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Concretes with synthetic aggregates for sustainability

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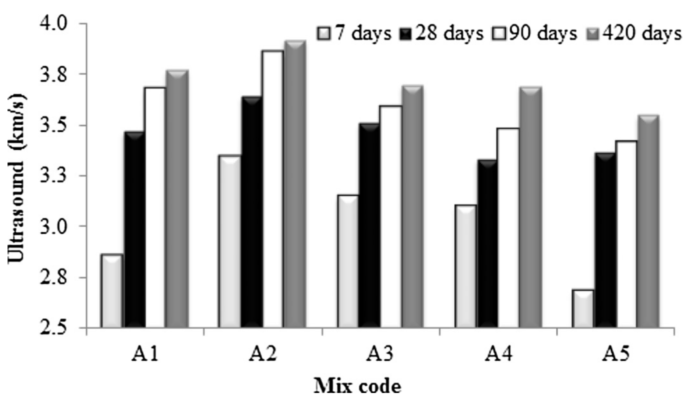
GRAPHICAL ABSTRACT

Variations in ultrasound pulse velocity for different concretes according to age. The trend in compressive strength behavior of the concretes is similar.



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ABSTRACT

We have used waste marble aggregates, marble dust and fly ash from thermic power plants as fillers in concretes for replacing natural aggregates. We have used two different kinds of cements. After curing, we have determined the workability (by slump tests), air content, unit weight, Schmidt hardness, ultrasound pulse velocity, compressive strength and carbonation depth. The concretes containing waste marble at least match or exceed the workability and strength of the control concrete type. Fly ash significantly improves the workability. Utilizing waste marble aggregate at the replacement ratio of 100% along with waste marble dust, fly ash and pozzolanic cements in concrete leads to lower cost – achieving at the same time environmentally friendly production process with decreased consumption of natural resources and energy. Our work also contributes to enhancement of sustainability by finding a use for marble waste and fly ash.

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1. Introduction

More and more materials to be used for any application are considered not only from the point of view of properties and cost, but also from the point of view of sustainability [1–3]. Therefore, materials based on waste have an advantage over virgin ones. In the case of concretes, other factors that need to be considered are light weight [4,5] and the service environment [6].

Turkey has significant marble reserves that constitute over 40% of total worldwide reserves. Over 7 million tons of marble are produced in Turkey annually. Egypt produces over 50 different types of marble and granite—with annual production of approximately 3.5 million tons [7]. While marble blocks are being processed, *marble wastes* are produced as dust and aggregates. Stored marble waste constitutes an environmental hazard [8]. Already in 2009, 1400 tons of waste marble per day were stored in depots in Turkey [9]. Similarly, waste from the cutting and sawing process in Brazilian decorative stone industry constitutes 20–25% of the total volume of the blocks [10]. Likewise, Hebhoub et al. [11] have reported on the considerable waste generated during marble production; almost 70% of the mineral gets wasted in the mining, processing and polishing stages—with an obvious impact on the environment.

The environmental impact of marble waste could be lowered in a cost-effective manner by utilizing the waste material in value-added applications. Some of us have demonstrated [12] the feasibility of using marble waste as aggregate in concrete paving blocks. Further, it has been shown in the same work that blocks prepared from a cement called CEM with marble waste substituted for a portion of the aggregate exhibits suitable mechanical strength along with improved freeze-thaw durability and abrasive wear resistance in comparison to controls.

Depending on the application, a choice has to be made between mineral and polymer concretes [13]. Previously we have considered the use of marble powder and other fillers in polymer concretes [14]. We now discuss effects of fillers in mineral concretes that are byproducts of industrial processes, therefore quite cheap, and finding use for these byproducts contributes to protection of our environment.

Fly ash (FA) is a by-product of coal thermal power plants. There are estimates showing that fly ash is created worldwide in the amount of some 500 million tons every year [15,16]. There is no dispute that fly ash by itself causes environmental pollution. Storage costs of fly ash are quite high—and constitute a palliative only. Given those costs, at some point the storage would have to stop—even if it suddenly became more affordable. Clearly progressive accumulation and storage of fly ash goes against the very idea of sustainability.

There are possibilities of using fly ash in mortar and concrete, an effort in which we also participate [16–20]. Thus, it is already known that fly ash improves mechanical properties as well as freeze–thaw resistance, sulphate resistance, alkali–silica reaction, durability and abrasion resistance when used as a supplementary cementitious material. Also, shrinkage and permeability of hardened concrete are decreased, a consequence of the filling of micropores. Still further, fly ash also reduces the chloride penetration and steel corrosion in concrete [17,18,20]. On the other hand, the usage of industrial waste materials in concrete mitigates the pollution and at the same time has a positive effect on the economy of a given country [17]. In Turkey, the annual fly ash production is about 18 million tons annually, more than all other industrial waste combined [21]. In India, approximately 80 million tons of fly ash are generated each year [22].

Until recently, marble wastes have been utilized as a *partial* replacement of natural aggregates. It is our intention to replace traditional fine and coarse aggregates fully by marble fine and coarse aggregates.

André and coworkers [23] used marble industry waste. Baeza-Brotons and coworkers [24] used sewage sludge ash in Portland cement systems. Bravo and coworkers [25] used aggregates from construction and demolition recycling plants. Discarded tire rubber has been used by Thomas and Gupta [26].

Our work reported below consisted of two series. In the first series we have mixed waste marble aggregates with CEM I 42.5 Portland cement. In the second series we have used CEM IV pozzolanic cement—in order to evaluate the effects of natural pozzolans. Moreover, fly ash has also been utilized to replace a portion of the cement.

2. Materials and methods

2.1. Cement

We have used Portland cement CEM I 42.5R, subsequently called A1, and CEMIV/B-M (P-LL) 32.5 R, subsequently called A5, (with trass) donated to us by Bati Soke Cement Factory. These materials comply with the requirements of the Turkish TS EN 197-1 [27] standard, equivalent to the European Standard EN 197-1. These cement types are commonly used in construction. Their properties are summarized in Tables 1 and 2.

2.2. Fly ash

Fly ash (FA) used is in compliance with ASTM C 618 [28]. The use of FA as an additive in cement based concretes is classified in ASTM C 618 into two types, as class C and class F. Content of major oxides, $SiO_2 + Al_2O_3 + Fe_2O_3$, must be more than 50% for class C and more than 70% for class F. Our FA belongs to the F type since its total of major oxides amounts to 79.4%. Our fly ash was obtained from the Yatagan thermal power plant, Mugla, Turkey. Its chemical composition is provided in Table 2. The respective Blaine fineness which serves as a measure of the particle size, or fineness of cement including supplementary cementitious materials, is

Table 1
Physical and mechanical properties of cements.

	A1	A5
Initial setting time (min)	146	169
Final setting time (min)	195	218
Le Chatelier (mm)	1	0.5
Specific gravity (g/cm^3)	3.13	2.92
Specific surface (cm^2/g)	3604	4623
Standard consistency (%) (water demand)	29.7	30.2
Compressive strength @ 2 days (MPa)	26.4	18.6
Compressive strength @ 28 days (MPa)	55.6	38.0

Table 2
Chemical analysis of cements and waste marbles (wt.%).

Compound	A1	A5	Fly ash	Waste marble
SiO_2	18.9	30.9	52.4	0.1
Al_2O_3	4.8	7.3	21.2	–
Fe_2O_3	3.6	3.5	5.8	0.1
CaO	64.7	47.3	9.4	52.2
MgO	0.9	1.2	2.1	1.8
SO_3	2.8	2.5	1.4	–
Na_2O	0.2	0.2	0.5	–
K_2O	0.8	1.1	1.2	–
Free CaO	1.5	1.7	–	–
LOI*	2.9	1.9	5.8	46.2

* Loss on ignition.

4860 cm^2/g. The specific gravity is 2.55 g/cm^3. Cement paste is crucial as an agent to keep together the aggregates and we expected that FA will increase the paste amount.

2.3. Aggregates

Waste marbles were prepared as an aggregate by crushing and grinding in a laboratory mill, then sorting via sieves into two groups of coarse (>4 mm) and fine (<4 mm) aggregates. Particle size distribution is displayed in Fig. 1. The maximum aggregate size was 25 mm. Size of aggregate and grading of mixture play an important role to get a good composite. Specific gravity and water absorption were determined according to ASTM C127 [29]; the results are reported in Table 3. Photographs of concrete with waste marble aggregates are shown in Fig. 2. The aggregates are calcareous (mostly containing calcium oxide), as seen already in Table 2.

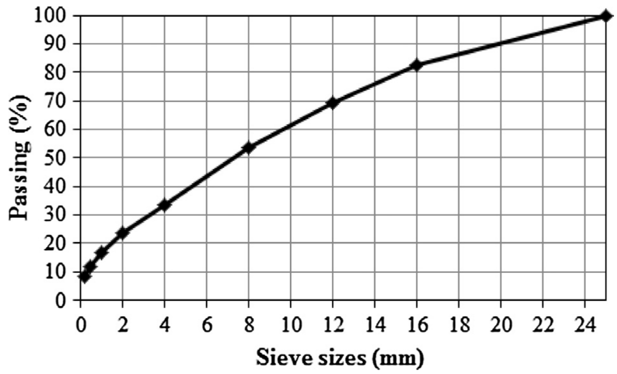

Fig. 1. Particle size distribution of mixture.

Table 3
Physical properties of aggregates.

Aggregate type	Specific gravity (g/cm^3)	Water absorption (%)	Mixing ratio (%)
Fine (0–4 mm)	2.61	1.21	33
Coarse (4–22 mm)	2.70	0.39	67

2.4. Mix design

Mix design was made in accordance with the absolute volume method. Binder content was kept constant ast 350 kg/m^3. To produce "green concrete", the cement content was kept low since cement production is responsible for about 8% of CO_2 emission in the world. Further, cement was replaced with fly ash at 10%, 20% and 30%. One can assume that approximately 1.5% air is trapped in fresh concrete. The concrete compositions are listed in Table 4; the water/cement ratio is listed as W/C. The aggregate content consisted of 67% coarse and 33% fine aggregate. Marble dust was used in the amount of 6% in all mixtures. No superplasticizer was used because it was not necessary and moreover it would have increased the costs.

2.5. Mixing, casting, curing and testing specimens

Concrete mixtures were prepared in a laboratory mixer with the capacity of 150 dm^3. In a typical mixing procedure, materials were placed in the mixer as follows: first coarse aggregates and fine aggregates and filler together, this initially dry material was mixed for 1 min; then cement and finally water were added. The total mixing time was 5 min. After the mixing procedure was completed, slump tests according to ASTM C143 [30] were conducted

Fig. 2. Distribution of aggregates in concrete specimens: from top (left) and from the side (right).

Table 4
Mixture proportions.

Code	Cement type	Cement (kg/m^3)	Fly ash (kg/m^3)	Fly ash (%)	Water (kg/m^3)	Waste marble (kg/m^3)	Marble Dust (%)	Marble Dust (kg/m^3)	W/C
A1	CEM I	350	0	0	190	1829	6	21	0.54
A2	CEM I	315	35	10	165	1889	6	21	0.52
A3	CEM I	280	70	20	140	1948	6	21	0.50
A4	CEM I	245	105	30	120	1995	6	21	0.49
A5	CEM IV	350	0	0	190	1808	6	21	0.54

on the fresh concrete to determine the workability. Air content of fresh concrete was measured according to ASTM C 231-04 [31]. Three specimens were used to determine the properties of hardened concrete for each test.

From each concrete mixture, six specimens were cast in molds of $350 \times 700 \times 150$ mm. Some representative specimens are shown in Fig. 2. After 24 h, specimens were demolded and all were cured by wetting twice a day in the laboratory. Unit weight according to ASTM C 138 [32], ultrasound pulse velocity according to ASTM C 597 [33], Schmidt hardness cording to ASTM C805 [34] and compressive strength tests were performed. The carbonation depth was measured according to the CPC-18 RILEM procedure [35].

3. Results and discussion

3.1. Workability

Slump values are presented in Fig. 3; they range between 55 and 90 mm. As seen in Fig. 3, workability increases with increasing fly ash concentration in the mixtures while W/C ratios are reduced. Compared to A1, slump increased 36.4% for A2, 27.3% for A3 and 63.6% for A4. We achieve here an important objective, substituting fly ash for a portion of cement increases the slump value. Apparently nearly spherical shape of fly ash particles provides a ball bearing effect that reduces internal friction in fresh concrete and thus increases the flowability and compaction of concrete. As also seen in Table 4, the water demand decreases from A1 to A4. Moreover, because of its lower density, FA increases the paste volume leading to improved workability. It is thus that the use of costly plasticizers or so-called superplasticizers can be avoided. Additionally, increasing the amount of FA in the mixture increases the fineness of concrete, resulting in improved cohesion. All these positive effects of FA impart improved workability of concrete—leading to easy handling without segregation.

A5 has a slump value 18.2% higher than that of A1. This outcome results from the waste marble in A5 that increases the cement paste volume and the workability of concrete. On the other hand, marble dust increases water demand, what might have mitigated the slump values to within the range 60–90 mm. All mixtures are workable. We note that an increase in the waste marble content increases weight – as some of us have discussed earlier [16].

According to several reports, waste marble dust aggregates decrease the slump loss thanks to their smooth surface textures and lower water absorption [23,36,37]. The same authors have shown that fresh marble coarse aggregate concrete improves workability and is more cohesive than ordinary limestone aggregate concrete [36]. All our mixtures contain waste marble aggregates; thus, the slump changes are related to the cement type, pozzolan type, and water to cement ratio. We conclude that fly ash significantly improves workability.

The volume of waste marble aggregate increases along with the increase in volume of FA. As known, FA has lower specific gravity than Portland cement. The specific gravities of FA and A1 are 2.55 and 3.13, respectively. To prepare specimens of the same volume, therefore, we had to decrease A1 amounts more than the amounts of FA introduced as a replacement. In order to obtain 1 m^3 concrete mixtures, we also had to increase the volume of waste marble aggregates and modify the water content because of the absence of superplasticizers. The improved workability of A2, A3 and A4 series, with respect to A1 and A5 series, can be attributed to the increases in the volumes and amounts of both FA and waste marble aggregate. Both FA and waste marble aggregate contribute to more smooth surfaces.

3.2. Air content

Air contents of mixtures are presented in Fig. 4. As seen from Fig. 4, air content is slightly higher than the targeted 1.5%. However, there is no significant effect of fly ash on air content of concrete produced with waste marble aggregates. Concrete produced with CEM IV (A5) cement type presents a little higher value that that of A1.

It seems that neither fly ash as mineral admixture nor the pozzolanic cement have significant effects on the air content of waste marble aggregate concretes. Some researchers have mentioned that if the air contents of concrete types containing FA mineral admixture and ordinary concrete are compared to each other, the variation of air contents is high and irregular [38]. Similarly, a correlation between FA content and air content may not easily be derived. Moreover, all series have air contents lower than 2%: this means that dense concrete with lower porosities can be produced using waste marble aggregates. It must be noted that A1, A2, A3, A4 and A5 contain exclusively marble fine and course aggregates without any other natural aggregates added. The slump losses and air contents are sufficient to produce concrete with ordinary concrete properties. In other words, it can be said that waste marble aggregates can be used instead of natural aggregates without sacrificing desired fresh concrete properties. A consequence of recycling waste marble for aggregate at high amounts is a considerable contribution toward the production of cost effective and environmental friendly concrete.

3.3. Bulk density

Unit weights of concrete are presented in Fig. 5. Unit weight varies between 2364 kg/m^3 and 2476 kg/m^3 according to mixture

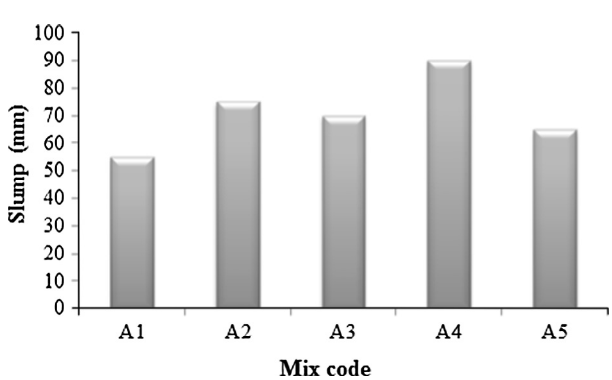

Fig. 3. Slump values of mixtures.

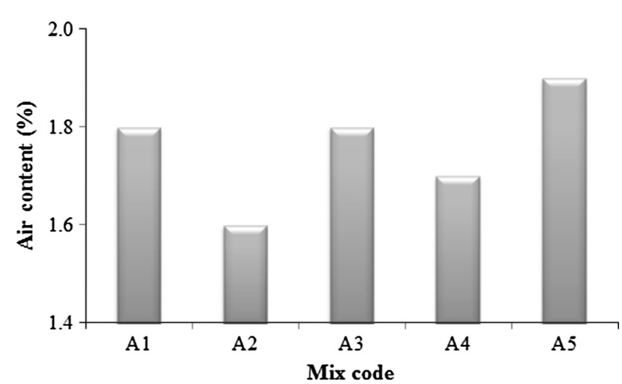

Fig. 4. Air contents of mixtures.

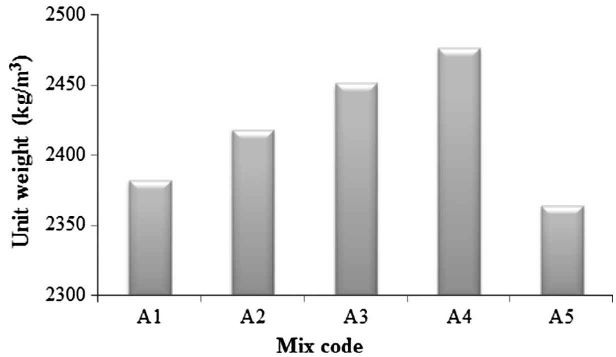

Fig. 5. Unit weights of concretes.

compositions. In the series produced with A1 cement, unit weight increases with increasing fly ash replacement. Actually, decreasing amount of cement, which has a specific gravity 3.15 g/cm^3, and increasing amount of FA, with lower specific gravity than A1, should lead to the decrease in unit weight with the increase in FA content. However, change in the paste volume causes an increase in waste marble aggregate volume. Although it has lower specific gravity between 2.60 and 2.70, the total amount of waste marble aggregate increases and the total weight of mixture also increases. In this manner, the unit weights of series A2, A3 and A4 increase with the increases in FA and waste marble aggregate volumes. In other words, marble aggregate content increment also results in increasing unit weight. On the other hand, unit weight of A5 is slightly lower than that of A1. This is a result of lower specific gravity of A5 cement than that of A1. For all the specimens prepared, the waste marble coarse and fine aggregates do not significantly alter the unit weight from the unit weight of conventional concrete. The weights for all are between 2350 and 2500 kg/m^3 and similar to ordinary concrete. Uygunoglu et al. [16] reported the same effect for the usage of waste marble as aggregate in concrete, namely that waste marble increases unit weight of concrete, and fly ash replacement decreases it.

3.4. Compressive strength

There is no need to argue that compressive strength is the most important property of concrete since compressive strength presents an overall picture of the quality and properties of concrete, and is invariably a vital element of structural design. Compressive strength results are presented in Fig. 6. Compressive strength values were 13.8, 17.1, 16.5, 16.5, 11.5 MPa for 7 days, 21.5, 25.5, 22.8, 17.1, 17.6 MPa for 28 days, 28.1, 31, 27.5, 26, 20.7 MPa for 90 days, and 31.3, 33.5, 29.8, 28.6, 23.7 for 420 days, respectively. As seen, FA replacement in A2, A3, and A4 does not affect significantly compressive strength compared to A1. However, as an artificial pozzolan, it contributes to the later time and ultimate compressive strengths especially for and after 28 days. The same behavior is observed for the compressive strengths at the ages of 90 and 420 days. This can be attributed to the fact that SiO_2 in fly ash can combine with $Ca(OH)_2$ in the presence of water to form calcium silicate hydrate, often called CSH, that has hydraulic binding properties. CSH is obtained in the reaction between the silicate phases of Portland cement and water. One believes that the reaction takes place as follows:

$$2Ca_3SiO_5 + 7H_2O \mapsto 3\,CaO \cdot 2SiO_2 \cdot 4H_2O + 3Ca(OH)_2$$

There have been extensive studies of CSH [39]. The exact stoichiometry of CSH in cement paste has not been defined and is believed to be variable.

To comply with disaster regulations for a building material to be used in structural applications, concrete must have a minimum compressive strength of 20 MPa at 28 days. In this respect, the specimens with 5% and 15% FA replacement satisfied this benchmark without using any chemical admixture and high cement contents. Compressive strengths of all specimens at 90 and 420 days were over 20 MPa.

The replacement of cement with pozzolan and the incorporation of waste marble aggregate each exert different effects on the compression strength. It seems that pozzolan type (FA versus natural pozzolan in A5) makes a difference. Overall A5 has lower compressive strength than A1. By contrast, the presence of FA results in higher compressive strength at all time-points for the A2 specimen (compared to A1). Because of the low replacement amount in A2, the hydration rate does not decrease significantly and the compressive strength for early ages are similar to A1. Going to A3, A4 and A5, the compressive strength decreases with respect to A1. This can be explained by relatively poor bonding between waste marble particles and the cementitious paste, an effect overwhelming the unit weight increase. That poor bonding result in lower hydration rates.

3.5. Ultrasound pulse velocity

Ultrasound pulse velocity results are presented in Fig. 7. As seen from Fig. 7, pulse velocity is significantly affected by the age of concrete, with velocity increasing with age. The jump in ultrasound value between 7 days and 28 days is drastic, but after 28 days the increment between measurements is slight. We find that the patterns in Fig. 7 are similar to the compressive strength behavior seen in Fig. 6. Actually, ultrasonic pulse velocity is used with high confidence as an indicator of strength.

Ultrasound is affected by the medium in which the pulse travels. Therefore, the unit weight of the medium is important: increasing unit weight of concrete typically results in increasing

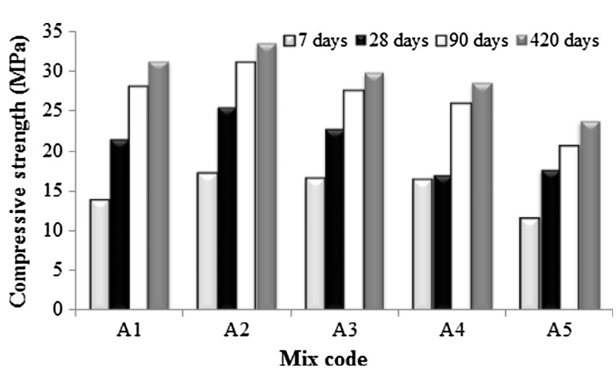

Fig. 6. Compressive strength variations of concretes.

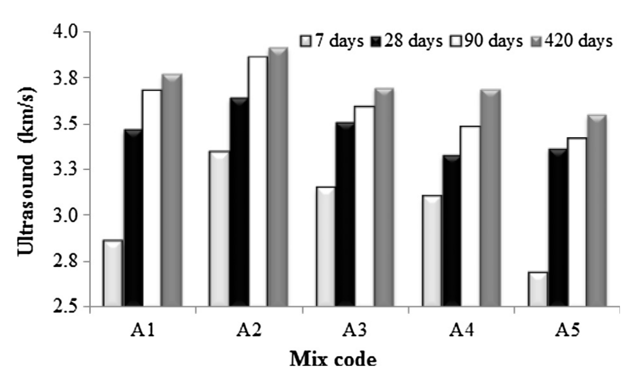

Fig. 7. Ultrasound pulse velocity variations of concretes.

ultrasound pulse velocity since propagation velocity of ultrasonic pulses is quicker in a dense medium. As mentioned above, fly ash replacement along with waste marble aggregate incorporation results in increased unit weight owing to their effects on volume, however, the air content varied irregularly among specimens. Thus, in spite of the suggested increases in ultrasound velocity we would expect based on unit weights, it appears that porosity, as well as poor interfacial bonding results in weaker hydration, also exert significant effects. Consequently, velocity does indeed increase for A2 compared to A1, but owing to higher porosity and weak interfaces the velocity is slightly reduced for A3 and A4. Not surprisingly, A5, with the lowest unit weight, also has the lowest pulse velocity.

3.6. Hardness

The Schmidt hardness test is a popular nondestructive test method. A uniform compressive stress of 2.5 MPa is applied to the specimen along a vertical direction (the same as the casting direction) before striking the specimen with a hammer; this prevents dissipation of the hammer striking energy due to lateral movement of the specimen. Striking points were uniformly distributed to reduce the influence of local aggregates distribution and averages of the rebound energy calculated. The results are presented in Fig. 8. Schmidt hardness is a method related to compressive behavior since it is based on the rebound ratio from surfaces of samples. Therefore, similar behavior is observed between compressive strength and Schmidt hardness as seen in Figs. 6 and 8. Also, relations between them are presented in Fig. 9. Schmidt hardness values increase when age of concrete increases. The effect of fly ash on Schmidt hardness is not significant.

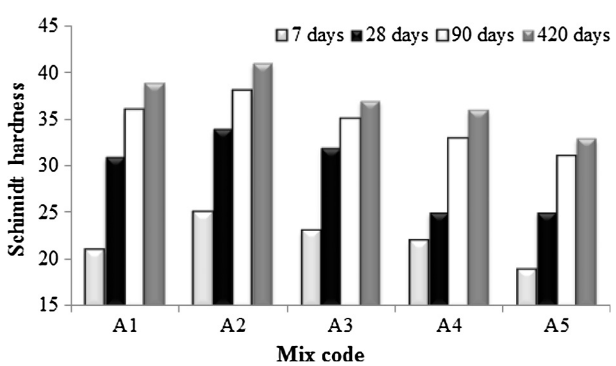

Fig. 8. Schmidt hardness variations of concretes.

3.7. Carbonation

Carbonation begins at the surface of concrete due to chemical reaction the hydration product $Ca(OH)_2$ and CO_2 of atmosphere. In this way, $Ca(OH)_2$ transforms to $CaCO_3$ which is a very hard and porous layer on the surface of concrete. This carbonated layer also has low compressive strength with respect to concrete. After that, CO_2 continues to penetrate through this carbonated layer and to react with $Ca(OH)_2$. As a result, carbonation leads to inner depths of concrete. As the carbonation continues, the carbonation depth increases with time.

As known, FA, as a pozzolanic mineral admixture, also reacts with the hydration product $Ca(OH)_2$ in concrete in order to produce additional calcium silica hydrate (CSH) gels and increase impermeability, unit weight and compressive strength while decreasing porosity especially at later ages. This statement is valid for all pozzolans. In this manner, FA and A5 reduce the $Ca(OH)_2$ content. Thus, $CaCO_3$ cannot form or else forms in little amounts. Thus, the carbonated layer cannot lead into the inner parts of specimens. This can clearly be seen in Fig. 10. When pozzolanic mineral admixture is employed, the carbonation depth is decreased compared to that of ordinary concrete produced with A1 type cement. Thus, carbonation depth has also been reduced with the increase in FA content, and the carbonation depth of A5 is likewise lower than A1 and even A2 thanks to the A5 pozzolanic cement. However, as evidenced by the results for A3 and A4, it seems that FA is more effective than A5 type cement at reducing the carbonation depth.

Fig. 9 verifies this observation. As seen in Fig. 9, the hardnesses of all series have relevant relationships with compressive strengths even after 90 days. Furthermore, the correlation coefficient between Schmidt hardness and the compressive strength, obtained by linear regression analysis, is $R^2 = 0.9715$ at the age of 420 days. Apparently FA, A1, A5 and waste marble fine-coarse aggregates have lower carbonation formation and lower carbonation depths than their counterparts without marble aggregates and pozzolanic admixtures. Therefore, the relationship between hardness and strength still remains relevant even after 420 days. If $CaCO_3$ continues to occur and carbonation depths increase, the Schmidt

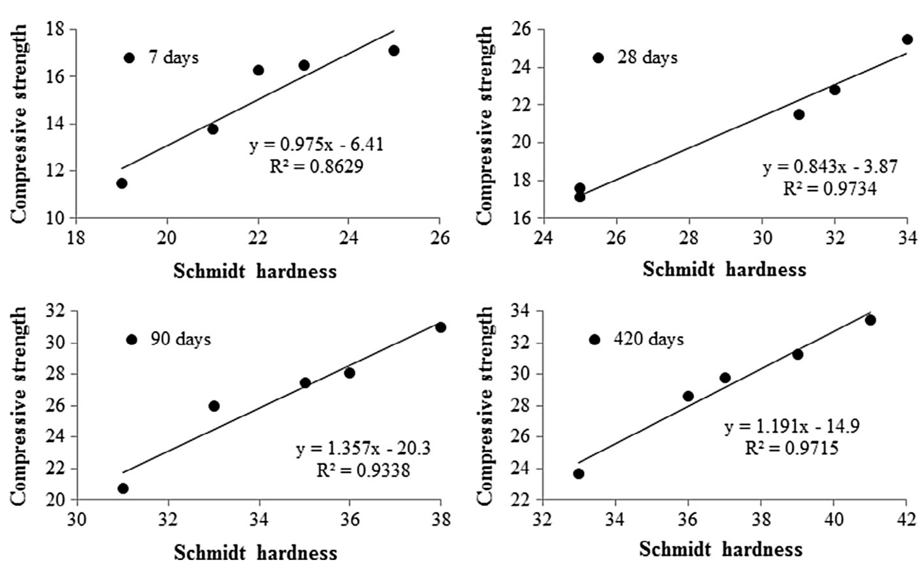

Fig. 9. Correlations between compressive strength and Schmidt hardness.

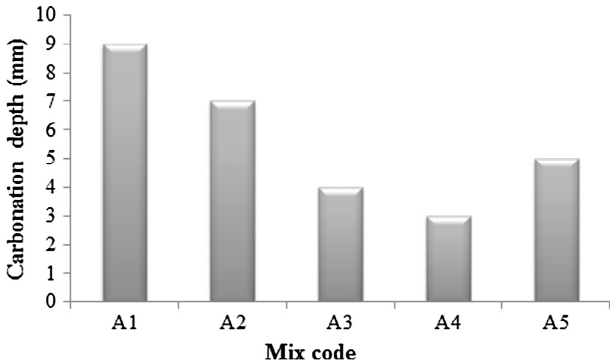

Fig. 10. Carbonation depths in specimens at 420 days.

hardness may not be able to predict compressive strength and both Schmidt hardness (rebound numbers) and ultrasonic pulse velocities have to be considered in order to estimate compressive strength by using non-destructive tests. In this manner, waste marble aggregate and pozzolans can make surface hardness easily used for estimating compressive strength by a non-destructive method.

We find that the paste volume and waste marble aggregate volume changes depending on FA content. Moreover, A5 also changes the volumes of these phases. André et al. [23] have indicated that carbonation depths of concretes containing coarse waste marble aggregate concrete are similar to those of the conventional concrete produced with natural aggregates such as basalt, limestone and granites. They replaced basalt, limestone, and granites with marble aggregates at different ratios. They found that with increasing bulk density, the carbonation depth decreased.

Gameiro and coworkers [37] reported that waste marble fine aggregate decreased carbonation depths when added as the secondary aggregate in granite aggregate specimens – but increased the carbonation depth when added to river sand concrete. Little effect on carbonation depth was observed for the addition of marble fine aggregate to basalt aggregate specimens. The changes appeared to be primarily due to variations in concrete permeability. Drawing from the results presented in [37], those of André et al. [23] and our own, factors such as porosity, permeability, interfacial adhesion and bulk density appear to be the larger determinants of carbonation depth—the inclusion of waste marble aggregate in and of itself does not have an entirely predictable effect on carbonation depth except as it affects these other properties.

4. Conclusions

Waste marble aggregates can improve the cohesion and workability of concrete. Pozzolans such as fly ash or pozzolanic cements contribute to and increase the intensity of this positive effect of waste marble aggregate. Waste marble aggregates and pozzolans do not have significant effects on air content of fresh concrete.

Waste marble aggregates yield concrete materials with unit weight, ultrasonic pulse velocity, Schmidt rebound numbers, and compressive strength similar—and sometimes better—to those of conventional concrete. Furthermore, FA and A5, pozzolans, may improve such hardened concrete properties.

The effect of waste marble fine and coarse aggregates on carbonation depths may not be clear. In this study, A5, FA (pozzolans) and FA replacement level contribute to reduction in the carbonation depths. Thus, waste marble aggregate concretes are less susceptible to carbonation, especially when they include pozzolans.

Waste marble aggregate concretes have sufficient physical, mechanical and durability properties to produce structural concrete similar to the conventional concrete produced with natural aggregates. Pozzolans can improve their properties. Therefore, waste marble aggregate can take place of natural limestone or such aggregates which are commonly used in concrete production. Furthermore, this is possible without the use of superplasticizers or any other chemical admixtures.

Utilizing waste marble aggregate at the replacement ratio of 100% along with waste marble dust, FA and pozzolanic cements in concrete will definitely lead to lower cost and environmental friendly concrete production with decreased consumption of natural resources and energy. In this manner, the use of A1 in concrete production and the production of natural aggregates can be reduced, while avoiding the use of chemical admixtures also improves the economical and environmental gains of waste marble aggregate concrete types. A further outcome of this method of concrete production is reduction of greenhouse gas emissions, and thereby also mitigation of air-environmental pollutions and global warming. Such concrete types we have described and produced will satisfy desired physical, mechanical, and durability properties and requirements of concrete produced with ordinary natural aggregates. In all these aspects, waste marble aggregate and waste marble dust along with pozzolans and pozzolanic cements in concrete will clearly improve the contribution of concrete industry to the sustainable development.

Acknowledgments

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