Rheological properties of self-consolidating concrete made by crushed waste tile aggregates

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Abstract

In the recent decades, the use of self-consolidating concrete has become widespread. Hence, recognizing the various properties of self-consolidating concrete are essential. In this study, several mixture designs have been tested and final mixture design of crushed tile aggregates which were replaced by 0%, 25 %, 50%, and 100% volume percentage of natural aggregates were conducted. To evaluate fresh properties of SCC, slump flow and rheometer tests were carried out. Results show that the percentage of fine aggregates has a significant impact on the properties of self-consolidating concrete. In addition, the results of rheometer test show by increasing the percentage of recycled aggregates increases yield stress and plastic viscosity, significantly.

Keywords: self-consolidating concrete; SCC; recycled aggregates; rheometer test; natural aggregates; fresh properties

1. Introduction

Today, concrete is the most consumable substance consumed by humans and due to the construction process, concrete industry is one of the most important industries in the world. Over the years, researchers in the construction industry have been working to make changes to the various components of concrete. These efforts have led to production of high strength concrete (HSC), high performance concrete (HPC), lightweight concrete (LWC), fibrous concrete, et al. One of these types of concrete, which appeared several decades ago, is self-consolidating concrete (SCC). It has provided the engineer societies with a proper feature that can be used to solve problems due to incomplete compaction in concrete structures.

Although the self-consolidating concrete is considered to be a particular concrete component, the SCC quickly became one of the most widely used types of concrete in the advanced world [1]. In 2013, Herbudiman and Saptaji [2] studied the self-consolidating concrete properties with tile powder from recycled roof tiles. The results show that the optimum mixture design with slump flow of 65 cm and the highest compressive strength of 67.72 MPa has sufficient flow capacity in the V-shaped funnel, as well as the use of crushed aggregates increases up to 17% in compressive strength and 42% in tensile strength.

In 2014, Tayfun et al. [3] studied the use of marble and recycled grains in their dense concrete. In this study, marble waste (MW) and recycled aggregate (RA) and broken limestone (LS) were used. The results show that the use of MW instead of LS increases the efficiency of fresh concrete, and also the use of RA reduces the specific gravity of self-consolidating concrete. In addition, no difference was observed in the mechanical properties of self-consolidating concrete using RA and MW.

Next year, Tennich et al. [4] studied the filling cones of marble and waste tiles in their concrete mix. The results show that the use of 150 kg/m3 of filler provides satisfactory fluidity in SCC and combining waste from marble and factory tile as a filler in self-consolidating concrete increases compaction and also increases compressive

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strength by more than 23%. Furthermore, it increases tensile strength and propagation velocity by 4.6% and 2.6%, respectively.

Vinay Kumar et al. [5] collaborated in a lab study on the use of coarse and fine grained aggregate recycled concrete in their self-consolidating concrete with 4 mixture designs. The results indicate that 20% replacement were satisfactory with respect to EFNARC acceptance criteria. Compressive and tensile strength of concrete containing recycled concrete aggregates is slightly higher than the control plane.

Iris et al. [6] predicted the properties of self-consolidating concrete using recycled aggregate. The results show that by increasing the amount of recycled aggregate, the compressive strength, the modulus of elasticity and tensile strength is reduced.

Ghodousi and Dolatiar [7] have studied and compared graphitic curves presented in the national method of Iranian concrete mixture design with some other models. The results indicate that the gradient curves located between the middle and upper limits are suitable for the construction of self-consolidating concrete mixtures. Sugarzizadeh [8] has also studied the effect of aggregate aggregation on the properties of fresh and hardened concrete. The results show that the quality and aggregation of aggregate have a great influence on the characteristics of fresh concrete behavior and mechanical properties of SCC.

In Farrokhzad et al. research [9] an optimum grading zone was developed in order to adopt aggregate proportions for SCC. They showed that the fine aggregates have more influence on the workability characteristics of SCC than coarse aggregates. Results show that by using an aggregate proportion with coarser aggregates the viscosity decreases, so in some cases bleeding, blocking and segregation would be palpable. Therefore, by using finer sand in the proportion, the yield stress decreases and the compressive strength will also get better.

Reuse of the waste of the fired clay materials in concrete is not a new research area in the concrete technology [10]. There are a number of good references on the use of fired clay materials in concrete [11-13]. In literature majority of the recycled fired clay waste studies have being carried out on crushed bricks as aggregates [14-

24]. There are also a few experimental researches concerning the properties concrete made with the crushed tile aggregate [25-28]. Besides, there are some studies on concrete made with crushed ceramic [29-31] and crushed porcelain [32].

Topcu and Canbaz [25] investigated the use of the concrete made with the crushed tile aggregate. From the experimental results it was concluded that crushed tile raised the water absorption ratio, but reduced the density, compressive and tensile splitting strengths of concrete. The density of crushed tile concrete has reduced by 4% according to their test results. The uses of the crushed tile aggregates have caused about 40% loss in the compressive and splitting tensile strengths. Additionally they reported that crushed tiles adversely affected the abrasion and freezing–thawing durability of the concrete. It was also recommended that 100% replacement of crushed tile as a coarse aggregate is not suitable.

Torgal and Jalali [26, 27] examined of permeation and durability performance of the concrete made with fine and coarse crushed tiles. They concluded that using crushed tiles in concrete can a small degree improved permeation and durability performance of the concrete.

Some other researchers [29-32] carried out laboratory investigations to evaluate the performance of ceramic electrical insulator waste as a partial replacement of aggregate in concrete production. They have concluded that the resulting concrete could easily provide the strength requirement for the normal concrete. They also reported that the main permeability characteristics of ceramic electrical insulator as waste coarse aggregate were greater than those of normal concrete. The similar results were also stated by Guerra et al. [33]. They investigated the mechanical characteristics of concrete produced with the natural aggregate and different ratio of crushed sanitary porcelain as an alternative for the coarse aggregates. They noted that the use of crushed sanitary porcelain as aggregate did not cause a remarkable reduction in the concrete strength.

Ay and Ünal [34] investigated the potentiality of using crushed waste ceramic tile as a cement replacement in concrete. They found that waste tile had pozzolanic activity and decided that it was reasonable to use waste tile up 35% by weight in replacement of the cement. Concrete made with

the crushed tile was also found to be non-alkali-silica reactive and decreased the alkali-silica reactivity considerable in concrete [35]. On the other hand using crushed tile in concrete has been found to have raised the drying shrinkage of concrete [36].

In addition, recently several studies have been carried out to determine the intrinsic rheological parameters of fresh concrete [37, 38], which are considering fresh concrete as a fluid. They simulate and describe its behavior with the Bingham model and the Herschel and Bulkley model. However there is no study on the rheological properties of self-consolidating concrete made with wall and floor tile. The main objective of this study is the usage of tile wastes %100 replacement as an alternative material to the natural aggregate in concrete. The usability of the tile wastes for concrete making has been investigated in rheological properties of self-consolidating concrete.

2. Experimental program

2.1. Materials and mixture design

In this study, Portland cement type II has been used. The C3S, C2S, C3A and C4AF contents of the cement by Bogue calculations were 52.72%, 21.52%, 6.61% and 10.68%, respectively. The chemical composition of the cement are given in Table 1. An optimized polycarboxylic ether based super plasticizer have been used according to ASTM C494 [39].

Natural aggregates used in mines of Qazvin province. The maximum nominal size of the used aggregates was #3/8, due to the fact that increasing the maximum nominal size of aggregates reduces the efficiency and the ability of concrete passing. The fine grained aggregates was according to ASTM-C136 standard [40]. The grading of aggregate are presented in Table 2 and Table 3. In Figure 1 the natural and crushed waste tile aggregate grading is visible. ASTM-C128 [41] has been used to determine the density and absorption of fine aggregate, and to determine the density and absorption of coarse aggregate, the ASTM-C127 standard [42] has been used. The gravity of the natural aggregate is 2538 kg/m3. The natural sand and gravel water absorption are 1.680% and 1.865%, respectively.

Vikan and Justnes [43], by conducting experiments on cement paste, to find self-consolidating concrete found that the replacement of cement with silica fume up to 10% by volume would increase the tensile yield. Therefore, in this study, silica fume was replaced with 10% of cement weight, which is considered constant in all mixture designs.

Table 1. Chemical properties of cement and silica fume.

Items	Cement	Silica fume
SiO2	21.38	93.6
Al2O3	4.65	1.3
Fe2O3	3.51	0.9
CaO	63.06	0.5
MgO	3.2	1
SO3	1.8	0.1

Table 2. Sand grading

Passing percentage	Sieve Number
100	3/8
50	1/4
0	4

Table 3. Gravel grading

Passing percentage	Sieve Number
100	4
95	8
77	16
50	30
30	50
15	100
7	200
0	pan

Figure 1. Grading of aggregates

Table 4. Mixture design

No. of experiment	Recycled aggregate volume (%)	W/C	aggregate (kg)	Cement (kg)	Silica fume (kg)	Super-plasticizer (%)
RA0	0	0.425	1260	450	50	1.5
RA25	25	0.425	1233.69	450	50	1.5
RA50	50	0.425	1207.38	450	50	1.5
RA75	75	0.425	1181.06	450	50	1.5
RA100	100	0.425	1154.75	450	50	1.5

Five mixture proportions of self-consolidating concrete are presented in Table 4. The control sample is made of natural aggregates and the percentage of broken tile is zero. In each case, 25% of the aggregate volume of natural aggregates is replaced by recovered aggregates, and finally 100% of the aggregates are replaced by recycled aggregates. The control sample is called RA0, in which RA, stands for Recycle Aggregate, and 0 represents the percentage of broken tile material, and RA25, RA50, RA75 and RA100 are also named in the same way.

2.2. Test methods

2.2.1. Slump flow Test

The slump test flow measures the consistency of fresh concrete before it sets. It is performed to check the workability of freshly made concrete, and therefore the ease with which concrete flows. It can also be used as an indicator of an improperly mixed batch. The test is popular due to the simplicity of apparatus used and simple procedure. The slump test is used to ensure uniformity for different loads of concrete under field conditions.

The test is carried out using a metal mold in the shape of a conical frustum known as a slump cone or Abrams cone that is open at both ends and has attached handles. The tool typically has an internal diameter of 100 millimeters at the top and of 200 millimeters at the bottom with a height of 305 millimeters. The cone is placed on a hard non-absorbent surface. This cone is filled with fresh concrete. Then the cone was lifted immediately and the concrete spreads over the table. The average diameter of the fresh SCC in two perpendicular directions is measured as the slump flow of SCC. According to the EFNARC [44] Slump-Flow classes is visible in table 5.

Table 5. Slump-Flow classes [46]

class	Slump-Flow (mm)
SF1	550-650
SF2	660-750
SF3	760-850

2.2.2. Rheometer test

The rheometer tests were performed according to the rheometer guidance. For the stress growth test, the software automatically selects the maximum recorded torque. The yield stress is computed with below Equation 1:

(1)

$$\tau_o = \frac{2T}{\pi D^3 \left(\frac{H}{D} + \frac{1}{3} \right)}$$

Where is the yield stress, T is the maximum torque, D is the diameter of the vane, and H is the height of the vane. In this equation, the shear stress is assumed to be evenly distributed on the side and ends of the vane.

A stress growth test involves rotating the vane at a low, constant speed while monitoring the build-up in torque. The maximum torque corresponds to the yield stress. The stress growth test is highly dependent on the shear history of the sample. A typical stress growth plot is shown in Figure 2. The rheometer software identifies the peak torque and computes the yield stress.
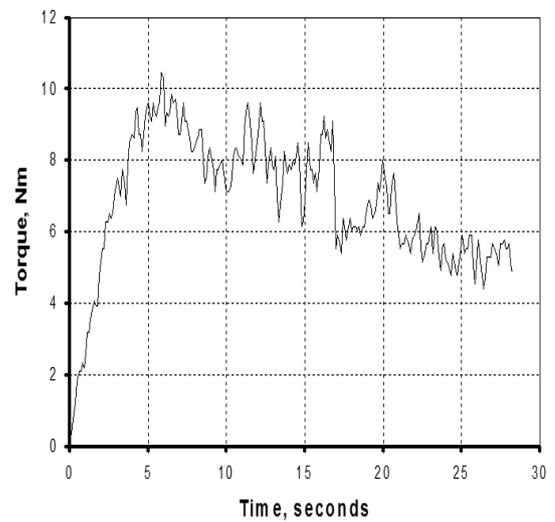
Figure 2. A typical stress growth plot (peak torque)

The calculation of the Bingham model parameters of yield stress and plastic viscosity is based on the Reiner- Riwlin equation, which is expressed in Eq. 2 for the case where all material within the annulus flows:

(2)

$$\Omega = \frac{T}{4\pi h \mu} \left(\frac{1}{R_1^2} - \frac{1}{R_2^2} \right) - \frac{\tau_0}{\mu} \ln\left(\frac{R_2}{R_1} \right)$$

Where, Ω: rotation speed (rad/sec), T: torque (Nm), Y: yield stress value (Nm), V: plastic viscosity value (Nm.s), N: rotation speed (rps), μ: plastic viscosity (Pa.s) and τ: yield stress (Pa).

In some cases, the shear stress in a portion of the material in the annulus is below the yield stress, resulting in a region where no flow occurs (zero shear rate). For cases where a portion of material

within the annulus does not flow, the Reiner-Riwlin are shown in Eq. 3 and Eq. 4.

$$(3)$$

$$\Omega = \frac{T}{4\pi h \mu}\left(\frac{1}{R_1^2} - \frac{2\pi h \tau_0}{T}\right) - \frac{\tau_0}{2\mu}\ln\left(\frac{T}{2\pi h \tau_0 R_1^2}\right)$$

In the cases

$$(4)$$

$$R_{2,eff} = \sqrt{\frac{T}{2\pi h \tau_0}}$$

Closed form solutions are available for Eq. 2 for cases where all material flows for all speed- torque points. It is necessary, however, to check whether all material in the annulus flows for each speed-torque point. If it does not, Eq. 3 must be used.

A flow curve tests consists of a breakdown, or pre-shear period, followed by a series of flow curve points (Figure 3). The purpose of the pre-shear period is to minimize the effects of thixotropy and to provide a consistent shear history. The pre-shear period consists of a single, constant speed, typically equal to the maximum test speed. No measurements are made during the pre- shear period. After the pre-shear period, the flow curve is immediately started. A single test consists of a specified number of points in ascending or descending order.

Two different tests- a stress growth test and a flow curve test- were carried out with the ICAR rheometer. The stress growth test is used to specify the static (at rest) yield stress, while the flow curve test is used for the relationship between shear stress and shear rate (flow curve) measurement which, once adjusted to a rheological model, allows the dynamic yield stress and plastic viscosity to be determined. The yield stress measured with the flow curve test is the dynamic yield stress because it is gauged after the structural breakdown of the mix, hence avoiding the effects

of thixotropy. In this research, the stress growth test started as soon as the rheometer vane was immersed into the concrete. The vane was revolved at a low and constant speed (0.025 rps) and the torque value was monitored on the computer screen .Once the peak torque was reached, the vane was removed and the concrete was remixed with a shovel. Then, the vane was reinserted into the concrete and the flow curve test started. In the second test, after a period of 20 seconds at a constant speed of 0.50 rps, the torques at decreasing speeds (from 0.5 to 0.05 rps in seven steps) were measured [45]. The details of rheometer apparatuse is shown in Figure 4.
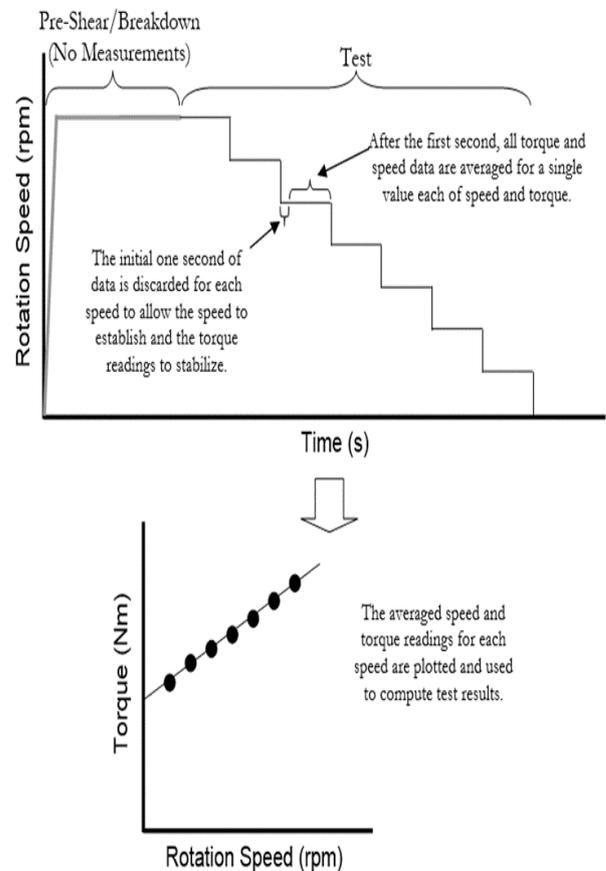
Figure 3. Results of the flow curve Test

Figure 4. The rheometer test

No. of experiment	Slump (mm)
RA0	775
RA25	750
RA50	730
RA75	710
RA100	605

3. Results and Discussion

The results of the slump flow are presented in Table 6. It can be seen that the RA0 having 775 mm slump flow in the concrete grade SF3, RA25, RA50 and RA75 having a slump flow in the range of 660-760 mm in the concrete grade SF2, and RA100 with the 605 mm slump flow is placed in the SF1 concrete category. As can be seen, increasing the percentage of recycled aggregates decrease the slump flow; the lowest slump flow in RA25 was decrease by 3.2% and the highest decrease was in RA100 with 21.9%.

Since the natural aggregates are rounded corners and recycled aggregates are sharp- edged and the percentage of water to cementitious materials (binder) in all designs is constant, and considering that the amount of water needed for sharp-edged aggregates is more than round-corner aggregates, and also the rounded corners of the aggregates makes them slip over each other easily. Therefore, with the increase in the amount of slag aggregates, the slump flow will decrease. In general, in many studies on concrete with recycled aggregates by different individuals, the results of the experiments show that that by increasing the replacement percentage of recycled aggregate slump flow decreases [14, 21, 18]. The diffusion of the slump flow in RA0, RA25, RA50, RA75 and RA100 designs is shown in Figure 5. As shown in Figure 5, there are no signs of segregation and water throbbing. Therefore, according to the ASTM definition, the stability and visibility index is zero.

The results of the stress growth test are presented in figure 6 and table 7. As can be seen in table 7, by increasing the percentage of broken tile substitutes for natural aggregates the yield stress are increased.

Table 6. Results of the slump flow
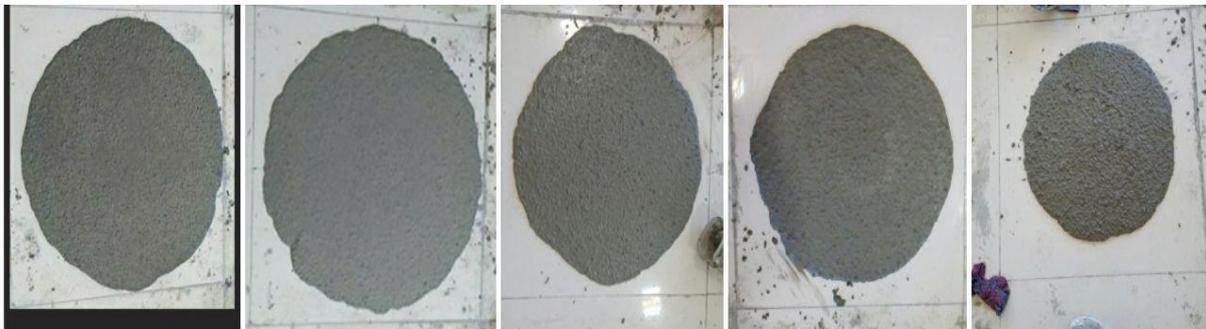
Figure 5. Slump flow
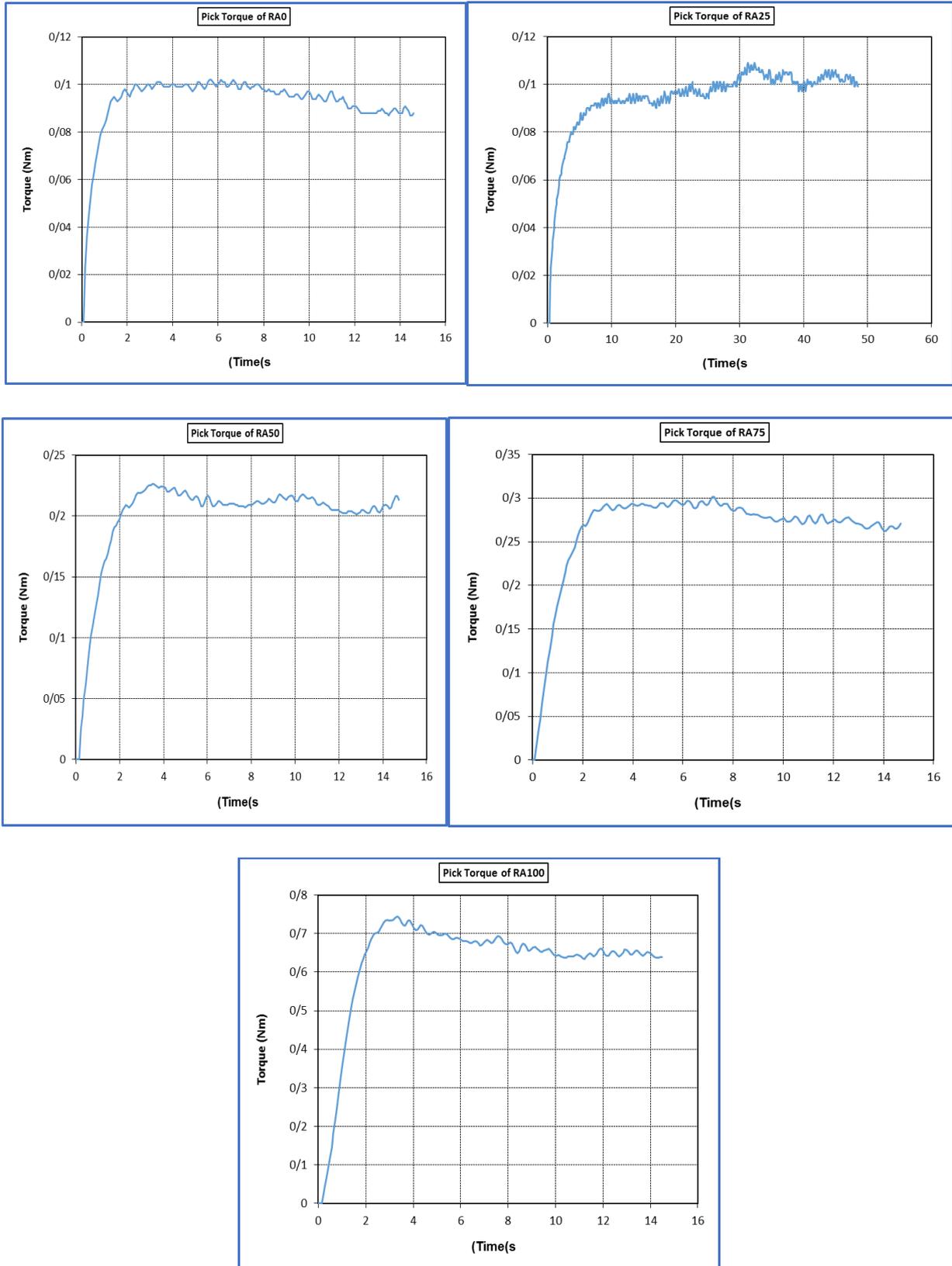
Figure 6. Results of the stress growth test

Table 7. Results of the Stress Growth Test

No. of experiment	Slump (mm)	Peak Torque (T)	Yield Stress ($\tau 0$ s)	Speed (S)
RA0	775	0.102	48.726	1/5
RA25	750	0.109	51.993	1/5
RA50	730	0.226	107.883	1/5
RA75	710	0.301	143.829	1/5
RA100	605	0.744	355.021	1/5
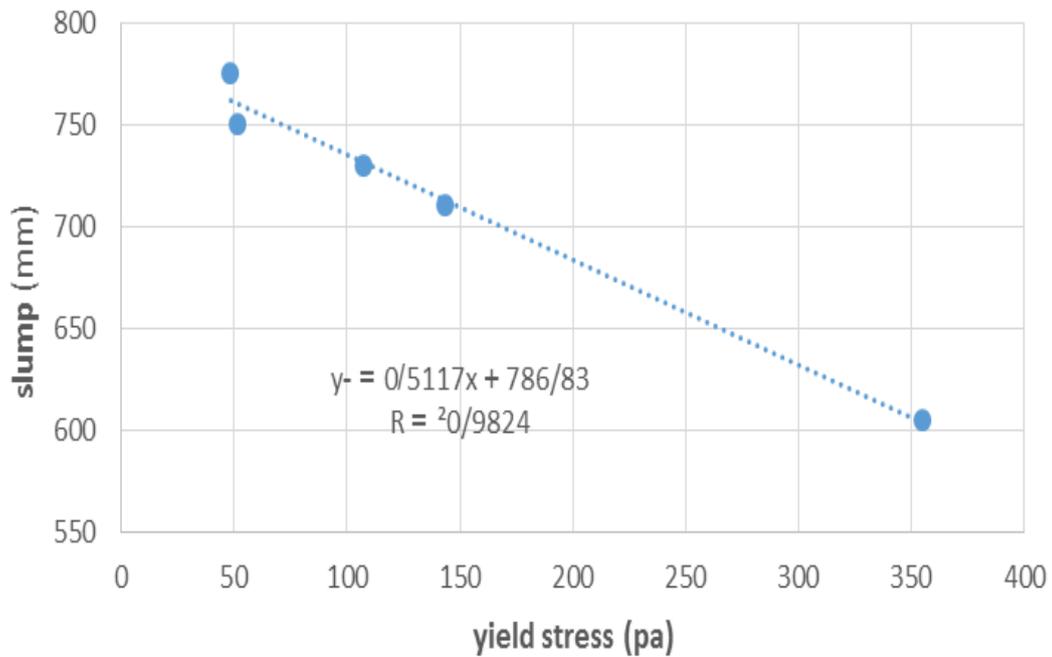
Figure 7. the relationship between slump and yield stress

Additionally, relationship between slump and yield stress is shown in figure7. As you can see, there is a good relationship between slump and yield stress with a correlation coefficient of 0.98. This graph shows that with decreasing slump flow, yield stress has increased. Due to the increase in the percentage of broken tiles that are sharp corners, the need for water in concrete has increased. But with constant maintenance of the amount of water consumed, the viscosity of concrete has increased. The result is an increase in yield stress. As expected from the nature of these two experiments, the slump flow decreased with increasing concrete viscosity. The results of the flow curve Test are presented in table 8, table 9. The Torque-Speed diagram for each mixture design is plotted in Figure 8.

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Table 8. Results of the flow curve Test

RA100		RA75		RA50		RA25		RA0	
Torque	Speed	Torque	Speed	Torque	Speed	Torque	Speed	Torque	Speed
1/498	3/747	0/834	3/746	0/715	3/745	0/631	3/737	0/565	3/744
1/288	3/172	0/711	3/171	0/612	3/168	0/547	3/165	0/479	3/171
1/084	2/598	0/591	2/601	0/511	2/604	0/448	2/599	0/392	2/598
0/89	2/021	0/479	2/017	0/419	2/018	0/359	2/016	0/328	2/019
0/687	1/434	0/372	1/444	0/326	1/438	0/269	1/434	0/237	1/432
0/478	0/867	0/252	0/868	0/225	0/866	0/197	0/865	0/171	0/866
0/228	0/291	0/121	0/291	0/104	0/291	0/101	0/291	0/075	0/283

Table 9. Results of the flow curve Test

No. of experiment	RA0	RA25	RA25	RA75	RA100
Yield Stress (Pa)	8.9874	12.4563	19/2126	19/2772	43/6480
Plastic Viscosity (Pa.s)	38.5876	43.6874	48/1527	56/9469	100/1787
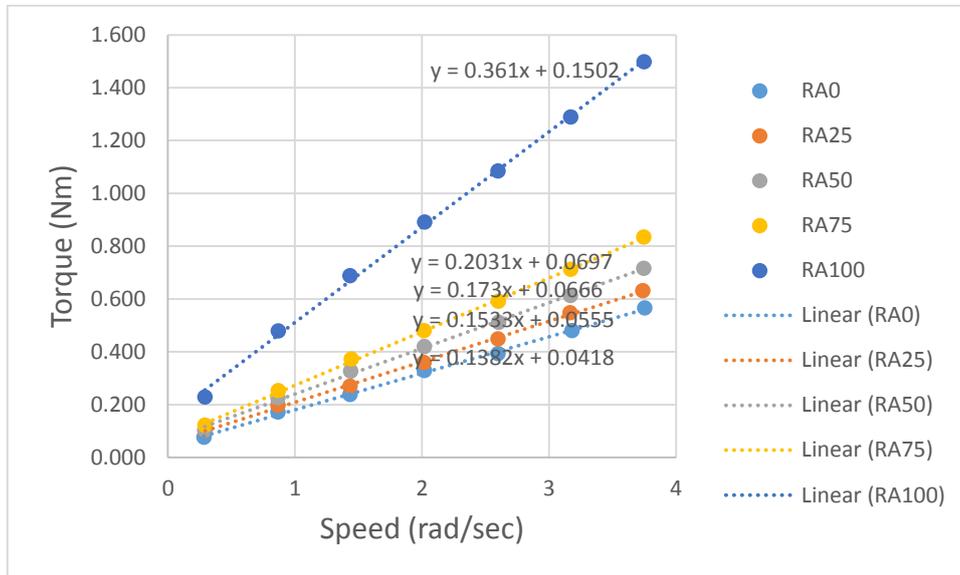
Figure 8. The Torque-Speed diagram for each mixture design

The relationship between slump and plastic viscosity, yield stress respectively are presented in Figure 9 and Figure 10. As can be seen, increasing the percentage of recycled aggregates and by decreasing the slump flow increases yield stress and plastic viscosity.

Natural aggregates are round corners and recycled aggregates are sharp-edged and sharp-edged aggregates have more water than round-corner aggregates. In addition, in a constant amount of water used in a concrete mixture, therefore,

increasing the percentage of recycled aggregates has increased the viscosity of concrete.
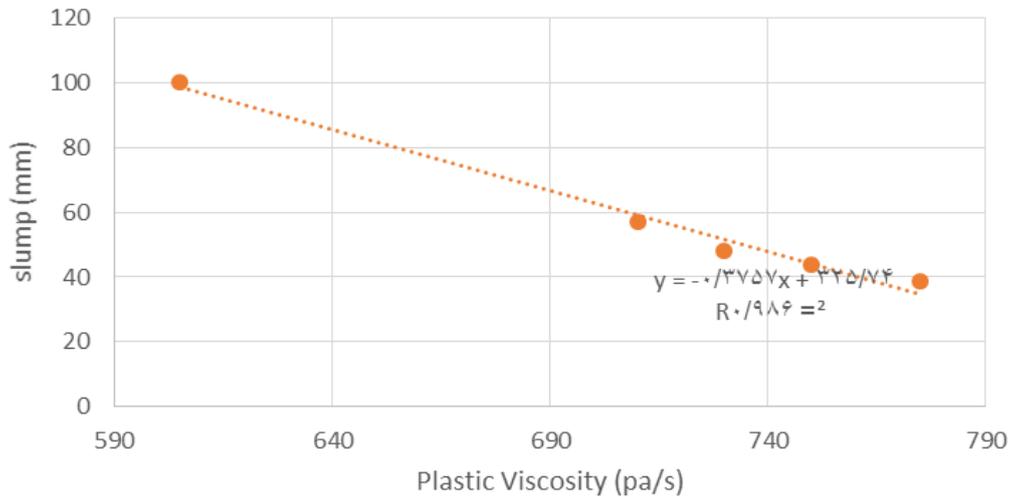
Figure 9. Relationship between slump and plastic viscosity
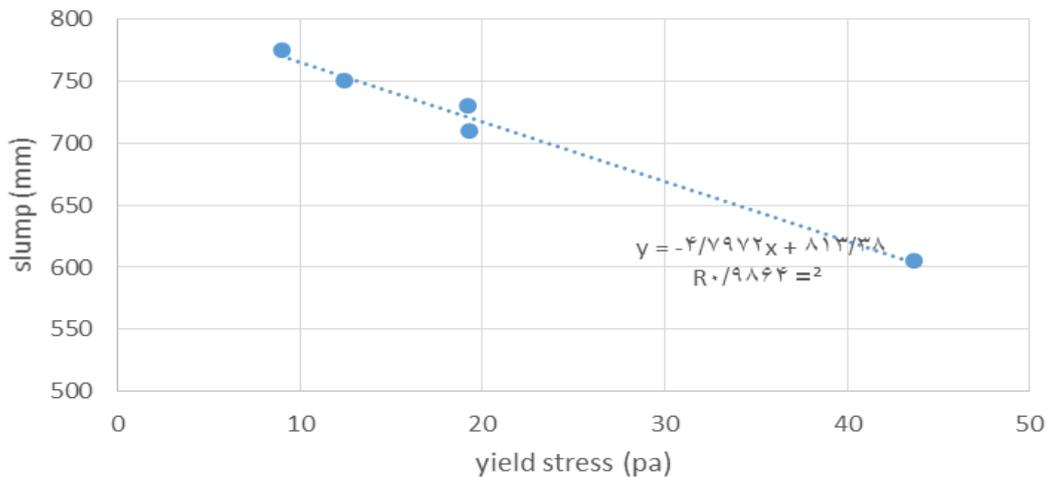
Figure 10. Relationship between slump and yield stress

4. Conclusions

Based on the obtained results from this study the following conclusions can be drawn:

1. Generally, the reduction of rheological properties of fresh concrete containing up to 75% broken tile compared to the control sample replacement is negligible. However, they were

significantly decreased in more percentages of recycle aggregates.

2. By testing self- consolidating concrete slump, increasing the percentage of broken tile replacing natural aggregate reduces the slump flow which indicates the increased viscosity of concrete. The highest amount of slump flow has been observed in the control sample and

that is 775 mm. By increasing the replacement percentage to 100%, the slump flow decreases to 21.9%. Slump flow changes up to 75% replacement is slight and changes are significant with its increase to 100%.

3. Both of flow curve and stress growth tests by increasing the percentage of broken tile replacing natural aggregate increases the amount of yield stress and also by increasing the percentage of recycle aggregate in flow curve test the plastic viscosity is increases which that shown the workability is reduces.

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