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REVIEW PAPER

Effects of Inclusion of SAP as an Internal Curing Agent in Concrete, A Review

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ABSTRACT: Concrete in today's world has a major role in construction industry and is the most frequently used material in construction having high compressive strength and durability. Concrete needs proper curing to achieve desirable properties and insufficient curing affects the strength of concrete badly. Nowadays, Internal Curing (IC) has come into research which has many positive advantages in terms of enhancement of properties of concrete. By utilizing the water that is already in the concrete and adding certain amounts of self-curing agents, this method of curing is used that helps in the curing of the concrete internally. It is done 'from the inside to outside' using internal reservoirs. Also, shrinkage reducing agents like Polyethylene-glycol and Light-Weight Aggregates (LWA) are used to achieve effective curing results. In cement-based materials, Superabsorbent Polymer (SAP) is generating a lot of debate. This study offers a review for cement-based materials containing SAP for different w/c values, the conclusions on the properties including workability, mechanical characteristics, and durability of SAP-modified concrete and SAP cement-based materials. In most of the studies found on high-performance concrete, w/c is restricted to 0.3 - 0.35. Hence, properties are described on the basis of different w/c ratios as mentioned in this paper. Total 60 articles are reviewed (including 59 research paper and 1 review report) in this study.

Keywords: Internal Curing, Concrete, Superabsorbent Polymer, Mechanical Properties, Hydration Process.

1. Introduction

There might be an urgent need to look into water conservation in concrete and building construction that water resources become more scarce. The curing effect is crucial to getting the desired qualities out of concrete. Efficient concrete curing preserves the moisture content of the concrete, which aids in the preservation of an efficient hydration process in early age. The process of curing involves keeping the concrete at the right temperature and moisture level for a certain period of time before it hardens. Promoting cement hydration and reducing shrinkage are two main objectives of curing, in order to enhance concrete properties at later stage.

There are various curing techniques,

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including internal, exterior, and sealed curing. According to Wang et al. (2019), Internal Curing (IC) can stop UHPC from desiccating on its own, while external curing methods like water curing cannot.

The effect of temperature altered thermal curing was also discussed by Shen et al. (2019). They concluded that the development of UHPC strength is significantly influenced by thermal curing. The process used to produce C-S-H gels results in a dense microstructure, which greatly boosts the material's strength. The formation of quartz and the formation of hydrates and microstructures as a result of different curing regimes are important factors in the erratic behavior of the strength ratio and the enhancement of mechanical properties.

IC is a potential approach to remove cracks in cement concrete, which have become a major problem. It is the process of adding porous substances into cement-based products to create "reservoirs" that quickly provide water when hydration is required or to compensate moisture loss. The water which is already present in cementitious materials may release during the hydration process due to the effect of capillary tension and humidity gradient. The advantages of internal curing include higher internal moisture content results in better hydration and higher relative humidity. Thus the concrete does not require external water curing (Amin et al., 2021). Super-Absorbent Polymers (SAP) and Lightweight Aggregates (LWA) like zeolite or natural pumice are frequently used as internal curing materials (Liu et al., 2019). Concrete experiences autogenous shrinkage during cement hydration, which is characterized by lack of moisture exchange with the surrounding environment. Although, autogenous shrinkage is minimal, it can be significant in concrete that has a very low water/cement ratio (Neville, 1995).

Hamzah et al. (2022) demonstrated that SAP aggregates can decrease the autogenous shrink ability of UHPC without changing its new behavior, mechanical properties, or density. Wang et al. (2022) demonstrated that SAP has a high moisture-carrying ability and may have enhanced self-healing properties. The qualities of concrete will be also improved by the size and quantity of SAP. When SAP is added, regulated water-filled microscopic inclusions are created.

These inclusions lessen autogenous shrinkage, encourage the hydration of anhydrate cement, and stop internal moisture evaporation from compensating for water loss during the curing process. The autogenous shrinkage and chemical shrinkage are roughly equal in the initial stages of hydrations, before hardness occurs (Ghanem et al., 2024). SAP has the following advantages over light-weight aggregates. IC may only require a small amount of SAP, and neither the workability nor the mechanical qualities will be significantly affected (Jensen and Hansen, 2001). To increase the resistance of material to the effects of freeze-thaw, SAP might be used as an air-entraining substance (Jensen and Hansen, 2001). During the preparation of the specimen, the water absorption rate of SAP can be determined.

1.1. SAP (Superabsorbent Polymer)

Superabsorbent Polymer (SAP), a cross-linked hydrophilic polymer, also termed as slush powder, mostly white in colour and in powdered form. Several studies have been made on the SAP regarding its cross-linked densities such as: Zhong et al. (2019) discovered that SAP exhibiting a high density of anionic groups or both ionic groups demonstrated an enhanced self-curing effect in minimizing autogenous shrinkage. Additionally, much less released water was seen in the case of SAP exhibiting a low density of anionic groups. Furthermore, a minor effect was observed for non-ionic SAP with increased crosslinking density, but lower equilibrium absorptivity was the result for ionic and zwitterionic SAP.

When SAP comes in contact with water,

it instantly increases in size after absorption of water and transforms into a hydrogel structure with a certain viscosity. SAP particles can absorb large amounts of water during the mixing process and then swell to produce a hydrogel, due to the creation of water incorporation which prevents self-desiccation during cement hydration (Yang et al., 2019) Superabsorbent polymers (SAPs) can be added to a concrete mixture to provide IC and reduce the risk for early-age shrinkage cracking. Jensen and Hansen (2002) used SAP as IC in high performance concrete. Dejian et al. (2020) utilized SAP in order to decrease the high-strength resistance to cracking of concrete.

The autogenous shrinkage was enhanced with SAP. There was a greater increase in the w/c ratio, which improved the mechanical properties, shrinkage, and creep. SAP has good water absorption and retention abilities. SAP readily absorbs water while making cement-based products. the development of a water wrapper vicinity of the SAP particles is facilitated by the absorption capabilities of SAP and the ionic concentration of cement paste. As the material's internal humidity lowers during the curing process, the osmotic pressure rises, causing the water inside SAP to slowly release.

Cement-based products may develop cracks during the course of their service lifespan as a result of loading and environmental influences. It has been demonstrated that materials made with SAP cement have self-healing qualities (Snoeck et al., 2014). Water can react with anhydrate cement in ordinary concrete with no SAP penetrates its tiny cracks, providing the hydration support and enabling the filling of the small cracks. The said self-healing crack width limit is 0.05 mm or smaller (Snoeck et al., 2014). However, the average crack width produced by external forces is more than 0.05 mm.

When SAP is used in cement-based products as a self-healing additive, it can slowly let go the water to interact with the surrounding anhydrate cement. The hydration products created may help in the healing and subsequent filling of the micro cracks. Additionally, when water enters SAP, the SAP gel expands and fills macro cracks, restricting the flow of water. It was previously noted that as water flows through cracks, the SAP molecules nearest to the upstream side expand into a gel-like substance that covers the voids and cracks in the SAP, while those towards the downstream face remain dry (Snoeck et al., 2014). Larger SAP particles may leave larger pore volume in cement-based products after they release water. Yet it was claimed that the cement's continued hydration was a result of a water loss, which led to decrease the porosity at hardened state (Igarashi, 2006). The high-water absorption capacity of SAP has an impact on the mechanical properties and fresh state of cement-based composites.

According to reports, SAP had a negative impact on mechanical properties, especially at early stage (Wehbe and Ghahremaninezhad, 2017). According to Klemm and Sikora (2013), the mechanical properties of SAP cement-based materials are significantly influenced by the SAP type and the water absorption and desorption kinetics. Faxiang et al. (2021) investigated the structural behavior of SAP concrete under constant load. Also, examined the shear and compression properties of concrete. They demonstrated that although the cohesive stresses and the friction coefficient of the compression-shear strength dropped as the SAP content increased, the resulting residual strength and the compression-shear strength of SAP improved linearly with the axial pressure.

Lokeshwari et al. (2021) assessed several strength analyses using a superabsorbent polymer to add SAP agent Polyethylene glycol 400 to M30 grade concrete mixture to produce high compression strength. As a result, concrete will have greater strength than regular concrete when PEG-400 is applied properly. In dealing with the issue of water scarcity, Khushpreet Singh (2020) explored a variety of techniques to address this issue. In addition to resulting in poor curing, self-desiccation can adversely affect the energy and durability of the concrete. According to Jensen (2008), the dried SAP particulate may alter the plastic viscosity of fresh concrete, which would affect the rheological behavior of the concrete.

The SAP content and additional water that should be included in a mix design for cement-based products must thus be carefully considered. Additionally, there is not any specific process for designing SAP cement-based material yet. Hence, there are variations between the diverse behavior of SAP materials based on cement. Critical issues include how to accurately calculate the SAP cement-based mix proportions products and comprehend how differing SAP contents affect the fundamental mechanical properties.

2. Rheological Properties of Sap-Based Cement Concrete (CC)

The rheological properties of CC with inclusion of SAP; are influenced by its tendency to absorb water and the gel formation. Although there are many characteristics that affect how workable CC is (including fluidity, viscosity, mobility, compaction ability, etc.). The concept of workability is a little bit complex. The Bingham's model by Bingham (1922) shows concrete as a non-Newtonian fluid and can be represented by the Eq. (1).

$$\tau = \tau\_0 + \mu\gamma \quad (1)$$

where τ: is shear stress; τ_o: is yield stress; μ: is plastic viscosity and γ: is rate of shear strain. The rheological characteristics of CC are influenced by the plastic viscosity (μ) and yield stress (τ_o). For illustrate, these previous two factors have an inverse relationship with the workability of the CC.

The extra water (IC water) provided has an impact on how SAP behaves to the matrix's rheological characteristics. For illustration, the workability of SAP incorporated CC will decrease if no additional water is supplied and the contrary will happen if IC water is provided (Jensen and Hansen, 2002). However, Shen et al. (2021) have shown that the workability of the cementitious composite is greatly reduced when SAP is used. The temperature, as well as the size of the SAP used, affect how well CC works as explained by Figure 1.

The solid lines indicate the absence of SAPs, while the dashed lines indicate the presence of SAPs (Secrieru et al., 2016). Figure 1 illustrates how cement pastes with and without SAP's plastic viscosity and yield stress change with temperature. It is clear that plastic viscosity and yield stress steadily rises at temperatures that are higher (20 °C and 30 °C) whereas at lower temperatures, the same parameter reduces rapidly.

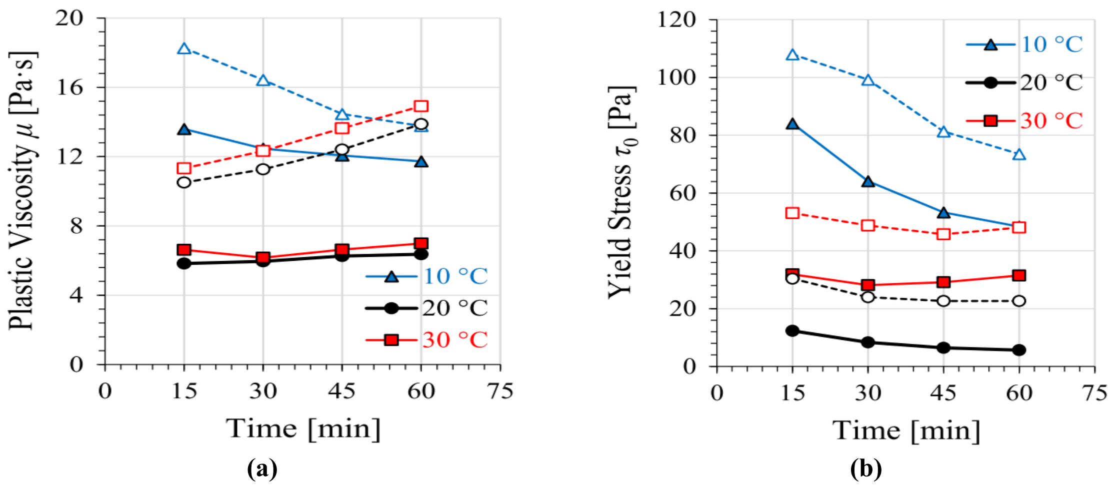

Fig. 1. Effects of temperature on plastic viscosity and yield stress

Table 1. Statistical parameters values for testing and training by M5P model

Type of composite	Compressive strength of reference mix (MPa)	w/c ratio	Size of SAP particles (µm)	Dosage of SAP	Slump (mm)		References
					Reference mix	Modified with SAP	
HPC (High performance concrete)	97.6	0.32	-	1.11 (kg/m^3)	45	75	Craeye et al. (2011)
				1.56 (kg/m^3)		40	
				2 (kg/m^3)		60	
UHPC (Ultra-high performance concrete)	-	0.15	< 63	0.206%	1060	770	Justs et al. (2015)
				0.313%		710	
HPC	93.2	0.25	441	0.18%	70	85	Savva and Petrou (2018)
			384	0.20%		80	
Normal concrete	45-50	0.38	25-425	0.2%	212	200	Dang et al. (2017)
			150-180			190	

It may also be observed that the SAP inclusion in cement pastes enhances yield stress and plastic viscosity, which reduces workability (Secrieru et al., 2016). However, SAP particle size has also an impact on the rheological characteristics of CC, as per a study that investigated the impact of particle size (fine versus coarse) and ways of addition of SAP (i.e. dry or pre-soaked). According to Ma et al. (2019) the workability with large particle size reduces due to increment of yield stress and plastic viscosity.

The findings displayed how fine SAP enhances workability significantly than coarse SAP and adding pre-soaked SAP is more effective in enhancing workability than using dry SAP, which can be related to dry SAP's ability to absorb more mixing water (required for hydration). In conclusion, the direct incorporation of SAP to the matrix causes an increase in CC's plastic viscosity (or its workability to decrease). To improve the matrix's utility, more IC water as well as pre-soaked SAP is required. But according to the literature analysis, because the method of water release for SAP during complicated hydration processes (of cement and water) is unforeseen, SAP's impact on rheological characteristics of CC can be unpredictable. Thus, additional research is essential for fully comprehending how SAP affects the characteristics of CC's rheology.

3. Mechanical Properties and SAP

According to the majority of research studies on CC with SAP, the development of pores and voids in the hardened CC matrix causes mechanical properties including compressive, flexural, and tensile strength decline with time, mainly in the first phases (Jensen and Hansen, 2002; Craeye et al., 2011; Wong, 2018). While other research has also demonstrated that mechanical strength makes up for age at maturity (Qin et al., 2011). Table 2 shows the effect of SAP on different mechanical properties; mentioned in different research studies which shows the variation in mechanical properties like compressive strength, flexural strength, split tensile strength, etc. at matured age. In conclusion of Table 2 it is clear that the mechanical properties at matured age has slight variations (i.e. slightly increased or decreased). Here, Table 3 shows the effect of SAP modified cc under different curing conditions.

In conclusion, the majority of the above findings show that CC's mechanical properties are decreased by SAP inclusion. However, by using different fibres or additives, the strength loss can be countered (or increased). Moreover, the mixture composition and curing circumstances influence how SAP inclusion will respond to CC's mechanical properties.

Table 2. Effect of SAP on different mechanical properties

Type of composite	w/c ratio	Mechanical property	Strength (MPa) (28-days) (without SAP)	Strength (MPa) (28-days) (with SAP)	References
Mortar	0.48	Compressive strength	42.02	63.92	Tan et al. (2019)
UHPC	0.15	Compressive Strength Flexural strength	183 24	184 26	Justs et al. (2015)
Mortar	0.30	Compressive Strength	89.6	92	Sensale and Goncalves (2014)
Cement paste	0.45	Compressive strength Flexural strength	43.35 6.5	41.8888 6	Pourjavadi et al. (2012)
HPC	0.38	Compressive strength	52 55.5	53 56	Dang et al. (2017)
Normal concrete	0.45	Compressive strength Flexural strength Split tensile strength	36.9 4.25 3.75	39.11 43 3.70	Karthikeyan et al. (2018)
Normal concrete	0.5 0.4 0.35	Compressive strength	51 69 73	43 58 67.5	Hasholt et al. (2010)
HPC	0.25	Compressive strength	93.2	80.4 81.6	Savva and Petrou (2018)

Table 3. Effect of SAP modified CC under different curing conditions

Composite types	Mechanical property	Various curing condition			Remarks	References
		Sealed	Dry	Moist		
HPC	Compressive strength	16-31	-	-	Decrease	Craeye and Schutter (2008)
Normal concrete	Compressive strength	28-35	26-28	-	Decrease	Lam (2005)
HPC	Compressive strength	-	-	3-22	Decrease	Igarashi and Watanabe (2006)
	Tensile strength	-	-	11-33	Decrease	
HPC	Compressive strength	12-14	-	-	Fluctuations at water curing i.e. almost same	Savva and Petrou (2018)
HPC	Compressive strength	30	20	-	decrease	Mechtcherine et al., (2006)
UHPC	Compressive strength Flexural strength	-	-	Same	No change	Dudziak and Mechtcherine (2008)

4. Impact of SAP on Durability

The ability of CC to withstand a number of damaging elements, the cost of long-term maintenance and repair of mechanical and aesthetic components and properties, to be designed as per requirement enhances its employability as a construction material. Many methods (including the integration of SAP in CC**)** are employed to make concrete constructions more durable because of the high expense of maintenance and reconstructions.

Here, literature pertaining to permeability and freezing behavior of concrete is discussed, on the behalf of which durability can be comprehend.

4.1. Permeability

The permeability of a concrete specimen under examination can be estimated by determining its pore structure, which includes pore size, pore distribution, and cumulative surface area. This information then helps to evaluate the specimen's durability (Jindal and Ransinchung, 2022). The property of CC that regulates the flow rate of fluids such as water, CO_2 etc.; into the porous solid is termed to as permeability. This characteristic is influenced by the size, connectivity of voids/pores, and viscosity of the fluid (Liu et al., 2018, 2019). This could be considered to explain why SAP incorporation in CC makes it more impermeable. SAP swells after absorbing water, which resists further water or gas entry. When SAP releases absorbed water, hydration takes place, and form hydration products which further leads to filling of voids and reduce ingress of water.

There is very less literature available regarding the effect on permeability of CC due to inclusion of SAP. However, the studies available are discussed to evaluate the effect of SAP on permeability of concrete. Snoeck et al. (2012) performed permeability test on samples having SAP and not having SAP. The results showed that the samples having SAP had diminished permeability because of swelling of SAP which cease the voids and lowered the ingress of water. On the other hand; the samples without SAP were susceptible to water penetration (even in less than 40 s).

The impact of SAP on concrete's chloride migration coefficient was investigated by Hasholt et al. (2015) using neutron tomography. In comparison to samples without SAP, the results showed that adding SAP (without IC water) improved chloride migration. This increase in chloride migration was attributed to the decline in the w/c ratio carried by SAP's water absorption. It was claimed that SAP could only enhance chloride migration and boost hydration in the presence of IC water.

Dang et al. (2017) conducted research on the chloride migration coefficient of concrete containing SAP. Compared to the SAP-free specimen, it was claimed that SAP dramatically lowers the concrete's chloride migration coefficient. They attributed this to the development of a pore structure with smaller pores following the addition of SAP, which prevents the capillary pores from connecting. Ma et al. (2017) investigated into the impact of the size of the SAP particle on the chloride migration coefficient in a cement mortar.

The results show that bigger SAP performs better than smaller SAP in preventing chloride ion migration. They provided an explanation for this by pointing out that between the hardened cement matrix and the SAP void, larger SAPs produced better ITZ than smaller ones. Graf et al. (1986) tested mixes at various temperatures to see how temperature affected the concrete and mortar's permeability including gas and fluid in different regions. They found that increasing moisture contents result in lower permeability. Furthermore, it was highlighted that SAP-incorporated specimens displayed lower permeability than reference specimens under standard climatic circumstances (temperature: 20 °C and RH: 65%), which might be related the delay in self-desiccation of specimens with SAP. In conclusion, adding SAP to CC may decrease permeability of ions, gases and liquids. But the size, curing conditions, w/c ratio, and inclusion of IC water all have an impact on how well SAP reduces permeability.

4.2. Frost Resistance

The phenomena of crack occurrence known as freeze-thaw only happens in cold climates when water that seeps into CC cracks and freezes to form ice which results in expansion due to volume enlargement of ice formed which results in further cracking known as freeze-thaw cracking. Many preventive measures, such as an efficient design of cement concrete, should be implemented because freeze-thaw cycles have a negative effect on CC. To produce CC for better frost resistance, air entrainment is generally used. Some of the technical difficulties expected to be noticed during the air entrainment process include the air void distribution and void reduction caused by pumping or other factors, and voids not being compatible with other admixtures such as superplasticizers.

Air entrainment is a void system that is problematic because of the issues mentioned that cannot successfully withstand freeze-thaw cycles. Although

SAP properties (such as size, volume distribution) may be customized to satisfy required criteria, SAP has been found to be a great substitute to increase CC's resistance to freezing as shown in Figure 2a (Wong, 2018; Mignon et al., 2017). As previously explained, the swollen SAP particles shrink after SAP desorption, causes uniform distribution of air-filled voids in the matrix as shown in Figure 2b. The voids produced by SAP can be used to generate space for pore water expansion during freezing, boosting CC's resistance to frost.

According to several research such as Mignon et al. (2017) on the effectiveness SAP's ability to provide frost protection, CC modified with SAP (with or without IC water) is more resistant to frost than CC that has not been modified with SAP. The improvement in frost resistance of concrete/mortar with SAP-incorporated (without extra water) can be explained by the decrease in the water cement ratio and the allocation of SAP-created voids to accommodate ice formation. Additionally, the creation of SAP voids and the further hydration of unreacted binder granules are responsible for the performance of SAP (with additional water) modified CC against protection from frost. Due to their greater stability during mixing and transportation, SAPs exceed air-entrained admixtures in terms of frost resistance. Moreover, voids produced by SAP are permanent and can be built in the optimal and as desirable.

In addition to the benefits of SAP against resistance to frost that have previously been mentioned, there are a few other areas that need to be investigated to establish SAP's incorporation. For instance, due to frequent freeze-thaw cycles or the hydration of SAP gaps, SAP incorporated CC cannot offer long-term frost resistance. A summary of a several research on how well SAP performs regards frost resistance is discussed as below.

According to Hasholt et al. (2015), smaller SAP voids are more effective in resisting frost than larger ones. But according to other research, freeze-thaw cycles are more likely to affect small SAP voids (Mignon et al., 2017). Jones et al. (2014) used concrete that had been pre-soaked SAP of size 1 mm and exposing it to three hundred thawing-freezing cycles. The results showed that concrete cannot be protected from cycles of freezing and thawing by large-size SAPs.

To analyze the SAP's interface form with a distinct particle sizes but identical quantity, Assmann et al. (2013) employed image analysis. As a result, it can be seen that amount of void space produced by SAP is not affected by the particle size. Additionally, it was shown that SAP's ability to absorb moisture is unrelated to how well it resists frost. According to Reinhardt et al. (2012), scaling in SAP-incorporated concrete with particle sizes lower than 63 m was twice as large following twenty-eight cycles of freezing and thawing as scaling in SAP with particulate having sizes between 63 and 125 μm. In conclusion, SAP provides better protection from frost when compared to air-entrained admixtures. Their output is influenced by the size, spacing, and number of SAP voids that are produced, among other factors.

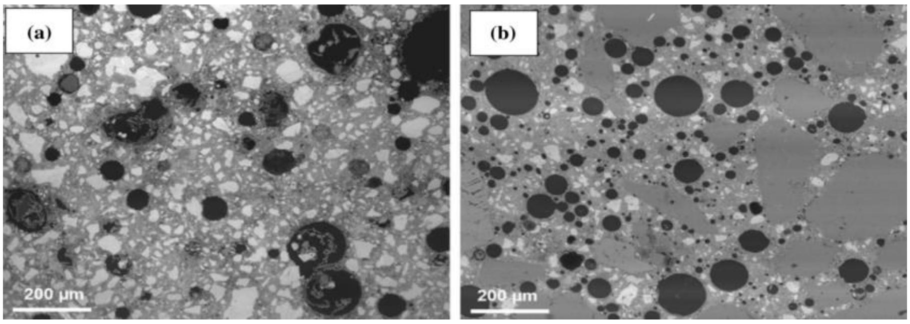

Fig. 2. For resistance to frost, CC with: a) SAP and; b) SAP-created air gaps (Wong, 2018)

Further, research should be carried out to extend SAP's resistance to the cracking brought on by freeze-thaw cycles. To get a unified conclusion, it is also important to thoroughly investigate the contradictory opinions of researchers regarding the variables (particularly the size of voids produced by SAP) that affect SAP's performance in terms of resistance to frost.

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5. Challenges and Discussions

The challenges are found as per the study are described below:

- Optimum dosage: One of the most challenging thing is to decide the optimum dosage/ amount of SAP to be added in the cement concrete
- Sorption kinetics: The testing methods to check the sorption kinetics such as absorption and desorption behavior.
- Design mix: It is also difficult to determine how much extra water needs to be added to the design mix in order to decrease issues like segregation, bleeding and to evaluate the workability, slump, handling of cement concrete etc.
- Durability criteria: The assessment of the resistance to cracking, shrinkage, chemical attack, and other durability concerns of SAP-modified concrete, over the life span of the structure is also not easy.
- Economic consideration: Considering the economic viability of SAP-modified concrete, including the additional cost of incorporating SAP compared to traditional concrete.
- Environmental impact: Evaluation of the environmental implications of SAP-modified concrete, such as the sourcing and disposal of SAP materials and their impact on the environment and sustainability is not being discussed yet.

6. Conclusion

From the investigation of the use of SAP as an IC agent in concrete in past studies, the following findings are made.

- Inclusion of SAP may lead to reduction in compressive strength at early ages. However, the compressive strength at 28 days (with matured age) could equally or slightly increased. Hence, the type of SAP has an influence on cement's mechanical properties and absorption/desorption kinetics of different SAP available.
- According to published research, adding SAP to concrete increases its tensile strength at mature age. Tensile strength is related to cracking; hence, self-desiccation and shrinkage reduction will increase cracking resistance.
- Tensile strength is sensitive to cracking; so there will be an improvement of cracking resistance by means of self-desiccation / shrinkage mitigation.
- Higher SAP dosage cause strength reduction, so SAP should be used in optimum amount (i.e. the behavior of concrete regarding its mechanical properties are influenced by the optimum amount and particle size of SAP used. The optimum dosage of SAP was found 0.3-0.4% of weight of cement).
- Although it has been discovered from earlier studies that additional water must be supplied for the IC in order to prevent SAP from absorbing the water provided for hydration, there will be a workability improvement. This will also result in a reduction of the w/c ratio, strength, and workability (slump).
- There will be reduction of permeability of water due to inclusion of SAP and improve chlorine migration as discussed above. SAP addition decreases permeability as per the curing conditions, the water-to-cement ratio, and the addition of IC water
- According to the literature cited above a bout the impact of freeze and thaw, SAP in clusion can lessen or resist the frost action.

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