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Research Article

Effect of Permeability-Reducing Admixtures on Concrete Properties at Different Cement Dosages

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Abstract

Concrete is the most common building material used worldwide. Significantly high strength values have been achieved owing to developing material technology. Besides compressive strength, durability properties should also be taken into consideration since concrete is exposed to several external effects throughout its service life. Durability properties are mainly associated with the voids in the internal structure and surface of the concrete. Even if not exposed to any external effects, concrete contains several pores and micro-cracks. These pores and cracks enlarge with the influence of external effects, and new cracks are developed. Therefore, various methods are used to prevent the permeability of harmful liquids and gases into concrete structures. This study used permeability-reducing admixtures (PRAs) and polycarboxylate-based superplasticizers of various cement dosages to produce concrete mixtures. The main purpose is to examine the interaction of these admixtures with the cement dosage. Workability, compressive strength, and depth of water penetration under pressure tests were conducted to observe the effect of PRA on these parameters. The admixture crystallized in the internal structure of the concrete and created a fuller volume. While the compressive strength increased as a result of the crystallized product, the depth of water penetration decreased. Slump tests revealed that the admixture was compatible with all cement dosages, and it did not significantly affect the workability properties of the concrete. Expectedly, the compressive strength increased as the cement dosage increased, while the positive effect of the PRA gradually decreased. The PRA admixture also contributed to the decrease in the depth of water penetration, but its impact decreased as the cement dosage increased. It was concluded based on present findings that the PRA admixture, which is the most effective at the lowest cement dosage, increased the compressive strength values by 9.44% at this dosage and decreased the depth of water penetration under pressure by 26.09%.

Keywords: Permeability-reducing admixture, Cement dosage, Depth of water penetration, PRA.

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1. Introduction

Concrete has high compressive strength and mechanical properties owing to developing material technology and new construction methods. However, preserving such properties is a highly complex process since concrete is exposed to several external effects throughout its service life. Concrete is a semi-brittle material that includes many gaps and cracks in its microstructure, especially between the cement matrix and aggregates, even if there is no external effect [1]. Gases, liquids, and ions leak into the concrete structure from existing cracks and voids, and they negatively affect the durability of concrete. Although the compressive strength and durability properties of concrete are generally positively correlated with each other, the durability properties should also be improved since the material is constantly exposed to external influences [2,3]. Permeability properties are of great importance for concrete to be resistant to external influences. Harmful chemicals pass through the cracks and gaps in the structure of concrete and cause various physical and chemical reactions, thereby disrupting the structure of concrete. These deteriorations directly affect the durability properties of concrete [4]. Fluid can enter concrete cavities in three different ways: permeability caused by hydrostatic difference; capillary conduction caused by water surface tension; and diffusion caused by the vapor pressure difference of liquid vapors [5]. The major factor that causes these three different transmissibility is the gaps and micro-cracks in the concrete structure.

Although permeability is associated with a low void ratio, various parameters, such as material ratios, curing conditions, etc., affect the durability and permeability properties of the materials [6,7]. Different methods and materials are used to reduce permeability. Mineral admixtures are commonly used in concrete mixtures to improve durability properties as well as strength properties. In concrete, admixtures bind $Ca\,(OH)_2$, which is easily soluble in water, and convert it into C-S-H gel. In this way, they block the gaps that the lime will cause by dissolving. In addition, most of the mineral additives create a fuller concrete volume by filling the voids in the interfacial transition zones (ITZ) between aggregates and cement paste, especially since the silica fume is a hundred times smaller than the average diameter of the cement. Thus, a more impermeable concrete design is possible with mineral additives [8,9]. It was observed that blast furnace slag reduced permeability-related properties such as chloride-ion permeability, diffusion coefficients, and corrosion [10]. Higher and more advanced structures are being built with developing construction technologies to meet the dwelling needs of increasing populations. Concrete strength classes have also increased, and difficult-to-pour concrete recipes have been created. With the development of plasticizer chemical admixtures, workability problems have been largely solved today. Permeability-reducing admixtures (PRAs) have been developed for construction that has to be built even in unfavorable conditions. The American Concrete Institute classifies PRAs into 5 different categories [11]. These are hydrophobic water repellents, polymer products, finely divided solids, hydrophobic pore blockers, and crystalline products. However, methods such as the closure of gaps with bacteria and the use of polymers in capsules, which have become more common after the publication of this report, are available even though they are not included in the classification. By closing the gaps inside and on the surface of the concrete, these methods produce more impermeable and highly durable concrete [12-14]. The admixture to be used under hydrostatic conditions for the samples to be tested for depth of penetration of water under pressure is mentioned as crystalline hydrophilic polymers (latex, water-soluble or liquid polymer). Admixtures with hydrophobic pore blockers push liquids into the concrete, allowing for less liquid to be found. However, they cannot block the liquid under any hydrostatic pressure and thus lose their working mechanism. However, the crystallized permeability-reducing admixture used in this study does not lose its mechanism of action under hydrostatic pressure. These admixtures, which are resistant to hydrostatic pressure, form crystallized structures with the ingress of water into the concrete, creating a more repellent structure [13]. The reaction of cement with calcium silicate and crystallized promoter is given in Eq 1. This reaction produces a modified calcium silicate hydrate and a pore-blocking precipitate. Furthermore, as illustrated in Figure 2, a product of cement hydration can react with Ca(OH)2 to form a C-S-H gel [15].

$$3CaO\text{-}SiO_2 + M_xR_x + H_2O \rightarrow Ca_xSi_xO_xR\text{-}(H_2O)_x + M_xCaR_x\text{-}(H_2O)_x \quad (1)$$

$$Ca\,(OH)_2 + \text{Silicate} \rightarrow \text{C-S-H} \quad (2)$$

PRAs reduce permeability through the closing of the gaps with resultant products. However, the formation of extra C-S-H gel seen in the reactions does not always mean that the compressive strengths will also increase. When using this type of permeability-reducing admixtıre, the chemical admixture quantity should be so selected as to reduce the effects on compressive strength. In some cases, additives may cause a loss of strength [16].

In previous studies, the use of such crystallized admixtures has been shown to improve various concrete properties. It has increased the compressive strength, water absorption, permeability, flexure strength, and durability properties by filling the voids in the concrete structure with crystallized formations [17–20]. However, the effect of PRA also depends on various variables, such as water/cement ratio and cement type [21]. Hassani et al. [19] concluded that the effectiveness of the admixture depended on binder type and that reported changing effectiveness values with increasing water/cement ratios. It was also observed that blast furnace slag had a positive effect on permeability properties. Khatib et al. [22] reported that metakaolin significantly reduced concrete permeability. There are studies also on the ratio of the admixture to be used [23].

The compatibility of the admixtures with different materials and different water/cement ratios was investigated under different conditions in previous studies. However, it has not been investigated how it will affect concrete mixtures containing cement at different dosages when there is a constant mineral admixture and water/cement ratio. Therefore, concrete mixtures containing blast furnace slag, which is a commonly used mineral additive, and cement in 3 different dosages were produced in this study. While the constant water/cement ratio and mineral additive dosage were used in the mixtures, only the cement dosage was changed. By adding permeability-reducing admixture (PRA) to each of these mixtures, a total of 6 types of concrete, with and without admixtures, were produced. Slump values, 7 and 28-day compressive strengths, and water penetration depth under pressure of the produced concrete were determined. Thus, the cement dosage-dependent effects of admixtures on workability, strength, and durability properties were investigated.

2. Materials and Methods

2.1. Materials

2.1.1. Binding materials

In this study, CEMI 42.5R type Portland cement was used in accordance with TS EN 197-1 standard [24]. All mixtures contained the same amount of blast furnace slag (BFS). Table 1 presents the chemical components of BFS and cement. The specific gravities of cement and BFS are 3.10 and 2.86, respectively.

Table 1. The chemical composition of cement and BFS (%, by weight).

Chemical compound	SiO_2	CaO	Al_2O_3	MgO	Fe_2O_3	K_2O	Na_2O	SO_3	Loss on ignition
Cement	20.12	62.38	5.88	1.87	2.40	0.93	0.38	3.28	1.82
BFS	40.20	35.90	11.66	5.88	1.68	1.47	0.30	0.90	0.88

The appearance of BFS and cement, the binding materials used in this study, is represented in Figure 1.

Figure 1. The appearance of BFS (left) and cement (right).

2.1.2. Aggregate

Three types of aggregates, 0–5 mm, 5–15 mm, and 15–22 mm crushed stone aggregates, were used in this study. The specific gravity values of these aggregates are 2.67, 2.70, and 2.71, respectively.

2.1.3. Water

Drinkable tap water was used as mixing water.

2.1.4. Chemical admixtures

In this study, a polycarboxylate-based superplasticizer and a permeability-reducing admixture were used. The properties of the plasticizer admixture and PRA based on manufacturer company analysis are given in Table 2.

Table 2. Properties of polycarboxylate-based superplasticizer and PRA.

Product	Appearance	Density (gr/cm^3)	pH	Chloride content (%)	Alkali Content (%)
Super Plasticizer	Brown-liquid	1.097	3.80	<0.1	<10
PRA	Yellow-liquid	1.13±0.02	9.80	<0.1	<0.4

2.2. Methods

2.2.1. Production of concrete mixtures

Concrete samples were produced with the use of three different cement dosages. In addition, two different types were produced from each sample type, with and without permeability-reducing admixtures, and a total of six different concrete mixes were produced. Concrete mix proportions are given in Table 3. While the superplasticizer was used as 1.6% by weight of the total binder, the permeability-reducing admixture was used as 2% of the cement. The dosages were determined based on manufacturers' recommendations.

Table 3. Concrete mix proportions (kg/m3).

Materials	D300	D300+PRA	D315	D315+PRA	D330	D330+PRA
Cement	300	300	315	315	330	330
Blast Furnace Slag	50	50	50	50	50	50
Water	147	147	153.3	153.3	159.6	159.6
Aggregate 1 (0-5mm)	899	899	889	889	874	874
Aggregate 2 (5-15mm)	430	430	426	426	419	419
Aggregate 3 (15-22mm)	526	526	520	520	512	512
Air content (%V)	2	2	2	2	2	2
Superplasticizer (SP)	5.6	5.6	5.84	5.84	6.08	6.08
PRA	-	6	-	6.30	-	6.60

The materials given in Table 3 were used in concrete production in accordance with the TS802 standard [25]. First, the dry mix was made by mixing cement, BFS, sand, and aggregates for 1-2 minutes. Then, some water was added, and the mixing continued. Superplasticizer was added to the mixture with the remaining water and mixing was continued for 2 more minutes. While the mixing process was continuing, a permeability-reducing admixture was added, and the mixing continued for 5 minutes. For the present experiments, 150 mm × 150 mm × 150 mm cubes and 100 mm x 200 mm cylindrical concrete samples were prepared. The samples were removed from the molds after 24 hours and cured in water until the day of the experiments.

2.2.2. Slump test

The test method was conducted according to TS EN 12350-2 standard [26]. The S3 class (10–15 cm) was chosen as the slump. Samples that gave slump in this range were cast into molds. In addition, the effect of PRA on the fresh state was examined. An image taken during the slump value measurement is shown in Figure 2.

Figure 2. Slump test.

2.2.3. Compressive strength test

According to the TS EN 12390-3 standard [27], the 7 and 28-day compressive strengths of cylindrical concrete samples (100mm×200mm) were determined. Three samples were used for each species. The appearance of the cylindrical concrete sample in the compressive strength press is shown in Figure 3.

Figure 3. Compressive strength measurement of a cylindrical concrete sample.

2.2.4. Depth of water penetration under pressure

The test method was used to determine the effect of PRA on the depth of water penetration at various cement dosages and it was carried out in accordance with the TS EN 12390-8 standard [28]. At 28 days of age, a 150 cm edge of cubic concrete samples were placed into the device and 500 kPa water pressure was applied for 72 hours. At the end of 72 hours, the sample removed from the device was split in half and the depth of water was measured with a digital caliper. Three samples were used for each species.

3. Results and Discussion

3.1. Slump

The permeability of concrete is largely influenced by its ability to be placed into a mold in a fresh state. Therefore, the negative effects of admixtures on slump value will directly affect hardened properties. The slump values of the concrete produced in the study are presented in Figure 4. Besides the control samples, all the samples containing admixtures were kept in the S3 slump class. Slump values decreased in the samples with all cement dosages. Slump values remained within the limits in all 3 sample types. PRA did not have any significant negative effects on workability. It was observed that PRA and the superplasticizer interact successfully. The effect of the decrease in slump values was observed to be primarily caused by cement. In a study by Michael et al. [29], it was found that permeability reducing admixture had no significant effect on slump value and did not affect workability properties, in parallel with this study.

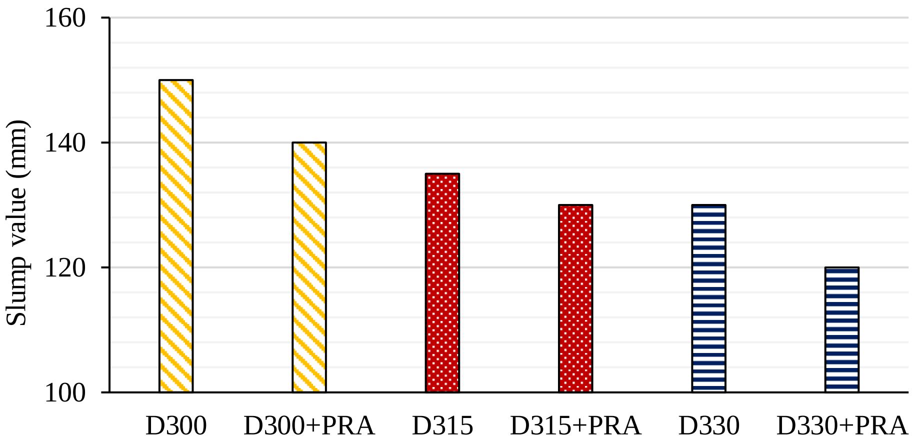

Figure 4. The slump values of all concrete mixtures.

3.2. Compressive strength

7 and 28-day compressive strength tests were conducted to observe the effect of PRA on compressive strength. The 7-day compressive strength results are presented in Figure 5. It was observed that PRA increased compressive strength by 9.44%, 5.33%, and 3.28% at cement dosages of 300, 315, and 330 kg/m3, respectively. The reason for this contribution is that PRA crystallized in the voids of concrete and so created a fuller volume. The effect of admixture continued as the concrete strength classes increased, but its effect decreased as the void ratio of concrete decreased. Thus, the effect of PRA was reduced by clogging fewer gaps. It was reported in a study by Yu et al. [16] that PRA supplementation to C30 and C40 concrete mixtures yielded similar results to the present ones, and the rate of contribution of PRA in strength decreased as the concrete grade increased.

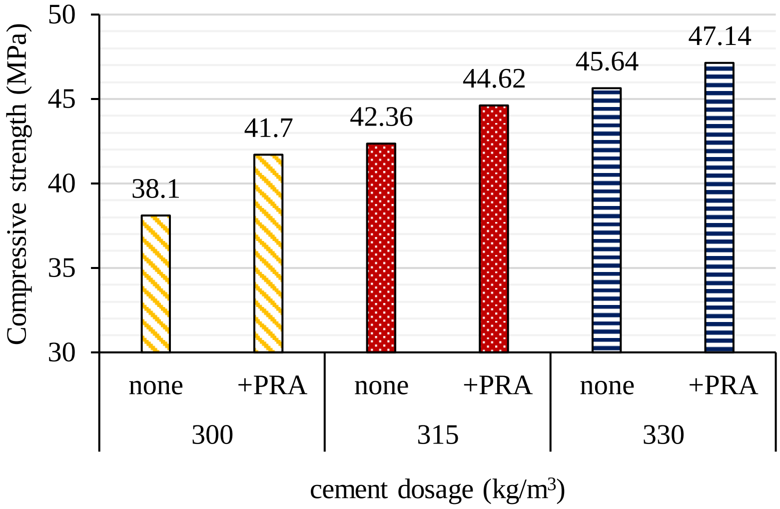

Figure 5. The 7-days compressive strength results.

The 28-day compressive strength results are presented in Figure 6. It was observed that PRA increased compressive strength by 4.35%, 2.78%, and 2.02% at cement dosages of 300, 315, and 330 kg/m3. Similar to the 7-day results, the contribution rate of the admixture to compressive strength decreased as cement dosage increased. However, it still contributed to increasing the compressive strength at each cement dosage.

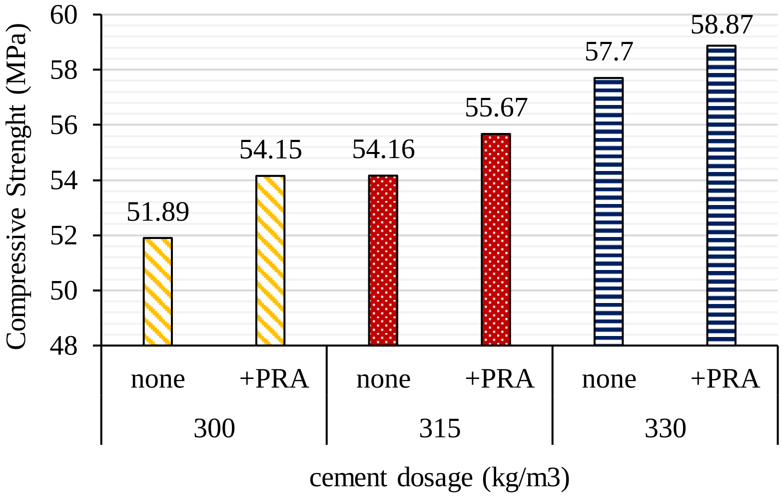

Figure 6. The 28-day compressive strength results.

3.3. Depth of water penetration under pressure

Three samples from each sample type were used for the test. A sample whose water penetration depth was measured during the experiment is presented in Figure 7. The average results are presented in Figure 8.

Figure 7. The process of measuring the depth of water penetration.

There are numerous pores in concrete structures, and these pores affect the permeability properties of concrete in many ways [30]. Crystal structures formed by using chemical admixtures can form in these pores and reduce the depth of water penetration values [31]. In parallel to this, in this study, PRA decreased the depth of water penetration in 300, 315, and 330 kg/m3 cement dosages by 22.06%, 26.90%, and 1.93%, respectively. A decreased depth of water penetration was observed when the cement dosage was increased from 300 to 315 kg/m3 in additived samples. However, the decrease due to increasing cement dosage was lower compared to the decrease owing to the use of PRA. This result is parallel to the study of Hassani Esgandani [32].

At these 300 and 315 kg/m3 cement dosages, the concrete structure had adequate voids that provided a suitable area for the crystallization of PRA. However, at a cement dosage of 330 kg/m3, suitable voids were not created for crystallization because the voids were already closed due to cement hydration. Thus, PRA was not effective at this dosage. At a cement dosage of 315 kg/m^3, the depth of water penetration decreased by up to 26.90% due to PRA supplementation into the concrete mixture. However, the effect of PRA on the depth of water penetration decreased with increasing cement dosage (330 kg/m^3). In previous studies, it has been observed that this type of admixture also contributes positively to self-healing behavior [33]. This study determined that PRA is more effective at lower dosages because it needs larger pores and cracks for its crystallization.

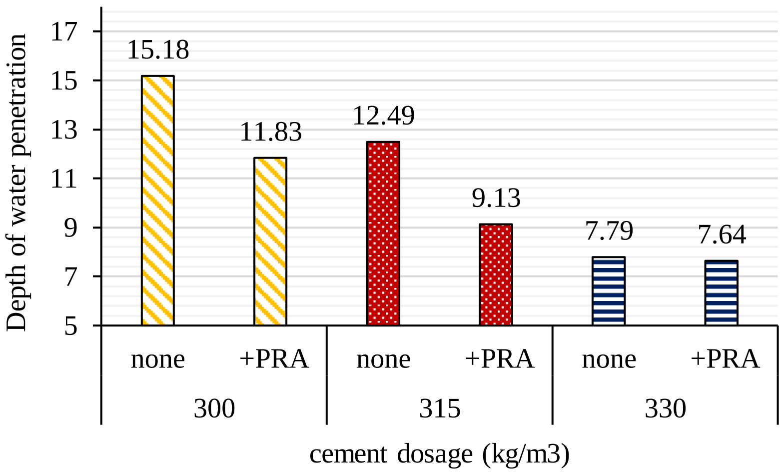

Figure 8. Depth of water penetration under pressure.

4. Conclusion

In this study, concrete samples containing three different cement dosages were produced, and the effects of PRA on the slump, compressive strength, and depth of water penetration were investigated. The following conclusions were drawn from the present findings:

- Although PRA worked in compliance with the superplasticizer, PRA generally reduced slump values, but present slump values were still within the limits.
- PRA increased the compressive strength values at all cement dosages. However, as the cement dosage increased, the compressive strength increased as expected, while the positive effect of the admixture on the strength decreased. At the lowest cement dosage, PRA had the highest effect (9.44%). In addition, as the curing day increased to 28 days, the contribution of the admixture to compressive strength decreased. While the compressive strength increased due to the closing voids because of the hydration of the cement, the effect of the admixture decreased because these voids were areas for the crystallization of the admixture to be formed.
- PRA was the most effective on the depth of water penetration under pressure. Decreases in water penetration depth of up to 26.90% were observed. However, while it was observed that the admixture was quite effective up to a certain dosage, the effect was quite low at high cement dosage.

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