Elaboration of a sustainable bottom ash geopolymer material

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Abstract. The use of Ordinary Portland Cement (OPC) has been the primary material used in the construction industry. Its production leads to 5% to 7% of total CO_2 emissions and 14% of the total global energy emissions [1,2]. The pollution caused by OPC production has encouraged researchers to discover new environmental and sustainable materials such as geopolymers [2]. The main objective of this study is to investigate the mechanical properties of metakaolin-based geopolymers made with bottom ash to produce an eco-friendly material while reducing waste generation. The following research determines the mechanical properties of French metakaolin-based geopolymer produced with bottom ash at different mass substitution rates ranging from 0% to 15%. The solid powders were mixed with a sodium-based alkali activator and poured into 4x4 cubical molds. The four different mix designs were cured at ambient temperature and varied according to the different percentages of bottom ash (0%, 5%, 10%, and 15%) inserted. The mechanical properties of the several mixes were assessed by the use of a UTM compression test machine on the respective days of testing: 7, 28, and 90 days. Results demonstrated that the geopolymer mortars produced with bottom ash gave promising mechanical properties regardless of the mass substitution rates inserted in the mixes. This behavior has induced the potential for incorporating such waste in producing a sustainable and eco-friendly cementitious material. In conclusion, the use of bottom ash as a recyclable source material in geopolymer mortar formulation has highlighted the importance of this development as a sustainable solution. The effectiveness of a study where the compressive strength showed high results when compared to OPC is encouraging.

1 Introduction

Ordinary Portland Cement (OPC) production is a leading cause of global pollution and greenhouse gas emanation as it contributes to 5% to 7% of the global CO_2 emissions as a result of raw material and fuel burning [1,2,3]. It is also responsible for 14% of the global energy use as a result of the energy used in limestone calcination and the production process [2]. In addition, it is also noticed that industrial activities cause a huge amount of waste generation on a global scale, and hence, is the reason behind the issues faced when wanting to dispose of such waste with the addition of energy emission they cause [4]. The construction industry has always favored cement as it is used the most among all cementitious materials when it comes to building and construction purposes [5]. This choice is due to OPC concrete's great mechanical, durable, and thermal properties [5]. However, this ruling choice that has encouraged the use of cement has led to the production of cement in bulk, resulting in a huge increase in pollution [5]. For instance, in the year 2020, the cement production volume in China was around 22489 thousand tonnes, and its production was also noticeable in India, and the United States [6]. Cement production kept increasing throughout the years, and is projected to reach 550 million tons by 2050 [4]. Moreover, with the increase in demand for cement, an increase of aggregate occurs, since they are used in cement production [6]. Aggregates used in cement production such as limestone are considered to be the earth's inexhaustible resources, and hence their extraction from the environment and their use for building and economic purposes is hindering the environment [6]. Mining these non-renewable materials and minerals found in nature in limited quantity contributes to biodiversity loss, global warming, climate change, ecosystem destruction, river damage, and dust contamination [6]. The industrial revolution that occurred has also augmented the CO_2 atmospheric concentration by 47% [6]. As for the process of OPC production, it is seen that a huge amount of energy is consumed and that almost 0.8 tonnes of CO_2 is released into the atmosphere for each tonne of cement produced [6]. The latter also causes dust generation into the air during transportation [6]. The CO_2 and dust emissions will negatively affect the human respiratory system due to the small particles of dust that are inhaled, and also affects the quality of air inducing the potential of diseases and health hazards [6]. The harmful impact of cement production has encouraged scientists to discover new cementitious materials that can reduce pollution, lower energy consumption, and encourage the use of recyclable materials [3,5]. Geopolymer, an

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inorganic material, that is heat resistant and made from aluminosilicates is considered to be a good replacement for OPC and the next ruling material in the construction industry, since it is an eco-friendly material that possesses good mechanical and durable properties [7]. This novel material is made by combining solid powders or raw materials made from alumina and silica with alkali solutions that help in the initiation of what is known as the polymerization reaction, and hence are also called alkali activators [7]. Compared to OPC, geopolymers (GP) are surely eco-friendlier as they are produced using wastes and industry byproducts [8]. The use of such waste in geopolymer production reduces 97% of the CO_2 emissions caused by OPC production and a 43% to 59% energy consumption reduction is noticeable, proving that geopolymers are a better alternative [9]. Some studies show that there is an 80% reduction in greenhouse gas emissions when manufacturing geopolymers instead of OPC [10]. Another factor that solidifies the possibility of geopolymer concrete replacing OPC concrete, is their ability to withstand loads, acid attacks, and high temperatures. After a study conducted by Saxena et al. (2022) on geopolymers made with fine granite waste powder, the geopolymer specimens admit great mechanical properties [11]. Their mechanical strength was between 21.5 MPa and 27.3 MPa [11]. Another study done by Rahmadina et al. (2017), shows the difference between the compressive strength of OPC concrete and geopolymer concrete when subjected to high temperatures [12]. The geopolymer samples withstood high temperatures up to 400 °C and also showed higher compressive strength than the ones which weren't exposed to high temperatures. As for the OPC specimens, their compressive strength was negatively affected by the high temperatures [12]. However, the compressive strength of both geopolymer and OPC samples decreased when exposed to temperatures as high as 800 °C [12]. Regardless of their inability to withstand extremely high temperatures, geopolymers still proved that they were able to be fire resistant, and were at a point positively affected by it [12]. In addition to geopolymer's great mechanical and thermal properties, it can also have great durability properties. According to Singh et al. (2013), metakaolin-based geopolymer withstood greatly the sulfate attack unlike the OPC concrete [13]. The compressive strength of geopolymer samples decreased by 2% to 29% after exposure to sulfate [13]. However, a higher loss in compressive strength was seen in OPC concrete after exposure to sulfate as it lost 9% to 38% of its strength, proving that geopolymer can better endure acid attacks [13]. Although previous studies presented the several aspects and benefits of geopolymer concrete's use and production as a building material, there are still plenty of studies that could be done on how to incorporate recyclable waste into geopolymer production and thus increases the possibilities of finding new solutions in the disposal of wastes. This is why this study is going to focus on the elaboration of a sustainable material by testing the mechanical properties of French metakaolin-based geopolymers made with bottom ash (BA), a coarse and granular incombustible material that is obtained from coal combustion, and comparing it to OPC. Another study conducted by Saba et al. (2021), assessed the chemical and mechanical properties of geopolymer concrete with cigarette filter mass substitutions [14]. The results indicate that with the increase of cigarette filter mass substitution from 0% to 20%, a decrease in compressive strength was observed [14]. Regardless of the decrease in compressive strength, it was noticed that all samples still gained compressive strength with aging and that is due to the continuous geopolymerization reaction that is happening [14].

2 Methodology

2.1 Mix Proportions

The mix designs of choice for this study were prepared using source materials such as cement, French metakaolin, and bottom ash. The cement used in this study is shipped from France to Lebanon [15]. The metakaolin used is an industrial one that is in powder form having a fineness that passes sieve No.200 and is of the color white. Likewise, the bottom ash is also very fine and was obtained from France which underwent a treatment process in which iron and aluminum were obtained from it [15]. After the separation process, 400 g of bottom ash was mixed with 600 ml of NaOH solution in a 2 Liters beaker and then agitated for 5 days, three times a day to make sure that the hydrogen gas is eliminated [15]. Lastly, it was washed with distilled water and dried at 110 °C for 48 hours [15]. As for the aggregate of choice, the normalized sand was used due to its well-graded properties where the size of the particles ranges between 0.08 mm and 2 mm. The alkali activator is the sodium base sodium-based solution where a sodium silicate solution was mixed with sodium hydroxide pellets, which were bought from Sigma-Aldrich, having the SiO_2/Na_2O ratio equal to 1.8. As for the mix design proportions, four different batches of metakaolin-based geopolymers were prepared, each having different mass substitutions of 0%, 5%, 10%, and 15% of bottom ash. Those batches were also compared to cement-based samples with identical bottom ash mass substitution rates. The dimensions of the molds for the mix designs in this study were 4x4 cm.

2.2 Preparation of the mixes

To create our samples, it is necessary to carefully follow the right steps. For the OPC specimens, the quantities of the materials required were weighed, followed by the oiling of the adequate molds, and the addition of water and cement into the mix [14]. After 30 seconds of mixing at a low speed, the sand was added and mixed with the other materials without changing the speed of mixing [15]. After the molds are scrapped for 15 seconds and are rested for 1 minute and 15 seconds, an additional mixing for 1 minute is done at high speed [15]. The mix was carefully poured in two phases, each consisting of half the quantity, into their molds and was vibrated for at least a minute [15]. The molds were later then placed in plastic bags and sprinkled with water, and then were let aside to rest for 2 days before demolding them and continuously curing them until the days of testing [15]. As for the geopolymer samples, their molds were oiled adequately and not in an excessive way. The industrial French metakaolin and bottom ash were prepared beforehand while making sure they weren't exposed to air. Similarly, the alkali solution was prepared 24 hours ahead of the mixing to avoid as much as possible the formation of an exothermic reaction. The needed quantity of solid powders and aggregates was weighed and carefully mixed at low speed until a homogeneous-like state is observed. After mixing the materials for 2 minutes, the alkali solution was poured into a beaker, before its gradual addition into the mix. Manually mix with a spatula the remainder of the mixture that is on the sides and bottom by stopping the mixer, which helped ensure that the materials are well mixed all together. The latter was poured into their respective molds, followed by their vibrating for 60 seconds with the use of a vibrating table, to eliminate all possible air bubbles formed in the process of mixing. After resting the molds for at least 24 hours, demold them and place them in room-temperature chambers until the days of testing.

2.3 Compression Testing

This study's main focus is to determine and compare the mechanical properties of the OPC and geopolymer samples prepared. Based on that, the samples will undergo compressive strength tests by using a UTCM-3744 machine as seen in Figure 1, where the rate used by the machine was 2.4 KN/s. The compressive tests were conducted on days 2, 28, and 90 for the OPC samples and on days 7, 28, and 90 for the geopolymer samples, after their production date.

Fig. 1. UTCM-3744 used for compressive strength testing.

3 Results & Discussion

3.1 Comparative Study Between the OPC and GP Samples

The mechanical strength of a material is a great indicator of whether the material is durable and whether it could be used in construction and building purposes. After the preparation of our samples, the compressive strength tests were conducted using the UTCM-3744 machine as seen in Figure 2, at 2 days and 7 days after production for the OPC and geopolymer samples, respectively indicating high early strength results for the samples.

Fig. 2. Compressive Strength test conducted on a sample.

The OPC samples with 0% BA mass substitution presented a compressive strength of 28.7 MPa at 2 days, while the geopolymer samples with 0% BA mass substitution presented a higher compressive strength of 47.04 MPa, showing better performance at early stages. Moreover, the OPC samples with 5%, 10%, and 15% BA mass substitution gave compressive strength results of 22.77 MPa, 21.59 MPa, and 21.56 MPa, respectively [15]. However, these results are still lower than the values of the GP samples with 5%, 10%, and 15% BA mass substitution, having their compressive strength results of 45.62 MPa, 40.40 MPa, and 35.46 MPa, respectively. On the other hand, different results were seen on day 28. For the OPC samples, it is realized that the compressive strength of the samples with 0% BA mass substitution was 52.97 MPa, higher than the compressive strength that the GP with 0% BA mass substitution shows, with 49.31 MPa. As for the samples with 5% BA mass substitution at day 28, the GP samples had a greater compressive strength of 57.88 MPa compared to the OPC sample which gave 47.06 MPa compressive strength. This signifies that the addition of BA helped the sample gain strength over time. Such a phenomenon can be explained due to the geopolymerization reaction that is happening faster than when no BA was present. The latter is the reason behind such an increase in strength and polymerization because of the small amount of mass substitution that contributes to a smaller amount of hydrogen gas release and a smaller porosity in the samples, which are the reasons that greatly affect the geopolymerization. The same behavior was also noticed in the samples with 10% mass substitution but with lower compressive strength of 43.06 MPa and 47.23 MPa for the OPC and GP samples, respectively as seen in Figure 3 and Figure 4.

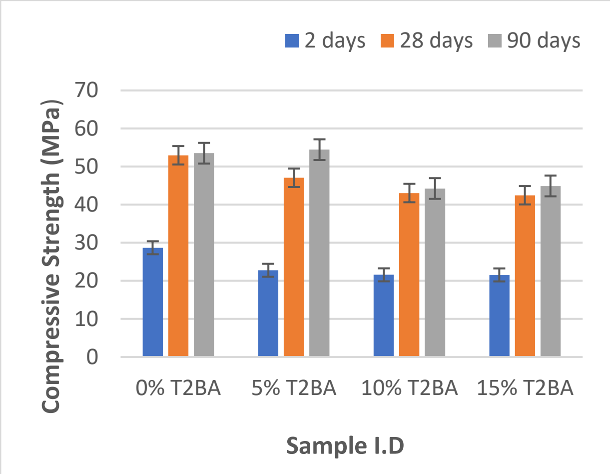

Fig. 3. OPC compressive strength results at 2, 28, and 90 days [15].

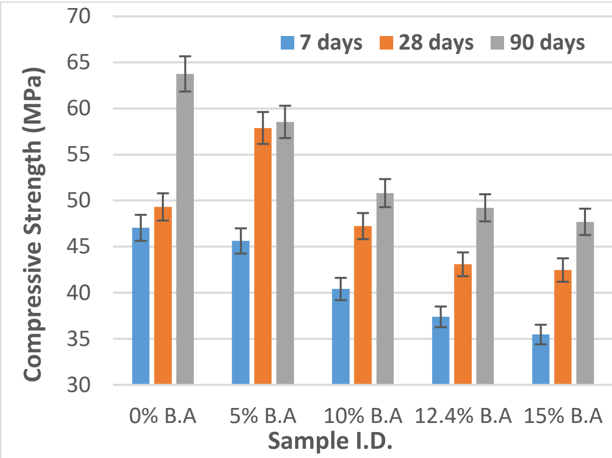

Fig. 4. GP compressive strength results at days 7, 28, and 90.

Such behavior has stopped when looking at the results that the 15% BA mass substitution samples gave. Both the OPC and GP samples experienced a decrease in compressive strength and gave approximately the same results of 42.48 MPa and 42.46 MPa, respectively. Lastly, it is seen that at 90 days all the GP samples gave higher compressive strength results compared to the OPC samples. With 63.75 MPa, 58.54 MPa, 50.81 MPa, and 47.69 MPa for the GP samples, and 53.51 MPa, 54.45 MPa, 44.25 MPa, and 44.92 MPa for the OPC samples with 0%, 5%, 10%, and 15% BA mass substitution, respectively. The higher compressive strength results of the GP samples at day 90 are the result of the polymerization reaction that occurs in the long term and which is the reason behind the sample's increased strength.

3.2 Comparative Analysis of the GP Samples

The result obtained at 28 days for the 0% BA mass substitution sample is considered the reference mix, having 49.31 MPa as the 100% compressive strength was reached. After analyzing the samples' compressive strength on days 7 and 28, it is seen that the compressive strength of the GP samples increased. However, a graduate loss in compressive strength occurred with the addition of BA mass substitution. This loss did not happen at a constant rate. The compressive strength increased by 17.38% in the 5% BA mass substitution sample on day 28. This is an indicator that this sample had faced an increase in early strength. However, when comparing the other samples with 10% and 15% BA mass substitution with the reference mix, a decrease in compressive strength occurs by 4.22% and 13.89%, respectively. Such decrease in compressive strength with the increase of BA mass substitution can be explained because of the dilution that happens to the metakaolin in the geopolymer and also can be explained by the presence of aluminum in the BA that leads to the gas formation that in itself leads to an increase of porosity in the samples. All these factors contribute negatively to the samples' compressive strength. Such an increase in compressive strength results regardless of the decrease that occurs because of the addition of BA gives a general idea of how the geopolymerization reaction can counter the negative effects of the dilution.

When comparing the compressive strength results of the geopolymer samples of this study with metakaolin and bottom ash-based geopolymers from previous studies, it is noticed that they are very consistent. Kumar et al. (2020) investigated the properties of alkali-activated metakaolin and bottom ash geopolymer [16]. The study showed that on day 1, the compressive strength of the metakaolin and bottom ash-based geopolymer was 23.0 MPa and increases to 45.5 MPa on day 3 [16]. As of day 7, the samples demonstrated a compressive strength of 48.6 MPa [16], which is very close when comparing it to the compressive strength of the reference mix, having a compressive strength of 47.04 MPa. This range of values is set and comparable with the results of compressive strength obtained in the 5%, 10%, and 15% bottom ash mass substitution samples with values ranging from 45.62 MPa, 40.40 MPa, and 35.46 MPa respectively. As such a general behavior can be elaborated; metakaolin and bottom ash-based geopolymers state high early compressive strength. Moreover, as of day 28, samples have shown an increase in strength reaching 58.95 [16]. The 0%, 5%, 10%, and 15% bottom ash mass substitution samples at day 90 attained results relatively close to the geopolymer samples in Kumar et al.'s study[16], thus highlighting the importance and consistency in the work done.

4 Conclusion

The production of OPC has caused several environmental issues and damages over the decades. As it is considered the most used material in the construction industry, the need to search for a new alternative cementitious material is of great importance. Geopolymers happen to not only be an environmentally friendly material but also happen to admit great mechanical properties. The strength and durability of the geopolymer put it on a pedestal and make it a possible alternative to OPC concrete as a building material. To determine a material's potential to replace OPC concrete, mechanical property tests shall be conducted. This work aims to elaborate on and compare the compressive strength of geopolymer mortars made with recyclable material and compare it to traditional OPC concrete. According to the test results obtained in this study, the following conclusions can be made:

- The use of 5% BA mass substitution samples can be a great solution when wanting to attain a high early strength.
- The 5% BA mass substitution samples can also be considered as the optimum mix, since high early and an overall great compressive strength was observed while simultaneously using recyclable material.
- Moreover, the use of BA in the mix design encourages its reuse helping in decreasing waste generation and therefore undergoes the waste stream cycle, boosts the circular economy, and maintains environmental sustainability.
- The compressive strength obtained for the GP was overall greater than the ones attained by the OPC samples and hence proves that GP is indeed a strong material that can replace OPC because of its good mechanical properties.
- The use of French metakaolin geopolymer with the integration of bottom ash can help in reducing pollution and lowerCO_2 emissions.

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