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Use of various industrial and eggshell wastes for the sustainable construction sector

Çeşitli endüstriyel ve yumurta kabuk atıklarının sürdürülebilir inşaat sektörü için kullanılması

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Use of Various Industrial and Eggshell Wastes for the Sustainable Construction Sector

Highlights

- *Eggshells can effectively be used as a cement replacement*
- *Marble powder and bottom ash can make positive contributions to engineering properties*
- *Ecological new building materials with triple binders are possible for future use*
- *Bottom ash can and eggshell can be utilized up to 20% and 0.75%, respectively, for the best performance*
- *Superior seawater resistance could be achieved with a combination of marble powder and eggshells*

Graphical Abstract

In this study the industrial wastes such as bottom ash and marble powder were blended wih eggshells to manufacture cement paste composites.

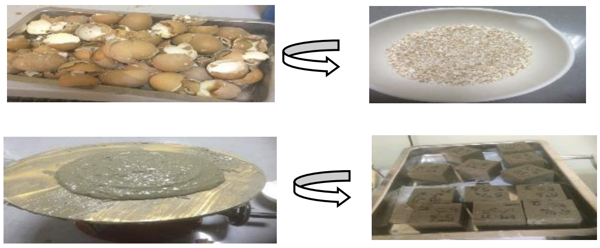

Figure 1. Production steps of eggshell cement paste composites

Aim

The aim of the study is to evaluate the performance of the final composites composed of bottom ash, marble powder, and eggshell in cement paste.

Design & Methodology

Two different sets of composites were prepared during this study. The composites containing cement (80%), BA (20%), and MP (20%) waste by weight with 0.3%, 0.75%, 1.5%, and 2.5% eggshell waste.

Originality

So far, no work in the literature uses BA and MP together with the eggshell combination in cement paste. This work can help to improve sustainability strategies in the construction sector.

Findings

The test results showed that 0.75% eggshell by weight of cement in bottom ash and marble powder mixture groups can be used as an optimum value for better performance. The highest compressive strength value was found at 56.03 MPa in the marble powder group and 52.79 MPa in the BA mixture groups at 56-days.

Conclusion

The eggshells have a promising alternative binder for concrete in the near future.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Use of Various Industrial and Eggshell Wastes for the Sustainable Construction Sector

Araştırma Makalesi / Research Article

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ABSTRACT

The alternative composites' production alleviates the serious problem generated by global warming. Methods to reduce the amount of cement used in concrete production, for example, are being investigated to determine how to reduce carbon dioxide emissions in many applications. Egg shells and various industrial wastes, which are recommended to use in the construction sector at an appropriately high rate, also cause serious environmental damage. Bottom ash (BA) and marble powder (MP) wastes are used today in civil engineering applications. In addition, it is important to increase the use of eggshells due to their rich calcium carbonate content. In this work, BA and MP wastes were blended with eggshells to produce cement paste composites. Two different sets of composites were prepared during this study. The composites were prepared with cement (80%), BA (20%), and MP (20%) wastes by weight with 0.3%, 0.75%, 1.5%, and 2.5% eggshell waste. The fresh (flow table), physical (dry unit mass, apparent specific gravity, and porosity), mechanical (unconfined compressive strength and flexural strength), and durability (water absorption, seawater resistance) tests were conducted. According to the experimental results, the composites can be classified as lightweight construction materials. The test results showed that 0.75% eggshell by weight of cement in bottom ash and marble powder can be used as an optimum value for better performance. The bottom ash mixtures groups are higher water absorption and porosity values when referring to the marble powder mixture groups. The highest compressive strength value was found at 56.03 MPa in the MP mixture group and 52.79 MPa in the BA mixture groups with these optimum eggshell combinations at 56 days. The MP mixture group showed better resistance to seawater when referring to the bottom ash blended mixtures. Laboratory-produced composites are possible candidates for cost-effective and environmentally friendly building materials. The eggshells have a promising alternative binder for concrete in the near future and they are utilized together with industrial wastes such as BA and MP in sustainable concrete construction.

Keywords: Eggshell, bottom ash, marble powder, waste, sustainability, environment.

Çeşitli Endüstriyel ve Yumurta Kabuk Atıklarının Sürdürülebilir İnşaat Sektörü için Kullanılması

ÖZ

Alternatif kompozitlerin üretimi, küresel ısınmanın yarattığı ciddi sorunu hafifletmektedir. Örneğin, beton üretiminde kullanılan çimento miktarını azaltma yöntemleri, birçok uygulamada karbondioksit emisyonlarının nasıl azaltılacağını belirlemek için araştırılmaktadır. Uygun bir oranda inşaat sektöründe kullanılması tavsiye edilen yumurta kabukları ve çeşitli endüstriyel atıklar da ciddi çevresel tahribatlara neden olmaktadır. Mermer tozu ve taban külü atıkları günümüzde inşaat mühendisliği uygulamalarında kullanılmaktadır. Ayrıca, zengin kalsiyum karbonat içeriği nedeniyle yumurta kabuğu kullanımının arttırılması önemlidir. Bu çalışmada, taban külü ve mermer tozu atıkları, yumurta kabukları ile harmanlanarak çimento hamuru kompozitleri üretilmiştir. Bu çalışma sırasında iki farklı kompozit seti hazırlanmıştır. Kompozitler, ağırlıkça %80 çimento ve %20 mermer tozu ile %20 taban külü olacak şekilde çimento ağırlığının %0.3, %0.75, %1.5 ve %2.5 'ı kadarı yumurta kabuğu karıştırılarak hazırlanmıştır. Çalışma kapsamında taze (akma tablası), fiziksel (kuru birim ağırlık, görünür özgül ağırlık, gözeneklilik), mekanik (basınç ve eğilme dayanımı) ve dayanıklılık (su emme ve deniz suyuna karşı direnç) deneyleri yapılmıştır. Deneysel sonuçlara göre kompozitler hafif yapı malzemeleri olarak sınıflandırılabilir. Test sonuçları, taban külü ve mermer tozu içindeki çimento ağırlığının % 0,75'i kadar yumurta kabuğunun daha iyi performans için optimum bir değer olarak kullanılabileceğini göstermiştir. Taban külü gruplarının mermer tozu gruplarına göre daha yüksek su emme ve gözeneklilik değerine sahip olduğu görülmüştür. Ellialtı günlük test sonuçlarına göre en yüksek basınç dayanımı mermer tozu gruplarında 56.0 3 MPa ve taban külü gruplarında ise 52.79 MPa olarak elde edilmiştir. Mermer tozu gruplarının deniz suyuna karşı direnci taban külü gruplarına göre daha yüksektir. Laboratuvarda üretilen kompozitler, uygun maliyetli ve çevre dostu yapı malzemeleri için bir alternatiftir. Yumurta kabukları yakın gelecekte beton için ümit vaat eden alternatif bir bağlayıcı olup, sürdürülebilir beton yapımında taban külü ve mermer tozu gibi endüstriyel atıklarla birlikte değerlendirilmektedir.

Anahtar Kelimeler: Yumurta kabuğu, taban külü, mermer tozu, atık, sürdürülebilirlik, çevre.

1. INTRODUCTION

Mankind has struggled with extreme temperatures, floods, and wildfires, which have reached serious levels due to global warming. The construction industry is at the center of criticism, as it is the leading actor in climate change and causes about 8% of carbon emissions worldwide [1]. Cement production also causes carbon emissions worldwide. In fact, the main problem is that

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the clinker is obtained at approximately 1400–1450 ^{0}C [2]. Testing of alternative raw materials required for cement production has led the literature to use the term "sustainability," which is a form of evaluation in which carbon emission, cost, and energy consumption parameters are included. Sustainability came to the fore via the United Nations with the Brundtland Report in 1989 [3-7].

For a sustainable construction sector, institutes and governments typically allocate resources for alternative building materials in their budgets. However, these studies, which have been carried out since the beginning of the 1990s, have not reached the desired point. With the increase in world population, the demand to settle human beings naturally increases. Parallel to this, the amount of waste increases and causes it to threaten our world. Some countries increase the taxes paid to landfills; some are supported by the state when waste is used in production to make waste use more attractive [8].

Today, as the world population reaches approximately 7.5 billion, production has decreased compared with previous years due to COVID-19. Although this has had a positive effect on carbon emissions, a significant increase is expected in all areas, especially in the construction sector, after the normalization process. In 2019, approximately 82 million tons of eggs were produced worldwide. The largest production is in China with 40%, followed by the United States, India, and Indonesia with 8%, 7%, and 5.8%, respectively. Turkey is in ninth place with a rate of 1.5% [9-11].

In 2019, 19.9 billion chicken eggs (approx. 1,2 million tons) were produced in Turkey. Chicken egg production in the 2020 January–November period was 1.1 million tons (approx. 18 billion chicken eggs), which is 0.6% higher when we compare the same periods of the previous year. Annual egg consumption in Turkey is approximately 300 eggs per person. Considering worldwide consumption, eggshell waste needs to be evaluated [12].

As with other waste collection methods, eggshells can be collected from houses, workplaces, bakeries, and hotels by raising public awareness. Local governments can create a separate waste collection unit in this regard; further, in order to increase contributions, workplaces, and locals can be offered benefits via annual tax reductions [13].

The use of industrial waste in cement production has long been studied. Fly ash, bottom ash, and marble powder are widely used waste in this area. It is used in concrete production, building material production, and highway applications. In addition, since it contains high amounts of lime, eggshells are used by mixing them with cement-based materials at a certain fineness [14-17].

Engineering properties of cementitious composites are mainly affected by numerous factors for example; the water-to-binder ratio (w/b), mineral, chemical composition, and microstructure. The cement-stabilized clays are primarily affected by the interaction of soil grains, which is controlled by the porosity of the samples [18].

The BA is composed of well-graded particles. They are more porous, lighter, and brittle compared with river sand. The specific gravity is low and helps in the manufacturing of lightweight materials. Siliceous byproducts generally alter the behavior of cement-based materials. The incorporation of supplementary cementitious products can enhance the fresh mixture's cohesiveness [19]. Flow and slump values of BA blends are more sensitive to the w/b ratio variations due to their grain size distribution. Kleib et al. investigated the properties of composites containing BA as a substitution in clinker manufacturing, finding that approximately 20% of cement clinker can be replaced with bottom ash [8]. Yang et al. produced concrete containing BA, as a fine aggregate replacement, to investigate the composites' drying shrinkage performance, concluding that BA significantly affects shrinkage strains; further, the study also notes that aggregate has an impact on volume fraction. The authors also proposed a design equation for shrinkage [20]. Muthusamy et al. investigated the strength and durability of concrete composed of palm oil shells and bottom ash as a sand replacement, finding that 10% bottom ash as a sand replacement was appropriate for higher acid resistance and best mechanical performance [21]. Zhang et al. used coarse BA as aggregate and eco-cement as a binder for green concrete, reporting that concrete containing 50% BA satisfied the current standard strength requirement [19]. Kim et al. evaluated the use of BA as an aggregate replacement for the concreting work to produce eco-friendly material. The authors used the design codes ACI-369R, CEB-FIB, and ACI318, which predicted strength and comparisons with the experimental findings, which revealed a high degree of accuracy in their experimental results [22]. Siddique et al. studied the performance of mortar composed of slag, BA, and fly ash, reporting that 50% BA as a sand replacement and 10% fly ash as an activator improves the mechanical performance of the composites [17]. Taherlou et al. studied the possibility of utilizing various amounts of BA in self-compacting concrete applications. In their study, tap water and treated wastewater were used, revealing that water absorption and permeability values were reduced with the higher BA replacement rates [23]. Singh and Siddique studied the properties of samples containing BA as a fine aggregate replacement in fresh and hardened states, concluding that the BA concrete strength is comparable with that of reference concrete beyond 90 days [24].

During marble cutting and polishing operations, waste marble powder accumulates near the production site and causes a huge impact on the environment and human health. The highest production of marble corresponds to China, Turkey, Brazil, Italy, and India [25]. Turkey has the capacity to hold the majority of production, which stands for 40% of the annual global production [7]. The use of MP waste, either as a cement replacement or as a fine aggregate replacement in powder form, helps sustainability strategies of the construction sector and also protects the environment to a large extent [26]. Vardhan et al. studied the microstructural characterization, permeability, and strength properties of concrete containing marble aggregates. The 40% marble aggregates showed the highest splitting tensile strength [27]. Vardhan et al. also showed that 10% marble power can be replaced by cement without any property change referring to the reference group. The authors also stated that an above 10% replacement level will have an adverse result on the microstructure of the concrete which becomes more porous [28]. The UCS and shrinkage results of composites composed of MP as a sand replacement were studied. Researchers concluded that a 40% replacement level showed promising results. The marble aggregates decreased the drying shrinkage values at 270 days [27].

Kumar et al. evaluated the effect of utilizing eggshell, fly ash (FA), and steel fibers on the durability (i.e. pore structure, water absorption) properties of concrete. The authors concluded that triple binders have positive effects on physical properties; in addition, 35% FA and 6% eggshell composed of 0.75% steel fiber showed the maximum performance for the concrete [18]. Binici et al. evaluated the performance of industrial eggshells for radiation protection of buildings. In their study, mortar composed of standard RILEM sand and eggshell was used. The authors reported that the performance of mortar in a sulfate environment decreased at 90 days. However, they also concluded that eggshells can be used as an effective radiation barrier in various regions where radiation risk is evident [29]. Other research investigated the hardness and toughness properties of composites prepared with eggshells using an artificial neural network, and genetic algorithm. The authors concluded that the composites' toughness and hardness properties can be easily determined using an artificial neural network method with high accuracy [30]. Prasath et al. prepared concrete containing sawdust ash, eggshell powder, and rice husk ash. The authors stated that using eggshell powder enhances the concrete properties when compared with the control mixtures [10]. Taylor et al. evaluated the fracture performance of commercially available hens' eggs, finding that the value of fracture toughness, K_c, 0.3 MPa$\sqrt{m}$, was lower than that reported in the previously published literature. The authors also stated that fracture toughness is important in understanding the exact mechanism of the mechanical performance of the composites [31]. The gypsum composite binder was prepared with a mineral admixture and eggshell powder. The results showed that eggshell and zeolite improved engineering properties and that eggshells have the filling ability to also improve the thermal and water stability of gypsum plaster composites [32]. Nath et al. used the treated eggshell to extract the calcium oxide to produce cement antibacterial composites. The produced mortar composites showed good performance when eggshells were sintered at 900°C. The authors stated that the amount of calcium oxide in egsell improves the effects on composites' behavior [13]. The recent work also proved that eggshells can be used as radiation shielding. The authors observed that composites composed of eggshells absorbed approximately 76% radiation at 59.9 keV [33]. Saldanha et al. investigated the environmental impact of commercially available limes and eggshell limes using life-cycle assessments for soil stabilization, concluding that eggshell limes have good physical and mineralogical characteristics and can be satisfactorily used for soil stabilization [34]. Another study by Hasan et al. showed that eggshell ash improved the undrained shear strength of kaolin clay; further, 6% eggshell ash was found as an optimum replacement for expansive soil [35].

Bottom ash and marble powder waste have created serious environmental problems, with higher amounts required in civil engineering applications. So far, no work in the literature uses BA and MP together with the eggshell combination in cement paste. This work can help to improve sustainability strategies in construction works.

2. MATERIAL and METHOD

2.1. Materials

Ordinary Portland cement grade 42.5 was used. The G_s and fineness of cement are 3.12 and 3845 g/cm^3, respectively. The BA was collected from the Levent brick factory (located in Nicosia). The bottom ash has a porous surface texture, angular in shape, and 90% passing a 4.75 mm sieve. The G_s was 2.13; The MP was collected from the Levent Stonite marble factory. The MP was collected in a powder form, which was dumped near the plant size during sawing and polishing of marble blocks. 90% of the used marble particles passing a 1.18 mm sieve. The G_s of MP was 2.43. Eggshells were collected from the local bakery in Nicosia. To remove the moisture the eggshells were dried (approx. 60°C in an oven). The eggshells were sieved through a 0.212 mm sieve; their G_s are 2.34. The oxide composition of the materials used is presented in Table 1.

Tap water was used throughout the experimental work.

2.2. Laboratory Work and Mixture Proportioning

The two sets of mixtures composed of bottom ash, cement, eggshell, and marble powder were mixed in dry form. The proportions of the mixes were chosen according to the author's previous works [4, 7, 14, 15]. The w/b was kept constant for all mixes and adjusted to 42%. The notations M, C, B, and E in Figures denote marble powder, cement, bottom ash, and eggshells, respectively. The number shows the percentage of masses in mixtures. Table 2 shows the mixture groups of the prepared mixtures and Fig. 2 shows the selected composites prepared during this study.

The Hobart-type mixture having a 2.5L volume was used for the preparation of laboratory samples. The eggshell was dried in the oven for one and a half days at 60°C. Then, the eggshells were crushed, sieved, and added to a Hobart machine.

Table 1. Oxide Compositions of Cement, Bottom ash, Marble powder, and Eggshell

Oxides	Cement	закладка BA	закладка MP	Eggshell
SiO_2 (%)	26.88	55.05	8.30	0.88
Al_2O_3 (%)	4.82	27.82	0.42	0.14
Fe_2O_3 (%)	3.88	7.48	0.31	0.26
CaO (%)	59.75	5.54	47.9	53.6
MgO (%)	0.43	0.31	0.70	0.23
SO_3 (%)	1.45	0.28	0.10	0.55
LOI (%)	2.79	3.52	42.27	44.34

Table 2. Mixture Groups

Mixture Set	BA %	MP %	Cement %	Eggshell %
1	20	0	80	0, 0.3, 0.75, 1.5, 2.5
2	0	20	80	0, 0.3, 0.75, 1.5, 2.5

Figure 2. Selected laboratory produced samples

Fresh composites were then vibrated to eliminate air bubbles. The water–binder ratio was 42% throughout the investigation. The 50 mm cubic molds and 40x40x160 mm molds were used. The molds were opened after one day and then immersed in water; the relative humidity of all testing is 85%±5%. Specimens were stored there until testing days. The consistency of the fresh mixtures was measured according to ASTM C230M-14 [36] and WK27311 [37] by flow table and mini slump test. The apparent specific gravity (ASG), water absorption (WA), and dry unit mass (DUM) were conducted in accordance with ASTM C127-15 [38] and RILEM [39]. The vacuum saturation testing apparatus was used for porosity tests. The values were calculated by the method proposed by Othuman and Wang [40]. Compression and flexural strength were tested by the compression/flexural testing device according to ASTM C109M-13e1 [41] and ASTM C348-14 [42] standards, respectively. The same methodology adopted for the sulfate test was used in the determination of seawater resistance. The composites were immersed in seawater for one week. After each week the composites' mass was measured and then dried in an oven at 105 ^{0}C. The samples were removed from the oven after one day and then the dry weight of each sample was recorded. Weight loss after each cycle was recorded until the first visible crack appeared on the samples. The test was stopped when the weights after the drying cycle become constant. Samples were directly immersed in pure seawater to check actual field conditions. Physical and mechanical tests were performed at 7, 28, and 56 days. Seawater tests were performed at 28, and 56 days. Six samples for physical and mechanical tests for each curing age were prepared; three samples were used for seawater tests for each curing period.

3. RESULTS AND DISCUSSION

The flow table test of the selected mixture group is shown in Fig. 3 and the test results are shown in Fig. 4.

Figure 3. Flow table of the selected mixture

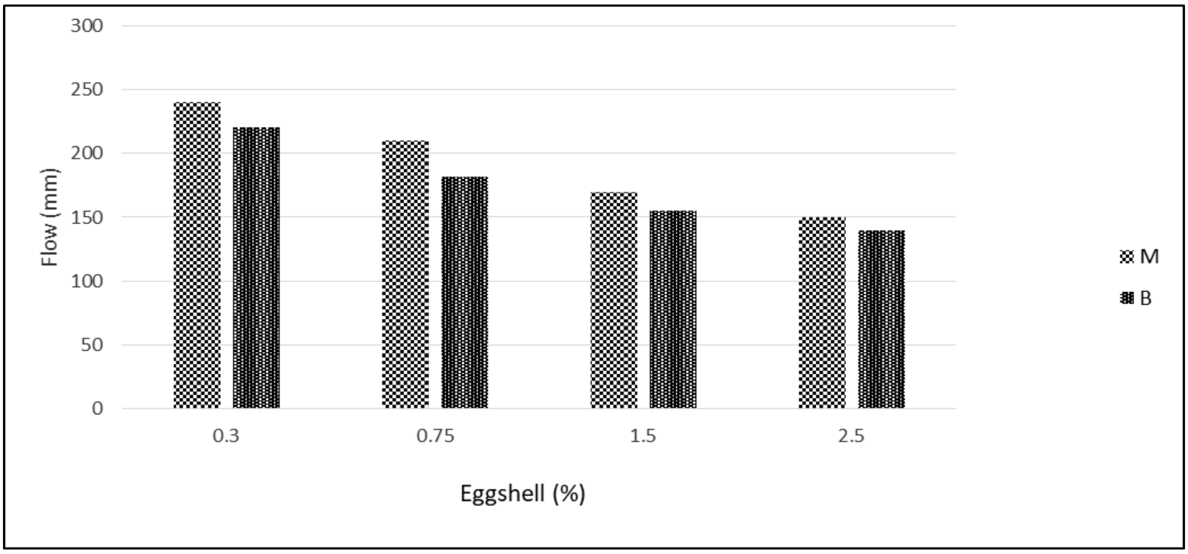

Figure 4. Flow Table results for the marble powder-bottom ash eggshell composites

The addition of eggshell decreases workability referring to the reference mixture (i.e. without eggshell). The irregular shape and rough surface of BA particles caused an increase in interparticle friction and this lowers the consistency of the mixture. Research reveals that water adsorbed the BA particles during mixing and captured them at pores. There is less water for the fluidity of the mixture, which might be another reason for the decrease in consistency. The use of MP decreases the cohesiveness of the blends. This can be due to the "irregular shape" of the marble particles, which increases the particles' surface area that needs to be wetted. Additionally, the increase in marble powder in the mix results in better workability (i.e. improved cohesiveness). The increase in cohesiveness and more water demand for wetness for the particles dedecreaseshe the workability of the mix. Similar findings can be found in [43-45].

The ASG values of the produced samples are shown in Fig. 5.

The decrease in ASG with curing age is due to the hydration process of cementitious products. The addition of eggshells caused increments in ASG values. The addition of MP and BA ash also had a decreasing effect on ASG values. It appears that continuous hydration products fill the pores and decrease the porosity values at later ages. Thus, an improved microstructure [46-47] showed better matrix properties and enhanced the ASG.

Dry unit mass (DUM) test results are shown in Fig. 6

There are no significant effects on DUM when considering the bottom ash, marble powder, and eggshell. However, the same eggshell amount increased in marble and bottom ash with the same amount causing an increase in DUM values. The DUM values were reduced with the increase in eggshell level.

This is attributed to the lower G_s of eggshells compared with cement. The contradictory results were reported in previous research. There is an increasing trend in some eggshell replacement levels, i.e., the dry density tends to decrease beyond the optimum value.

The porosity values of the tested samples are shown in Fig. 7. The porosity values tend to be decreased with an increase in the amount of eggshell. However, the porosity values were increased above 0.75% eggshell amount. This shows that there is an optimum level for the reduction and beyond this point, the matrix properties are adversely affected. The marble powder with eggshell mixture groups has lower porosity than the bottom ash mixture groups. Fig. 8 shows water absorption (WA) values of tested composites.

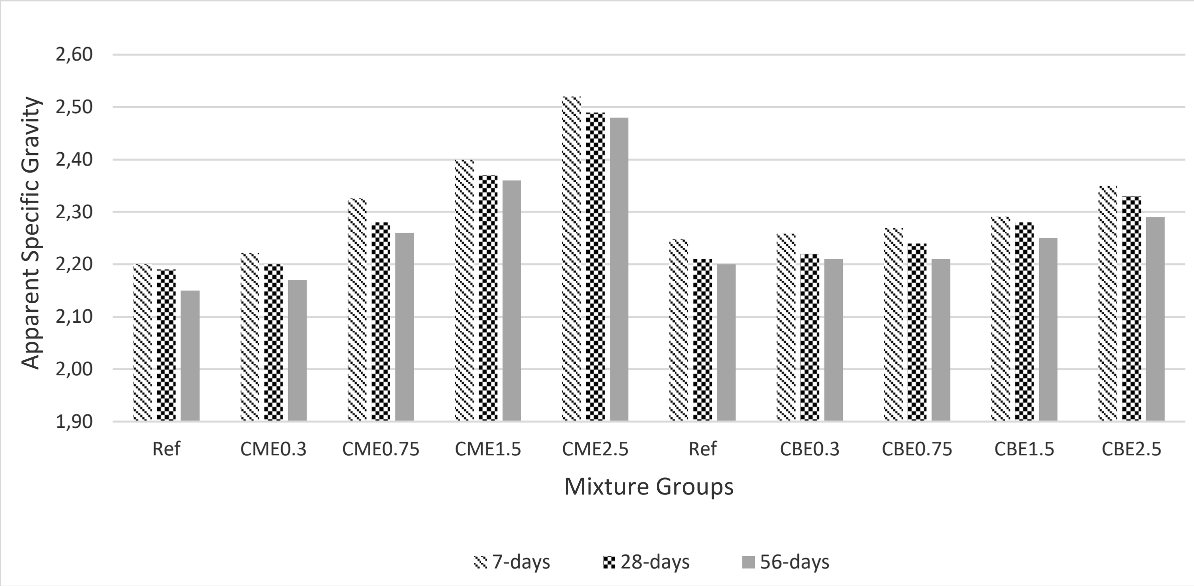

Figure 5. Apparent Specific Gravity of the tested composites

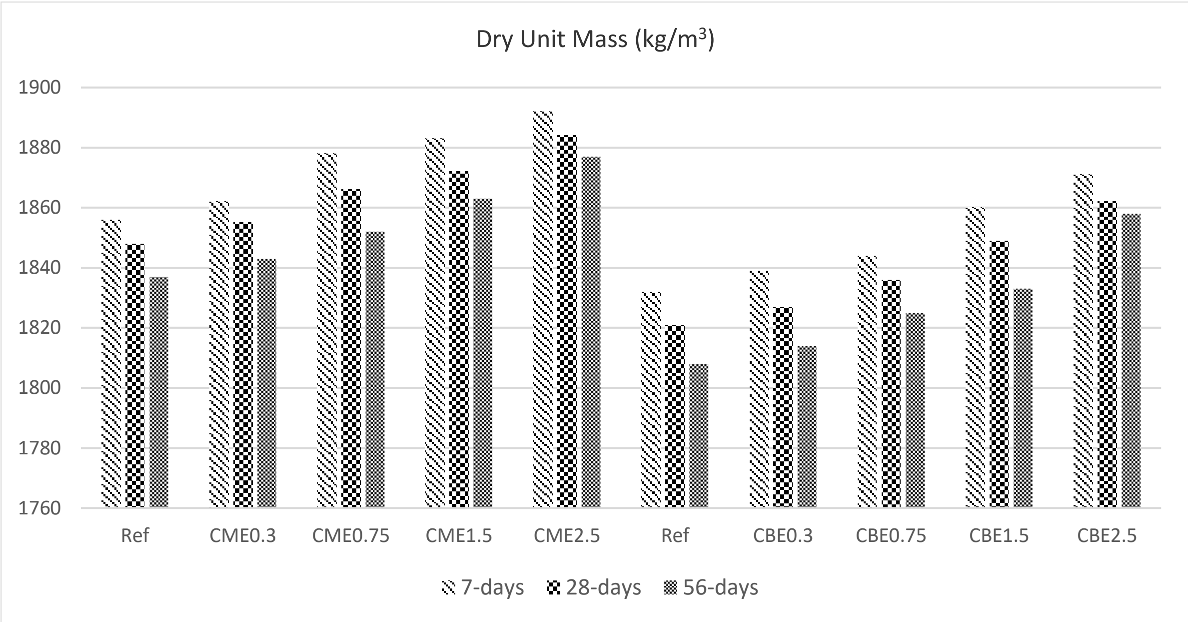

Figure 6. Dry unit mass of the tested composites

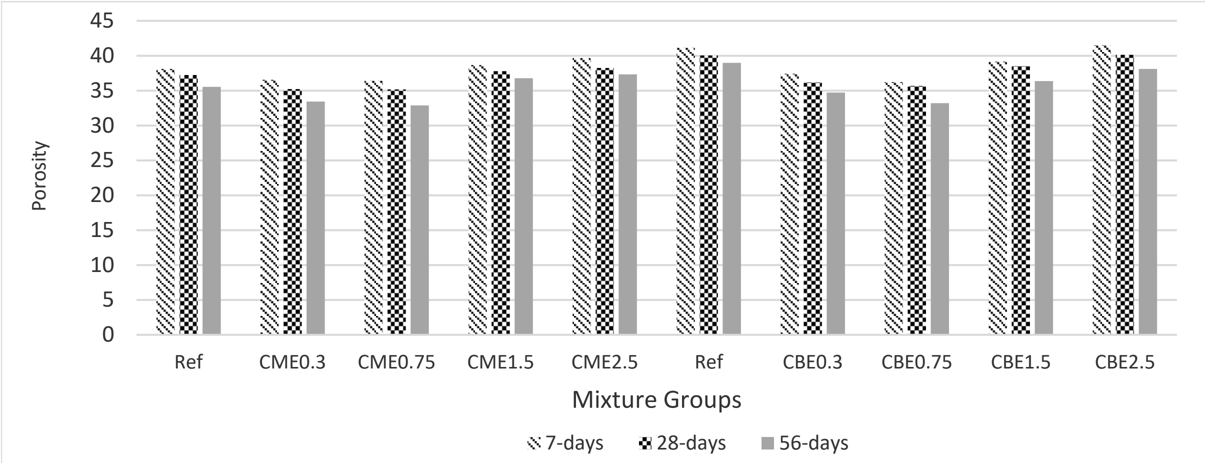

Figure 7. The porosity results of the laboratory-prepared composites

The WA values for both MP blended groups and BA blended groups were increased beyond 0.75% eggshell amount. The increase in WA values in the BA mixture groups is more when compared with the MP mixture groups. The BA particles are porous in nature and have higher WA values. However, the marble powder alone decreases WA values. In addition, those trends become insignificant after longer curing periods (i.e., 28 and 56 days). The WA values have decreasing rate when compared with the curing period from seven to 56 days. The decrease in WA value at later ages leads to the "pore refinement" of the composites. The development of the hydration products decreases the pores and thus decreases WA values as reported in [48-50]. The increase in the eggshell replacement levels caused a reduction in WA values due to lesser porosity values. Additionally, previous research demonstrated that more uniform distribution of pores with better calcium silicate hydrate gel formation compared with the samples without eggshells. Research proved that the amount of eggshell helps more gel formation, which fills the pores; thus, a lower rate of water absorption was reported in mixes that contain more eggshells. This can also be attributed to the increment in the density and more compact structure formed for the samples that contained more eggshells. The compatible test results are found in the literature [46, 51, 52].

The UCS values of the composites are shown in Fig. 9.

The marble powder mixture groups have higher UCS than the bottom ash mixture groups. However, eggshell addition has positive effects on the strength when compared to both mixture groups: The eggshell beyond 0.75% shows a reduction in UCS values. The pozzolanic reaction effects improve the microstructure of the composites, which can be reported at later ages, as reported in earlier studies [28, 46, 47].

Additionally, the BA has higher WA and porosity had caused additional water demand. The increase in water amount results in higher porosity, which lowers the composite strength. In order to coat all BA particles, more water is needed. Additionally, the increase in bottom ash and eggshell reduced UCS values at 7-days; this trend seems insignificant beyond 56 days. This can be attributed to the heavy metals available in bottom ash. The eggshell availability increases the calcium carbonate amount in the mixture, which has an acceleration effect on hydration, which causes increments in UCS at early ages.

Additionally, research revealed that calcium oxide in eggshell is a more uniform morphology; further, its pozzolanic activity improves mechanical bonding [53]. Also, an increase in the density with the amount of eggshells created a more compact structure and improved strength up to an optimum value. Solidification of the pores reduces porosity values at later ages when eggshell was used with BA and MP. The pozzolanic reaction with the BA and MP with the eggshell could be a positive contribution to strength, which might also be the reason for such increments beyond 56 days. Furthermore, BA particles act as a water reservoir due to their porous nature; the stored water can be used for later ages to contribute to hydration and better formation of bonds and gels [9, 11, 18]. However, increments beyond the optimum replacement rates can cause a reduction in UCS values due to increments in porosity, which cause stress accumulation in the lateral direction during compression tests. The initiation of cracks in those areas can cause sudden failure of the composites.

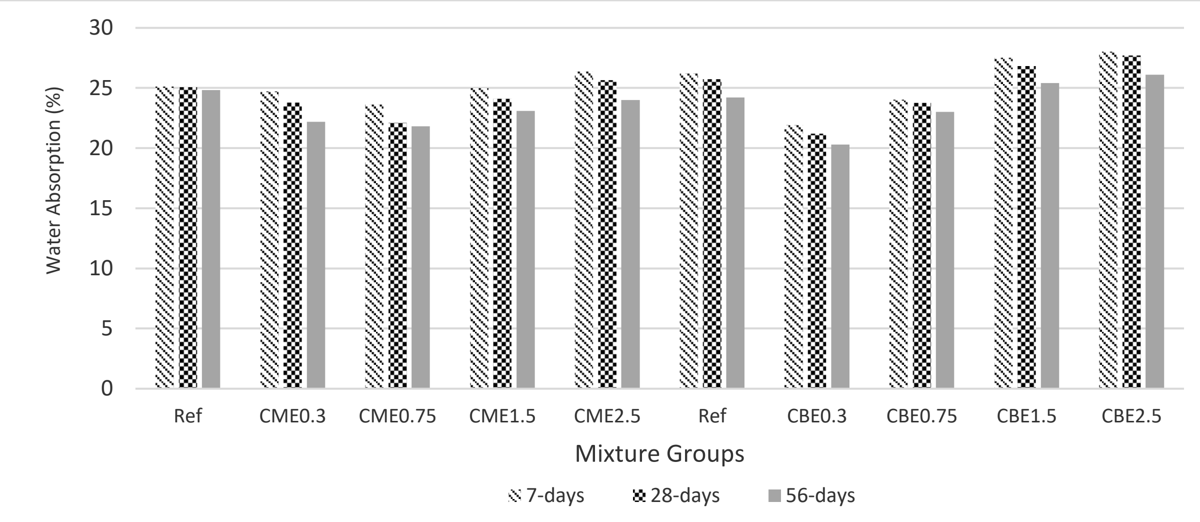

Figure 8. Water absorption values of the tested composites

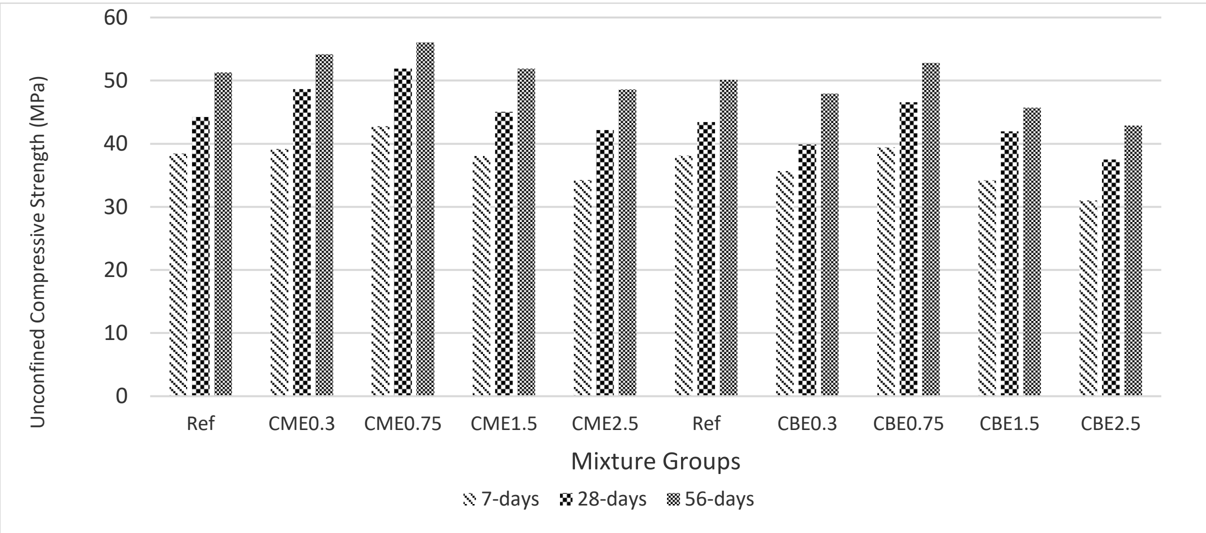

Figure 9. Compressive Strength test results of composites

Fig. 10 shows the flexural strength (FS) test results. Since the strength of eggshell is low compared with that of cement, it is expected to decrease in strength. Additionally, the adherence of the binding material decreases as the eggshell amount increases. A lower amount of cement in the mixtures causes a slight decrease in UCS. This is due to the higher amount of $Ca(OH)_2$ and lower amount of silica availability for the reaction to produce calcium silicate hydrate. The availability of a higher $CaCO_3$ amount causes a reduction compared with the control sample at later ages. The same behavior, as can be seen in UCS, is also valid for FS values. However, the effects of ingredients on FS are more noticeable. The eggshell addition increased FS values, and the decrease was reported with the addition of BA and MP. Bottom ash causes more reduction in FS when compared with marble powder. This might be due to the higher WA and porous structure of BA. Also, the availability of weaker and porous BA particles availability increases in the matrix, which causes a decrease in FS values. The result of BA and MP was reported higher beyond later ages (i.e. above 28 days). This is believed to be the amount of SiO_2, which is higher in BA, which is responsible for the promotion of pozzolanic reactions. Additionally, the eggshell provides additional lime into the mixtures, which improves porosity. However, the rate of increase was lowered at later curing ages. The formation of extra calcium silicate hydrates gels and improves in pore system responsible for this trend. Higher loss on ignition values of BA particles indicates the porous character of the BA and the high amount of unburned carbon residues. The pores fill with water and act as a reservoir for further hydration processes beyond 28 days.

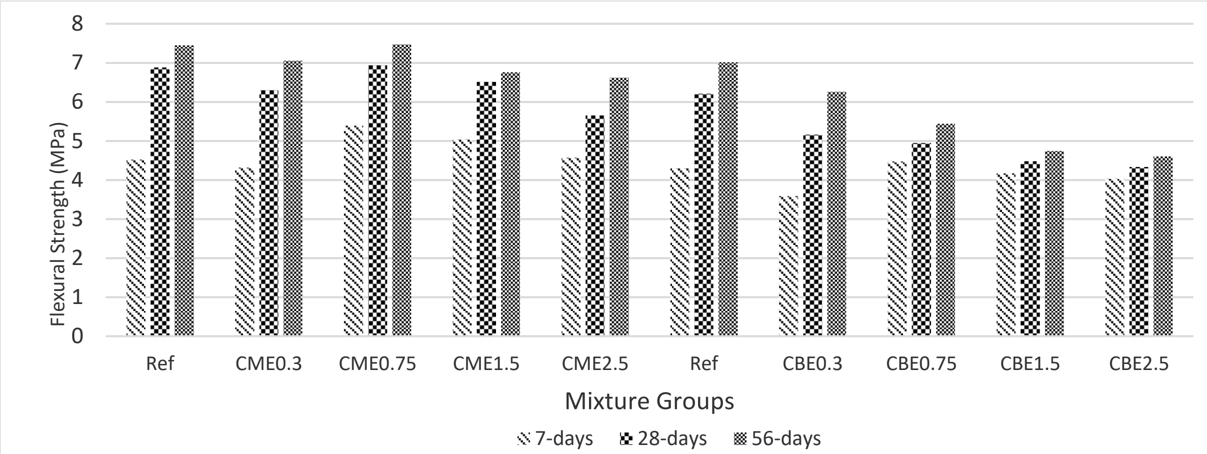

Figure 10. Flexural Strength test results

Additionally, the reaction with bottom ash and calcium hydroxide creates extra calcium silicate hydrates gels. This reaction is slower at early curing periods and then increases. Thus, the FS increment rate tends to be higher at later ages. However, studies showed that higher loss in ignition value causes strength reduction due to the weak bond formation and segregation, which cause a porous network. Fig. 11 shows seawater resistance of the laboratory prepared composites. There is no significant difference in seawater resistance. Accumulation of salt can cause internal stress development. The increase in WA value leads to a higher decrease in the mass of the composites that are immersed in seawater. The combination of BA, marble powder, and eggshell shows excellent resistance to seawater. If the porosity is low, the salt crystals do not provide enough internal stress to cause the failure of the composites. The availability of BA or MP can cause a deficiency in particle packing, and the composites become more vulnerable to seawater attack. Furthermore, weakening of the bonds at higher replacement levels can cause an increase in porosity values. The higher the porosity, the lower the resistance. The eggshell addition caused a reduction in seawater resistance, which might be due to the lower strength of eggshells and the weakening of the bonds between the bottom ash-marble powder-cement interfaces. As the quantity of the eggshell increases, so does the amount of $Ca(OH)_2$ in the mixture increases. Therefore, the reduction in mass was expected to be higher. The cement should be fixed to 80% for minimum weight loss against seawater. This can be attributed to the improvement of the pore system due to the pozzolanic reaction of BA and the refinement effect of MP that causes densification [9, 47, 54, 55]; further, the more compact structure at the end improves resistance against seawater. One study reported that the calcite in marble and tri-calcium aluminate in cement form more a compact structure and lower the pores. Lesser interaction from outside makes the composite more resistant to aggressive seawater. The improvement against seawater resistance may be due to the highest cement amount and optimum amount of MP and BA. Beyond the maximum limit, the bonds become weaker and, due to an increase in water demand, can result in internal stress, which can reach limits which the composites cannot tolerate.

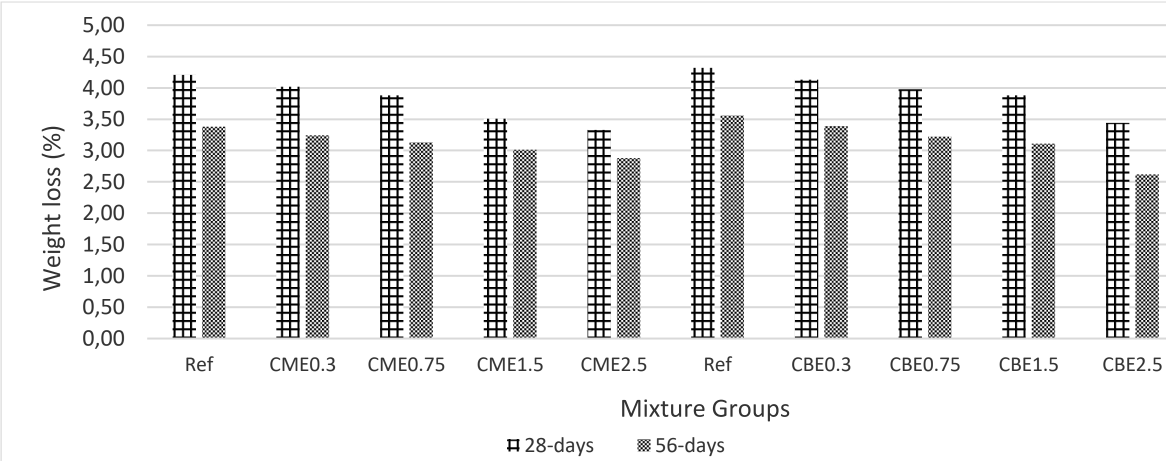

Figure 11. Sea water resistance of laboratory prepared composites

4. CONCLUSION

Due to increase in population and human needs for shelter, huge amounts of waste affect our environment, health, and social lives. Eggshells, bottom ash, and marble powder are examples of this waste. The world has made many attempts to combat global warming, which includes most countries and research institutions utilizing various industrial and poultry waste in different civil engineering applications. However, the current situation has not yet been alleviated to the desired level. There is limited research considering those three binders in cement paste in one mixture. The author believes that the results of this study will help future work to utilize eggshell, bottom ash, and marble powder together in the same mixture to replace cement and help sustainability strategies all around the world. Notably, eggshells are found in abundance. Based on the experimental results, the following key outcomes are presented here.

Bottom ash and marble powder should be 20% and eggshell should be 0.75% for better engineering performance. The cement amount significantly affects the performance of the composites. The eggshell addition improves the pores of the pastes and improved the unconfined compressive strength and flexural strength. The addition of bottom ash and marble powder decreases the strength and adversely affects the physical properties, especially during early curing periods. This trend was insignificant in later ages. However, marble powder works better with eggshell when compared with bottom ash. The addition of eggshells is effective against seawater resistance. The composites can be classified as lightweight and satisfactorily used in civil engineering works.

It is recommended to investigate microstructures for a better understanding of composite behavior. Also, the addition of fibers would be beneficial for cement-based composites to improve mechanical properties.

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DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Ertug AYDIN: Performed the experiments and analyze the results. Wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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