A comparative analysis of elasticity modulus of recycled aggregate concrete with silica fume

Silis dumanı katkılı geri kazanılmış agregalı betonların elastisite modüllerinin karşılaştırılarak analizi

Abstract

Recycling of waste materials has significant influence on the concept of sustainability in construction industry due to the conservation of natural resources and minimizing the environmental impacts which leads to habitable future. Construction activities, in general, result in huge amount of construction and demolition waste (C&DW) and C&DW has a great potential for possible disposal as recycled aggregate (RA) in civil engineering applications, especially in recycled aggregate concrete (RAC), after recycling processes. In this concept, concrete mixtures including RA and silica fume (SF) at various ratios (0-30-40-70-100%) and (0-5-10%), respectively, are produced in order to determine the elasticity modulus of RAC. This work aims to examine elasticity modulus of RAC determined according to the formulas of standards and studies. Analytical and statistical assessments are performed and experimental and theoretical results are compared. When RA content increases, the elasticity modulus decreases. SF utilization in RAC improves the mechanical parameters (elasticity modulus and compressive strength). The American standard (ACI 318-05) predicts the elasticity modulus approximately to the experimental results although it has the highest relative standard deviations in comparison to the regarded standards. Moreover, proposed equations for RAC by researchers estimate the elasticity modulus values greater than those of standards and the experimental results. An elasticity modulus equation is also proposed for RAC with and without SF.

Keywords: Recycled aggregate concrete, Silica fume, Elasticity modulus, Standards

1 Introduction

The change in the human demands requires much more resources due to overconsumption. Hence, it causes intensive utilization of natural sources in many countries. As a result, aggregate shortage for concrete production commences to occur [1]. Moreover, rapid growing of urbanization around the world produces great-amount of construction and demolition waste (C&DW). It is clear that disequilibrium between the excessive usage of natural sources and increasing amount of C&DW is in contradiction with the sustainability concept. The gap between excessive consumption of natural resources and C&DW generation is growing day after day. Nowadays, in order to amend the disequilibrium, the researches are conducted with a aim of C&DW use in concrete as recycled aggregate (RA), and many of studies intend to examine the RA effect on concrete behaviour (fresh state and hardened state) [2]-[4]. Using RA reduces the need for virgin aggregates but modifies the engineering parameters of concrete.

Design parameters of materials are crucial for engineering structures. In many times, it may not be possible to conduct all material tests due to limited time, high costs of tests etc. Hence the strong relations between material properties are used to obtain approximate value of engineering parameters. The relationship among engineering parameters of concrete is well-known (i.e., elasticity modulus-compressive strength relation). In this concepts, many codes present formulas to estimate approximate values of elasticity modulus [5]-[10]. For instance,

Öz

Atık malzemelerin geri dönüşümü, doğal kaynakların korunmasından ve yaşanabilir bir gelecek için önemli bir eylem alanıdır. Yapım ve inşaat sektöründe sürdürülebilirlik kavramı üzerinden öneri ve çaba sahiptir. Yapım işlemleri, genellikle, yüksek miktarda yapı ve yıkıma uğrada (YYA) olup çöpüne sonucu vermek ve geri dönüştüm işlemi ardından YYA bertaraf edilmesi için uygun mühendisliği uygunlamanın, özellikle geri kazanılmış agregalı betonda (GKA-B), geri kazanılmış agreget (GKA) olarak kullanımı büyük potansiyele sahiptir. Bu bağlamda, çeşitli oranelarda GKA (0-30-40-70-100%) ve çeşitli oranelarda silis dumanı (SD) (0-5-10%) içeren beton karışımları GKA-B’ nin elastisite modülünün belirlemek üzere uygulanmıştır. Bu çalışma, çeşitli standartlar tarafından ve çeşitli araştırmacılar tarafından önerilen teorik elastisite modülü formüllерince hesaplanan GKA-B elastisite modülü değerlerinin deneyel olarak elde edilen GKA-B elastisite modülü değerlerine yakınınlıklarını oluşturduğu görülmüştür. Analitik ve istatistik değerlendirme yöntemlerini uygulamıştır. Sonuç olarak, GKA oranının betondaki artışına ve elastisite modülü azalmaktadır. GKA-B’da SD kullanımı elastisite modülünü ve basınç dayanımını artırılmaktadır. İrdelenen standartlar göz önüne alınmadığından, Amerikan standardı (ACI 318-05) elastisite modülünü deneyel sonuçlara göre, en yüksek standart sapma göstermesini rağmen, yakın tahmin vermektedir. Diğer taraftan araştırmacılar tarafından GKA-B elastisite modülü tahmini için önerileri denklemeler, İrdelenen standartlar ve deney sonuçlarının üzerinden sonuç vermektedirler. SD içeren ve içermeyen betonlar için bir elastisite modülü denklemi de bu çalışmada önerilmektedir.

Anahtar kelimeler: Geri kazanılmış agregat beton (GKA-B), Silis dumanı (SD), Elastisite modülü, Standartlar
Also, the usage of additional materials affects the discontinuity in the structure of RA [3],[24]. However, the performance variation of RAC due to different crushing processes is found limited (6%) [22].

Concrete’s elasticity modulus is strongly dependent on the phases of stiffness (these are interfacial transition zones, cement paste and aggregates) [25]. RA with low properties (i.e. higher porosity, low elasticity modulus) is the weakest point in concrete [3]. The contaminants, low strength and low density etc. of RA are the poor properties. According to this, RA is found effective on the mechanical performance of RAC [3],[26]-[29]. Hence, it can be stated that higher deformability of RAC due to RA in comparison to NAC is considerably reasoned by lower elasticity modulus of RA [3],[29]. It is reported that RA strength (at medium and high level) has a little influence on RAC parameters although low quality of RA has higher water absorption and porosity, and hence this leads lower stiffness of concrete [26]. However, some contaminants (i.e. brick and tile) did not have considerable effect on elasticity modulus of RAC [3]. Also, the usage of additional materials (i.e., chemical admixtures, mineral additions) in conventional concretes is found useful for RAC to improve the low properties of RAC (i.e. higher porosity, low elasticity modulus) [30]-[32].

Based on the explanations given above, there is a strong relation between the mechanical properties (i.e., compressive strength values) and experimental results are compared to each other.

It can be seen from the literature that many researchers propose elasticity modulus equations and/or use equations given in standards (i.e., Refs. [36]-[38]). However, there is only a few studies examined elasticity modulus of RAC considering equations proposed in both literature and standards. Also, only few proposed equations by researchers are examined clearly in the literature considering various research results and the predictability of the proposed equations. It is expected that previously existing relations given by many researchers don’t work due to the various effective parameters (i.e., impurities in RA, super plasticizer, w/b) on RAC. A distinctive elasticity modulus formula derivation can be more appropriate for each different RAC. This paper aims to examine elasticity modulus of RAC determined according to the formulas of standards and studies. Analytical and statistical assessments are performed and experimental and theoretical results are compared to each other. Also, an elasticity modulus equation for RAC with and without SF based on this experimental results is proposed to contribute the literature. The specimens contained 0-30-40-70-100% RA and 0-5-10% silica fume (SF) are produced in the laboratory. The tests are applied at the age of 28 days. Then, also, elasticity modulus (chord elasticity modulus and tangent elasticity modulus) are calculated by using stress-strain data recorded while compressive strength test is being conducted. Then, the experimental elasticity modulus results are analyzed in comparison to standards [5],[6],[9],[17] and the elasticity modulus equations proposed by researchers [16],[33],[39],[40] and by the authors in this study.
2 Experimental stage

Fifteen groups of concrete mixtures are produced in laboratory. The slump classes of mixes are selected as S4 for fresh state of concretes. The notations of the specimens are defined (Table 1).

Table 1: The notations.

| Notation | Definition                                                                 |
|----------|---------------------------------------------------------------------------|
| NAC      | Concrete with natural aggregates such as natural sand, natural fine, and natural coarse |
| RA1C     | Recycled aggregate concrete with recycled aggregate and natural aggregate such as recycled fine, natural coarse and natural sand |
| RA2C     | Recycled aggregate concrete with recycled aggregate such as natural fine, recycled coarse and natural sand |
| RA12C    | Recycled aggregate concrete with recycled aggregate and natural aggregate such as recycled fine, recycled coarse and natural sand |
| RA123C   | Recycled aggregate concrete with recycled aggregate such as recycled fine, recycled coarse and recycled sand |
| NACSF5   | Concrete with natural aggregate such as natural fine, natural coarse and natural sand, and 5% SF |
| RA1CSF5  | Recycled aggregate concrete with recycled aggregate and natural aggregate such as recycled fine, natural coarse and natural sand, and 5% SF |
| RA2CSF5  | Recycled aggregate concrete with recycled aggregate and natural aggregate such as natural fine, recycled coarse and natural sand, and 5% SF |
| RA12CSF5 | Recycled aggregate concrete with recycled aggregate such as recycled fine, recycled coarse and recycled sand, and 5% SF |
| RA123CSF5| Recycled aggregate concrete with recycled aggregate such as recycled fine, recycled coarse and recycled sand, and 5% SF |
| NACSF10  | Concrete with natural aggregate such as natural fine, natural coarse and natural sand, and 10% SF |
| RA1CSF10 | Recycled aggregate concrete with recycled aggregate and natural aggregate such as recycled fine, natural coarse and natural sand, and 10% SF |
| RA2CSF10 | Recycled aggregate concrete with recycled aggregate and natural aggregate such as recycled fine, recycled coarse and natural sand, and 10% SF |
| RA12CSF10| Recycled aggregate concrete with recycled aggregate and natural aggregate such as recycled fine, recycled coarse and recycled sand, and 10% SF |
| RA123CSF10| Recycled aggregate concrete with recycled aggregate such as recycled fine, recycled coarse and recycled sand, and 10% SF |

Specimens with cylindrical shape and 150x300 mm dimensions cured for 28-days. While the design of mixtures, TS 802 is considered [41]. The concrete strength class is chosen as C30/37. The diameter of the maximum aggregate size (D_{max}) is chosen as 31.5 mm. The dosage of the concrete mixes are 350 kg/m³ CEM I 42.5R Portland cement (PC). Also SF is used and is compatible with ASTM C 1240-12 (Table 2). The curing conditions are suitable with TS EN 12390-2 (2010) [42].

It is known that mineral addition (i.e., SF and fly ash) in the RAC, improves the properties (i.e., mechanical and physical properties) of RAC [32]. Hence, SF is used in the mixtures and is replaced by weight of cement at various ratios (0-5-10%). The utilized aggregate types are basalt aggregate and siliceous sand as NA, and C&DW as RA.

In this study, NA is replaced with RA. The replacement of NA considering natural coarse aggregate (4-8mm) (NA1), natural coarse aggregate (4-32 mm) (NA2) and natural sand (0-4mm) (NA3) is done with RA considering recycled coarse aggregate (4-8mm) (RA1), recycled coarse aggregate (4-32mm) (RA2) and recycled sand (0-4 mm) (RA3), respectively. The utilization ratios of “NA1 and RA1”, “NA2 and RA2”, and “NA3 and RA3” are 40%, 30% and 30%, respectively. RAs are obtained crushing the C&DW. The concrete mixtures are contained 0.5-10% SF. The components of concrete mixes are given in Table 3. Figure 1 presents aggregates graduation curves considered in this paper. Aggregates such as recycled aggregate (i.e., RA1, RA2 and RA3) and natural aggregate (i.e., NA1, NA2 and NA3) are utilized. Also a constant water to binder ratio is considered and selected for all concretes as 0.5.

![Figure 1: Gradation of aggregate.](image)

Table 2: SF and cement properties.

| Contents | SF | Cement |
|----------|----|--------|
| SO₃     | >85% | Fe₂O₃ (%) |
| CaO     | <1% | CaO (%) |
| SO₃     | <2% | SO₃ (%) |
| Color   | Amber | MgO (%) |
| Structure of material | Condensed microsilica | Al₂O₃ (%) |
| Chlorine ratio (%) | <1 | SO₃ (%) |
| Density (kg/liter) | 0.55-0.70 | Specific gravity (gr/cm³) |
| Activity index (%) | >95 | Loss on ignition (%) |
| Particle ratio (≤0.045mm) | <40% | Specific surface area (cm²/g) |
| Specific surface area (m²/kg) | 15000 |

The properties of aggregates are obtained according to TS EN 1097-6 [43] and TS EN 1097-2 (2010) [44]. Also, chemical properties of aggregates are obtained (TS EN 1744-1) [45]. The defined properties of aggregates are in Table 4.
Super plasticizer (SP) based on polycarboxylic ether is used in concrete production to enhance low workability of the mixtures. The workability of all mixtures is constant and slump class of mixes is set to S4. It is expected that the workability of RAC mixtures are low due to the shape characteristics of crushed RA (i.e., the texture of granular surface and greater angularity) in comparison to the shape characteristics of NA (i.e., the smooth and rounded shape). Owing to its high water absorption rate, the RA1 and RA2 are pre-soaked in water for 24 hours before casting, and also RA3 is passed through the same process. Hence SP amount is approximately same for the mixes while increasing RA content in the mixtures (Table 3). Also S4 slump class is obtained adding SP in small quantities step by step and determining slump value at every step. Hence bleeding or segregation for all concrete mixtures is not observed.

Fifteen groups of fresh concretes are produced and fresh concretes are vibrated by using shaking table. In total 300 mm cylindrical) of each group. In total, 45 strength test and elasticity moduli test are carried out on three samples (150φ300 mm cylindrical) of each group. In total, 45
cylindrical specimens (150ϕ300 mm) are tested at the age of 28th day. The compressive strengths of specimens are determined in accordance with TS EN 12390-3 (2010) [46]. The test results of compressive strength are presented in Table 5. The elasticity modulus test is performed in accordance with ASTM C 469 [47]. The elasticity modulus test setup is shown in Figure 3.

3 Stress-Strain data analysis

The elasticity moduli experiments are conducted on 150ϕ300 mm cylindrical specimens and the data of load-displacement are assessed and recorded properly, the experiments. Stresses and strains are calculated using the recorded load-displacement data. Eq. (1) estimates the stress-strain data closer with the experimental data (coefficient of determination ($R^2$)>0.99) [48]. Hence Eq. (1) is utilized for all specimens as follows:

$$\sigma = A \times \varepsilon - B \times \varepsilon^2$$  \hspace{1cm} (1)

Here, $\sigma$ and $\varepsilon$ is stress and strain, respectively.

According to EN-1992-1 [9], the curve of stress-strain in the rising branch can be portray by a second degree polynomial. In subsection 3.1.7 of EN-1992-1, Eq. (2) is given.

$$f_c = (2 \times f_{cd}/\varepsilon_{c2}) \times (1 - (\varepsilon_c/\varepsilon_{c2})^2)$$  \hspace{1cm} (2)

Because $f_{cd}$ and the corresponding $\varepsilon_{c2}$ are constants for a particular concrete, it is obvious from Eq. (2) that stress is a function of strain in the form of a 2nd degree polynomial passing through the origin. With the symbols used herein, Eq. (1) can be written as:

$$\sigma = A \times \varepsilon - B \times \varepsilon^2$$  \hspace{1cm} (3a)

where, the coefficients $A$ and $B$ are defined as:

$$A = 2 \times \sigma_{\text{max}} / \left( \text{strain versus } \sigma_{\text{max}} \right)$$  \hspace{1cm} (4)

$$B = \sigma_{\text{max}} / \left( \text{strain versus } \sigma_{\text{max}} \right)^2$$  \hspace{1cm} (5)

As a result compatible with Eq. (3) and Eq. (3a) only a few 2nd degree polynomials are fitted to stress-strain points and the equations of the most fitted curve functions are given in Table 6 for each concretes.

3.1 Theoretical and experimental elasticity modulus calculations

3.1.1 Experimental elasticity modulus calculation

Stress-strain curves of concretes are determined, elasticity modulus (tangent elasticity modulus ($E_{\text{Tangent}}$) and chord elasticity modulus ($E_{\text{Chord}}$)) of concretes are determined. The moduli of elasticity are can be calculated as the chord modulus of elasticity and the tangent modulus of elasticity. Also, stress-strain curves are generated for each specimens using up to the stress equals to 70% of $\sigma_{\text{max}}$ beyond the maximum stress $\sigma_{\text{max}}$ (Figure 4).

The curves are also plotted for all concrete specimens, and are not given in the paper for conciseness. Also, the parameters of Eq. (1) (i.e., constants A and B) are determined and the results are given in Table 6. Also the experimental elasticity modulus ($E_{\text{Chord}}$ and $E_{\text{Tangent}}$) values are demonstrated in Table 6.

Figure 3: Elasticity modulus test setup.

Considering this situation, Eq. (1) is derived and the steps are given in below [4].

$$f_c = f_{cd} \times \left[ 1 - \left( \frac{\varepsilon_c}{\varepsilon_{c2}} \right)^2 \right]$$  \hspace{1cm} (3)

Figure 4: Stress-strain curve and the chord and the tangent lines for NAC specimen.
3.1.2 Theoretical elasticity modulus calculation

In this study, in the first step, the experimental results of concretes (NAC and RAC with and without SF) are compared with the results of the codes [5],[6],[9],[17]. The standards propose elasticity modulus formulas for NAC. Hence, the modulus of elasticity prediction ability of the codes for RAC is analyzed and compared with the experimental results. In the second step, due to the difference between the experimental and the results of the equations given in the literature, it is considered that elasticity modulus formulas proposed for RAC may give approximate results. In the literature researchers offered some formulas for elasticity modulus of RAC (i.e., [30],[36]). However, the offered formulas for RAC differ to each other due to the parameters and ingredients utilized in mixes (i.e., NA type, RA ratios, and water to binder ratio (w/b)). Ravindrarajah and Tam [39] produced 9 mixes at various w/b ratios and proposed an elasticity modulus equation for RAC. 15 mixes at various w/b ratios from 0.40 to 0.60 are produced by Corinaldesi [16] and Corinaldesi proposed an equation to estimate RAC elasticity modulus. Then the results of the equation proposed by Corinaldesi were compared with the results of elasticity modulus equations given in literature. The same approach was followed by Dhir et al. [33]. In their work, 13 mixes were produced and an equation was offered by [33]. In [40], the procedure is different. A review is conducted and over 1200 test results are examined and using the data a formula of elasticity modulus composed [40]. Beside, 15 concrete mixes including RA (0-100%) at constant c/b of 0.5 are produced in this experimental study. An equation is to estimate moduli of elasticity. The considered equations given in the literature and standards are shown in Table 7. Also, the results of the equations are given in the Table 8.

4 Results and discussions

According to the results (Table 8), the elasticity modulus decreases when RA incorporation ratio increases in concrete. The elasticity modulus is dependent on the phases of stiffness (these are interfacial transition zones, cement paste and aggregates) [25]. RA with low properties (i.e. higher porosity, low elasticity modulus) decreases compressive strength of concrete [26]. This leads peak stress decrease with an increase of RA ratio in concrete and it is revealed that the values of elastic energy capacities decrease [50]. Also SF utilization in RAC improved the strength of RAC [3], and SF increase the peak value of compressive strength as a result of the pozzolanic and filler effect of SF improve the compressive strength [3]. Hence, the values of elastic energy capacities decrease [50]. Also SF utilization in RAC improved the strength of RAC [3], and SF increase the peak value of compressive strength as a result of the pozzolanic and filler effect of SF improve the compressive strength [3].
is cured long. On the other hand, the bond in concrete (between RAC and the new cement paste) improves [36], thus the elasticity modulus increases. For instance, when the elasticity modulus of mixes RA123C, RA123CSF5 and RA123CSF10 are considered, the results are 13805 MPa, 17668 MPa and 21581 MPa, respectively.

Table 8 also presents the test results of the elasticity modulus normalized with NAC. It is found that EN-1992-1-1 [9] and TS 500 [5] predict the moduli of elasticity in comparison to relative chord moduli of elasticity results with higher relative average elasticity modulus values (1.143 and 1.101, respectively) and these codes (TS and EN) overestimate the elasticity moduli of concretes in comparison to relative tangent elasticity modulus results with higher relative average elasticity modulus values (1.111 and 1.070, respectively). However, CSA A23.3-04 [7] underestimates the relative average chord and tangent elasticity modulus (0.910 and 0.884, respectively). Beside although ACI 318M-05 underestimate the values, those of ACI 318M-05 [6] are the most approximate results with experimental results in comparison to considered codes (0.950 and 0.924, respectively).

Besides, when the concrete includes RA, especially with the incorporation of 100% RA, the standards predict unsuitable results All standards (i.e., ACI 318M-05 [6], TS 500 [5], EN-1992-1-1 [9] and CSA A23.3-04 [7]) usually give approximate results with test results in comparison to the equations offered by [16][39][33][40].

Table 7: Elasticity modulus equations.

| Equations |
|-----------|
| $E = 14000 \times 3.25 \sqrt{f_{c}}$ (MPa) |
| $E = 4700\sqrt{f_{c}}$ (MPa) |
| $E = 22 \left( {f_{c}}/10 \right) / \left( 0.33 + 0.002 \sqrt{f_{c}} \right)$ (GPa) |
| $E = 220 \sqrt{f_{c}}$ (MPa) |
| $E = 7770 f_{c}^{0.22}$ (MPa) |
| $E = 370 f_{c} + 13100$ (MPa) |
| $E = 18000 \sqrt{0.083 f_{c}} / (225 + 0.4 f_{c})$ (MPa) |
| $E = 160000 f_{c}^{0.225 + 0.4 f_{c}}$ (MPa) |

$f_{c}$ is the cylinder compressive strength, $f_{c}$ is the cube compressive strength in MPA.

Table 8(a): The theoretical and the statistical values of the elasticity modulus.

| Notations | Elasticity Modulus According to Standards (MPa) | Experiments (MPa) |
|-----------|-------------------------------------------------|------------------|
|           | TS 500 | ACI 318M-05 | EN-1992-1-1 | CSA A23.3-04 | $E_{\text{Chord}}$ | $E_{\text{Tangent}}$ |
| 1st Group | NAC    | 33446     | 28122      | 32254      | 26925      | 28830 | 29651 |
|           | RA1C   | 32670     | 26999      | 31476      | 25851      | 23437 | 20559 |
|           | RA2C   | 32978     | 27446      | 31787      | 26278      | 25167 | 23261 |
|           | RA12C  | 31532     | 25354      | 30310      | 24275      | 22896 | 20483 |
|           | RA123C | 30217     | 23453      | 28926      | 22455      | 13805 | 9863  |
| 2nd group | NACSF5 | 34529     | 29688      | 33321      | 28425      | 25619 | 23633 |
|           | RA1CSF5| 33172     | 27726      | 31981      | 26546      | 25541 | 22805 |
|           | RA2CSF5| 33282     | 27985      | 32091      | 26698      | 25571 | 23968 |
|           | RA12CSF5| 32726    | 27081      | 31533      | 25929      | 22926 | 19576 |
|           | RA123CSF5| 31978  | 25999      | 30771      | 24893      | 17668 | 15424 |
| 3rd group | NACSF10| 35922     | 31703      | 34660      | 30354      | 27721 | 25692 |
|           | RA1CSF10| 33822    | 28666      | 32628      | 27446      | 24968 | 22828 |
|           | RA2CSF10| 34166    | 29163      | 32966      | 27922      | 21162 | 23738 |
|           | RA12CSF10| 31472   | 25267      | 30248      | 24191      | 22998 | 20596 |
|           | RA123CSF10| 32183  | 26295      | 30980      | 25176      | 21581 | 20616 |

| Notations | $E_{\text{Chord}}$ |
|-----------|------------------|
| Relative standard deviation value | 0.047 | 0.068 | 0.047 | 0.065 | - |
| Relative average value | 1.143 | 0.950 | 1.101 | 0.910 | - |
| $E_{\text{Tangent}}$ |
| Relative standard deviation value | 0.045 | 0.066 | 0.046 | 0.063 | - |
| Relative average value | 1.111 | 0.924 | 1.070 | 0.884 | - |

Table 8(b): The theoretical and the statistical values of the elasticity modulus.
It is thought that the studies’ elasticity moduli prediction ability [16],[39],[33],[40] is noticeably weaker than codes. It should be noted that, although the codes considered in this paper are designed for NAC, they are suitable to predict elasticity modulus of RAC, as well. On the other hand, the formulas offered by [16],[39],[33],[40] predict weaker results than the codes in comparison to chord and tangent elasticity modulus values (Table 8 and Figure 5). The highest values owned by Corinaldesi (1.622 and 1.811) [16], however, the smallest relative standard deviations (0.171 and 0.309) and relative average values (1.080 and 1.208) obtained for Xiao et al. [40] except for the proposed formula. The results of Xiao et al. [40] are closer with experimental results in comparison to relative average elasticity modulus values than others [16],[33],[39]. This might be due to the number of examined test results. Xiao et al. [40] considered over 1200 test results in their research while others examined limited numbers of their test results. Large number of test data gives opportunity to compose a formula which predicts more precise results.

According to the codes and the studies considered in this experimental and analytical study, ACI 318M-05 [6] in comparison to codes [5],[7],[9] and Xiao et al. [49] in comparison to the studies [16],[33],[39],[40] give approximate results. However, when the elasticity modulus obtained by using equations proposed by Xiao et al. [40] and given in ACI 318M-05 [6] are compared with the experimental elasticity modulus, the equations proposed by Xiao et al. [40] and given by ACI 318M-05 [6] are commenced to give results unsuitably with an increase of RA ratio from 0% to 100% in mixes. For instance, when the results of RA1C and RA123C are considered, the chord elasticity modulus are 23437 MPa and 13805 MPa, respectively, and the tangent elasticity modulus are 20559 MPa and 9863 MPa, respectively.

| Notations | Elasticity modulus according to the studies in literature (MPa) |
|-----------|-------------------------------------------------------------|
|           | Ravindranjanah and Tan [43] | Dhir et al. [44] | Corinaldesi [47] | Xiao et al. [48] | Proposed |
| 1st group |                            |                |                |                  |          |
| NAC      | 26089                       | 28973          | 35475          | 23551            | 23791    |
| RA1C     | 26373                       | 29502          | 36062          | 23813            | 24479    |
| RA2C     | 25029                       | 27097          | 33313          | 22523            | 21301    |
| RA123C   | 23774                       | 25077          | 30815          | 21202            | 18533    |
| 2nd group|                            |                |                |                  |          |
| NACS10   | 26550                       | 29839          | 36430          | 23974            | 24915    |
| RA1C5F   | 26651                       | 30031          | 36639          | 24064            | 25162    |
| RA2C5F   | 26141                       | 29069          | 35583          | 23600            | 23916    |
| RA12C5F  | 25447                       | 27819          | 34161          | 22939            | 22268    |
| 3rd group|                            |                |                |                  |          |
| NACS10   | 27141                       | 30993          | 37665          | 24493            | 26389    |
| RA1C5F   | 27451                       | 31619          | 38318          | 24756            | 27176    |
| RA2C5F   | 24972                       | 27001          | 33198          | 22466            | 21171    |
| RA12C5F  | 25638                       | 28155          | 34549          | 23124            | 22715    |

Figure 5: The elasticity moduli results of the specimens according to the equations.

On the other hand, the results of Ref. [40] for RA1C and RA123C are 23551 MPa and 21202 MPa, respectively, and the results of ACI 318M-05 [6] for RA1C and RA123C are 26999 MPa and 23453 MPa, respectively. It is can be seen that the difference between the results is clear, especially for RAC included 100% RA.

In this concept, generalization of formula for RAC may not be suitable due to various effective parameters (i.e., RA impurities, SP, w/b) on RAC. The formula offered by Xiao et al. [40] do not give approximate results with the experimental results and the relative standard deviations are obtained for this research. Hence, it can be concluded that distinctive elasticity modulus formulas may be composed for each different mixes/studies due to the variety in parameters.

As demonstrated in Table 8, the proposed formula predicts modulus of elasticity most approximately with experimental
results (i.e., tangent and chord modulus of elasticity). The smaller relative standard deviation (0.124) is determined for the proposed formula in comparison to those of studies [39],[33],[16] and the minimum average elasticity modulus (1.002) of the proposed formula is obtained. Also, in comparison to the relative tangent elasticity modulus, the minimum relative standard deviation (0.209) and the minimum relative elasticity modulus (1.113) values are calculated for the proposed equation. As can be seen in Figure 5, trend line of the results of the formulas given in [16],[33],[39],[40] and the proposed equation are approximately similar. The highest estimation of Corinaldesi [16] is visible in Figure 5, and it can be seen that the slope of the trend line of the equation given in [40] is the lowest.

5 Conclusion

In this research, the experimental moduli of elasticity of fifteen concrete mixes with and without SF are analyzed in comparison to the theoretical formulas of codes and the proposed elasticity modulus equations of RAC by researchers are presented. According to the results, the followings can be drawn:

- While increasing RA ratio in concrete, the elasticity modulus decreases. SF utilization in RAC increases the moduli of elasticity and compressive strength,
- In the evaluation of the modulus of elasticity, TS 500 [5] overestimates the elasticity modulus whereas ACI 318M-05 [6] estimates the relative average elasticity modulus values close in comparison to those of considered codes although it has the highest relative standard deviations in comparison to the regarded codes,
- The prediction ability of the codes considered in this paper is stronger than the studies considered in this paper. The proposed equations by researchers estimate the elasticity modulus greater than those of standards although the researchers propose the formulas specifically for RAC. Moreover, the considered equations display high deviations with the increase of RA fraction in RAC, especially for RAC incorporated 100% RA,
- A generalized elasticity modulus equation for RAC may not be suitable due to the various effective parameters (i.e., impurities in RA, SP, and w/b) on RAC. A distinctive elasticity modulus formula derivation might be more suitable for each different mixes/studies. Hence, an equation is proposed for the elasticity modulus in this paper.

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