THE USE OF WATER REDUCING ADDITIVES FOR DEVELOPMENT OF NEW ECOLOGICAL AND HIGH-PERFORMANCE MATERIALS

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Abstract

The decreasing amount of the world's water supply is a significant issue nowadays. Global warming is one of the key factors contributing to the increasing loss of water supplies, but wasteful water usage for domestic and industrial use is also a major factor. The water consumption reduction by using proper additives is a technique to reduce high water consumption in the construction sector. Sulphonated melamine formaldehyde, sulphonated naphthalene formaldehyde, modified lignosulphonates and polycarboxylate derivatives are examples of additives providing this feature. Condensed polymers are the basis for producing these additives. Their action mechanism consists in the de-flocculation of the cement granules and improving the workability of freshly mixed concrete. The water reduction potency of polycarboxylate derivatives is substantially higher than that of other additives. In the same time, the use of modified lignosulphonates also solves the problem of associated environmental pollution, being a by-product from the wood pulp processing by the sulfite process. Details about water consumption reducing additives will be presented in this paper based on literature review and on the author's own experience: the preparation methods, chemical composition and properties of the obtained building materials.

Keywords: *water consumption reduction, additives, environmental pollution, condensed polymers*

1. INTRODUCTION

The innovations have succeeded in the new building materials development in the last years, particularly in terms of ensuring sustainability and green technologies [1-3]. More studies are dedicated to the replacement of ordinary cement with alternative green materials [4, 5]. In order to meet the increasing demand for construction market, the concrete is produced in billions of tons per year [6, 7] and therefore all the components involved for concrete production should be diminished [8, 9]. The studies regarding the reducing of the above mentioned components are especially dedicated to raw materials or cement, and only a few studies are related to the water consumption involved in building materials production, without taking into consideration the water importance especially for the places where this is missing [10-13].

Water is the most important ingredient for life on Earth [14-16]. Nowadays, for complex reasons, mankind encounters a global water shortage [17, 18]. People struggle to obtain the amounts of water with proper quality needed for drinking, cooking, bathing, washing, personal hygiene and agricultural production. The problem of water scarcity can be alleviated by reducing or eliminating the wasteful water usage in both residential and industrial settings.

Water is a common ingredient in the concrete formula and the consumed amounts are not negligible. Therefore, the use of additives for water consumption reduction, often known as superplasticizers (SPs), is considerable for the green approach of concrete technology [19-21]. When cementitious ingredients are well-dispersed with a superplasticizer added in the concrete recipe, the formation of agglomerates is roughly avoided and the fluidity of the cement paste is enhanced.

The concrete flowability depends on the water/cement ratio (W/C) and is highly increased by the presence of superplasticizers in the recipe [22-24]. Moreover, the same flowability can be achieved by including a SP and reduce the W/CM ratio, while increasing the concrete strength and durability in the meantime with paste volume reduction, improving also its dimensional stability.

The use of a proper superplasticizer and by optimizing the mixing design of concrete preparation can enhance all of aforementioned properties at the same time. In this respect, the SP use popularity has grown, to the extent that now they are a required constituent in concrete fabrication [25].

Over the years, the SPs have progressed from the first generation, lignosulfonate-based, to the second generation melamine- or naphthalene-based ones, and finally to the third generation polycarboxylate-based [26, 27]. The earlier SPs disperse the cementitious materials primarily through electrostatic repulsion between particles, caused by imparting similar electrostatic charges to particle surfaces, whereas the newest polycarboxylate-based ones furthermore induce steric repulsion by wrapping the cement particles with co-polymer side chains [28-30], being often more effective.

Despite the performed research on the SPs effects on cement paste, mortar and concrete, there are few standards for the usage of SPs. In reality, using SP correctly is difficult. Firstly, the SP amount need for reaching a particular flowability is affected not only by the kind of cement, but also by the types and fineness of additional cementitious materials and fillers used in the cement paste preparation [31-33]. In general, the higher the fineness of the particles in the cement paste is, the higher the necessity for SP. Secondly, the efficiency of a SP is maximal at a certain dose defined by a specific saturation dosage, above which further addition yields limited or even no return [34-36]. As a result, using a SP above the saturation dosage is not cost effective. Thirdly, the use of SP improves the flowability of cement paste, mortar and concrete, but also reduces the cohesiveness, raising the danger of concrete bleeding, sedimentation, and segregation [37, 38].

When the efficiency of the SP is high and/or the dosage is high (when a polycarboxylate-based SP is employed at high dosage), the problem of diminished cohesiveness becomes more severe [39, 40]. To avoid this problem, the SP dose should exceed the amount that causes segregation [41, 42].

The SP requirement, saturation dosage and dose value producing segregation are all affected by the kinds and fineness of the powder content (cementitious materials and fillers) from the cement paste. Because SP is a surface reactant adsorbed onto the particle surfaces of the powder content, the amount used per surface area of the powder content should determine its efficiency [43].

A common approach is to assess the SP dose relative to the bulk of the powder component [44, 45]. In order to account the variation of solid density, SP dose measurements were performed relative to the solid volume of the powder content [46, 47]. However, regardless of whether the SP dosage is assessed by mass or by solid volume, the experience has shown that the SP demand, saturation dosage and dose value producing segregation may all vary significantly when the powder content changes.

The main objective of this paper is to collect the useful information related to water consumption reducing additives involved in the new building materials production, based on literature review and according to the authors' own experience.

2. MATERIALS AND METHODS

2.1. Materials

As was previously mentioned, the main aspects of using the additives for water consumption reduction, namely as well superplasticizers (SPs), will be presented using some examples where the properties of the new obtained materials are characterized based on the methodology presented in this section.

For the investigation of the effect of using SPs combined with various additives to cement paste, 5 mixture compositions were considered, Table 1 [48].

When the results for dust filler, gypsum filler, and gypsum binder are compared, it is possible to determine if the particle shape and size or particle chemical composition influence the slump. Polycarboxylate ether (PCE) and sulphonated naphthalene formaldehyde (SNF)-based SPs were utilized in this investigation. For all tests, the SU was used to replace some of the water, in order to keep constant the total amount of fluid matter in the mix [48].

	Reference	Fines filler	Gypsum filler	Gypsum binder	Fly ash binder
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3
CEM II 52.5 N	802	802	802	753	740
Sand	963	946	946	962	945
Dust	–	17	–	–	–
Gypsum	–	–	17	48	–
Fly ash	–	–	–	–	47
Water	401	401	401	400	394

Table 1. Constituents and mixing proportions [48]

Al-Shwaiter and Awang [49] created concrete foam using river sand, palm oil fuel ash (POFA), Portland cement, protein foam, normal tap water and five different types of SPs. Table 2 displays the chemical and physical features of these SPs.

Symbol	Chemical composition of SPs	Specific gravity, kg/m^3	Color
SP 1	Sulphonated polymer-based	1190	Dark brown
SP 2	Selected synthetic and organic polymers based	1220	Dark brown
SP 3	PCE based	1040	Yellowish-brown
SP 4	PCE based	1030	Brown
SP 5	PCE based	1080	Dark brown

Table 2. SPs characteristics [49]

The use of cement-sand ratio of 1:2 by weight to fabricate foamed concrete with a target density of 1500 kg/m^3 was possible by adding 20% POFA filler and 80% of the sand (by weight). For the reference specimen, the minimum ratio water-cement (W/C) necessary for full hydration was determined to be 0.5. For exploring the impact of SP, the W/C ratio was kept constant for all mixes. Eleven composition recipes were chosen by using 5 different SPs added in proportions of 1.0% and 2.0% by weight of cement. Cement having a density of 468.3 kg/m^3, containing 479.3 kg/m^3 sand, 187.3 kg/m^3 POFA and 234.2 kg/m^3 water were thus prepared. The mixtures compositions are displayed in Table 3 [49].

Notation	SP %	SP kg/m^3
SP 0	0	0
SP 1-1	1	0.47

SP 1-2	2	0.94
SP 2-1	1	0.47
SP 2-2	2	0.94
SP 3-1	1	0.47
SP 3-2	2	0.94
SP 4-1	1	0.47
SP 4-2	2	0.94
SP 5-1	1	0.47
SP 5-2	2	0.94

Table 3. SPs content in mixtures [49].

2.2. Methods

The influence of adding SPs was tested by using the Marsh cone test, to assess the flowing duration, using the standard code ASTM C939-10 (2010). This test is used to study the flow behavior of superplasticized cement pastes with a W/C ratio higher than 0.5 [48, 50].

The same mixing strategy was used for all experiments in this study: the dry components were blended for exactly 30 seconds at a steady speed in a 10-liter cake mixer. Then, 80% of the water was added and mixed for 2 minutes before adding the remaining 20% of liquid, which contained water and superplasticizer, and mixing for another 2 minutes.

Al-Shwaiter and Awang [49] used a vertical shaft mixer. After mixing the cement, sand, POFA, and water, the appropriate type and quantity of SP is added to the ready mixed concrete. The pre-foamed approach produced foam by diluting the foaming ingredient in water at a 1:30 weight ratio.

The foam generation was made by mixing the resultant suspension with compressed air, to generate foam with a density of 653 kg/m^3. To avoid losses of stability and viscosity, the foam was employed directly. Fresh foam concrete density was kept at about 1630 kg/m^3, to maintain the hardened concrete foam density within the desired range of 1500±50 kg/m^3. To minimize the moisture loss, the specimens were covered with a plastic sheet for 24 hours after casting [49].

Slump flow and spread ability tests were utilized to evaluate workability. The slump flow test was performed in accordance with ASTM C 1611/C 1611M 2005 [51], by inserting a sample of new concrete in the cone without compacting or vibrating it. The average of two diameter measurements was obtained.

Meanwhile, an open-ended cylinder with the diameter and height of 107 mm was set on a 400 x 400 mm steel plate. After lifting the cylinder vertically, the diameter was measured twice on perpendicular directions. The mix stability was evaluated by calculating the ratio of the actual foam weight added until the aimed elastic density was attained. Meanwhile, the new mixture consistency was calculated by dividing the fresh material density by the prescribed density.

Cubes with dimensions of 100 x 100 x 100 mm were manufactured and tested in compliance with BS-EN-12390-3 2009 [52] using a 3000 KN hydraulic compression machine. Samples were loaded at a rate of 0.6 MPa/sec [53]. A total of 99 cubes were examined at the ages of 7, 14, and 28 days. The average of three specimens was calculated. The flexural strength was determined using a prism with 160x160x40 mm sized in line with BS-EN-12390-5 2009 [54]. After 28 days, a focused load was applied on the specimens mid-span, and the average value of three specimens was noted.

The splitting tensile strength was measured in accordance with BS-EN-12390-6 2009 [55], by constructing samples with 100 mm diameter and 200 mm length under 0.05 MPa/sec loading rate. At 28 days, three specimens were examined for each combination, and the average value was calculated.

3. RESULTS

The obtained results [48] pointed out how different SPs influence the concrete flowing. The data from Fig. 1 indicate that polycarboxylate ether (PCE) had a more noticeable effect at the lowest dose used (0.2%) than sulphonate naphthalene formaldehyde (SNF), but the last continued to improve the effects up to doses higher than 0.5%.

PCE only produced modest improvements after 0.2% dosage, up to a dose of 0.7%, where the stability was reached. The SP could not be effectively absorbed when the tricalcium silicate component was used alone [48, 56]; the behavior in this case was similar to regular water mixture.

The flowing times of the samples containing SPs and other additives are compared by displaying them in comparison with the reference sample (Fig. 2-5).

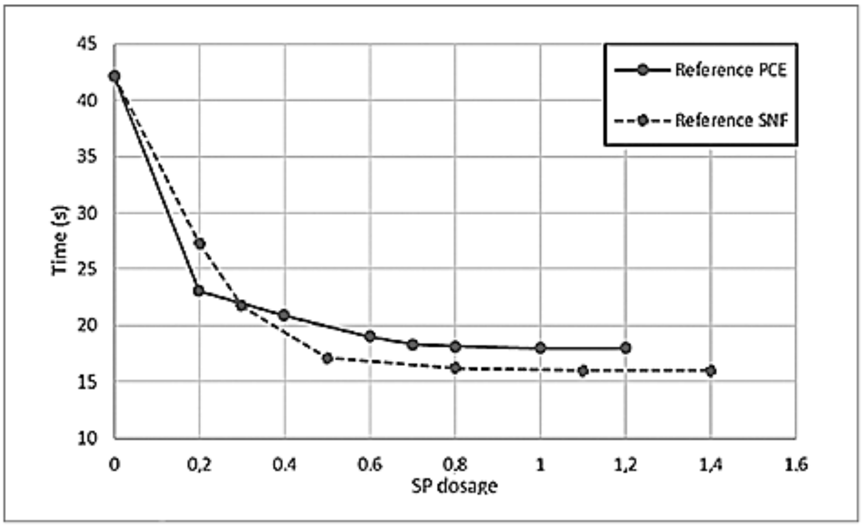

Fig. 1. Marsh cone test results for the reference mix using PCE and SNF

Source: Adapted from [48] L. Stone, 2020, pp. 200-208

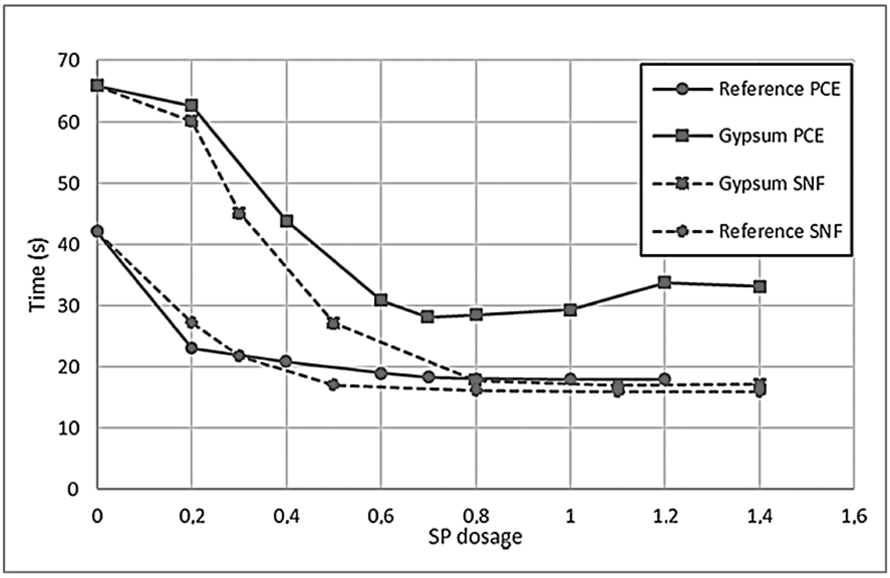

Fig. 2. Marsh cone test results for the Gypsum Binder mix

Source: Adapted from [48]: L. Stone, 2020, pp. 200-208

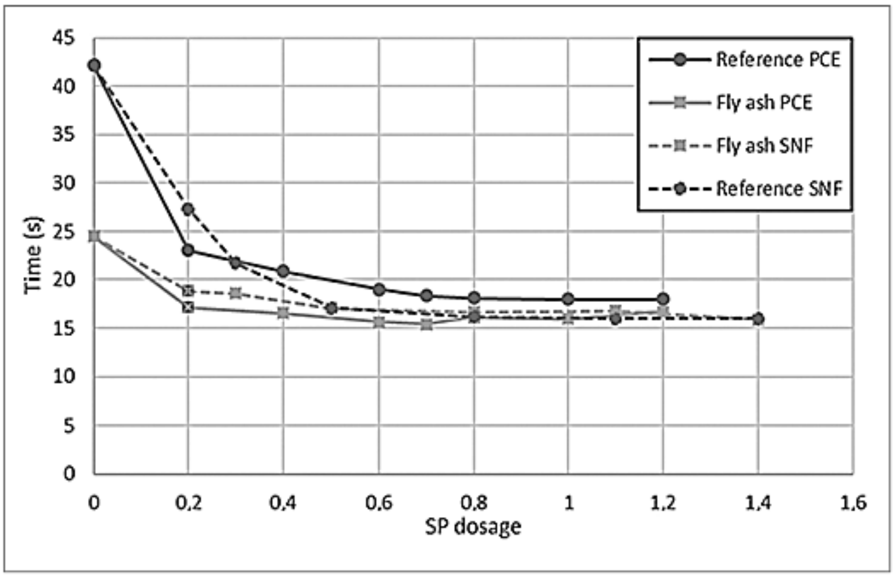

Fig. 3. Marsh cone test results for the Fly Ash Binder mix

Source: Adapted from [48] L. Stone, 2020, pp. 200-208

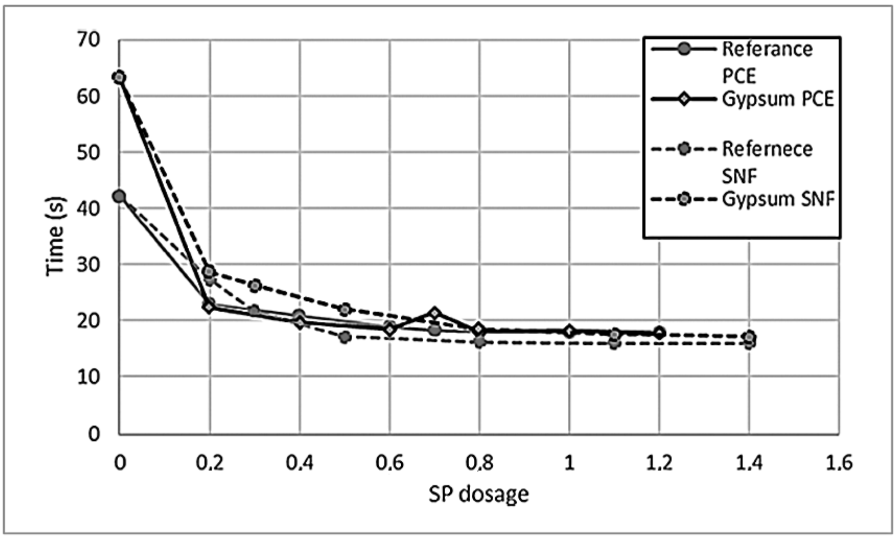

Fig. 4. Marsh cone test results for the Gypsum Filler mix

Source: Adapted from [48] L. Stone, 2020, pp. 200-208

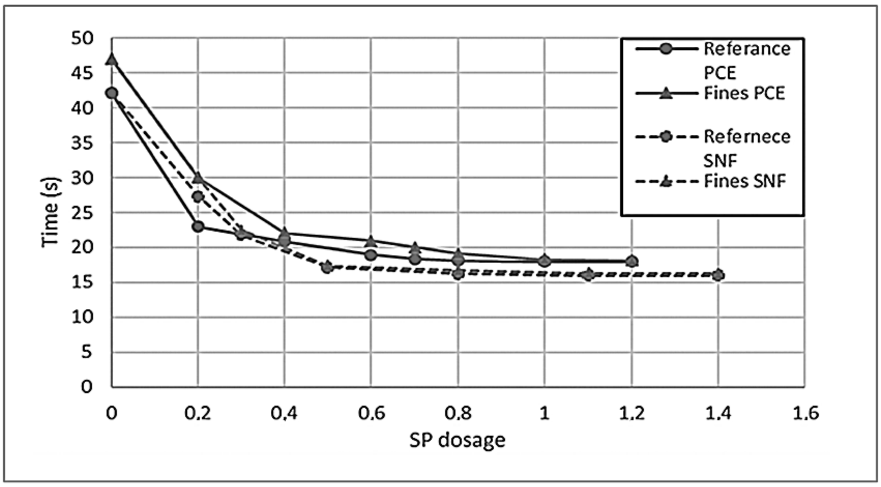

Fig. 5. Marsh cone test results for the Dust Filler mix

Source: Adapted from [48] L. Stone, 2020, pp. 200-208

The values obtained by Al-Shwaiter and Awang [49] concerning the compression, flexure and tension of foamed concrete samples with various forms of SP are given in Table 4.

SP type	Compression [MPa] 28 days	Tension [MPa] 28 days	Flexural [MPa] 28 days
SP O	12.7	0.9	4.3
SP 1-1	17.3	1.2	4.2
SP 2-1	22.6	1.5	8.1
SP 2-2	44.2	2.4	10.4

SP 3-1	16.7	1.0	5.0
SP 4-1	14.4	1.1	3.4
SP 4-2	19.4	1.4	5.3
SP 5-1	11.2	0.89	2.7
SP 5-2	18	1.8	5.0

Table 4. Mechanical properties of foamed concrete [49].

All samples compressive capacities grew with aging. Additionally, using SP significantly raises the compressive strength of foamed concrete [49]. Age-related increases in compression resistance may be detected for all specimens.

Additionally, adding SP significantly increases the compression strength of foam concrete. This improvement varies depending on the SP type and dose, which is in line with earlier research carried out by Mangane [57], who showed an improvement in compression strength for different SPs at same W/C ratios after 28 days. Additionally, the compression strength of the SP content of the same kind improved. This behavior is due to the effect of SPs to raise the slurry capacity to optimize and redistribute its big pores, making them more uniform than previously. This result is consistent with that obtained by Wu [58], who report that the compression strength significantly increased over time when the SP concentration increased from 1.0 % to 2.0 %. Fig. 6 illustrated the influence of superplasticizers on compression strength.

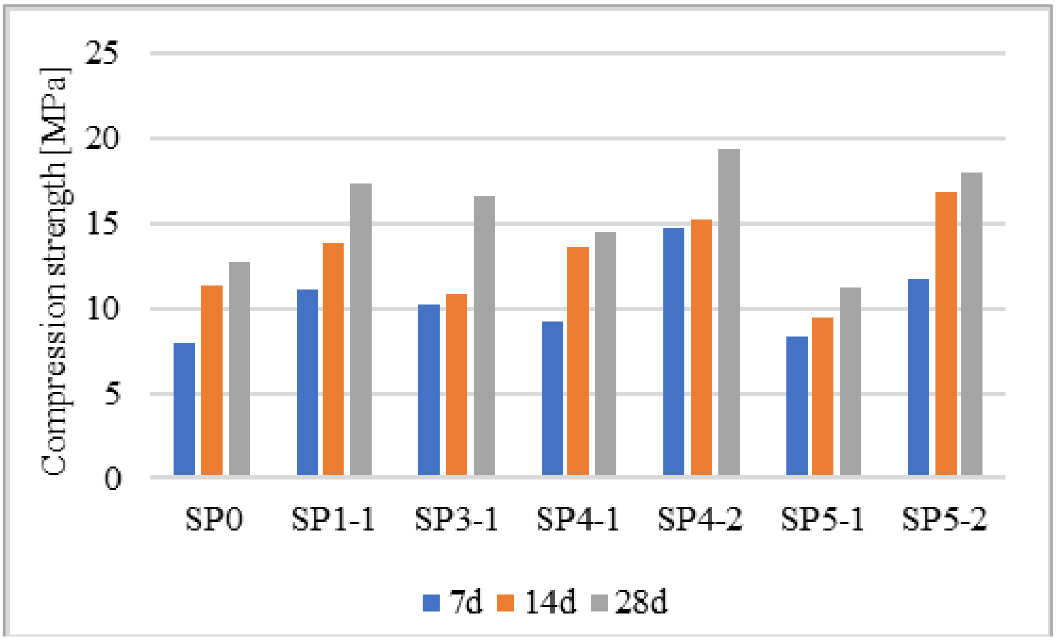

Fig. 6. Influence of superplasticiser on compression strength

Source: Adapted from [49]: Al-Shwaiter, 2020, pp. 57-65

The splitting tensile strength test was performed following a 28-day curing of the seal. The splitting tensile strength of all specimens increased when the SP was used, with the exception of SP5-1, which exhibited a decrease because of its low density. SP's impact on splitting tensile strength is highlighted in Fig. 7.

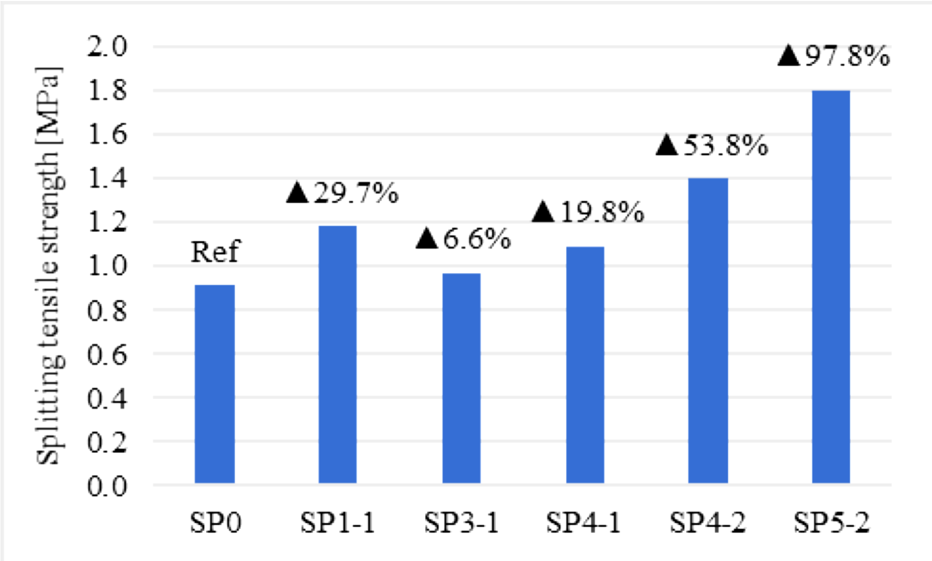

Fig. 7. Influence of SP on splitting tensile strength

Source: Adapted from [49]: Al-Shwaiter, 2020, pp. 57-65

According to the data presented in Fig. 8, the specimen flexural strength varied between 3.4 and 5.3 MPa when the required density was achieved. The SP4-2 sample (2% SP) had the highest flexural strength, exhibiting an increase of 21.5% compared with the reference. Interesting to note is that when using the same SP at a ratio of 1.0%, the flexural strength decreased by 21% compared with the reference [49].

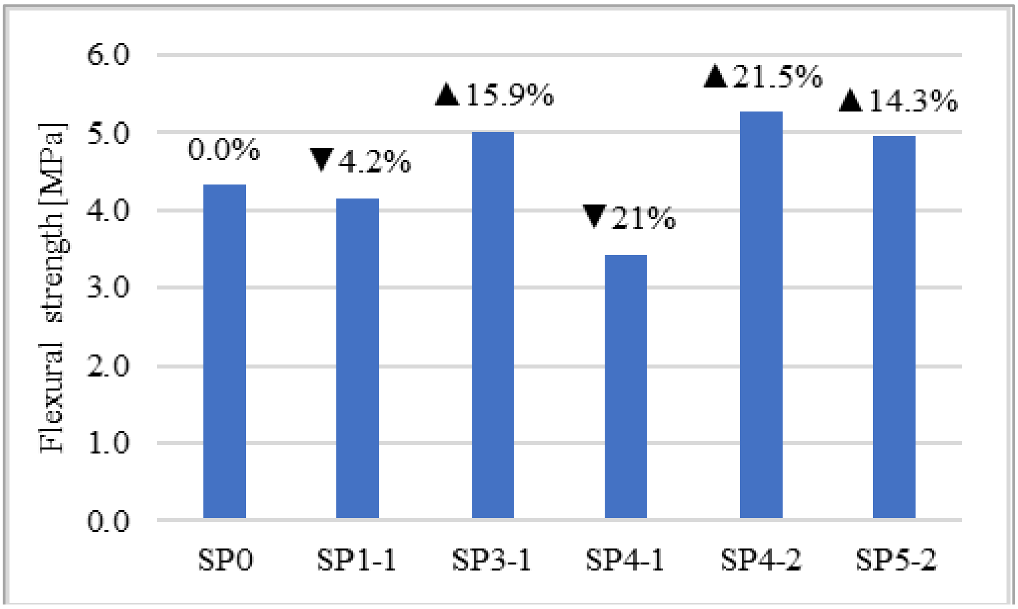

Fig. 8. Influence of superplasticizer on flexural strength [49].

4. DISCUSSION

Although the PCE initially had the greatest effect at lower doses [59, 60], Stone et al. [48] demonstrates that the SNF eventually has the greatest benefit at higher dosages. Additionally, exceeding the recommended dosage has no positive impact, smaller dosages are necessary for the greatest improvements.

There is a clear interaction between the gypsum and the SP when more gypsum is introduced, requiring also a higher SP dose. Furthermore, in the presence of a gypsum excess and high SP doses, the electrostatic repulsion mechanism of the SNF operates more successfully than the steric hindrance of the PCE.

The SP had not the same pronounced impact on the flowability when fly ash was added in the concrete formulation. SPs were substantially less effective in the fly ash mix, although both demonstrated the most notable effects for both mixtures at the 0.2% dose. At this low ratio, the addition of SP caused an instantaneous increase in flowability, demonstrating that the amount of gypsum inserted was insufficient to have the same substantial impact.

The results for the gypsum and dust filler show that the chemical makeup of the particles had a more significant impact on the efficiency of the SP than the shape of the particles.

All mixes were easier to deal with when a SP with predetermined water content was used. The workability of the reference specimen was poor, but the workability of the SP-added specimens varied depending on the kind and dose of SP.

The flexural strength steadily rose with increasing the bulk density, much as the compression and tensile strength for all specimens; the increase in bulk density is due to the reduction of porosity with positive effects on the mechanical properties [61].

5. CONCLUSIONS

The reduction of the water amount in concrete preparation mixture by using additives (superplasticizers – SPs) has a direct impact on the resulted material mechanical characteristics; improvements are noticed when the water-to-cement ratio is reduced. An optimal additive dose could be defined; the excess is not beneficial.

The compatibility between fly ash, gypsum, fines, and cement added as filing agents together with superplasticizers was tested and allowed to conclude that high gypsum doses have a substantial impact on the SP efficiency, involving the need to use higher SP doses to get comparable results with the reference. High SP doses increase the danger of overdose drawbacks. Also, the presence of fly ash in the formulation reduces the SP effectiveness.

The concrete flowability is greatly improved by the fly ash, leaving little opportunity for the SP to augment the flowability. The flowability and superior mechanical properties of the SP-containing samples were significantly influenced by the particle size and shape. The flowability reduces when using finer sand, but is recovered when more SP is added.

The impact of various kinds and concentrations of SPs on the mechanical behavior of foam concrete indicate that the workability and mechanical behavior of foamed concrete are significantly improved.

By comparing the effects of polycarboxylate ether to all other SP species, the former exhibits a better workability and higher compressive strength and flexural strength. Additionally, it allowed obtaining a stable mixture and the incorporation of an appropriate quantity of air to generate foam concrete at higher ratios.

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