

## Research Article

# Waste Foundry Sand Usage for Building Material Production: A First Geopolymer Record in Material Reuse

Neslihan Doğan-Sağlamtimur 

*Department of Environmental Engineering, Niğde Ömer Halisdemir University, Niğde 51240, Turkey*

Correspondence should be addressed to Neslihan Doğan-Sağlamtimur; neslihandogansaglamtimur@gmail.com

Received 6 December 2017; Accepted 26 April 2018; Published 17 May 2018

Academic Editor: Evangelos J. Sapountzakis

Copyright © 2018 Neslihan Doğan-Sağlamtimur. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In order to bring a solution to the problem of waste foundry sand (WFS) in the foundry sector and achieve its reuse, geopolymer building material (as a cementless technology) was produced from the WFS for the first time in the literature in this study. The physical and mechanical characteristics of this material were determined. In the first part of the experimental step, the sieve analysis, loose/tight unit weight, and loss of ignition of the WFS were obtained as well as the ultimate analysis. In the second step, the water absorption percentage, porosity, unit weight, and compressive strength tests were conducted on the WFS-based geopolymer specimens activated by chemical binders (sodium hydroxide: NaOH and sodium silicate: Na<sub>2</sub>SiO<sub>3</sub>). As the unit weights of all the produced samples were lower than 1.6 g/cm<sup>3</sup>, they may be considered as lightweight building materials. The minimum compressive strength value for building wall materials was accepted as 2.5 MPa by national standards. In this study, the maximum compressive strength value was measured as 12.3 MPa for the mixture incorporation of 30% Na<sub>2</sub>SiO<sub>3</sub> at the curing temperature of 200°C in 28 days. It was concluded that this geopolymer material is suitable for using as a building wall material.

## 1. Introduction

The method of obtaining a desired shape by solidifying molten metal in a mould that has space in it is called foundry [1]. Foundry involves production of parts by melting down metals or alloys and pouring them into the space in a pre-prepared mould. In one step, parts with simple or complex shapes may be produced out of any material that can be moulded. The foundry sector is an industrial sector where various iron, scrap steel, and ferroalloys are melted down in arc furnaces or cupolas, shaped in sand, ceramic, or metal moulds, and the cast, steel, nodular, and tempered foundry products needed in industry are produced as raw or processes materials [1, 2].

Especially in establishments such as factories and workshops that produce parts of the automotive, construction, and machine and in steel industry, foundry sand is used to mould foundry products (iron-steel industry and aluminium- and copper-based alloys). A large part of foundry process is achieved using sand moulds. Foundry

sand is used to prepare metal foundry moulds. For 1 ton of foundry, 4-5 tons of sand is required. This ratio may be changed based on the type of the metal that needs to be casted, part size, and moulding technique. Sands that contain more than 90% of silica and 7-15% clay (bentonite or kaolinite clay) and have a sintering temperature of over 1500°C are defined as foundry sands. Foundry sands are found freely in the nature, and they have a loose structure. The physical and chemical characteristics of foundry sand are dependent on the type of the foundry process and the industrial sector it is to be used in [3]. Foundry sand typically has a semicornered or circular shape [4]. It has a uniform distribution of grain size; 85-95% of it has grain sizes of 0.6 to 0.15 mm, while 5-12% of it has grains smaller than 0.075 mm [5]. After each foundry operation, the moulds are opened up, large parts in the foundry sand are sieved and removed, and new sand is added to the system in the amount the sand that is removed. After a certain number of cycles, foundry sand becomes unusable for the moulds, which is discarded from the foundry as waste foundry sand (WFS).

The reasons for this are (i) physical and chemical degradation of the sand, (ii) exposure of the sand to 1500°C molten metal during moulding, (iii) loss of the binding properties of the bentonite in the sand, and (iv) loss of resistance in sand grains due to mechanical abrasion [6].

Studies on usage of the WFS, which was the raw material of this study, started only recently, and they are limited. There are various fields in the world that would achieve usage of the WFS in large amounts in the construction sector, especially in geotechnics and highway constructions. In general, in cases where the shipping processes in reuse do not exceed the costs of the shipping processes used for the primary form of sand, usage of the WFS becomes advantageous [7]. The WFS may be used as filling with or without controlling hydraulic conductivity. One of the areas where WFS is used most frequently is highway construction operations. It is possible to use this material in various states of highway constructions. It may be used as a foundation material for the lower and upper structure of the road or for the purpose of increasing the friction coefficient of the road coating material in the struggle against snow and ice in winter months. The WFS is being used successfully as fine aggregate in hot asphalt mixtures. Studies have shown that the WFS may be used to constitute 25% of the fine aggregate in the mixture. Ordinary Portland cement (OPC) consists of calcium oxide, silica, and iron oxide in suitable amounts. In cement production, the chemistry of the WFS as a source of silica is more important than its grain size and shape. The WFS is one of the highest-quality silica sources for the cement industry. The amount of natural sand that is needed may be reduced by replacing it with the WFS. While various usage areas have been found and are being used in the world for the WFS, the entropy of the foundry system may be the enthalpy of another party that needs it. As the price for various raw materials has started to increase in Turkey, the WFS has started to be used by other industries as input (enthalpy). In addition to the WFS usage areas such as tarmac, road construction, cement, filling material, and briquette construction which are used everywhere, usage of the WFS as agricultural soil popularised in recent years [8]. Due to its consistency and dark colour, the WFS is ideal for agricultural soil production. It is a suitable material as it is needed to have high sand content in agricultural soil. It reduces clustering during fertiliser application and prevents mixing due to compression. Additionally, it allows air flow in the material. The Ohio Plantation uses foundry sand for ornamental plants by mixing it with soil and fertiliser. Kurtz brothers from Ohio also used it successfully for golf course greening. In this practice, presence of clay is useful, and it makes it easier to intake nutrients. In addition to this, it is also utilised as fine aggregate on making mixtures, and for its rich silica content, it is used in production of mineral wool and fiberglass [9].

Experiments were conducted by replacing 20% of aggregates in concrete mixtures with the WFS and increases of up to 10% were achieved in water absorption and capillary absorption values. This increase reduced compressive strength (CS) by a certain amount. Another study with addition of recycled sand by 15% reported that this addition

increased ultrasonic pulse velocity and reduced chloride ion penetration. In high-strength concretes, it was found that addition of the WFS above 10% was not usable. Another study found that the best WFS ratio for CS is 5–10%, and this ratio preserved the CS of mixtures made with standard sand, but ratios up to 5% and higher than 10% reduced the CS of samples by about 10% [10].

In a study which investigated usability of the WFS and type-F fly ash (FA), it was reported that usage of FA in mixtures increased CS (by more than 32%), abrasion resistance, and durability, and the WFS or type-F FA used in cool environments may replace sand by up to 25% [11].

Studies have been conducted on usage of foundry sands in highways and berms [12, 13], hydraulic barriers [14, 15], inside tarmac mixtures [16], investigation of permeability values with usage of slurry materials [17], potentials of usage as waste in civil engineering and ways of recycling [18], improvement studies using biological or other materials [19, 20], investigation of seepage water quality in landfill areas filled with foundry sand [21], foundry sands' characteristics [22], and reuse and removal [23, 24].

Usage of the WFS was investigated for using in Portland-cemented concrete. For this purpose, 15% WFS and various ratios of water/cement (W/C) mixtures were added into standard concrete mixtures instead of sand, and their effects on the physical and mechanical properties of concrete were observed. Accordingly, the slump test was conducted on the fresh concrete, and compression, indirect tensile force, water absorption percentage, specific weight, sorptivity, and ultrasound pulse velocity were analysed on hardened concrete. Experiment results showed that the WFS damaged the mechanical and physical characteristics of concrete to some extent. Despite this damage, it was reported that WFS-based concrete may be used safely in large-mass concrete blocks that are not ferroconcrete. Using WFS in such applications would be suitable for economy [24].

It was found in thermal analyses of foundry sands that 98% may be used by recycling, and this will provide various economic and environmental benefits; green metal foundry sands may be used as filling in areas such as ditches, holes, and trenches. While the electrical method is recommended to remove Zn, Mn, and Pb from foundry sand, there are also recommendations to regain the chromium and silica in the sand. As foundry sand contains sand and bentonite, their mechanical behaviour resembles sand bentonite mixtures [24].

Indirect tensile strength experiment results of samples with and without WFS addition were in parallel with CS experimental results. In comparison with the values found in the non-WFS mixtures, the water absorption in 28-day samples with 15% WFS addition was 1.5% higher in low W/C ratios and 2.9% higher in high W/C ratios. Sorptivity and visible porosity rates of samples with 15% WFS were higher than those of samples without WFS addition. Accordingly, the clay that is found in the WFS to some extent and particles on the WFS grains weakened adherence, and as they led to an increase in the rate of pores in the concrete, they reduced the mechanical and physical properties of the concrete. This reduction may be caused by high rates of

WFS added into the concrete mixture. It is thought that the WFS may be used in backfill concrete [24].

Deng and Tikalsky [25] stated that the WFS can be converted into flowable fill for geotechnical applications. In the related study, the WFS samples were obtained from 17 independent metal casting facilities with different casting processes, thus representing a good range of the WFS properties. The laboratory studies include physical, geotechnical, and leaching properties of flowable fills consisting of the WFS, cement, and FA mixed to different water contents. The main properties measured include WFS physical properties (density, particle gradation, grain shape, and fine content), WFS flowable fill geotechnical properties (unconfined compressive strength, hydraulic conductivity, setting time, and bleeding), and the fill's leaching properties (heavy metals and organics in the bleed water and the leachate extracted from hardened WFS flowable fills). The test results indicate that, in terms of the physical properties, most of the data fall within narrow ranges, although data from the copper/aluminum-based WFS samples might fall beyond the ranges. Geotechnical properties of the WFS flowable fills in both fresh and hardened phases were verified conforming to the features of specified flowable fills. Material leaching analyses indicate that the toxicity of the WFS flowable fills is below regulated criteria. A mix formulation range originated from the study is proposed for the design of the WFS made flowable fill.

Siddique and Noumowe [26] present an overview of some of the research published on the use of spent foundry sand (SFS) in controlled low-strength materials and concrete. In the related study, effects of SFS on controlled low-strength materials (CLSM) characteristics like plastic properties, such as CS, permeability, and leachate analysis, and concrete properties such as CS, splitting tensile strength, modulus of elasticity, freeze-thaw resistance, and shrinkage are presented.

Siddique et al. [27] present the results of an experimental investigation carried out to evaluate the mechanical properties of concrete mixtures in which fine aggregate (regular sand) was partially replaced with used-foundry sand (UFS). In this study, fine aggregate was replaced with three percentages (10%, 20%, and 30%) of UFS by weight. CS, splitting tensile strength, flexural strength, and modulus of elasticity were determined at 28, 56, 91, and 365 days. Test results indicated a marginal increase in the strength properties of plain concrete by the inclusion of UFS as partial replacement of fine aggregate (sand) and that can be effectively used in making good quality concrete and building materials.

Guney et al. [28] investigated the potential reuse of the WFS in high-strength concrete production. In this study, the natural fine sand is replaced with the WFS (0%, 5%, 10%, and 15%). The findings from a series of test program showed reduction in CS, tensile strength, and the elasticity modulus which is directly related to waste foundry inclusion in concrete. The slump and the workability of the fresh concrete decreased with the increase of the WFS ratio. However, the freeze-thaw significantly reduced the mechanical and physical properties of the concrete. The obtained results

satisfy the acceptable limits set by the American Concrete Institute (ACI).

Siddique et al. [29] present the design of concrete mixes made with UFS as partial replacement of fine aggregates. In this study, test results indicate that industrial by-products can produce concrete with sufficient strength and durability to replace normal concrete. CS, and split tensile strength, was determined at 28, 90, and 365 days along with carbonation and rapid chloride penetration resistance at 90 and 365 days. Comparative strength development of foundry sand mixes in relation to the control mix (i.e., mix without foundry sand) was observed.

Singh and Siddique [30] performed an experimental investigation to evaluate the strength and durability properties of concrete mixtures, in which natural sand was partially replaced with the WFS. In this study, natural sand was replaced with five percentages (0%, 5%, 10%, 15%, and 20%) of the WFS by weight. A total of five concrete mix proportions (M-1, M-2, M-3, M-4, and M-5) with and without WFS were developed. The CS test and splitting tensile strength test were carried out to evaluate the strength properties of concrete at 7, 28, and 91 days. The modulus of elasticity and ultrasonic pulse velocity test were conducted at 28 and 91 days. In case of durability property, the rapid chloride permeability test was performed on all five mix proportions at 28 and 91 days. Test results indicate a marginal increase in strength and durability properties of plain concrete by inclusion of the WFS as a partial replacement of fine aggregate.

Singh and Siddique [31] investigated the abrasion resistance and strength properties of concrete containing the WFS. In this study, sand (fine aggregate) was replaced by 0%, 5%, 10%, 15%, and 20% of WFS by mass. The W/C ratio and the workability of mixtures were maintained constant at 0.40 and  $85 \pm 5$  mm, respectively. Test results indicated that replacement of sand with the WFS enhanced the 28-day CS by 8.3–17%, splitting tensile strength by 3.6–10.4%, and modulus of elasticity by 1.7–6.4% depending upon the WFS content and showed continuous improvement in mechanical properties up to 365 days. It was determined that inclusion of the WFS as sand replacement significantly improved the abrasion resistance of concrete at all ages. Strong correlation exists between the abrasion resistance and each of the mechanical properties investigated.

Akkaya [32] examined UFS with some additives as a landfill cap layer material. For this purpose, laboratory tests were performed with these samples: UFS (for two different types of foundry sand: green sand and resin-bonded sand), UFS + bentonite (various proportions), and UFS + bentonite + waste rubber (with different shapes). It was found that increasing bentonite content (9%) decreased the hydraulic conductivity below the requirements ( $10^{-9}$  m/s) for all UFS. Adding rubber (3%) to UFS bentonite mixture increases the split tensile strength for all types of samples, and it also increased hydraulic conductivities; only 1 result was found below the requirements. In this study, results showed that UFS with bentonite and rubber revealed a good candidate for construction of a landfill cap layer material.

About 300 thousand tons of foundry sand is used annually in various sectors in Turkey, and the used sand is released into the nature as waste. Top users of foundry sand in the world include Russia by 10,800 thousand tons, Germany by 2,754 thousand tons, the USA by 6,032 thousand tons, France by 1,428 thousand tons, and Italy by 1,245 thousand tons [24]. Turkey is in the 12th place in the world and 4th place in Europe in terms of the foundry industry, and this is a significant market share.

In the industry, there is the tripod of raw material-process-product, and waste formation is an inevitable problem in most industrial establishments [33]. Today, where environmental issues are substantial, utilisation of industrial wasted supplement materials in building material technologies is an important issue that needs to be focused on as it will reduce costs and fight environmental problems [9]. In parallel with advancement of today's technology, building material technology has entered a rapid change and advancement process.

Geopolymer is a group of cementitious materials formed by activating aluminosilicate-based material with alkaline solution containing a mixture of hydroxide and silicate of alkali earth metal (sodium or potassium) [34]. Geopolymers, with their great physical and chemical characteristics, may be used in the prefabricated construction industry, bearing and nonbearing building materials, sculpting and ornament arts, concrete-based road coatings, ground improvement, storage of toxic and nuclear waste, refractory ceramic material production, production of wall coatings that are resistant against challenging climate conditions like fire, reinforcement and restoration of bearing system of historical buildings, plane and race car industry, and nuclear power plants [35]. Oven cured FA-based geopolymer concrete was found to behave in a more brittle manner than the conventional OPC-based concrete [36].

Transformation of the waste into another product in terms of environmental technology is known in the waste management hierarchy pyramid as "reuse." It is needed to develop usage areas for this waste within the concept of industrial ecology. In Turkey and worldwide, it seems possible by utilising the WFS, an industrial/sectoral waste, to reduce CO<sub>2</sub> emissions, produce more inexpensive building materials, support the country's economy by reusing the waste material, protect the ecological balance with natural raw materials, and prevent environmental pollution. Reuse of this waste as an input for the economy is a necessity which is increasingly adopted in Turkey as it is in the world for a priority policy goal to a sustainable environment and development.

Besides the environmental benefits of waste disposal and CO<sub>2</sub> sequestration [37, 38], the WFS is suitable raw material for building material production. Selection of reuse the geopolymer building material among alternatives in utilising WFS in this study was based on that fact that the construction sector satisfies the most basic human need of shelter; it usually acts as a leverage for the economy of Turkey, and the world in terms of the added value and employment opportunities it creates, its annual growth rate is 7.1% and its contribution to gross national product is 6%;

TABLE 1: Elemental analysis of the WFS.

Compounds	Amount (%)
SiO <sub>2</sub>	98.64
Al <sub>2</sub> O <sub>3</sub>	0.74
CaO	0.35
Fe <sub>2</sub> O <sub>3</sub>	1.01
K <sub>2</sub> O	0.21
MgO	0.50
Na <sub>2</sub> O	1.07

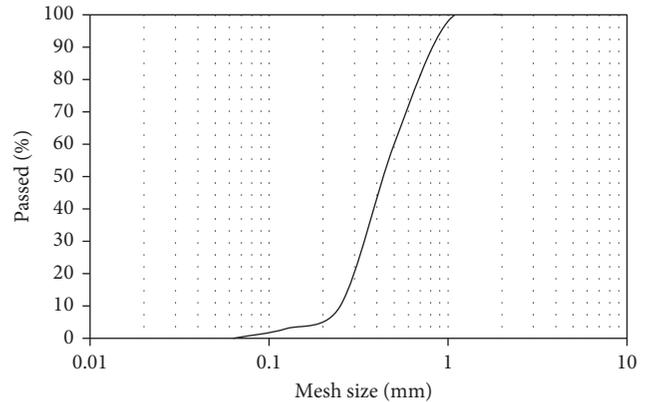


FIGURE 1: Granulometric distribution of the WFS.

they are some of the most abundantly used materials per person following water [39].

## 2. Materials and Methods

Classification of foundry sand may depend upon the type of binder (bentonite or resinous). The WFS used in this study contained bentonite, and it was supplied from the province of Konya in central Turkey. In this study, it was worked on 4 different types of WFS, and it was decided to continue with one type after the preliminary results. Elemental analyses of this WFS were carried out, and then, preliminary experiments (the sieve analysis, loose/tight unit weight, and loss of ignition tests) were conducted on this material. The study included experiments of chemical binder and sample collection from the WFS and on the geopolymer building material samples, which involved (i) water absorption percentage (WAP), (ii) porosity, (iii) CS, (vi) unit weight (UW) tests. Related Turkish standards were used in the experiments conducted in the scope of the study.

The WFS elemental analysis was carried out in an accredited laboratory based on the EPA 3051 A (microwave-assisted digestion "preliminary process") [40] and EPA 200.7 (analysis in ICP-OES) [41] standard test methods, and the results are given in Table 1.

SiO<sub>2</sub> is significantly abundant in terms of its ratio in the WFS content. The ratios of the other components are very low in comparison with SiO<sub>2</sub>.

The sieve analysis of the WFS was conducted (Figure 1). According to TS EN 933-10 [42], the material was categorised based on size.

TABLE 2: Production parameters of geopolymer samples including the chemical binders and the WFS (in w/w basis).

Sample number	Ratio in total amount (%)	The amount of chemical binder (NaOH or Na <sub>2</sub> SiO <sub>3</sub> ) (g)	The amount of WFS (g)
1	10	125	1250
2	15	187	1250
3	20	250	1250
4	25	312	1250
5	30	375	1250

For combustible material calculation of the WFS, firstly crucible tare weighted 1 g of WFS is put into a crucible and left on the stove at 105°C for 1 hour. Then the sample is left in a desiccator for cooling. The sample that is taken out of the desiccator is weighed on a precision scale and left in a muffle furnace at 750°C for 2 hours. After 1 day, it is taken to the desiccator again for cooling. Combustible material is calculated by the formula:  $(y-x/\text{sample weight}) \times 100$  (crucible tare =  $x$ , sample weight = 1 g, after-stove  $N + K = y$ ). However, the WFS is a solid industrial waste which also contains the substance used during moulding in its structure. During the foundry operations, automobile parts were left in the WFS used as a raw material in this study. Therefore, as in high temperatures in geopolymer production processes, issues of gas release and smell occurred as the temperature increased (>200°C), and the temperature of 750°C could not be reached. So, combustible matter calculation could not be achieved. Naturally, the UW of an aggregate varies in the range of 1.20 to 1.80 kg/dm<sup>3</sup>. UW values are dependent on the granulometry of the aggregate, amount of faulty materials, form of positioning, and the specific weight of the aggregate. The compressed UW values for the WFS were calculated as given below:

- (i) Air-dried compressed UW: 1.60 g/cm<sup>3</sup>
- (ii) Oven-dried compressed UW: 1.59 g/cm<sup>3</sup>

WFS-chemical substance mixture rates were calculated to produce geopolymer building material samples from the WFS with chemical binder (Table 2). The mixtures prepared based on these calculations were poured into moulds with the dimensions of 4 × 4 × 16 cm. The samples were obtained in different ratios by volume (10%, 20%, and 30%); they were then dried for 24 hours in an oven at different temperatures (75, 100, 150, and 200°C).

While preparing the samples, as gas emission was observed at temperatures over 200°C, the upper limit for temperature was determined as 200°C. These experiments suggested that the WFS may be activated by chemical binder. Consistency tests were conducted in preparation of the samples as water ratios may influence sample characteristics, and the consistency ranges of all samples were held constant.

As the UWs of the samples in the study were very diverse, the mixture parameters were determined based on volumes. Three groups of samples were prepared in the study:

- (a) Samples prepared with NaOH (at least 97% purity)
- (b) Samples prepared with 38 bome Na<sub>2</sub>SiO<sub>3</sub>
- (c) Samples prepared with 48 bome Na<sub>2</sub>SiO<sub>3</sub>



FIGURE 2: Geopolymer building material samples activated by using chemical binders. ADK is the Turkish name of the WFS.

CS experiments were conducted on samples at 7-day and 28-day curing times. New samples were prepared based on the optimum design parameters. Additionally, samples were also prepared based on the  $\pm 5\%$  interval values of the optimum design (Figure 2). Based on these results, necessary tests were carried out on the obtained samples in order to determine their physical-mechanical characteristics.

For CS analyses on the geopolymer samples, the volatility of the spherical bearing was checked before starting the experiment. The surfaces of the loading trays and the samples were carefully cleaned, and the sample was placed on the lower tray. Adjustments were made in a way to ensure that the sample axis and the tray on the spherical bearing had the same centre of compression. In order to ensure that the load to be applied on the sample is distributed evenly on the surface, the tray was adjusted in a way to contact the surface of the sample completely. The loading was adjusted in a continuous way so that the loading rate is as constant as possible (in a period of 3–5 minutes), and the CS was measured by using mangle.

Cube-shaped samples were used for WAP experiments on the geopolymer samples. The samples were dried at 105°C for 24 hours and left at room temperature for 30 minutes, and then their weights were measured. The dried samples were left in a container filled with water at 20–25°C temperature for 24 hours. They were then weighed right away after wiping the water drops on them with a damp sponge and put back into the water. This measurement operation was repeated in 24-hour intervals. In the last state, their water-saturated constant weights were determined. The WAP values could be measured in

TABLE 3: The results of the WFS-based geopolymer materials produced by using NaOH.

Curing temperature (°C)	NaOH amount (with respect to WFS amount, w/w) (%)	UW (g/cm <sup>3</sup> )	CS (MPa)		WAP (%)	Porosity (%)
			7 days	28 days		
50	10	—	—	—	BIW*	BIW
	20	—	—	—	BIW	BIW
	30	—	—	—	BIW	BIW
75	10	1.42	1	1	BIW	BIW
	20	1.44	1	1	BIW	BIW
	30	1.50	1	1	BIW	BIW
100	10	1.41	2.4	2.5	29	35
	20	1.44	1.8	1.9	29	33
	30	1.51	1.1	1.2	28	33
150	10	1.40	1.7	1.8	28	34
	20	1.45	1.6	1.6	27	32
	30	1.52	1.5	1.6	26	31
200	10	1.42	1.8	1.8	26	33
	20	1.45	1.6	1.6	24	31
	30	1.57	1.6	1.6	24	31

\*BIW: breakup in water.

TABLE 4: The results of the WFS-based geopolymer materials produced by using Na<sub>2</sub>SiO<sub>3</sub>.

Curing temperature (°C)	Na <sub>2</sub> SiO <sub>3</sub> amount (with respect to WFS, w/w) (%)	UW (g/cm <sup>3</sup> )	CS (MPa)		WAP (%)	Porosity (%)	
			7 days	28 days			
75	38 bome	10	1.69	—	—	BIW	BIW
		20	1.60	—	—	BIW	BIW
		30	1.65	—	—	BIW	BIW
	48 bome	10	1.68	—	—	BIW	BIW
		20	1.80	—	—	BIW	BIW
		30	1.73	—	—	BIW	BIW
100	38 bome	10	1.65	0.7	—	BIW	BIW
		20	1.69	2.7	—	BIW	BIW
		30	1.57	0.9	—	BIW	BIW
	48 bome	10	1.67	0.9	1.3	BIW	BIW
		20	1.72	0.9	—	BIW	BIW
		30	1.55	0.9	—	BIW	BIW
150	38 bome	10	1.61	0.9	—	BIW	BIW
		20	1.56	0.9	1.3	BIW	BIW
		30	1.43	2.1	2.0	BIW	BIW
	48 bome	10	1.62	0.3	—	BIW	BIW
		20	1.59	0.6	2.6	BIW	BIW
		30	1.52	4.4	4.2	BIW	BIW
200	38 bome	10	1.64	0.9	0.7	BIW	BIW
		20	1.61	3.2	2.75	BIW	BIW
		30	1.39	4	4.3	BIW	BIW
	48 bome	10	1.63	1.1	1.1	BIW	BIW
		20	1.53	4.6	4.25	BIW	BIW
		30	1.41	9.1	12.3	BIW	BIW

the samples where NaOH was used as the chemical binder in geopolymerisation in the 100–200°C temperature range; as the samples were prepared at 50 and 75°C curing temperatures dispersed in water, no measurements could be made in terms of WAP values at these temperatures. All geopolymer samples where Na<sub>2</sub>SiO<sub>3</sub> was used as the chemical binder had a tendency to disperse in water (Tables 3 and 4) during WAP measurements.

The WAP of a material is also its visible porosity. This parameter could also be measured at the curing temperatures where the WAP could be measured, but again, it could not be measured at the temperatures where the WAP could not be determined.

The TS 699 [43] standard was used to determine the UW of the geopolymer samples. The arithmetic average of the unit weights of three samples was taken to obtain the UW

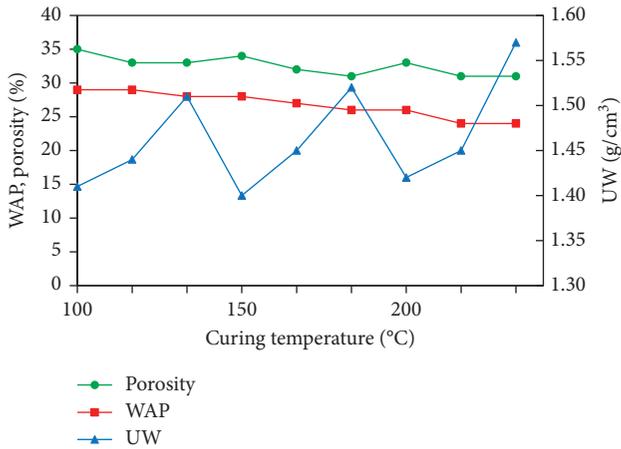


FIGURE 3: The relationship between WAP, porosity, UW, and curing temperatures (100–200°C) for the WFS-based geopolymer materials produced by using NaOH (10–30% in the total amount).

value for that group. The following equation was used to calculate the UW values:

$$\rho_{g,u} = \frac{m_{dry,u}}{V_{g,u}} \quad (1)$$

where  $m_{dry,u}$  is the dry UW,  $V_{g,u}$  is the gross volumes of the samples (obtained by multiplying length, width, and height),  $\rho_{g,u}$  is the UW.

### 3. Results

The experiments of this study were carried out at temperatures under 200°C. The remaining foundry wastes (automobile parts) in the WFS had a tendency to burn in curing trials at higher temperatures, and the design of the experimental setup had to be set at temperatures under 200°C. The WFS samples were passed through a 1 mm sieve; the study was carried out using different ratios of mixing NaOH and Na<sub>2</sub>SiO<sub>3</sub> and different curing temperatures, and geopolymer building materials were produced.

The collective results of the tests applied on the geopolymer materials during the production process in this study are given in Tables 3 and 4 and Figures 3–6. In the curing temperature, ticks between marks indicate the NaOH amount given in Table 3 (from 10 to 30%, Figures 3 and 4) and Na<sub>2</sub>SiO<sub>3</sub> amount given in Table 4 (from 10 to 30%, Figures 5 and 6), respectively.

Previous studies produced building materials from the WFS by using cement as the binder. In the method applied in this study which used this waste (WFS) as a raw material in geopolymer production, the optimum amounts of the chemical binders added onto different ratios of the WFS by w/w basis were 10% (curing temperature of 100°C) for NaOH and 30% (curing temperature of 200°C) for Na<sub>2</sub>SiO<sub>3</sub>.

### 4. Discussion and Conclusion

The SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio in the WFS by weight was not in the range of 2–3.5. In addition to this, excessive rates of Fe<sub>2</sub>O<sub>3</sub> (during metal moulding) slow down the geopolymer

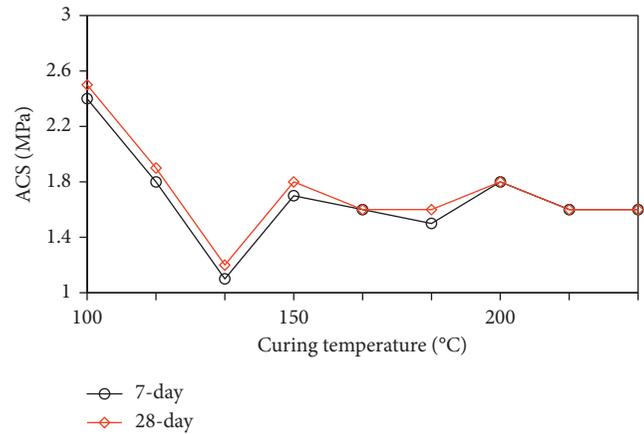


FIGURE 4: The relationship between CS values (7 and 28 days) and curing temperatures (100–200°C) for the WFS-based geopolymer materials produced by using NaOH (10–30% in the total amount).

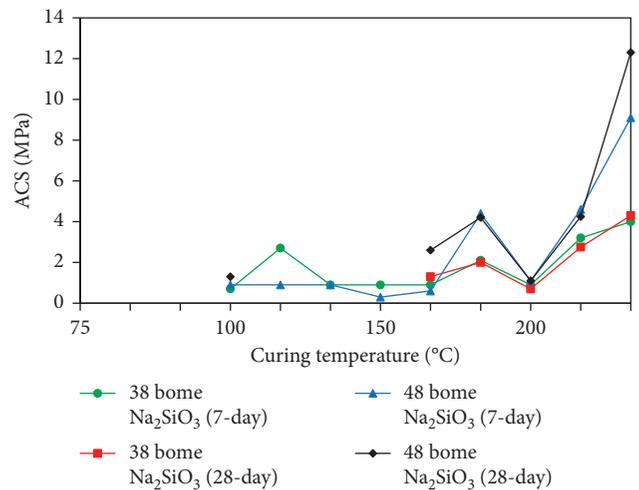


FIGURE 5: The relationship between CS values (7 and 28 days) and curing temperatures (100–200°C) for the WFS-based geopolymer materials produced by using 38 and 48 bome Na<sub>2</sub>SiO<sub>3</sub> (10–30% in total amount).

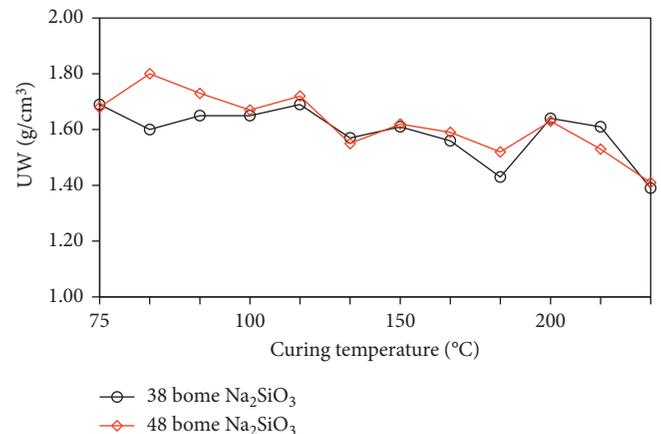


FIGURE 6: The relationship between UW values and curing temperatures (100–200°C) for the WFS-based geopolymer materials produced by using 38 and 48 bome Na<sub>2</sub>SiO<sub>3</sub> (10–30% in total amount).

reaction and provide low CS in some samples (with different chemical compositions). American Society for Testing and Materials (ASTM) categorised building concretes as normal ( $UW \geq 2 \text{ g/cm}^3$ ), medium ( $1.6\text{--}2.0 \text{ g/cm}^3$ ), and lightweight ( $<1.6 \text{ g/cm}^3$ ). In this study, the UW values of all the specimens produced with NaOH were lower than  $1.6 \text{ g/cm}^3$ , and these may be considered as lightweight building materials. On the contrary, the UW values of the specimens produced with  $\text{Na}_2\text{SiO}_3$  were in the range of  $1.39\text{--}1.80 \text{ g/cm}^3$ , which covers both medium and lightweight building materials.

Among the geopolymer building material specimens prepared by using NaOH binder and the WFS, the material produced by 10% NaOH addition at a curing temperature of  $100^\circ\text{C}$  had the highest CS value (2.5 MPa) at 28th day. Relevant national standards determined the minimum CS value for wall materials as 2.5 MPa. Thus, this material could be suitable for using as a wall material. Different amounts of NaOH added into the WFS-based samples led to losses in CS values. These losses had the highest value in the specimens produced with 30% NaOH addition. This result showed that usage of NaOH binder and the WFS is not effective on CS values of the specimens. As the geopolymer building materials were deformed during WAP measurements, it was seen that they were not resistant against external effects. The maximum UW ( $1.52 \text{ g/cm}^3$ ) value was measured at a curing temperature of  $150^\circ\text{C}$  in the sample produced with 30% NaOH addition; however, almost the same values were found in all mixtures as no expanding agent was used in any material. WAP and porosity values of the samples were similar. This was an expected result due to similarity in UW values. The geopolymer building materials produced at the curing temperatures of  $50$  and  $75^\circ\text{C}$  broke up in the water, and therefore, their WAP and porosity values could not be determined. In the materials produced in the curing temperatures of  $100\text{--}200^\circ\text{C}$ , WAP and porosity values were in the range of  $24\text{--}29\%$  and  $31\text{--}35$ , respectively. Due to the sand contents of the WFS, our expectation was to measure a lower value for WAP. As the NaOH binder ratio decreased, porosity increased due to gas emission during curing and UW values decreased (Table 3 and Figures 3 and 4).

In terms of the physical and mechanical values, similar results were obtained for the geopolymer building materials produced by using  $\text{Na}_2\text{SiO}_3$  or NaOH binder and the WFS. The materials with  $\text{Na}_2\text{SiO}_3$  binder were produced by using two types of bome (38 and 48), and no noticeable difference was found between these two types. However, as opposed to the case in the NaOH-binded samples, better results were reached in the physical and mechanical properties for the  $\text{Na}_2\text{SiO}_3$ -binded samples at a 30% ratio. The geopolymer building material that was produced with  $\text{Na}_2\text{SiO}_3$  (in 30% ratio) binder at a curing temperature of  $200^\circ\text{C}$  reached the values of 9.1 and 12.3 MPa at 7 and 28 days, respectively, and got closer to the literature values of geopolymer building materials produced with FA. The maximum UW ( $1.80 \text{ g/cm}^3$ ) value was obtained in the sample produced at a curing temperature of  $75^\circ\text{C}$  by using 48 bome  $\text{Na}_2\text{SiO}_3$  in the ratio of 20%. As the geopolymer building materials produced by using  $\text{Na}_2\text{SiO}_3$  (as the binder) had a tendency to breakup in water,

and their WAP and porosity values could not be determined (Table 4 and Figures 5 and 6).

In this study, at 28th day, the CS values of the geopolymer materials produced with 48 bome  $\text{Na}_2\text{SiO}_3$  (in the ratios of 20% and 30%) at the curing temperature of  $150^\circ\text{C}$  were found as 2.6 and 4.2 MPa, respectively. Additionally, the 38 and 48 bome  $\text{Na}_2\text{SiO}_3$  samples that were produced with 20% and 30%  $\text{Na}_2\text{SiO}_3$  addition at  $200^\circ\text{C}$  curing temperature reached the CS values of 2.75, 4.3, 4.25, and 12.3 MPa, respectively, at 28th day. These samples are suitable for using in walls as building materials.

Geopolymer building material production is technology where cement as binder is not used and production is achieved using chemical binders. In cost calculations, the price of chemical substances is dependent on date and the firm that supplies them. In case of industrial geopolymer production, it is possible to obtain these chemicals in bulk within a price range of 0.70–1 Turkish Lira (₺)/kg. Additionally, the cost will also fall (by around 75%) when the chemical is used in a diluted (1/3) form. Therefore, as research and development (R&D) advances, there will be a possibility to industrially produce geopolymer building materials with a much lower cost (approximately 1/4) than cemented building materials.

It is expected that better results may be obtained in terms of CS, WAP and porosity values if geopolymer building materials are produced by different rates of NaOH and  $\text{Na}_2\text{SiO}_3$  addition in combination. Advancement of research and development (R&D) practices may result in more efficient production processes. Additionally, potential future studies on the WFS, which are in the class of hazardous wastes, should investigate the options of vitrification and solidification.

This study that sheds light on the problem of industrial WFS is the first record in the literature in terms of geopolymer building material production by using this waste (WFS) as the raw material. It is believed that, with the help of this study, important steps will be taken in terms of usability of the WFS in geopolymer building material production not only in Turkey but also in the world, increasing the effectiveness of its usage. Building material production by using WFS and its steps constitute an industrial solution for all firms that plan to reuse this waste into an usable/valuable product.

## Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

## Acknowledgments

This study was supported by the Turkish Scientific and Technical Research Council (TUBITAK), project Grant no. 1139B411602109, and by ÇİMSA Cement Inc. Co. Niğde Factory. The author acknowledges Associate Professor Dr. Ahmet Bilgil for scientific contribution; Dr. Adnan Güven for technical supports; Mustafa Keşçi for supplying WFS; Erdem Bilginol, Şeyma Acar, and Funda Yolcu for

some experimental parts of this study; Civil Engineering Department of Niğde Ömer Halisdemir University for laboratory facilities; editor and referees for valuable comments; and Veysel Yahşi for improving the text.

## References

- [1] H. M. Başar and N. D. Aksoy, "Recovery applications of waste foundry sand," *Journal of Engineering and Natural Sciences*, vol. 30, pp. 205–224, 2012.
- [2] Ü. Kepez, *Foundry Sector in Turkey-Iron Casting*, TUBITAK TÜBİTAK Metal Technology Platform Creation Workshop, Kocaeli, Turkey, 2007, in Turkish.
- [3] R. Siddique, G. Kaur, and G. Rajor, "Waste foundry sand and its leachate characteristics," *Resources, Conservation and Recycling*, vol. 54, no. 12, pp. 1027–1036, 2010.
- [4] I. Kaur, *Mechanical Properties of Concrete Incorporating Used Foundry Sand*, MSc thesis, Thapar Institute of Engineering and Technology, Deemed University, Punjab, India, 2006.
- [5] S. Javed and C. W. Lovell, "Use of waste foundry sand in civil engineering," *Transportation Research Board*, vol. 1486, pp. 109–113, 1994.
- [6] H. M. Başar and N. D. Aksoy, "Investigation of usability of waste foundry sand in ready-mixed concrete," *Journal of Engineering and Natural Sciences*, vol. 31, pp. 517–528, 2013.
- [7] E. Schultes, *Life 'Hawaman' Project, LIFE06 TCY/TR/000292*, Management of Hazardous Solid Waste generated from Foundries, 2006, in Turkish.
- [8] G. Yaylalı, "New world, new trends, technologies and Turkish foundry sector," *Metallurgy Journal*, vol. 173, pp. 22–40, 2015, in Turkish.
- [9] P. Solmaz, *Reuse of Waste Foundry Sand as Hydraulic Barriers*, Msc thesis, Graduate School of Natural and Applied Sciences, İstanbul Technical University, İstanbul, Turkey, 2008, in Turkish.
- [10] T. Gönen, O. Onat, S. Cemalgil, B. Yılmaz, and Y. T. Altuncu, "A review on new waste materials for concrete technology," *Electronic Journal of Construction Technologies*, vol. 8, no. 1, pp. 36–43, 2012, in Turkish.
- [11] T. Kaya and C. Karakurt, "Investigation of the engineering properties of implementation concrete paving stones," *Duzce University Journal of Science and Technology*, vol. 2, pp. 469–474, 2016, in Turkish.
- [12] P. B. Kirk, *Field Demonstration of Highway Embankment Constructed using Waste Foundry Sand*, Ph.D. thesis, Purdue University, West Lafayette, IN, USA, 1998.
- [13] D. G. Mast and P. J. Fox, "Performance evaluation of highway embankment constructed using waste foundry sand," *Geotechnical Special Publication*, vol. 79, pp. 66–85, 1998.
- [14] T. Abichou, C. H. Benson, T. B. Edil, and B. W. Freber, "Using waste foundry sand for hydraulic barriers," *ASCE American Society of Civil Engineers, Geotechnical Special Publication*, vol. 79, pp. 86–99, 1998.
- [15] T. Abichou, C. H. Benson, and T. B. Edil, "Foundry green sands as hydraulic barriers: laboratory study," *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, vol. 126, no. 12, pp. 1174–1183, 2000.
- [16] S. Javed, C. W. Lovell, and L. E. Wood, *Waste Foundry Sand in Asphalt Concrete*, Transportation Research Record no. 1437, Transportation Research Board, Washington, DC, USA, 1994.
- [17] R. N. Tarun and S. S. Shiw, "Permeability of flowable slurry materials containing foundry sand and fly ash," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 123, no. 5, pp. 446–452, 1997.
- [18] C. V. Lovell and J. Sayeed, "Use of waste foundry sand in civil engineering," in *Proceedings of Symposium on Engineering Geology and Geotechnical Engineering*, vol. 31, pp. 115–123, Reno, NV, USA, March 1995.
- [19] H. Greinert, "Biological remediation of the iron foundry wastes," *Soil and Environment*, vol. 5, pp. 1227–1228, 1995.
- [20] L. N. Reddi, G. P. Rieck, and A. P. Schwab, "Stabilization of pheolics in foundry sand using cementitious materials," *Journal of Hazardous Materials*, vol. 45, pp. 89–106, 1996.
- [21] R. K. Ham, W. C. Boyle, and F. Blaha, "Leachability of foundry process solid wastes," *ASTM Special Technical Publication*, vol. 933, pp. 28–44, 1986.
- [22] P. Devaux and J. Vecoven, "Les dechets de sables de fonderie en technique routiere," *Bulletin of the International Association of Engineering Geology*, vol. 30, no. 1, pp. 375–378, 1984.
- [23] Institute of British Foundrymen, "Re-usage advantageous of molding sand," *Foundryman*, vol. 89, no. 11, pp. 401–402, 1996.
- [24] M. Yalçın, Y. Güney, H. Koyuncu, and ÖanF. Baş, "Usability of waste foundry sand in concrete," in *Proceedings of the 5th National Concrete Congress*, İstanbul, Turkey, 2003, in Turkish.
- [25] A. Deng and P. J. Tikalsky, "Geotechnical and leaching properties of flowable fill incorporating waste foundry sand," *Waste Management*, vol. 28, no. 11, pp. 2161–2170, 2008.
- [26] R. Siddique and A. Noumowe, "Utilization of spent foundry sand in controlled low-strength materials and concrete," *Resources, Conservation and Recycling*, vol. 53, no. 1–2, pp. 27–35, 2008.
- [27] R. Siddique, G. de Schutter, and A. Noumowe, "Effect of used-foundry sand on the mechanical properties of concrete," *Construction and Building Materials*, vol. 23, no. 2, pp. 976–980, 2009.
- [28] Y. Güney, Y. D. Sari, M. Yalçın, A. Tunçan, and S. Dönmez, "Re-usage of waste foundry sand in high-strength concrete," *Waste Management*, vol. 30, no. 8–9, pp. 1705–1713, 2010.
- [29] R. Siddique, Y. Aggarwal, P. Aggarwal, E.-H. Kadri, and R. Bennacer, "Strength, durability, and micro-structural properties of concrete made with used-foundry sand (UFS)," *Construction and Building Materials*, vol. 25, no. 4, pp. 1916–1925, 2011.
- [30] G. Singh and R. Siddique, "Effect of waste foundry sand (WFS) as partial replacement of sand on the strength, ultrasonic pulse velocity and permeability of concrete," *Construction and Building Materials*, vol. 26, no. 1, pp. 416–422, 2012.
- [31] G. Singh and R. Siddique, "Abrasion resistance and strength properties of concrete containing waste foundry sand (WFS)," *Construction and Building Materials*, vol. 28, no. 1, pp. 421–426, 2012.
- [32] U. Akkaya, *Use of Foundry Sand as a Landfill Cap Layer Material*, Msc thesis, Middle East Technical University, Ankara, Turkey, 2005.
- [33] N. Doğan-Sağlamtimur, A. Bilgil, M. Demir et al., "Reuse study from Niğde, Turkey: the conversion of industrial ash to geopolymer," *Desalination and Water Treatment*, vol. 57, no. 6, pp. 2604–2615, 2016.
- [34] T. O. Yusuf, M. Ismail, J. Usmanx, and A. H. Noruzman, "Impact of blending on strength distribution of ambient cured metakaolin and palm oil fuel ash based geopolymer mortar," *Advances in Civil Engineering*, vol. 2014, Article ID 658067, 8 pages, 2014.
- [35] J. Davidovits, *Geopolymer Chemistry and Applications*, Institut Géopolymère, Saint Quantin, France, 2008.

- [36] P. K. Sarker, R. Haque, and K. V. Ramgolam, "Fracture behaviour of heat cured fly ash based geopolymer concrete," *Materials and Design*, vol. 44, pp. 580–586, 2013.
- [37] N. Ukwattage, P. Ranjith, M. Yellishetty, H. Bui, and T. Xu, "A laboratory-scale study of the aqueous mineral carbonation of coal fly ash for CO<sub>2</sub> sequestration," *Journal of Cleaner Production*, vol. 103, pp. 665–674, 2015.
- [38] R. R. T. Dananjayan, P. Kandasamy, and R. Andimuthu, "Direct mineral carbonation of coal fly ash for CO<sub>2</sub> sequestration," *Journal of Cleaner Production*, vol. 112, pp. 4173–4182, 2016.
- [39] INTES The Turkish Employers' Association of Construction Industries, *Construction Industry Report*, 2014, <http://www.intes.org.tr/content/MArt-2014.pdf>.
- [40] Method 3051A: Microwave Assisted Acid Digestion of Sediments, Sludges, Soils, and Oils, 2015, <https://www.epa.gov/sites/production/files/2015-12/documents/3051a.pdf>.
- [41] Method 200.7: Determination of Metals and Trace Elements in Water and Wastes by Inductively Coupled Plasma-Atomic Emission Spectrometry, 2018, <https://www.epa.gov/homeland-security-research/method-2007-determination-metals-and-trace-elements-water-and-wastes>.
- [42] TS EN 933–10, Tests for Geometrical Properties of Aggregates-Part 10: Assessment of Fines-Grading of Filler Aggregates (Air Jet Sieving), 2018, <https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073088121069048051067102099115100056>.
- [43] TS 699, Natural Building Stones-Methods of Inspection and Laboratory Testing, 2018, <https://intweb.tse.org.tr/standard/standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073097080105101118119097052047104083>.

