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ORIGINAL PAPER

The impact of calcium stearate on characteristics of concrete

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Abstract

Moisture and aggressive ions transferring into concrete have detrimental effects on durability of reinforced concrete structure. To tackle this problem, damp-proofing admixtures, like calcium stearate, can be incorporated in the mixture design of concrete to restrict water and aggressive ions' ingress into concrete. Calcium stearate is a damp-proofing admixture which can provide a water-repellent layer along the capillary pores. As a result, it can reduce permeability of concrete under non-hydrostatic condition. This study investigates the effects of calcium stearate on properties of fresh and hardened concretes. To this end, 12 mixtures with different water-to-cementitious materials (w/cm) ratios but constant ratio of cement paste-to-aggregate were prepared and moist-cured for 180 days. The major outcomes of fresh concrete analysis showed that high dosage of calcium stearate in low w/cm ratios increased the air content and reduced the density of fresh concrete. It also decreased the workability of fresh concrete, regardless of the w/cm ratio and the dosage of calcium stearate. The findings of compressive strength analysis indicated that calcium stearate reduced compressive strength, even when low dosage of calcium stearate was added to the concrete mixture. Based on permeability test results, calcium stearate could improve permeability under non-hydrostatic pressure. However, incorporation of calcium stearate was not found to be an effective approach to decrease permeability under hydrostatic pressure. Finally, microstructure analysis showed that CS has adverse effect on the interfacial transient zone.

Keywords Calcium stearate · Damp-proofing admixtures · Durability · Water absorption · Microstructure analysis

Introduction

Water and aggressive ions' transfer into concrete is always accompanied by detrimental effects on durability of reinforced concrete structures. To deal with this problem, a wide range of approaches such as using supplementary cementitious materials and limiting water to cementitious materials (w/cm) ratio in the mixture proportion can be adopted (Nemati et al. 2016a, b, 2018; Sabet et al. 2013). To be more precise, inclusion of SCMs occupied a large segment of recent research to improve mechanical properties and durability of concrete (Hajforoush et al. 2019; Vishvanath et al. 2018). Moreover, inclusion of damp-proofing admixtures (DPAs) can be considered a more innovative method to decrease permeability of various types of construction and building materials (Corinaldesi 2012; Falchi et al. 2013; Lagazzo et al. 2016; Lanzón et al. 2008, 2017; Maryoto 2015; Tittarelli 2009; Tittarelli and Moriconi 2010, 2011; Tittarelli et al. 2014; Vejmelková et al. 2012; Wong et al. 2015; Zhu et al. 2013). According to ACI 212.3-R16 (2017), DPAs just provide a water-repellent layer along the capillary pores without any noticeable improvement in the structure of the pores such as blocking or disconnecting the capillaries. As a result, DPAs are supposed to be beneficial to reduce permeability under non-hydrostatic condition because they cannot enhance the structure of capillary pores significantly.

Among available DPAs, calcium stearate (CS) can be considered an available and easily processed DPA which has been widely utilized in the recent studies to decrease the permeability of a broad range of concretes (Ma and Chen 2016; Maryoto 2017 and 2015) and mortars (Falchi et al. 2013; Izaguirre et al. 2011; Lanzón et al. 2008; Lagazzo et al. 2016). The outcomes of these investigations unanimously demonstrated that CS could noticeably enhance the

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durability parameters of investigated materials (Falchi et al. 2013; Izaguirre et al. 2011; Lagazzo et al. 2016; Lanzón et al. 2008; Ma and Chen 2016; Maryoto 2015, 2017). To be more accurate, improvement in permeability of CS-incorporated materials under non-hydrostatic condition including decrease in the results of bulk and capillary water absorption is quite pervasive in the recent research studies (Falchi et al. 2013, 2015; Lagazzo et al. 2016; Lanzón et al. 2008; Lanzón and García-Ruiz 2009; Ma and Chen 2016; Maryoto 2017). However, the impact of CS on permeability of concrete under hydrostatic condition is not fully discussed in the recent research studies. Plus, the impact of CS on mechanical characteristics is still under debate because contradictory results have been reported about the effects of CS on mechanical characteristics of CS-incorporated materials. To illustrate, Maryoto (2015) showed that CS (up to 4 kg/m^3) slightly improved compressive strength of CS-incorporated concretes in comparison with the reference mixture. Additionally, Izaguirre et al. (2011) showed that incorporation of CS, in dosages of 0.06% and 0.5% of the dry mortar's weight, did not have any adverse effect on the compressive strength of lime-based mortars. By contrast, Falchi et al. (2015) showed incorporation of CS reduced the compressive strength of Portland limestone cement mortars. But, the major deficiency of the recent research studies is the fact that the majority of them studied the effects of CS in a constant w/cm ratio (Ma and Chen 2016; Maryoto 2015, 2017), or they compared the effect of CS with other DPAs in constant w/cm (Falchi et al. 2015). For example, Maryoto (2015) investigated the effects of various amounts of CS (1–4 kg/m^3) on mechanical and durability aspects of concretes which were prepared in constant w/cm of 0.42 and cement content of 480 kg/m^3. Moreover, Ma and Chen (2016) compared the effects of various dosages of CS, potassium trimethyl silanolate, and siloxane-based polymer (0.8–4.8 kg/m^3) on properties of foam concretes in fixed w/cm of 0.35 and total cementitious materials of 400 kg/m^3. Falchi et al. (2015) compared the impact of CS and zinc stearate (at the dosage of 1% of dry materials weight) on properties of Portland limestone cement mortars which were prepared in constant w/cm ratio. Apparently, the recent research studies did not adopt a comprehensive approach to study the effect of CS in their research studies.

Clearly, regarding the recent research studies, more actions need to be taken so that the impact of a certain DPA, such as CS, on properties of concrete in different w/cm ratios to be fully highlighted. Moreover, another disputable point of the recent research studies is the impact of CS on the mechanical characteristics of concrete. To compensate the deficiencies of the recent research studies, and to shed more light on their ambiguous aspects, the effect of CS on the properties of fresh and hardened concrete is investigated. To this end, 12 concrete mixtures in various w/cm ratios but constant ratio of cement paste volume-to-aggregate were prepared and moist-cured until the age of 180 days. To study the effects of CS on fresh concrete, density, workability, and air content of fresh concrete were studied. The impact of CS on mechanical characteristics is investigated by performing compressive strength test after different ages of moist curing. Additionally, to highlight the impact of CS on permeability aspects of concrete, bulk water absorption, depth of water penetration electrical resistivity tests, and microstructure analyses were conducted.

Experimental program

Materials

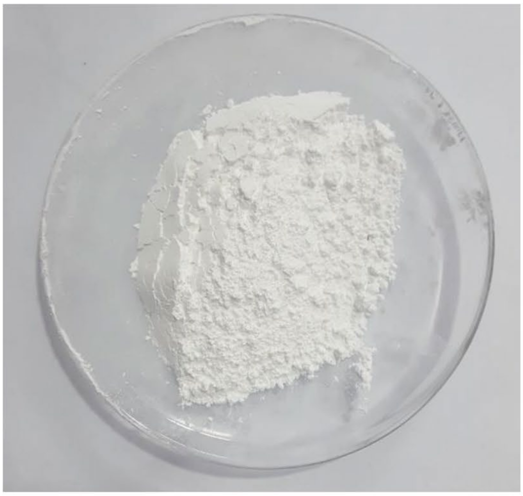
Common type II cement with specific gravity of 3.15 and Blaine of 315 m^2/kg was used to prepare the mixtures. Chemical composition of this cement is presented in Table 1. CS is a white and non-soluble powder. Figure 1 shows physical shape, insolubility of CS in water, and morphology of CS. The grading of aggregate and the recommended limits according to ASTM C33 (2016), physical shape, and properties of fine and coarse aggregates are shown in Fig. 2 and Table 2. The superplasticizer which was used to adjust the workability of the mixtures was poly-carboxylate-ether based with specific gravity of 1.10.

Mixture proportion

To study the effects of CS on properties of fresh and hardened concrete, 12 mixtures in four groups were prepared. Each group was allocated to one w/cm ratio and consisted of three mixtures, one of which was the reference mixture (without CS) and two of which were CS-incorporated mixtures (1 and 4 kg/m^3). Table 3 provides information about the mixture proportion of the prepared concretes. As is observed in Table 3, all the mixtures were designed in constant cement paste volume-to-aggregate ratio to evaluate the permeability properties of CS-incorporated concretes as accurate as possible. Furthermore, to study the effects of CS on properties of fresh concrete in constant amount of SP, the reference mixture is designed to reach the slump of 12.5 ± 2.5 cm. Then,

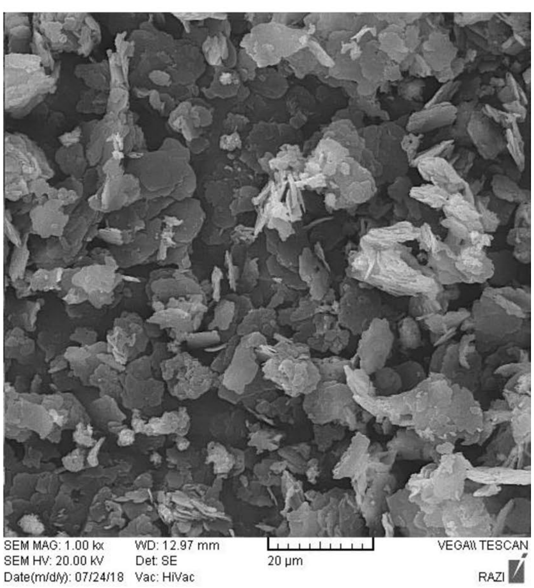
Table 1 Composition of cement

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	C3S	C2S	C3A	C4AF
(%)	64.3	21.8	4.5	3.9	1.5	0.54	0.17	56	20	5	12



(a) Physical shape

(b) Insolubility of calcium stearate in water



(c) morphology

Fig. 1 Calcium stearate

the dosage of SP is kept constant through a specific w/cm ratio. This test method enabled the authors to study the direct effect of CS on workability of fresh concrete.

Specimen preparation and test method

After preparing the mixtures in the laboratory pan mixer, the required specimens were casted in cylindrical and cubic moulds. These specimens were left covered in moist room in the temperature of 23 ± 2 °C for 24 h. After demoulding, the specimens were moist-cured in the water at 23 ± 2 °C until the intended age for testing. To evaluate the properties of fresh concrete, air content (AC), density of fresh concrete (DFC) and slump tests were conducted immediately after preparing the mixtures according to ASTM C231 (2017), BS-EN 12350-6 (2009) ASTM C143 (2015), respectively. Compressive strength test was performed on cubic specimens having 15 cm length after 7, 28, 90, and 180 days of moist curing according to BS EN 12390-3 (2009). It must be mentioned that the reported results are the average of the compressive strength of three specimens.

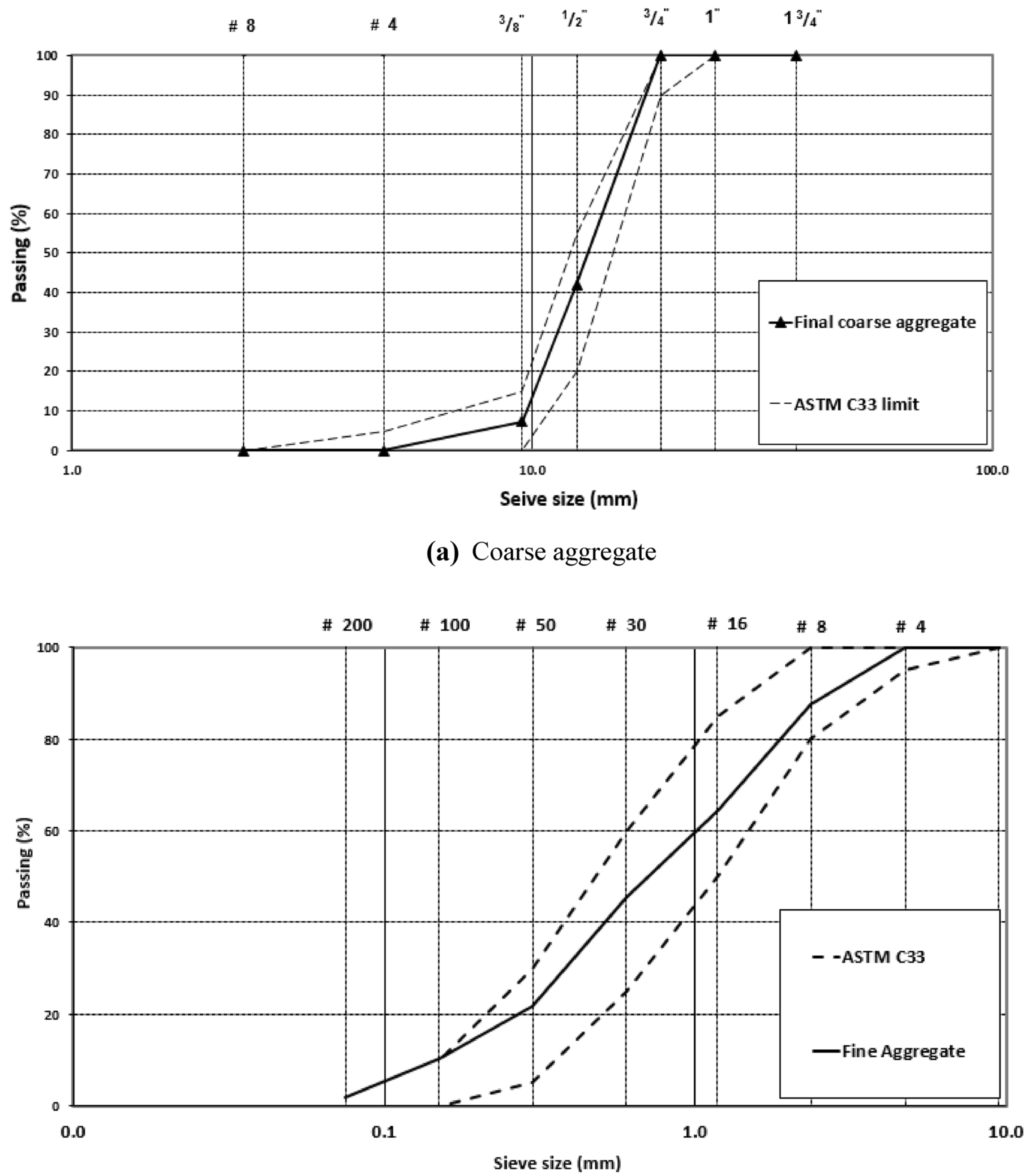
To study the effect of CS on the rate of water absorption (WA), WA test was performed based on BS EN 1881: part 122 (2011) after 180 days of moist curing. To this aim, three cylindrical specimens, 7.5 cm in height and 7.5 cm in diameter, were cut from a cubic specimen having 15 cm length. Then the specimens were oven-dried until the constant mass and were cooled in a desiccator for 24 ± 0.5 h. Subsequently, the specimens were returned to the water tank and their mass was recorded after 30 min, 60 min, 4 h, and 90 days to calculate the percentage of WA. It must be mentioned that the total water absorption (TWA) was calculated by means of Eq. 1.

$$A_{\mathrm{t}} = \frac{w_{\mathrm{ssd}} - w_{\mathrm{d}}}{w_{\mathrm{d}}} \times 100 \tag{1}$$

where w_{ssd}: mass of saturated surface-dry specimen (g); w_{d}: mass of totally dried specimen (g) and A_{t}: total water absorption (%).

Water penetration depth (WPD) was calculated according to BS EN 12390-8 (2009). The test was performed on saturated surface-dry, cubic specimens having 15 cm length. Electrical resistivity test was performed based on AASHTO T358-17 (2017). It must be noted that the average of four measurements was reported as the electrical resistivity of the specimens after 7, 28, 90, and 180 days of moist curing.

Microstructure analysis was conducted by means of scanning electron microscopy (SEM) to investigate the effect of CS on microstructure based on ASTM C 1723 (2016). To this aim, specimens were moist-cured until 90 days. Then, the effect of CS on microstructure was investigated.



(a) Coarse aggregate

(b) Fine aggregate

Fig. 2 Grading of coarse and fine aggregates

Table 2 Properties of fine and coarse aggregate

Coarse aggregate	Fine aggregate	Property
2.56	2.55	Specific gravity (saturated surface-dry)
1.8	2.8	Water absorption (%)
Crushed	Well-rounded	Physical shape

Results and discussion

Fresh concrete

Table 4 and Fig. 3 provide information about properties of fresh concrete when CS was added to mixture proportion. Overall, density of fresh concrete (DFC) and workability of fresh concrete reduced due to incorporation of CS. While,

Table 3 Mixtures proportions

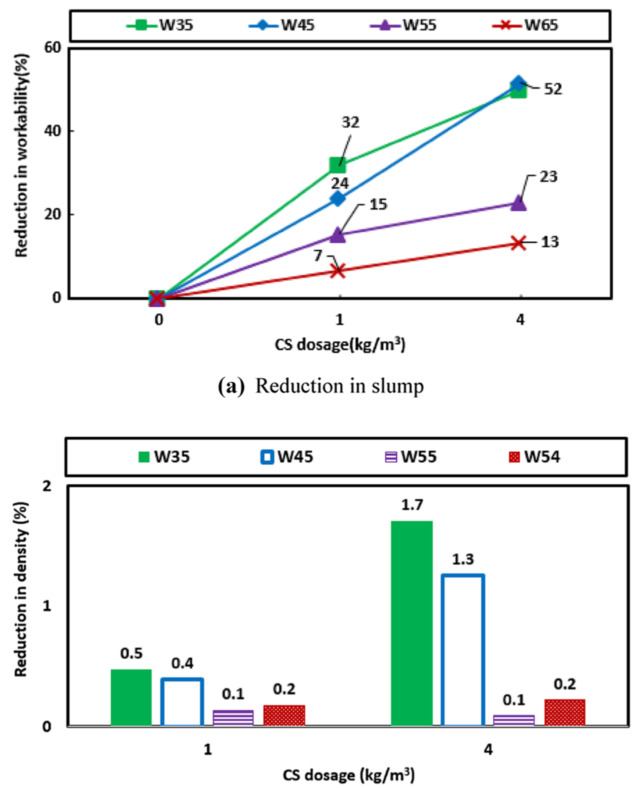
Group	Mixture ID	Cement	Water	w/cm	Fine aggregate	Coarse aggregate	SP	CS
1	W35-CS0	433	151	0.35	1148	618	2.15	0
	W35-CS1							1
	W-35-CS4							4
2	W45-CS0	376	169	0.45	1148	618	1.32	0
	W45-CS1							1
	W45-CS4							4
3	W55-CS0	333	183	0.55	1148	618	0.83	0
	W55-CS1							1
	W55-CS4							4
4	W65-CS0	299	194	0.65	1148	618	0.21	0
	W65-CS1							1
	W65-CS4							4

All the quantities are expressed in kg/m^3

All the mixtures were designed in constant ratio of cement paste volume-to-aggregate

Table 4 Properties of fresh concrete

Group	Mixture ID	Slump (cm)	Air content (%)	Density (kg/m^3)
1	W35-CS0	11.0	2.2	2341
	W35-CS1	7.5	2.4	2330
	W35-CS4	5.5	3.2	2301
2	W45-CS0	14.5	2.0	2311
	W45-CS1	11.0	2.3	2302
	W45-CS4	7.0	2.9	2282
3	W55-CS0	13.0	1.8	2275
	W55-CS1	11.0	1.9	2272
	W55-CS4	10.0	1.8	2272
4	W65-CS0	15.0	1.7	2265
	W65-CS1	14.0	1.8	2261
	W65-CS4	13.0	2.0	2260



(a) Reduction in slump

(b) Reduction in density in comparison with the reference mixture in each group

Fig. 3 Variations in the properties of fresh concrete

air content (AC) increased. Moreover, the effects of CS were more pervasive in lower w/cm ratios (0.35 and 0.45). The following points can be concluded by studying these figures in more detail:

Table 4 and Fig. 3a demonstrate that all groups experienced a reduction in workability, regardless of the included dosage of CS. However, the variations were more noticeable in the w/cm of 0.35 and 0.45. In fact, in the W35 and W45 groups the slump of fresh concrete underwent a drastic decrease of 50% due to addition of 4 kg/m^3 of CS. While, in W55 and W65 groups the equivalent decreases are roughly 23% and 13%, respectively. It can also be concluded that in certain w/cm ratio a direct relationship does exist between the incorporated dosages of CS with reduction in slump of fresh concrete.

In all groups an upward trend can be observed as far as AC is concerned. Although Table 4 showed that AC (%) increased by roughly 1% in W35 and W45 groups due to addition of CS, the increase of AC in other two groups was negligible. This observation shows that the impact of CS on AC is more significant in lower w/cm ratios.

When it comes to DFC, Table 4 and Fig. 3b showed that DFC remained relatively constant, particularly due to inclusion of 1 kg/m^3 of CS. However, a mild decrease occurred in DFC due to incorporation of 4 kg/m^3 of CS in W35 and W45 groups. Moreover, the decrease in DFC was relatively negligible in higher w/cm ratios. Interestingly, the results of DFC and AC analysis were compatible, because in both evaluations the most significant increase in AC and the most noticeable reduction in DFC were observed in lower w/cm ratios.

Hardened concrete

Electrical resistivity

Figure 4 shows the electrical resistivity of the mixtures in different ages. Generally, incorporation of CS is not a constructive approach to increase electrical resistivity. Electrical resistivity is one of the most important factors which participate in concrete durability (Sabet et al. 2013). It can be expressed that higher electrical resistivity can represent denser structure of cement paste and capillary pores (Ahmadi and Shekarch 2010; Sabet et al. 2013). While, Fig. 4 showed that electrical resistivity did not undergo any significant change due to incorporation of CS. Thus, not only is CS ineffective to increase electrical resistivity, but it also has no positive impact on the density of the cement paste or the structure of capillary pores.

Water penetration depth

Figure 5 demonstrates the water penetration depth (WPD) in all groups. Overall, incorporation of CS was not influential on WPD. In fact, WPD analysis shows the ease with which water flows through the capillary pores of concrete under hydrostatic pressure (Saleh Ahari et al. 2015). Although the results of WPD test showed that the WPDs of CS-incorporated concretes were somewhat less than the WPD of the reference mixture in each group, the authors think that CS cannot improve permeability under hydrostatic condition.

The results of WPD are compatible with the results of electrical resistivity test. To be more accurate, electrical restively showed that CS could not improve the density of cement paste or structure of capillary pores. Plus, WPD

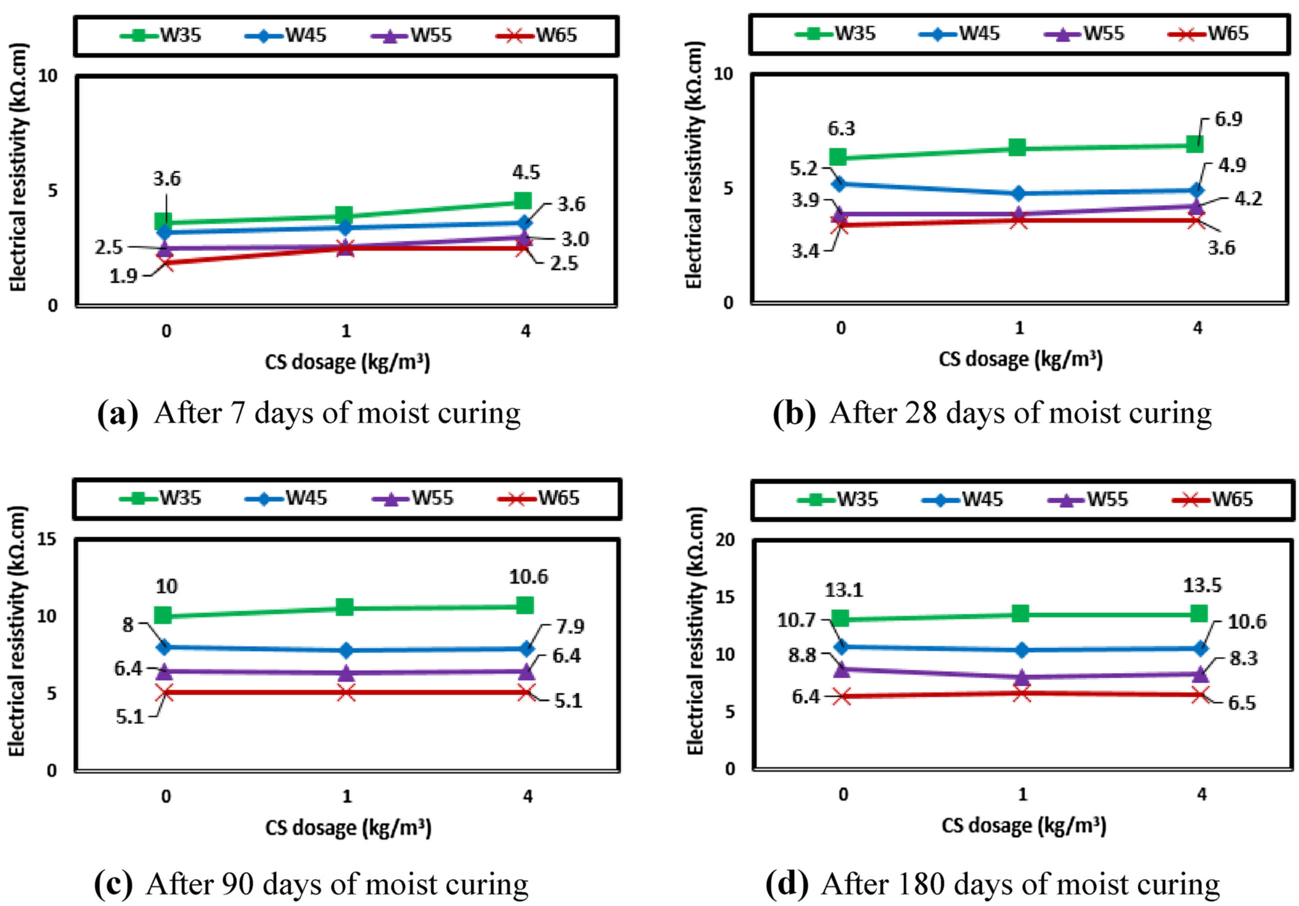


Fig. 4 Electrical resistivity

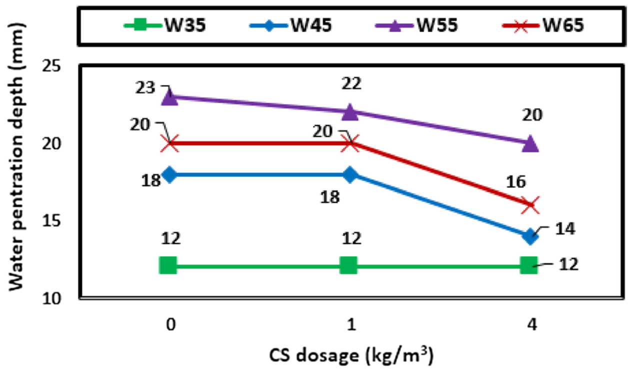


Fig. 5 Water penetration depth

analysis shows that CS cannot increase the difficulty with which water flows through capillary pores which can be interpreted as disability of CS to improve the structure of the capillary pores. Although a slight decrease can be observed in WPD in W45, W55, and W65 groups, this reduction does not indicate any improvement in permeability under hydrostatic condition (see the next paragraph). Clearly, either WPD test or electrical restively test is relatively indicating the fact that CS had insignificant influence on structure of capillary pores in the specimens.

Figure 5 shows that WPD underwent a slight reduction in all groups, except W35 group. However, the authors think that CS cannot improve permeability under hydrostatic condition. To determine the depth of water penetration in concrete in WPD test, hydrostatic pressure gradient plays the biggest role when the test specimen is saturated surface-dry. However, due to the test duration and the relative humidity of the laboratory environment, the moisture content of the capillary pores may undergo a decrease. In other words, the pores which are located near the surface will not be completely saturated. In this case, the capillary suction of the pores can be considered another factor in moisture ingress to the capillary pores which are situated near the surface. It can be argued that CS reduced the water which was absorbed by capillary suction, and this reduction lead to decrease in WPD in W45, W55, and W65. As a result, it did not reduce the water which penetrated due to hydrostatic pressure. This explanation makes sense, because WPD in W35 group did not undergo any change. In fact, the prime reason for constant WPD in W35 group is the fact that moisture loss does not play a crucial role in this w/cm ratio. In fact, this w/cm ratio moisture loss occurs with difficulty due to narrow width of capillary pores (Nemati et al. 2016a, b). Thus, the pores remained saturated, and the no-significant variation can be detected in WPD.

Another disputable point is the comparison with WPD in different groups. This observation can be also interpreted based on the moisture content of the pores and the test method of the research. In this research, saturated surface-dry specimens were used to perform the test, and the depth of the highest point of water profile was measured as WPD. Moreover, as discussed in the last paragraph, hydrostatic pressure gradient and capillary suction play a role in WPD, and moisture loss from the pores which are near the surface is common. But the important point is that the specimens of W35 and W45 groups could offset this moisture loss due to stronger capillary suction of their narrow pores. Plus, in lower w/cm ratios process of capillary suction does not play a big role, because the concrete does not lose significant amount of moisture due to the narrow width of the capillary pores (Nemati et al. 2016a, b). According to this explanation, water penetration depth of the specimens of W35 and W45 groups seems reasonable. But, when it comes the specimens of W55 and W65 the situation is completely different. In the specimens of these groups the capillary suction is not strong enough to absorb moisture from the surrounding of the specimens. Moreover, high width of the capillary pores facilitates the process of moisture loss. Consequently, the capillary pores which are located at the surface experienced became drier in comparison with pores which are situated at the core of concrete. It is possible that the difference between the degrees of saturation of the pores in different parts of the specimen disrupted the profile of penetrated water. As a result, water penetrated the drier pores which were located at the surface of the specimens not only under hydrostatic pressure but also by capillary absorption. Clearly, this disruption can be considered as the reason of higher WPD of the specimens of W55 group compared with the specimens of W65 group.

The result of WPD test in this research is not compatible with the results of an experimental study by Mariyoto (2015). Maryoto showed that incorporation of 4 kg/m^3 of CS could reduce the water penetration depth by 55% in concretes prepared in cement content of 480 kg/m^3 and w/cm ratio of 0.42. While, this research demonstrated that incorporation of CS cannot significantly reduce WPD, regardless of w/cm ratio and cement content. According to the results of electrical resistivity and ACI 212.3R16, results of the current research makes more sense in comparison with the results of the research done by Mariyoto.

Water absorption

Figures 6, 7, and 8 provide information about the impact of CS on water absorption (WA). In general, a direct relationship can be detected between the dosage of CS and decrease in the rate of water absorption. In other words, CS had appreciable impact on WA after 30 min, 1 h, and 4 h of immersion in water. It also had minor impact on WA after 90 days. But its effect on total water absorption (TWA) was quite negligible.

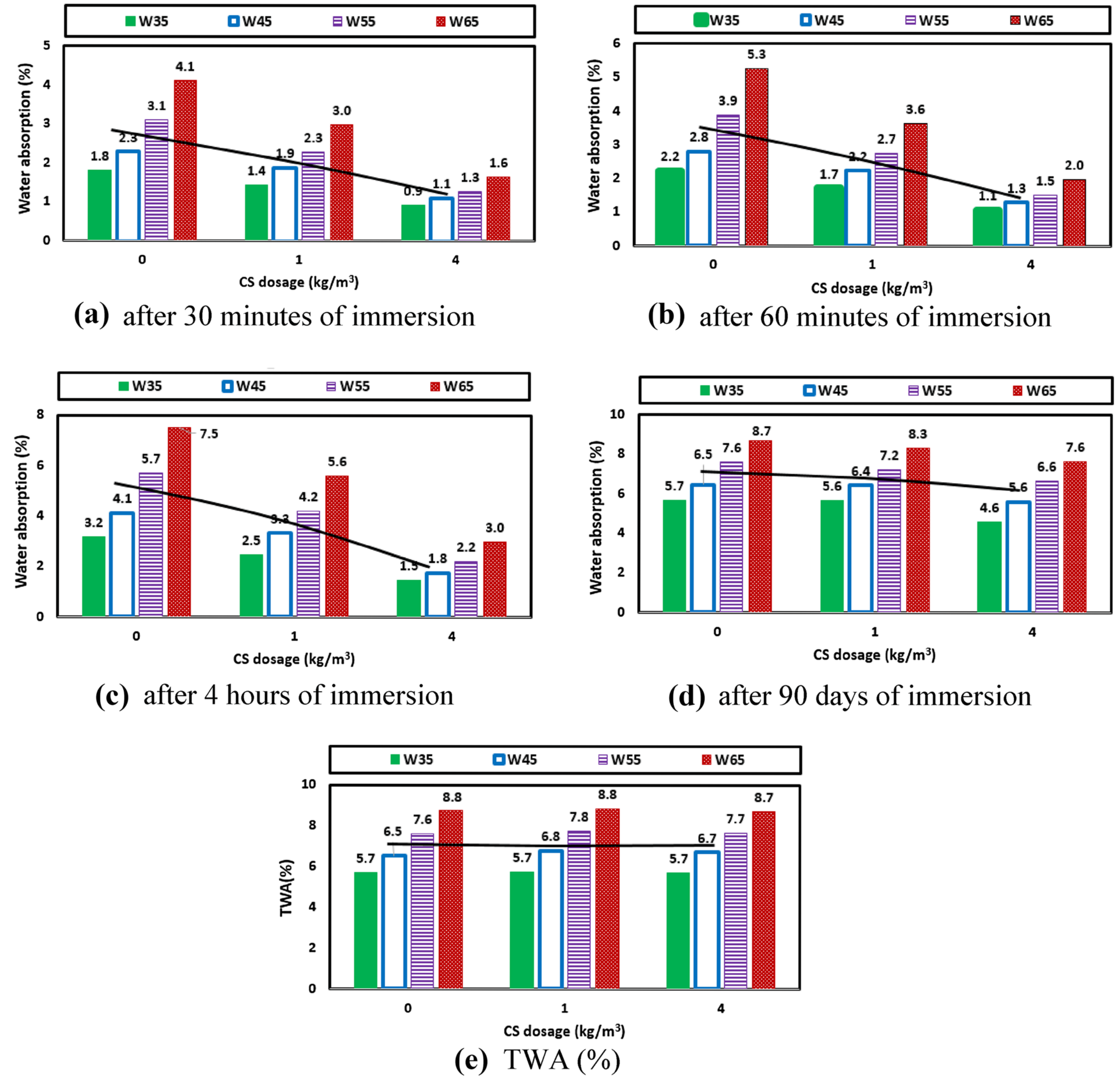


Fig. 6 Water absorption (WA). The black line connects the average WA of concretes containing the same dosage of CS

Figure 6 shows the WA of concrete mixtures after different periods of immersion in water. Figure 7 also demonstrates the reduction in WA in comparison with the reference concrete in each group. Figures 6 and 7 show that 4 kg/m^3 of CS can reduce WA after 30 min, 1 h, and 4 h of immersion by at least 50%. However, the exact percentage of reduction depends on w/cm ratio. Figure 7 also shows that WA after 90 days of the reference mixture of each group reduced by at least 13%. But, CS had not any significant impact on TWA.

Reduction in the rate of WA can be definitely attributed to the water-repellent layer on the pore walls. It can be also observed that the reduction in WA depends on the degree of saturation of the capillary pores. To be more precise, in lower degrees of saturation of capillary pores (during the initial 4 h of immersion) 4 kg/m^3 of CS could decrease WA roughly 50%. But, in higher degrees of saturation of capillary pores (90 days of immersion) the same dosage of CS could only decrease WA up to 19%. This means that in higher degrees of saturation of the capillary pores, CS has weaker effects to reduce WA. The above-mentioned positive impact of CS shows that CS can decrease the permeability of

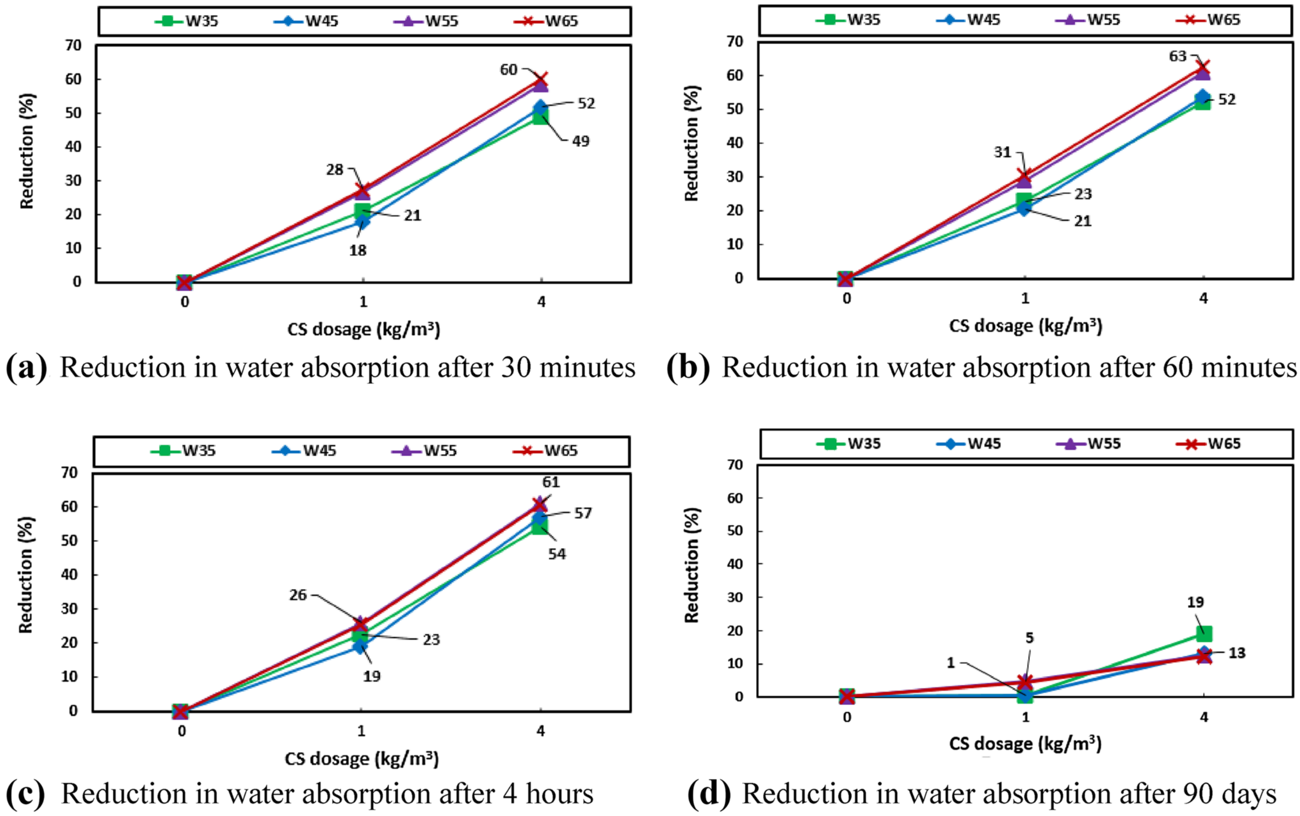


Fig. 7 Reduction in water absorption in comparison with the reference mixture

concrete in non-hydrostatic condition. Plus, the effects of CS are more pervasive in lower degrees of saturation.

When it comes to the effects of CS on TWA, Fig. 6e shows that CS is not effective to reduce TWA. Ineffectiveness of CS on TWA can show that CS cannot change the volume of capillary pores. This conclusion makes sense, because according to ACI 212.3R16 (2017) CS just forms a water-repellent layer along the capillary pores and do not generate calcium silicate hydrate or pore-blocking deposit.

As far as the effect of CS in various w/cm ratios is concerned, Fig. 7 shows that the effect of CS in various w/cm ratios is relatively the same. However, it seems that in higher w/cm ratios (0.65 and 0.55) CS was more effective to reduce WA after 30 min, 1 h, and 4 h of immersion in comparison with lower w/cm ratios (0.45 and 0.35). But, it must be mentioned that after 90 days of immersion in water, CS was relatively more effective in W35 group, particularly when 4 kg/m^3 of CS was added to the reference mixture in each group.

Figure 8 compares the rate of water absorption of the reference concrete with CS-incorporated concretes in different groups and after different periods of immersion. It is apparent that CS reduced the rate of WA. To be more precise, after 30 min, 1 h, and 4 h of immersion, the ratio of absorbed water-to-TWA of the reference mixtures is higher than the equivalent ratio of CS-incorporated mixtures in all groups. It can be clearly observed that after 90 days of immersion, the reference mixtures of all groups become saturated. While, the degree of saturation of the CS-incorporated concretes is below 1. This observation shows that the provision of the water-repellent layer along the pores effectively restricted water and moisture transfer through the capillary pores, and it postponed complete saturation of the pores.

The results of water absorption analysis in this study are relatively compatible with the results which were presented by Mariyoto (2017) because both research demonstrated a significant decrease in water absorption due to incorporation of CS. But when it comes to the quantity of reduction in WA, pervasive differences do exist between two studies. Mariyoto demonstrated that inclusion of merely 1 kg/m^3 of CS can reduce WA after 30 min of the specimens which were moist-cured for 28 days by 55% (in concretes which were prepared with w/cm of 0.45). However, this research showed that 1 kg/m^3 of CS can reduce water absorption after 30 min by merely 20% (in the same w/cm ratio and after 120 days of moist curing).

Other research also expressed the lower WA of CS-incorporated foam concretes and rendering mortars (Lanzón and García-Ruiz 2009; Ma and Chen 2016). But the results cannot be numerically compared with the results of this research due to significant differences in the characteristics of studied

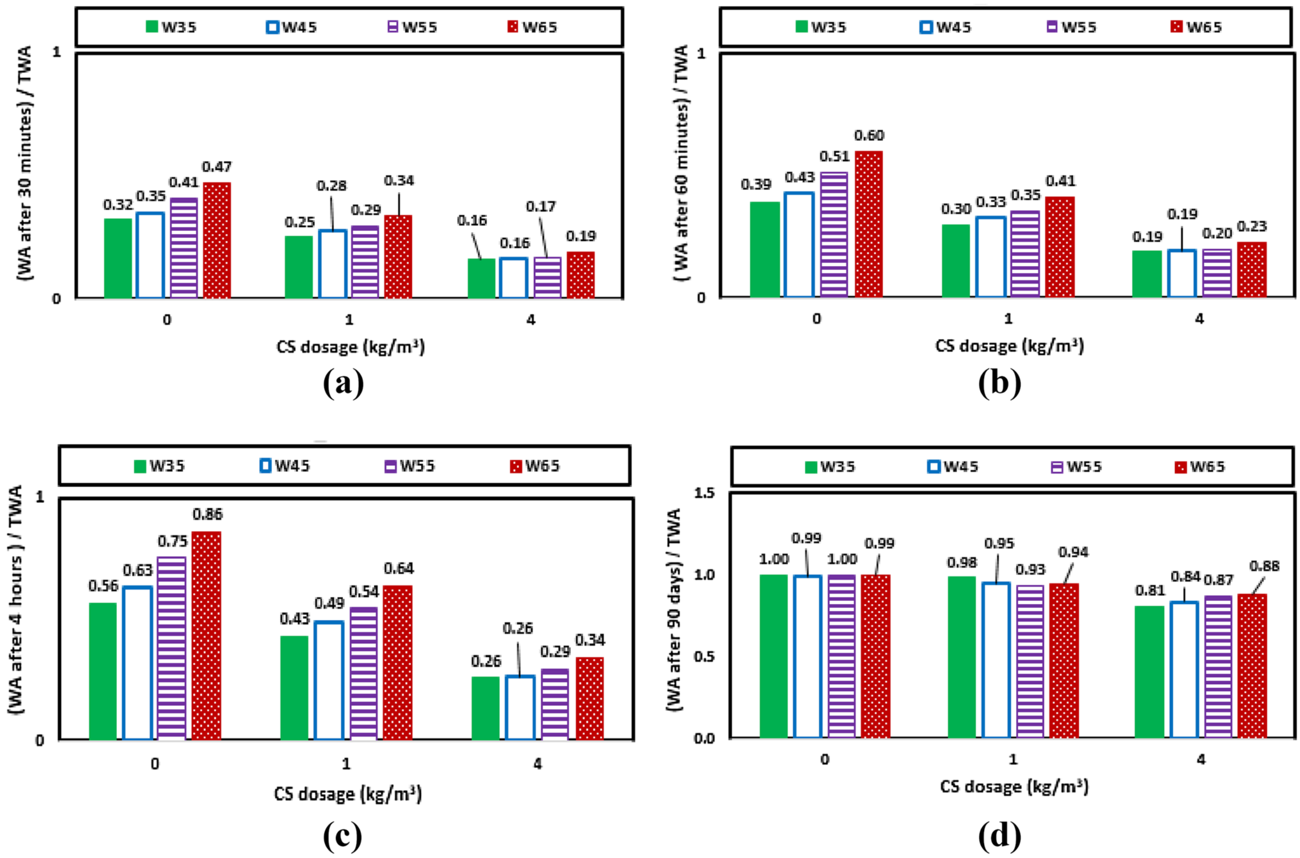


Fig. 8 The ratio of WA after different periods of immersion to TWA

material. As a result, it can be concluded that the effect of CS on mechanical and durability properties intensely depends on the mixture proportion because it can be observed that the effect of CS is different in various w/cm ratios.

Compressive strength

Figures 9 and 10 provide information about the impact of CS on compressive strength. Overall, incorporation of CS in the mixture design reduced compressive strength.

A direct relationship does exist between the incorporated dosages of CS with reduction in compressive strength. In fact, the higher dosages of CS are to blame for more strength reduction. It is also worth mentioning that the strength reduction is more noticeable in W45, W55 and W65 groups. By contrast, the reduction in compressive strength is relatively negligible in W35 group. This finding will be more discussed in the rest of the interpretation.

Although the analysis of the fresh concrete showed increase in air content of fresh concrete, this increase was not as significant to cause averagely 7% and 15% reduction in compressive strength after 28 and 180 days of moist curing. In other words, increase in air content can be considered the subordinate reason of reduction in compressive strength. Thus, the major cause of strength reduction is probably related to other properties of the hardened concrete. This issue will be discussed further in the microstructure analysis section.

The result of current research contradicts with the results which were reported by some other researchers who studied on damp-proofing admixtures. To illustrate, Mariyoto (2015) showed that incorporation of 4 kg/m^3 of CS in concretes which were prepared with w/cm of 0.42 and cement content of 480 kg/m^3 increased compressive strength by roughly 3%. According to his research, at least it can be said that CS has no detrimental impact on compressive strength. But, the results of current research show that CS reduces compressive strength and this reduction is quite pervasive in higher w/cm ratios. According to the results of CS on fresh concrete (increase in air content and reduction in density of fresh concrete), the findings of current research make more sense. However, the reason of strength loss in CS-incorporated concrete is still under debate and more actions need to be taken to shed light on the problem. Accordingly, the next section will be presented to study the microstructure of CS-incorporated concretes.

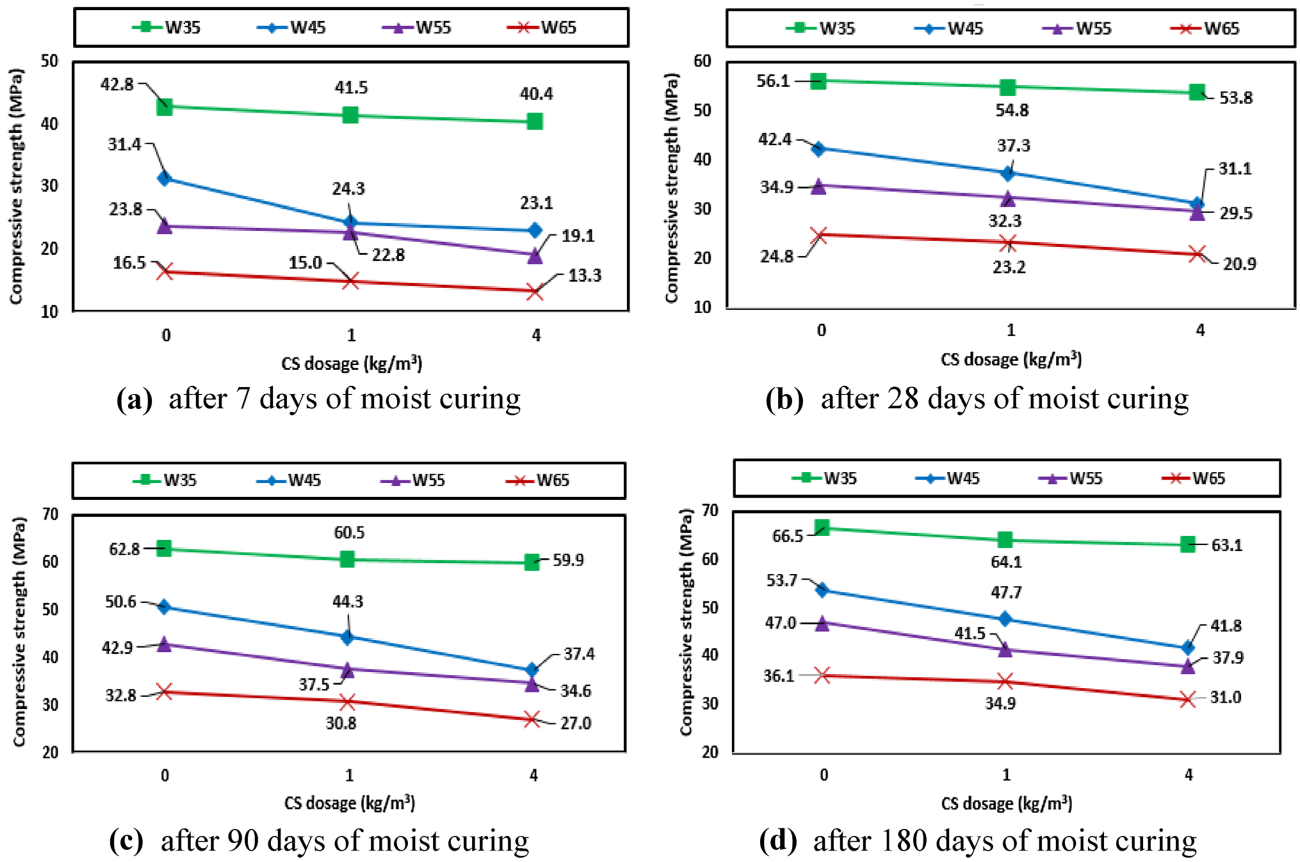


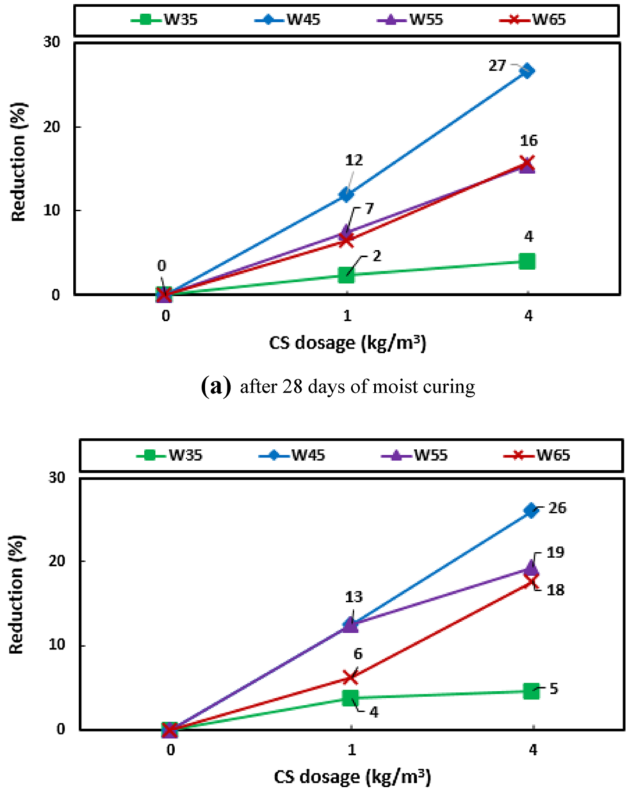
Fig. 9 Compressive strength

Microstructure analysis

Figure 11 compares the interfacial transient zone (ITZ) in W45-CS0 with the ITZ in W45-CS4. Overall, incorporation of CS had negative effect on microstructure. To be more precise, Fig. 11b shows that the cement paste in ITZ of the W45-CS0 seems to be more compact than the ITZ of W45-CS4 (see the cement paste). In fact, the presence of Ca(OH)2 is quite noticeable in the ITZ of W45-CS4. While, it seems that the more crystals of calcium silicate hydrate do exist in the ITZ of W45-CS0. It can be argued that presence of more $Ca(OH)_2$ in W45-CS4 can verify the lower density of W45-CS4 in comparison with W45-CS0. Therefore, it seems that the bonding between the aggregate and the cement paste is weaker in the W45-CS4 compared to W45-CS0.

The findings of SEM analysis are compatible with the findings of permeability analysis. In fact, electrical resistivity and WPD tests showed that CS did not increase electrical resistivity and did not significantly reduce WPD. Therefore, it had not any positive effect on density of the cement. SEM analysis also verified the fact that CS did not improve the structure of the capillary pores. By contrast, the adverse effect of CS on ITZ is obvious.

In addition to the above-mentioned points, the findings of SEM analysis are also compatible with the results of compressive strength test and density analysis. To be more precise, density analysis showed that CS-incorporated concretes had slightly lower density in comparison with the reference mixture in each group. Lower density of the cement paste in CS-incorporated mixture was apparent (zone a) in microstructure of the W45-CS4 compared with the reference mixture. Additionally, compressive strength analysis showed that reduction in density is not the only factor which is playing a role in strength loss. SEM analysis showed that the bonding between aggregate and the cement paste seemed to be weaker in CS-incorporated concrete. The low level of adhesion between the aggregate and the paste can be considered another reason for strength loss when CS is included in the mixture design.



(a) after 28 days of moist curing

(b) after 180 days of moist curing

Fig. 10 Reduction in compressive strength in comparison with the reference mixture in each group

Conclusions

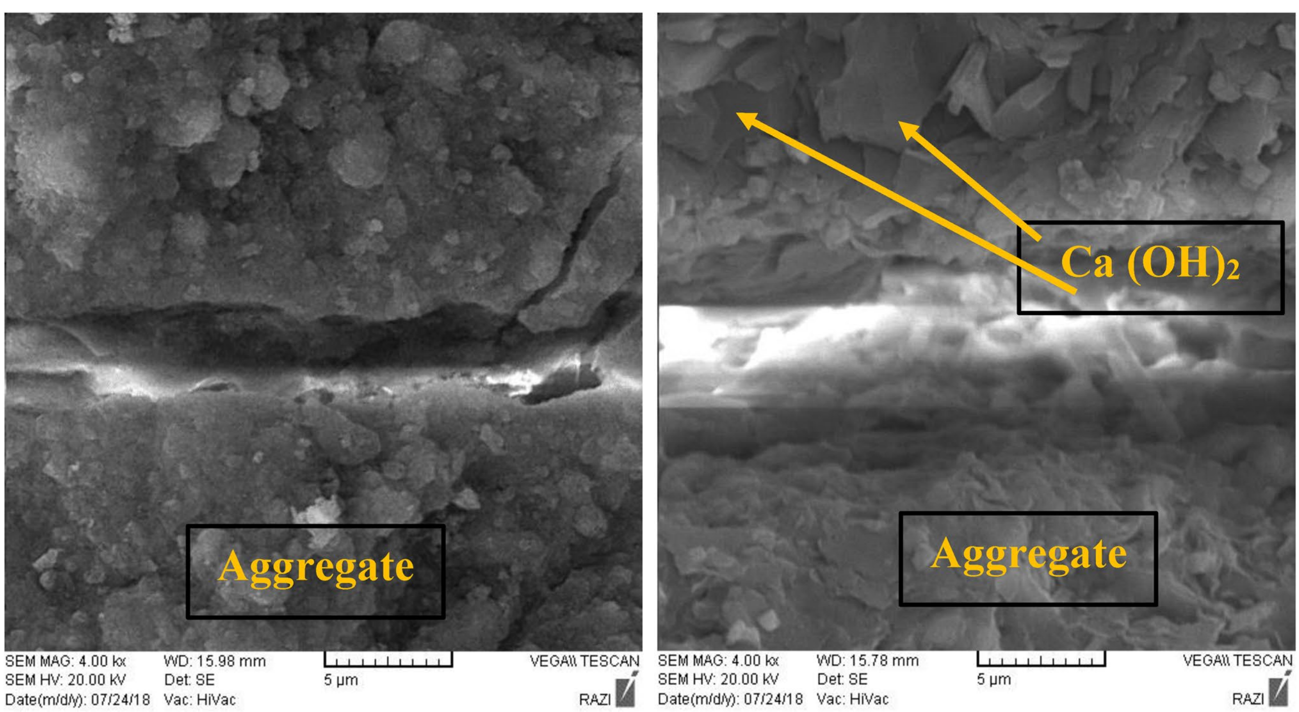
In this research the effects of CS on properties of fresh and hardened concretes prepared in different water to cementitious materials, ranging from 0.35 to 0.65, were investigated. It must be noted that to carry out this experimental research 12 mixtures in constant ratio of aggregate-to-cement paste were prepared. The major findings of this research can be listed as following:

Incorporation of calcium stearate (CS) reduces workability of concrete, regardless of water-to-cementitious materials (w/cm) ratio. However, this reduction is more significant in lower w/cm ratios such as w/cm of 0.35 and 0.45.

Incorporation of CS increases the air content and reduces the density of fresh concrete in low w/cm ratios (0.35 and 0.45). But, it had no influence on air content and density of fresh concrete in higher w/cm ratios (0.55 and 0.65).

CS can reduce 30-min, 1-h, and 4-h water absorption. There is also a direct link between the dosage of CS and reduction in water absorption. To be more precise, 4 kg/m^3 of CS can reduce water absorption after 30 min, 1 h, and 4 h of immersion by at least 50%. However, CS cannot reduce total water absorption (TWA) in concretes which were prepared in different w/cm ratios.

CS does not have considerable effect on electrical resistivity and water penetration depth of concretes which were prepared in different w/cm ratios.



(a) ITZ of W45-CS0

(b) ITZ of W45-CS4

Fig. 11 Scanning electron microscopy of ITZ

CS reduces compressive strength, regardless of the incorporated dosage and w/cm. It also must be taken into account that the higher dosage of CS can cause more significant reduction in compressive strength.

CS had adverse effect on microstructure of concrete. Since the interfacial transient zone (ITZ) in CS-incorporated mixture seems to be less compact than the ITZ in the reference mixture.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest

References

ACI 212.3R-10. (2017). Report on Chemical Admixtures for Concrete, Chapter 15: Permeability reducing admixtures. Reported by ACI committee 212.

Ahmadi, B., & Shekarchi, M. (2010). Cement & Concrete Composites Use of natural zeolite a supplementary cementitious material. *Journal of Cement and Concrete Composite., 32*(2), 134–141.

ASTM C1723-16. Standard Guide for Examination of Hardened Concrete Using Scanning Electron Microscopy.

ASTM C231/C2131 M-17a. Standard Test Method for Air Content of Freshly Mixed Concrete by Pressure Method.

BS-EN 12350-6 (2009). Testing fresh concrete- Part6: Density.

BS-EN 12390-3 (2009). Testing hardened concrete- Part3: Compressive strength of test specimens.

BS-EN 12390-8 (2009). Testing Hardened Concrete. Depth of Penetration of Water Under Pressure.

BS-EN 1881-122 (2011). Testing concrete- Part 122: Method for determination of water absorption.

Corinaldesi, V. (2012). Combined effect of expansive, shrinkage reducing and hydrophobic admixtures for durable self compacting concrete. *Journal of Construction and Building Materials., 36,* 758–764.

Falchi, L., Müller, P., Fontana, F., Izzo, C., & Zendri, E. (2013). Influence and effectiveness of water-repellent admixtures on pozzolana-lime mortars for restoration application. *Journal of Construction and Building Materials., 49,* 272–280.

Falchi, L., Zendri, E., Müller, U., & Fontana, P. (2015). The influence of water-repellent admixtures on the behaviour and the effectiveness of Portland limestone cement mortars. *Journal of Cement and Concrete Composite, 59,* 107–118.

Hajforoush, M., Madandoust, R., & Kazemi, M. (2019). Effect of simulataneous utilization of natural zeolite and magnetic water on engineering properties of self-compacting concrete. *Asian Journal of Civil Engineering., 20,* 289–300.

Izaguirre, A., Lanas, J., & Alvarez, J. (2011). Effect of water-repellent admixtures on the behaviour of aerial lime-based mortars. *Journal of Construction and Building Materials., 25*(2), 992–1000.

Lagazzo, A., Vicini, S., Cattaneo, C., & Botter, R. (2016). Effect of fatty acid soap on microstructure of lime-cement mortar. *Journal of Construction and Building Materials., 116,* 384–390.

Lanzón, M., & García-Ruiz, P. A. (2008). Effectiveness and durability evaluation of rendering mortars made with metallic soaps and powdered silicone. *Journal of Construction and Building Materials., 22*(12), 2308–2315.

Lanzón, M., & García-Ruiz, P. A. (2009). Evaluation of capillary water absorption in rendering mortars made with powdered waterproofing additives. *Journal of Construction and Building Materials., 23*(10), 3287–3291.

Lanzón, M., Martínez, E., Mestre, M., & Madrid, J. A. (2017). Use of zinc stearate to produce highly-hydrophobic adobe materials with extended durability to water and acid-rain. *Journal of Construction and Building Materials., 139,* 114–122.

Ma, C., & Chen, B. (2016). Properties of foamed concrete containing water repellents. *Journal of Construction and Building Materials., 123,* 106–114.

Maryoto, A. (2015). Improving microstructures of concrete using Ca(C18H35O2)2. *Journal of Procedia Engineering, 125,* 631–637.

Maryoto, A. (2017). “Resistance of concrete with calcium stearate due to chloride attack tested by accelerated corrosion. *Journal of Procedia Engineering., 171,* 511–516.

Nemati Chari, M., Shekarchi, M., Ghods, P., & Moradian, M. (2016a). A simple practical method for determination of moisture transfer coefficient of mature concrete using a combined experimental-numerical approach. *Journal of Computers and Concrete., 18*(3), 367–388.

Nemati Chari, M., Shekarchi, M., Sobhani, J., & Nemati Chari, M. (2016b). The effect of temperature on the moisture transfer coefficient of cement-based mortars: An experimental investigation. *Journal of Construction and Building Materials., 102,* 306–317.

Nemati Chari, M., Shekarchi, M., Tadayon, H., & Moradian, M. (2018). Prediction of chloride ingress into blended cement concrete: Evaluation of a combined short-term laboratory-numerical procedure. *Journal of Construction and Building Materials., 162,* 649–662.

Sabet, F., Libre, N., & Shekarchi, M. (2013). Mechanical and durability properties of self consolidating high performance concrete incorporating natural zeolite, silica fume and fly ash. *Journal of Construction and Building Materials, 44,* 175–184.

Saleh Ahari, R., Erdem, T. K., & Ramyar, K. (2015). Permeability properties of self-consolidating concrete containing various supplementary cementitious materials. *Journal of Construction and Building Materials., 79,* 326–336.

Tittarelli, F. (2009). Oxygen diffusion through hydrophobic cement-based materials. *Journal of Cement and Conrete Research., 39*(10), 924–928.

Tittarelli, F., Carsana, M., & Ruello, M. L. (2014). Effect of hydrophobic admixture and recycled aggregate on physical-mechanical properties and durability aspects of no-fines concrete. *Journal of Construction and Building Materials., 66,* 30–37.

Tittarelli, F., & Moriconi, G. (2010). The effect of silane-based hydrophobic admixture on corrosion of galvanized reinforcing steel in concrete. *Journal of Cement and Conrete Research., 52*(9), 2958–2963.

Tittarelli, F., & Moriconi, G. (2011). Comparison between surface and bulk hydrophobic treatment against corrosion of galvanized reinforcing steel in concrete. *Journal of Cement and Conrete Research., 41*(6), 609–614.

Vejmelková, E., Koňáková, E., Čáchová, M., Keppert, M., & Černý, R. (2012). Effect of hydrophobization on the properties of lime-metakaolin plasters. *Journal of Construction and Building Materials., 37,* 556–561.

Vishvanath, N., Kanthe, Shirish V., & Deo, Meena Murmu. (2018). Effect of fly ash and rice husk ash on strenght and durability of binary and ternary blend cement mortar. *Asian Journal of Civil Engineering., 19,* 963–970.

Wong, H. S., Barakat, R., Alhilali, A., Saleh, M., & Cheeseman, C. R. (2015). Hydrophobic concrete using waste paper sludge ash. *Journal of Cement and Concrete Research, 70,* 9–20.

AASHTO T358-17. Standard Method of Test for Surface Resistivity indicating Concrete's Ability to Resist Chloride Ion Penetration. Standard by American Association of State and Highway Transport Officials.

ASTM C143/C143 M-15a. Standard Test Method for Slump of Hydraulic-Cement Concrete.

ASTM C33/C33 M-16. Standard Specification for Concrete Aggregates. American Society for Testing and Materials.

Zhu, Y. G., Kou, S. C., Poon, C. S., Dai, J. G., & Li, Q. Y. (2013). Influence of silane-based water repellent on the durability properties of recycled aggregate concrete. *Journal of Cement and Concrete Composite., 35*(1), 32–38.