Utilization of large amounts of industrial wastes to improve sustainability of the construction sector

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Abstract. The concept of “sustainability” in the construction sector has increasingly led to the manufacturing of thermal comfort products composed of natural or recycled materials. Several such products are readily available in the market while others are still in the early stages of production or under research. The assessment of the sustainability potential of building materials as well as of entire buildings or structures is a significantly complex issue as it involves the quantification of three interacting and interdependent parameters: the environmental impact, the technical performance, and the lifetime. From this it is decidedly apparent that simply protecting the environmental impact (e.g., during the construction process) will not benefit the environment as long as an equivalent technical performance and lifetime cannot be ensured. This situation can be analysed using the definition of the so-called “sustainability potential”. To this end, bottom ash and marble dust were used as a replacement for cement (up to 70%). In this study, technical performance of the laboratory-produced composites was evaluated using mechanical and durability tests. The sustainability potential of the composites was also analysed using the reduction in cost and the reduction in carbon dioxide emissions of the produced composites. The test results showed that the pure cement paste composites are adequate for targeting controlled low strength and non-load-bearing elements in civil engineering works. Durability performance also proved that the composites are moderately resistant to sulphates.

1. Introduction
Understanding the effects of global warming is more important than ever before [1]. A systematic sustainability approach for better construction has continued [2-3], and research on industrial wastes in concrete construction has become popular, providing a sustainable future [4-7]. Various types of industrial waste, such as bottom ash [8-10], fly ash [11-13], marble dust [14-16], and agricultural wastes like rice husk ash and coconut husk ash [17-18], have been satisfactorily used in building construction.

In recent years, climate change and its effect on our planet have led world leaders to take action. In a framework of growing international awareness focused on sustainability, numerous policy makers have recognized the need to decrease the amount of industrial wastes and enhance the utilization rate of those wastes. To date, the commonly accepted strategies have been either adopting a waste management plan on site or increasing taxes for landfills [19-20].

From the government’s perspective, local authorities should engage in a precise evaluation of industrial waste in order to launch appropriate policies and adopt new regulations, guidelines, and practical application for sustainable construction. In addition, the correct level of waste charge, suitable encouragements for construction companies to consider practical methods, and the
development of ideal waste treatment facilities have been considered in recent years for green building applications [21].

The movement towards sustainable strategies has put pressure on the acceptance of appropriate approaches to protect the planet throughout all engineering activities. The majority of pollution currently comes from construction activities and accounts for 70% of the total waste production. Furthermore, approximately 25% of the world’s entire energy is depleted during the production of building materials such as cement and steel. The construction sector consumes raw materials during production, including nearly two billion tons of cement, ten billion tons of sand and gravel, and one billion tons of water. Several efforts to improve concrete sustainability and to alter concrete to a “low impact construction material” have been investigated in recent years [1, 22, 23]. An estimated 25 billion tons of concrete are produced globally every year [1]. In sustainable building strategies, especially in the case of green buildings, structures have been designed in such a way to reduce carbon emissions and optimize resources from the beginning of construction to the end of service life [1, 19]. When considering the social and environmental concerns, green buildings have the highest rank in the construction industry and have become popular in recent years [2, 19].

Evaluations of industrial by-products in pure paste and mortar are increasing. The use of such wastes as a cement replacement in paste, mortar, and/or concrete shows excellent performance. In addition, applications can help with the safe disposal of industrial wastes and the protection of the dumping site or nearby surroundings. Such efforts have a positive impact on social, environmental, and economic sustainability [24]. The European Union Directive No. 2008/98/CE encourages the reuse and recycling of waste materials. It is projected that by 2020 new buildings will be composed of at least 5% of recycled materials. [25].

Bottom ash is composed of granular particles that collect at the “bottom of coal-fueled boilers”; it has to be sieved through smaller fractions and grinded to increase its “pozzolanic activity” [10]. Bottom ash is replaced as either cement or an aggregate (fine aggregate or coarse aggregate) to produce concrete used for manufacturing building blocks and low-strength applications [26].

Singh and Siddique [25] evaluated the workability and strength of concrete containing bottom ash as a fine aggregate replacement. Their experiments revealed that the compressive strength beyond 28 days of hardening the concrete incorporated with bottom ash was identical to that of the samples produced without bottom ash. Siddique et al. [26] cast self-compacting concrete specimens containing fly ash and bottom ash with different water-to-cement ratios and evaluated the strength properties. The study revealed that the ideal percentage for replacing bottom ash with cement was less than 20%.

Maschio et al. [27] evaluated the rheological behaviour of paste and mortar samples containing fly ash and bottom ash. The composite’s rheological properties were improved with bottom ash and fly ash. However, when considering the same samples, a substantial decrease in strength and an increase in the level of replacement beyond 180 days of hardening were observed.

Marble wastes have long been widely used in concrete construction to achieve the sustainability requirements. In Turkey, annual production approaches 7 million tons, accounting for 40% of worldwide production. During manufacturing processes, approximately 25% of the bulk product is transformed into large pieces or dust. Thus, dumping the products has caused serious environmental problems. However, these wastes can be effectively managed in the construction sector to produce various concrete elements, such as sewage pipes, drainage utility units, and paving for walk-ways [22, 28, 29, 30].

Mixture proportioning of self-compacting concrete composed of marble powders was proposed in one study [29]. Gesoğlu et al. [30] prepared a highly workable concrete mixture containing marble powder and fly ash and evaluated the performance of the produced samples in fresh and hardened states. Their study revealed that strength and durability properties were improved with the addition of marble powder. Topçu et al. [31] examined the self-compacting concrete properties to propose the ideal level of marble necessary to ensure a high performance. The study showed that blending no more than 200 kg/m³ of marble wastes promises excellent engineering properties. Ergun [32] studied the
effect of marble wastes on the mechanical characterization of concrete. The results demonstrated that the maximum replacement level was 5% of marble wastes in high strength applications.

Li et al. [5] and Li et al. [6] prepared mortar samples composed of marble wastes and proposed a new technique for mixture proportioning: the paste replacement method. In this technique, they replaced the marble powder with a portion of paste, instead of replacing cement or fine aggregate, and considered the fixed water-to-cementitious ratio. The model developed in these studies offers numerous advantages. The model consists of large waste utilization and necessitates using less cement content in mixture proportioning. In addition, the mortar samples prepared using this technique have a smaller carbon footprint and are superior in strength and durability.

The current study focuses on the performance of pure cement paste composites. To date, few studies have considered the physical, mechanical, and durability properties in one research program. In this research, a high amount of bottom ash and marble powder were used as replacements in cement compositions to manufacture sustainable construction materials.

2. Materials and Methodology

2.1 Materials

In this study, Ordinary Portland cement (Type I) was used. The Blaine fineness and specific gravity of the cement are 302 m²/kg and 3.10, respectively. Bottom ash was obtained from the local brick factory plant. The specific gravity was 1.40. Bottom ash particles were sieved through a 200 micrometre sieve and were then used to prepare the pure paste composites. The marble wastes were collected from a dumping site near Stonite Marble Ltd. Tap water was used in all stages of the study. The chemical composition of the materials used in this study is presented in table 1.

### Table 1. Chemical composition of cement, bottom ash and marble dust.

| Oxides (%) | Cement | Bottom ash | Marble dust |
|------------|--------|------------|-------------|
| SiO₂       | 20.8   | 53.3       | 9.2         |
| Al₂O₃      | 5.7    | 27.2       | 1.1         |
| Fe₂O₃      | 2.3    | 9.6        | 0.6         |
| CaO        | 65.3   | 0.9        | 44.1        |
| MgO        | 0.7    | 0.6        | 5.8         |
| K₂O        | 0.4    | 1.2        | 0.04        |
| SO₃        | 1.2    | 0.4        | 0.07        |
| Loss on ignition | 2.9 | 4.1 | 38.7 |

3.2.2. Methodology

Four mixture groups contained a high volume of bottom ash and marble dust. The bottom ash and marble powder replacement level varied from 70%–100% by mass. Samples were demoulded after 1 day. The composites were immersed in a curing tank containing lime-saturated water at a temperature of 25°C and a relative humidity of 90%. Fresh and hardened tests were used to evaluate the overall performance of the laboratory-produced composites. Flow table, dry unit mass, water absorption, and porosity tests were used to characterize the quality of the cement paste composites. The compressive and flexural strength tests were used to evaluate the mechanical performance. Sulphate tests were used to analyse the behaviour of the samples under aggressive environment. All tests were performed after 7 and 28 days. Sulphate tests were conducted at 28 days. The averages of the eight samples were used for analysis. The study’s mixture groups are presented in table 2, where BA denotes bottom ash, M denotes marble dust, and C denotes cement by % mass. Figure 1 shows the flow table and mini slump test measurement of pure cement paste composites. The water-to-binder ratio was chosen based on the previous laboratory works of the author [1, 4, 10]. Figure 2 shows the flow measurement results for the tested composites.
Table 2. Mixture groups of the study.

| Group      | Bottom Ash (BA) (%) | Marble dust (%) | cement (%) | Water/binder (w/b) |
|------------|---------------------|-----------------|------------|-------------------|
| M100C0     | 0                   | 100             | 0          | 0.42              |
| BA100C0    | 100                 | 0               | 0          | 0.42              |
| M70C30     | 0                   | 70              | 30         | 0.42              |
| BA70C30    | 70                  | 0               | 30         | 0.42              |

3. Results and discussions

Figure 2 demonstrates that pure bottom ash decreased the flow values more than pure marble composites. This can be attributed to the coarser character of the bottom ash particles. For the same flow values, bottom ash particles need more water than marble particles. Comparable results were obtained in previous researches [1, 4, 18, 20, 33]. Interparticle friction loss and cohesion of the mixture by the addition of marble wastes contribute to better dispersion in the matrix, thereby improving the workability of the mix.

Figure 2. Flow values for marble-bottom ash cement paste composites.
Figure 3 shows the dry unit mass (DUM) for the tested composites. The DUM values for all mixture groups were in the range of the lightweight material category. Incorporating marble wastes and bottom ash into DUM had the same effect for all ages. Due to the ongoing hydration process, water was used by cementitious material and DUM values tended to decrease after 7 days.

![Dry Unit Mass](image)

**Figure 3.** Dry unit mass values for marble-bottom ash cement paste composites.

DUM values for pure marble wastes are higher than pure bottom ash mixture groups. This can be due to the available water amount in pure marble composites as also recorded in flow table values. Since more water was available in pure marble composites, more gel formation is expected (i.e. amount of calcium silicate hydrates more in M100C0 mix groups).

Figure 4 shows the water absorption values for laboratory produced composites. All water absorption values are higher than the specified international standard limit (WA<16%) for manufacturing of building materials [34, 35]. Pure bottom ash mixture groups due to the coarser nature of the bottom ash particles had higher water absorption values compared to marble wastes. A decrease in water absorption values were observed for both bottom ash and marble waste groups. When the amount of cement increased in the mixture water absorption values tends to decrease.
Figure 4. Water absorption values for marble-bottom ash cement paste composites.

Figure 5 shows the apparent specific gravity (ASG) results of the tested composites. ASG values of the marble wastes are higher than those of the bottom ash mixture groups. Due to ongoing hydration, ASG values have a tendency to decrease, which can be attributed to the pore-refinement of the matrix. The densely packed arrangement of particles and the reduction of the overall pore of the system causes ASG values to decrease. Interestingly, the bottom ash replacement was more efficient with cement than the marble replacement. Figure 6 shows the porosity values of the tested composites.

Figure 5. Apparent specific gravity values for marble-bottom ash cement paste composites.
As expected, the porosity values of the bottom ash groups were higher than the marble waste groups. Bottom ash particles are coarser than marble wastes and, thus, produce a more porous structure. A decrease in porosity was recorded based on the lower replacement level. The increase in the amount of cement also led to the formation of more gel products, which can reduce the porosity of the composites.

Figure 7 shows the unconfined compressive strength (UCS) results of the composites. As expected, the pure bottom ash and pure marble waste groups had lower UCS values. Cement showed a greater contribution in the bottom ash groups, which could be due to the amount of SiO₂, which is higher in bottom ash. In addition, the total amount of Al₂O₃+Fe₂O₃+SiO₂ in bottom ash is 90.1%, which helps
generate more gel formation and higher strength. When compared with the porosity values, which are higher in the bottom ash group, the strength was expected to be lower in the bottom ash groups. However, as previously mentioned, the chemical reaction—not the filler effect or closer packing of the particles—governed the overall behaviour. The M70C30 mixture groups attained 25 MPa compressive strength at 28 days. This value was approximately 30 MPa for the BA70C30 mixture groups at the same testing age. Figure 8 illustrates the flexural strength (FS) of the tested composites. The same trend as in the UCS was observed here. However, when comparing the UCS values of the M70C30 and BA70C30 mix groups and the FS values, the increase in FS in B70C30 is higher. The experimental results showed that the behaviour of composites composed of bottom ash are more sensitive to bending. A significant reduction in flexural strength was recorded in the bottom ash mix groups, and the contribution of cement in bottom ash was more pronounced based on the test results shown in Figure 8.

![Figure 8. Flexural strength for marble-bottom ash cement paste composites.](image)

Figure 9 shows the mass loss from the sulphate solution. Mass loss was greater in the bottom ash groups. However, as the amount of cement increased in the system, this reduction almost diminished and values quite similar to those at 28 days were measured in the bottom ash mixture groups. These results are compatible with the porosity values. The mass loss values were higher in the pure bottom ash and pure marble waste groups, but remained in the range of the building materials specified by the standards. The mass loss values were less than 16% for all mixture groups, indicating that the composites have moderate resistance to sulphate attack.
The results showed that the bottom ash and marble wastes can be satisfactorily utilized at higher rates (i.e., up to 70%). The flexural strength of marble wastes proved that these composites are weak in tension. The bottom ash mixture groups showed better improvement when the replacement level did not exceed 70%. The chemical stability was more pronounced in the bottom ash mixture groups. The results demonstrated the superior characteristics of both the bottom ash and marble waste mixture groups. Thus, it is believed that the utilization of a large amount of these wastes in the concrete sector could reduce carbon dioxide emissions. The amount of the reduction would be based on the replacement level. In a previously published study [1], the author reported that “replacing cement with 10% marble powder would reduce CO$_2$ by 2.62 million tons for Turkey and 3.55 billion tons worldwide”. Furthermore, when considering the cost of C20 concrete in Turkey (approximately US$35) and the reduction in cost for the 30% replacement level (i.e., around 35%), the reduction in cost also depends on the replacement level. Thus, it would be more economical and environmentally feasible to utilize large amounts of industrial wastes to become more sustainable. Such wastes could also be an alternative binder for the concrete industry.

4. Conclusions and recommendations

Based on the test results, the following conclusions can be drawn:

1. Bottom ash decreased the flow values more than marble wastes due to its granular nature.
2. The composites were classified as lightweight according to their dry unit mass values. The highest and lowest dry unit mass values were measured as 15.82 kN/m$^3$ and 12.32 kN/m$^3$, respectively.
3. Water absorption values were higher than the specified limits for the manufacturing building materials.
4. Marble wastes had higher apparent specific gravity values than bottom ash groups.
5. Bottom ash composites had higher porosity values than marble waste groups.
6. Unconfined compressive strength values proved that up to 70% of bottom ash and marble waste can be satisfactorily used to produce a strength of 25 MPa at 28 days.
7. The flexural strength of the BA70C30 mixture groups showed better performance than the M70C30 mixture groups.
8. The mass loss values for both bottom ash and marble wastes showed that the composites are classified as having moderate resistance to sulphate attack.

9. The behaviour of bottom ash cement paste composites under bending should be investigated in detail to understand the overall mechanisms encountered for reductions in strength values.

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