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Superplasticized vs. Conventional Concrete: A Comparative Review

Mark Bediako

Advanced Material Science Division, CSIR-Building and Road Research Institute, Kumasi, Ghana
Email: b23mark@gmail.com

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Abstract

The global awareness and utilization of superplasticizers (SPs) in concrete have significantly contributed to developing resilient and sustainable infrastructure. Despite this, many developing nations face limited adoption of SPs in construction practices due to a lack of knowledge. This study provides a concise overview of concrete's mechanical and durability properties, comparing formulations with and without superplasticizers. The focus is on compressive and flexural strengths, modulus of elasticity, water sorptivity, and chloride penetration. The results underscore the considerable improvement in both mechanical and durability properties when SPs are incorporated. The study recommends the widespread use of SPs, particularly in developing countries, to enhance the longevity of concrete structures.

Keywords

Superplasticizers, Concrete, Mechanical Properties, Durability, Developing Countries

1. Introduction

Ensuring the attainment of designated strength and improved durability in concrete remains a paramount concern for building engineers. Nevertheless, achieving these benchmarks proves challenging due to the inherent difficulty in precisely controlling water content, particularly in field conditions. In an attempt to enhance concrete workability, additional water is often introduced, yet this practice can lead to heightened porosity once the water evaporates. Theoretically, the ideal water-to-cement ratio for full hydration is around 25% of the cement mass [1]. Unfortunately, achieving flowable concrete with such a low water content is practically unattainable.

The advent of superplasticizers has emerged as a solution, offering building engineers a more accessible means to achieve desired mechanical properties and bolster concrete durability. Superplasticizers facilitate high early and late strength development, improved modulus of elasticity, and reduced porosity, thereby enhancing overall concrete durability [2]-[4]. The widespread use of superplasticizers in concrete is well-established in developed countries, impacting various concrete types such as lightweight, heavyweight, prestressed, vacuum, self-compacting, autoclaved aerated, and fiber-reinforced concrete (FRC) [4]. However, in many developing countries, this innovation is not as widely recognized.

Many building engineers adhere steadfastly to traditional concrete formulation methods in numerous developing nations, including West African countries. Their reliance on prescriptive European Standards is unwavering, making it challenging to advocate for adopting superplasticizers. Despite the proven benefits demonstrated in developed countries, building engineers in these regions remain skeptical about incorporating superplasticizers into their concrete practices.

In the absence of knowledge about superplasticizers, engineers typically resort to increasing water content as the sole means to enhance workability. However, this practice, aimed at improving workability, inadvertently leads to high porosity, negatively impacting the mechanical and durability aspects of concrete, particularly in developing countries. The widespread issue of poor-grade concrete due to elevated porosity is a common challenge faced in these regions. In contrast, advanced and developed countries successfully achieve superior mechanical and durability properties by incorporating superplasticizers. For example, in Japan, superplasticizers are reported to be an integral component in almost all concrete production [1].

While superplasticizers play a crucial role in optimizing cement hydration for superior performance, the acknowledgment of their contribution to concrete is often understated by many authors. In contemporary concrete formulation, attaining high-performance concrete is relatively straightforward with the use of superplasticizers. These substances disperse cement particles through either electrostatic or steric repulsive forces, promoting the repulsion of cement powder and an increase in shear potential. Consequently, this leads to improved workability without the need for additional water, which could introduce more pores and compromise the mechanical and durability characteristics of concrete.

Second-generation superplasticizers, such as Sulphonated Naphthalene Formaldehyde (SNF) and Sulphonated Melamine Formaldehyde (SMF), as well as the latest generation in the form of polycarboxylate ethers, have proven successful in enhancing the technical properties of concrete. It is crucial to highlight and disseminate information on the successful applications of superplasticizers in improving concrete properties. This study aims to provide comprehensive data on the use of superplasticizers and their impact on the mechanical and durability behavior of concrete. Mechanical properties considered in this study encompass compressive, flexural, and modulus of elasticity, while durability parameters include sorptivity and the rapid chloride penetration test.

2. Superplasticizers in Concrete

Superplasticizers, recognized as potent water reducers, are commonly employed to enhance the workability of concrete. These substances, characterized by high-density molecular polymers, are soluble in water [5]. Widely used superplasticizers include sulfonated melamine formaldehyde condensate (SMF), sulfonated naphthalene formaldehyde condensates (SNF), and polycarboxylate ether-based superplasticizers (PCE) [6] [7]. The second-generation admixtures encompass SMF and SNF-based SPs, while PCE-based SPs are classified as new-generation.

Various types of superplasticizers exhibit distinct actions on cement particles, yet their fundamental impact is to disperse these particles by adsorbing superplasticizer molecules onto the surface of hydrating cement particles [8] [9]. Cement grains possess surface charges, and Vander Waal forces cause these particles to flocculate upon contact with water [8]. This results in the entrapment of water needed to enhance concrete workability, requiring less water for cement hydration [10]. Superplasticizers adsorbed onto cement grain surfaces eliminate attractive interparticle forces responsible for yield stress, thereby enhancing concrete workability [11] [12].

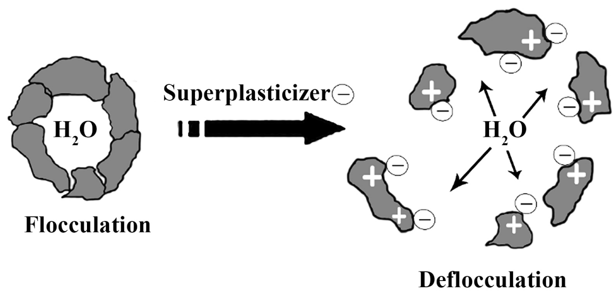

Figure 1. Deflocculation mechanism by creating a charge on cement particles [8].

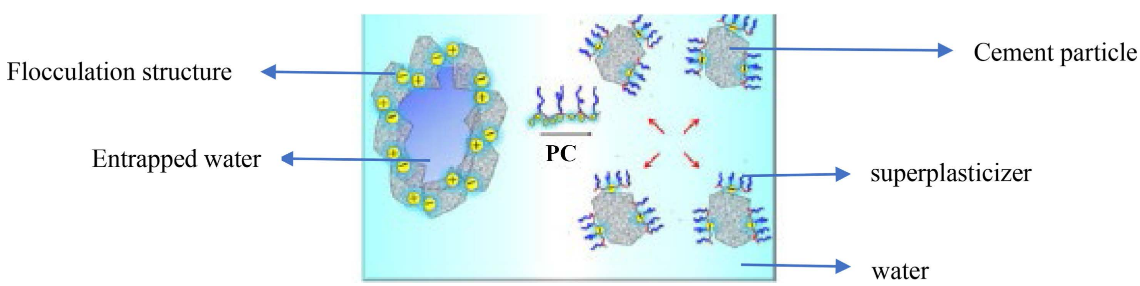

Figure 2. Deflocculation mechanism by electrostatic/stearic repulsive forces [10].

The second-generation and new-generation admixtures, while both functioning to deflocculate cement particles, employ different mechanisms for this action. SNF and SMF induce dispersions of cement agglomerates through the presence of negatively charged anionic groups, ensuring polymer adsorption on cement powder surfaces [13]. **Figure 1** illustrates the mechanism of second-generation SPs. In the case of PCEs, the mechanism involves adsorption on the cement particle surface and neutralization of heterogeneous charged distributions on the cement powder. The adsorbed PCE on cement particles then introduces electrostatic/stearic repulsion among cement particles (refer to **Figure 2**) [10].

3. Mechanical Properties of Concrete with and without Superplasticizers

3.1. Compressive Strength

Compressive strength serves as a widely employed parameter for assessing the load-bearing capacity of structures. The utilization of superplasticizers (SPs) in concrete contributes to the enhancement of compressive strength properties. In their study on fiber-reinforced concrete, Aruntaş *et al.* [4] observed that the inclusion of SPs led to increased concrete strength compared to the control concrete, evident after curing for 28, 90, and 180 days. Matias *et al.* [14] incorporated SPs in concrete utilizing recycled coarse aggregates as a substitute for natural coarse aggregates. Despite the recognized strength loss associated with saturated recycled aggregates, the introduction of SPs by Matias *et al.* [14] mitigated this effect, resulting in concrete strength similar to the control concrete.

In a study by Manami *et al.* [15], four distinct superplasticizers (PCE, LC, SMF, and SNF) were employed in concrete containing fly ash (refer to **Figure 3**). The compressive strength of the control concrete was 46 MPa, while those of the concrete containing SMF, SNF, LS, and PCE superplasticizers were 58, 56, 52, and 53 MPa, respectively. These findings emphasize that the incorporation of SPs in concrete enhances the overall strength performance of the material.

Cheah *et al.* [16] demonstrated the positive impact of polycarboxylate ether-based superplasticizers (PCEs) in their research on ternary blended binder concrete, employing 50% cement with a combined 50% ground granulated blast furnace slag (GGBS) and fly ash (FA). The compressive strength of concrete with 50% Ordinary Portland Cement (OPC) containing GGBS-PFA at 50% and 60% cement levels exhibited a significant increase ranging between 9% and 42% at both early (7 days) and late ages (28 days), surpassing the compressive strength of the control concrete.

In a separate study, Arslan *et al.* [17] investigated the application of a novel chitosan-based superplasticizer in concrete. As depicted in **Figure 4**, their findings indicated an increase in compressive strength rates for sulfonated graft and sulfonated chitosan. Specifically, the observed enhancements were 9.1% and 5.5% for 1-day compressive strength, 13.4% and 10.2% for 3 days compressive strengths, 8.3% and 4.1% for 7 days compressive strengths, and finally, 13.3% and 10.9% for 28 days compressive strengths, respectively.

Numerous studies by various researchers, such as those conducted by Cheah *et al.* [18], and Arslan *et al.* [19], have consistently demonstrated that the use of superplasticizers (SNFs and PCEs) contributes to higher compressive strength in concrete. Sardinha *et al.* [20], in their investigation on the replacement of cement with fine marble dust, noted that the inclusion of superplasticizers resulted in increased concrete strength even with a reduced cement content.

The improvement in compressive strength observed in concrete containing superplasticizers can be attributed to the enhanced compactness facilitated by the presence of superplasticizers, coupled with a low water-cement ratio. This is particularly notable in concrete containing pozzolan [15] [17] [21]. Tkaczewska's study [22] further revealed a reduction in voids in concrete when superplasticizers are utilized, leading to increased early and late strength in the material.

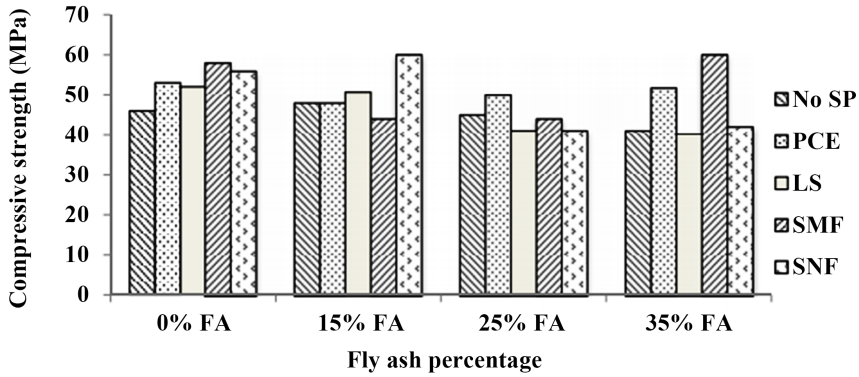

Figure 3. Compressive strength of fly ash concrete containing different types of superplasticizers [15].

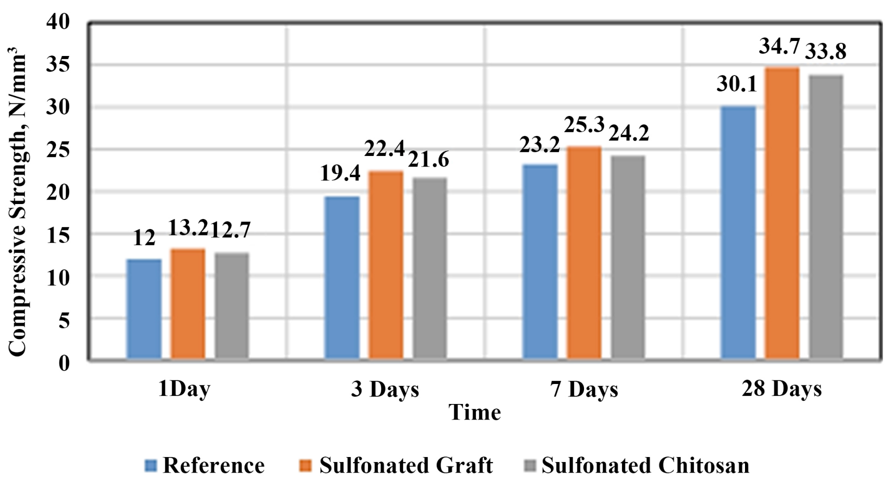

Figure 4. Compressive strength of reference and superplasticizer concrete [17].

3.2. Flexural Strength

The flexural strength of concrete, which assesses a concrete beam's ability to withstand bending loads before failure, is a critical property in structural design. Numerous studies have consistently indicated that the incorporation of superplasticizers (SPs) in concrete leads to an enhancement in flexural strength. In a study by Cheah *et al.* [16], the impact of SP on the flexural behavior of concrete with a ternary mixture of cement, slag, and fly ash was investigated. Their findings revealed that concrete with 50% and 60% replacement of Ordinary Portland Cement (OPC) by GGBS-PFA exhibited higher flexural strength values at 7, 28, 56, and 90 days compared to the control concrete.

The superior performance of the ternary blended concrete over the control concrete is attributed to the SP-induced improvement in the brittleness of the cement system and the increased density of the concrete resulting from a lower water-cement ratio [23].

In their investigation, Al-Hussaini *et al.* [24] examined the impact of superplasticizers (SPs) on concrete reinforced with waste plastic fibers. Their results demonstrated a notable enhancement in the flexural behavior of the concrete, particularly during the late curing period of 28 days, when SPs were added. The improvement in flexural behavior with the addition of SPs exceeded 289% compared to the control concrete. This significant enhancement can be attributed to the improved workability and reduced water content in the concrete containing SPs. The reduction in water content contributes to an improved density of the concrete, thereby enhancing its flexural properties.

3.3. Static Elastic and Dynamic Modulus of Concrete

The modulus of elasticity (MoE), also known as Young's modulus, is a crucial property in concrete, playing a defining role in the deformability of structures and the interaction between reinforcement and concrete [25]. MoE significantly influences the safety, durability, and service life of reinforced concrete structures [3]. This parameter is directly linked to the shortening of concrete components under compressive stress and is impacted by factors like creep and shrinkage [26]. The creeping effect or stress shortening induces the redistribution of internal stresses within reinforced concrete structures, affecting columns, beams, or walls.

Currently, establishing a consensus on the ideal procedure for determining the modulus of elasticity (MoE) poses challenges due to the nonlinear nature of concrete under stress-strain deformation. Various empirical models for static elastic modulus exist in different standards and codes, establishing relationships between MoE and compressive strength [27]-[29].

Dynamic elastic modulus holds significant importance in applications where concrete is subjected to dynamic loads, such as scenarios involving sudden loads on concrete structures. Several models have been developed to establish correlations between static elastic modulus and dynamic modulus using pulsonic velocity in nondestructive testing (NDT) methods [30]. These models are found in standards like ACI, EN, and IS, as well as those developed by researchers [27]-[29] [31] [32]. Despite the wealth of research in the field of static elastic modulus, there is a limited body of work concerning dynamic elastic modulus in concrete with and without chemical and mineral admixtures.

Pereira *et al.* [25] investigated the static elastic modulus using two distinct superplasticizers, namely lignosulphonate and polycarboxylate ether, in concrete incorporating recycled coarse aggregates. Their findings revealed a significant increase in the modulus of elasticity (MoE) when superplasticizers were employed, with an improvement ranging between 20.7% (lignosulphonate) and 33.0% (PCE) compared to concrete without a superplasticizer.

In a related study, Bravo *et al.* [18] explored the impact of polycarboxylate-based superplasticizers on recycled aggregate concretes. **Table 1** illustrates their results, incorporating recycled aggregates at various percentages (0%, 10%, 25%, 50%, and 100%). The outcomes presented in **Table 1** demonstrate that the modulus of elasticity in recycled aggregate concretes containing superplasticizers exhibited superior performance compared to concretes without superplasticizers.

The enhanced performance of the static elastic modulus in concrete containing superplasticizers is ascribed to the improved bonding observed at the interfacial transition zone between cement and coarse aggregates [18]. Zhu and Bartos [33] have pointed out that the aggregate paste transition zone undergoes densification and stiffening, consequently leading to an improvement in the overall stiffness of the concrete.

Table 1. MoE of recycled aggregate concrete with no SP and with SP [18].

		RA incorporation (%)									
		0		10		25		50		100	
		Ecm28	St. Dev	Ecm28	St. Dev	Ecm28	St Dev	Ecm28	St Dev	Ecm28	St Dev
No SP	Valnor CRA	40.5	0.2	39.1	0.4	34.6	0	29.2	0.9	21.1	0.5
	Retria CRA			37.7	0	35.5	0.4	31.5	0.2	26.3	0
	Vimajas FRA			38.6	0.9	34.9	0.5	31.9	0.2	23.3	0.6
	AmbileiFRA			40.3	0.3	38	0.2	37.4	0.4	32.5	0.6
With SP	Valnor CRA	44.6	0.5	46.5	1	40.7	1.1	39	0.1	29.2	0.4
	Retria CRA			42	0.3	40.9	0.4	37.2	0	28.3	0.8
	Vimajas FRA			43.8	0.1	38.4	0.4	32.5	0.1	26.8	0.3
	AmbileiFRA			49.1	0.1	47.6	0.1	42.9	0.6	38.1	0.2

4. Durability

Concrete durability is characterized by its ability to withstand various forms of deterioration, including weathering, chemical attacks, abrasion, and other deteriorative processes. In essence, durable concrete retains its original form, quality, and functionality when subjected to environmental exposure [34]. The service life of concrete is deemed complete when it becomes unsafe and economically impractical.

The assessment of concrete durability involves various methods that examine transport mechanisms, such as sorptivity, porosity, water absorption, and sorption. These transport properties provide insights into the nature of pore size within the concrete material. Additionally, studies on chloride migration and penetration, as well as evaluations of resistance against sulfate and acidic attacks, are common methods employed to gauge concrete performance in the face of chemical challenges. This overview will specifically focus on sorptivity and rapid chloride penetration as key parameters in assessing concrete durability.

4.1. Sorptivity

Sorptivity, defined as the rate of water absorption in concrete pores through capillary suction, is a critical parameter [15]. Capillary sorptivity is influenced by the pore distribution and microstructural properties inherent in the concrete [2]. The sorptivity value of concrete plays a crucial role in assessing its susceptibility to the ingress of aggressive chemicals through the pores, potentially causing deterioration. Aggressive substances, such as sulfates and chlorides, known for their capacity to damage concrete, typically infiltrate through water transport. In experimental setups, water is commonly utilized as the primary transport medium, and a lower sorptivity value indicates greater resistance to water absorption, while a higher value implies the opposite.

In the investigation conducted by Manami *et al.* [15], the sorptivity of fly ash concrete was examined using various superplasticizers, namely PCE, LC, SMF, and SNF, and compared with control concrete. **Figure 5** illustrates the findings of Manami *et al.* [15], wherein the control concrete with 35% fly ash content is compared to superplasticizer concretes, also containing 35% fly ash. The study revealed that all concretes containing superplasticizers exhibited lower sorptivity compared to the control concrete. Furthermore, the research demonstrated that PCE-based admixtures were more effective in reducing the sorptivity of concrete than LS, SMF, and SNF superplasticizers.

Andrade Neto *et al.* [19] explored the utilization of sugarcane bagasse ash in concrete, replacing up to 20% of cement by weight with bagasse ash. The incorporation of bagasse in the concrete was accompanied by the addition of a polycarboxylate-based superplasticizer admixture. The sorptivity values obtained for reference, 5%, 10%, and 15% bagasse content were 0.21, 0.07, 0.05, and 0.04 $kg/m^2/min^{1/2}$, respectively. Their findings indicated that a combination of physical and pozzolanic effects played a role in reducing pore interconnectivity, consequently decreasing sorptivity.

In the studies conducted by Sardinha *et al.* [20], it was established that the inclusion of superplasticizers in concretes incorporating marble dust led to a reduction in water absorption. This reduction was attributed to the superplasticizers' ability to decrease the water-to-cement (w/c) ratio, consequently lowering the porosity of the concrete. **Figure 6** illustrates the results of sorptivity studies from Sardinha *et al.* [20].

Najimi *et al.* [35] conducted a study to assess the impact of natural zeolite on the durability properties of concrete. In their investigation, cement was replaced by 15% and 30% weight of natural zeolite, and a melamine-based superplasticizer was incorporated. The water penetration or sorptivity performance of the control concrete at 28 and 90 days was measured at 15 mm. However, in concrete with 15% and 30% zeolite content, the sorptivity levels were reduced to 13 mm and 11 mm, and 9 mm and 10 mm, respectively. After 28 days of curing, the water penetration depths of concrete with 15% and 30% zeolite were reduced by about 13% and 40% compared to the control specimens. At the age of 90 days, the performance of concrete with 15% and 30% zeolite was nearly identical and approximately 33% better than non-zeolite concrete.

Various studies have highlighted the reasons why incorporating superplasticizers (SPs) in concrete results in lower sorptivity. Authors suggest that SPs enhance cement hydration and improve the compactness of the concrete matrix, thereby reducing permeability [36] [37]. In the case of concretes containing both SPs and pozzolans, SPs enhance the pozzolanic action, contributing to the denseness of the concrete and consequently lowering sorptivity [35].

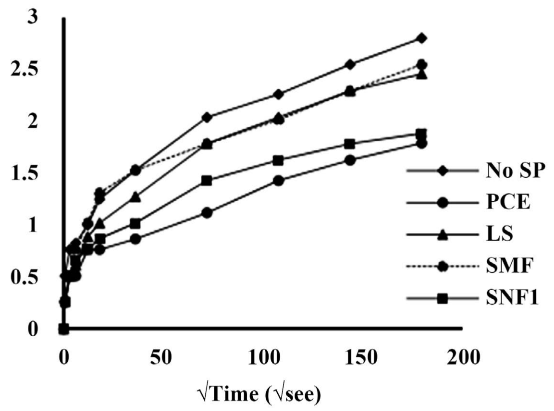

Figure 5. Sorptivity coefficient of concrete containing different types of superplasticizers [15].

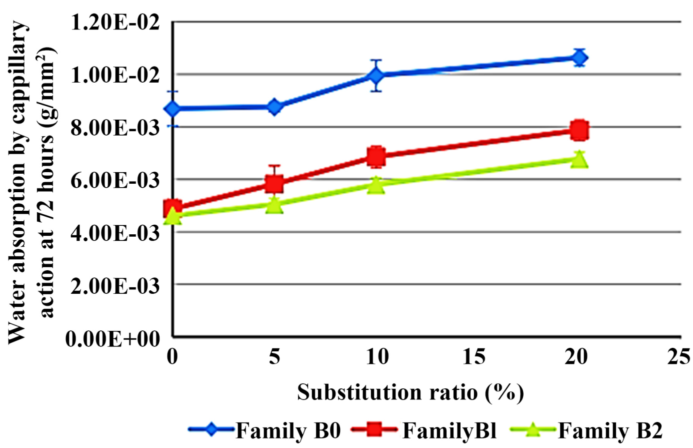

Figure 6. Water absorption after 72 h [20].

4.2. Rapid Chloride Permeability Test (RCPT)

The assessment of concrete durability commonly involves studying its resistance to chloride penetration, which is closely linked to low permeability, a dominant factor in the deterioration process [38]. Chloride ion corrosion represents a major failure mode leading to a decline in the mechanical properties and durability of concrete [39]. The Rapid Chloride Penetration Test (RCPT) is a widely used method for evaluating concrete durability. This test is based on the principle that negatively charged chloride ions are attracted to a positive electrode. It involves measuring the total charge passed through a concrete sample over a six-hour duration, applying a direct current potential difference of 60 V across the sample ends [40]. The total charge passing through the concrete is considered indicative of the permeability of the concrete to chloride ions.

Table 2 presents the findings from the research conducted by Ramachandran *et al.* [2], where three different types of concrete were produced: one without a superplasticizer (NC), another with SNF superplasticizer (SP), and the third with fly ash and SNF superplasticizer (FA). The results indicate that concretes labeled FA and SP exhibited lower permeability compared to the concrete without SP and/or FA. The combined effect of FA and SP significantly reduced chloride permeability.

Summarizing the performance of concretes containing superplasticizers, it is evident that they offer superior resistance to the ingress of chloride ions compared to concrete without superplasticizers. This enhanced performance is attributed to the increased compactness of concrete when superplasticizers are included. Superplasticizers are recognized for reducing the water-to-cement ratio of concrete while simultaneously improving its workability. Tkaczewska [22] has suggested that as the water-to-cement ratio decreases, total porosity is also reduced, leading to an improved density of the concrete.

Table 2. Chloride permeability test [2].

Concrete type	Chloride permeability test (in Coulombs)		
	90 days	180 days	365 days
NC	7302.6	2261.5	2730
FA	284.1	526.5	120
SP	3030	2332.5	2180

5. Conclusions and Recommendations

While the use of superplasticizers (SPs) in concrete is well-established in the global north, there is a notable lack of awareness in the global south regarding their application in concrete works. This study provides a concise overview of the mechanical and durability properties of concrete with and without SPs. Mechanical properties such as compressive strength, flexural strength, and modulus of elasticity are covered, along with durability indicators like water sorptivity and chloride penetration using the rapid chloride permeability test.

The overview underscores that the inclusion of SPs in concrete enhances both mechanical (compressive strength, flexural strength, and modulus of elasticity) and durability properties (water sorptivity and chloride penetration) compared to concrete without SPs.

In the case of compressive and flexural strength, the superior performance of concrete with SPs is attributed to lower porosity resulting from reduced water content and increased denseness or compactness of the concrete. Regarding modulus of elasticity (MoE), the enhancement seen in SP-included concrete is linked to the improved interfacial transition zone (ITZ) between the paste and aggregates, leading to a stiffer and denser concrete matrix. These factors of denseness, concrete compactness, and low porosity are also key in explaining the improved performance of SP-included concrete compared to non-SP concretes.

Given that the overview demonstrates the positive impact of SPs on the mechanical and durability properties of concrete, it is anticipated that this study will provide valuable information to building professionals, particularly in the global south, emphasizing the importance of incorporating SPs in concrete formulation.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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