha and Mathew [12] performed an investigation on the effect of aggregate content on the properties of geopolymer concretes made from fly ash. Varying the filler content was studied along with other properties such as heat curing effects and

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chemical activators' influence on the properties of the produced matrix. Conclusions revealed the fact that after optimizing the other studied factors, the right content ratio of filling materials could together form the right mix proportion for the intended geopolymer concrete. Thus, the resulted concrete holds the best properties in terms of strength and physical behavior as well as durability and microstructural characteristics. Sreenivasulu et al. [13] performed a study on the mechanical properties of fly ash geopolymer concrete with various ratios of filling materials. The conclusions stated that the strength properties increase with increasing aggregates ratio up to a certain limit. After that, the strength rate begins to decrease with the increasing aggregate to binder ratio.

In the matter of using waste foundry sand, a partial replacement was found to exhibit a certain improvement in the investigated properties up to a limited extent. Bhardwaj and Kumar [14] conducted a review of the experimental work done on the partial replacement of normal sand with foundry sand. They came up with a general conclusion which stated that adding waste foundry sand to a certain percentage yields an enhancement in strength and durability properties.

Guney et al. [15] tended to investigate the effect of replacing the normal sand with waste foundry sand. As a general conclusion, they found that up to a certain extent, the existence of foundry sand is responsible for enhancing the strength properties of the fabricated composites.

Singh and Siddique [16] tested the effect of partially replacing waste foundry sand with normal sand on the strength and durability properties. The replacement was done from (0–20) % as a weight percentage. The general drawn-out conclusion came up with a fact that a marginal improvement could be acquired by using a partial replacement of foundry sand. Concerning the various activator dosages in geopolymer, an increase in NaOH molarity is up to a certain extent responsible for increasing the compressive strength of the produced specimens. Alvarez-Ayuso et al. [17] studied the effect of different molarities of sodium hydroxide on the strength and leaching properties of fly ash geopolymer composites. Findings stated that increasing the concentration of hydroxide yielded a certain improvement in strength and leaching behavior of the specimens.

Chindaprasirt et al. [18] performed a study on the different molarities' effect on the behavior of the manufactured mortar and paste composites. Mortars were fabricated to understand the strength properties while paste samples were synthesized to inspect the microstructural composition and the chemical structure of the produced matrix. In their investigation, graduation from low molarities to high ones was conducted to construct a better understanding of the studied mixes. The main conclusions indicated that the best results could be obtained from moderate molarities. In addition to that, different industrial by-products were used as main materials. This led to a conclusion that investigated molarities along with the performed tests proved that the type and strength of the fabricated matrix strongly depend on the type of the main materials.

Somna et al. [19] tested the effect of using various NaOH molarities on the strength and microstructural characterization of the manufactured samples. They found out that the growing molarity yields a strength improvement. Moreover, their findings stated that the overdosage of sodium hydroxide could deteriorate the strength gain of the samples.

Görhan and Kürklü [20] investigated the effect of both curing temperatures and different molarities on the physical properties and the physical properties of fly ash geopolymer mortars. Their main goal was to clarify the effect of different sodium hydroxide dosages on the general behavior of the resulted matrix regardless of the curing time or the curing temperature of the experiments. Although they obtained small compressive strength values in their experiments, they proved the importance of NaOH concentration and clarified its effect on the investigated properties.

So many research attempts have been conducted considering various factors separately, however, there is a need to investigate the combined effect of activators and filling materials on the behavior of the samples. In the light of this fact, the main objective of this paper is to investigate the influence of using waste foundry sand as a partial replacement within the geopolymer specimens fabricated with a standard sand and crushed limestone. Moreover, the effect of different sodium hydroxide molarities will be tested. The designated tests will be strength properties, physical properties, abrasion resistance, and freeze-thaw behavior. The aforementioned tests will be conducted along with a microstructural characterization which includes scanning electron microscopy (SEM) and X-ray diffraction (XRD) to observe the compactness degree of the fabricated samples.

2. Materials characterization

A class F fly ash which is consistent with ASTM C618 [21] was supplied from an electrical production in Zonguldak, Turkey, and Slag (GGBS) were provided from Bolu Cement. The chemical properties of the aforementioned materials are illustrated in Table 1. The used activating solution consisted of Na_2SiO_3 and NaOH and the studied molarities were 12 M and 8 M. Na_2SiO_3 contained 8.21% Na_2O, 27% SiO_2, and a modulus of 3.291 with a pH value of 13.85 and 14.15 respectively. Rilem sand which is consistent with BS EN 196-1[22] was used. Crushed limestone had a specific gravity of 2.70 g/cm^3 and the gradation was between 0 and 4 mm. Waste foundry sand was obtained from DOKMAK Foundry Industry/ Darica-Gebze/Turkey. The particle size distribution and laboratory specimens of crushed limestone and waste foundry sand are shown in Fig. 1.

3. Experimental procedure

Sodium hydroxide was firstly prepared at least one day before the mixing day. On the day of mixing, sodium hydroxide and sodium silicate were mixed. This metasilicate solution was then added to fly ash to start the first step in the geopolymerization process. The resulted paste is mixed with GGBS and then this resin is mixed with the designated sand. A partial replacement of waste foundry sand is conducted to finish the geopolymeric mixing process. The conducted mixture procedure is illustrated in Fig. 2. Cubes of 50 mm side, prisms with the dimensions of $40 \times 40 \times 160$ mm, and cylindrical samples of Φ 10 mm $\times$ 7.5 mm were cast in this investigation. The samples were then heat cured in the oven for 24 h with 80 °C. The mixing proportions and the identification of the mixes are shown in Tables 2 and 3, respectively. The samples were denoted based on the molarity of NaOH and the type of the used filling material. R stands for Rilem sand, FS stands for foundry sand and L stands for crushed limestone. For instance, R-10FS-12 means Rilem sand replaced with 10% foundry sand with a molarity of 12 M.

After mixing, cubes, prismatic specimens, and cylinders were prepared for testing compressive strength, flexural strength, and abrasion resistance, respectively. All the samples were heated with 80 °C for one day. After heating, the samples were left and scheduled to be tested. Compressive and flexural strength tests were done after 7 and 28 days. A compressive strength test was conducted according to ASTM C 109 [23] while the flexural strength test was performed according to ASTM C 348 [24]. Ultrasonic pulse velocity test was conducted before flexural testing on the prismatic specimens to inspect the quality of the manufactured samples.

Table 1
Chemical composition of Fly ash and GGBS (%).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	Free CaO	Cl^-	LOI
FA	54.07	26.09	6.68	2.003	2.67	0.73	0.78	0.11	0.092	1.37
GGBS	40.54	12.84	1.11	35.59	5.86	0.181	0.77	–	0.014	0.035

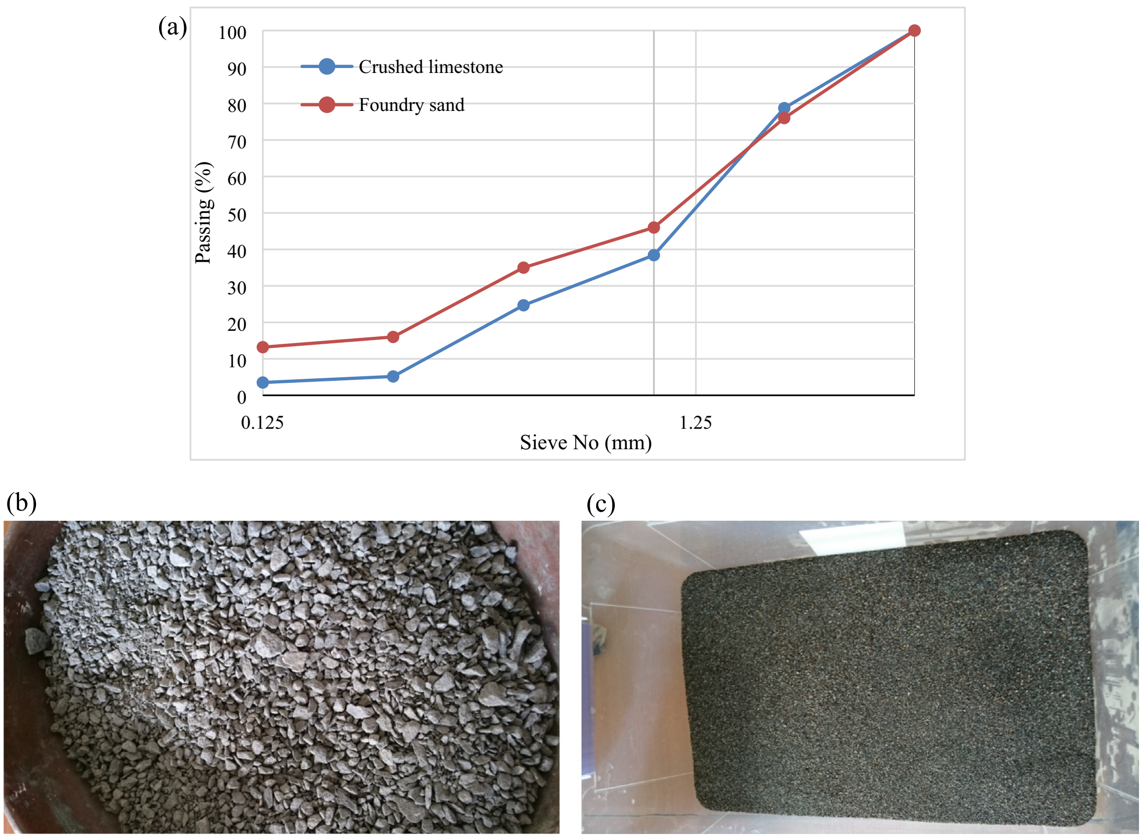

Fig. 1. a) Grading of crushed limestone and waste foundry sand (top), b) Foundry sand (left) and c) Crushed limestone (right).

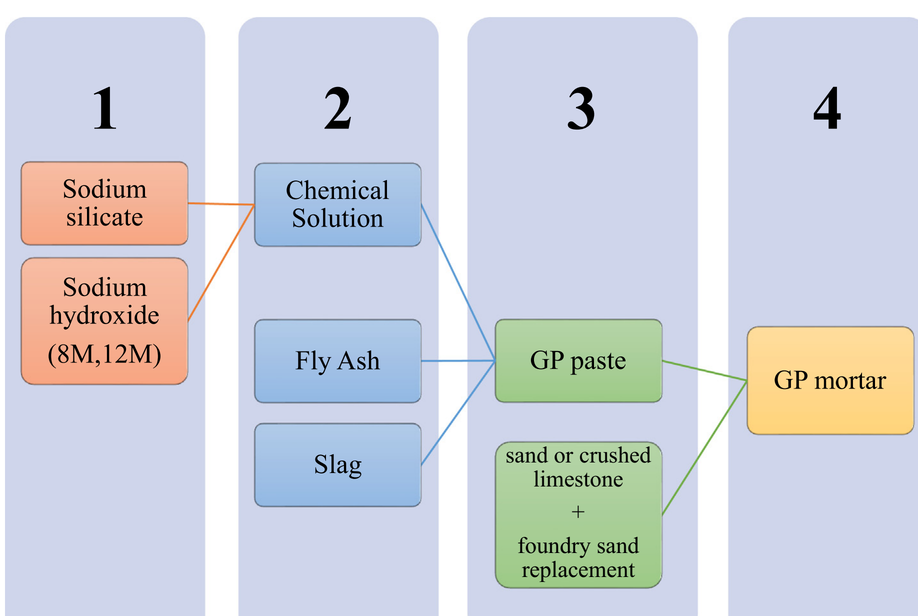

Fig. 2. Mixture procedure.

Table 2
Mixing proportions of manufactured geopolymer composites (g).

Fly Ash (g)	Filler (g)	Slag (g)	NaOH (12 M or 8 M) (g)	Na_2SiO_3 (g)
450	1237.5	60	50	175

Table 3
Identification of the conducted mixes.

12 M		8 M	
R-12	100% Sand	R-8	100% Sand
R-10FS-12	90% Sand + 10% FS	R-10FS-8	90% Sand + 10% FS
R20FS-12	80% Sand + 20% FS	R20FS-8	80% Sand + 20% FS
L-12	100% LS	L-8	100% LS
L10FS-12	90% LS + 10% FS	L10FS-8	90% LS + 10% FS
L20FS-12	80% LS + 20% FS	L20FS-8	80% LS + 20% FS

FS: waste foundry sand, LS: crushed limestone.

Also, abrasion test was carried out according to ASTM C 944 [25], Abrasion resistance or wear resistance of binders is one of the tests that represent the main point of interest to many researchers, it is very important to determine the wear resistance for concrete or screed finishing surfaces. Moreover, some of the samples were tested for freeze-thaw behavior, they were subjected to a total of 56 freeze-thaw cycles. In each cycle, the freezing period was 90 min while the thawing period was 30 min. Meanwhile, the temperature of the test was ranging from 4 °C to −18 °C. After the cycles were finished, the difference in compressive and flexural strengths and weight loss ratios were calculated and compared to the specimens which were not exposed to the freeze-thaw cycles.

4. Results and discussion

4.1. Physical properties

In general, all of the fabricated samples exhibited an improvement in mechanical strength performance concerning the control samples (plain fly ash geopolymer mortar). This is related to the fact that fly ash and GGBS particles are of small size and hence are responsible for less porosity. Particle size, however, played an important role in increasing the voids ratio of the geopolymeric samples, to be more specific, the existence of waste foundry sand and crushed limestone in the geopolymeric matrix resulted in more porosity because of the larger particle size of waste foundry sand and crushed limestone in comparison to standard Rilem sand. Regarding different molarities, different molarities were found to have a slight effect on the investigated physical properties, the results of 8 M were very close to the ones of 12 M samples. This means that mixing is possible with both molarities and physical properties are achievable when using low molarities because the reaction mechanism will be almost similar. The results which are shown in Table 4 also state that is feasible to use both waste foundry sand and crushed limestone since the samples were manufactured with these fillers.

Table 4
Physical properties of the samples.

Mix ID	Water absorption (%)	Unit weight (g/cm^3)	Voids ratio (%)
R-12	6.79	2.27	11.23
R10FS-12	6.45	2.26	11.47
R20FS-12	6.83	2.16	11.63
L-12	7.03	2.41	11.57
L10FS-12	6.82	2.34	11.79
L20FS-12	6.97	2.21	12.14
R-8	6.88	2.42	11.37
R10FS-8	6.52	2.34	11.49
R20FS-8	7.06	2.35	11.88
L-8	7.08	2.47	11.92
L10FS-8	6.71	2.48	12.33
L20FS-8	7.12	2.45	12.51

4.2. Strength properties

Compressive and flexural strength results were obtained at the ages of 7 and 28 days. As seen from the results in Figs. 3 and 4, most of geopolymeric samples showed an improvement in both compressive and flexural results. The 10% partial replacement of waste foundry sand was found to be beneficial in improving the investigated strength properties, the percentage of strength development was approximately 3% for 28th day's compressive strength results and around 8% for 28th day's flexural strength results. In compliance with the findings of Singh and Siddique [16], the existence of foundry sand yielded a slight improvement in strength properties. Further inclusion of this sand, however, was observed to decrease the obtained results. This might be related to the crystalline phase domination within the matrix instead of the amorphous phase. This finding is in line with the findings of Guney et al. [15]; they concluded that a 10% partial replacement was found to be the best replacement ratio. They concluded that this ratio resulted in the best bonding with the other ingredients of the fabricated matrix. Based on these facts and following the former research attempts concerning foundry sand replacement such as Bhardwaj and Kumar [14], a replacement ratio of 10% results in the best-fabricated mix in terms of waste utilization. In the same concern, Khatib and Ellis [26] performed a study on the partial replacement of waste foundry sand with natural sand and they have generally concluded that a 10% replacement resulted in an enhancement in strength and elasticity properties.

Crushed limestone was also seen as a feasible material to be used as a filler within the geopolymeric matrix. The results were acceptable when compared to the samples which were manufactured using standard Rilem sand. The shape and the grading of the aggregates were responsible for a good degree of bonding and therefore an improvement in strength properties concerning the reference samples in consistence with the conclusions of Hardjito and Rangan [27]. Crushed limestone aggregates possess a surface area and a shape which could result in acceptable adherence characteristics and thereby good strength behavior. The obtained results indicated relevance with the former studies performed by Mermerdas et al. [28], they observed that it is possible to fabricate geopolymer composites using crushed limestone as a filler, also, acceptable strength results could be gained when these aggregates were used. It is noteworthy that no significant strength gain was observed for different ages of the fabricated samples. This is related to the fact that heat curing is responsible for the rapid strength gain of the manufactured composites, heat accelerates the reaction and therefore the geopolymeric bonds form rapidly. This means that the desired strength is achievable after a short time. Moreover, the difference in molarity yielded a slight improvement in strength, however, a certain conclusion is that a higher dosage of sodium hydroxide results in higher strength behavior.

4.3. Ultrasonic pulse velocity

To evaluate the homogeneity of the fabricated matrix and to investigate the effect of different conditions on the manufactured

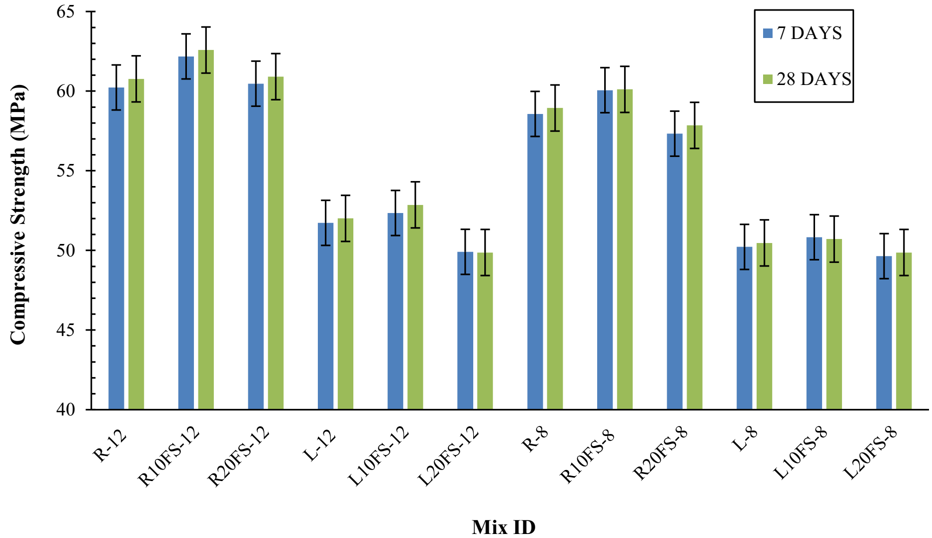

Fig. 3. Compressive strength results (MPa).

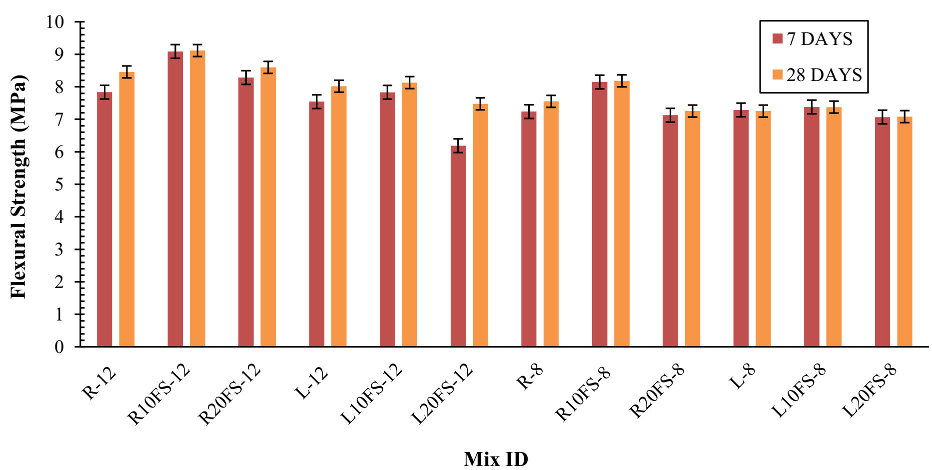

Fig. 4. Flexural strength results (MPa).

composite, nondestructive tests are always in the benefit of determining the performance of the matrix when other test results are definitive. Among those tests, the ultrasonic pulse velocity test is classified as one of the most important in situ tests to understand the pattern of the obtained results. In this investigation, UPV tests were conducted on the geopolymeric samples to inspect the effect of adding various materials and different conditions (such as freezing-thawing conditions) on the ultrasonic wave flow of the final produced samples and the results are shown in Table 5. In terms of mechanical strength performance, the tested samples showed a trend that could be considered in line with the former research attempts in this field such as Al-mashhadani et al. [29] and Celik et al. [30]. Like strength observations, no significant changes in UPV results were obtained due to the rapid matrix formation which resulted because of heat curing. The results reveal the fact that the addition of waste foundry sand and crushed limestone were neither positively nor negatively affect the waves flow of the fabricated samples. The addition of waste foundry sand resulted in a performance similar to that if strength behavior, a 10% partial replacement also yielded a slight improvement but a 20% replacement exhibited a reduction.

Table 5
Ultrasonic pulse velocity results (m/sec).

	UPV 7	UPV 28
RS-12	3541	3563
RS10FS-12	3566	3571
RS20FS-12	3512	3558
LS-12	3525	3547
LS10FS-12	3551	3554
LS20FS-12	3510	3529
RS-8	3498	3536
RS10FS-8	3508	3550
RS20FS-8	3516	3528
LS-8	3468	3485
LS10FS-8	3473	3492
LS20FS-8	3447	3467

4.4. Abrasion resistance

Abrasion resistance test could be performed according to different conditions and regarding various standard specifications such as ASTM C944, ASTM C779M, and Böhme test which is based on the British standards. In this investigation, an attempt was carried out to find out the effect of the added materials on the abrasion resistance of the resulted specimens. Standard specification ASTM C944 was followed when performing the test, specimens were abraded using a rotating cutter which contains dressing wheels, then, the abrasion process was made for three 2-minute time intervals (total 6 min) for every specimen. The weight loss is then recorded after the first abrasion and an average weight loss or abrasion resistance is calculated. In general, the geopolymeric samples yielded relatively comparable results when compared to the control samples, all of geopolymeric samples exhibited an average weight loss of fewer than 1 g. The results were consistent with the earlier findings of Al-mashhadani et al. [29], they concluded that performance of the geopolymer samples is generally better when compared to other matrices in terms of compactness performance under the abrasive load.

It could be concluded from the results which are shown in Fig. 5 that the compactness of the resulted matrix yields a good behavior under the effect of abrasion following the findings of Uysal et al. [31]. Their findings revealed the fact that geopolymeric samples are compact under the abrasive load with a small weight loss.

This is related to the fact the composition of the geopolymeric matrix possesses a comparable degree of compactness. The abrasion resistance results show that up to a partial replacement of 10%, the weight-loss behavior was improved, approximately 8% improvement was obtained for R10FS-12. However, similar to the performance of the previously investigated properties, further addition of this sand led to a decrease in the abrasion resistance. This is related to the fact that the distribution of this material results in a good adherence degree for 10% partial replacement, a ratio of 20% is responsible for decreasing the degree of compactness and therefore weaker behavior in this investigated parameter. The samples which were manufactured with crushed limestone were slightly more resistant to abrasive load, the samples in both molarities exhibited less weight than that of normal sand samples. Also, combining both foundry sand and crushed limestone aggregates were observed as a beneficial procedure in improving the abrasive behavior of the produced specimens. However, further foundry sand additions were also seen to have a negative effect on the obtained results. It was seen that higher molarity was responsible for a slight improvement in the results. This might be explained by the fact that higher dosages of sodium hydroxide are responsible for a matrix with higher bonding and thereby better in terms of weight loss properties.

4.5. Freezing-thawing resistance

The effect of freezing-thawing cycles on the strength properties, ultrasonic pulse velocity values, and weight loss was investigated as shown in Tables 6–8. As a primary observation, the geopolymeric samples performed relatively comparable results, the manufactured geopolymeric matrix well compacted and possessed an acceptable degree of bonding which in turn positively affected the behavior under the freeze-thaw conditions.

The performance of the investigated mixes was following the previous results, to be more specific, the existence of waste foundry sand and using crushed limestone were feasible in terms of resistance to freeze-thaw cycles.

It is noteworthy that the mechanical strength results of some mixes exhibited an increase instead of decreasing. This is mainly related to the fact that the geopolymeric matrix is compact possesses a good adherence degree which makes it resistant to the effect of freezing and thawing, in addition to that, it is expected that freeze-thaw cycles are responsible for a promotion process which happens to the matrix during these cycles. The matrix then yields better results in terms of strength properties. Such results are considered consistent with the findings of Yunsheng et al. [32]. Concerning the strength reductions, no significant changes were observed in the investigated mixes. These findings are in line with the previous studies on freezing-thawing for geopolymers [33,34]. Due to the humid medium in which the test was done, it is expected that the voids within the produced samples were filled and hence the weight was increased as well as the ultrasonic pulse values.

4.6. Microstructural analyses

The SEM micrographs of the main mixes were taken and the results are shown in Fig. 6. As a general observation, the micrographs of the investigated samples indicate a satisfactory degree of compactness and good microstructural bonding between the components of the geopolymeric matrix. Some unreacted fly particles were observed in the micrographs, the existence of unreacted

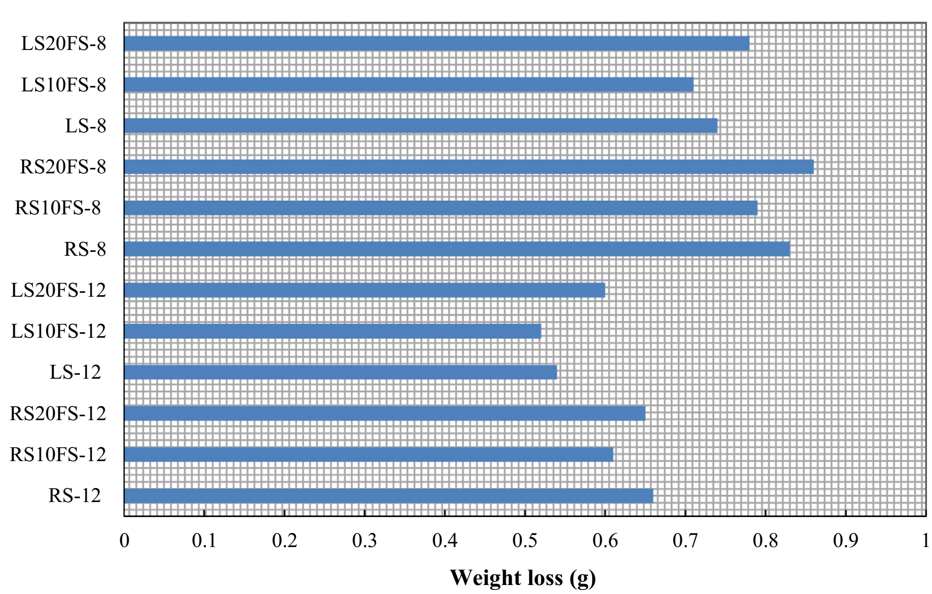

Fig. 5. Abrasion resistance results (weight loss) (g).

Table 6
Strength results before and after the freeze-thaw effect (MPa).

Mix ID	Compressive strength (before test) (MPa)	Compressive strength (after test) (MPa)	Flexural strength (before test) (MPa)	Flexural strength (after test) (MPa)
RGP	60.77	62.68	8.456	8.132
LGP	52.01	51.77	8.016	7.823
R10FS	62.58	62.07	9.114	9.008
L10FS	52.83	53.18	8.128	8.233

Table 7
Ultrasonic pulse velocity test results before and after the freeze-thaw effect (m/sec).

Mix ID	UPV (before test) (m/sec)	UPV (after test) (m/sec)
RGP	3563	3809
LGP	3547	3892
R10FS	3571	3661
L10FS	3554	3669

Table 8
Samples' weights before and after the freeze-thaw effect (g).

Mix ID	Weight (before the test) (g)	Weight (after test) (g)
RC	581.2	576.4
LC	592.1	576.7
RGP	549.4	553.5
LGP	584.7	583.6
R10FS	550.1	554.2
L10FS	571.7	578.5

particles is an indicator of a good strength behavior because these particles will affect positively in the bonding pattern of the manufactured samples [35]. Also, following [36] findings, the prismatic columns which are given in Fig. 6 (top right) are more likely to be Si and Al compounds, this observation represents a clear geopolymerization first starts by the dissolution of the precursor and forming the polymeric Si-O and Al-O bonds which are the main chains in the geopolymeric system. The micrographs reveal the fact that no significant visual changes are observed on the matrix which in turn means that the composition of the matrix was not affected by the change of the dosage of sodium hydroxide.

The micrograph of the sample with waste foundry sand (R10FS-12) shows that the partial replacement of standard sand with this type of waste did not change the morphology of the resulted matrix which is consistent with the results which were obtained from other tests.

XRD patterns of the main mixes are given in Fig. 7. Generally, the main observed compounds of the geopolymerization process were quartz, mullite, and calcite in case of a crushed limestone sample. The patterns mainly show the crystalline phase of the fabricated samples following the observations of Uysal et al. [31] and Provis et al. [37]. This phase is observed by the peaks of quartz within the range of (25–28) 2θ. In addition to that, the sharp peaks in the patterns are believed to be related the existence of unreacted fly ash particles.

4.7. Correlation relationships between some investigated properties

To evaluate the degree of consistency between the some investigated properties, an attempt was carried out to determine the correlation between strength properties and non-destructive test results. Correlation relationships were obtained for flexural strength- abrasion resistance and compressive strength-UPV test

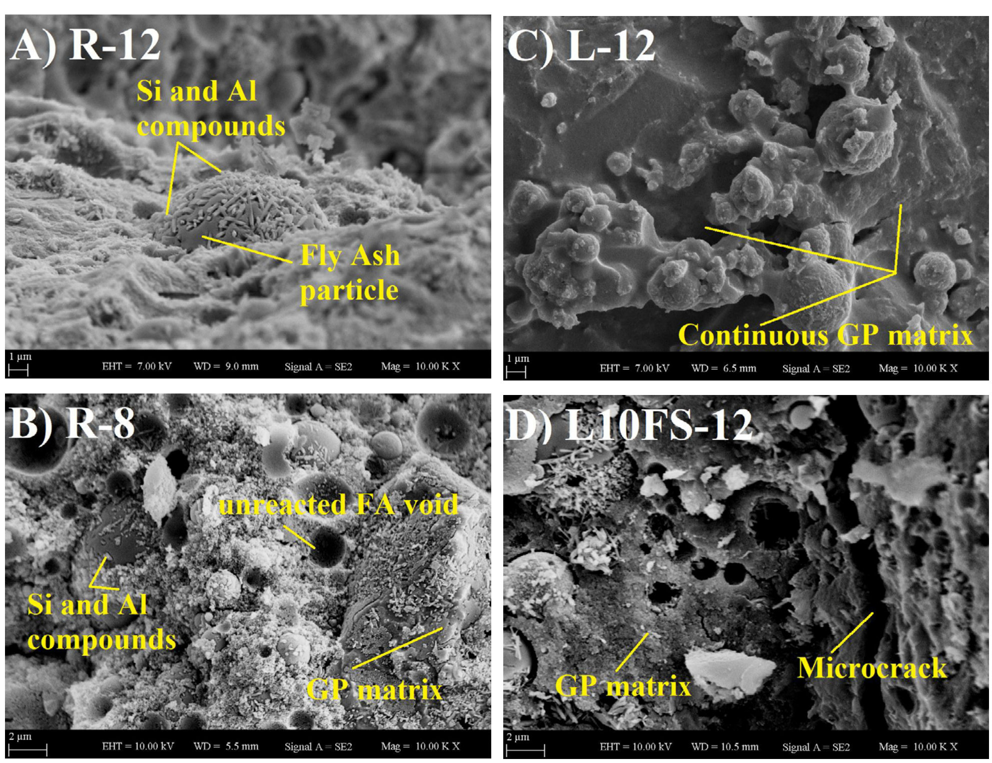

Fig. 6. SEM micrographs: a) R-12, b) R-8, c) L-12 and d) R10FS-12.

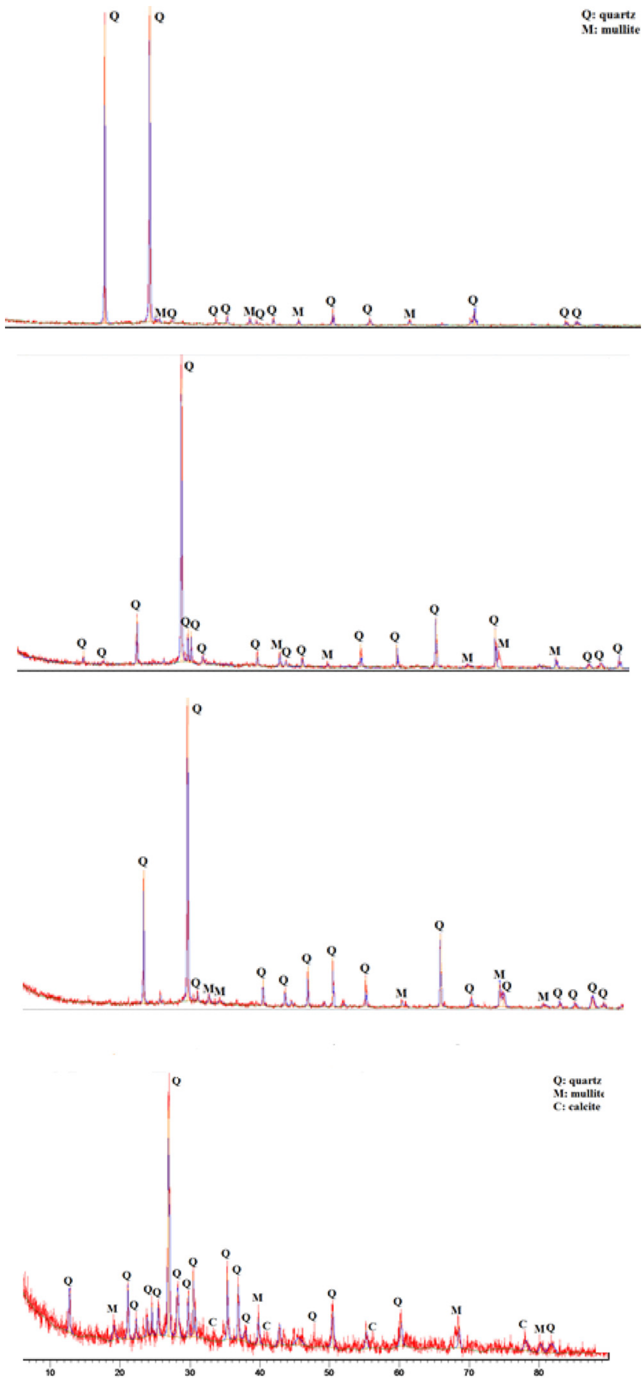

Fig. 7. XRD pattern of (R-12, R-8, R10FS-12, L-12).

results. R^2 is a factor that represents the degree of correlation between the investigated properties if this factor yields a value of more than 0.75, and then a certain trend of correlation could be seen through performing this calculation. In general, the results showed that a satisfactory correlation was obtained for all the samples. The results were in accordance with the former findings of Al-mashhadani et al. [29] and Uysal et al. [31], they generally came up with a result that flexural strength-abrasion resistance, compressive strength-UPV test results are proportional to each other. As shown in Figs. 8 and 9, the results exhibited a correlation value of 0.92 for the aforementioned tests.

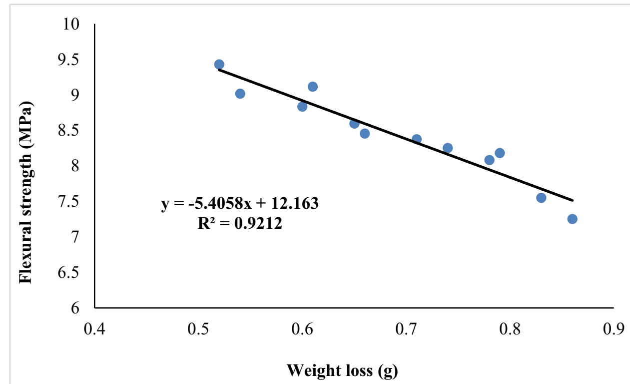

Fig. 8. Correlation relationship between flexural strength and abrasion resistance results.

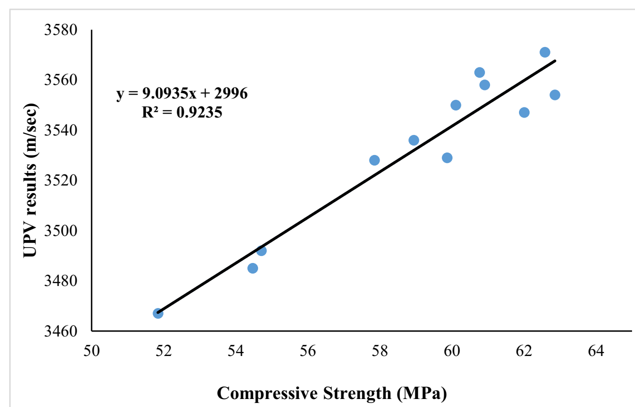

Fig. 9. Correlation relationship between compressive strength and UPV results.

5. Conclusions

- The higher concentration of sodium hydroxide showed slightly better mechanical strength results compared to the samples with low sodium hydroxide molarity. The most significant improvement was approximately 3% for the 28th day's compressive strength results.
- The existence of waste foundry sand was found as a reliable and sustainable attempt, to illustrate this, a partial replacement of 10% yielded mechanical strength improvement to the studied properties. Almost 3% improvement was obtained for compressive strength results, while 8% of the development was observed for flexural strength results
- The replacement of 20% waste foundry sand yielded lower strength results when compared to the ones of 10% replacement. However, the results indicated that 20% of waste foundry sand may be utilized for the geopolymeric matrix for the lower strength requirements.
- In addition to the wide range of applications of the used materials, their combination in a geopolymeric matrix would add a practical value since the used materials are by-product orientated. For instance, waste foundry sand is already used in bricks manufacturing, pavement works, precast panels, soil stabilization, hydraulic barriers, or liners. In the same concern, crushed limestone is beneficial in various concrete technology application areas.
- In general, the specimens which were fabricated with crushed limestone yielded comparable results in terms of general performance (approximately 50 MPa for compressive strength, 7 MPa for flexural strength, and less than 1 g for abrasion resis-

tance). This leads to a conclusion which states that using crushed limestone in the geopolymeric matrix could be considered as a feasible procedure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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