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Research Article

Effects of accelerator type and dosage on the mechanical and durability properties of rapid-setting precast concrete

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ABSTRACT

Precast concrete construction is frequently preferred all over the world because of its rapid production and low cost. Prefabricated structures are constructed by assembling, the structural elements that were produced in the factory, at the construction site. However, some connection types such as wet connection used in prefabricated buildings eliminate the rapid installation feature. The wet connections are the method of assembling with fresh concrete. In the wet connections, the setting time of concrete decreases the installation rapid of prefabricated structures. In the past years, various additives have been used to accelerate the setting time. However, these additives consisting of organic salts cause corrosion in the reinforcement. In recent years, the use of inorganic salts with low ions activity as the accelerator has become widespread. Rapid-setting concrete is suitable for producing precast concrete. This paper deals with the determination of optimal accelerator type and dosage for precast concrete. Sodium aluminate and Polycarboxylic ether-based chemicals were utilized as the accelerator to obtain rapid-setting concrete mixtures. Mechanical and durability tests were performed to analyze each chemical effect on the fresh and hardened properties of the concrete mixes. Polycarboxylic ether-based chemical is observed as a potential accelerator for precast concrete, especially for the connection concrete parts. With polycarboxylic ether-based chemicals, it is observed that rapid strength gain is achieved without much loss of final strength. Besides, polycarboxylic ether-based chemicals increase the workability of mixtures. However, it is observed that the workability feature is lost in a short time due to the rapid-setting feature.

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INTRODUCTION

Concrete is one of the most significant materials in terms of the volume and widespread areas of use[1,2]. Precast concrete construction is frequently preferred all over the world due to its fast production and low cost. [3–5]. It is possible to produce high-quality structures with prefabricated production at a low cost and in the shortest time [3,6]. Precast concrete structure creates a new production process which consist of 2 phases. The first phase, which is called production, is carried at in the factory The second phase called installation is performed at the construction site [7]. The design of the connections is crucial due to the individual production of precast elements [6]. There are two types of connection, wet and dry. Wet connections seem to provide integrity in terms of earthquake behavior [8,9]. However, strength gaining time of concrete in wet connections eliminate the rapid construction feature of prefabricated structures [6]. Dry connections such as welds [10–12], bolted connections [13–15] and dowel connections [16,17] might be more suitable for prefabricated structure and contribute to its spread. It is substantial that the type of connection to be used in the structure increases the speed of construction. Due to increased demand for prefabricated structures, manufacturers are required to increase daily level of production. In order to achieve this, the concrete to be used in the connection should gain early strength [18].

The processes to be carried out for the concrete to develop early strength should not reduce the hardened and fresh properties of the concrete. Properties such as consistency, flowability, finishability [19] should be maintained during early strength gain. Particularly workability of connection concrete contributes to the full filling of the concrete on the connection area and to provide full adherence between surfaces. The workability feature can be affected by the mixture and placing method [20]. Hardened concrete properties of connection concrete are significant throughout its service life. Hardened concrete has disadvantages such as brittleness, low tensile strength, low flexural strength [21]. Fiber additives [21–24] can be used to improve such disadvantages of concrete.

Some chemicals are used as accelerators for the concrete to gain early strength. The accelerators are divided into two groups, namely setting and hardening accelerators [25]. The accelerating effects of inorganic salts have been reported until now [26]. Anions and cations in organic salts have an accelerating effect on C3S hydration [25]. Therefore, many researchers have reported it as an important accelerator of the CaC_l2 salt [27,28]. However, corrosion occurs in the reinforcement inside the concrete due to chloride ions [29,30]. Therefore, it has become widespread to use inorganic salts containing ions with lower activity such as $Ca(NO_2)2$, $Ca(NO_3)2$, $NaNO_2$, and $NaNO_3$ as accelerators in recent years [31,32]. However, as a result of the interaction of the accelerators used with other admixtures, acceleration or deceleration may be observed in the setting-time [33]. Therefore, it is extremely important to investigate the use of accelerators together with other chemicals [25].

There are many studies investigating early strength gain of concrete. Yang et. al. [26] examined the effects of calcium silicate and marble wastes on gaining early strength. Das et. al. [18] investigated the effects of previously prepared nano CSH crystals on initial strength. Li and Jiang [34] investigated the contribution of limestone powder to early strength on slag concrete. Lee et al. investigated the optimum value of admixtures and accelerators for the early development of concrete strength. They examined the factors such as cement amount per unit, type of admixtures, and accelerator that affect the strength of concrete [25]. Lin et al. found that polycarboxylate-based accelerators can increase the fluidity of cement pastes as a result of the increase in the molecular weight of the cross-linkers [35]. Lin et al. investigated the effects of polycarboxylate-based super plasticizers produced with different cross-linking agents on dispersion performance and mechanical properties and the microstructure of cement paste [36]. Dalas et al. determined the chemical structure factors affecting the adsorption properties of polycarboxylate ether-based admixtures to increase the competitive sulfate adsorption and to minimize the using dosage. They reported that changing the anionic function is a good way to increase resistance to competitive sulfate adsorption. In this regard, the best results have been obtained with carboxylate polymers [37]. Altun et al. investigated the effect of side chain length, molecular weight hangers and adsorption amounts of polycarboxylate ether based high range admixtures with fixed main chain length, free nonionic amount and anionic / nonionic ratio on fresh and hardened concrete properties. The increase in the side chain length of the additives had a positive effect on the time-dependent fresh state performance of the concrete mixtures [38].

RESEARCH SIGNIFANCE

There are very limited number of studies on the concrete connection parts for the prefabricated concrete sector. Studies investigating chemical additives are very rare. In this study, concrete mixes were prepared with different accelerators. Fresh and early strength gaining properties of the concrete mixes were examined. The effects of chemical accelerators on fresh and hardened concrete properties were also investigated. Since the concrete mixture is used in prefabricated wet connections and open to environmental attack, durability tests were also conducted on examining sulfate resistance and freezing and thawing properties.

MATERIAL AND METHODS

Materials

In this study, standard CEM II 42.5 portland cement was used. The density of cement is 3.2 g/cm3. The chemical composition of cement is given in Table 1.

Silica sand was used in the mixtures. The density of silica sand is 2.54 g/cm3. SiO_2 ratio is 92.5%. The chemical composition of silica sand is given in Table 2. The particle size distribution of silica sand is given in Figure 1.

The used hyper plasticizer is polycarboxylic ether-based. It was used 0.5% of the cement weight. It was used to obtain workability on concrete. The technical properties of the hyper plasticizer are given in Table 3. The hyper plasticizer was used as 0.5% of the cement weight in all mixtures.

Two different types of accelerators were used. Technical properties of the accelerators are given in Table 4. Type 1 and type 2 are sodium aluminate-based, polycarboxylic ether-based accelerators, respectively. The accelerators were added to the mixtures in proportion to the cement weight. It was added to the mixtures at varying rates between 0.5% and 1.25%.

Table 1. Chemical composition of cement

Chemical composition	(%)
CaO	54-62
Al_2O_3	3.5-5.7
SO3	2.2-3.5
Cl	0-0.17
MgO	0.8-2.3
Na_2O	0.2-0.7
SiO_2	20-26
Fe_2O3	2.1-3.7
K_2O	0.2-0.8

Table 2. Chemical composition of silica sand

Chemical composition	(%)
SiO_2	92.5
TiO_2	0.087
CaO	2.16
Al_2O3	1.63
SO_3	0.0228
Cr_2O3	0.178
MgO	0.145
ZnO_2	0.0176
BaO	0.00548
Fe_2O3	1.65
K_2O	0.348
Na_2O	0.027

Method

9 different types of concrete mixtures were prepared according to the accelerators. The contents of the concrete mixtures were given in Table 5. The W / C ratio was taken as constant for all mixtures. 9 different mixtures were obtained with the change in accelerator ratios.

Flow table test is conducted with TS-EN 12350-5 [39]. Cement paste was placed in the mold in two layers. Each layer is compacted with the help of a steel bar. Then the spreading diameter was measured by dropping the table 15 times [39]. Figure 2 shows the flow table test of the S5 sample.

Three samples were taken from each mixture for 6 hours, 7 hours, 8 hours, 1 day, 7 days, and 28 days tests. 150x150x150 mm sized molds are used for samples according to TS-EN 12390-1 [40]. The mixture is placed in two layers with help of a steel bar. The test samples were taken into the curing pools at 20 °C after 16 hours in the mold [41]. The samples were tested with a loading speed of 0.6 N/mm2 per second [42]. The compressive strength tests were performed with a standard compression test machine. It has a maximum loading capacity of 3000 kN. The upper and lower compression plate are 300x300 mm. The distance between the upper and lower plate is 320 mm. The compression test machine is exhibited in Figure 3.

The samples were compromised to freezing at - 20 °C. Then, they were put back to normal curing (20 °C)

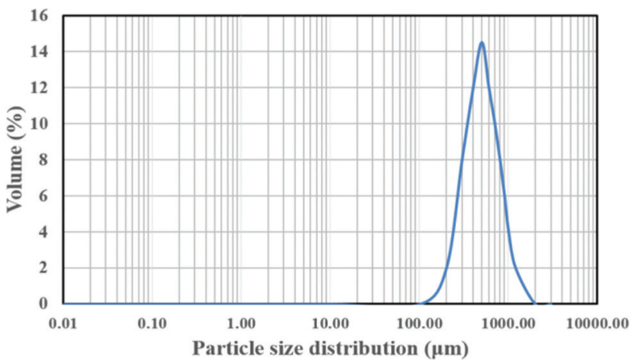


Figure 1. The particle size distribution of silica sand.

Table 3. Technical properties of hyper plasticizer

Technical properties of hyper plasticizer	Value
Colour	Milky brown
Boiling point	95-105 °C
Thermal decomposition	> 720 °C
Density	1.25 g/cm_3
pH value	9.2-12.0
Water solubility	Water-soluble

Table 4. Technical properties of the accelerator

Technical properties of the accelerator	Type 1	Type 2
Material structure	Sodium aluminate based	Polycarboxylic ether-based
Colour	White	Light Brown
Density	1.2±0.05 kg/cubic meter m3	1.13±0.05 kg/liter
Melting point	> 380 °C	-
Burning point	-	-
pH value	6.5-7.5	-
Chlorine content % (EN 480-10)	-	<0.1
Alkali content % (EN 480-10)	-	<3

Table 5. The contents of the concrete mixtures (per 0.6 cubic meter m3)

Sample	Water (kg)	Cement (kg)	Silica sand (kg)	Hyper plasticizer (kg)	Accelerator (kg)	
					Type 1	Type 2
S1	155	480	500	2.4	-	-
S2	155	480	500	2.4	2.4	-
S3	155	480	500	2.4	3.6	-
S4	155	480	500	2.4	4.8	-
S5	155	480	500	2.4	6.0	-
S6	155	480	500	2.4	-	2.4
S7	155	480	500	2.4	-	3.6
S8	155	480	500	2.4	-	4.8
S9	155	480	500	2.4	-	6.0

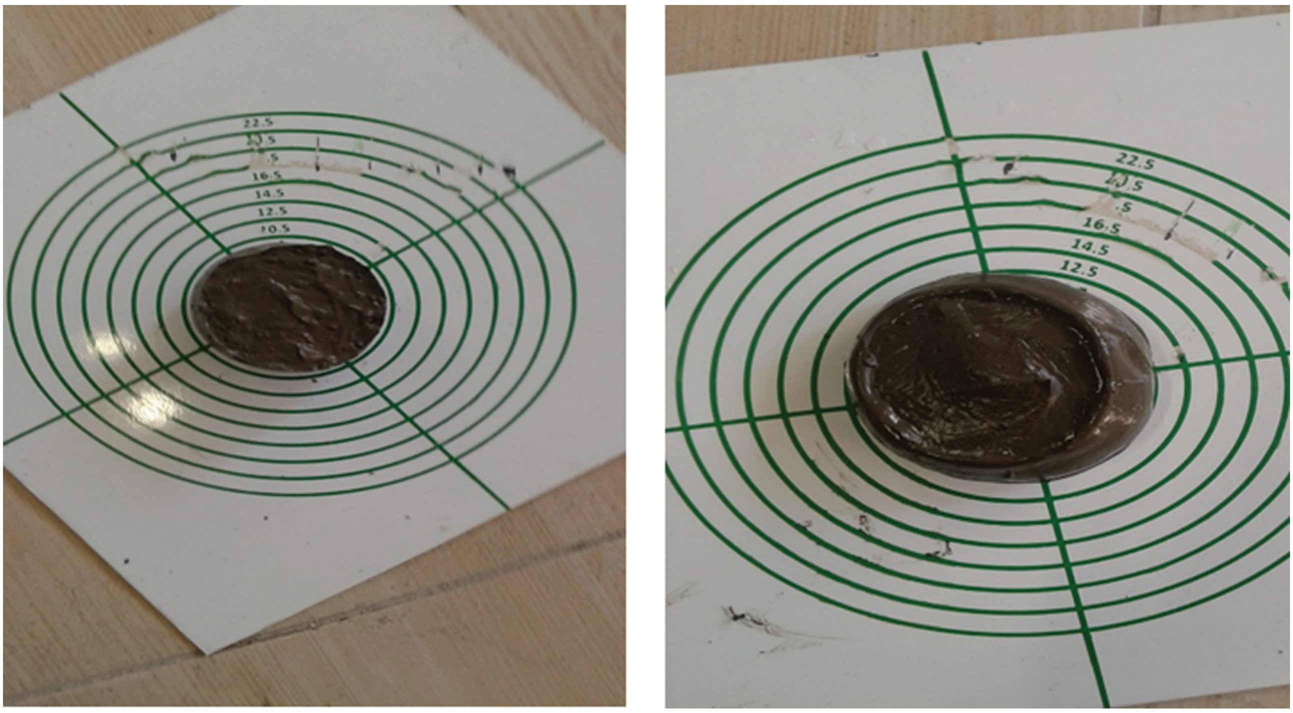


Figure 2. Flow table test.

conditions. This cycle was repeated 100 times. Then a compressive test of the samples was conducted [43].

Industrial structures can be exposed to wastes such as acid, chloride, and sulfate according to their working conditions. These wastes can damage fresh and hardened concrete. [44,45]. For this reason, a sulfate test was conducted for the samples. Samples were left in a solution containing 10% $MgSO_4$ for 28, 90, and 180 days. Then compressive tests of the samples was determined.

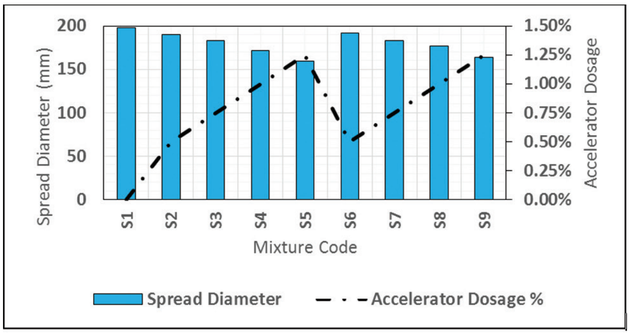
RESULTS AND DISCUSSION

The spreading diameters for 6, 7, and 8 hours of the samples according to the accelerator dosage are given in Figure 4. Polycarboxylic ether-based chemical showed better performance compared to the sodium aluminate-based accelerator. As seen in Figure 3, increasing the amount of the accelerator decreases the spreading diameter. As the test time increases, the reduction in the spreading diameter continues. The mixture loses its plasticity as the setting continues as the test time increases. The best results for type 1 and type 2 accelerators were obtained with S2 and S6, respectively. Better results were obtained with the polycarboxylic ether-based accelerator with a difference of about 1.1%. The increase in the amount of accelerator accelerates the formation of C-S-H gel and ettringite, which is a hydration product. Therefore, the plasticity of the mixture decreases rapidly. The increase in the amount of accelerator decreases the nucleation in hydration products. Therefore, the hydration rate of cement increases [26]. These results are consistent with the literature studies [46].

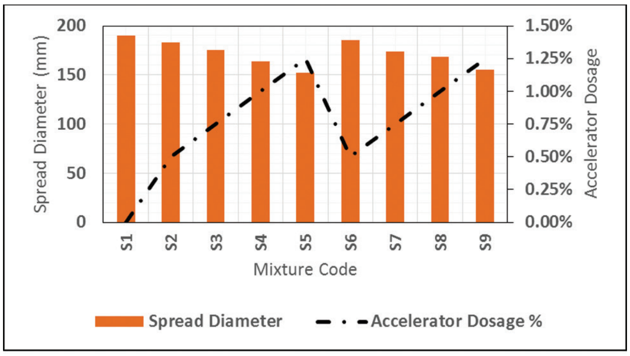
6 hours, 7 hours, 8 hours, 7 days, and 28 days compressive strength test results and standard deviations for 9 different concrete mixtures are given in Table 6. The results of the 3 samples prepared for each test were similar. With polycarboxylic ether-based accelerators, more compressive strength was obtained than sodium aluminate-based accelerators. As seen in Figure 5, an increase in the amount of type 1 and type 2 accelerators increased the early compressive strength development. 1-day compressive strength test results of the mixture without accelerator (S1) were almost reached with the S9 containing 1.25% accelerator. However, when the 28 days compressive strength test results are examined, the S9 decreases its compressive strength by 5% compared to the reference sample. In the S5, the 28 days compressive strength decreased 6.4% compared to the reference sample. Type 1 and type 2 accelerators caused an increase in 28 days compressive strength up to 1% dosage. Therefore, the S8's 28 days compressive strength was 3.03% lower than the

Figure 3. The compressive strength test.

reference sample. In other words, the sample containing 1% polycarboxylic ether-based accelerator showed early strength development without losing much of the final compressive strength. Increasing the dosage of the accelerator increases the formation of C-S-H gel and ettringite, thus increasing the early compressive strength [47]. While accelerators accelerate C-S-H gel formation, they cause a decrease in the amount of C-S-H gel to be formed in the final state. The decrease in the amount of C-S-H gel in the final situation causes a decrease in the final compressive strength. These results are consistent with the literature studies [48].



(a)



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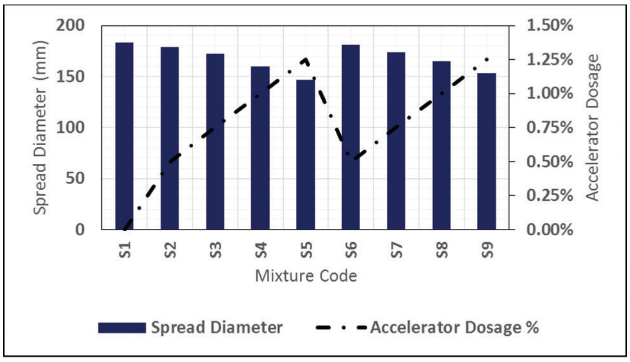

(c)

Figure 4. Spread diameters; (a) 6 hours, (b) 7 hours and (c) 8 hours.

Table 6. The compressive strength test results

Samples										
Compressive Strength		**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
6 Hours	Avg. (MPa)	-	3.88	3.76	3.92	3.97	3.92	3.95	4.01	4.05
	Standard Deviation	-	0.219	0.313	0.335	0.127	0.257	0.305	0.185	0.0877
7 Hours	Avg. (MPa)	-	3.97	3.81	4.03	4.09	4.02	4.04	4.13	4.17
	Standard Deviation	-	0.208	0.142	0.293	0.106	0.179	0.251	0.425	0.215
8 Hours	Avg. (MPa)	-	4.19	4.28	4.36	4.42	4.23	4.35	4.52	4.57
	Standard Deviation	-	0.362	0.319	0.341	0.326	0.229	0.349	0.133	0.351
1 Day	Avg. (MPa)	4.65	-	-	-	-	-	-	-	-
	Standard Deviation	0.183	-	-	-	-	-	-	-	-
7 Days	Avg. (MPa)	33.71	30.45	31.06	32.40	31.65	30.68	31.37	32.66	32.04
	Standard Deviation	0.973	1.364	1.253	0.817	1.191	1.131	1.624	0.991	1.179
28 Days	Avg. (MPa)	45.43	40.88	41.77	43.68	42.53	41.34	42.25	44.05	43.16
	Standard Deviation	2.367	1.973	2.162	2.350	1.593	1.554	1.921	1.052	1.586

The compressive strength losses obtained after 100 cycles for the freeze and thaw resistance test are given in Figure 6. Freeze-thaw damage of concrete is a form of physical corrosion damage. The voids in the concrete are exposed to water and filled with the water. The freezing of the water in the voids causes additional stresses due to the increase in the volume of water. When the temperature rises, the ice can melt into water, and the additional stresses in the voids are relieved [49]. As a result of the continuous freeze-thaw cycle, significant damage may occur in concrete. Therefore, the reduction of the voids in the concrete reduces the freeze-thaw damage. As seen in Figure 6, for type 1 and type 2 accelerators, the loss of compressive strength decreased in freeze-thaw tests up to 1% dosage, while it had a negative effect on 1% dosage. The accelerators reduced the freeze-thaw damage by reducing the voids in the concrete. The best results were obtained from the s8 sample. S8 sample lost 7.31% strength compared to the reference sample. The results obtained are coherent with the studies in the literature [50].

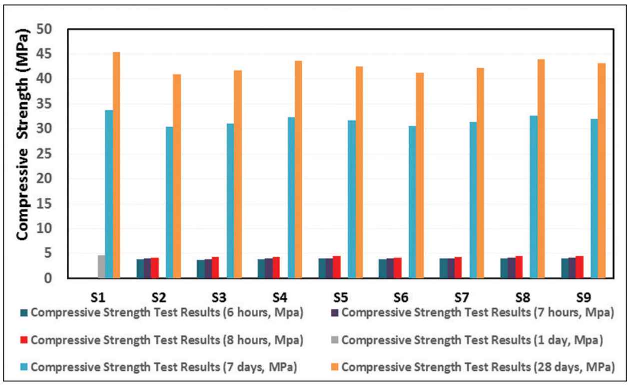

Figure 5. Compressive strength test results.

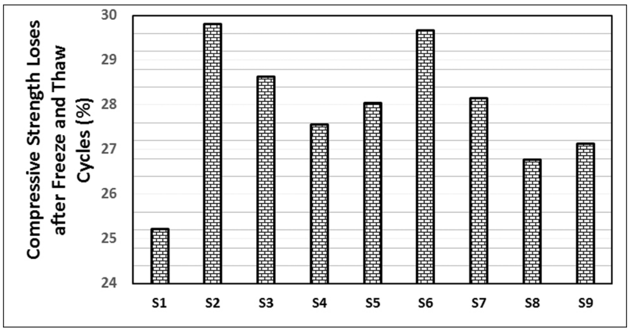

Figure 6. Freeze and thaw resistance test results.

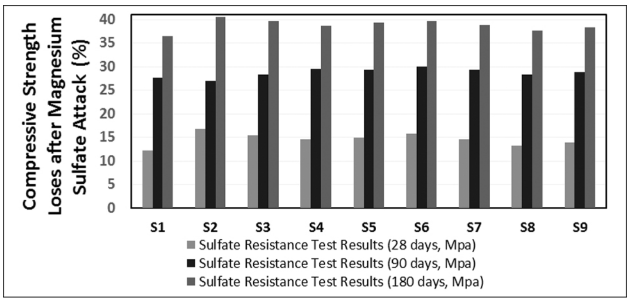

Figure 7. Sulfate resistance test results.

The sulfate attack is a complex degradation mechanism in concrete that consists of physical and chemical processes such as ion diffusion and expansion damage [51]. The sulfate ions entering the concrete from outside reduces the formation of C-S-H gel and cause the formation of expansive products [52]. Microcracks occur as a result of filling the enlarged pores of products such as ettringite [53]. The decrease in the amount of C-S-H gel and the micro-cracks that occur reduce the compressive strength of the concrete [54]. Compressive strength losses of the samples exposed to a solution containing 10% $MgSO_4$ for 28, 90, and 180 days are given in Figure 7. Loss of strength occurred in samples exposed to magnesium sulfate [55]. It has been observed that type 1 and type 2 accelerators reduce the loss in compressive strength up to 1% dosage. This is because the pores in the concrete are reduced due to the accelerator dosage. S8 sample lost 1.55% strength compared to reference sample for 180 days magnesium sulfate attack. The results obtained are consistent with the studies in the literature [56].

CONCLUSIONS

In this study, two different types of accelerator's effect on the mechanical and durability properties of silica sand added cementitious concrete was investigated. According to the laboratory study results, the following results can be concluded:

- Polycarboxylic ether-based accelerator performed better results compared to the sodium aluminate-based chemicals in terms of mechanical and durability properties for precast concrete mixtures.
- In the samples prepared with the accelerator, early strength development was obtained without much loss of final strength.
- The increase in the amount of accelerator up to 1% caused a decrease in the spread diameter. Hence, the increase in the amount of accelerator above 1% caused increase in the spread diameter compared to 1% dosage. Therefore, the use of accelerators is not suitable for concretes requiring plasticity.
- The use of accelerators reduces the amount of voids in the concrete. Therefore, it contributes to the freeze-thaw resistance of concrete. Freeze and thaw resistance of composites decreases compared to the reference's mixtures; however, differences are within the acceptable limits for precast concrete.

- The reduction of voids in the concrete reduces the damage of industrial acids exposed to the concrete.
- The amount of accelerator above 1% affects the mechanical and durability of the concrete negatively.
- Compressive strengths decrease as the early ettringite formation due to utilization of accelerators.
- In the precast industry, it is appropriate to use a polycarboxylic ether-based accelerator to ensure rapid assembly in wet connection.
- Early compressive strength development of concrete prepared with the accelerator in wet connection will reduce the destructive effect of dynamic loads that prefabricated structures will be exposed to during assembly.
- The combination of accelerators and hyper plasticizers can be subject to various optimization methods.
- Combined effects of accelerators and hyper plasticizers were analyzed. This can be a base of detailed and future studies.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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