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Effect of mineral admixtures on properties of self-compacting concrete

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ABSTRACT

In this study, the benefits of limestone powder (LP), basalt powder (BP) and marble powder (MP) as partial replacement of Portland cement are established. Furthermore, LP, BP and MP are used directly without attempting any additional processing in the production of self-compacting concrete (SCC). The water to binder ratio is maintained at 0.33 for all mixtures. The examined properties include workability, air content, compressive strength, ultrasonic pulse velocity, and static and dynamic elastic moduli. Workability of the fresh concrete is determined by using both the slump-flow test and the L-box test. The results show that it is possible to successfully utilize waste LP, BP and MP as mineral admixtures in producing SCC. Due to its observed mechanical advantages, the employment of waste mineral admixtures improved the economical feasibility of SCC production on a unit strength basis.

1. Introduction

In recent years, there has been a dramatic increase in using self-compacting concrete (SCC) [1–6]. Self-compacting concrete (SCC), requiring no consolidation work at site nor concrete ready-mix plants, was developed in Japan to improve the uniformity and reliability of concrete in 1988 [7]. One of the most important differences between SCC and conventional concrete is the incorporation of a mineral admixture. Thus, many studies about the effects of mineral admixtures on the properties of SCC have been completed. These studies show the advantage of mineral admixture usage in SCC, such as improved workability with reduced cement content [8,9]. Since cement is the most expensive component of concrete, reducing cement content is an economical solution. Additionally, the mineral admixtures can improve particle packing and decrease the permeability of concrete. Therefore, the durability of concrete is also increased [10]. Industrial by-products or waste materials such as limestone powder, fly ash and granulated blast furnace slag are generally used as mineral admixtures in SCC [11–14]. Thereby, the workability of SCC is improved and the used amount of by-products or waste materials can be increased. Besides the economical benefits, such uses of by-products or waste materials in concrete reduce environmental pollution [15].

In limestone and basalt quarries, significant amounts of limestone (LP) and basalt (BP) powders are produced as by-products of stone crushers. Large volumes of these powders are accumulated and it is a big problem to propose utilization of these byproducts from the aspects of disposal, environmental pollution and health hazards [16]. Moreover, marble powder (MP) is a waste material with limestone origin and 511,000 tons of MP are produced per year and are deposited as wastes in Turkey [11]. This means that MP is not recycled and used in any areas in Turkey. Thus, it would be profitable if MP could be used in SCC as a mineral admixture and thereby prove valuable for the concrete industry [16]. In conventional concrete, the introduction of high volumes of mineral admixtures to concrete mixtures is limited due to their negative effects on water demand and strength of the hardened concrete. However, these mineral admixtures can be efficiently utilized as viscosity enhancers particularly in powder-type SCC. Thus, the successful utilization of LP, BP and MP in SCC could turn these materials into a precious resource [17]. Moreover, these mineral admixtures can significantly improve the workability of self-compacting concrete [14]. When used in SCC, these mineral admixtures can reduce the amount of superplasticizer necessary to achieve a given fluidity [18]. It should be noted that the effect of mineral admixtures on admixture requirements is significantly dependent on their particle size distribution as well as particle shape and surface characteristics. From this viewpoint, a cost effective SCC design can be obtained by incorporating reasonable amounts of LP, BP and MP.

In this study, it is aimed to investigate the effect of LP, BP and MP as mineral admixtures on the fresh and hardened properties of SCC. Fresh concrete tests such as slump-flow, L-box, required time of SCC to reach 500 mm length slump-flow radius (T_{50}), unit weight, air content and hardened concrete tests such as compressive strength, ultrasonic pulse velocity (UPV), and static and dynamic elastic moduli were conducted to achieve this objective and determine the appropriateness of using these different mineral admixtures in SCC.

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2. Experimental procedures

2.1. Materials

Ordinary Portland cement used in this study was produced according to the European Standards EN-197/1 and labeled as CEM I 42.5 R. The maximum size of coarse aggregate was selected as 16 mm in order to avoid any blocking effect of SCC. Besides, MP, BP and LP were used as mineral admixtures in SCC. Specific surface area by Blaine and 28 d compressive strength of the cement according to European Standards EN-196/1 were 3996 cm^2/g, and 48.3 MPa, respectively. MP was provided from a marble managing plant in Bilecik and directly used in SCC without any further processing. LP and BP were by-products of quarry crushers and collected from their filtration systems. The characteristic properties and mineralogical composition of these three mineral admixtures and the cement are given in Table 1.

2.2. Mixture proportions

One control and nine mixtures with mineral admixtures were prepared and examined to quantify the properties of SCC. Table 2 presents the composition and labeling of the SCC mixtures. As seen in that table, the mixtures were labeled such that the ingredients were identifiable from their IDs. In the mixtures, cement was replaced with MP, LP, or BP at the same contents of 10%, 20% and 30% by mass. After some preliminary investigations, the water–powder mass ratio (w/p) was selected as 0.33 and the total powder content was fixed at 550 kg/m^3.

A polycarboxylate-based high range water reducing admixture (HRWRA) was also used in the mixtures at the ratio of 1.6% of binder materials by weight for providing the desired fluidity of the SCC. The solids content and pH of the HRWRA were 20.57% and 8, respectively. Tap water used was obtained from the city waterworks of Sakarya for the production of concrete mixtures.

2.3. Casting, curing and testing

100 mm × 100 mm × 100 mm cubic molds were used for the determination of compressive strength and ultrasonic pulse velocity (UPV), while cylindrical molds Φ150 mm × 300 mm were used for the determination of static and dynamic elastic moduli. For each mixture, 15 cubes and 3 cylinders were prepared. Before casting, slump-flow test, T_{50} test, and L-box test were conducted to characterize the workability of the fresh concrete to access filling and passing abilities. During the slump-flow test, the required time of SCC to reach 500 mm length slump-flow radius (T_{50}) and the final diameter of the concrete circle through two directions were measured. In the L-box test, the test was started by removing the control gate at once to allow the flow of SCC through the horizontal part of the L-box. After this, the flow times were measured by determining the arrival times of the SCC batch at 200 mm, 400 mm, and 700 mm lengths (the end of the horizontal part is 700 mm away from the control gate). When the flow of fresh SCC stopped, the heights of the concrete at the end (h_2) and the beginning (h_1) of the horizontal section were also measured. Then, the blocking ratio was calculated as the ratio "h_2/h_1". Air void content and unit weight of fresh concrete were measured by using an air meter and a constant volume bucket, respectively [19,20]. Specimens (cubes and cylinders) were then cast in steel molds and were not subjected to any compaction other than their own self-weights. The specimens were kept covered in a controlled chamber at 20 ± 2 °C for 24 h until demolding. Thereafter, specimens were placed in water pre-saturated with lime at 20 °C. Hardened concrete testing was conducted at 7 d, 28 d, 90 d and 400 d, except static and dynamic elastic moduli that were determined at 28 d only.

Table 1
Properties of Portland cement and mineral admixtures.

Component (%)	Cement	Marble powder	Limestone powder	Basalt powder
Chemical composition (%)				
SiO_2	19.10	0.70	4.93	54.62
Al_2O_3	4.85	0.29	0.82	9.60
Fe_2O_3	3.24	0.12	0.58	4.14
CaO	61.86	55.49	51.97	12.80
MgO	2.02	0.23	0.58	4.66
SO_3	2.63	–	–	0.66
Loss ignition	2.90	42.83	40.40	9.94
Cl^-	0.00	–	–	–
Na_2O	–	2.44	–	0.84
K_2O	–	1.80	–	1.62
Physical properties				
Specific Gravity	3.08	2.71	2.79	2.76
Blaine (cm^2/g)	3996	8889	2500	6284

3. Results and discussion

In this study, fresh and hardened properties of SCC were investigated by using waste materials (LP, BP, MP) at three replacement rates for cement. The ability of SCC for compacting under its own weight is generally the main subject of such studies according to appropriate criteria given by the EFNARC Committee [21]. In the present study, such properties of SCC produced with LP, BP and MP were investigated based on fresh concrete tests, specifically workability tests.

3.1. Workability

The slump-flow values for SCC with LP, BP and MP immediately after the mixing process are presented in Fig. 1. The conventional slump test is not appropriate to quantify the workability of SCC [16]. The slump-flow test is a value-system for the ability of concrete to deform under its own weight against the friction of the surface with no external restraint present [22]. All mixtures exhibited good workability with flow values of at least 690 mm. Slump-flows of 650 mm to 800 mm are typically required for SCC [21], and all the mixtures under investigation fall into this category. The water demand and workability are controlled by particle shape, particle size distribution, particle packing effects and the smoothness of the surface texture [23]. As shown in Fig. 1, the results of slump-flow tests suggest that in the mixtures containing LP, there is a further increase in slump-flow values compared with the control and those containing other mineral admixtures. This might be explained by the increased surface area of the BP and MP particles (Table 1) increasing the water demand [14]. The water content was kept constant for all of the mixtures in this study. So, LP needs less water and it has provided more slump-flow. Generally, the mixtures which contain mineral admixtures have shown better performance than the control mixture in regards to workability. The use of mineral admixtures in SCC aims to increase the particle distribution of the powder skeleton, and thus, reduce the interparticle friction. This can provide some free mixing water, otherwise entrapped water in the system. Related to the various parameters, such as the dosage, the reactivity of the LP and the w/p control the volume of the entrapped voids in the system, the total volume of voids in the fresh system and the required volume of fine particles to fill voids. Thus, the packing density increases and the flow resistance decreases [16].

The L-box ratio characterizes the filling and passing ability of SCC. There is generally a blocking risk of the mixture when the

Table 2
Mixture proportions for 1 m^3 of SCC.

Materials (kg/m^3)	Control	LP10	LP20	LP30	BP10	BP20	BP30	MP10	MP20	MP30
Cement	550	495	440	385	495	440	385	495	440	385
LP	–	55	110	165	–	–	–	–	–	–
BP	–	–	–	–	55	110	165	–	–	–
MP	–	–	–	–	–	–	–	55	110	165
Water	182	182	182	182	182	182	182	182	182	182
w/c	0.33	0.37	0.41	0.47	0.37	0.41	0.47	0.35	0.37	0.39
w/p	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Sand	869	866	863	860	866	863	861	867	865	863
CSI	467	464	463	461	465	463	462	466	465	463
CSII	311	311	308	307	310	309	307	311	309	312

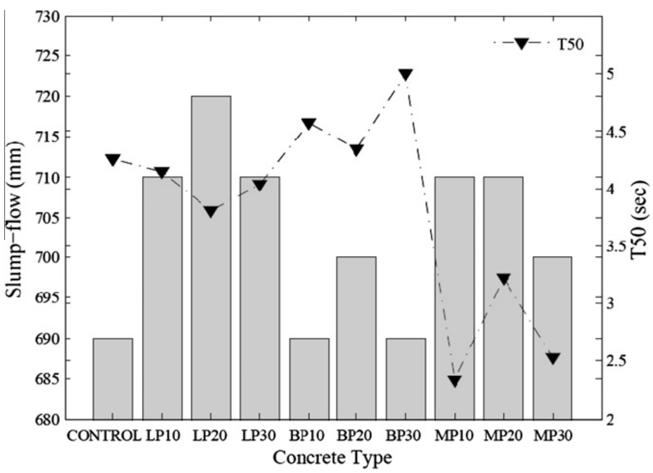

Fig. 1. Slump-flow and T_{50} time of SCC with LP, BP, and MP.

L-box blocking ratio is below 0.8 [21]. The blocking ratios of SCCs produced with LP, BP and MP are given in Fig. 2. The blocking ratio (h_2/h_1) should be between 0.8 and 1.00. All mixtures of SCC are within this target range. The blocking ratio (h_2/h_1) of the MP30 mixture was 1.00, although the yield stress of this mixture was high compared with other MP mixtures, because the MP30 mixture includes more mineral admixture than the other two MP mixtures [24]. When LP, BP and MP content have increased, it has not negatively affected the blocking ratio because of the concurrent decrease in viscosity [16]. However, it can be noted that each SCC investigated in the present study has adequate filling capability and passing ability.

The results of air void content and unit weight of SCC with mineral admixtures can be seen in Fig. 3. Air void content of SCC is increased by using LP, BP and MP as mineral admixtures. Increasing mineral admixture content for the same w/p ratio has affected the water demand for lubrication of the mineral admixture particles. Moreover, this situation affects the void content of concrete due to improper compacting in the mold. Because of this increase in void content, the unit weight of these SCC mixtures has also decreased. In addition, unit weight decreases because LP, BP and MP have a lower specific gravity than the cement that they are replacing. By using mineral admixtures such as LP, BP and MP in SCC, the unit weight can decrease while obtaining improved workability. The self weight of SCC and thus, the dead weight of structure can be decreased with this decrement in unit weight.

3.2. Compressive strength

Fig. 4 presents the compressive strength determined at different ages. When compared to the control mixture increasing amounts of mineral admixtures generally decrease the strength. Here, the roles of LP and BP are also better understood as they only act like inert mineral admixtures reducing the compressive strength of the LP and BP series. But, the MP series has shown the best performance both at 7 d and at 28 d. This is due to the physical nature of better packing, as addition of MP governs the compressive strength due to the denser matrix and the better dispersion of cement grains [25]. Furthermore, the surfaces of the MP will act as nucleation sites for the early reaction products of CH and CSH, which will accelerate the hydration of cement clinkers (especially C_3S) and consequently increase the early age compressive strength [26,27]. MP is the finest material in all the mixtures. The effect of nucleation on the strength is dependent on the mineral

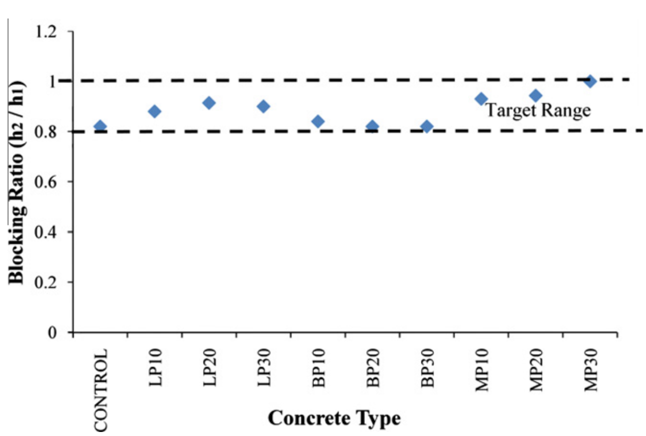

Fig. 2. Blocking ratio (h_2/h_1) of SCC with LP, BP, and MP.

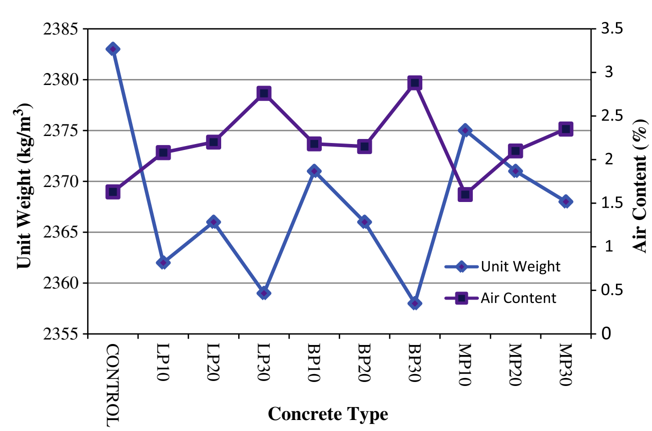

Fig. 3. Unit weight and air void content of SCC mixtures.

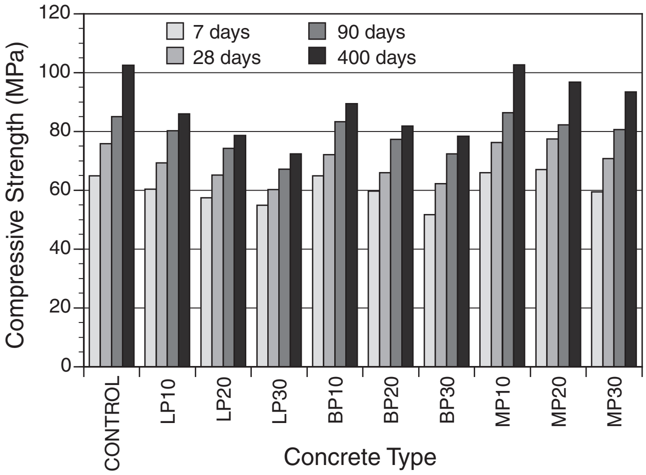

Fig. 4. Compressive strength of SCC mixtures at different ages.

admixture's affinity to cement hydrates, and it increases with fineness and specific surface area of the mineral admixture. MP is not pozzolanic, but nor fully inert as it reacts with the alumina phases of the cement. If the cement has a significant amount of tricalcium aluminate (C_3A), calcium carboaluminate will be produced from the reaction between calcium carbonate ($CaCO_3$) from the MP and the C_3A [28–30]. This reaction, accelerating the hydration and increasing the compressive strength, increases with the C_3A content of the cement and the fineness and specific surface area of the mineral admixture. Thus, MP produced as increase in early age performance of SCC.

3.3. Ultrasonic pulse velocity

Fig. 5 presents the relationship between the compressive strength and the ultrasonic pulse velocity of the SCC mixtures. The UPV values ranged from 4222 m/s to 4998 m/s. The MP10 mixture had the highest UPV value while the lowest UPV value was measured for the BP30 mixture. Whitehurst has classified concretes as excellent, good, doubtful, poor and very poor for UPV values of 4500 m/s and above, 3500–4500 m/s, 3000–3500 m/s, 2000–3000 m/s and 2000 m/s, respectively [31]. All produced concretes were classified as good as all measured UPV values were greater than 3500 m/s. The use of mineral admixtures caused a reduction in UPV. The trend in UPV values is to increase with increasing compressive strength for all the mixtures. In other words, an increase in UPV was accompanied by an increase in the compressive strength. Similar results have been obtained by other researchers [14]. The correlation between the compressive strength and UPV is quite strong ($R^2 = 0.75$ for all ten mixtures).

3.4. Static and dynamic elastic moduli

Static and dynamic elastic moduli tests were performed at 28 d for all 10 mixtures with the results shown in Fig. 6. Static elastic modulus was measured according to ASTM C 469 [32]. Concrete strain gages measured strains, and the strains and stresses were accumulated. The following equation is used to represent the dynamic elastic modulus of concrete.

$$E_d = 10^5 \times V^2 \times (\Delta/g) \tag{1}$$

where E_d is the dynamic elastic modulus (GPa), V is ultrasonic pulse velocity (m/s), Δ is unit weight of the specimen (kg/dm3) and g is the acceleration due to gravity (9.81 m/s^2).

Static and dynamic elastic moduli of concrete are nominally related to its compressive strength. As a special concrete type, SCC could indicate a different stress–strain relationship, since SCC mixtures typically have a lower amount of coarse aggregate [33]. Miscellaneous studies on static and dynamic elastic moduli of SCC have resulted in contradictory results. According to Persson, static elastic modulus of SCC corresponded well with the same properties of traditional concrete when strength was kept constant [34]. Other researchers made similar observations [35]. SCC mixtures are usually designed with higher volumes of paste than conventional concrete mixtures. Roziere et al. reported that the elastic modulus of the SCC mixtures decreased with an increase in volume of paste. This can be explained by the assumption that aggregates are generally stiffer than paste [36]. Leemann et al. conducted research to investigate the influence of the paste volume and the cement type on E-modulus and compressive strength development on three SCC mixtures and three mixtures of conventional concrete. It was found that SCC mixtures reached lower values for elastic modulus and compressive strength than conventional concrete mixtures [37]. Hunkeler and Jacobs indicated that at a given strength, the static elastic modulus of SCC is lower than that of a conventional concrete [38]. This is due to the smaller maximum

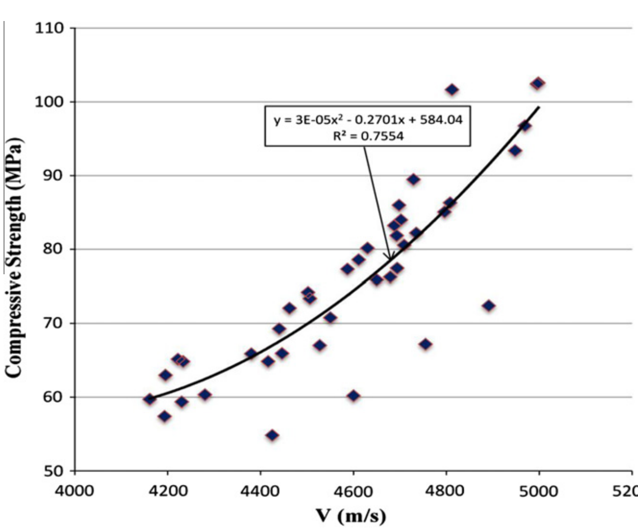

Fig. 5. Relationship between compressive strength and ultrasonic pulse velocity.

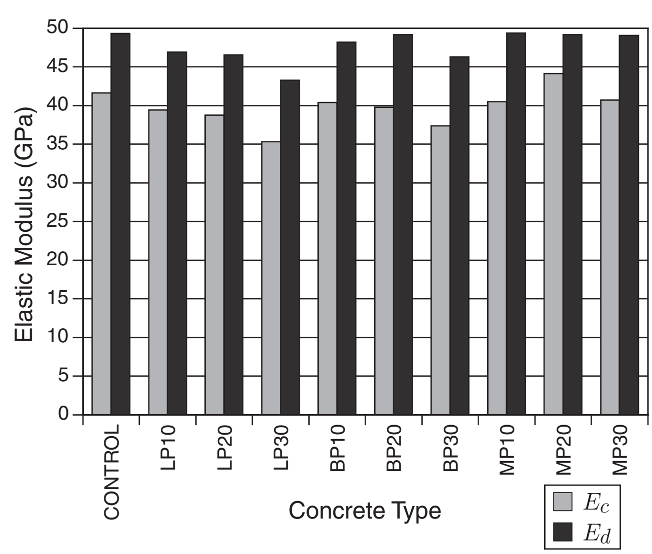

Fig. 6. Static and dynamic elastic moduli of SCC with LP, BP, and MP.

Table 3
Unit costs of materials used in analysis.

	Cement	LP	BP	MP	Water	Fine aggregate	Coarse aggregate	HRWRA
Unit cost ($/kg)	0.060	0	0	0	0.0012	0.0028	0.0013	0.78

grain size of SCC and its higher cement paste content. According to the test results presented here, if the strength of SCC mixtures increased, static and dynamic elastic moduli also increased. The highest static elastic modulus has been obtained for MP20 while the highest dynamic elastic modulus was obtained for MP10. In general, increasing replacement rates of mineral admixtures have decreased both static and dynamic elastic moduli.

3.5. Cost analysis of SCC mixtures

Despite its advantageous technical properties, the use of SCC by the concrete construction industry is limited to special applications, due to the high material costs of additional ingredients, in particular HRWRAs and additional cement. SCC can only be cost effective if more economical mixture ingredients are introduced into the market [39,40]. Incorporation of LP, BP, MP as substitutions for high amounts of cement may significantly improve the material cost effectiveness of SCC. As waste materials, the costs of LP, BP and MP are not prohibitively high. From this viewpoint, LP, BP, and MP bring no additional cost to producers and can be effectively employed in SCC applications. In order to compare the costs of the 10 investigated SCCs, the local unit costs of materials were collected and are presented in Table 3. Note that, factors that change the overall cost of concrete production, i.e. the transportation, handling, placement and quality control were not taken into account.

The costs of 1 m^3 of each mixture have been presented in Fig. 7. As could be expected, there is a significant material cost difference between the control mixture and the SCCs prepared with LP, BP, and MP. However, the cost of 1 m^3 of material is not enough to provide a comprehensive cost comparison of SCCs, since the final strength values of these ten SCC mixtures are also different. Therefore, the costs per unit compressive strength (1 MPa) of the mixtures were calculated and are presented in Fig. 8. It can be seen that for all mixtures, the increase in mineral admixtures replacement level decreased the unit strength cost of SCCs. The reduction was 0.103 $/MPa/$m^3$ for MP30 as the most economical mixture.

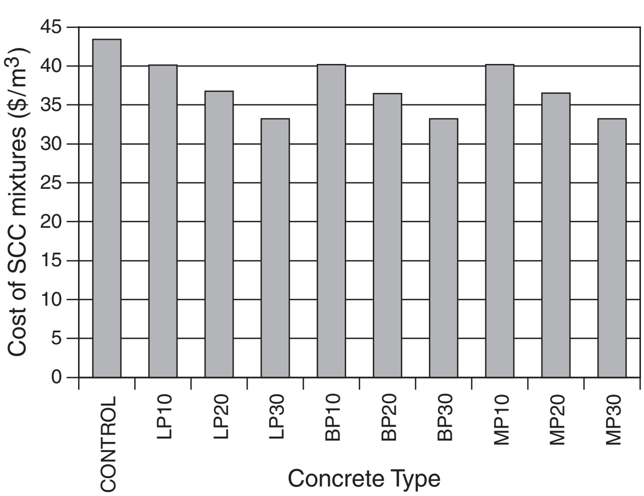

Fig. 7. Cost of 1 m^3 of SCC mixtures with LP, BP, and MP.

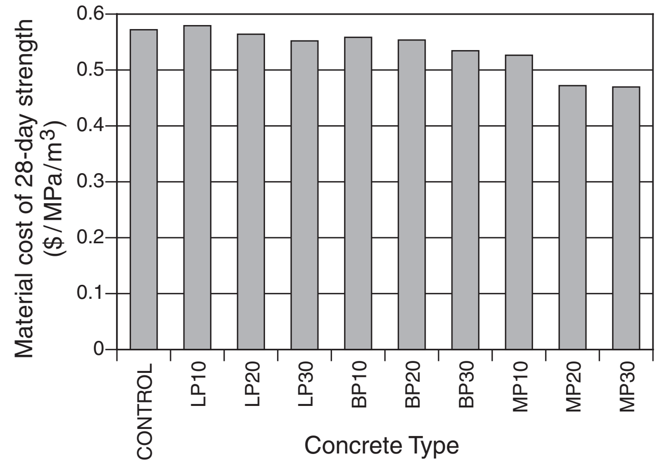

Fig. 8. Unit strength material costs of SCC mixtures.

4. Conclusions

As a result of this experimental study, the following conclusions can be drawn:

- All the mixtures had satisfactory self-compacting properties in the fresh state. The addition of LP, BP, and MP had positive effects on the workability. When the properties of fresh SCC such as slump-flow, T_{50} time, L-box ratio, air content and unit weight are considered as a criterion to determine the best mineral admixture among LP, BP and MP, it can be said that MP is the most suitable for improving all of them.
- The results for hardened properties of the SCC mixtures containing different mineral admixtures were investigated; all the mineral admixtures have shown significant performance differences and the highest compressive strength has been obtained for the MP mixtures. There was a reasonable correlation between the compressive strength and UPV of the ten SCC mixtures. When the strength of SCC mixtures increased, static and dynamic elastic moduli also increased and the highest static elastic modulus and dynamic elastic modulus have been obtained for MP20 and MP10, respectively. Generally, the addition of mineral admixtures has decreased both the static and the dynamic elastic moduli of these SCC mixtures.
- Incorporation of mineral admixtures reduced the cost per unit compressive strength of these SCC mixtures, for all investigated cases. The reduction was approximately 0.1 $/MPa/$m^3$ for MP30, which is the most economical mixture among the entire SCC series.

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