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Research Article

Effect of Inert and Pozzolanic Materials on Flow and Mechanical Properties of Self-Compacting Concrete

Mehrdad Mahoutian[1] and Mohammad Shekarchi[2]

[1] *Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, QC, Canada H3A 0C3*
[2] *Construction Materials Institute, University of Tehran, Tehran, Iran*

Correspondence should be addressed to Mehrdad Mahoutian; mehrdad.mahoutian@mail.mcgill.ca

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This research investigates the fresh behaviour and mechanical properties of self-compacting concrete (SCC) containing high volume of limestone, metakaolin, silica fume, zeolite, and viscosity modifying admixture. Two fine aggregates with different fineness modulus were also utilized to evaluate the effect of sand's gradation on the mechanical and flow properties of SCC containing inert and pozzolanic powder. Slump flow, V-funnel for fresh concrete and 5-minute-old concrete, J-ring, Orimet with and without J-ring, and L-box and U-box tests were performed on all 14 fresh concrete mixtures to examine the fresh properties of self-compacting concrete. Compressive strength of hardened specimens was measured at 7 and 35 days and tensile strength was also determined at the age of 28 days. The results show that sand grading significantly affects the fresh properties of SCC. It is also concluded that high volume of active powders including metakaolin, zeolite, and silica fume could not improve both the flow and mechanical properties of SCC at the same time. Limestone can be effectively used as filler in SCC in high volume content. A new set of limits for the L-box and U-box tests for SCC containing silica fume is also recommended as the existing criteria are not satisfactory.

1. Introduction

Self-compacting concrete (SCC) is a well-known construction material developed in the last two decades to address the engineer requests demanding more workable concrete [1]. It is used to facilitate and ensure proper filling and good structural performance of high congested reinforced structural members [2, 3]. Regarding the promising performance of SCC, it has been widely used in constructions across the world [4]. In Iran, in the last few years, several successful attempts were made to use SCC in infrastructural structures. For example, in some parts of the fourth tallest communication tower in the world, Milad Tower, and Resalat Tunnel in Tehran, SCC has been employed [5].

The common practice to obtain self-consolidation behaviour in SCC is the limitation of the coarse aggregate content, reduction of maximum size of aggregates, and use of superplasticizer [6]. One of the consequences of reducing coarse aggregate content was reported as the increase of the mortar content in the mixture. Due to the increased paste volume, the powder content in SCC is considerably higher compared to the traditional concrete. As we all know, high cement content in concrete may cause problems in certain types of structures including an increase in the shrinkage potential, cost of construction, and heat of hydration [7]. on one hand it is necessary to increase the mortar content to make a better quality SCC and on the other hand an increase of the cement-based mortar results in some technical problems. Therefore, powder was introduced to solve a part of the problems. Commonly used powders include coal fly ash, limestone powder, calcined clays, ground glass, and blast furnace slag [8–12]. Metakaolin was also introduced to the SCC mixture by up to 30% of cement weight [13]. Powders significantly affect the requirement of superplasticizer, deformability, filling capacity, and strength of concrete [14]. For example, some mineral additives including fly ash may increase the workability, durability, and long-term properties of concrete [15]. As a result, use of these types of mineral additives in SCC makes it possible not only to decrease the cost of SCC but also to increase its long-term performance [16–18].

Due to the considerable impact of powder, specifically high volume content, on the SCC properties, several researchers have started evaluating the effect of powders on fresh and mechanical properties of self-compacting concrete. Mnahoncakova et al. [19] introduced fly ash and limestone powders in SCC and reported that concrete containing fly ash powder displays good mechanical properties and high density compared to SCC made with limestone. They also showed that fly ash introduces SCC with low permeability and high resistance against freeze and thaw. Sukumar et al. [20] evaluated the compressive strength of SCC made with high volume fly ash as an indicator of the mechanical properties at early ages and reported that strength of SCC that contained fly ash at early ages is greater compared to the strength of traditional concrete. Other investigations have been also performed to address the influence of fly ash on other SCC rheological behaviors such as setting time [21, 22]. It has been reported that the setting time of SCC incorporating fly ash was 3 to 4 hours longer compared to those determined on traditional concrete (i.e., normal slump and with no fly ash). They also demonstrated that the use of fly ash, up to 80% of cement weight, resulted in lower segregation where an adequate strength can be also achieved.

The effects of limestone and chalk powders on SCC are investigated by Zhu and Gibbs [23]. They stated that limestone powder can accelerate cement hydration and increase early strength. They also showed that utilization of finer powder in the SCC mixture apparently leads to higher strength gain. Shi [24] investigated the effects of four mineral powders including coal fly ash, limestone dust, blast furnace slag, and ground glass on the properties of SCC. He found that the morphology and particle size of the mineral powders play an important role in flowability and workability of SCCs. The spherical particles of fly ash can facilitate the flow of concrete mixture. He also concluded that SCCs containing crushed limestone dust are set faster compared to those containing fly ash or glass powder. Poppe and De Schutter [25] showed that the use of the coarser limestone powder seems to positively affect the flowability of SCC. In addition, the air content of fresh concrete was found to be considerably smaller when coarser limestone powder was used. They finally indicated that the shape of the grading curve of the powder clearly shows no influence on the compressive strength of SCC.

In addition to the fresh behavior and mechanical properties of SCC, its microstructure has been also subjected to investigation [26, 27]. Microstructure of cement pastes of SCC containing limestone was studied by Ye et al. [27]. They indicated that hydration is influenced by the presence of the limestone as filler and it acts as an accelerator during the cement hydration at the early ages. The effect of other untraditional powders including brick powder and kaolinite on the properties of SCC was also investigated by Şahmaran et al. [28]. Their findings are not discussed here as they are beyond the scope of this paper.

The focus of the research presented in the above paragraphs mostly concentrates on the impact of fly ash and limestone powders on the SCC properties as these powders are easily available across the world and therefore they can be cheaply provided. There are limited published researches addressing the effect of other mineral powders including silica fume, metakaolin, and zeolite on the properties of SCC [29, 30]. It should be noted that in these few published papers, the properties of SCC containing low-volume powder (less than 50%) were investigated. Meanwhile, as discussed earlier, high paste content is required to obtain SCC with proper quality. A higher paste content can be obtained by adding a higher powder content into a mixture. Furthermore, consuming the waste and/or by-product materials as a part of concrete ingredient is increasingly considered in the recent years to reduce carbon dioxide emission and landfill wastes [31–33]. Therefore, the current study aims at addressing the properties of SCC containing high volume of different powders including silica fume, zeolite, metakaolin, and two different limestone powders. This study investigates the effect of viscosity modifying admixture (VMA) on the properties of SCC as well. The effect of high-volume fly ash is not studied in this research as this material is not commonly used in Iran.

Another goal of this study was to examine the influence of sand's fineness on the flow and mechanical properties of SCC. Each powder or VMA was mixed with two different types of sand (i.e., low and high modulus of fineness) to consider the effect of sand gradation and fineness on SCC properties as well. The current study investigated if incorporation of VMA or powders could improve the fresh properties of mixes made with the courser sand. Most accepted/recommended tests [34] including slump flow, V-funnel of fresh concrete and 5-minute old concrete, J-ring, Orimet with and without J-ring, and L-box and U-box tests designed to evaluate the fresh behavior of SCC were performed on all 14 fresh concrete mixtures. Visual stability indexes (VSI) were also determined for all the mixtures. The compressive strength test was conducted at 7 and 35 days when the tensile test was carried out at 28 days.

2. Experimental Program

2.1. Materials. As mentioned in the previous section, in this study, the effect of three pozzolanic powders, two inert powders, two fine aggregates, and two VMAs on the properties of SCC was investigated. The following paragraphs describe the properties of these additives, cement, and sands used in the current study.

Portland cement conforming to ASTM type I with specific gravity and Blaine fineness of 3.1 and 320 m^2/kg was used, respectively.

Two limestone-based natural types of sand were used. The nominal size and the specific gravity of the sand were measured as 4.75 mm and 2.6, respectively. The fineness modulus of the courser and finer sands was calculated as 2.65 and 3.30, respectively.

Coarse aggregate displayed the maximum nominal size and bulk density of 19 mm and 1500 kg/m^3. Figure 1 shows the gradation curves of the two sands and the coarse aggregate. The sand satisfies the limitation of the standard test method ASTM C33 [35] where its gradation curves lay down between the recommended upper and lower curves. For gravel, the

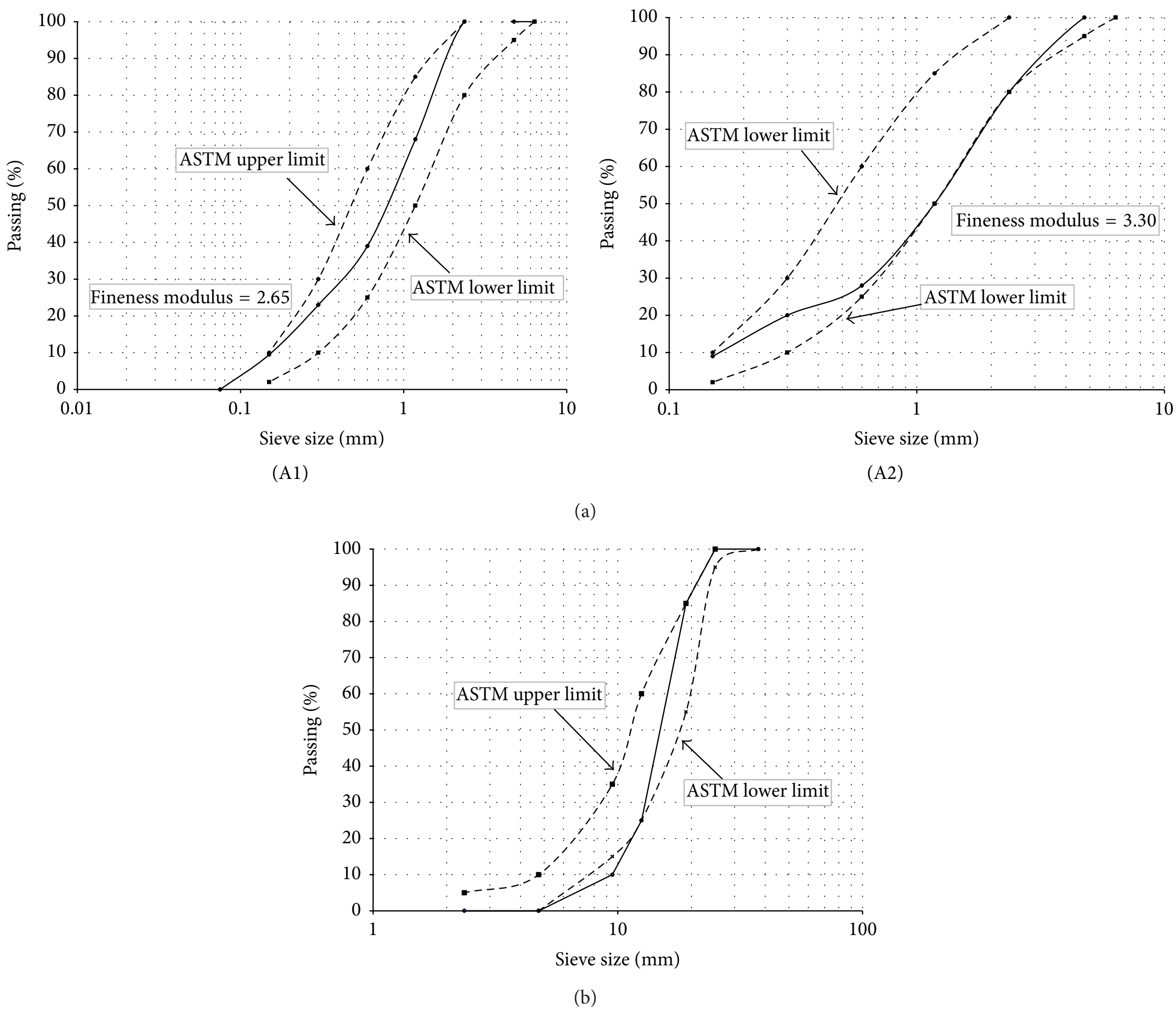


FIGURE 1: (a) Particle size distribution of sand and (b) gravel.

gradation curve is out of the limit for the aggregate size of 4.75–9.50 mm.

Polycarboxylic based superplasticizer confirming to ASTM C494 was introduced to mixes. Two polysaccharide-based viscosity modifying admixtures (VMAs) with two different solid contents were used to improve the stability of SCC mixes containing no filler. Total dissolved solids in VMA1, VMA2, and superplasticizer were 17.8, 18.8, and 357.4 g/L, respectively. The specific gravity and PH were reported by the producers as 5.7 and 1.18 for VMA1 and 5.9 and 1.19 for VMA2.

Silica fume with specific surface (measured by the nitrogen absorption technique) and specific gravity of 16000 m^2/kg and 2.2, respectively, was used as a pozzolanic powder.

Zeolite was another pozzolanic powder employed in this research. Natural zeolite as volcanic or volcano-sediment materials has a unique crystal structure and is classified as a hydrated alumino silicate of alkali and alkaline earth cations [36]. Zeloite shows an infinite three-dimensional structure. Crystals are characterized by a honeycomb like structure with extremely small pores and channels, varying in size from 3×10^{-4} to 4×10^{-4} μm. Zeolite exhibits the specific surface area of 40000 m^2/kg. XRD analysis shows 90–95% clinoptilolite in the mineralogy composition of this zeolite. Cation exchange capacity of zeolite was previously reported by Ahmadi and Shekarchi [37] as 190–200 meq/100 gr.

High reactive metakaolin (HRM) was selected as the third active powder. HRM, one of the newest supplementary cementitious materials to prove its merit in field application, has been used in concrete to offer an increase in compressive strength and a reduction in permeability while offering good workability [38–40]. Specific surface and the specific gravity of metakaolin utilized in this study were 2300 and 2.3 m^2/kg, respectively. Figure 2 shows the X-ray diffraction (XRD) pattern of the metakaolin used in this study, showing high amounts of quartz phase. High quartz content is in agreement with the high SiO_2 content (51.85%) measured by the XRF analysis. The existence of both humps and peaks at the

Table 1: Chemical analysis of the cement and various powders in use.

Material	Chemical analysis (% mass)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Ignition lsoss
Cement	20.03	4.53	3.63	60.25	3.42	2.23	—	—	1.37
Silica fume	98.78	0.27	0.52	0.2	—	—	0.1	0.01	0.07
Zeolite	67.79	13.66	1.44	1.68	1.2	0.5	2.04	1.42	10.23
Metakaolin	51.85	43.78	0.99	0.2	0.18	—	0.01	0.12	0.57
Limestone 1	2.74	0.25	0.34	50.98	1.40	—	0.12	0.42	43.00
Limestone 2	1.36	0.10	0.20	50.96	2.60	—	0.11	0.40	44.41

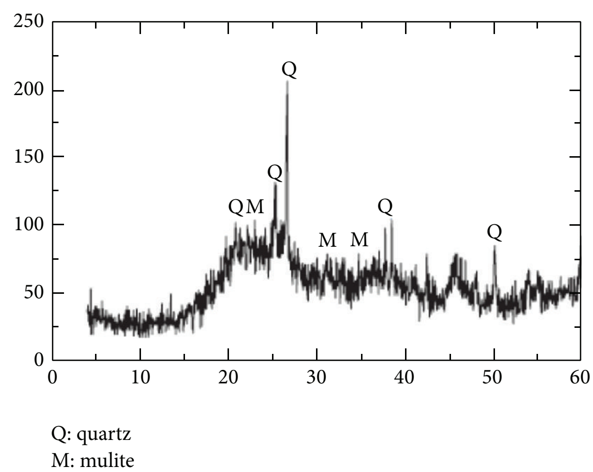


Figure 2: XRD pattern of metakaolin used in this study [40].

diffraction angle of 15° to 30° suggests the mixed semicrystalline and amorphous structure of metakaolin.

Two inert powders including limestone 1 and limestone 2 were introduced to few SCC mixes in this study. Limestone 1 exhibited coarser size compared to limestone 2. The former was produced as the by-product of a stonework factory in Esfahan where the latter was regularly made as an original product in a chemical factory. The density of limestone 1 and limestone 2 was measured as 2600 kg/m^3 and 2700 kg/m^3 and their residue on 45 μm sieve was quantified as 26% and 7%, respectively. Chemical compositions of powders and cement are shown in Table 1.

2.2. Mixture Proportioning. As shown in Table 2, fourteen SCC mixtures were designed. Two control mixtures with no powder (PL1 and PL2) and 12 mixtures with different types of powders and VMAs were considered. Each powder, including silica fume, zeolite, metakaolin, and limestone were separately mixed with two different sands described in the materials section. As the current research aims at investigating the effect of high volume powder on the flow properties of SCC, the cement content, slump flow, and powder content were kept constant in all mixes. As the cement weight and values of slump flow were constant in all mixtures, one is able to investigate the effect of powders and sand gradation on the flow properties of SCC.

The powders were introduced to the mixture at 50 percent of cement mass when the cement mass was kept constant at 500 kg/m^3 in all mixtures. Therefore, in the mixtures containing powder (all mixes except PL1, PL2, VMA1, and VMA2), the total amount of cement and powder reached 750 kg/m^3. The weight of aggregate in PL1, PL2, VMA1, and VMA2 mixes was designed as 1700 Kg/m^3. Since the total weight of sand and powder should be constant, in other mixtures, the weight of aggregate dropped to 1450 kg/m^3. In the VMA1 and VMA2 mixes, viscosity modifying admixture was introduced at 5 kg/m^3.

One percent superplasticizer was added to all mixtures in addition to the sufficient water added to obtain the slump flow value of 650–750 mm. The water required for each SCC mix to reach to the desired slump value varied as powders displayed different water absorption. Figure 3(a) shows the water to power (W/P) ratio for the mixtures. The sand content was fixed at 60% of total aggregate in all mixtures. Figure 3(b) shows the water demand for each mixture needed to reach the required slump flow.

The ZE1 and ZE2 mixtures made with zeolite required greater amount of water to reach the specified slump flow value as zeolite shows high water absorption compared to other powders. Figure 3(b) shows a higher water demand (about two times) in SCC containing zeolite compared to the control mixtures (PL1 and PL2). The values of the water demand also reveal that mixes made with the finer sand required more water compared to the coarser sand in order to reach to the desirable slump. For example in the mixes incorporating zeolite, the water demand increased by 25 percent to keep the slump value constant when the coarser sand was replaced by the finer one.

Concrete mixtures were mixed in a pan shear mixer. After flow properties of fresh concrete were investigated, it was cast into the 300 × 150 mm cylindrical molds. The specimens were removed from the molds after one day and they were cured in a controlled temperature (25 ± 2°C) and humidity (95% ± 5% RH) room prior to the compressive and tensile tests.

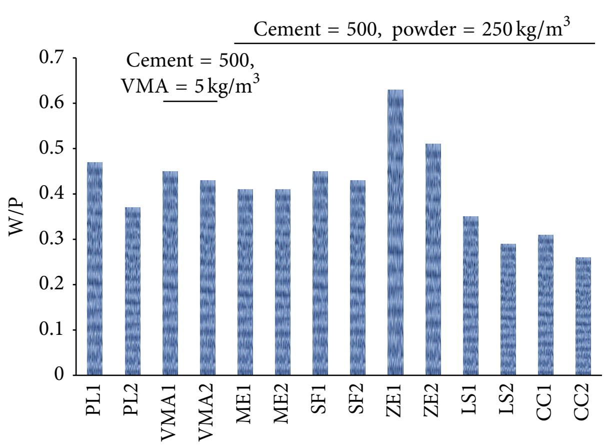
3. Testing Procedure

3.1. Fresh SCC. Conforming to the EFNARC (2005) recommendations, the following tests were performed on the fresh self-compacting concrete.

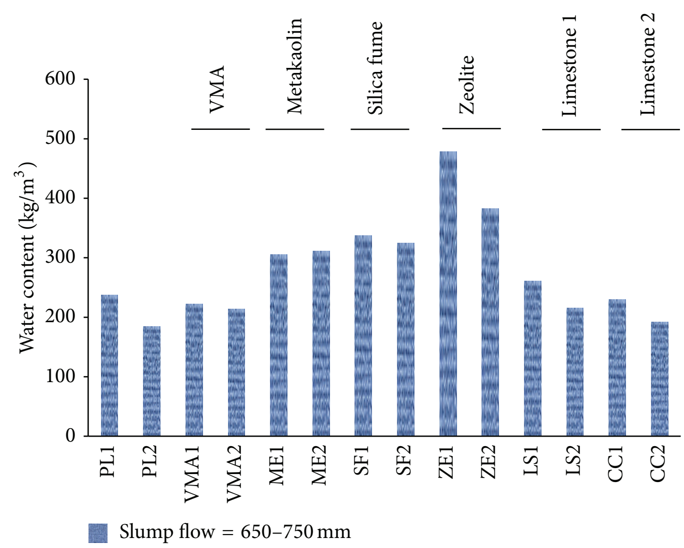
Slump Flow. This test method is extremely suitable for evaluating the flow gradient and distance of concrete flow at the time of placing.

Table 2: Mixture proportion.

No.	Mix	Powder or VMA type	Powder (kg/m^3)	Sand type	Aggregate (kg/m^3)	Super plasticizer (by powder mass)	W/C	W/P
1	PL1	—	—	1	1700	1%	0.47	0.47
2	PL2	—	—	2	1700	1%	0.37	0.37
3	VMA1	VMA-B	—	2	1700	1%	0.45	0.45
4	VMA2	VMA-F	—	2	1700	1%	0.43	0.43
5	ME1	Metakaolin	250	1	1450	1%	0.61	0.41
6	ME2	Metakaolin	250	2	1450	1%	0.62	0.41
7	SF1	Silica fume	250	1	1450	1%	0.68	0.45
8	SF2	Silica fume	250	2	1450	1%	0.65	0.43
9	ZE1	Zeolite	250	1	1450	1%	0.96	0.63
10	ZE2	Zeolite	250	2	1450	1%	0.77	0.51
11	LS1	Limestone 1	250	1	1450	1%	0.52	0.35
12	LS2	Limestone 1	250	2	1450	1%	0.43	0.29
13	CC1	Limestone 2	250	1	1450	1%	0.46	0.31
14	CC2	Limestone 2	250	2	1450	1%	0.39	0.26



(a)



(b)

Figure 3: (a) W/P and (b) water demand.

V-Funnel. The V-funnel test is used to assess the viscosity and filling ability of self-compacting concrete. The dimentions of the funnel bottom outlet are 65 × 75 mm while the height of the funnel is 600 mm.

J-Ring. This device excellently shows the passing ability of SCC. Meanwhile, this test is unable to assess the homogeneity of SCC.

L-Box. The L-box test is used to assess the passing ability of SCC to flow through tight openings including spaces between reinforcing bars and other obstructions without segregation or blocking.

U-Box. This test is generally used for assessing the filling and passing ability of SCC. Neverthelss, this test is unable to evaluate the bleeding of SCC unless it is left untouched for some time.

Orimet. This test is similar to the V-funnel test. Also if J-ring is used in combination with the Orimet device, the dynamic segregation of the sample could be evaluated.

Visual Stability Index (VI). A rating of the visual appearance of the slump flow patty to evaluate several parameters as an indication of the stability of the SCC mix. The VSI ranges from 0 for excellent, 1 acceptable, 2 needs improvement, to 3 unacceptable [41].

Table 3: Results of slump flow, V-funnel, and Orimet.

Mixture	Slump flow (mm)	Slump flow classification	V-funnel (sec)	V-funnel classification	Orimet (sec)
PL1	665	SF2	4.8	VF1	2.7
PL2	675	SF2	23.5	VF2	6
VMA1	650	SF1	3.4	VF1	0.9
VMA2	665	SF2	8	VF2	13.3
ME1	635	SF1	2.7	VF1	2.5
ME2	540	—	1.9	VF1	2
SF1	650	SF1	1.3	VF1	0.9
SF2	640	SF1	1.8	VF1	1
ZE1	715	SF2	1.2	VF1	0.6
ZE2	655	SF2	1.3	VF1	1.1
LS1	755	SF3	4	VF1	3
LS2	755	SF3	5.4	VF1	2.5
CC1	705	SF2	2.4	VF1	1.5
CC2	660	SF2	7.9	VF1	7.5

3.2. Hardened Concrete. The compressive strengths of the specimens were determined in accordance with ASTM C39 [42] standard test method at 7 days and 35 days. The reported compressive strength is the average of 3 values. Since silica fume and zeolite powders show pozzolanic characteristics [43, 44], the strength can develop up to 90 days. Nonetheless, the authors stopped measuring the compressive strength at 35 days. For measuring the tensile strength, the cylindrical specimens were tested in accordance with the ASTM C496 standard test method at 28 days. The presented tensile strength results are the average of three values.

4. Results and Discussion

4.1. Fresh Properties. The results of slump flow, V-funnel, and Orimet tests showing the flowability of SCC are presented in Table 3.

As determined, the slump flow of all mixtures ranged from 650 to 750 mm. The high value of the Orimet test in PL2, VMA2, and CC2 mixes indicates the high potential of segregation and blocking. The utilization of the coarser sand in these mixtures led the segregation though the incorporation of VMA and limestone powder. The results of the V-funnel test were similar to the results of the Orimet test as both are representative of the same concept. One may conclude that in the PL2, VMA2, and CC2 mixes, blocking occurred based on the long discharging time in the V-funnel test. However, the mixes containing VMA showed lower discharging time in the V-funnel test compared to the reference mixes (PL1 and Pl2). A decrease in the discharging time in mixes incorporating VMA was also reported by Lachemi et al. [45].

The results of the V-funnel test also show that the ME1, ME2, SF1, SF2, ZE1, and ZE2 mixes (mixes with metakaolin, silica fume, and zeolite powders) did not experience either segregation or instability with time. Analyzing the results of the V-funnel and Orimet tests for the LS2 and CC2 mixes suggests that limestone 1 made the SCC more flowable compared to limestone 2. This is in agreement with a study performed by Poppe and De Schutter [25] showing that the coarser limestone can lead to a more flowable SCC and it displays a positive influence on the viscosity. One may conclude that SCC containing either limestone 1 or limestone 2 resulted in the lower discharging time compared to the reference SCC. Corinaldesi and Moriconi [46] also reported that limestone decreases the discharging time of SCC compared to the reference one in the V-funnel test.

In Table 4, the results of L-box, J-ring, and U-box tests are presented as they define the passing ability characteristics of SCC. The result of the J-ring test shows that all mixes, except ZE2 and PL2, meet the EFNARC [34] requirements. The negative values of the U-box test indicate that level of concrete in the second part of the U-box was surprisingly higher than the height of concrete in the first side of the U-box. This case occurs rarely and it cannot be seen in the normal self-compacting concrete. The negative values of the SF1, SF2, and ZE1 mixes in the U-box test indicate the high speed of flow and low viscosity of concrete. Kwan and Ng [47] used the U-box to demonstrate that silica fume improves the filling ability. They showed that the difference of concrete level in two sides of the box was lower in SCC containing silica fume compared to the reference one. The results of the U-box test also demonstrate that the PL2, VMA2, ME2, and ZE2 mixes could not satisfy the EFNARC recommendations [34]. In these mixes, the presence of the coarser sand in the mixture resulted in an incompatible SCC. It should be noted that the U-box test is well known as the most severe test [48]. For instance, while the results of J-ring test for the ME2 mix approve it as SCC, the result of U-box suggests otherwise. Finally, the result of the U-box test shows that VMA did not significantly affect the SCC properties. In other words, VMA did not improve the bleeding and segregation of SCC. Figure 4 shows the U-box test setup for the LS1 mixture. As the difference of two sides in this case is zero, the definition of self-leveling concrete can be assigned to this concrete.

The result of the L-box test shows the negative value for the SF1, SF2, ZE1, and ZE2 mixes containing silica fume and zeolite. It means that the level of concrete at the end of the box exceeded the level at the beginning of the box. The negative

Table 4: The results of L-box, J-ring, and U-box tests.

Mixture	L-box end difference (cm)	L-box classification	$t20$ (sec)	$t40$ (sec)	J-ring (cm)	U-box (cm)
PL1	0.5	PA1	1.2	2.5	0	1
PL2	1.4	PA1	2.6	4.5	1.9	27.5
VMA1	1	PA1	0.5	0.7	0.5	25.5
VMA2	2	PA1	1.8	3.3	—	25
ME1	2	PA1	0.8	1.2	0.5	3
ME2	1.8	PA1	—	—	0.4	17
SF1	−2	—	—	0.5	0.7	−1
SF2	−2.5	—	—	1	0.5	−1
ZE1	−1.6	—	—	0.6	0.4	−4.6
ZE2	−4	—	—	0.5	1.1	7
LS1	0.4	PA1	—	1.4	0	0
LS2	0.2	PA1	—	—	0.4	1.8
CC1	0.5	PA1	—	1.6	0	0
CC2	0.5	PA1	1.2	1.9	0.4	0.5

Figure 4: LS1 mixture in the U-box.

value in U-box test was also observed for these mixtures. Low viscosity leading to high initial speed attributes to the negative value in these mixes. Other mixes, except VMA1 and VMA2, showed the reasonable end difference satisfying the EFNARC [34] requirements.

The same conclusion made from the U-box test can be drawn from the results of the L-box test. It can be concluded that VMA did not help to improve the stability of SCC in the VMA1 and VMA2 mixes. The results of $t20$ and $t40$ can be used to estimate the viscosity of mixtures. Higher viscosity led to greater flow time. For instance, for the PL2 mixture, the values of $t20$ and $t40$ were recorded as 2.6 and 4.5, respectively, which is an indicator of relatively high viscosity. The results show that incorporation of both limestone 1 and limestone 2 in SCC led to decreasing the difference in height of concrete at the end of the L-box compared to the plain SCC. A drop in the concrete level between the beginning and the end of the box was also reported by Corinaldesi and Moriconi [46] where limestone was used.

The results of 5-minute V-funnel, visual stability index (VSI), and Orimet with J-ring are presented in Table 5. These tests are suitable for evaluating the stability of SCC. If the value of VSI for a mixture is 3, it means that concrete cannot be classified as SCC and so they should be defined as a normal concrete with the high slump value.

The result of the Orimet test with J-ring helps to evaluate the dynamic stability of SCC. The difference in height of two sides of J-ring after concrete drops from the Orimet was measured for the PL1, PL2, VMA2, and CC2 mixes. The results show that high dynamic segregation occurred in the plain concrete. Meanwhile, the VMA and limestone powder were not effective in eliminating the dynamic segregation. The results of the V-funnel test after 5 minutes can show the stability characteristic of SCC after certain time. The values show that high segregation, blocking, and instability occurred in the PL2 and CC2 mixes. Short discharging time in the V-funnel test in ME1, ME2, ZE1, ZE2, SF1, and SF2 indicates that no segregation and instability happened. Also, one can expect that in these mixes the viscosity of concrete did not increase after 5 minutes. However, Şahmaran et al. [28] reported that the discharging time of concrete containing kaolin increased compared to the reference mix.

According to the VSI values, the mixtures made with limestone powder, LS1, LS2, CC1, and CC2, can be definitely considered as SCC. In these mixtures, no segregation was observed in the slump flow test. On the other hand, the VSI value of 3 was assigned to the PL2, SF1, SF2, and ZE2 mixes, indicating the high level of instability.

The authors conclude that if sand with a lower fineness modulus is utilized in the SCC mixture, it is possible to make a stable and homogenous SCC without incorporating any additive. Finer sand helps particles to move easily and also parts of the sand can behave as filler. Meanwhile, the coarser sand results in the segregated and unstable SCC as suggested by the U-box test.

An increase in the discharge time of the Orimet test indicates that by adding VMA to the SCC mixes the viscosity of concrete can slightly improve. Nonetheless, the incorporated

Table 5: V-funnel after 5 minutes, visual stability index (VSI), and Orimet with J-ring test results.

Mixture	V-funnel (sec)	VSI	VSI classification	Orimet with J-ring (cm)
PL1	6.9	1	Acceptable	1.9
PL2	29.1	3	Unacceptable	2.4
VMA1	11.5	2	Needs improvement	0.5
VMA2	14.5	2	Needs improvement	2.1
ME1	3.7	1	Acceptable	1.1
ME2	2.5	2	Needs improvement	—
SF1	1.4	3	Unacceptable	0
SF2	1.9	3	Unacceptable	0
ZE1	1.2	2	Needs improvement	0
ZE2	1.6	3	Unacceptable	—
LS1	5.3	0	Excellent	—
LS2	6.7	0	Excellent	0.5
CC1	4.5	0	Excellent	0.5
CC2	20.1	0	Excellent	2.1

Figure 5: SCC containing silica fume.

VMA did not significantly affect the flow properties of SCC and could not compensate the adverse effect of improper sand gradation. Therefore, one may expect consequential segregation and bleeding in SCC made with VMA and coarse sand.

The results of SCC containing metakaolin reveal that metakaolin could not introduce significant effects on the fresh properties of SCC. The sand gradation shows a stronger effect compared to metakaolin. The results of the U-box test clearly demonstrate that the metakaolin could not enhance the fresh properties of concrete made with coarse sand.

Silica fume could improve the flow properties of SCC. Self-compacting concrete made with silica fume did flow at high speed causing the concrete to expel from horizontal part of L-box, without segregation, as shown in Figure 5.

It is important to note that although the mix containing silica fume meets the criteria proposed for fresh properties of SCC, its low viscosity makes it unusable in concrete structures. Therefore, it is recommended to restrict the limitations offered by EFNARC [34]. Consequently, in mixes containing silica fume, upper and lower limits for the L-box and U-box tests should be applied. In the L-box test the height ratio at both ends should be higher than 0.8 and smaller than 1.0. The lower limit in the U-box test can be defined by limiting the height difference to zero.

The same results observed for concrete containing metakaolin could be observed when zeolite powder was added to the mix. The results of the J-ring test exhibit that the viscosity of concrete decreased significantly and concrete did quickly spread when metakaolin and zeolite powders were introduced to the mixes. Thus, after the flow of concrete stopped, a "petal-shape" pattern was formed. This type of concrete could not be classified as self-compacting as it is not able to fill the entire free space of the form due to its weak filling ability. Figure 6 shows the "uniform-shape" and the "petal-shape" patterns created in the J-ring test.

Utilization of limestone powder as inert powder could improve the workability of SCC without changing the viscosity. Yahia et al. [49] also showed that the addition of limestone filler within a certain range did not affect the viscosity. The only exception of this improvement was observed in the results of the Orimet test where limestone was utilized. Therefore, the use of limestone powder as filler in SCC could offer cost benefit.

4.2. Mechanical Properties. The compressive strength results of hardened concrete are shown in Figure 7. SCC containing zeolite powder exhibits a lower compressive strength compared to the mixtures incorporating other powders. Due to the high absorption capacity of zeolite, the water to cement ratio of mixture increased for reaching the required flowability. This increase in W/C decreased the compressive strength by 50%. The same conclusion was taken by Cioffi et al. [36]. They showed that the 7-day compressive strength of traditional concrete containing natural zeolite was 30% lower compared to the reference one.

In the ME1, ME2, ZE1, and ZE2 mixes, the finer sand results in the higher compressive strength. The values of 35-day compressive strength indicate that silica fume did not change the compressive strength of reference mix that is in agreement with results of a study performed by Kwan and Ng [47].

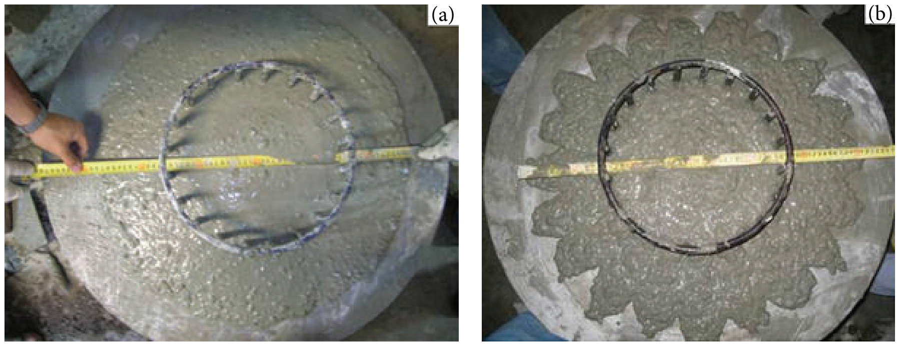


Figure 6: SCC distributed as (a) uniform and (b) petal-shape in the J-ring test.

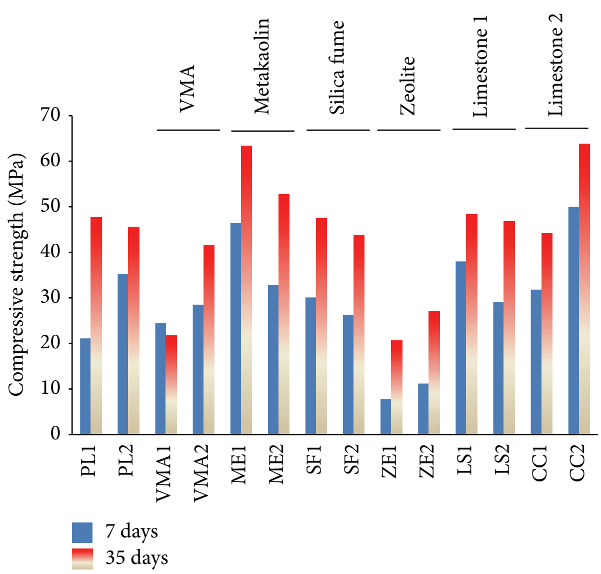


Figure 7: Compressive strenght at 7 and 35 days.

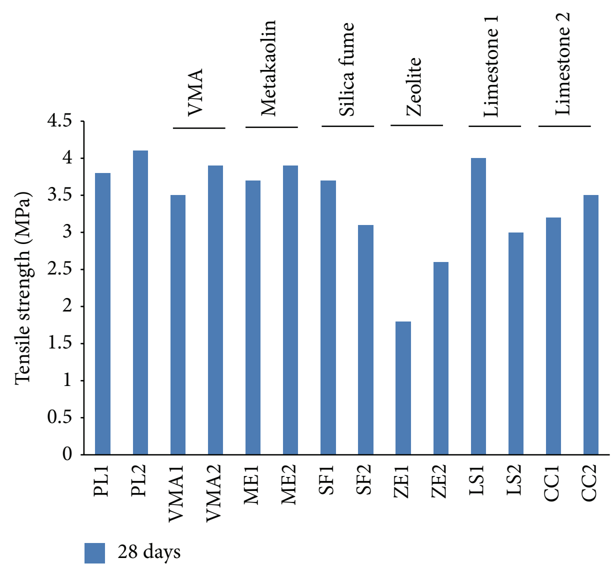


Figure 8: Tensile strength at 28 days.

In the plain concrete and concrete containing VMA, where segregation and bleeding occurred, complete consolidation could not be obtained. Poor compaction led to porous concrete as well as to low compressive strength. The results also show that VMA did not improve the 7-day compressive strength of SCC. The same conclusion was also drawn by Lachemi et al. [45]. They used 5 different types of VMA and reported that the compressive strength of the reference concrete at 7 days was not influenced by the VMAs. Leemann and Winnefeld [50] also revealed that VMA does not change the 28-day compressive strength of SCC.

Comparison of the values of compressive strength for PL1 and LS1 at 7 days suggests that the incorporation of limestone increased the compressive strength by 100%. The same conclusion was observed by Zhu and Gibbs [23]. They showed that the 7-day compressive strength of SCC containing limestone was higher by 60–80% compared to the corresponding reference concrete. Boel et al. [51] also showed that limestone filler increases the compressive strength of SCC compared to the plain SCC with no filler. Ye et al. [27] confirmed that the limestone in SCC behaves as an accelerator during early cement hydration. However, Uysal and Yilmaz [52] showed that limestone decreases the compressive strength of SCC that is in contrast with the results of current and previous studies. The compressive strength of LS1 and CC1 at 7 and 28 days exhibits the same values indicating that the particle size of limestone does not affect the compressive strength. However, the values of the compressive strength test for LS2 and CC2 demonstrate that a finer limestone led to a higher compressive strength. Poppe and De Schutter [25] showed that the compressive strength of SCC is more influenced by the cement content rather than the gradation curve of limestone.

The results of tensile strength of SCC mixtures are shown in Figure 8. Generally speaking, the tensile strength of SCC containing different powders, except zeolite, was of the close values. Similar to the compressive strength value, high water to cement ratio is considered as the reason of the low tensile strength of concrete incorporating zeolite.

5. Conclusion

The effect of different powder materials incorporated at high volume and fine aggregate with different fineness modulus on the flow and mechanical properties of SCC was investigated. Based on the results of the current research, the following conclusions can be drawn.

(1) If fine aggregate exhibits a low fineness modulus and proper gradation, there is no need to use any powder as filler to help the flow properties. The best value of the fineness modulus for fine aggregate is recommended to be 2.65.

(2) VMA cannot significantly improve the flow properties of SCC when it is utilized in a mix containing coarse sand. When coarse sand is incorporated in the mixture, the addition of VMA shows no effect on the stability, including bleeding and segregation.

(3) Metakaolin powder cannot improve the flow properties of SCC.

(4) Silica fume compensates the poor sand quality. However, it results in SCC with low viscosity that may attribute to some problems in practice, although SCC made with silica fume can successfully pass the tests.

(5) Limestone powder greatly increases the stability and homogeneity of SCC. These fillers are relatively of low cost and are widely available.

(6) Due to the high water absorption of zeolite and silica fume, the mechanical strength of SCC containing these powders deteriorates. In comparison with the reference mix, compressive and tensile strength of SCC exhibits a decrease of about 50% and 60%, respectively, when zeolite powder is used.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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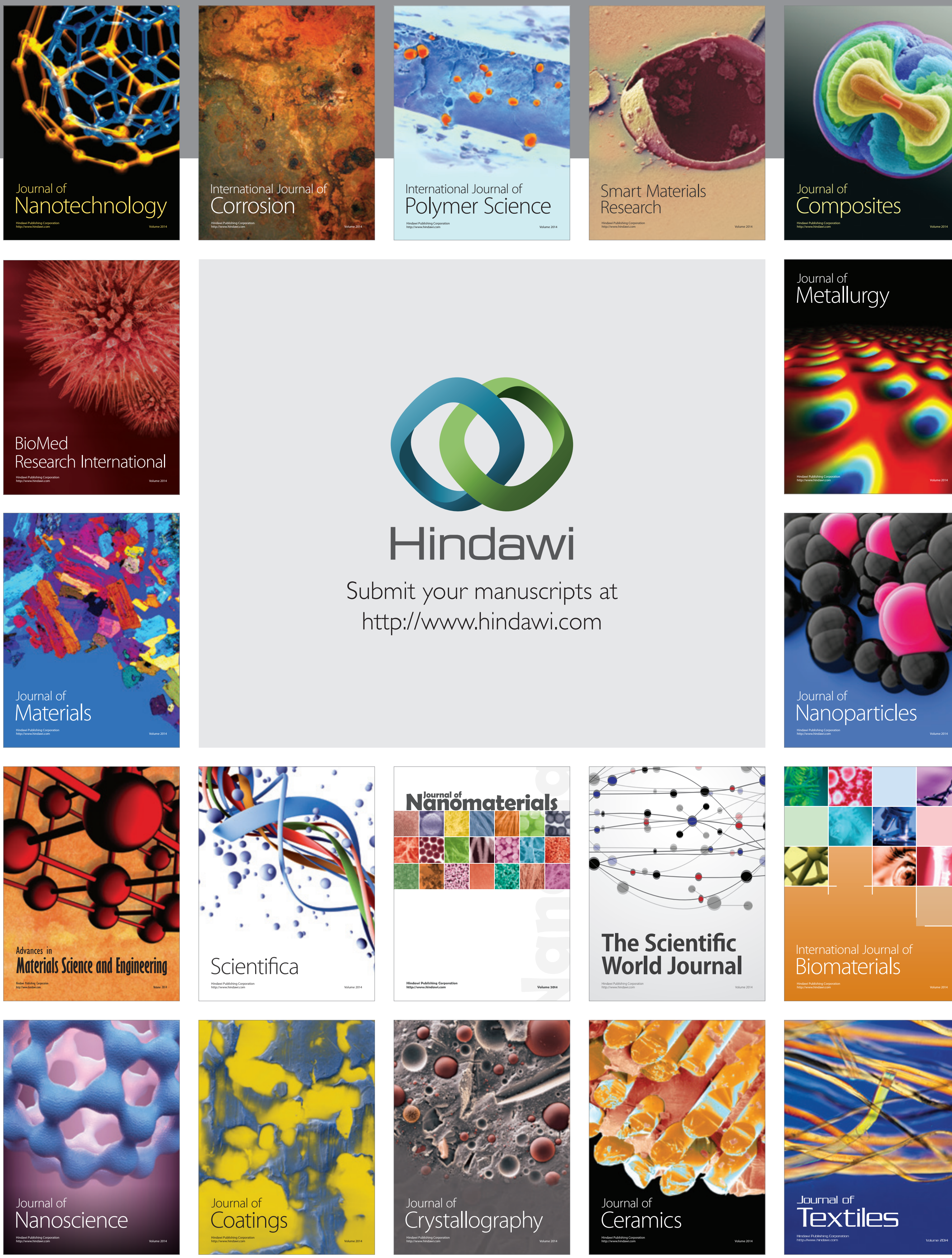
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