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Re-Use of Waste Marble in Producing Green Concrete

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***Abstract*—**In this study, literature related to the replacement of cement with waste marble and the use of waste marble as an aggregate in concrete production was examined. Workability of the concrete decreased when marble powder was used as a substitute for fine aggregate. Marble powder contributed to the compressive strength of concrete because of the $CaCO_3$ and SiO_2 present in the chemical structure of the marble. Additionally, the use of marble pieces in place of coarse aggregate revealed that this contributed to the workability and mechanical properties of the concrete. When natural standard sand was replaced with marble dust at a ratio of 15% and 75%, the compressive strength and splitting tensile strength of the concrete increased by 20%-26% and 10%-15%, respectively. However, coarse marble aggregates exhibited the best performance at a 100% replacement ratio. Additionally, there was a greater improvement in the mechanical properties of concrete when waste marble was used in a coarse aggregate form when compared to that of when marble was used in a dust form. If the cement was replaced with marble powder in proportions of 20% or more, then adverse effects were observed on the compressive strength and workability of the concrete. This study indicated that marble dust at a cement-replacement ratio of 5%-10% affected the mechanical properties of concrete by decreasing the global annual CO_2 emissions by 12% and also lowering the costs from US$40/m^3 to US$33/m^3.

***Keywords*—**Cement production, concrete, CO_2 emission, marble, mechanical properties.

I. INTRODUCTION

CONCRETE is ranked as the most widely used construction material worldwide [1]. Cement provides necessary adherence in concrete production [2]. However, the production of cement requires more resources in terms of both money and energy when compared to that required by other components of concrete [3]. Excessive costs are incurred when cement is required in large amounts [4]. Furthermore, the production of cement contributes to CO_2 emissions and environmental pollution [5]. For example, the production of 1 t of cement requires 1.5 t of raw materials, 0.3 t of air, and 6 GJ of fuel. As a result of the production process, 0.94 t of CO_2 is released into the atmosphere. Data reports indicate that 69.7 million tons of cement was produced in 2014 in Turkey, resulting in the release of 65.52 million tons of CO_2 into the atmosphere. [6]

It is possible to reduce the amount of cement produced by replacing a proportion of the cement with waste materials.

This could potentially improve the specifications of both fresh and hardened concrete, and reduce the number of industrial processes involved in concrete production, thereby improving cost and time effectiveness and reducing environmental pollution [7]. Thus, replacing the cement used in concrete production with industrial and agricultural wastes can make the production process of concrete more economical and reduce its environmental impact [8]. This in turn, given the high demand for cement throughout the world, can provide economic and environmental benefits on a global scale [9].

Mining byproducts were extensively targeted for concrete production. These byproducts include marble dust, which is emitted when marble is cut in marble mines [10]. Turkey has nearly 3.872 x 106 m^3 of marble reserves [5], of which, almost 125 x 103 t/year from marble reserves are generated in Afyon City alone. There are over 250 types of marble in Turkey, each with different colors and characteristics [11]. Other countries with significant marble reserves include the United States, Belgium, France, Spain, Sweden, Italy, and Egypt [12].

Large amounts of wastes are generated during the production of marble. Marble waste is an industrial byproduct of marble production and is formed in two sizes, namely coarse marble waste and dust waste [14]. Coarse aggregates include both scraps of improperly cut marble, as well as larger marble pieces that are discarded as production surplus [15]. The latter exists as colloids of 150 mm-diameter particles with a maximum size of 2 mm [16]. These two types of wastes collectively comprise up to 60% of the marble production [17].

These waste products cause environmental pollution [18] as they are generally non-biodegradable and persist for a long term in natural environments [19]. Thus, the disposal of these marble wastes presents a serious environmental issue [20], and using the waste generated during marble production is of utmost importance [12]. Gencel *et al.* found that using marble dust in a proportion of 40% reduced the cost of paving block production from US$34/m^3 to US$30/m^3 [21]. Additionally, according to Alyamaç and Ince, Turkey owns 40% of the world's marble reserves [12]. Thus, using waste marble in concrete production could be an important step towards the sustainable development of marble production [21], as using these byproducts assists the environment and contributes to the national economy by realizing an environmentally friendly concrete production process [22].

II. STUDIES EVALUATED IN THIS REVIEW

A. The Substitution of Cement with Marble Dust in Concrete

Shirule et al. [23] substituted cement with marble dust and investigated the impact of the substitution on the mechanical properties of concrete. The measurements conducted on the 28th day indicated an increase in the compressive strength and the tensile strength of concrete by 17% and 11.5%, respectively, when cement was replaced with marble dust at a cement replacement ratio of 10% [23].

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Uysal and Sumer [24] studied the effects of various mineral supplements including marble dust on the performance of self-compacting concrete. In the study, the marble dust supplements were incorporated at cement-replacement ratios of 10%, 20%, and 30%. In the compression tests conducted on the 7th, 28th, 90th, and 400th days of the study, the sample with 10% cement-replacement ratio exhibited the best performance relative to the reference sample. For example, measurements performed on the 400th day indicated that the samples substituted with 10%, 20%, and 30% marble dust had compressive strengths of 97.6 MPa, 96.8 MPa, and 93.4 MPa, respectively. In contrast, the compressive strength of the reference sample was 100 MPa. Additionally, the loss of compressive strength relative to the reference sample was 13% in 10% magnesium sulfate solution, and 12.3%, 20%, and 8.5% in samples with 10%, 12%, and 20% cement-replacement ratios, respectively [24].

Uysal and Yılmaz [25] analyzed the effects of different mineral supplements on the performance of self-compacting concrete. They obtained results similar to that of Uysal and Sumer [24]. In the study, cement was replaced with 10%, 20%, and 30% marble dust. The compressive strength measured on the 90th day was 82 MPa in the reference sample, and 84 MPa, 81 MPa, and 80 MPa in samples substituted with 10%, 20%, and 30% marble dust, respectively. They also conducted a cost analysis relative to the compressive strengths measured on the 28th day and obtained US\$0.58/MPa/m^3 cost of compressive strength for the reference sample, and 0.52 US\$/MPa/m^3, 0.48 US\$/MPa/m^3, and 0.47 US\$/MPa/m^3 costs of compressive strength for the samples substituted with 10%, 20%, and 30% marble dust, respectively [24], [25].

Rana et al. [26] studied the sustainable use of marble slurry in concrete production and replaced cement with 5%, 10%, 15%, 20%, and 25% marble slurry. The compressive strengths of the reference sample measured on the 7th, 28th and 90th days of the study were 36 MPa, 43 MPa, and 51 MPa, respectively. In contrast, the compressive strengths of the sample with 5% marble slurry measured on the 7th, 28th and 90th days were 50 MPa, 42.5 MPa, and 35.5 MPa, respectively. Thus, an increase in substitution ratio of the marble slurry resulted in a decrease in the compressive strength across all three test days. The flexural strengths measured on the 7th, 28th and 90th days were 5.4 MPa, 6.5, and 6.8 MPa, respectively, in the reference sample. In contrast, the compressive strengths measured on the 7th, 28th and 90th days in the sample substituted with 5% marble slurry were approximately 5.3 MPa, 6.4 MPa, and 6.5 MPa, respectively [26].

The mechanical properties of concrete were analyzed by Rodrigues et al. [27] after substituting cement with 5 %, 10 %, and 20% marble dust. They also produced a series with no chemical supplements, a super plasticizer supplement, and a hyperplasticizer supplement for purposes of comparison. An investigation of the mechanical properties revealed that the ultrasonic pulse velocity was least sensitive to the substitution ratio, and that a maximum alteration was observed in the abrasion resistance (a decrease of 4.4%) at a substitution ratio of 20%. Hence, the authors argued that the marble dust substitution compensated for the reduced compressive strength. In the study, a marble substitution ratio of up to 10% revealed no reduction in compressive strength. However, the strength decreased by 25% at a substitution ratio of 20%. The measurements of the compressive strengths on the 7th, 28th, and 56th days in each series indicated that compressive strength was a decreasing function of the marble dust substitution ratio. The largest recorded reduction in the compressive strength was 33.9%. In conjunction with the decreases in the compressive strength, a reduction in the 28th day splitting tensile strength was also observed in the study, and it was maximized at 30.9%. It should be noted that these values were approximated from the data presented in the study [27].

Aliabdo et al. [13] replaced cement and natural sand with marble dust and investigated the impact of the substitution on the properties of concrete. In the study, marble dust was substituted at ratios of 5%, 7.5%, 10%, and 15%. In a similar vein to Rodrigues et al. [27], the results indicated that when 15% of the cement or sand was replaced with marble dust, there was no significant impact on the ultrasonic pulse velocity. Additionally, replacing 10% of the sand with marble dust increased the compressive strength of the concrete by 14%. The strength was increased by 22% in a low w/c (water to concrete) ratio series. In contrast, the sample replaced with 15% marble dust had a compressive strength that was similar to or below that of the reference sample. However, there was a noticeable improvement in the steel-concrete bond strength (adherence) in this sample. The maximum improvement in the adherence was observed in the sample with a substitution ratio of 10%. The findings of this study also suggested that replacing 10% of the cement or natural sand with marble increased the splitting tensile strength by 15%. Furthermore, the splitting tensile strength was reduced when the replacement ratio was increased to 15%, but the sample in this case performed better than the reference sample. In the experiments, the samples with low w/c ratios consistently exhibited the best performance [13], [27].

Ergun [28] replaced cement with marble dust at ratios of 5%, 7.5%, and 10% and measured the properties of the modified concretes to find that marble dust acted as a filler material. This was similar to the study conducted by Corinaldesi et al. [20]. Thus, substituting cement with marble dust at 5% increased the compressive and bending strengths of concrete by 12% and 5%, respectively, and decreased the porosity of the physical matrix. The addition of super plasticizers produced positive effects at lower ratios of marble dust replacement. There was an improvement in the mechanical properties of concrete and an increase in its compressive strength when the cement-replacement ratio was 5% because of the filler property of the marble dust [20], [28].

The effects of marble dust on the mechanical properties of self-compacting concrete were investigated by Topçu et al. [29]. They replaced cement with marble dust at ratios of 30% (150 kg/m^3), 40% (200 kg/m^3), 50% (250 kg/m^3), and 60% (300 kg/m^3). The compressive and bending strengths of the concrete decreased when the cement was increasingly replaced with marble dust. Marble replacement at 300 kg/m^3 reduced the compressive and splitting tensile strengths by 51% and 47%, respectively. Furthermore, an increase in the marble dust ratio reduced the slump flow (measured in mm) [29].

Belaidi et al. [30] investigated the effects of replacing cement with natural pozzolana and marble dust on self-compacting concrete. They prepared two series of samples for testing. The first series replaced cement with pozzolana at ratios of 5%, 10%, 15%, 20%, and 25%. The other series replaced cement with marble at replacement ratios of 10%, 15%, 20%, 30%, and 40%. In both series, a replacement ratio of 40% increased the slump value and decreased the compressive resistance by 50% [30].

Gesoğlu et al. [31] investigated the mechanical properties of concrete as a function of replacement ratios of cement. The results indicated that the slump values of samples produced with 5%, 10%, and 20% replacement ratios were decreased relative to those of the reference samples and that the setting time was an increasing function of the ratio of marble dust used. The compressive strength on the 28th day was 13.46% lower in the sample with a 20% marble dust ratio than that in the reference sample. There was a significant change in the compressive strength on the 90th day at a 5% substitution ratio. However, this was reduced by 3% when the substitution ratio doubled to 10%. In contrast, substitution with 5% and 10% marble dust reduced the splitting tensile strength by 14% and 5.2%, respectively, relative to the reference sample. It should be noted that the above-mentioned data were approximated from the data presented in the study report [31].

Elyamany et al. [32] applied marble dust as a filler material in self-compacting concrete and investigated the effect of the marble dust on the mechanical and physical properties of the modified product. Specifically, 30 kg/m^3 (7.5%), 40 kg/m^3 (10%), and 60 kg/m^3 (15%) marble dust were added to a mixture of 400 kg/m^3 cement and 50 kg/m^3 (10%) marble dust, and a preparation of 500 kg/m^3 cement. The compressive strengths of the mixtures prepared with 15% silica fume and 15% marble dust as measured on the 7th day were approximately 31 MPa and 36.5 MPa, respectively. These compressive strengths increased to 47.5 MPa and 46.5 MPa on the 56th day. Hence, it was concluded that the filler type crucially influenced the segregation and bleeding values. In particular, a non-pozzolanic filler material reduced both values [32].

Gencel et al. [21] investigated the feasibility of using marble dust in concrete paving blocks. Two series of samples based on cement types 32.5 and 42.5 were prepared to replace the fine aggregates with marble dust at ratios of 10%, 20%, 30%, and 40%. The observations revealed that in both series, the compressive strength, splitting tensile strength, and bulk weight decreased as the marble dust ratio increased. The study compared the compressive strengths of the test sample and the reference sample on the 28th day, and found that at cement-replacement ratios of 10%, 20%, 30%, and 40%, the compressive strengths decreased by 94.3%, 91.7%, 86%, and 76.4%, respectively. The results of the study also indicated that using marble dust in a proportion of 40% reduced the cost of paving block production from US$34/m^3 to US$30/m^3 [21]. In contrast, Gesoğlu et al. [31] stated that replacing cement with marble dust at a ratio 20% or higher adversely affected the mechanical specifications of concrete [31]. Furthermore, previous studies including Gesoğlu et al.; Ergun; Uysal and Sumer; and Uysal and Yılmaz suggested an optimal concrete replacement ratio of 5% [24], [25], [28], [31]. These disparate results could be caused by the varying C_3A contents in the cement used across the different studies. Specifically, there are two possible explanations. First, the hydration reaction between the cement and water produces $Ca(OH)_2$. This in turn reacts with the silica in the marble dust (if it is sufficient), and an extra binding phase results from the additional pozzolanic properties. Second, calcium carboaluminate is formed when tricalcium aluminate (C_3A) in the cement reacts with the calcium carbonate ($CaCO_3$) in the marble dust. Calcium carboaluminate increases both the hydration speed and the compressive strength of the cement.

Rodrigues et al. [27] indicated that super-plasticizer additives were required to obtain the desired performance of cement partially substituted with marble dust. The study reported negative effects on the mechanical specifications of concrete at replacement ratios of up to 10% in the absence of super-plasticizers. All these studies suggested that substituting cement with more than 10% marble dust decreased the compressive strength of the concrete. High contents of marble dust were considered to increase the capillarity structure of the concrete. Thus, the fore-mentioned studies suggested that when cement was substituted with marble dust at ratios of 5%-10%, it could improve the mechanical properties of the concrete [27].

B. Replacement of Fine Aggregates with Waste Marble in Concrete

Gameiro et al. [33] studied the impact of finely aggregated marble pieces on the durability of concrete. In the study, granite, basalt, and river sands were substituted with waste marble at volume ratios of 20%, 50%, and 100%, respectively. The results revealed that substitution with 20% waste marble reduced the water absorption because of capillary action. The carbonation depth on the 28th day was 8.5 mm in the reference granite sample and 7.2 mm, 6.5 mm, and 5.5 mm in the samples substituted with 20%, 50%, and 100% marble dust, respectively. The density changes in the marble-substituted samples (~1.3%) were almost imperceptible. However, within 20 days, the drying shrinkages decreased when all sand types were replaced with marble dust [33].

From an environmental sustainability perspective, Uygunoğlu et al. [34] investigated the effects of aggregated marble pieces on the mechanical properties of self-compacting concrete. They formed mixtures with water-to-concrete (w/c) ratios of 0.31, 0.34, 0.37, and 0.40 by using recyclable and waste marble aggregates. The compressive strength of the recyclable aggregate mixture with a 0.31 w/c ratio on the 7th day was 49 MPa, compared to the marble aggregate sample, which had a compressive strength of 44 MPa. Similarly, the compressive strengths of the samples produced from recyclable and marble aggregates were 54 MPa and 53.5 MPa, respectively on the 28th day. There was a decrease in the compressive strength with an increase in the w/c ratio [34].

Talah et al. [35] investigated the effects of marble dust on the mechanical properties of high performance concrete (HPC). The study examined a reference sample with no marble dust and an HPC sample with 15% marble substitution. The compressive strengths measured on the 7th, 28th, 90th, 180th, and 365th days were 26 MPa, 38 MPa, 44 MPa, 46 MPa, and 48 MPa, respectively in the reference sample. In contrast, the compressive strengths measured on the 7th, 28th, 90th, 180th, and 365th days in the test sample were 39 MPa, 52 MPa, 58 MPa, 62 MPa, and 65 MPa, respectively. The study emphasized that the durability of the concrete substituted with 15% marble dust could be further enhanced [35].

Hebhoub et al. [36] investigated the replacement of fine aggregates with marble dust in concrete production. Marble dust samples at replacement ratios of 25%, 50%, and 100% were prepared. It was observed that changes in the marble dust content did not alter the mass density of concrete. Measurements on the 28th day indicated that relative to the reference sample (with no marble dust), increases of 22.2%, 16.84%, and 16.84% were observed in the compressive strength measurements of samples with replacement ratios of 25%, 50%, and 75%, respectively. Furthermore, splitting tensile strengths of the samples as measured on the 90th day increased by 13%, 33%, and 11%, respectively. However, both compressive strength and splitting tensile strength decreased in the sample with 100% substitution ratio. The study also observed that the workability decreased when the ratio of substitution by the marble dust increased. At a substitution ratio of 100%, the workability declined by 80%. The study concluded that replacing fine aggregates with marble dust significantly increased the compressive and tensile strengths of concrete [36].

Belachia and Hebhoub [37] examined the use of waste marble aggregates in concrete production. The study involved generating mixtures at substitution ratios of 25%, 50%, 75%, and 100%. The highest compressive strength was achieved at the substitution ratio of 25%. When the ratio was maintained at 0.45 w/c, the results indicated that the samples without waste marble had a compressive strength of 33 MPa, while the compressive strength increased to approximately 36 MPa in the samples with 25% waste marble. The study concluded that waste marble was a suitable alternative material for natural aggregates [37].

Corinaldesi et al. [20] explored the necessary characteristics of marble dust in concrete production, and replaced fine aggregates in concrete with 10% and 20% marble dust. It was concluded that marble dust negatively affected the mechanical properties of concrete. Additionally, the hydration time was unaffected in samples with 10% marble dust and no super plasticizer. However, the compressive strength decreased by up to 10% as the concrete aged. In contrast, when the 10% marble dust sample was supplemented with a super plasticizer, the marble dust acted as a sealant. It should be noted that the above data were approximated from the data presented in the study [20].

Omar et al. [38] replaced the sand in concrete with marble dust at ratios of 5%, 10%, and 15%, and compared the strengths of the concretes with sand and marble dust. The findings indicated that marble dust at a ratio of 15% increased the modulus of elasticity by 1.2%-5.1%, but decreased the workability of the concrete. At all ratios, the marble dust noticeably increased the compressive strengths measured on the 7th, 28th, and 90th days. In samples with 350 kg/m^3 cement density and 5% marble dust substitution, the compressive strengths on the 7th, 28th, and 90th days increased by 10%, 5%, and 5%, respectively, relative to the reference sample with no marble dust. The corresponding increases in the 10% marble dust sample were 17%, 15%, and 15%, and those in the 15% marble dust sample were 22%, 17%, and 17%. Moreover, all marble dust samples exhibited a 10% increase in the splitting tensile strength [38].

Tennich et al. [39] examined the effects of various filler materials on the mechanical properties of self-compacting concrete. The results from the study determined that mixing cement with 200 kg/m^3 marble dust (approximately 75% of the cement weight) as a filler material increased the compressive strength of the concrete by 42.7% when compared with that of ordinary vibrated concrete. This increase was accompanied by decreases of 2.6%, 12.8%, and 16% in the ultrasonic pulse velocity rate, dynamic modulus, and static elastic modulus, respectively, and a 41% increase in the splitting tensile strength of the concrete [39].

Alyamaç and Ince [12] incorporated marble dust from various types of marbles and measured the mechanical properties of the concretes. The study indicated that samples prepared with 50 kg/m^3, 100 kg/m^3, 150 kg/m^3, 200 kg/m^3, and 250 kg/m^3 of white marble dust exhibited better results than equivalent density samples prepared from gold marble dust. Additionally, the compressive and splitting tensile strengths of the prepared samples were greater than that of the reference sample by 27% and 22%, respectively. At densities of up to 200 kg/m^3, marble dust increased the compressive and splitting tensile strength of the samples. At higher densities, the sample strengths decreased below the reference levels, although the concrete strengths continued to increase. Among the tested samples, the optimal composition was presented by white marble prepared at 200 kg/m^3 with a low w/c ratio [12].

Hameed and Sekar [40] investigated the mechanical properties of a material referred to as environmental concrete in the study. This was produced from marble dust and stone powder. The compressive strengths measured on the 7th and 28th days in samples prepared with 50% marble dust and 50% stone powder were higher by 6.49% and 9.49%, respectively than those of the sand-based concrete. Accordingly, the corresponding splitting tensile strengths of the marble dust and stone powder samples were higher by 14.62% and 8.66%, respectively, than those of the reference samples. Furthermore, water absorption measured on the 28th day was 31.22% higher in the sample containing marble dust than that in the reference sample, and the weight losses of the samples in Na_2SO_4 and

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$MgSO_4$ solutions were lower than those in the reference samples. The study concluded that the marble dust enhanced the mechanical performance when it was supplemented with 50% stone powder [40].

Rai et al. [22] replaced sand with marble dust at ratios of 5%, 10%, 15%, and 20%, and examined the mechanical properties of the resulting concretes. The measurements on the 28th day revealed that relative to the reference sample, the compressive strength increased by 5% for replacement ratios up to 15%. However, the compressive strength was slightly decreased in the 20% sample. The incorporation of 15% waste marble increased the bending strength by 25%, and the bending strength slightly decreased at higher ratios. The slump value increased with increases in the waste marble ratio [22].

Demirel [41] investigated the effects on the mechanical properties of concrete when sand was replaced with marble dust at ratios of 25%, 50%, and 100%. The measurements on the 28th day indicated that the compressive strength and dynamic modulus of elasticity of the 100% replacement samples increased by 9.67% and 25%, respectively, and the porosity decreased by 8%, relative to the reference sample [41].

Omar et al. [38] and Wu et al. [42] obtained similar moduli of elasticity in marble-containing concrete. However, unlike the studies conducted by Rodrigues et al. [27] and Aliabdo et al. [13], a 10% increase in the ultrasonic pulse velocity was observed in the study conducted by Demirel [41].

Binici et al. [43] replaced the sand in concrete with fine aggregates of marble dust, and measured the mechanical properties of the concrete. All samples with a marble dust replacement ratio of 15% exhibited higher compressive strengths than the reference samples and 71.42% better results than the reference samples [43].

Samples containing marble dust were found to be more resistant to sodium sulfate than the reference samples according to Hameed and Sekar [40]. Monica and Dhoka [44] adopted an approach similar to Hameed and Sekar [40], wherein fine aggregates were replaced with 50% marble dust and 50% quarry dust as a supplement, and the mechanical properties of the concrete were examined. Relative to the reference sample, increases of 7.7% and 25% were observed in the compressive strength and splitting tensile strength as measured on the 28th day. Furthermore, the study findings revealed that green concrete was more durable against sulfates than conventional concrete. The immersion results produced by the samples placed in 7.5% sulfate solution were similar on the 28th and the 90th days. The concrete workability increased at replacement ratios exceeding 50%, but the splitting tensile strength reduced and the water absorption values increased relative to the reference sample [40], [44].

Binici et al. indicated that 15% of the fine aggregate sand should be replaced with marble waste to obtain an optimal performance [43]. Similarly, Rai et al. reported that marble dust at a ratio of 15% increased the compressive and splitting tensile strengths of the concrete [22]. Conversely, Demirel reported that replacing 100% of the fine aggregate sand with marble waste improved the compressive strength [41]. Tennich et al. observed that marble dust as a filler material enhanced the mechanical properties of concrete, and that 75% of the cement weight constituted an optimum ratio [39]. This result was attributed to the filler ability of marble dust with low water absorption ratio. That is, the compressive strength increased with decreases in the porosity [39]. Additionally, Tennich et al. indicated that marble dust could have negative impacts [39]. Omar et al. argued that replacing sand with marble dust at 15% appropriately enhanced the mechanical properties of concrete [38].

As observed by Rodrigues et al. [27] and Gesoğlu et al. [31], increasing the marble dust substitution to 20% reduced the compressive strength of concrete. Furthermore, Gesoğlu et al. also reported a reduction in splitting tensile strength [31].

Hameed and Sekar argued that there was an improvement in the compressive and splitting tensile strengths of concrete when 50% marble waste as fine aggregate was supplemented with stone powder [40]. Monica and Dhoka reported similar enhancements in 50% marble dust supplemented with quarry dust [44]. Rodrigues et al. [27] and Hebhoub et al. [36] reported that increasing the marble waste ratio does not significantly change the mass density of concrete.

Demirel observed that replacing 100% of the sand with marble dust increased the modulus of elasticity by 25% [41]. Omar et al. arrived at a similar conclusion, but argued that the modulus of elasticity increased at much lower marble-dust replacement ratios (15%) [38]. Hence, the fore-mentioned studies suggested the substitution of natural fine aggregates with waste marble at a ratio of 10% - 75% could positively influence the mechanical properties of concrete. The observed increases in the compressive strength could be related to the concrete structure and to the marble dust that originated from limestone. However, increasing the proportion of marble dust increased the apparent porosity values of the concrete. The adverse effects on capillarity structure compromised the increased mechanical strength of the concrete. These effects could be attributed to the non-homogenous dispersion of the marble dust within the mixture.

C. Substitution of Coarse Aggregates with Waste Marble in Concrete

André et al. [45] studied marble chippings as a coarse aggregate and investigated the properties of the resulting concrete. The study varied the replacement ratios of the marble chippings as 20%, 50%, and 100%, and found that increasing the replacement ratio decreased the compressive strength of the samples as measured on the 28th day. The study also determined the immersion values of the samples, and reported absorption rates similar to those of the reference sample. This could be because the marble and natural aggregates had similar microstructures. The addition of coarse marble aggregates significantly increased the chloride migration coefficient of the mixtures. The durability and carbonation depths were also similar across the test and reference samples [45].

Binici et al. [46] added marble chippings as coarse aggregates and investigated the mechanical properties of the modified concrete. The marble aggregate sizes in the study were varied as 19 mm, 12.7 mm, 9.5 mm, and 4.5 mm. The study findings revealed that replacing the coarse aggregates with marble aggregates reduced the chloride penetration depth and sulfate resistance measured on the 28th day by up to 70% when compared to those of the reference sample. Measurements performed on the 365th day indicated that the compressive strength increased by 49% and 55% for all samples when compared to the measurements on the 7th day and that of the reference sample, respectively. Additionally, the bending and splitting tensile strengths of the test samples recorded on the 28th day were higher than those of the reference sample by 64% and 57%, respectively [46]. These studies highlighted the role of aggregated marble chippings in improving the mechanical properties of conventional concrete.

Wu et al. investigated the mechanical properties of high strength concrete embedded with coarse aggregates of different w/c ratios (0.26, 0.44, and 0.55) [42]. The compressive strengths of the samples decreased with increases in the w/c ratio. In the sample with a w/c ratio of 0.44, the compressive strength, splitting tensile strength, modulus of elasticity, and flexural strength were lower by 28%, 49%, 8%, and 12%, respectively, than those of the sample with a w/c ratio of 0.26. The corresponding losses in the sample with a w/c ratio of 0.55 were 77%, 80%, 16%, and 16%, respectively. The study concluded that marble pieces as coarse aggregates could enhance the mechanical properties of concrete when incorporated at low w/c ratios [42].

Sudarshan and Vyas [18] conducted a feasibility study of using coarse aggregates of waste marble instead of limestone, and prepared mixtures with substitution ratios of 20%, 40%, 60%, 80% and 100%. The compressive strength increased up to a substitution ratio of 80%, and thereafter it decreased by 8%.

André [47] substituted primary aggregates with coarse aggregates of waste marble chips in concrete. Over 28 days, the compressive strength declined for substitution ratios exceeding 50%, whereas an increase in the compressive strength for substitution ratios exceeding 50% was observed in the reference sample. However, the water absorption values during immersion and carbonation were similar across the test and reference samples [47].

Binici et al. [46] found that coarse aggregates of marble dust increased the flexural strength of concrete. However, Wu et al. [42] argued that the flexural strength decreased at higher w/c ratios. This contradiction could be caused by the different w/c ratios of the mixtures prepared across the different experimental studies. At ratios of 50%-80%, substituting waste marble as coarse aggregates appeared to improve the mechanical properties of concrete. However, further research on different types of waste marbles is required to examine and verify this idea and develop new industrial applications.

III. Cement Production and CO_2 Releases in Turkey and Worldwide

In 2014, 69.7 million tons of cement was produced in Turkey. The global cement production in 2014 was approximately 4.2 billion tons, and it is expected to increase by 2.9% (to 5.4 million tons) by 2018 (TÇMB, 2014) [6]. Given that each ton of produced cement expels 0.94 t of CO_2 into the atmosphere, it could be concluded that in 2014, Turkey alone released 65.52 million tons of CO_2 in comparison to the 3.95 billion tons released by industries globally. Thus, replacing cement with alternative materials would minimize the tremendous environmental effects of concrete production. The cement production/CO_2 ratio over the past 10 years in Turkey is plotted in Fig. 1. The results in Fig. 1 and the above-reviewed studies indicated a sharp increase in the demand for concrete and cement production driven by the accelerated growth of the real estate sector in Turkey. This demand is accompanied by the increase in CO_2 emissions. Studies by Ergun [28], Rodrigues et al. [27], Uysal and Yılmaz [25], and Gesoğlu et al. [31], suggested that replacing 10% of the cement with marble dust would reduce cement production from 65.52 to 62.73 million tons and the CO_2 released from 69.7 to 58.96 million tons. This amounts to a 12% annual reduction of CO_2 emissions in Turkey alone. Additionally, worldwide cement production would decrease from 4.2 billion tons (as recorded in 2014) to 3.78 billion tons, and correspondingly, the CO_2 emissions would decrease from 3.95 billion tons to 3.55 billion tons.

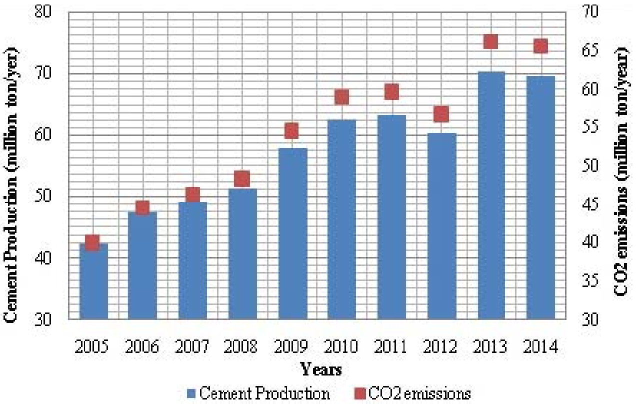

Fig. 1 Concrete production/CO_2 emissions in Turkey from 2005 to 2014 [6].

IV. The Economic Benefits of Waste Marble

According to 2014 data, concrete production in Turkey costs US$40/m³, and would reduce to US$33/m³ when 10% of the cement is replaced by marble dust. The cost would be US$36/m³ if 50% of the fine aggregates were replaced with marble dust. The fore-mentioned studies implied that replacing cement with marble dust at ratios of 5%-10% enhanced the mechanical properties of concrete with no negative impacts. Based on the conclusions of the reviewed studies, Fig. 2 presents a cost-compressive strength analysis of concrete with a compressive strength of 30 MPa, given marble dust substitution. According to Ergun [42], marble dust replacement of 5% increased the compressive and flexural strengths of concrete by 12% and 5%, respectively. Additionally, an increase of 12% in the compressive strength reduced the cost by US$4/m³.

Rodrigues et al. [27] reported that the compressive strength was maintained for marble substitution ratios of up to 10%. They also stated that a substitution rate of 10% decreased the cost by US\$7/m^3 with no remarkable changes in the compressive strength. Similarly, Uysal and Yılmaz [25] reported that replacing cement with marble dust at a ratio of 10% preserved the compressive strength of concrete. In contrast, marble dust at a replacement ratio of 20% reduced the cost by US\$12/m^3 because it decreased the compressive strength by 10%-20%. Gesoğlu et al. suggested that replacing cement with 20% of marble dust reduced the compressive strength by 13.46% [31]. Topçu et al. [29] determined that marble dust substitution at 40% reduced the compressive strength by 42% [29].

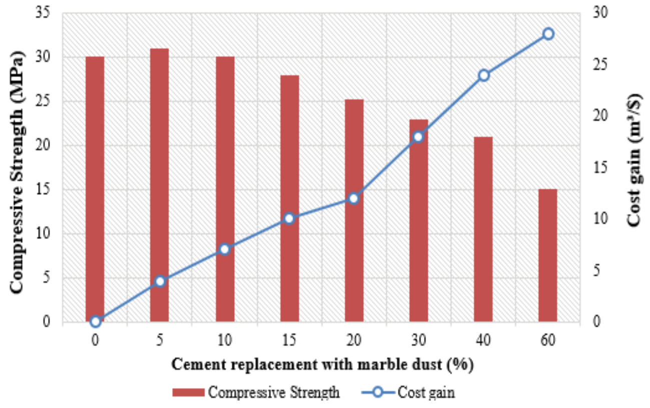

Fig. 2 Relationship of the cost and the compressive strength of concrete relative to the ratio of cement substituted by marble dust [25], [27], [28], [29], [31]

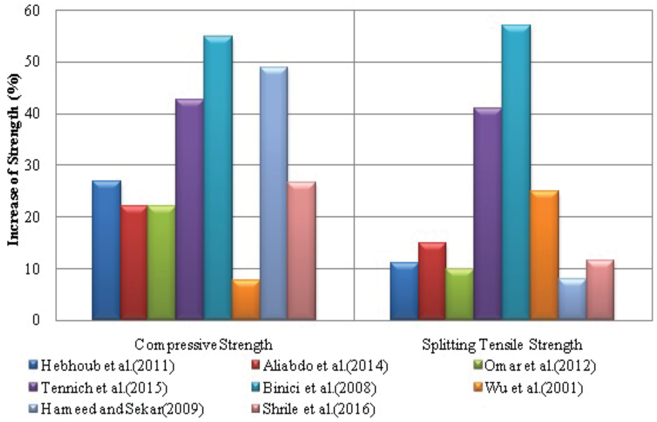

Fig. 3 Improvements in the compressive strength and splitting tensile strength of concrete as documented by previous studies [13], [36], [38], [39], [40], [42], [46], [48]

V. Summary of the Previous Studies

Table I summarizes the properties of the marbles used in the reviewed studies (where relevant information was available). The results of the reviewed studies were compared, and the compressive and splitting tensile strengths determined in the classifiable studies are shown in Figs. 3 and 4, respectively. Fig. 3 shows the selected reviewed studies that demonstrated positive effects on the mechanical properties and the relative improvements in the compressive strength and splitting tensile strength as indicated by these studies. Additionally, it indicates the studies with similar findings. Conversely, Fig. 4 shows the researchers examined in this study, and illustrates the relative decreases in the compressive strength and splitting tensile strength as documented by these studies. An examination of Fig. 3 reveals that the w/c ratio specifically affected the compressive strength and splitting tensile strength of concretes that contained marble waste as coarse aggregates. Hence, the differences in strength increases documented across the studies was likely to result from the experimental differences between studies such as those in Wu et al. [42] and Binici et al., [46]. Fig. 4 depicts studies in which the cement is substituted with fine aggregates of marble dust at 20%.

Gesoğlu et al. [31] and Rodrigues et al. [27] both reported that substituting cement with marble dust enhanced the mechanical properties of concrete at a substitution rate of 5%, but degraded the mechanical properties at a substitution rate of 20%. Table II classifies and tabulates the previously discussed studies. Collectively, the reviewed studies suggested that the mechanical properties of concrete were improved by three mechanisms, namely replacing cement with marble dust at replacement ratios of 5%-10%, incorporating marble dust as coarse aggregates rather than fine aggregates at replacement ratios of 10%-75%, and replacing up to 75% of the cement weight with marble dust as a filler material. A careful analysis of Figs. 1 and 2 suggests that marble dust is beneficial in reducing CO_2 emissions and production costs. In contrast, these benefits were compromised by a loss of compressive strength at substitution ratios exceeding 10%. Therefore, 10% could be considered as the optimum substitution ratio of marble dust in cement based on the reviewed articles.

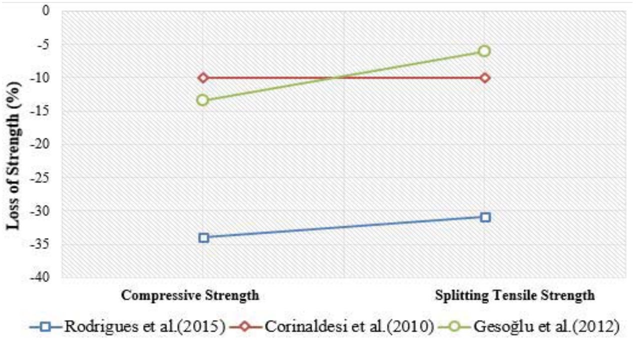

Fig. 4 Decreases in compressive and splitting tensile strengths as documented by previous studies [20], [27], [31]

VI. Conclusion

In this review, the use of waste marble in concrete production was examined and three main categories of the waste marble were investigated. Previous studies on the substitution ratios of waste marble were analyzed and their differences and similarities were assessed. The aims of this review included identifying a common substitution ratio and providing a coherent picture of the selected studies for readers.

TABLE I
CHEMICAL CHARACTERISTICS OF WASTE MARBLE AS REPORTED BY PREVIOUS STUDIES

Researchers	SO_3 %	MgO %	CaO %	Fe_2O_3 %	Al_2O_3 %	SiO_2 %
Aliabdo *et al.* (2014) [13]	0.56	0.52	83.22	0.05	0.73	1.12
Rodrigues *et al.* (2015) [27]	3.28	1.54	63.61	3.53	4.83	18.95
Uysal and Sumer (2011) [24]	-	0.23	55.49	0.12	0.29	0.7
Uysal and Yılmaz (2011) [25]	-	0.23	55.49	0.12	0.29	0.7
Mashalya *et al.* (2016) [48]	0.13	0.11	55.32	0.04	0.1	0.15
Hebhoub el al. (2011) [36]	-	1.03	54.86	0.04	0.08	0.15
Alyamaç and Ince (white) (2009) [12]	-	4.17	54.55	0.32	-	0.14
Belaidi *et al.* (2012) [30]	0.07	2.1	52.6	0.2	0.2	1
Gesoğlu *et al.* (2012) [31]	0.11	-	52.45	0.78	0.39	1.29
Topçu *et al.* (2009) [29]	-	0.4	51.8	0.03	-	4.67
Ergün (2011) [28]	0.08	0.4	51.7	0.44	0.67	0.18
Binici *et al.* (2007) [43]	-	2.72	50.13	1.98	0.4	5.1
Alyamaç and Ince (gold) (2009) [12]	-	0.4	49.53	0.32	-	1.25
Tennich *et al.* (2015) [39]	0.08	0.23	49.46	0.66	0.46	7.36
Omar *et al.* (2012) [38]	-	2.77	42.14	1.94	2.69	14.08
Rana *et al.* (2015) [26]	-	3.72	42.13	2.98	2.2	44.1
Demirel (2010) [41]	-	16.25	40.45	9.7	0.42	28.35
Binici *et al.* (2008) [46]	1.2	7.3	6.8	36.8	21.9	14.8
Hameed and Sekar (2009) [40]	-	8.74	1.58	11.99	4.45	64.86
Monica and Dhoka (2013) [44]	-	8.74	1.58	2.33	4.45	64.86

*- = There is no content

TABLE II
MAIN RESULTS OF THE STUDIES EVALUATED IN THIS REVIEW

Research by	Compressive Strength	Splitting Tensile Strength	Workability	UPV	E_{cm}	Flexural Strength	Suggested Repl. Ratio
Wu *et al.* (2001) [42]	Inc. 28–77%	Inc. 49–80%	-	-	Inc. 8–16%	Dec. 12–16%	As Coarse Aggregate (results better than 0.44 and 0.55 W/C ratios)
Binici *et al.* (2007) [43]	Inc. 71%	Inc.	Dec.	-	-	-	15% with sand (as fine aggregate)
Binici *et al.* (2008) [46]	Inc. 55%	Inc. 57%	-	-	-	Inc. 64%	As Coarse Aggregate
Topçu *et al.* (2009) [29]	Dec. about 50%	Dec. about 47%	-	-	-		40% with Cement
Rana *et al.* (2015) [26]	Dec. 43%	-	-	-	-	Dec. 4.6%	Marble slurry 5% with cement
Tennich *et al.* (2015) [39]	Inc. 42.7%	Inc. 41%	Dec.	Dec.	Dec.	-	200 kg/m³ (as filler) (as cement 75%)
Rodrigues *et al.* (2015) [27]	Dec. 33.9%	Dec. 30.9%	Dec.	Dec. 4.4%	Dec. 10%	-	5–10% with Cement
Hebhoub *et al.* (2011) [36]	Inc. 26.9%	Inc. 11%	Dec.	-	-	-	25% with Sand
Omar *et al.* (2012) [38]	Inc. 22%	Inc. 10%	-	-	Inc. 1.2–%5.1	-	15% with Sand
Aliabdo *et al.* (2014) [13]	Inc. 22%	Inc. 15%	-	Dec. 1–3%	-	-	10% with Sand and low w/c
Corinaldesi *et al.* (2010) [20]	Dec. 10–20%	Dec.	Dec.	-	-	-	10% with Sand and low w/c
Gesoğlu *et al.* (2012) [31]	Dec. 13.46%	Dec. 6%	-	-	-	-	5–10% with Cement
Ergün (2011) [28]	Inc. 12%	-	Dec.	-	-	Inc. %5	5% with Cement
Uysal and Yılmaz (2011) [25]	Dec. 11.3% (at 400 days)	-	Inc.	-	Dec. 7.5%	-	10% with cement
Demirel (2010) [41]	Inc. 9.67%	-	-	Inc. 10%	Inc. 25%	-	100% with sand (as fine aggregate)
Hameed and Sekar (2009) [40]	Inc. 6.49–9.49%	Inc. 14.62–8.66%	Inc.	-	-	-	50% with sand and (supplemental 50% rock dust)
Monica and Dhoka (2013) [44]	Inc. 7.7%	Inc. 25%	Dec.	-	-	-	50% with fine aggregate (supplemental 50% quarry dust)
Uysal and Sumer (2011) [24]	Dec. 7.1 % (at 400 days)	-	Inc.	Dec. 1%	-	-	10% with Sand and low w/c

UPV = ultrasonic pulse velocity; Ecm = modulus of elasticity; - = no experiment; Inc. = increase, Dec. = decrease.

The conclusions of this review may be summarized as follows:

The standard production cost of concrete in Turkey is US\$40/m^3. This cost could be reduced to US\$34/m by replacing 10% of the aggregates with marble dust in the same production procedure in which cement was used. Furthermore, replacing cement with 5%-10% marble dust improved the mechanical properties of concrete. As a result, the CO_2 emissions potentially caused by the production of the replaced cement could be reduced by 12%. Additionally, supplementing up to 75% of the cement weight with marble dust as a filler material enhanced the compressive strength and the splitting tensile strength of the concrete by 42%.

In coarse aggregate form, replacement of cement by marble waste exerted an increasingly positive impact with decreases in the w/c ratio. In fine aggregate form, marble dust performed best at replacement ratios of 50% and 75%. In these cases, the compressive and splitting tensile strengths increased by 20%-26% and 10%-15%, respectively. Moreover, in coarse aggregate form, marble dust increased the compressive strength by 20%-70% and the splitting tensile strength by 50%-80%. When marble dust was used as a filler material, it improved the compressive and splitting tensile strengths of concrete by 42% and 41%, respectively. The least favorable results were indicated in the case where cement in concrete was replaced by 20% marble dust.

Hence, researchers proposed substituting a proportion of concrete with marble dust and slurries from by-products/wastes found in waste ponds located at workplaces and plants, to improve the economic recovery of wastes. Other studies investigated the recovery of useless marble wastes by grinding them into coarse aggregates that could be substituted for concrete. When substituted at appropriate ratios, the marble exerted no adverse effects on concrete quality, and could instead enhance the mechanical specifications of the concrete. The reviewed studies suggested that the use of marble in concrete production benefits the economy and reduces environmental pollution. Particularly, aggregates of marble wastes appeared to be suitable for concrete production in ready-mixed concrete plants.

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