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Research Article

Utilization of Metakaolin and Calcite: Working Reversely in Workability Aspect—As Mineral Admixture in Self-Compacting Concrete

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In this work, utilization of metakaolin (MK) and calcite (C), working reversely in workability aspect, as mineral admixture in self-compacting concrete (SCC), was investigated. MK and C replaced cement in mass basis at various replacement ratios, separately and together. In total, 19 different SCCs were produced. Binder content and water to binder ratio were selected as 500 kg/m^3 and 0.4, respectively. Workability tests including slump flow, T_{50}, L-box, and V-funnel tests were performed. Consistency and setting times of binder paste were measured. While replacement of MK with cement increased the amount of plasticiser requirement, calcite worked reversely and decreased it. Reverse influence of MK and C on plasticiser requirement of SCC made possible to produce SCC at total 45% replacement ratio of MK and C together. Samples of SCC were cured in water at 20°C temperature. Compressive strengths of SCC samples were measured up to six months to evaluate the influence of MK and C, separately and together. Ultrasonic pulse velocity, abrasion, and capillary water absorption values of samples were determined at specified age. MK inclusion in concrete reduces workability, while C inclusion increases it. C and MK inclusion together remedied workability of concrete and enabled to produce SCC with high volume of admixtures. Furthermore, C incorporation increased one-day compressive strength, while MK incorporation reduced it in comparison with control concrete. In long term, C inclusion reduced compressive strength; however, MK inclusion increased it. C inclusion remedied one-day strength of concrete when it was used together with MK. MK inclusion remedied long-term compressive strength when it was used together with C and enabled to produce high-strength SCC with high volume of admixtures. SCC containing MK and C together showed better durability-related property.

1. Introduction

Portland cement, as being the main component of concrete which takes places in a broad range of utilization in building and construction sector, was produced about 3.3 billion ton in the year of 2010 in the world [1]. Production process of cement consumes intensive energy; thus it brings problems to contribute global warming, climate changes, and environmental pollution to natural habitats. Cement clinker production contributes at about 7% to world total carbon dioxide emission. A ton of cement production causes a ton of carbon dioxide emission into atmosphere due to fuel and energy used in sintering process and disintegration of calcareous matter used as raw materials at high temperature [2–4]. Increased environmental concern and environmental policies and green peace movements is required to control and reduce the carbon dioxide emission and carbon foot print of cement production from cement producers. In this context, utilization of natural pozzolan or pozzolanic industrial waste and by-products such as fly ash, silica fume, powdered slag, rice husk, and metakaolin as cement replacement materials were taken into consideration by cement producers and researchers as a significant method in sustainable and green concrete production technology to reduce carbon foot print of Portland cement [3].

These cement replacement materials as mineral admixtures with their pozzolanic property find utilization places in production of self-compacting concrete (SCC) which is known as a special type of concrete with their high binder dosage compared to conventional concrete. SCC drops in high performance class of concretes type, and they exhibit better properties at fresh and hardened state (i.e., high workability, high strength, and better durability-related properties) compared to conventional concrete [5]. A special type of concrete, namely, self-compacting concrete, which does not need vibration and flows and compacts itself by its weight, was designed to solve poor workmanship and placing of concrete as well as durability-related properties at the beginning of 1980 in Japan. SCC was introduced to the world by Professor Okamura, after carrying out intensive laboratory studies in Tokyo University. SCC was accepted by concrete world and become very popular, since then investigation on properties of SCC still goes on intensively [6–11].

While high flowability of SCC is provided by usage of hyperplasticiser with strong dispersion capacity, stability of SCC to segregation was provided by using high dosage of fine powdered material [12]. As being significant parameters in the mixture design of SCC, type and amount of mineral admixtures play a vital role in fresh-state behaviour of SCC [5]. Fly ash [12–17], ground granulated blast-furnace slag [14, 15, 17, 18], silica fume [19–22], and metakaolin [17, 22–26] were the most frequently employed supplementary cementitious materials in SCC.

Metakaolin is obtained by calcination of pure kaolinite clay at 500°C–800°C temperature; it is an amorphous-structured alumina-silicate with high pozzolanic property [27]. It was reported in the published literature that usage of metakaolin in concrete as cement replacement materials at proper amount improves mechanical properties of concrete [28, 29], reduces permeability and capillary water absorption value of concrete [30], and thus results in better durability properties for a concrete [22, 26, 27].

It is reported that SCC designed by inclusion of MK increased the amount of water and plasticiser requirement compared to SCC designed by inclusion of ground slag. However, SCC designed by MK exhibited higher compressive strength and excellent durability properties compared to control Portland cement concrete, which is attributed to its high pozzolanic property [17].

Karoline and Arnoldo [27] stated that metakaolin inclusion in concrete design badly influenced consistency of concrete by increasing water demand or plasticiser demand of mixture. Increase in MK in mixtures resulted in need of more water or plasticiser for mixture.

One of the mineral admixtures used to increase the paste phase of SCC cohesion in fresh state is limestone powder, known as calcite [1, 31, 32]. Calcite is a mineral of carbonated rock which contains 95–97% calcium carbonate ($CaCO_3$) in its chemical structure, and it is a main mineral of carbonated rock including limestone, marble, and chalk [33, 34]. Blending and utilization of calcite with Portland cement has technical and economic benefit for blended cement production. Introducing calcite to cement clinker is rather new compared to other cement replacing materials including fly ash, ground slag, silica fume, by-product pozzolan, or natural pozzolan. Studies showed that incorporating calcite in binder blend results in nucleation effect in binder paste at earlier ages; thus, it causes an increase in strength properties of mixture in short term. This result was attributed to high fineness of calcareous blend cement as well as filler effect of fine calcite grains. However, in long-term age, cement incorporating calcareous fine powder not only did not improve strength properties but also somewhat reduced in comparison with control Portland cement [35, 36]. This behaviour and effect of calcite on strength property prove that calcite is not a pozzolan.

It is known that size distribution of cement grain or fineness of cement has an important influence on water requirement of cement paste. In calcareous cement production, during grinding of clinker of cement and calcareous matter, grinding process results in narrow size distribution of cement grain; however, it results in wider size distribution of calcareous grain since clinker is harder than calcareous matter. Thus, it can be stated that fineness of cement grain is coarser than that of calcareous grain present in calcareous cement. Therefore, fineness of calcareous cement becomes higher in comparison with Portland cement without calcer. Finely ground calcareous particle in blended cement fills the large gap, which increases water requirement of paste, between coarser cement grains. This results in reduction of water requirement of paste, and hardened blended cement paste gets denser structure despite the higher fineness of calcareous cement which leads to better mechanical and durability-related properties [35, 37–40]. It was reported that the main influence of powdered calcareous particle on cement property hydration is physical rather than chemical. Calcareous grain creates nucleation effect in paste as well as dilutes cement grain in paste mix and provides liberation between cement grains; thus, it accelerates hydration of cement grains [36, 41, 42].

Zhu and Gibbs [43] studied on utilizing three different limestone powders and two different chalk powders in production of SCC at various replacement ratios with cement. They reported that limestone powder inclusion in concrete developed higher compressive strength in comparison with concrete incorporating chalk powder. Furthermore, they [43] stated based on their study that SCC containing limestone or chalk powder showed significantly higher compressive strength than that of conventional vibration-control concrete at an equal water-cement ratio. Compressive strengths of limestone and chalk powder containing SCC were 70% and 35% higher in comparison with reference concrete made of only Portland cement at 7 and 28 days of curing, respectively. This is attributed to higher fineness of limestone and chalk powder in comparison with Portland cement fineness; resulting in filling and seeding effect. Moreover, it was reported that plasticiser requirement of reference concrete made with Portland cement was higher when compared to SCC containing limestone or chalk powder. Therefore, they concluded that producing more economic SCC was possible through utilizing higher amount of limestone in making of SCC.

Esping [44] incorporated calcite with different fineness in concrete and reported that autogenic shrinkage of concrete increased with an increase in the calcite amount used in concrete. Calcite results in a reduction of water evaporation of concrete, tendency to plastic cracking of concrete increased, and compressive strength increased.

Topçu et al. [45], based on their laboratory study, stated that utilizing powdered limestone, at lower amount than 200 kg/m^3, in SCC would be appropriate to improve rheological properties of SCC. However, it would be detrimental to mechanical properties of SCC when utilized at higher amount than 200 kg/m^3.

Although there are numerous studies published on utilizing mineral admixture in SCC with binary or ternary binder composition, there were a scanty amount of published material on utilizing MK and C together in SCC mixture and their combined influence on the properties of SCC mixtures at fresh and hardened state. In this work, two different mineral admixtures, MK influencing workability of mixture unfavourably and C influencing favourably, were used in concrete as cement replacement, and in total, 19 SCCs were prepared by inclusion of MK and C separately and together. Influence of utilizing MK and C in SCC mixture separately and together as mineral admixture, in fresh-state properties and hardened-state properties of SCC including workability, setting times, compressive strength, ultrasonic pulse velocity value, abrasion value, and capillary water absorption coefficient, was investigated.

2. Experimental Program

2.1. Materials, Mix Proportions, and Sample Preparation. Portland cement (PC 42.5 type) for general use and complied with the current standard of TS EN 197-1 [46] was employed in the laboratory work. Metakaolin and calcite in powder form were used in SCC production. Chemical compositions of cement, metakaolin, and calcite and their physical properties are provided in Table 1. The particle size distributions of cement, metakaolin, and calcite are illustrated in Figure 1.

High-performance superplasticiser conforming to TS EN 934-2 [47] was used in preparing fresh concrete mixtures to maintain their workability. The superplasticiser utilized was ether-based polycarboxylic type; it was in liquid form, and its density was 1.14 kg/dm^3. Coarse aggregate used in concrete was crushed stone with a maximum size of 16 mm. As a result of trial mixes, as fine aggregate, equal parts of crushed stone and river sand blend were employed in concrete mixture due to workability concern of SCC. Specific gravity, water absorption capacity, and proportions of aggregates used in concrete are presented in Table 2.

Throughout this study, the amount of cement for a cubic meter of concrete mixtures was set to 500 kg/m^3, and the water-cement ratio was set to 0.40. Cement was replaced with MK or C admixture, at 10%, 15%, and 20% ratios for separate mixtures made with inclusion of only MK or C. During the trial mix study to determine replacement ratios of admixtures (MK or C) with cement, concrete mixture made with 25% calcite replacement with cement was seemed as a gelly concrete rather than self-compacting concrete. However, concretes made with MK and C together utilizing 25% replacement of calcite were complied with the criteria required to be SCC. Therefore, it was decided to utilize 25% C replacement together with all MK replacement ratios. The amount of superplasticisers was changed for each concrete mixture so that each concrete mixture produced was made to comply with criterions suggested by EFNARC for a concrete to be classified as SCC. Therefore, in total, including control Portland cement concrete, 19 different SCC mixtures were produced. Concrete mixtures proportions are given in Table 3 for a cubic meter volume.

During fresh concrete mixing, coarse aggregates first and fine aggregates second were placed in the mixer and blended

Table 1: Chemical composition and physical data for cement, MK, and C.

Oxide	Cement	MK	C
SiO_2	20.5	52.68	0.05
Al_2O_3	5.7	43.11	0.15
Fe_2O_3	2.6	1.38	0.06
CaO	62.5	0.3	55.4
MgO	2.5	0.2	0.68
SO_3	3.7	—	—
K_2O	0.7	0.3	—
Na_2O	0.2	0.62	—
LOI	1.6	1.4	41.2
Fineness (cm^2/gr)	3251	—	—
Specific gravity	3.10	2.42	2.65
Mean diameter (μm)	12.50	2.60	1.30

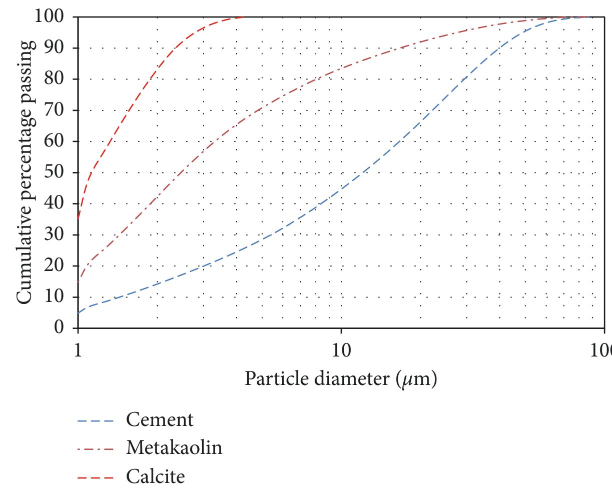

Figure 1: Particle size distribution of cement, metakaolin, and calcite.

Table 2: Specific gravity, water absorption capacity, and proportions of aggregates.

	Coarse crushed aggregate	Crushed sand	River sand
Mixing ratio (%)	40	30	30
Specific gravity	2.55	2.51	2.48
Absorption (%)	1.41	2.63	1.65

Table 3: Concrete mixture proportion for a cubic meter (kg/m^3).

Mix code	Coarse crushed aggregate	Crushed sand	River sand	Cement	MK	C	Water	SP (%)
Control	631.1	465.9	460.3	500	—	—	200	1.7
MK10	631.1	465.9	460.3	450	50	—	200	2.0
MK15	631.1	465.9	460.3	425	75	—	200	2.3
MK20	631.1	465.9	460.3	400	100	—	200	2.6
C10	631.1	465.9	460.3	450	—	50	200	1.0
C15	631.1	465.9	460.3	425	—	75	200	0.8
C20	631.1	465.9	460.3	400	—	100	200	0.6
MK10-C10	631.1	465.9	460.3	400	50	50	200	1.5
MK10-C15	631.1	465.9	460.3	375	50	75	200	1.3
MK10-C20	631.1	465.9	460.3	350	50	100	200	1.1
MK10-C25	631.1	465.9	460.3	325	50	125	200	1.1
MK15-C10	631.1	465.9	460.3	375	75	50	200	1.9
MK15-C15	631.1	465.9	460.3	350	75	75	200	1.8
MK15-C20	631.1	465.9	460.3	325	75	100	200	1.7
MK15-C25	631.1	465.9	460.3	300	75	125	200	1.6
MK20-C10	631.1	465.9	460.3	350	100	50	200	2.4
MK20-C15	631.1	465.9	460.3	325	100	75	200	2.3
MK20-C20	631.1	465.9	460.3	300	100	100	200	2.2
MK20-C25	631.1	465.9	460.3	275	100	125	200	2.0

for 30 s, and later on, cement or binder was added to the mixer and blended for 30 s in the mixer. Half of the mixing water was introduced in mixture and mixed for 3 minutes; then remaining half of the mixing water mixed with superplasticiser was added to fresh concrete mixture, and mixing was continued for further 2 minutes. The same sequence was followed for MK and C added concrete mixture. However, the blended binder phase, cement-MK, cement-C, or cement-MK-C, was blended together prior to placing in the mixture to obtain the homogenous binder phase. Dispersing calcite homogenously in mixture is particularly important since calcite tends to stick on aggregate particles due to electrostatic attraction between calcite (negatively charged) and aggregate (positively charged). Mixing and mixing sequence of materials need to be carefully carried out to prevent this attraction. In the case of the blending binder phase prior to adding to concrete mixture, better performance was obtained from hardened concrete supported by the microstructural analysis study [33].

Setting times of cement and blended cement with MK and C together were measured in accordance with TS EN 196-3 standard [48] at normal consistency water requirement. Pozzolanic indexes of mineral admixtures used were measured according to the method described in ASTM C 311 [49] standard.

Fresh concrete workability tests including slump flow, T_{50} flow time, V funnel, and L-box, which are particularly suggested for SCC by European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC), were carried on fresh concrete produced in the study [50]. Concrete was subjected to standard curing complied with TS EN 12390-3 standard [51] at 20°C in water. Compressive strength testing was carried out on cubic specimens with a side of 15 cm at 1 d, 3 d, 28 d, 90 d, and 180 d after curing in water. Before compression testing, ultrasonic pulse velocity of concrete samples was measured according to the ASTM C 597 standard [52]. The compression testing result was an average of three specimens. Abrasion value measurement in accordance with the TS 2824 EN 1338 [53] standard and capillary water absorption test in accordance with the TS 4045 [54] standard were carried out at 28 d, 90 d, and 180 d curing ages. Cubic samples with a side of 70 mm were used for the abrasion value and capillary water absorption tests.

3. Results and Discussion

3.1. Pozzolanic Activity Test Results. Pozzolanic activity index tests were carried out for MK and C. Pozzolanic activity index testing was carried out in accordance with the method described in the ASTM C311 standard [49]. The activity index results are presented in Table 4.

The testing results showed that the pozzolanic activity index of MK was increasing in time, while it was 105% at 2 d, it increases to 112% and 124% at 7 d and 28 d, respectively. However, the pozzolanic activity index was 122%, which is significantly high, for C, and it decreases to 90% and 79% at 7 d and 28 d, respectively.

3.2. Consistency and Setting Time Results of Binder Paste. Water needed for standard consistency of cement and blended cement paste with MK and C separately was determined in accordance with TS EN 196-3 [48]. Water for standard consistency was used in the measurement of setting times of cement and blended cement paste. Initial and final setting times of paste produced are presented in Table 5 together with the amount of water for standard consistency of paste.

It can be observed from Table 5 that MK replacement with cement caused a substantial increase in the water amount needed for standard consistency in comparison with control cement paste. The higher replacement ratio of MK with cement caused more water reduction for standard

Table 4: Pozzolanic activity results for MK and C (%).

Mixture name	2 d	7 d	28 d
Metakaolin	105	112	124
Calcite	122	90	79

Table 5: Standard consistency water and setting times of binder paste.

Mix code	Water for standard consistency (%)	Initial setting time (min)	Final setting time (min)
Control	30	140	240
MK10	35	60	235
MK15	38	75	247
MK20	39	45	210
C10	28	60	175
C15	27	50	170
C20	26	45	167

consistency. Contrary to this, replacement of calcite with cement significantly reduced the water amount for standard consistency compared to control paste. Higher replacement caused more water reduction for standard consistency for binder paste.

MK and C replacement with cement caused a reduction in initial setting times of blended cement paste in comparison with control cement paste. While calcite replacement with cement reduced final testing time of paste, influence of MK replacement with cement on final setting times was found to be insignificant when compared to control paste. As concluded in this work for calcite inclusion, Valcuende et al. [55] reported that inclusion of limestone in SCC and increasing the amount of limestone as cement replacement reduced both initial and final setting times.

3.3. Fresh Concrete Workability and Consistency Results. It is known that workability and consistency of self-compacting concrete are very important since these parameters make concrete self-compacting concrete also its meaning lies in its name. Workability and consistency of SCC are determined with various methods described in EFNARC [50]. There are testing results and criteria to be satisfied when a concrete to be classified as self-compacting concrete. These testing methods are slump flow, T_{50} flow time, V funnel, and L-box. The testing results to be obtained from these methods should be higher (or equal) than a minimal value and lower (or equal) than a maximal value, meaning it should drop between two specific values. The workability and consistency testing results obtained in this study are illustrated in Table 6, with the specific values for each testing methods specified by EFNARC [50].

A closer look and observation of Table 6 shows that all concrete mixtures (in total, 19 mixtures) produced in this work are classified as SCC since they satisfy all testing criteria including slump flow, T_{50} flow time, V funnel, and L-box described by EFNARC [50]. These 19 self-compacting concretes did not show any segregation and blocking.

It can also be concluded from Table 6 that addition of MK in concrete increased the superplasticiser amount, which was attributed to high fineness of MK [29], to maintain specific criteria for the workability of fresh concrete. Contrary to this, introducing calcite in concrete as cement replacement reduced the amount of superplasticiser needed to maintain the specific workability value.

Despite the fact that mixture C20 containing 20% C as cement replacement complied with the required criteria for being SCC, it seemed as softer conventional fresh concrete rather than SCC. Increase in the C amount in ternary mixture made with MK and C blend also reduced water requirement of mixture. The workability improvement property of calcite inclusion and employment of superplasticiser in ternary mixture were utilized together to bypass unfavourable influence of MK causing an increase in water or plasticiser amount.

Depending on the calcite replacement ratio, reduction in the superplasticiser amount was evidently observed from T_{50} and V-funnel tests. The lowest T_{50} and V-funnel flow times were measured from only concrete mixture containing calcite as cement admixture.

The published literature on influence of utilizing MK in concrete on water or superplasticiser requirement supports the finding reported in the study. For instance, it is reported that incorporating MK in SCC results in an increase in water or plasticiser requirement [22, 56, 57]. Additionally, Kavitha et al. [58] reported that inclusion of MK as cement replacement at about 5%–15% by mass results in an increase in superplasticiser requirement at about 3–5 $\mathrm{kg \cdot m^{-3}}$.

The published literature [35, 38, 59, 60] also supports water or superplasticiser reduction ability of calcite in fresh concrete as reported in current work. Although fineness of calcite particles was higher than fineness of Portland cement particles, its ability to increase workability and consistency of concrete was physically attributed to its spherical and smooth surfaced particles by Sua-iam et al. [61].

3.4. Compressive Strength Results of Concrete Produced. The results of compressive strength testing measurement carried out on all SCC mixtures produced in the study are illustrated in Figure 2 for all curing times. Compressive strength of all concretes increased in curing time; however, they performed differently from each other when comparison was made between them.

One-day compressive strength results showed that inclusion of MK in concrete reduced compressive strength of concrete in comparison with that of control Portland cement concrete. The higher replacement of MK with cement caused more reduction in compressive strength; this is attributed to slow pozzolanic reaction of MK with portlandite in the presence of water. The highest reduction was observed for 20% replacement of MK, and it was in the order of 38%.

Contrary to this, inclusion of C in concrete developed higher compressive strength than that of control Portland cement concrete at one of the ages. Increase in compressive strength was varied for different replacement ratios, and the highest increase was observed from 15% calcite replacement

Table 6: Fresh concrete workability and consistency testing for SCC.

Mix code	T_{50} flow time (2–5 s)	Slump flow diameter (65–80 cm)	V-funnel flow time (6–12 s)	L-box (H_2/H_1: 0.8–1.0)	SP (%)
Control	3.1	75	8.2	0.84	1.7
MK10	3.6	74	9.6	0.81	2.0
MK15	4.1	71	10.2	0.94	2.3
MK20	5.0	70	11.3	0.84	2.6
C10	3.2	70	7.2	0.82	1.0
C15	2.9	71	9.1	0.83	0.8
C20	2.1	72	6.5	0.84	0.6
MK10-C10	3.4	72	8.2	0.82	1.5
MK10-C15	3.2	71	9.1	0.80	1.3
MK10-C20	4.2	67	9.3	0.89	1.1
MK10-C25	3.3	66	7.4	0.89	1.1
MK15-C10	4.1	73	9.4	0.82	1.9
MK15-C15	4.2	72	8.7	0.85	1.8
MK15-C20	3.5	69	8.4	0.89	1.7
MK15-C25	4.3	69	7.6	0.85	1.6
MK20-C10	4.4	69	10.3	0.80	2.4
MK20-C15	3.3	70	7.5	0.86	2.3
MK20-C20	4.5	72	8.3	0.89	2.2
MK20-C25	4.6	71	8.2	0.89	2.0

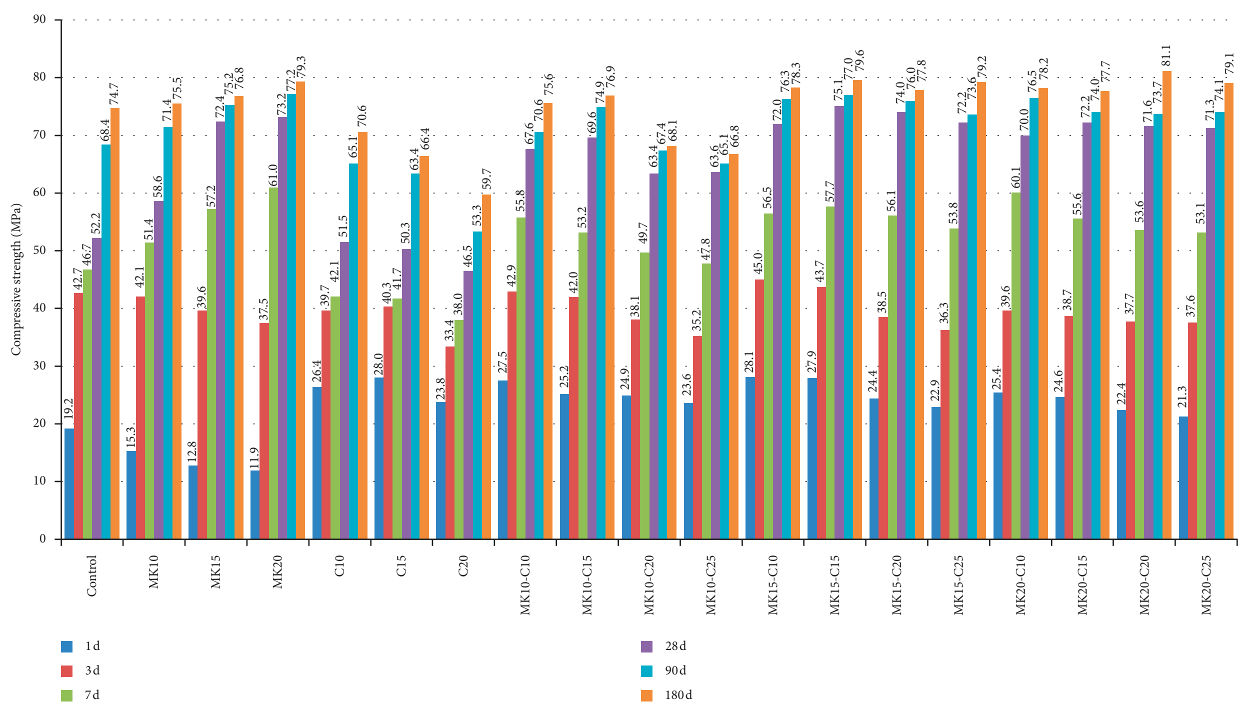

Figure 2: Compressive strength of all concretes produced at different curing times.

ratio with cement that was in the order of 45%. The published literature supports this finding; increase in early compressive strength was reported when calcite was utilized in concrete mixture [62–64]. The increase in compressive strength due to calcite was attributed to filler effect and seeding effect of calcite due to its fine particle which fills the small pores in binder paste and accelerates the hydration of Portland cement.

Furthermore, it can be observed from Figure 2 that MK and C blend containing concrete mixture developed higher compressive strength than control Portland cement concrete at one day of curing. Inclusion of MK and C blend together worked in harmony and developed higher compressive strength than control Portland cement concrete at one day. The increment rate of compressive strength was varied with the replacement ratio. The increment rate was reduced with increase in the total replacement ratio; however, compressive strength remained higher than that of control concrete at one day. The lowest increase, which was 10% compared to control mixture, was observed from concrete containing

20% MK and 25% C. The highest increase, which was 46% compared to control mixture, was observed from concrete containing 15% MK and 10% C.

Compressive strength of all concretes improved at 3 days of curing in comparison with that at one-day curing time. MK incorporating concrete showed better compressive strength development compared to C incorporating concrete mixture. Compressive strength of concrete containing 10% MK was found to be equivalent to compressive strength of control mixture. However, compressive strengths of other concrete containing 15% and 20% MK become closer to compressive strength of control mixtures than one-day compressive strength. Contrary to this, concrete containing calcite did not perform as it performed at one day of curing age. Compressive strength of concrete containing calcite reduced in comparison with control mixture. The highest reduction belongs to concrete made with 20% calcite replacement that was in the order of 20%.

Moreover, concrete containing MK and C blend together worked in harmony and developed higher or equivalent compressive strength to control mixture. For instance, MK10-C10 and MK10-C15 mixtures developed equivalent compressive strength to control mixture. MK15-C10 and MK15-C15 mixtures developed higher compressive strength than control mixtures did. Concrete containing 20% MK and various amounts of calcite developed lower compressive strength than control mixtures did at 3 days of curing age.

MK containing concretes developed higher compressive strength than control mixtures did at 7 days of curing. While replacement of MK increased, compressive strength development was found to be improved. However, calcite containing concrete did not show favourable development in compressive strength. Calcite inclusion reduced compressive strength in comparison with control mixture at 7 days of curing age. Concrete containing MK and C at the same time showed a good compressive strength development. They developed higher compressive strength than that of control mixture. Increase in compressive strength was varied due to the total MK and C replacement ratio. The higher replacement ratio of mineral admixtures resulted in lower increase of compressive strength; however, resultant compressive strength was still higher than control compressive strength was. Concrete containing 10% calcite with various amounts of MK developed higher compressive strength than control mixtures did. It was observed that compressive strength increased with increasing the MK amount, and the increase was reduced by increasing the C amount.

At 28 days of curing, similar findings to 7-day curing age were observed from compressive strengths of concrete containing MK and C together or separately. MK containing concretes developed higher compressive strength compared to control mixtures, while only calcite inclusion in concrete as mineral admixture reduced compressive strength. MK and C blend together in concrete mixture results in higher compressive strength than that of control mixture. All concretes containing MK and C gave high compressive strength in the order of 70 MPa. However, highest compressive strength was observed from concrete containing 15% MK and various amounts of C.

Compressive strength of concrete containing only MK, or MK and C together, was found to be higher than that of control mixtures at 90 d and 180 d. These compressive strengths were in the order of 70 MPa or larger. However, compressive strengths of concrete containing only calcite were lower than compressive strengths of control mixtures; they were in the order of 55–65 MPa. Furthermore, some concrete containing MK and C blend together provided higher compressive strength than not only control mixture but also concrete containing only MK as mineral admixtures.

Based on the above discussion, it was concluded that utilizing MK and C together results in better and higher strength development compared to control mixture, only MK containing mixture, or calcite containing mixture. Utilizing both admixtures together MK and C allows replacing higher amount of mineral admixtures, for instance, 20% MK and 25% C in a concrete mixture with high strength. Calcite inclusion together with MK remedies low compressive strength of only MK containing concrete at early age. They work in a harmony and develop favourable long-term high compressive strength with good workability in fresh state caused by softening effect of calcite. The increase in compressive strength with MK and C blend attributed to pozzolanic property [27–29] of MK which binds portlandite and produces additional calcium-silicate-hydrate gel as well as filler effect of calcite [62, 63].

3.5. Relation between Compressive Strength and Ultrasonic Pulse Velocity. In the context of the study, ultrasonic pulse velocity (UPV) of concrete was also measured for comparison purposes. UPVs were measured from all concretes as well as for all curing ages up to 180 days. UPVs were measured from cubic samples before the compression test.

An attempt was made to relate compressive strength of self-compacting concretes and UPV value. Graphical representation of the relationship between UPV and compressive strength is given in Figure 3 regardless of the replacement ratio of mineral admixture. Figure 3 shows that there is a good relationship existing between UPV and compressive strength with high R^2 value (0.90). The UPV value and compressive strength increase together in time, and increase in the UPV value corresponds to an increase in compressive strength.

3.6. Results of Abrasion Testing of Concrete. Abrasion testing of concrete was carried out using the Böhme abrasion testing apparatus complying with the TS 2824 EN 1338 standard [54]. The cubic sample with a side of 71 mm was used for abrasion testing. The abrasion value was calculated in weight loss and then converted to per cent weight loss and evaluated. Abrasion values for control Portland mixture and concrete containing MK and C together and separately are presented in Figure 4 at 28 d, 90 d, and 180 d of curing time.

It can be seen from Figure 4 that the abrasion value was reduced when curing time increased for each concrete. This is due to compressive strength increase in curing time that is directly related with the abrasion value, that is, higher compressive strength corresponds to a lower abrasion value. When a comparison was made between MK containing

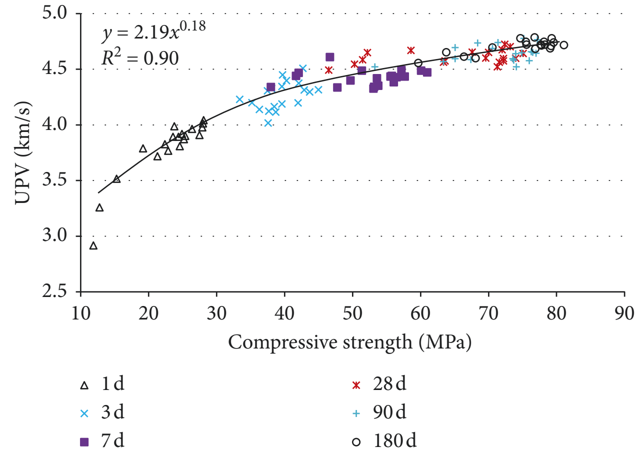

Figure 3: Relationship between compressive strength and UPV value.

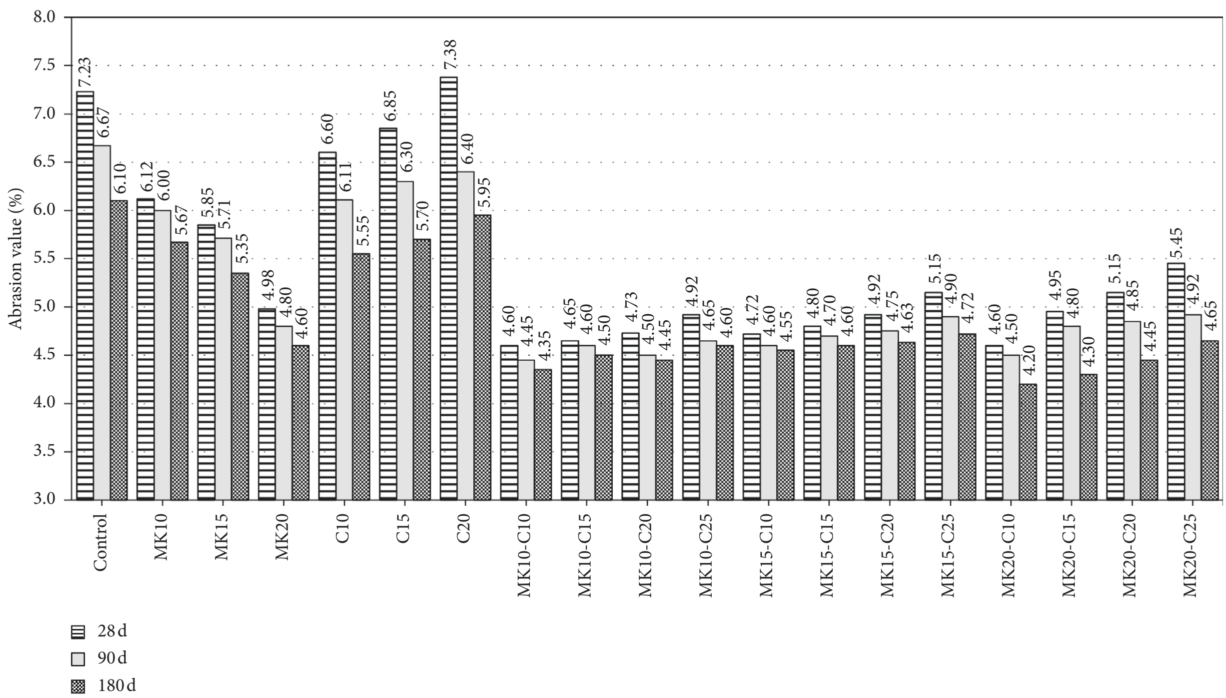

Figure 4: Abrasion value of all concretes.

concrete and control Portland cement concrete, it can be stated that MK inclusion in concrete resulted in the lower abrasion value than that of control mixture. MK inclusion in concrete increased compressive strength of concrete and thus resulted in the lower abrasion value. Calcite containing concrete mixtures showed an equivalent or a comparable abrasion value to control mixture; however, the abrasion value of calcite containing concrete increased due to the reduction in compressive strength while the calcite amount increased in concrete mixture.

Concrete made with MK and C blend together shows the lower abrasion value in comparison with control mixture. This is attributed to compressive strength development of MK and C blend containing concrete which was higher than that of control mixtures compressive strength due to pozzolanic reaction of MK and filler effect of C. It can be stated that utilizing MK and C blend together in concrete made concrete more resistant to abrasive forces.

3.7. Capillary Water Absorption Coefficient of Concretes. Durability of self-compacting concrete is important. Capillary water absorption is a significant parameter as an indicator of durability-related property. In the current work, capillary water absorption coefficients of all self-compacting concretes were measured for comparison purpose at 28 d, 90 d, and 180 d of curing time. The capillary water absorption values for all concretes are presented in Figure 5 as the graphical form.

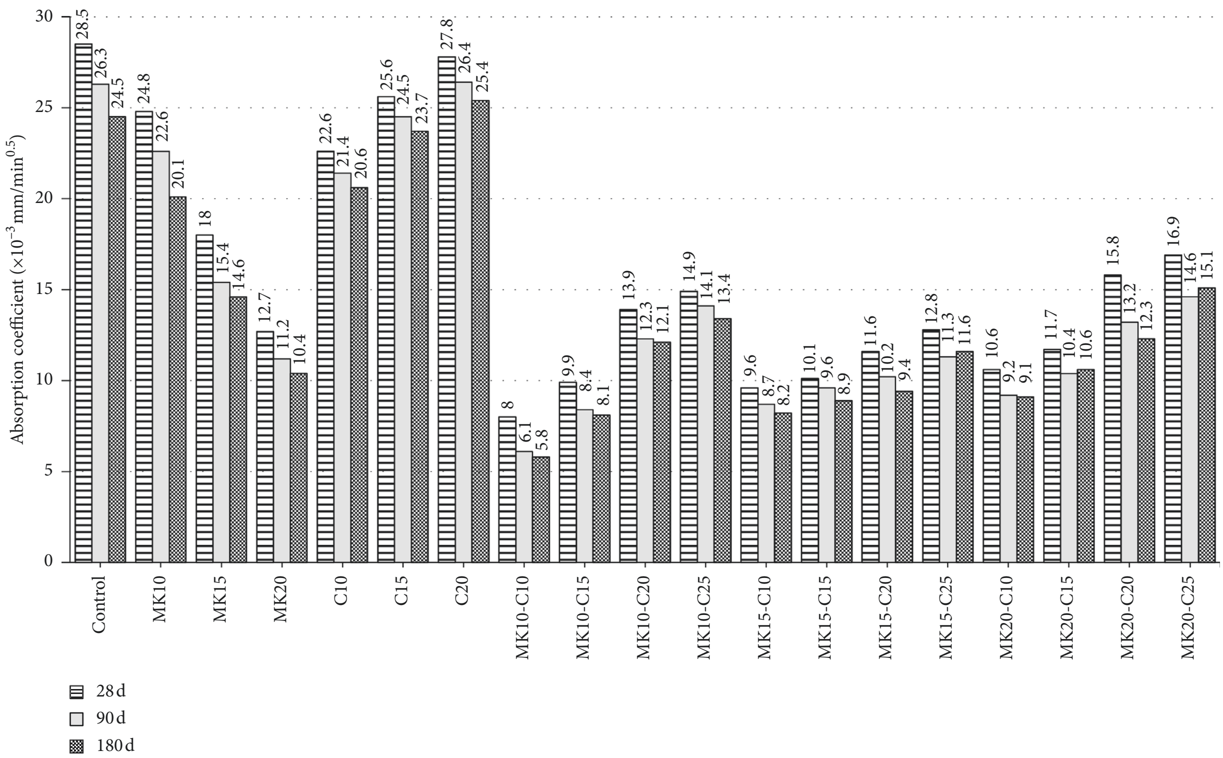

Figure 5: Capillary absorption coefficient for all mixes.

It can be observed from Figure 5 that increase in curing time results in the reduction of the capillary water absorption coefficient, and this is directly related with the hydration process of Portland cement which fills the pores by hydration products resulting lower porosity and permeability of concrete. Also, Figure 4 shows that the capillary water absorption coefficient of concrete made with MK inclusion was lower than control mixture. The higher replacement ratio of MK led to lower water absorption coefficient due to its pozzolanic reaction that produces low-density additional hydration products other than hydration products of Portland cement. Contrary to this, concrete containing only calcite as mineral admixture gave a lower or an equivalent water absorption value to control mixtures. Increase in the calcite amount replaced in concrete results in the increase of the capillary water absorption coefficient.

Moreover, inclusion of MK and C blend together in concrete as mineral admixtures led to the lower water absorption value in comparison with not only control mixture but also concrete made with MK used as admixtures. Synergetic effect between MK and C results in the lower water absorption coefficient of concrete; this is due to pozzolanic reaction of MK and filler effect of C. When comparison was made between concretes containing MK and C together, increase in the C amount in concrete resulted in somewhat increase in the capillary water absorption coefficient while the MK amount was kept constant. All concretes containing MK and C together show good performance, and concrete containing 10% MK and 10% calcite together showed best performance in terms of the capillary water absorption coefficient.

4. Conclusions

The results obtained from separate and together usages of MK and C in self-compacting concrete are summarized below:

(1) Consistency testing carried out on paste specimens shows that MK replacement in cement paste increased the water amount needed for normal consistency, while C replacement reduced it. Influence of MK inclusion on the water amount for normal consistency was found to be more dominant than the influence of C inclusion.

(2) MK replacement caused an increase in the superplasticiser amount for a required constant workability parameter. Higher amount of MK results in more requirement of the superplasticiser amount. C replacement behaved inversely to MK replacement and improved workability of concrete. Higher amount of C results in more improvement of workability.

(3) Utilizing MK and C together in concrete provided a synergy between MK and C, and thus C inclusion remedied workability of fresh concrete loss due to MK inclusion.

(4) MK replacement caused a reduction in compressive strength at one day of curing age, while C replacement caused an increase in compressive strength. Utilizing both mineral admixtures in concrete results in higher compressive strength than control mixture at one day. C inclusion remedied

reduced compressive strength due to MK addition at early age.

(5) While compressive strength reduction was observed from only MK containing concrete at early age, higher compressive strength than control mixture was observed for long-term curing age. However, while only C inclusion increased compressive strength at early age, it reduced compressive strength at long-term curing age.

(6) Utilizing MK and C together increased compressive strength at both early and long-term curing times. Concrete containing 15% and 20% MK with various C replacement ratios gave good performance in terms of compressive strength.

(7) There was a good relationship between UPV value and compressive strength of concrete. The UPV value increased in time as compressive strength increased.

(8) Abrasion resistance of MK containing concrete was higher than control mixture, while abrasion resistance of C containing concrete was lower. Concrete made with MK and C together performed better than control mixture to abrasive forces.

(9) Only MK replacement in concrete caused a reduction in the capillary water absorption value in comparison with control mixture, while only calcite replacement gave a low or an equivalent capillary water absorption value. However, utilizing MK and C together as admixtures in concrete reduced capillary water absorption in comparison with control mixture and concrete containing only calcite as well as concrete containing only MK. The reduction rate of the water absorption coefficient was found to be significant.

(10) Study shows that utilizing MK and C as admixtures in concrete separately was possible. However, utilizing both admixtures in concrete together provides a synergy and allows utilizing more amounts of admixtures in concrete which provides better workability in fresh state and high strength, low abrasion, and capillary water absorption value as the durability-related parameter.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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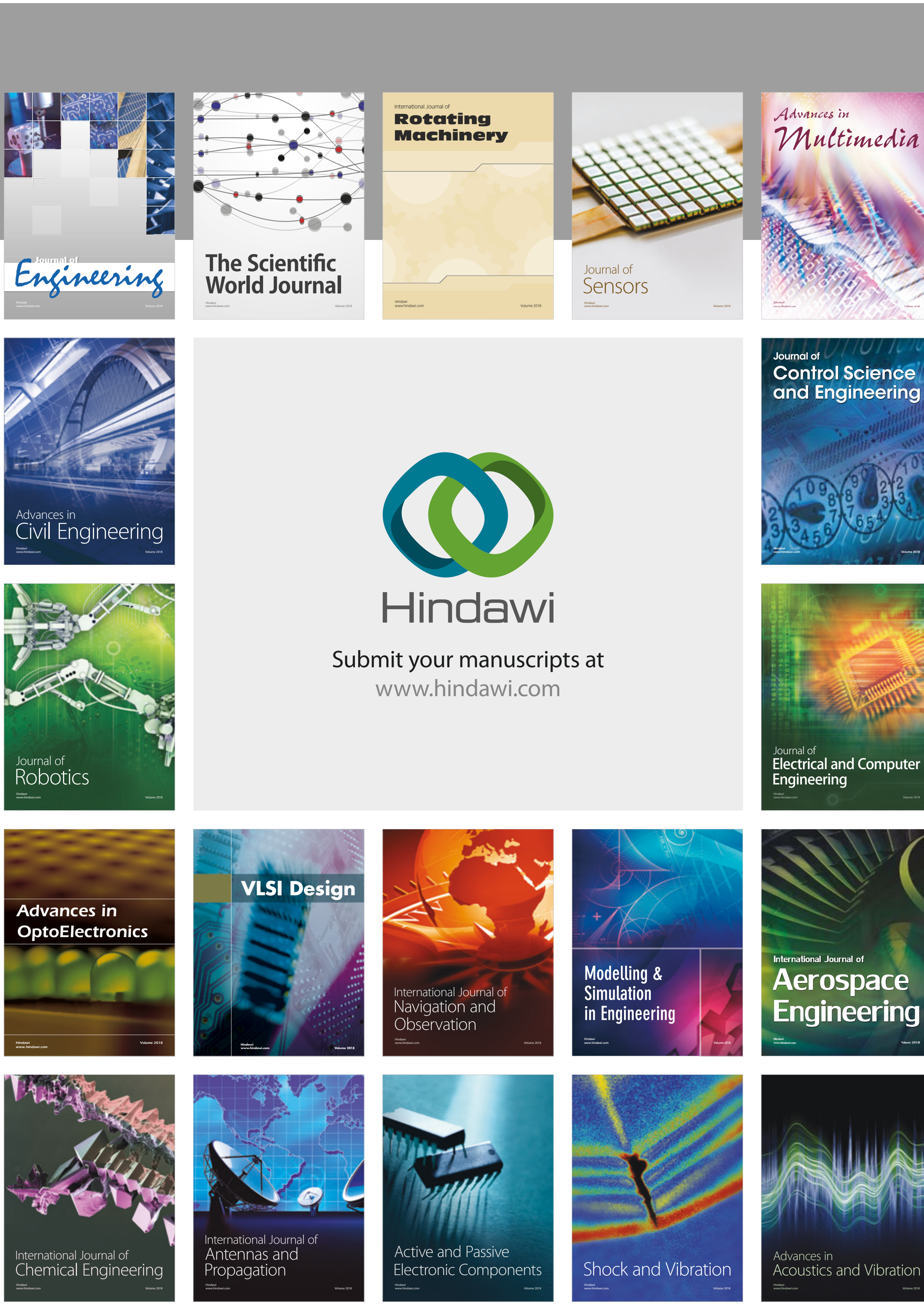
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