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# Use of waste marble and recycled aggregates in self-compacting concrete for environmental sustainability

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ABSTRACT

Nowadays, due to an increase in marble and concrete production, emerged wastes are disposed into empty fields. This waste causes environmental pollution. In this study, the use of marble waste (MW) and recycled aggregate (RA) from crushed concrete in the production of SCC was investigated. Control series were produced with crushed limestone aggregate (LS) in different water to binder ratios. Then, LS was replaced with MW or RA in ratio of 100%. Fresh concrete experiments such as slump-flow, the J-ring test, unit weight and air content were carried out. Furthermore, compressive strength, splitting-tensile strength, stress–strain relationship, modulus of elasticity and ultrasonic pulse velocity experiments on the hardened specimens were carried out, and mechanical properties of all the concrete types were compared. According to the results obtained, workability of SCC such as flow-ability, blocking resistance and segregation resistance is increased by use of pieces of MW instead of LS. Moreover, important differences were not observed in the mechanical properties of SCC by using MW and RA. For this reason, crushed marble stone and recycled coarse aggregates that were obtained using lower energy than that required for obtaining the LS, can be used in the SCC.



## 1. Introduction

In developing countries, the methods used to recycle and re-use waste materials should be investigated in order to benefit from natural resources effectively. Reuse of construction and demolition waste is one of the most important goals of the construction industry. Conversion of raw materials, used or waste materials provides significant energy savings by reducing the number of industrial processes in the production of materials (Ismail and Ramli, 2013). In our country, there are a lot of waste materials which have economic value. One of them is waste marble. Marble is a metamorphic rock, such as limestone, that contains largely calcium carbonate ($CaCO_3$) (Topçu et al., 2009; Topçu İB and Uygunoğlu, 2009). Furthermore, in marble, small amounts of silica, feldspar, iron oxide, mica, fluorine and organic matters may be found. Today, as a result of an increased demand for marble in our country and in the world in general, the number of marble businesses has also increased. The number of processed blocks of marble has also increased in facilities, due to the increase in production (Topçu et al., 2009; Saboya et al., 2007). The marble dust and crumbs of up to 60% of marble blocks are dumped into the streams near factories or in disposal sites (Cengiz and Kulaksız, 1996). Particularly, in areas where there is a concentration of marble business facilities, the marble waste causes the proliferation of the disposal sites (Terzi and Karaşahin, 2003; Hebhoub et al., 2011). In general, this type of waste is used as fill material in floor and wall tiles for decorative purposes. In the literature, many studies have been conducted on the use of waste marble dust. However, studies on the re-use of marble pieces are very limited (Terzi and Karaşahin, 2003; André et al., 2013; Thomas and Gupta, 2013; Gazi et al., 2012). The destruction of the environment would be reduced by the use of waste pieces of marble as aggregate in concrete. On the other hand, the use of marble waste will contribute directly to the evaluation of environmental waste.

Belachia and Hebhoub (2011) used waste marble as aggregate in concrete in ratios of 0%, 25%, 50%, 75% and 100%. The authors investigated the rheological properties of fresh concretes and mechanical properties of hardened concretes with different aggregate proportioning from waste of marble. They reported that high concrete strengths were obtained by the 25% substitution rate. The maximum density was obtained for concretes of a 50% substitution rate. Hence, it can be say that satisfactory workability and

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acceptable strengths were obtained in the study. The results show that recycled aggregates which come from marble waste can be used as alternate aggregates for their economic aspects. Topçu et al. (2009) carried out a study on the utilization of waste marble dust (MD) as a filler material, in self-compacting concrete (SCC). MD replaced the binder of SCC in contents of 0, 50, 100, 150, 200, 250 and 300 kg/m$^3$. Compressive and flexural strength, ultrasonic velocity, porosity and compactness were determined at the end of 28 days for the hardened concrete specimens. It was concluded that the mechanical properties of hardened SCC decreased by using MD exceeding 200 kg/m$^3$ in the contents. Hebhoub et al. (2011) used marble wastes as aggregate in normal strength concrete. They reported that the mechanical properties of concrete specimens produced using marble waste were found to conform with concrete production standards and that the substitution of natural aggregates by waste marble aggregates of up to 75% in any formulation, is beneficial for concrete resistance. Uygunoglu et al. (2012) studied the effect of fly ash content and replacement of crushed sand stone aggregate with concrete waste and marble waste on pre-fabricated concrete interlocking blocks (PCIBs). They compared properties of PCIBs such as compressive strength, tensile splitting strength, density, apparent porosity, water absorption by weight, abrasion resistance, alkali–silica reaction, and freeze–thaw resistance. When comparing the PCIBs with crushed sand stone, they stated that the replacement of crushed sand stone with concrete waste and marble waste results in lower physical and mechanical properties. Gencel et al. (2012) conducted a study on the usability of waste marble in the production of cement based pavement blocks. They reported that mechanical strength decreases with an increase in marble content while freeze-thaw durability and abrasive wear resistance increase. Waste marble is utilizable instead of the usual aggregate in the concrete paving block production.

One of the most important wastes, due to its wide range of reuse possibilities, is concrete waste from the construction industry and laboratory. The aggregates referred to as recycled aggregate are derived from the processing of materials previously used in a product or in construction. In particular, recycling of concrete members, which make up 37% of construction waste, is an important issue to be promoted (Eguchi et al., 2007). Etxeberria et al. (2007) investigated the influence of the amount of recycled coarse aggregates and the production process on properties of recycled aggregate concrete. They produced four different recycled aggregate concretes with 0%, 25%, 50% and 100% recycled coarse aggregates. The mixture proportions were designed in order to achieve the same compressive strengths. Recycled aggregates were used in a wet condition, but not saturated, to control their fresh concrete properties, effective w/c ratio and lower strength variability. The lower modulus of elasticity of recycled coarse aggregate concrete with respect to conventional concrete, was found. Tabsh and Abdelfatah (2009)a,b conducted a study on the effect of recycled concrete aggregates on strength properties of concrete. It was found that the strength of recycled concrete can be 10–25% lower than that of conventional concrete. Safiuddin et al. (2011) investigated the usability of recycled concrete aggregate (RCA) in new concrete. RCA was used as partial and full replacements of natural concrete aggregate to produce self-consolidating concrete (SCC). Different SCC mixtures were produced with RCA substituting 0%, 30%, 50%, 70%, and 100% natural concrete aggregate by weight. The test results revealed that the filling ability and passing ability of SCC improved for 30% and 50% RCA. The SCC mixtures with 30% and 50% RCA also possessed adequate segregation resistance. It is suggested that RCA can be used to produce SCC, substituting up to 50% without affecting the fresh properties of concrete.

Concrete remains an indispensable construction material and allows engineers to evaluate many materials by incorporating them into concrete. Thus, the use of waste materials, industrial waste in the production of concrete is growing in importance (Barrera-Diaz et al., 2011). Limestone is used in the production of about all concrete types due its many advantages. It is a material that can be found almost anywhere in our country. To obtain the aggregate from this material, limestone rocks are exploded and sieved with different mesh sizes. However, in order to obtain the aggregate, the environment is harmed. Even though there are some studies on the use of waste or recycled aggregates in concrete production, current field experience with the use of recycled concrete aggregates for structural applications is scarce. Because, comparing with the natural aggregates, the recycled aggregates density is lower and the water absorption is higher. These differences are due to the incrustation of cement paste on the recycled aggregates surfaces. Thus, the increased of the content of recycled aggregates in normal vibrated concrete, both coarse and fine, causes a loss of the mechanical properties. Furthermore, the coarse recycled aggregate shows a greater negative influence than the recycled fine aggregate (Pereira-de-Oliveira et al., 2014). This is probably due to that recycled aggregates has lower strength than natural aggregates. However, waste marble pieces are as strong as limestone aggregates (Uygunoglu et al., 2012). For this reason, in this study, the usability of waste pieces of marble as crushed stone instead of limestone in self-consolidating concrete (SCC) was investigated, and results are compared with ordinary and recycled aggregate concrete.

## 2. Experimental studies

### 2.1. Materials

In the study, crushed limestone origin aggregate (LS), recycled aggregate (RA) and marble waste aggregate (MW) with a maximum size of 22 mm were used. Marble waste aggregates were obtained by crushing and sizing marble pieces obtained from marble factories in Afyonkarahisar. The recycled aggregates were derived from crushed concrete in Afyon Kocatepe University, Civil Engineering Laboratory. Some properties of LS, RA and MW aggregates are presented in Table 1 (EN 1097-6, 2002; EN 1097-2, 2010; EN 933-3, 2012). Furthermore, the alkali reactivity of all the aggregates was investigated and a dangerous situation was not found as a reaction of the alkali-aggregate (Uygunoglu, 2009). Natural sand in the grain size of 0–4 mm was used as fine aggregate in all the series. The specific gravity and water absorption of the sand were 2.62 and 3.73% respectively. Portland cement (CEM I 42.5R) and Seyitömer fly ash (F class) were used as binding materials. The chemical properties of both materials are given in Table 2. To ensure the workability of the SCC mixtures, a new generation high range water reducing superplasticizer chemical admixture was used. Its specific gravity and solid content were 1.1 and 20%, respectively. Tap water was used in all the series.

### 2.2. Mix proportions and test program

In the production of all SCC series, cement and fly ash contents were kept constant at 350 kg/m$^3$ and 100 kg/m$^3$, respectively.

**Table 1**
Properties of aggregates.

| Properties | Limestone (LS) | Recycled limestone (RA) | Crushed marble-stone (MW) | Standard |
|---|---|---|---|---|
| Specific gravity | 2.72 | 2.44 | 2.77 | EN 1097-6 |
| Loss of wear, % | 23.2 | 39.3 | 34.9 | EN 1097-2 |
| Grain shape (flakiness) | 11.5 ($FI_{15}$) | 13.3 ($FI_{15}$) | 24.5 ($FI_{35}$) | EN 933-3 |

**Table 2**
Chemical components of Portland cement, fly ash and marble-stone.

| | | Cement, % | Fly ash, % | Marble, % |
|---|---|---|---|---|
| *Chemical properties* | | | | |
| CaO | | 63.56 | 0.67 | 51.8 |
| $SiO_2$ | | 19.3 | 46.51 | 4.67 |
| $Al_2O_3$ | | 5.57 | 25.47 | – |
| $Fe_2O_3$ | | 3.46 | 4.88 | 0.03 |
| MgO | | 0.86 | 15.94 | 0.4 |
| $SO_3$ | | 2.96 | 1.7 | – |
| $K_2O$ | | 0.8 | 1.35 | – |
| $Na_2O$ | | 0.13 | 0.36 | – |
| LOI | | 1.15 | 2.78 | 41.16 |
| $C_3S$ | | 66.75 | – | – |
| $C_2S$ | | 5.15 | – | – |
| $C_3A$ | | 8.9 | – | – |
| $C_4AF$ | | 10.53 | – | – |
| *Physical properties* | | | | |
| Initial setting time, h | | 2.52 | – | – |
| Final setting time, h | | 4.36 | – | – |
| Volume expansion, mm | | 3 | – | – |
| Blaine fineness, $cm^2/g$ | | 3212 | 6445 | – |
| Specific gravity | | 3.07 | 2.13 | – |
| *Mechanical properties* | | | | |
| Compressive strength, MPa | 7 days | 38.7 | – | – |
| | 28 days | 46 | – | – |

Therefore the total amount of binder content (cement plus fly ash) was 450 kg/m$^3$. Four different ratios, 0.31, 0.34, 0.37 and 0.40, were selected as the water-binder ratio. The chemical admixture content was different for each water-binder ratio, and it was reduced by an increase of the water content. Accordingly, the superplasticizer admixture was added to the mixing water in ratios of 2.4%, 2.1%, 1.8% and 1.5%. Different series were designed with all the aggregate types for each water-binder ratio. In the series, the grain size distribution was kept constant. Accordingly, a constant grain size distribution curve was obtained by the use of 60% of coarse aggregate and 40% of the fine aggregate. The sieve analysis for the aggregates used is given in Table 3. In the concrete mixtures, the crushed limestone aggregate was replaced throughout by MW and RA, respectively. Thus, the usability of MW and RA as aggregates was investigated. The material content per cubic metre is presented in Table 4. SCC mix design was performed according to absolute volume method. The unit composition of the series also given in Table 4. It would be clearly seen that aggregate content (S + A) of SCC series are decreased due to increase of water content. On the other hand, aggregate content was also changed by use of different type of aggregate for the same water to binder ratio. This differences between the sum of sand and aggregates for each series are due to specific gravity of aggregates.

On fresh SCC, unit weight, air content, slump-flow and J-ring experiments were carried out. The slump flow test was used to determine the ability of the SCC to flow in a non-restricted condition. To determine the slump flow the traditional hollow Abrams cone was placed on a slump flow plate with an edge length of 1000 × 1000 mm and filled with SCC and lifted slowly. In order to prevent any thixotropic effect, the Abrams cone was lifted immediately after having been filled with the SCC. The slump-flow of the final deformed, or slumped, SCC was measured by two perpendicular diameters, 2 min after the lifting of the cone (Fig. 1). During the slump-flow test, the required time of SCC to reach a 500 mm length slump-flow radius ($T_{500}$) was measured.

**Table 3**
Size distribution of the aggregates (passing, %).

| Sieve gap, mm | 0.25 | 0.5 | 1 | 2 | 4 | 8 | 16 | 22 |
|---|---|---|---|---|---|---|---|---|
| MW | 3.2 | 6.7 | 13.7 | 24.2 | 33.5 | 46.8 | 83.3 | 100 |
| RA | 3.2 | 6.7 | 13.7 | 24.2 | 33.5 | 55.8 | 92.3 | 100 |
| LS | 3.2 | 6.7 | 13.7 | 24.2 | 33.9 | 47.8 | 80.9 | 100 |

The J-ring test was used to assess the passing ability of the concrete in a restricted condition. To determine the slump flow in a restricted condition, the traditional hollow Abrams cone was placed centrally inside the J-ring on the slump flow plate with an edge length of 1000 × 1000 mm and filled with SCC and lifted slowly. The diameter of the ring of vertical bars is 300 mm, and the height is 100 mm. Similar to the slump-flow test, SCC was measured by two perpendicular diameters 2 min after the lifting of the cone. Furthermore, the difference in height between the concrete, just inside the bars and that just outside the bars, was measured (Fig. 2). On the outside of the J-ring, four measurements were taken as $k_1$, $k_2$, $k_3$ and $k_4$ around the ring in a perpendicular angle. The arithmetic average of the $k$ values ($k_1$, $k_2$, $k_3$ and $k_4$) was used for the outside height ($h_{\text{outside}}$) of the J-ring. Step-height ($\text{st}_\text{j}$) was determined by the difference of the outside ($h_{\text{outside}}$) and inside ($h_{\text{inside}}$) concrete height in the J-ring by Eq. (1). Then, a blocking index was defined using Eq. (2) dependant on step-height (Fig. 2).

$$\text{st}_\text{j} = (h_{\text{outside}} - h_{\text{inside}}) = \left[\left(\frac{k_1 + k_2 + k_3 + k_4}{4}\right) - h_{\text{inside}}\right] \quad (1)$$

$$\beta j = \frac{V_{\text{blok}}}{V_c} = \frac{\frac{\pi D^2}{4}\cdot \text{st}_\text{j}}{V_c} \quad (2)$$

Finally, the fresh concrete was placed into cylindrical and cubic moulds in the size of Ø150 × 300 mm and 150 × 150 × 150 mm, respectively. The specimens were de-moulded after 24 h, and they were cured in lime saturated water (20 ± 2 °C) until the day of the experiments. Compressive strength tests were performed on the cube specimens at 7 and 28 days according to EN 12390-3 (2010). Splitting strength was defined on 28 aged cube specimens in accordance with TS 3323 (2012). These were carried out along the sections of the concrete specimens. A load was then gradually applied and the test was terminated when the specimen split into two halves. The failure load was recorded and the tensile splitting strength was calculated based on the failure load. Furthermore, ultrasonic pulse velocity tests were performed on cube specimens before the compressive test.

The load–displacement values were taken on the cylindrical specimens with a strain-gauge possessing a sensitivity of 0.2%. For this purpose, a fully automatic compressive test machine with a capacity of 2000 kN was used. Deformations were taken approximately at every time increment of 6 s with an extensometer. Strains and corresponding stress were calculated and then stress-strain curves were drawn for each series, with stress at the vertical axis and strain at the horizontal axis. The method of secant modulus was used to determine the modulus of elasticity of the concrete series from these curves. Three samples are used for all the experiments from each series.

## 3. Results and discussions

### 3.1. Fresh SCC properties

Using different types of aggregates with a water to binder (w-b) ratio from 0.31 to 0.34 (Fig. 3), it was observed that the slump-flow values of the SCC series, LS, RA and MW, ranged between 500 and 650 mm. The slump-flow values increased with an increase in water-binder ratio for each series. The slump-flow value of SCC with LS, RA and MW was 530, 505 and 535 mm, respectively, in a 0.31 w-b ratio. When the w-b ratio was 0.40, the slump-flow value reached 645, 590 and 635 mm for SCC with LS, RA and MW

**Table 4**
Component of materials for SCC series.

| Series | w-b ratios | Unit ratio | Materials, kg/m$^3$ | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | C:S:A:FA:w-b | Cement (C) | Sand (S) | SP[a] | Water (W) | FA[a] | Aggregate (A) |
| LS-1 | 0.31 | 1:2:2.8:0.28:0.31 | 350 | 720 | 10.8 | 140 | 100 | 986 |
| LS-2 | 0.34 | 1:2:2.76:0.28:0.34 | 350 | 706 | 9.5 | 153 | 100 | 966 |
| LS-3 | 0.37 | 1:1.97:2.7:0.28:0.37 | 350 | 692 | 8.1 | 167 | 100 | 947 |
| LS-4 | 0.40 | 1:1.94:2.65:0.28:0.40 | 350 | 678 | 6.8 | 180 | 100 | 927 |
| MW-1 | 0.31 | 1:2:3.17:0.28:0.31 | 350 | 720 | 10.8 | 140 | 100 | 1109 |
| MW-2 | 0.34 | 1:2:3.1:0.28:0.34 | 350 | 706 | 9.5 | 153 | 100 | 1087 |
| MW-3 | 0.37 | 1:1.97:3:0.28:0.37 | 350 | 692 | 8.1 | 167 | 100 | 1065 |
| MW-4 | 0.40 | 1:1.94:2.98:0.28:0.40 | 350 | 678 | 6.8 | 180 | 100 | 1043 |
| RA-1 | 0.31 | 1:2:2.86:0.28:0.31 | 350 | 720 | 10.8 | 140 | 100 | 1002 |
| RA-2 | 0.34 | 1:2:2.81:0.28:0.34 | 350 | 706 | 9.5 | 153 | 100 | 982 |
| RA-3 | 0.37 | 1:1.97:2.75:0.28:0.37 | 350 | 692 | 8.1 | 167 | 100 | 963 |
| RA-4 | 0.40 | 1:1.94:2.69:0.28:0.40 | 350 | 678 | 6.8 | 180 | 100 | 943 |

[a] SP: Superplasticizer; FA:fly ash.

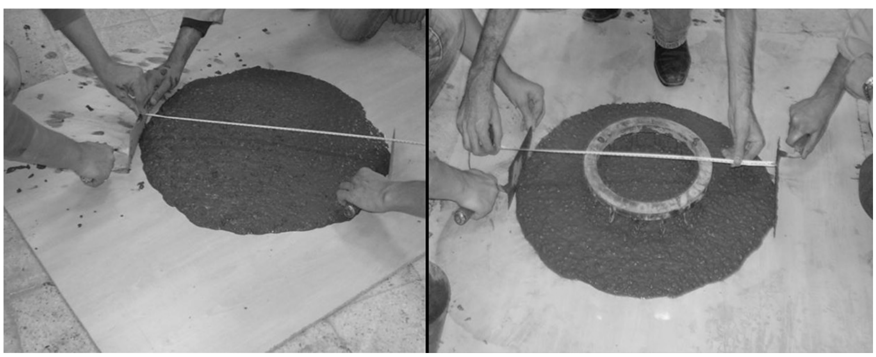

**Fig. 1.** Free and restricted slump-flow.

respectively. When the w-b ratio was considered, the slump-flow value of SCC with LS increased in ratio to 2.8%, 14% and 22%, due to an increase of the w-b ratio from 0.31 to 0.40. The slump flow increased in ratio of 6%, 8% and 17%; and increased in ratio of 4%, 16% and 19% for SCC with RA and MW, respectively, for the same w-b ratio increment. This can be attributed to the higher water content in the mixtures increasing the lubrication between the aggregate particles and thus, decreasing the yield stress and easing the flow ability of the concrete (Roussel et al., 2005). The slump-flow reached the maximum value when LS was used in the production of SCC, regardless of the w-b ratio, except for MW series at the lowest w-b ratio. This was due to the surface structure of RA and MW being rougher than LS. Also, recycled concrete mixtures require more water than conventional concrete to maintain the same slump without the use of admixtures. This affects the quality and strength of the concrete, resulting in lower concrete strength (Brostow and Uygunoğlu, 2014; Sago-Crentsil et al., 2001; Ajdukiewicz and Kliszczewicz, 2002).

It was observed that the unit weight of all fresh concrete series increased in all the water to binder ratios by use of MW aggregate in the production of SCC, when compared to the other series (Table 5). This is due to the higher specific gravity of marble aggregates compared to limestone and recycled aggregates. However, the density of the recycled aggregates is lower than the natural aggregates. As a result, a lighter SCC can be obtained the desired qualities for concrete made with recycled aggregates. Thus, formwork pressure would be decreased by use of SCC with lower unit weight than traditional concrete. On the other hand, an important change was not observed in the air content of either type of series. The air content of concrete with all types of aggregate decreased with an increase of the w-b ratio due to the placement of high workability concrete into the mould.

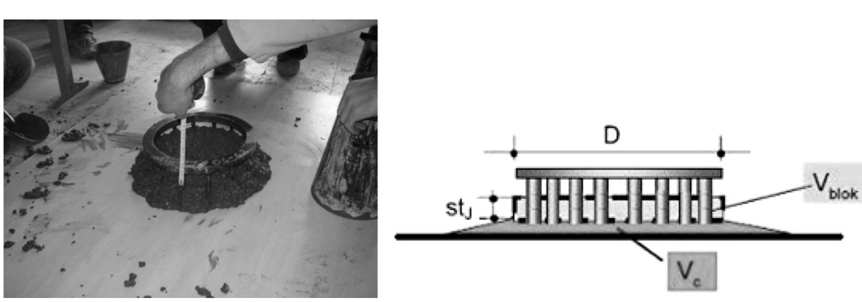


**Fig. 2.** Measurement of blocking concrete in J-ring.

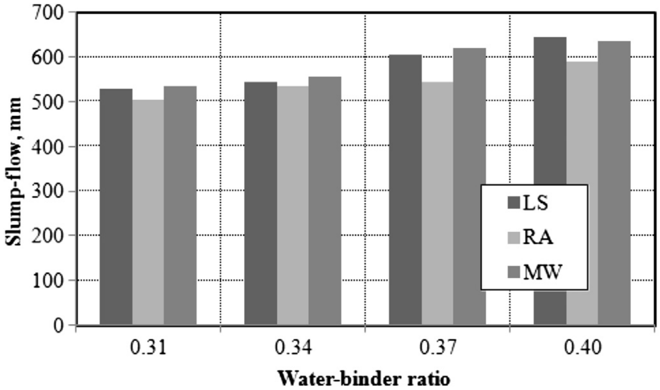


**Fig. 3.** Slump-flow test on SCC with different type of aggregates.

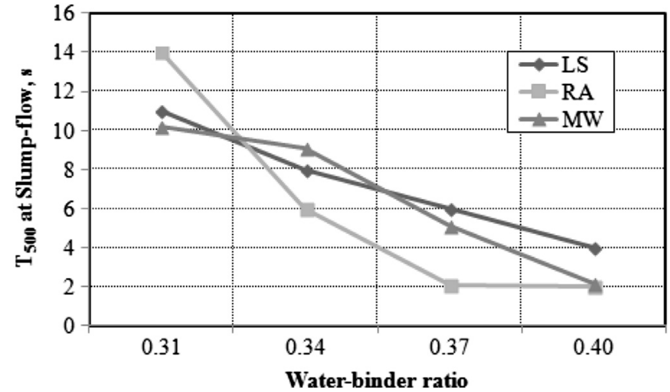


**Fig. 4.** Time to $T_{500}$ during the slump-flow test.

The change of the $T_{500}$ time of SCC with different types of aggregate, dependant on the w-b ratio, is given in Fig. 4. The $T_{500}$ time is an indicator of viscosity. In other words, the viscosity increases with an increase of the $T_{500}$ time. However, it must be kept in mind that $T_{500}$ time is often used to estimate the apparent viscosity of a mixture. Many factors influence the results of the $T_{500}$ time: the amount, shape and size distribution of aggregates and also the viscosity and amount of paste and so on. This means that the $T_{500}$ time does not necessarily correspond with the viscosity of a mixture measured, for example, by a rheometer (Uygunoglu and Topçu, 2011). Also, the shapes of crushed aggregates are often more angular and have rougher surfaces than natural aggregates. Plain and self-consolidating concrete with crushed aggregate often requires higher cement and water content in order to reach the same workability as concrete with spherical aggregates. The results indicate that the lowest $T_{500}$ time was obtained on SCC with RA after the w-b ratio of 0.34. This is due to the fact that the SCC mortar easily moves the RA aggregates which are lighter than the LS and MW aggregates. On the other hand, the highest viscosity was observed on SCC with RA at the lowest w-b ratio. The viscosity of SCCs with LS, RA and MW is within the limits according to the limit values (6–12 s) given by EFNARC (2002), in general, w-b ratios of 0.31 and 0.34.

The variations of the slump-flow in free and restricted conditions are compared in Fig. 5a–c for SCC with LS, RA and MW, respectively. As seen, the slump-flow value was lower in the J-ring slump flow test than the free slump-flow due to obstacles. It can be noted from Fig. 5a–c that the lowest slump-flow difference in between free and restricted conditions is obtained in the highest w-b ratio, regardless of aggregate type. The passing ability of SCC with a w-b ratio of 0.40 is too high with all the aggregate types. However, the slump-flow difference between "with" and "without restriction" increased with a decrease in water-binder ratio (w-b) for each series, regardless of the aggregate type. This was due to the fact that SCC in a low w-b ratio was blocked between the obstacles because of high viscosity. When aggregate type is considered, it can be clearly seen that the highest slump-flow difference was obtained in SCC with recycled aggregates due to a rough surface covered with mortar.

The effect of the aggregate type on the blocking index of SCCs depending on the w-b ratio is shown in Fig. 6. With the increase in the w-b ratio, there is a substantial decrease in the blocking index. It is evident that for a given aggregate type, a lower w-b ratio leads to a lower passing ability of SCC, due to the low lubrication between the aggregate particles. The high blocking index value is an indication of a blocking risk of SCC. When aggregate type is considered, it can be clearly seen in Fig. 6 that the blocking index ($B_j$) of SCC with MW is lower than that of SCC with LS and RA for all the w-b ratios. $B_j$ of SCC with MW was 0.62, 0.58, 0.51 and 0.41, respectively, in w-b ratios of 0.31, 0.34, 0.37 and 0.40. The highest blocking risk was observed in SCC with RA. SCC with high blocking ratio is resulted with low pump-ability in site. It ranged from 0.68 to 0.54 depending on the w-b ratio, while it changed from 0.65 to 0.50 for the SCC with LS. When the fresh properties of SCC are considered, it would be seen that the best behaviour both in terms of flowability, blocking resistance and flow-segregation resistance was obtained for the SCC with pieces of MW as aggregate at the low w-b ratio.

**Table 5**
Experimental results for concretes with limestone and marble aggregate.

| Series | w-b ratios | Fresh concrete | |
|---|---|---|---|
| | | Unit weight, kg/m$^3$ | Air content, % |
| LS-1 | 0.31 | 2320 | 2.1 |
| LS-2 | 0.34 | 2339 | 2.1 |
| LS-3 | 0.37 | 2309 | 1.7 |
| LS-4 | 0.40 | 2307 | 1.5 |
| MW-1 | 0.31 | 2394 | 2.0 |
| MW-2 | 0.34 | 2377 | 1.85 |
| MW-3 | 0.37 | 2347 | 1.80 |
| MW-4 | 0.40 | 2327 | 1.55 |
| RA-1 | 0.31 | 2240 | 8 |
| RA-2 | 0.34 | 2230 | 2.1 |
| RA-3 | 0.37 | 2190 | 2 |
| RA-4 | 0.40 | 2180 | 1.9 |

### 3.2. Hardened SCC properties

#### 3.2.1. Compressive strength

The compressive strength of 7 aged SCC produced with LS aggregate varied between 50 and 39.4 MPa (Fig. 7) while the compressive strength of 28 aged concretes values had between 57 and 55.6 MPa depending on the water-binder ratio (Fig. 8). A replacement of LS with RA or MW aggregate resulted in a decrease in the compressive strength, especially for 28 days. Aggregates have a very significant effect on the strength properties of SCC. The effect of the strength properties of cement paste increased with the interfacial bond strength of the cement paste-aggregate. In addition to the strength properties of SCC, many other properties of SCC are also controlled by properties of the aggregate. The reduction in compressive strength is related to the weakness, shape, and grain size distribution of recycled aggregates (Xiao et al., 2005). When the compressive strength of SCC with MW varied between 44 and 34 MPa for 7 days, it ranged between 53.6 and 38 MPa for 28 days. It varied between 49 and 42 MPa for 7 days, and varied between 54 and 51.7 MPa for the SCC series with RA dependant on the water-

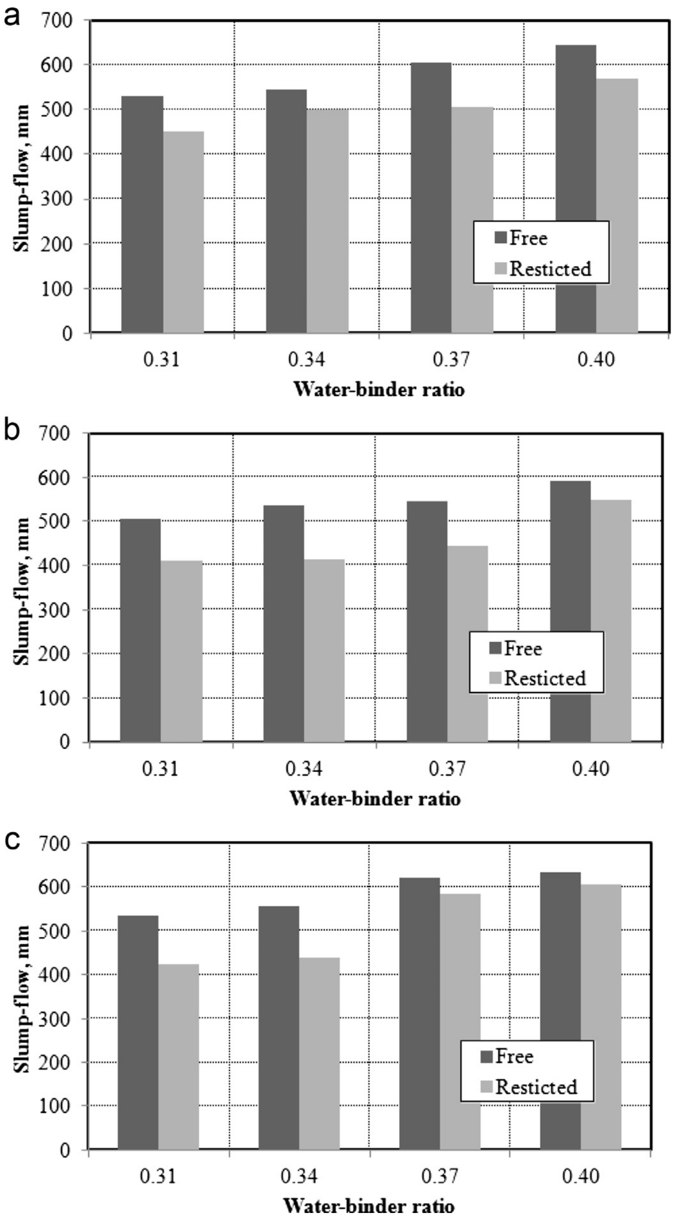


**Fig. 5.** a. Free and limited slump-flow of SCC with LS. b. Free and limited slump-flow of SCC with RA. c. Free and limited slump-flow of SCC with MW.

binder ratio for 28 days. In the lowest water-binder ratio (w-b: 0.31), the reduction ratio in compressive strength values of the MW and RA series were 6% and 5.6%, respectively, compared to the LS series, for 28 days. However, for the same aged SCCs, the reductions in the compressive strength value of the MW and RA series were 31.5% and 7% compared to the LS series in the highest water-binder ratio (w-b: 0.40). The compressive strength of SCC with the LS, RA and MW series decreased when the water to binder ratio increased. However, the decrease in the MW series was higher than that of other series. Although the MW aggregate has lower wear strength than RA, the lowest compressive strength values were obtained in SCC with MW. This is due to the fact that the MW aggregates are flakier in shape than LS and RA, and it results with increase of bleeding in SCC at the highest water to binder ratio.

### 3.2.2. Splitting strength

In all of the SCC series, tensile strength decreased due to a reduction of adherence in the interfacial transition zone (ITZ) of aggregate and the hydrated cement matrix by increment of the water to binder ratio (Fig. 9). However, the difference between the splitting strength of SCC with the LS and RA series was lower than that of the difference between the LS and MW series. While the splitting tensile strength of SCC with LS ranged between 3.5 and 2.8 MPa depending on the water-binder ratio, it ranged between 3.1 and 2.4 MPa and ranged between 3.7 and 2.8 MPa, respectively, for the SCC with MW and RA aggregates at 28 days. The SCC with RA had a higher splitting strength (5.7%) than that of LS, at a w-b ratio of 0.31. However, the difference between the splitting tensile strength of the LS and MW series increased when the water to binder ratio increased. The most important reason for this is that the MW series had more flaky aggregate than the LS and RA series. Thus, these shapeless types of aggregates caused the decrease of adherence between the aggregate surface and the hydrated cement matrix. On the other hand, coarse aggregates have a significant effect on the compressive and tensile strength. Marble aggregates have a lower strength compared to limestone aggregates (Wu et al., 2001). Therefore, the tensile and compressive strength of the MW series has lower values according to the LS series. Similar results were also observed by Wu et al. (2001). In their study they reported that high strength concrete with marble aggregate has lower flexure and compressive strength when compared to high strength concretes with limestone aggregates.

### 3.2.3. Stress and strain behaviour

The strain capability under stress and the concrete modulus of elasticity are fundamental parameters necessary in structural

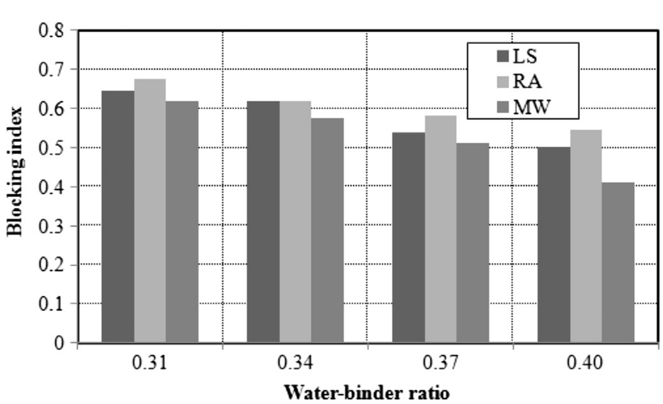


**Fig. 6.** Blocking index of SCC with different type of aggregates.

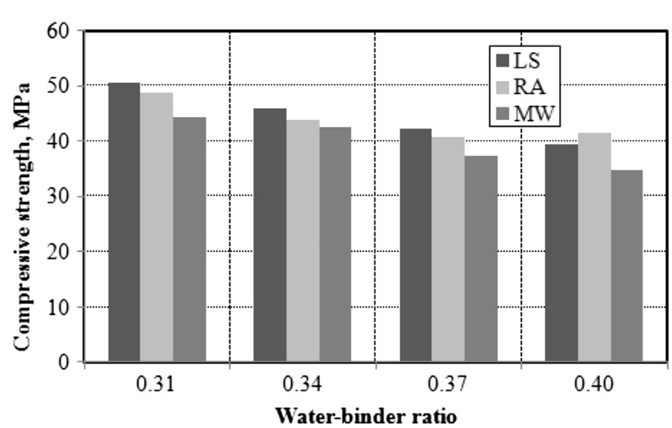


**Fig. 7.** Comparison of compressive strength of 7 aged specimens.

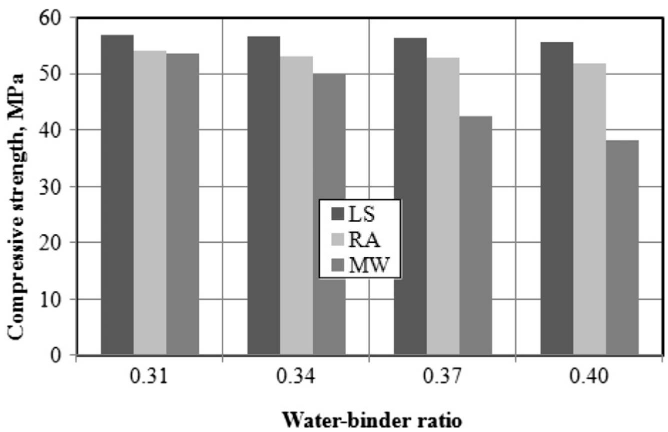


**Fig. 8.** Comparison of compressive strength of 28 aged specimens.

analysis for the determination of the displacements and strain distributions, especially when the design is based on elasticity considerations. In Fig. 10a–c, stress-strain curves obtained from load–deformation values can be seen for SCC with LS, RA and MW aggregates. The LS series has a very rigid structure in each water-binder ratio. However, the MW and RA series are more ductile when compared to the LS series. It can clearly be seen that SCCs with the LS, RA and MW series have different strain values for a given stress value. For the same stress value, the MW and RA series have higher strain values than that of the LS series at a constant water to binder ratio. The cubic shape of aggregates and the rough surface of aggregates prevent the micro-crack formation in the interfacial zone of the aggregate-hydrated cement matrix, and they also delay the crack-growth (Neville and Brooks, 1987; Erdoğan, 2003; Topçu and Uygunoglu, 2008). This situation makes the concrete more brittle (Alexander and Milne, 1995; Alexander, 1996; Özturan and Cecen, 1997). When the w-b ratio is considered, the strain of the SCC series corresponding to the maximum stress of the stress-strain curve was the largest at the lowest water-binder ratio. However, the strain ability of SCCs decreased rapidly with the increase of the w-b ratio. The stress-strain relationship of concrete has a curved shape, due to the fact that aggregate and cement paste, having different stiffness characteristics, are connected in one bearing system. In concrete types where the stiffness of the matrix is close to the stiffness of the aggregate, the stress-strain relationship of concrete will also be close to linear. It can also be clearly seen that SCC with MW has the highest strain capability. The strength of the mortar in the SCC with LS, RA and MW is approximately the same, and the difference in strength between these concretes has mainly to do with the quality of the coarse aggregate types. MW is a more flaky aggregate when compared to RA and LS. However, the surface of RA is covered with hydrated cement. These hydrated mortars cause the lower stiffness of the aggregate. Thus, SCC with lower strength and flaky aggregates shows higher strain ability and lower strength under compression stress (Corinaldesi, 2010; Matias et al., 2013).

### 3.2.4. Modulus of elasticity

The static modulus of elasticity for SCC obtained from the stress-strain curves was compared with the LS, RA and MW series in Fig. 11. In general, high modulus of elasticity values were obtained in the LS series when compared to the RA and MW series. In the lowest w-b ratios, the elasticity modulus of the MW and RA series was almost 33% and 5.3% lower than that of LS series, when the reduction ratio was 57.3% and 54.7% at the highest w-b ratios, respectively. The factors on the stress-strain curves also directly affected the modulus of elasticity. The roughness of the surface structure of aggregates and the shape of aggregate in the concrete plays an important role in the interfacial zone of the aggregate and hydrated cement matrix. The adherence between the aggregate-hydrated cement matrix is decreased by an increase of the amount of imperfect aggregate. As a result, the elastic modulus of concrete was decreased (Neville and Brooks, 1987; Erdoğan, 2003; Topçu and Uygunoglu, 2008). On the other hand, the modulus of elasticity of all the SCC series was reduced by an increase in the water to binder ratio. The most important reason for this is that the shear stress in the aggregate-cement interfacial zone is easier exceeded due to the amount of increase of porous medium by an increase of the water to binder ratio, and thus, the material has a higher strain capability (Alexander, 1996). In other words, the modulus of elasticity of materials decreases (Alexander and Milne, 1995). The reduction in elasticity of the MW series depending on the water-binder ratio was higher than that of the LS and RA series. Also, the use of high percentages of recycled aggregates in concrete would usually worsen the concrete properties (Kovler and Roussel, 2011). RA concrete has higher water demand and gave lower compressive strength than control concrete made from natural aggregate. At an equal water to binder ratio RA concrete has lower elastic modulus than the control series (Sagoe-Crentsil et al., 1996; Ravindrarajah, 1996; Topcu and Sengel, 2004).

The correlation between the modulus of elasticity and the compressive strength of the SCC mixtures, regardless of the water to binder ratio and aggregate type, is presented in Fig. 12. A suitable linear relation is developed between E-moduli and compressive strength for various grades of SCC ranges from 15 to 56 MPa. It can clearly be seen in Fig. 12 that the modulus of elasticity increases linearly with the increase of the compressive strength of the mixtures. A relation has been proposed, which is suitable for all types of SCC. The proposed equation is given by:

$$E = 2.177 fc - 49 \tag{3}$$

Where $E$ is modulus of elasticity (MPa); and $fc$ is cylinder compressive strength (MPa).

In the codes and standards related with the design of concrete structures, the modulus of elasticity of concrete is usually proposed by empirical equations depending on a function of the compressive strength of concrete. Therefore, the E-moduli values that obtained experimentally are compared with codes and standards, and it was observed that they are relatively high when comparing them with the recommendations found in ACI 318 (2002) and TS 500 (2000). The following equations are recommended by ACI 318 (2002) and TS 500 (2000) for the relationships between compressive strength (fc) and the E-moduli is as follows for plain concretes:

$$\text{(ACI) Ec} = 4730 \times (f_c)^{1/2} \tag{4}$$

$$\text{(TS 500) Ec} = 14000 + 3250 \times (f_c)^{1/2} \tag{5}$$

The power functions given by ACI 318 and TS 500 are proposed for normal concretes. Experimental E-moduli is lower than proposed power functions up to 35 MPa. This is because of the SCC includes higher hydrated mortar than normal concrete. The modulus of elasticity of concrete depends upon the modulus of elasticity of the hydrated cement matrix, type and content of aggregates, the water to binder ratio, and the volume of the cement (Topçu and Uygunoglu, 2010).

### 3.2.5. - Ultrasonic pulse velocity

When the ultrasonic pulse velocity (UPV) values that were measured on all types of SCC were examined (Fig. 13), it was seen

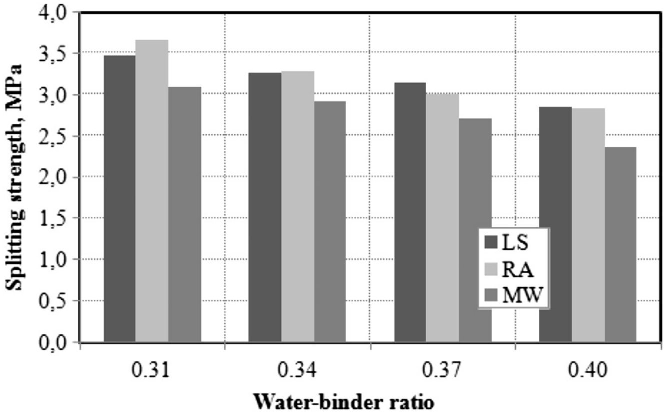


**Fig. 9.** Comparison of splitting tensile strength of 28 aged specimens.

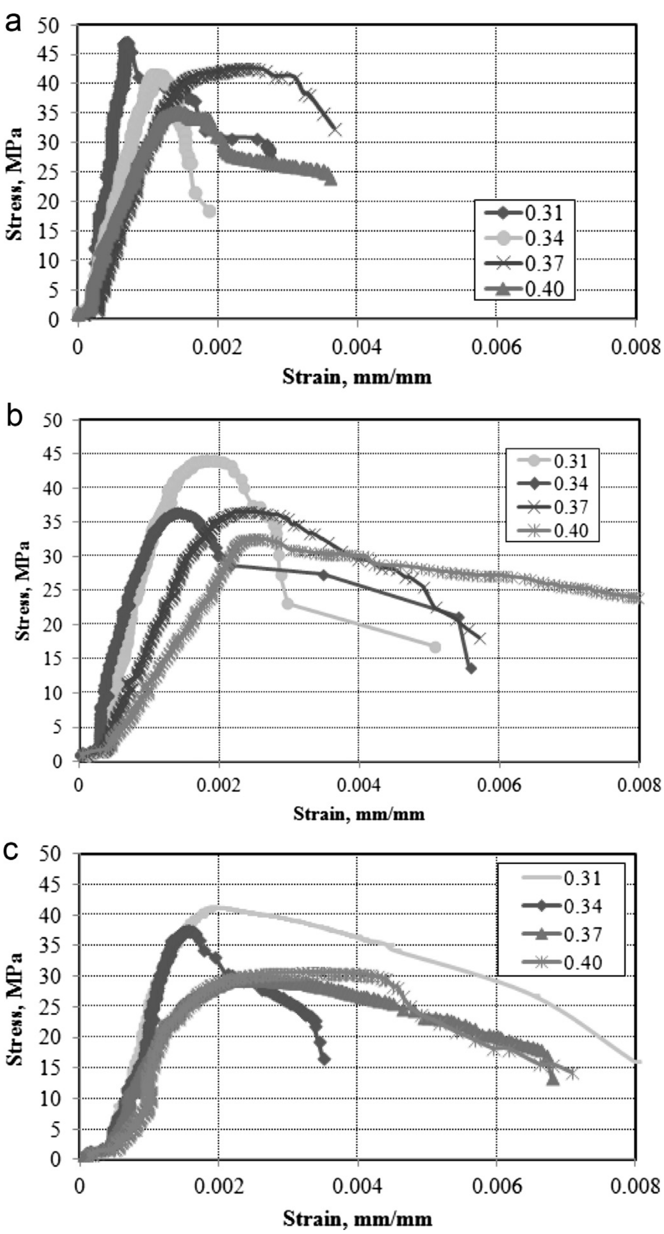


**Fig. 10.** a. Stress-strain curves for LS series. b. Stress-strain curves for RA series. c. Stress-strain curves for MW series.

that the UPV values of LS decreased very little by an increase of the water-binder ratio. The situation was the same for the RA and MW series, but, the UPV values for the RA and MW series were lower than those of the LS series. However, for MW, this difference was about 0.4% and 4.7% at a w-b ratio of 0.31 and 0.40, while it was 6% and 13.7% for RA series at the same w-b ratios. All concretes are classified as high quality concrete based on UPV values (Erdoğan, 2003). UPV can be evaluated as an indicator of the amount of pore medium in the concrete (Yaşar et al., 2004). Therefore, it can be said that the concretes contain a small amount of space due to the UPV values for all water to binder ratios.

When all the experimental results are considered, it can be seen that there are not important changes in the mechanical properties of the series in the lowest w-b ratio when compared to the control series in the case of the utilization of waste marble pieces and recycled aggregate in the SCC. It is well known that a large quantity of concrete wastes often generates from demolished old structures, tested concrete, and excess or returned concrete. The removal and disposal of these wastes cause significant environmental problems. In this context, the recycling of concrete wastes and marble wastes is important because it can minimize the environmental pollution and reduce the huge consumption of natural aggregates in construction (Safiuddin et al., 2011). Therefore, environmental pollution can be reduced for sustainability of structures and more efficient use of existing fields can be created by evaluation of marble waste as aggregate in concrete (Katz, 2003). Moreover, the destruction of nature to obtain the aggregate would be prevented.

## 4. Conclusions

In this study, evaluation of waste marble pieces and recycled aggregates instead of limestone aggregates for use in self-consolidating concrete production was investigated. The results obtained are summarized below:

- The experiment results showed that the workability of SCC strongly depends on characteristic properties of aggregate such as unit weight (or bulk density), shape and surface texture. However, the significance of aggregate characteristics becomes less important as the w-b ratio increases. The highest passing ability and filling ability were obtained in SCC with LS and MW aggregates.
- A lighter SCC can be obtained the desired qualities for concrete made with recycled aggregates. Thus, formwork pressure would be decreased by use of SCC with lower unit weight than traditional concrete.
- The compressive strength of concrete with waste marble and recycled aggregate in the lowest water to binder ratio was lower

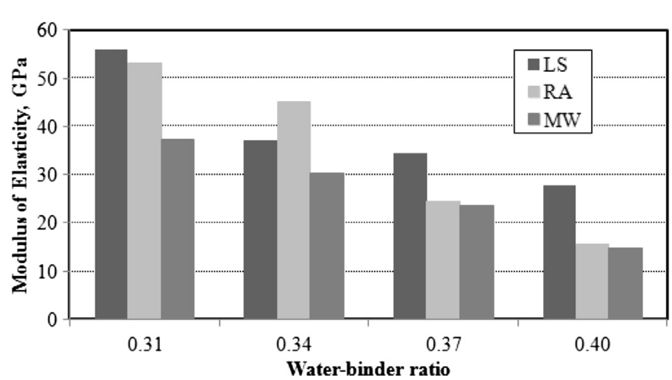


**Fig. 11.** Comparison of modulus of elasticity for SCC series.

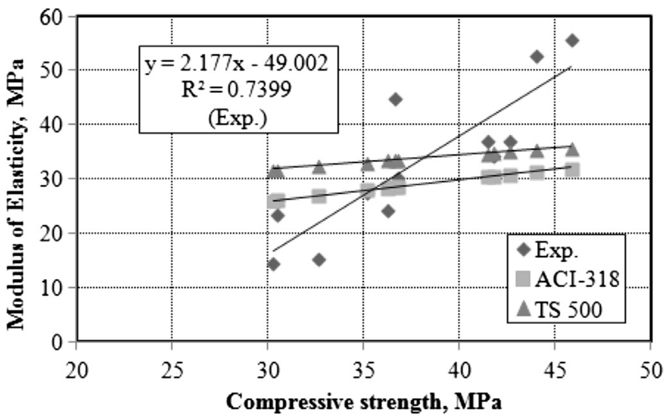


**Fig. 12.** The relationship between E-moduli and compressive strength.

in 6% and 5.6%, respectively, than the compressive strength value of SCC with limestone aggregate. However, the reduction in the compressive strength value of the MW and RA series was 31.5% and 7% compared to the LS series in the highest water-binder ratio (w-b: 0.40). In general, there was not an important strength reduction when using marble or recycled aggregates instead of limestone aggregate in SCC at low w-b ratios.

- In the SCC with RA and MW aggregate, lower strength and higher strain capability corresponding to the maximum stress was found when compared to stress-strain curves of SCC with LS. Moreover, a replacement of LS with MW and RA causes a decrease in the modulus of elasticity compared with that of SCC due to lower strength. On the other hand, a suitable linear relation is developed between the E-moduli and compressive strength for various grades of SCC ranges from 15 to 56 MPa.
- The required strength grade can be obtained by keeping the water-binder ratio low. In this way unit costs of buildings depending on aggregate and concrete cost would be decreased, hence of economic benefit. On the other hand, environmental pollution would also be reduced by evaluation of waste marble and recycled aggregate which is environmental, and industrial waste in the production of SCC.

Consequently, the mechanical properties of concrete were investigated by replacing limestone aggregate with waste marble, and it was proposed that the durability of concrete can be studied in further investigations. The self-compacting concrete mixture seems to be achievable by the simultaneous use of marble waste

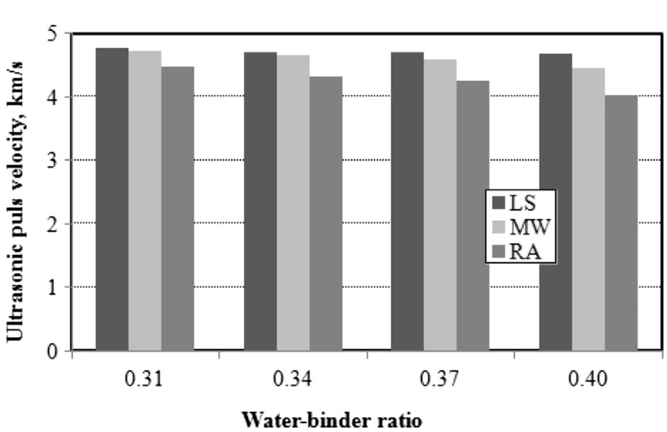


**Fig. 13.** Comparison of ultrasonic pulse velocity of the SCC series.

with improved fresh concrete performance and unchanged concrete mechanical strength. The marble wastes and recycled aggregates can be used in the production of self-consolidating concrete as aggregate, and thus an advantage can be provided in terms of the sustainability of buildings and the environment.

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