International Journal of Civil Engineering
https://doi.org/10.1007/s40999-020-00562-z

RESEARCH PAPER

Investigating the Effects of Mixing Time and Mixing Speed on Rheological Properties, Workability, and Mechanical Properties of Self-Consolidating Concretes

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Received: 14 May 2020 / Revised: 7 August 2020 / Accepted: 17 August 2020
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Abstract

The mixing process performs a critical role in the concrete microstructure, which defines the final product's quality. Optimizing mixing time and mixing speed during the mixing process can reduce the unit price and energy consumption without impacting product quality. Furthermore, the energy consumption to manufacture self-consolidating concretes (SCC) is more than that of conventional concretes due to their compositions and structures. Due to the fact that rheological and mechanical properties assess the performance of concrete, the effects of mixing energy on the mentioned properties of self-consolidating concretes are taken into consideration simultaneously in the current investigation. Accordingly, different mixtures contained polysaccharide-based viscosity modifying agent and limestone powder are made under different mixing speeds and mixing times. Drawing on the results of mixing time, the optimum time for mixing is 8 min in this study in order to improve the workability and to provide ideal levels of rheological features such as minimum yield stresses (static and dynamic). In the aspect of mixing speed, double increasing from 20 to 40 rpm rises the slump flow by 5%. Besides, accelerating mixing speed increases dynamic yield stress by 37% for 11 min mixed mixtures, which is more than that of other mixing times mixtures' dynamic yield stress increment. In the aspect of mechanical properties, mixing time increment increases the concrete's compressive strength. Nevertheless, other mechanical characteristic criteria do not significantly depend on mixing energy.

Keywords Mixing energy · Mixing time · Mixing speed · Workability · Rheological properties · Mechanical properties

1 Introduction

The mixing procedure can significantly impact workability, one of the critical criteria for self-consolidating concretes (SCC). The self-consolidating concretes performance is usually determined by their homogeneity. SCC mixtures require more mixing energy so as to change into a homogeneous mixture because their ingredients are different from conventional concretes [1].

Some researchers have investigated the importance of mixing time [2–5]. De França et al. [5] theorized that inappropriate mixing conditions could be caused by inadequate short mixing times. On the flip side, long mixing time increases production cost [5, 6]. Besides, flocculated cement particles are dispersed, and accordingly, the mixture's water film thickness and fluidity increase due to prolonged mixing time. Water film thickness increment decreases the solid contacts. Therefore, the mixture's

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Published online: 03 September 2020

stability and cohesiveness decrease [7], and may cause deterioration in fluidity [4]. França et al. [5] stated that mixing time had the most significant influence on the mixture's behavior.

Due to the importance of mixing time, Chopin et al. [8] defined a power consumption stabilization time recorded during the mixing process. According to a general rule, when the concrete arrives at stabilization time, it is pulled out [2]. Therefore, the possible shortest time for mixing can be detected by stabilization time. Moreover, Juez et al. [9] introduced a novel method, which allowed the characteristic point of the mixture detection, where the mixture was adequately fluid to guarantee the flow of paste at speed imposed by mixing. The mentioned point depended on the mixing geometry and mixing speed; it might potentially be valuable for a more detailed explanation of the state of mixing.

Several researchers [10–12] stated that the necessary mixing time could be shortened by increasing the mixing speed. Likewise, Dils et al. [13] admitted the previous findings; nevertheless, they expressed that accelerating the mixer's speed more than the suitable level (mixture requirement) may cause overmixing.

Hence, the mixing time and the mixing speed of mixers are two critical criteria which should be analyzed and optimized before manufacturing self-consolidating concretes [14].

Controlling the rheological features' variations is vital to ensure SCC's appropriate characteristics during different preparation steps, including mixing, transport, and placement. The mentioned variations can lead to segregation in case of yield stress or plastic viscosity reduction, or a loss of filling capacity in case of yield stress or plastic viscosity increment [15–17]. Over the past few years, based on the importance of mixing procedure's effect on rheological properties of self-consolidating concretes, several studies have been done [18–22].

Asghari et al. [15] expressed that mixing energy changing seemed to have a minor, less significant importance on rheological properties changing during the time. Rupnow et al. [23] indicated that the pastes with low rheology curves are provided from high mixing energy. The plastic viscosity, thixotropic area, and peak stress are lessened by increasing the mixing energy (long duration mixing time and high mixing speed). This trend is in line with all of the data sets and shows that mixing energy increment manufactures a more thoroughly-mixed slurry. Once the mixing energy arrives at a particular value, mixing energy increment may not enhance the paste's rheological properties. That is to say, when the mentioned point has been obtained, the slurry has been mixed uniformly, and more mixing energy is not required. Furthermore, the results postulated that different mixture proportions require different mixing energy to become homogeneous.

The links between slump flow time (plastic viscosity), slump flow (yield stress), and composition of high-performance self-consolidating concrete (HPSCC) mix and mixing time were investigated in Kostrzanowska [19] Study. The results indicated that rheological properties of fresh concrete change over time, yield stress, and plastic viscosity are increased. Also, the slump flow diameter is increased over time, while slump flow time is reduced. Nehdi [20] investigated the relation of rheological properties and concretes' workability. The outcomes of this analysis revealed that slump flow and yield stress have a negative correlation. Nevertheless, there is not any correlation between slump flow and plastic viscosity.

Some researches investigated the relationship between the mixing process and the mechanical process [2, 7, 24–26]. The outcomes of these studies indicated that the mixing time increment resulted in increased compressive strength. Kırca et al. [24] deduced that compressive strength increment is due to a reduction in water to cement, having finer constituent particles generated from the impact and friction between the particles and mixing tools, caused by mixing time increment. Meanwhile, the researchers have found some results about concrete's porosity [5, 27]. França et al. [5] declared that the hardened mortar porosity seemed to increase when mixing time is short and consequently the mechanical properties will be improved. The dispersant might change the hydrate products' chemical reaction affecting directly the system's porosity. Prasittisopin and Trejo [28] reported increased mixing time and increased mixer revolution counts result in rapid increase of the 28-day porosity at early mixing times and lower revolution counts.

According to all the above references, mixing energy, including mixing time and mixing speed, affects self-consolidating concretes properties remarkably. Accordingly, it is necessary to find the optimal amount of mixing speed and mixing time based on mixtures' properties. Furthermore, rheological and mechanical characteristics of self-consolidating concrete have become a significant concern. Accordingly, these features are scrutinized simultaneously in this investigation. In this regard, various experimental tests in different conditions and applying various materials are conducted in this study to analyze their influences on the properties of self-consolidating concretes and spot the optimal mixing time and mixing speed.

2 Research Significance

In the current study, different SCC's properties, including workability, rheological properties, mechanical properties, durability, and microstructure features, are investigated.

Besides, the incorporation of viscosity modifying agent (VMA) and limestone powder in the mixture proportion of SCC are analyzed. Several specimens are designed, and subsequently, these mixtures are mixed by different mixing energies. That is to say, the mentioned specimens are mixed for various mixing times, and they are combined under different mixing speeds to determine the optimal mixing energy. Ultimately, optimal mixing energy is investigated based on SCC's workability, rheological properties, mechanical characteristics, durability, and microstructure features. Additionally, the microstructural analysis has been applied to answer the questions on the relationship between mixing parameters and rheology, workability, and mechanical properties of SCC.

3 Experimental Program

3.1 Materials

Portland cement Type II, which its gravity is 3150 kg/m^3, is used in this investigation. In this study, two SCC types are analyzed, including powder-type mixtures and VMA-type mixtures. These two mixtures contain limestone powder and viscosity modifying agent (VMA), respectively. Limestone powder with the gravity of 2660 kg/m^3 is used as filler. The chemical composition of cement and limestone powder is presented in Table 1. The viscosity modifying agent is manufactured of polysaccharide. The crushed aggregate is utilized in mixture design produced by a combination of gravel, coarse sand, and fine sand. The maximum size of gravel, coarse sand ,and fine sand is 12.5 mm, 8 mm, and 3 mm, respectively. The percentage of gravel, coarse sand, and fine sand are considered 40%, 40%, and 20% in the order mentioned, and the aggregate grading curve based on ASTM C33 [29] is indicated in Fig. 1. Meanwhile, the minimum and maximum allowed range of grading curve is indicated in Fig. 1 [30]. The water absorption rate in gravel, coarse sand, and fine sand was 3.03%, 3.23% and 2.94% in the order named. The superplasticizer is made of the poly-carboxylate, which its gravity is 1100 kg/m^3.

Table 1 Chemical composition of cement and powder aggregates (%)

Chemical composition	Cement	Limestone powder
SiO_2	20.74	2.80
Al_2O_3	4.90	0.35
Fe_2O_3	3.50	0.50
MgO	1.20	1.80
CaO	62.95	51.22
SO_3	3.00	1.24
Loss on ignition (LOI)	1.56	39.06
Insoluble residue	0.74	2.80

3.2 Mixture Proportions

The mixture proportions applied in this investigation are represented in Table 2. Although the primary aim of this study is not to optimize SCC's mixture design, two mixture proportions, containing limestone powder and viscosity modifying agent, are investigated to analyze the effect of mixing energy on the utilized materials. The mixtures contained limestone powder and viscosity modifying agent are named powder-type mixtures and VMA-type mixtures, respectively. A Rantek pan type mixer is applied for the mixing process. The pan's effective capacity is 56 L, and it works under the voltage and frequency of 220–240 V and 50–60 Hz. The diameter of the mixer cup is 65 cm.

3.3 Mixing Methods

All of the specimens are made in the same condition, and a similar technique is applied to manufacture all samples. In other words, all materials are picked with the same batching, the humidity of aggregate is evaluated by particular equipment, and the experimental test is conducted with the same equipment for all of the specimens. The considered mixing speeds and mixing times are as follows:

- *Mixing speed* The circumferential velocity (speed) of the mixer is taken into consideration 20 rpm [24] and 40 rpm [31] in different samples. According to the mixer's cup diameter (65 cm), the considered mixing speeds are equal to 0.733 m/s and 1.4661 m/s.
- *Mixing time* Three different times are considered to investigate the mixing time, including 3 min (According to Iran Concrete Commentary (ABA)), 8 min [32], and 11 min (according to the mixing steps of the mentioned procedures and authors experience). These

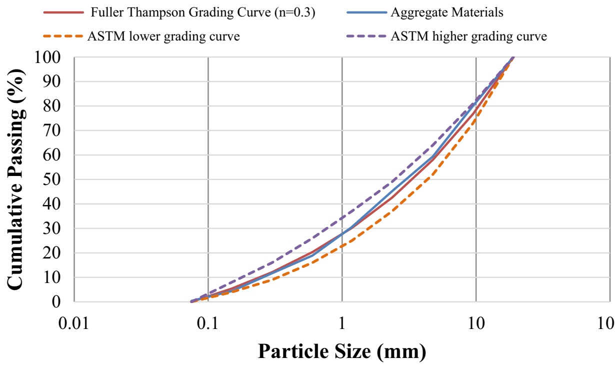


Fig. 1 Aggregate grading curves which is used in this study

Table 2 The mixture proportion of mixtures

ID	Mixture	W/C	Water (kg/m^3)	Cement (kg/m^3)	Limestone powder (kg/m^3)	Aggregate (kg/m^3)	Superplasticizer (kg/m^3)	VMA (% of cement volume)
1	Powder type	0.42	176.4	420	70	1711.6	0.95	0
2	VMA type	0.42	176.4	420	0	1781.5	0.69	0.4

three mixing modes are comprehensively explained in the following section.

Two speeds (20 rpm and 40 rpm), three different times (3, 8, and 11 min), and two different mixture proportions (powder-type mixtures and VMA-type mixtures) are considered to investigate the effects of mixing time and mixing speed on SCC characteristics. Thus, 12 mixtures are compared based on rheology and mechanical properties.

To make the samples, initially, coarse aggregates, fine aggregates, and 33% of water content are mixed for 1 min. Then, to improve the water absorption of aggregates, the mixing process is stopped for 1 min. Afterward, cementitious materials (limestone powder should be considered if it is used) are added to the mixture. Subsequently, the remaining water content is mixed with superplasticizer and VMA (if it is used), and this liquid part is added to the mixture gradually. While all of the concrete ingredients are incorporated in the mixture, three different mixing times are considered as follows:

First mode The concrete is mixed for 3 min.

Second mode The total mixing time (including initial mixing time, resting time, and final mixing time) is taken 8 min. Initially, the mixture is mixed for 3 min. Then, the mixture is resting (mixer stops working) for 3 min, and finally, the mixture is mixed for 2 min.

Third mode The total mixing time (including initial mixing time, resting time, and final mixing time) taken is 11 min. Initially, the mixture is mixed for 3 min. Then, the mixture rests (mixer stops working) for 3 min, and ultimately, the mixture is mixed for 5 min. These modes are presented in Table 3.

The mixing energy is calculated based on Eq. (1) presented by Rupnow et al. [23].

$$\frac{E}{M} = \frac{K \times \omega^2 \times t}{V}. \tag{1}$$

where E is the mixing energy (kJ), M implies the sample's mass (kg), ω is the circumferential velocity (rpm), t is the mixing time (min), V is the mixture's volume (m^3), and $K = 6.4 \times 10^{-9}$ (N m/Kg/m^3/rpm) (experimental constant).

Analyzing each parameter's effects on the concrete characteristics is essential, and parameter analysis plays a critical role in model verification [33]. Accordingly, the impact of mixing energy on the SCC characteristics is scrutinized. To this end, a one-way analysis of variance (ANOVA) is employed in order to detect the SCC features, which are considerably affected by mixing energy variation. The reliability of 5% is considered as the confidence level [34]. Hence, a P value lower than 0.05 implies that the particular criterion's impact is statistically significant, with a confidence level of 95%.

3.4 Test Procedures

In this section, the utilized experimental tests and their process are explained. This section is classified into three sub-sections. The mentioned sub-sections provide information about the process and standard methods of workability tests, rheological tests, mechanical characteristic tests, durability, and microstructure properties tests.

3.4.1 Workability

The slump flow test is the most straightforward and most widely used test for SCC [35]. Ergo, based on ASTM C1611 [36], slump flow is used to measure the workability. The T_{50} test is performed based on the ASTM C1611 [36] procedure to assess concrete's filling ability. According to methods of EFNARC [37], the J-ring test is used to measure the passing ability. The V-funnel test is applied based on the guidelines presented by EFNARC [38]. Furthermore, according to the procedures provided by ASTM C1611 [36], the visual stability index (VSI) test is applied in order to evaluate segregation resistance. VSI reveals the stability and condition of freshly mixed SCC. VSI is classified into four groups for SCC. VSI = 0 implies the SCC is highly stable. VSI = 1 refers to stable SCC. VSI = 2 signifies the SCC is unstable. VSI = 3 indicates that SCC is highly unstable [39].

Table 3 Mixing time procedure

Step	Duration (min)			Action
	First mode	Second mode	Third mode	
1	1	1	1	Mixing aggregates with a third of water
2	1	1	1	Scraping (resting)
3	3	3	3	Initial mixing
4	–	3	3	Scraping (resting)
5	–	2	5	Final mixing
Total duration of concrete mixing	3	8	11	

3.4.2 Rheology

The rheological behavior of self-consolidating concrete is examined by a coaxial type rheometer, similar to the ICAR device utilized in Koehler and Fowler's study [40]. The features of the mentioned rheometer are presented in Ghoddousi and Salehi investigation [31]. Moreover, the mentioned device can perform a growth stress test and measure the flow curve. Hence, by virtue of this ability, it is possible to define static yield stress, dynamic yield stress, plastic viscosity, and thixotropy [41]. These tests are conducted based on the procedure presented in Koehler and Fowler [40] and Roussel [42] investigations.

3.4.3 Mechanical properties, durability, and microstructure analysis

Various experimental tests, including compressive strength at different ages, flexural strength, ultrasonic pulse velocity, water absorption rate, and SEM analysis, are conducted to evaluate SCC mixtures' performance. Three samples are manufactured for each mechanical and durability tests. That is to say, mechanical characteristics and durability test results are considered the average value obtained by three specimens. The mentioned tests and their procedures are described in this part.

Cubic samples (100 × 100 × 100 mm) have been tested by a compressive testing machine (hydraulic jack) 7 and 28 days after manufacturing the specimens to evaluate the concrete's compressive strength. The tests are conducted based on BS EN-12390/3/2019 [43]. The flexural strength at the age of 28 days is measured according to ASTM C293/C293M-16 [44]. A hydraulic jack with a minimum loading capacity of 2000 KN is employed to assess the compressive strength and flexural strength of samples. The mentioned hydraulic jack is the same as the jack applied by Ghoddousi and Salehi [31].

An ultrasonic device performs the ultrasonic pulse velocity test according to the method described in ASTM C597-16 [45]. A Pundit Lab plus is applied as an ultrasonic pulse velocity test instrument. The utilized Pundit Lab plus instrument can measure the transit time with the transit time range of 0.1–9999 µs, and resolution of 0.1 µs. Besides, the Pundit Lab plus instrument includes a receiver with a bandwidth ranging between 20 and 500 kHz.

The water absorption rate is considered as a concrete durability criterion. The samples' water absorption rate is determined based on ASTM C1585-13 [46]. This permeability test is conducted for SCC mixtures 28 days after making them.

The SEM images have been taken by the VEGA2 TESCAN device to study the microstructural behavior of mixtures. With the assistance of this device, the pore sizes can be determined easily. The SEM analysis is performed based on the details provided by Rupnow et al. [23] and Manuel et al. [47]. Moreover, MIP4 software, as a robust SEM analyzer [48], is applied to analyze SEM images and determine the pores' percentage and size.

4 Results and Discussions

In this part, the results of different tests relevant to workability, rheological properties, mechanical characteristics, durability, and microstructure analysis are presented. The ANOVA is performed to assess the impacts of mixing energy on concrete characteristics. These results are analyzed, and the influences of mixing energy and mixture proportion on SCC properties are scrutinized.

4.1 Workability

According to the concepts mentioned above, the slump flow test, T_{50} test, J-ring test, V-funnel test, and VSI test are conducted to investigate the workability properties. The results of slump flow tests and slump loss are presented in Figs. 2, 3, and 4.

As can be perceived from the results of Fig. 2, the slump flow value of all samples is located in the range

(530–740 mm) defined by ASTM C1611 [36]. Increasing the mixing time until a particular level increases the slump flow, and afterward, the amount of slump flow is decreased. Moreover, the results indicate that the most value of slump flow is relevant to the sample, which its mixing time is 8 min for a mixture with a given mixing speed. Increasing mixing time up to 8 min improves the slump flow, and growing mixing time more than this level is not appropriate, leading to a decrease in the slump flow amount.

According to Fig. 3, if the mixing speed is accelerated, the slump flow amount is increased considerably for 3- and 8-min mixed specimens. Nonetheless, this trend is entirely different in 11-min mixed mixtures. Hence, the effects of mixing time and mixing speed on slump flow are quite different. Nevertheless, increasing mixing speed enhances the slump flow and workability steadily for 3 and 8 min mixed mixtures. Furthermore, accelerating the mixing speed of 11 min blended mixture causes to reduce the amount of slump flow.

Lowke and Schiessl [11] and Rupnow et al. [23] stated that increasing mixing energy up to a particular level enhances slump flow, and afterward, the slump flow is deteriorated. Therefore, the current investigation results are consistent with other researches findings [11, 23]. According to the results, it can be postulated that to improve the workability, optimal mixing time and mixing speed are 8 min and 40 rpm, respectively.

As can be seen from Fig. 4, until taking delay time up to 40 min after mixing the mixtures, the slump flow loss is increased steadily for both mixture proportions. The particles reconnect and flocculate when they remain stationary for a considerable time resulting in structural rebuilding. This process results in higher resistance to flow and hence a smaller spread. Therefore, once the paste is put to rest, for increasing hold time, the spread goes on decreasing. These findings resemble those of other investigations [19, 49]. From another perspective, slump loss is increased by mixing time increments. Kırca et al. [24] and Erdoğdu [25] reported the same results, consistent with the results obtained in this study. In powder-type mixtures, increasing the mixing speed is a major cause of growing slump flow loss. In contrast, increasing the mixing speed does not have considerable effects of slump flow loss in VMA-type mixtures (mixtures which contain VMA).

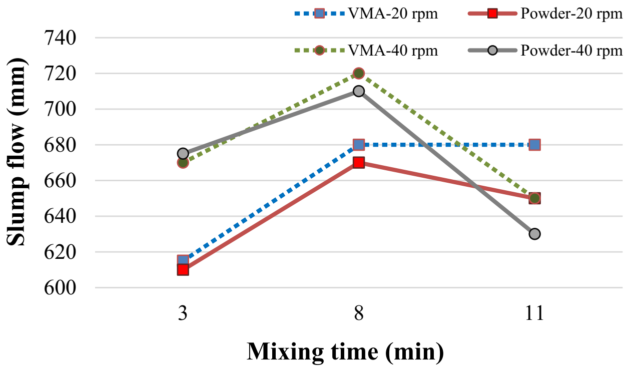


Fig. 2 Effects of mixing time on slump flow

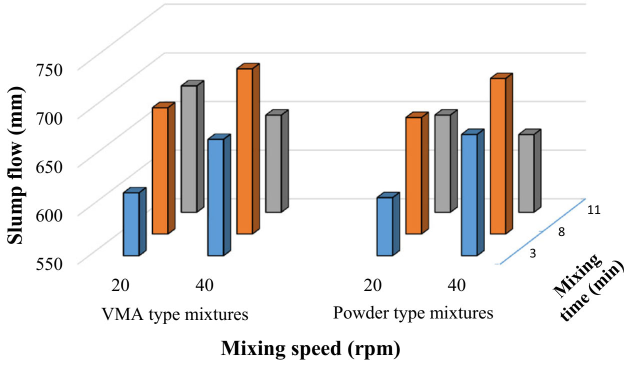


Fig. 3 Effects of mixing speed on slump flow

Table 4 presents the workability test results, including J-ring, T_{50}, V-funnel, and VSI. As can be perceived, Similar to slump flow results, the specimens mixed for 8 min offer the best results in the T_{50} test, and this outcome is in accordance with the results reported in recently-published articles [30]. Additionally, the T_{50} test is decreased if the mixing speed is accelerated. However, all T_{50} test values are higher than two seconds. The J-ring test results indicate that the mixtures mixed for 8 min outperform other samples based on the passing ability. By increasing (from 8 to 11 min) and decreasing (from 8 to 3 min) the mixing time, the J-ring test value is grown. J-ring test value of most of the mixtures is located on the allowed range defined by EFNARC [37] (< 10 mm); however, some mixtures violate this range, which may be due to overmixing. This process is the same as the slump flow trend. Increasing the amount of the J-ring test correlates with increasing the segregation and falling slump flow. Gettu et al. [50] expressed that VMA incorporation seems to increase the J ring test results, and it is in accordance with the current study outcomes.

Meanwhile, According to the V-funnel test outcomes, the mixtures mixed for 3 min are not homogeneous, and segregation between aggregates and cement paste may be seen. The mixtures seem to be homogenous by increasing the mixing time up to 8 min, and accordingly, the segregation is considerably decreased. Moreover, the mixtures mixed for 8 min are better than 11-min mixed specimens. The allowed range of V-funnel test value is between 9 and 25 s [38], and accordingly, all mixtures provide appropriate V-funnel values. Mehdipour et al. [7] found the same results. They explained that overmixing could break down the formation of the mixture's viscous behavior results in aggregate blockage.

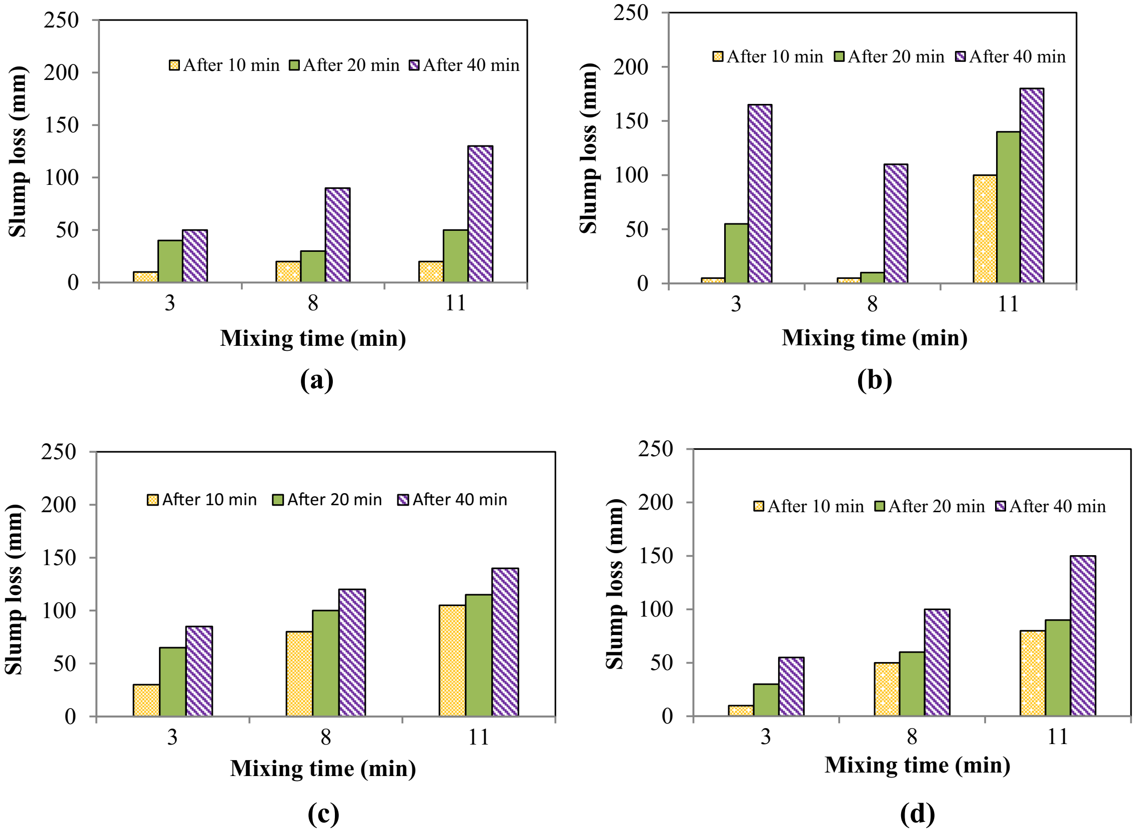


Fig. 4 Influences of mixing time on slump loss based on delay time of test after making the mixtures **a** limestone -ype mixtures, mixing speed is 20 rpm, **b** limestone powder-type mixtures, mixing speed is 40 rpm, **c** VMA-type mixtures, mixing speed is 20 rpm, **d** VMA-type mixtures, mixing speed is 40 rpm

Table 4 The workability test results

Mixture type	Mixing speed (rpm)	Mixing time (min)	J-ring (mm)	J-ring spreading (mm)	T_{50} (s)	V-funnel (s)	VSI
Limestone powder type mixture	20	3	8.75	610	3.47	11.49	1
		8	7.50	660	3.00	11.05	0
		11	8.75	650	3.57	11.76	1
	40	3	5.00	670	2.00	9.53	0
		8	3.00	710	2.00	9.10	0
		11	17.50	590	2.00	9.93	1
VMA type mixture	20	3	10.00	625	5.00	12.10	0
		8	6.25	660	3.03	11.37	1
		11	12.50	660	2.31	10.33	1
	40	3	7.50	670	2.35	10.77	0
		8	5.00	700	2.00	10.14	0
		11	11.25	640	3.57	11.61	2

The visual stability index (VSI) is a standard method to assess the concretes' quality. Segregation is not noticeable in most of the mixtures. However, few segregations are spotted in six specimens, demonstrated in Table 4. According to this table results, the powder-type mixtures mixed for 11 min under 20 rpm and 40 rpm, the powder-type mixture mixed for 3 min by 20 rpm, and the 8- and 11-min mixed VMA-type mixtures under 20 rpm are stable. The powder mixture, which is mixed for 11 min by mixing speed of 40 rpm is unstable, and other specimens are highly stable. Based on the results presented by Mehdipour et al. [7], surface settlement, bleeding, and aggregate segregation were caused by mixing time increment. The mentioned results are consistent with the results obtained in the current study.

Concerning all the above tests, the optimal mixing time and mixing speed based on workability tests are 8 min and 40 rpm, respectively.

The ANOVA analysis is applied to scrutinize the influence of mixing speed on workability tests, and the mentioned results are presented in Table 5. As can be seen, the P-value of all workability tests is lower than 0.05. Therefore, it can be deduced that the impact of mixing energy on workability tests is statistically significant. The results of ANOVA analysis are in harmony with the outcomes of experimental tests.

4.2 Rheological Properties

4.2.1 Static Yield Stress

The effects of mixing time and mixing speed on static yield stress are illustrated in Figs. 5 and 6, respectively. As can be seen, the least static yield stress value is related to the mixtures, which are mixed for 8 min. If 8-min mixing is considered an ideal level, the static yield stress is increased by 22% and 42% with mixing 3 min and 11 min in the order mentioned. Lower yield stress needs less stress to initiate flow and generally corresponds to higher slump flow [5]. If the mixing speed is accelerated from 20 to 40 rpm, the average static yield stress is reduced by 8%. Similarly, this part's results resemble other researchers' findings [18, 23].

4.2.2 Dynamic Yield Stress

The relations between mixing time, mixing speed, and dynamic yield stress are shown in Figs. 7 and 8, respectively. Drawing on results, the mixtures mixed for 8 min has the least amount of dynamic yield stress. Provided that 8-min mixing is taken into account an ideal level, for 3- and 11-min mixed mixtures, the dynamic yield stress is 25% and 64% more than the ideal level in the order mentioned.

Table 5 The ANOVA analysis for workability

Performance test	ANOVA test results			
	Factor	Adj. MS	*F* value	*P* value
Slump flow	Mixing energy	15,400	5.60	0.000
J-ring	Mixing energy	30.98	3.97	0.042
J-ring spreading	Mixing energy	2298.8	9.43	0.008
T_{50}	Mixing energy	1.7103	4.65	0.044
V-funnel	Mixing energy	1.9848	4.44	0.049

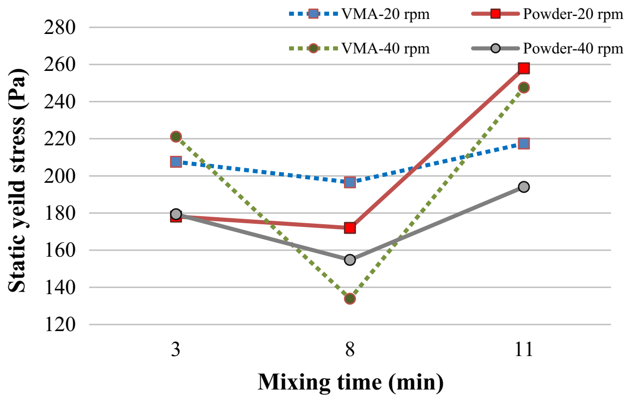


Fig. 5 The effects of mixing time on static yield stress

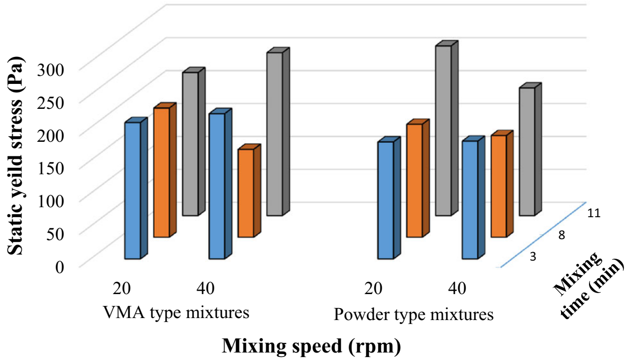


Fig. 6 The effects of mixing speed on static yield stress

As França et al. [5] declared, increasing the mixing time for tested mixture reduced equivalent yield stress for the evolution of values corresponding to the first cycle. An efficient system dispersion could be promoted by more mixing times due to yield stress reduction. On the flip side, mixing time extension influenced the fresh concrete's microstructure. Mixing time increment increased the

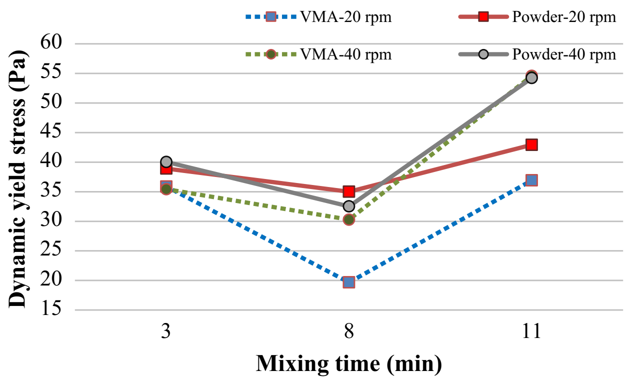


Fig. 7 The impacts of mixing time on dynamic yield stress

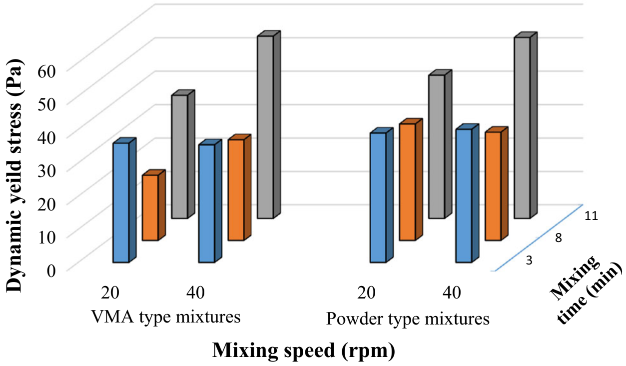


Fig. 8 The impacts of mixing speed on dynamic yield stress

secondary particles' specific surface area, i.e., the clusters, which remained combined during the shearing movements in fresh concrete. The rubbing contact surfaces number thereby rose, lead to raising the yield stress [22]. These results are in accordance with this investigation's findings. According to the achieve results, it can be theorized that overmixing impacts dynamic yield stress more than mixing less than the ideal level.

The double increase of speed (from 20 to 40 rpm) increases the average dynamic yield stress by 8% in mixtures, which are mixed for 3 and 8 min. Nonetheless, the dynamic yield stress increment reaches 37% in mixtures, which are mixed for 11 min. Thus, increasing the mixing speed does not have an appropriate impact on dynamic yield stress for 11-min mixed mixtures. These results are in accordant with the results of other researchers [6, 11, 18].

4.2.3 Plastic Viscosity

Figure 9 presents the effect of mixing time on plastic viscosity. The viscosity highest value is related to the specimens mixed for 8 min. In this graph, if the 8-min mixed mixture is taken into consideration the origin of coordinates, the plastic viscosity is reduced by 16% and 10% in the 3-min mixed mixture and 11-min mixed mixture, in the order given. It can be postulated that increasing the mixing time up to a particular level enhances plastic viscosity, and increasing mixing time more than this level deteriorates this rheological parameter. These results are in accordant with the results of Asghari's investigation [18]. Han and Ferron [51] declared that as the mixing time increased, the tested mixtures' viscosity increased in a tested protocol by 8.8% and in another one by 45.9%. This trend is spotted in Limestone type mixtures before 11 min mixing time.

The effect of mixing speed on plastic viscosity can be perceived in Fig. 10. As can be seen, mixing speed increment generally reduces plastic viscosity value. Asghari et al. [18] expressed that accelerating the mixing speed contradicts with improving the rheological properties. In mixtures with minimum mixing time, the amount of plastic viscosity is decreased by increasing the mixing speed [23]. Felekoglu et al. [52] proved that the self-consolidating mortar's viscous behavior was evident for low mixing speeds. On the other hand, flowable behavior was dominant at higher mixing speed. During the mixing process, the shear-thinning impact broke down the mix's high viscous behavior formation at rest. That is to say, when local shear or vibration facilitated the flow, strain rate increment reduced the apparent viscosity. Roy and Asaka [53] and Williams et al. [54] showed that by increasing mixing speed, viscosity decreases.

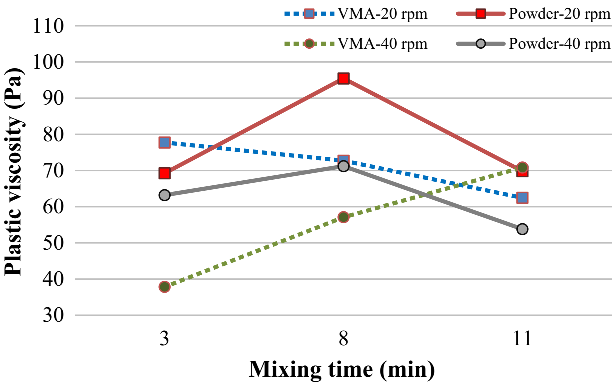


Fig. 9 The effect of mixing time on plastic viscosity

In the current study results, the maximum viscosity value can be seen in mixtures mixed for the feasible shortest time slowly. Besides, the viscosity minimum amount is associated with mixtures mixed for a longer time quickly.

4.2.4 Thixotropy

The thixotropic properties of mixtures based on mixing time and mixing speed are presented in Fig. 11. The amount of thixotropy reaches the highest level in mixtures mixed for 8 min, and concrete's trend to recovery is better than the other mixtures. As Ghoddousi et al. [55] declared,

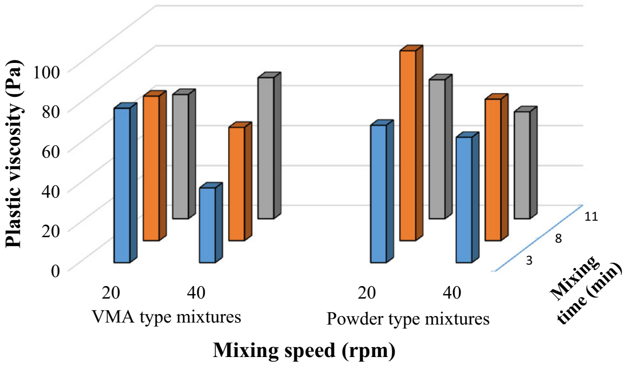


Fig. 10 The effect of mixing speed on plastic viscosity

increasing the thixotropy level increases the concrete's stability. Moreover, As Lowke [56] described, thixotropy reduced by increasing surface coverage for similar particle sizes. Besides, low thixotropic behavior is affected by large particle distance, strong steric interactions, and high surface coverage. This trend can be seen in mixing the specimens after 8 min. Adding VMA to the mixtures may probably increase the thixotropic properties [57] and Fig. 11 validates this statement.

The ANOVA is employed to scrutinize the effect of mixing energy on SCC's rheological, and its outcomes are presented in Table 6. Drawing on this table's results, the P-value of mixing energy in the plastic viscosity test is more than 0.05 (0.212). Hence, it can be realized that the influence of mixing energy on the plastic viscosity of SCC is not significant, and it may be because of the dissimilar behavior of VMA-type mixtures, which are mixed under the mixing speed of 20 rpm and 40 rpm. Notwithstanding, the other P-values are lower than 0.05, and the influence of mixing energy on static yield stress, dynamic yield stress, and thixotropy is statistically noticeable.

4.3 Mechanical Properties, Durability, And Microstructure Analysis

Table 7 presents the results of the compressive strength test, flexural strength test, ultrasonic pulse velocity test, and volumetric water absorption. The compressive strength test is conducted for all mixtures 7 and 28 days after manufacturing them. Increasing the mixing time increases SCC's compressive strength, and the highest compressive strength values are obtained by specimens mixed for 11 min. Limestone powder mixtures significantly outperform VMA-type mixtures based on the compressive strength. The most amounts of compressive strength are related to limestone powder mixtures, which are mixed for 11 min. There is no correlation between mixing speed and compressive strength.

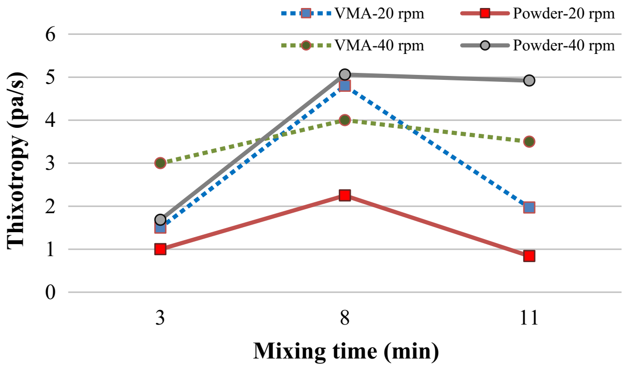


Fig. 11 The thixotropic properties of mixtures based on mixing time and mixing speed

Table 6 The ANOVA analysis for rheological properties

Performance test	ANOVA test results			
	Factor	Adj. MS	*F* value	*P* value
Static yield stress	Mixing energy	2381.0	4.72	0.043
Dynamic yield stress	Mixing energy	172.21	6.74	0.019
Plastic viscosity	Mixing energy	247.40	2.00	0.212
Thixotropy	Mixing energy	4.1953	5.38	0.032

Longer mixing periods generate new surfaces by either superficial layers from cement grains or removing hydrates. Subsequently, higher plasticizer content is adsorbed. Therefore, massive hydrates precipitation occurs, and earlier hydration is accelerated [4].

Mixing time increment creates new surfaces by removing superficial layers or hydrates from cement grains or modifying the cement grains themselves. Subsequently, more superplasticizer can be adsorbed. Hence, hydrates' massive precipitation occurs, and earlier hydration is accelerated [4]. Moreover, increasing mixing time makes the cement finer and enhances the stickiness of cement. Ergo, mixing time increment leads to an increase in the compressive strength [22, 24–26]. The results presented by these researchers [22, 24–26] are in line with the outcomes obtained in this paper.

The results also indicate that limestone powder mixtures' flexural strength is more than those of VMA-type mixtures. In most mixtures, increasing mixing time enhances flexural strength, while some other mixtures do not follow a similar trend.

Likewise, the results of mixing energy on ultrasonic pulse velocity and the volumetric water absorption as a concrete permeability symbol are presented in Table 7. According to Table 7, mixing speed reduction increases the ultrasonic pulse velocity. That is to say, the ultrasonic pulse speed of mixtures mixed by 20 rpm is more that of mixtures mixed by 40 rpm. On the other hand, a specific correlation is never seen between mixing time and ultrasonic pulse speed.

Based on the water absorption test results, powder-type mixtures mixed by 40 rpm speed have a peak time. In other words, these 28-day aged mixtures have the least amount of volumetric water absorption if they are mixed for 8 min. When the mixing time is increased to 11 min, the water absorption is grown up to five times. Likewise, powder-type mixtures, which are mixed by 20 rpm speed, have the minimum amount of water absorption when they are mixed for 8 min. Water absorption in the VMA-type mixtures reaches the highest level if they are mixed for 8 min. Generally, the water absorption of VMA-type mixtures is by far more than mixtures containing limestone powder.

Table 7 Mechanical properties, durability, and microstructure behavior of mixtures

Mixture type	Mixing speed (rpm)	Mixing time (min)	7-days compressive strength (Mpa)	28-days compressive strength (Mpa)	Flexural strength (Mpa)	Ultrasonic pulse velocity (km/s)	28-days Volumetric water absorption (%)
Limestone powder type mixture	20	3	18.0	25.8	24.0	4.90	3.20
		8	26.4	31.0	33.5	4.95	1.43
		11	29.8	60.5	35.0	5.10	2.22
	40	3	36.1	47.0	23.5	4.80	2.98
		8	37.0	54.8	33.5	4.90	0.64
		11	37.2	55.2	33.0	5.04	5.65
VMA type mixture	20	3	23.1	33.2	22.0	4.67	6.12
		8	26.2	37.0	20.0	4.70	6.92
		11	30.3	53.0	23.0	4.64	1.54
	40	3	20.0	26.0	20.5	4.77	5.49
		8	37.6	46.6	26.0	4.64	6.91
		11	39.1	56.9	24.0	4.55	5.34

Long mixing time increases the concrete’s pores. Hence, the water absorption and the chloride ion permeability increase by mixing time increments [58], which can be seen in 11-min mixed mixtures in this investigation.

Table 8 presents the results of ANOVA analysis applied to determine the effect of mixing energy on the compressive strength, flexural strength, ultrasonic pulse speed test, and water absorption of SCC. According to the results of this table, the influence of mixing energy on the compressive strength (7 and 28 days) are statistically considerable because the *P* value of mixing energy in 28 days‘ compressive strength and 7 days‘ compressive strength is equal to 0.034 and 0.043, respectively, and these values are lower than 0.05. Nonetheless, the *P* value of mixing energy is more than 0.05 in the flexural strength (0.744). Therefore, it can be deduced that the impact of mixing energy on the flexural strength is not statistically significant. These results are consistent with the results of the experimental tests.

The *P* value of mixing energy in ultrasonic pulse velocity is 0.998, and this value is by far more than 0.05. Accordingly, it can be theorized that the influence of mixing energy on ultrasonic pulse velocity is not statistically significant, and it may be due to a lack of correlation between mixing time and ultrasonic pulse speed. Similarly, the impact of mixing energy on the volumetric water absorption is not statistically noticeable because of providing a *P* value of higher than 0.05 (0.825). This process may be owing to the different behavior of VMA-type and powder-type mixtures. Likewise, The outcomes of ANOVA analysis is in line with the results of the experimental tests.

This section aims to analyze the effects of mixing time, mixing speed, and mixture proportion on the SCC porosity. To this end, three powder-type samples with a similar mixing speed (20 rpm) and different mixing time (3 min, 8 min, and 11 min) are considered to investigate the influences of mixing time on SEM microstructure. Moreover, two powder-type mixtures with the same mixing time (11 min) and different mixing speeds (20 rpm and 40 rpm) are taken into account to analyze mixing speed effects of porosity. Besides, two different mixture proportions

Table 8 The results of ANOVA analysis for the mechanical characteristics and durability

Performance test	ANOVA test results			
	Factor	Adj. MS	*F* value	*P* value
Compressive strength (28-days)	Mixing energy	287.65	5.24	0.034
Compressive strength (7-days)	Mixing energy	92.320	4.72	0.043
Flexural strength	Mixing energy	21.350	0.54	0.744
Ultrasonic pulse velocity	Mixing energy	0.0027	0.05	0.998
Volumetric water absorption	Mixing energy	2.9170	0.41	0.825

(powder type and VMA type) and constant mixing time (11 min) and constant mixing speed (20 rpm) are utilized to compare the impact of VMA and limestone powder on the SCC microstructure. That is to say, five samples, including Powder-20 rpm-3 min, Powder-20 rpm-8 min, Powder-20 rpm-11 min, Powder-40 rpm-11 min, and VMA-20 rpm-11 min, are selected. The SEM images of the mentioned samples are taken and scrutinized by MIP4 so as to determine the porosity percentages.

The analyzed pictures are presented in Fig. 12. As can be perceived, by increasing mixing time from 3 to 8 min in a fixed mixing speed, the porosity of Powder-type mixture is reduced from 18.18 to 1.96%. Hence, it can be deduced that mixing time increment reduces the porosity volumes. Nonetheless, mixing time increment from 8 to 11 min increases the porosity contents from 1.96% to 3.94%. Hence, it can be deduced that mixing time increment reduces the SCC porosity volume. However, extended mixing times lead to higher porosity percentages. These results are in line with the results presented by other researchers [4, 59].

On the other hand, if the mixing speed of 11 min mixed specimens is doubled, the porosity value is decreased by 1.57% (from 3.94 to 2.37%). A more detailed look at Fig. 12 reveals that the VMA mixture porosity value is significantly higher than that of Powder mixture in the given mixing time (11 min) and mixing speed (20 rpm). In other words, the porosity value in VMA-20 rpm-11 min is 7.94%, while this value is 3.94% in Powder-20 rpm-11 min.

Figure 13 illustrates the MIP4 software reports presenting the vertical and horizontal porosity lengths and the corresponding porosity numbers of considered specimens. SEM images with a scale of 20 µm are used to evaluate the contents of $Ca(OH)_2$ crystal and C–S–H particles' aggregation with the dimension of approximately 1 µm. Moreover, SEM images with a scale of 500 µm (as can be seen in Fig. 13) are employed by MIP4 software in order to determine air bubble values with the approximate dimension ranging from 50 µm to 1 mm. By analyzing the maximum porosity size, it is revealed that the highest porosity content with the maximum size is spotted in Powder-20 rpm-3 min, the mixture with the minimum mixing time. Hence, Powder-20 rpm-3 min includes the highest air bubble values. The air bubble's length in cement paste is larger than the capillary bubble's length, and accordingly, air bubbles reduce compressive strength [60]. Hence, this result justifies the low strength of 3-min mixed samples. In contrast, the minimum number of porosities is obtained in Powder-20 rpm-8 min. The number of porosities in Powder-20 rpm-11 min is more than that of Powder-20 rpm-8 min, which indicates that 8 min is the optimal mixing time to reduce porosity length and porosity values. Comparing Powder-20 rpm-11 and Powder-40 rpm-11 reveals that mixing speed increment increases the length of the largest pores. That is to say, specimens mixed by the speed of 40 rpm outperforms the specimens mixed by the speed of 20 rpm based on porosity reduction. The VMA mixture contains more air bubbles compared with powder-type mixture, and hence, the powder-type mixture outweighs the VMA mixture based on inappropriate porosity reduction. In SEM images with a scale of 20 µm, it can be perceived that mixing speed acceleration makes the texture more regular.

5 Conclusion

In this study, the impacts of mixing time and mixing speed on the SCC are taken into account. To this end, the workability, rheological properties, mechanical characteristics, durability, and microstructure features of different mixtures are assessed. The ANOVA analysis is applied to scrutinize the influence of mixing energy on SCC characteristics. The following conclusions can be drawn from the results of this study:

- In slump flow-mixing time trend lines, there is a maximal point. This point represents that increasing mixing time up to a certain level (8 min) enhances the slump flow, and mixing the SCC more than 8 min decreases the slump flow (by 6%). Similarly, the other workability tests obtain the same result in which 8 min is the optimal mixing time.
- Increasing the mixing speed from 20 to 40 rpm leads to a 5% increment in the average value of mixtures slump flow. A more detailed look at the results of workability tests reveals that 40 rpm is the optimal value of mixing speed for the mixtures mixed for 8 min (optimal mixing time). The mixing energy significantly affects the workability test results based on the outcomes of ANOVA.
- The least amount of static yield stress and dynamic yield stress is related to specimens mixed for 8 min. If 8 min mixing is considered an ideal level, the static yield stress is increased by 22% and 42% by mixing for 3 min and 11 min, respectively. Meanwhile, these values increased to 25% and 64% for dynamic yield stress results and changes to 16% and 10% decrease for plastic viscosity results. Hence, it can be theorized that 8-min mixing is the ideal level of mixing time based on rheological tests.
- The double increase of mixing speed causes average static yield stress reduction by 8%. The dynamic yield stress for 3- and 8-min mixed samples increased by 8% by accelerating the mixing speed from 20 to 40 rpm.

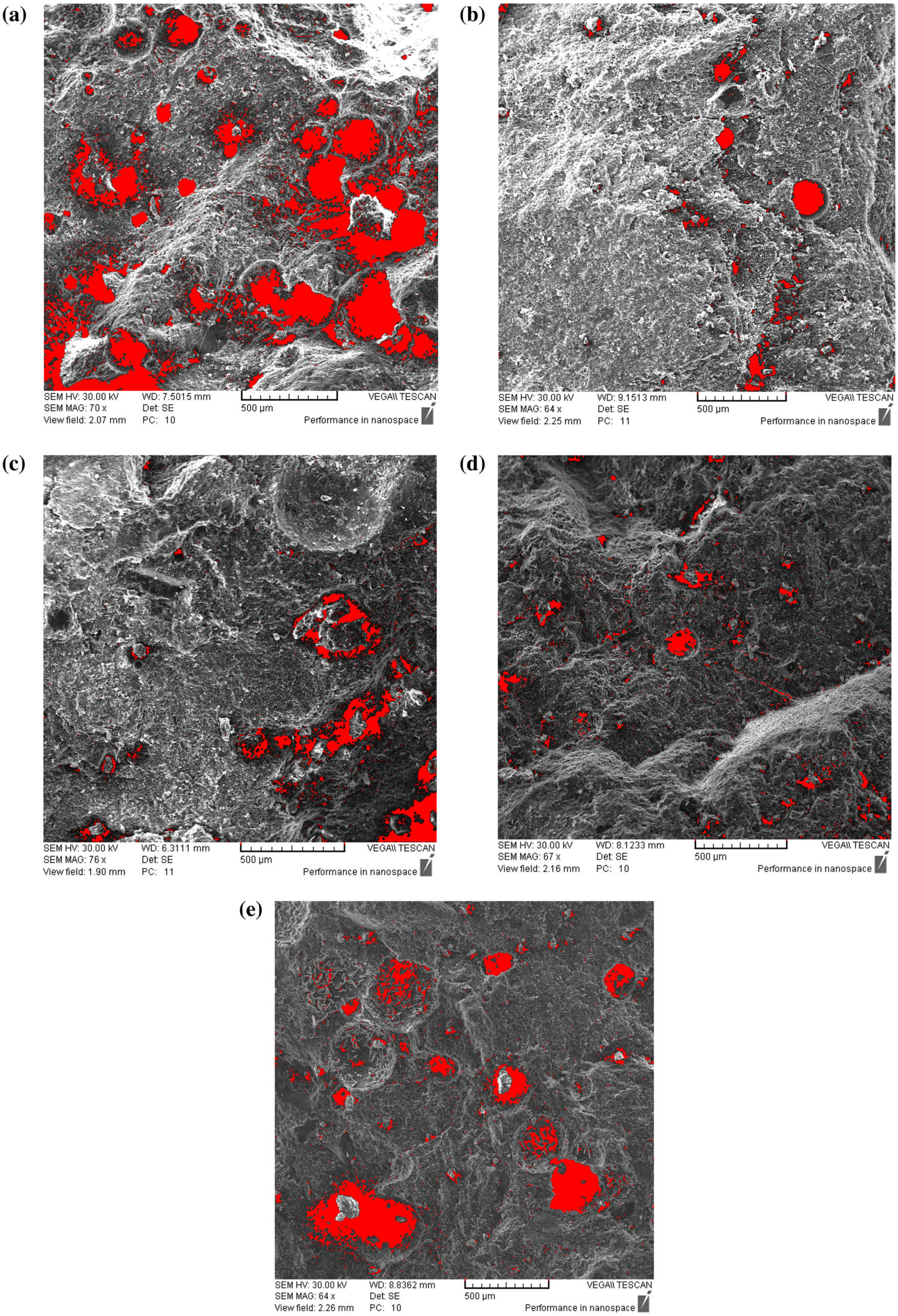


Fig. 12 The SEM porosity analysis, **a** powder-20 rpm-3 min, **b** powder-20 rpm-8 min, **c** powder-20 rpm-11 min, **d** powder-40 rpm-11 min, **e** VMA-20 rpm-11 min

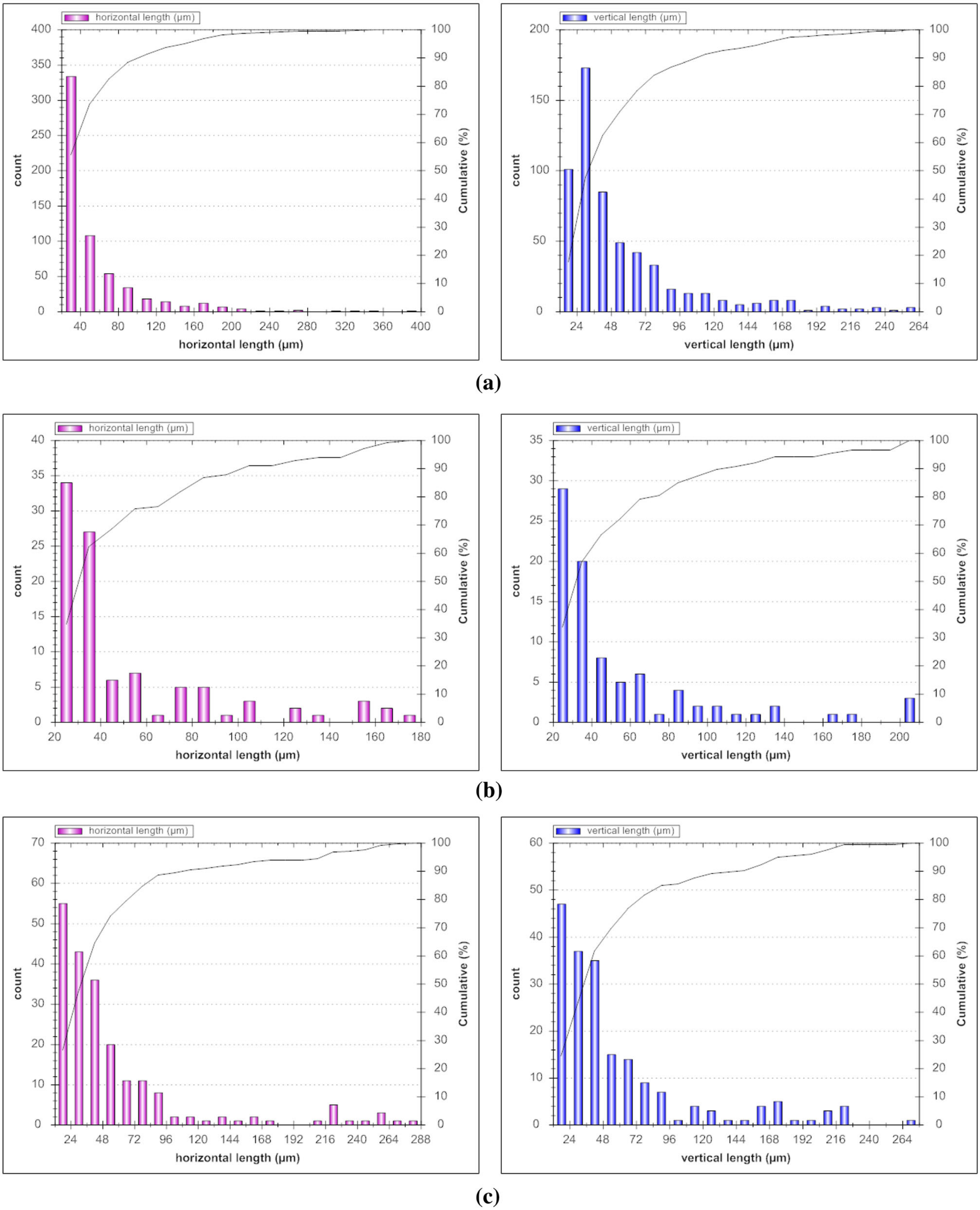
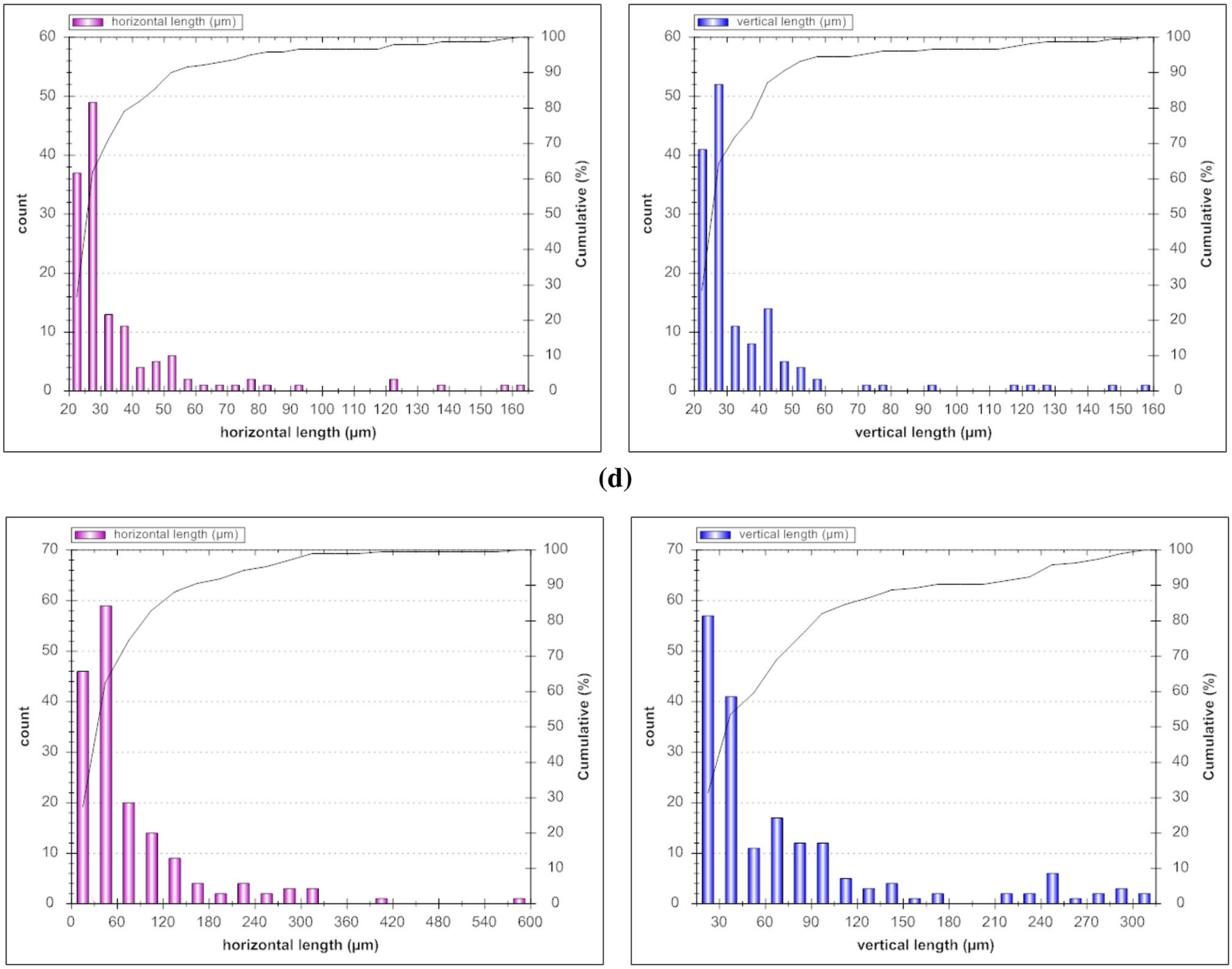


Fig. 13 The horizontal and vertical porosities length and their counts in SEM images with a scale of 500 µm **a** powder-20 rpm-3 min, **b** powder-20 rpm-8 min, **c**: powder-20 rpm-11 min, **d** powder-40 rpm-11 min, **e** VMA-20 rpm-11 min



(d)

(e)

Fig. 13 continued

Mixing speed increment increases the dynamic yield stress by 37% for mixtures mixed for 11 min. The mixing speed increment gets the plastic viscosity decreased by 19%.

- According to compressive strength tests, increasing the mixing time increases SCC's compressive strength, and the most amounts of compressive strength are related to samples mixed for 11 min. The highest compressive strength values are achieved by limestone powder mixtures mixed for 11 min. Based on ANOVA results, although mixing energy increment enhances SCC's compressive strength, the impact of mixing energy on other mechanical characteristics is not statistically significant. Therefore, increasing the mixing time and using limestone powder on SCC samples result in the increase of the compressive strength. Likewise, similar results are achieved by other mechanical characteristics and durability tests.
- The SEM analysis results indicate that 8 min is the optimal mixing time in order to reduce undesired porosities, followed by 11 min and 3 min, with the porosity percentage of 1.96%, 3.94%, and 18.18%, respectively. The mixing speed increment results in the porosity percentage reduction. Therefore, the optimal mixing speed is 40 rpm based on porosity analysis. The porosity length, number, and percentage in powder-type mixture are significantly lower than those of the VMA-type mixture.
- The presented results of rheological properties analyzed the effects of mixing time and mixing speed on SCC meticulously. Generally, higher mixing energy provides a lower shear stress level, and this result indicates that mixing energy increment enhances the flowability. Even though increasing the mixing energy improves the compressive strength, mixing energy does not considerably affect the mechanical properties.

However, mixing energy ought to be controlled, and mixing energy more than the appropriate value deteriorates the mentioned features.

- In this investigation, optimizing SCC's mixture design is not considered, and only two mixture proportions are analyzed. Accordingly, SCC's mixture proportioning based on mixing energy can be considered in future studies. Moreover, it is recommended to analyze the effects of mixing energy on concretes containing various types of supplementary cementitious materials.

Compliance with ethical standards

Conflict of interest The authors of study entitled "Investigating the effects of mixing time and mixing speed on rheological properties, workability, and mechanical properties of self-consolidating concrete" certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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