DOI: https://doi.org/10.52756/ijerr.2024.v38.007 ***Int. J. Exp. Res. Rev.*, Vol. 38: 69-88(2024)**

Review Article | *Peer Reviewed* | *Open Access*

International Journal of Experimental Research and Review (IJERR)

ISSN: 2455-4855 (Online)
www.iaph.in
ISSN 2455-4855

Polycarboxylate Superplasticizers Used in Concrete: A review

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Article History:

Received: 08th Oct., 2023
Accepted: 14th Mar., 2024
Published: 30th Apr., 2024

Keywords:
Cement, chemical admixture, concrete, PCE, polycarboxylate, superplasticizers, water-reducer

How to cite this Article:
Uppala Venkata Narayana Rao, Namepalli Venkata Sairam Kumar, Chagarlamudi Kavitha, Yellinedi Madhavi and Ponduri Samatha Chowdary (2024). Polycarboxylate Superplasticizers Used in Concrete: A review. *International Journal of Experimental Research and Review*, *38*, 69-88.
DOI:
https://doi.org/10.52756/ijerr.2024.v38.007

Abstract: Modern concrete frequently uses a variety of chemical admixtures, like setting time-retarding admixtures, viscosity-modifying admixtures (VMA), and superplasticizers (SPs). These chemical admixtures greatly impact cement components like film-forming capacity, flowability, and film drying time. Currently, the market provides a broad variety of chemically distinct polycarboxylate (PCE) products; of these IPEG and HPEG PCEs have a wide market share due to their cost-effectiveness. New PCE types such as GPEG and EPEG PCEs are currently being introduced, which will expand the family of vinyl ether (VPEG) SPs. In summary, this study examines the chemistry, functionality, the interaction between the chemical structure of PCEs and their behavior with concrete and/or cement-based materials (CBM). The performance of concrete and/or CBM is significantly influenced by the chemical structure of PCE, along with their main chain, anchoring group, side chain, molecular weight, and structure. In conclusion, more precise quantitative micro-analytical methodologies and modelling tools are required to get a comprehensive grasp of the variables influencing the microstructure of concrete and to apply PCE SPs to create more durable concrete.

Introduction

SPs are used to make concrete more fluid without adding much water. These molecules physically separate the particles by using steric and/or electrostatic forces to oppose the cement particles' attraction forces. Therefore, the concrete becomes easier to place. Long-term (at least one to two hours) concrete workability is advantageous for various operations, including pumping, pouring, transport, compaction, and casting. Because of these significant and varied advantages, SPs are now essential components of contemporary concretes. They can be employed, for instance, to improve workability by not changing the water-to-cement (w/c) ratio, which regulates the properties of CBM (Gelardi and Flatt, 2016; Rani et al., 2022).

Further, SPs are used to reduce the workability of concrete by lowering its w/c ratio without sacrificing it (Aitcin, 1998; Dodson, 1990). When cement is partially replaced with mineral admixtures that react slower with water, SPs can be used to make up for the cement's initial lack of strength (Bilodeau and Malhotra, 2000; Caric and Mladenka, 2001). As a result, SPs can be used to lower the cement quantity in concrete, thereby lowering the carbon footprint of concrete produced. Reducing water use, using less concrete to reach its load-bearing capacity,

***Corresponding Author:** sairam852@gmail.com and increasing the service life of concrete through improved properties are a few more environmental advantages (Flatt et al., 2012). The concrete must satisfy all specifications both in the hardened and fresh states, and manufacturers of modern concrete must make sure that it does. Concrete can contain a variety of chemical admixtures. It is best to avoid situations when admixtures and/or cements are incompatible with one another. Sometimes, in certain situations, the producer is forced to discard some batches of concrete due to unanticipated behavior. The toughness of the concrete mixture is weakened as a result, and it becomes harder to maintain a consistent quality over time (Kumar, 2021; Kumar et al., 2019; Nkinamubanzi et al., 2016).

With the rise of high-rise structures and infrastructure, cement concrete is a building material that is widely utilized worldwide. By 2050, demand for it will reach a high of 18 billion tonnes annually. New/advanced materials with remarkable endurance and strength are being created in the market thanks to the advancement of material technology (Kumar et al., 2022; Tran et al., 2024). To be more precise, because of its exceptional strength and longevity, high-strength cement concrete is widely utilized across the globe. One of the main ingredients in the creation of concrete is cement, which accounts for around 8% of all CO_2 emissions worldwide. One tonne of cement, for example, produces 1.25 tonnes of CO_2 emissions because of the decarbonization of limestone and the energy needed for high temperatures of the cement kiln, which accounts for 60-45% and 35-40% of CO_2 emissions, respectively. Researchers and material specialists are calling for a drastic reduction in the amount of cement used in concrete. Efforts are being made in labs and industry to identify low-carbon additives to lower the amount of carbon released into the atmosphere (Kumar et al., 2024; Antunes et al., 2021).

Modern concrete still depends on chemical admixtures to improve its properties, and they are necessary for producing different types of quality concrete. Concrete frequently uses a variety of admixtures, such as setting-retarding admixtures, viscosity-modifying admixtures (VMA), and SPs. SPs are, without a doubt, at the cutting edge of chemical admixture technology, both in terms of their sheer amount and their potential to improve the properties of construction materials (Aitein and Baalbaki, 1994; Mehta, 1999; Kumar et al., 2022). The yearly output of PCE SPs alone has topped 10 million tones, and manufacturers are continuously joining the industry with SPs based on cutting-edge molecular designs or advanced technological knowledge uniquely adapted to local demands (Flatt, 2004; Ma et al., 2021; Flatt et al., 2001).

A cementitious material's rheological characteristics, such as its thixotropy, plastic viscosity, and yield stress, dictate how well it works in the construction field including mixing, pumping, and even the strength and durability properties. Several PCE SPs have been developed and extensively applied to achieve appropriate rheological qualities during the past few decades. Research on augmenting SPs and their relationships to rheological behavior under different building needs has drawn more interest from both industry and academics. Even though cementitious materials seem appropriately flowable after mixing, processing them after a resting period can be challenging since they do not return to their initial flowability. In the case of CBMs combined with PCE-SPs, the formation of hydrates may bury, cover, or over-absorb the PCE that has been adsorbed on the particle surface, which will reduce its capacity to disperse and cause fluidity loss. Yet, retarders are used in conjunction with PCE to decrease the hydration impact. But this could, especially easy on, lead to a reaction in the cementitious material's mechanical strength. The impact of resting time on the rheological properties is associated with the persistent hydrate development as well as the presence of various ions and PCE molecules in the suspension's liquid phase (Ji et al., 2024; Costa et al., 2023; Boukhsib et al., 2023).

Utilizing inorganic/organic composite techniques, several researchers have successfully produced high-quality composite materials. Polymer molecules with an extended side chain attached to a backbone resembling a comb are PCE-SPs. Functional groups that are negatively charged, like phosphonic, sulfonic, or carboxyl groups, are incorporated into the backbone (Wang et al., 2024). PCE nanocomposites have shown good early strength characteristics and notable improvements in mechanical properties when compared to CBMs. Their efficiency makes them ideal for emergency repair jobs needing quick construction as well as non-steam curing, high-strength concrete projects. Furthermore, partial cement substitutes like pozzolanic and or non-pozzolanic admixtures are commonly used in the cement industry to reduce CO_2 emissions. Unfortunately, the performance of cement is negatively impacted when these additional cementitious components are integrated since they frequently slow down the pace at which cement hydrates. These shortcomings are successfully offset by utilising PCE nanocomposites, improving low-carbon cement's overall performance and early hydration rate. This innovation could broaden the range of applications for low-carbon cement applications (Shu et al., 2016; Sabzi et al., 2024; Wang et al., 2024).

Polycarboxylate Superplasticizers

In 1981, a PCE concrete water reduction agent was developed. In comparison to lignosulfonate, melamine, and naphthalene-based SPs, it has several advantages, including the ability to maintain concrete workability and diffuse cement particles at low dosages without increasing setting periods (Ran et al., 2010; Liu et al., 2013). As a result, it is being utilized in producing high-performance concrete (Yamada et al., 2010; Erzengin et al., 2018). Due to the PCE's typical structure, it can be redesigned or altered by alternating the functional group composition, the backbone's length, or the density or length of the side chain with obtaining favorable properties of cementitious products (Etsuo and Masaki, 2002; Winnefeld et al., 2007; Zingg et al., 2008; Abile et al., 2018). According to many experiments, PCEs with various chemical structures performed quite differently when made of cementitious materials. For instance, PCEs with a high carboxylic group content (-COO^-) readily adsorb on cement particle surfaces and show poor slump retention but good initial dispersion. PCEs with many grafts or long side chains exhibit a distribution effect on the cement, and the side chain length influence on cement hydration will be delayed (Liu et al., 2013; Yamada et al., 2010; Erzenign et al., 2018).

It is widely believed that the anions on the PCE backbone serve as anchors, adsorb on the surface of the cement, and produce electrostatic repulsion when they react with the hydrated cement products. In the interim, side chains of the PCE extend into the cement paste, causing steric obstruction. The cement particles are evenly dispersed by the two effects working together to reduce the amount of water present. According to numerous studies, the main factor in the diffusion effect of PCEs is the steric barriers caused by the side chain. Anion groups on the cement particles' backbones control the adsorption of PCE, which is a key factor in how well the cement disperses (Etsuo and Masaki, 2002). As a result, the main functionality and mechanism of PCEs in cementitious products depend on their chemical compositions (Ran et al., 2010; Winnefeld et al., 2007; Zingg et al., 2008; Abile et al., 2018). The effects of a PCE on cement when used as a dispersant depend on the PCE adsorption properties, like the quantity of adsorption, the degree of surface coverage, and the thickness of the adsorption layer. Charge density and the main chain structure greatly impact how much adsorption occurs. The adsorption and initial diffusion capacities of PCEs with high charged densities are also high. However, because the form of PCE in the cement matrix, the main chain length, and the adsorption layer are significantly responsible for determining the surface coverage degree, PCE with a higher ratio of -COO^- will lead to the coiled shape of PCE in solution and limited adsorption capacity. The side chain plays a major role in controlling thickness. The steric hindrance effect is improved with longer side chains, and cement pastes have greater flowability (Sonebi et al., 2013; Ma et al., 2014).

PCE SPs have several advantages, yet some applications are still difficult to use. For instance, they can significantly reduce the strength and workability of concrete as they are greatly reactive with impurities like clay in aggregates. Additionally, it is commonly known that concrete with a lower w/c ratio has a thick, honey-like viscosity that is very undesirable. The key advantages of PCE SPs are as follows:

- Compatibility with different types of cement: PCE SPs can be used with various cement types, such as blended cement, regular Portland cement, and even specialty types of cement. They can be used in various construction projects and applications because of their adaptability.
- High water reduction: When it comes to lowering the W/C ratio in concrete mixtures, PCE SPs are quite successful. As a result, the concrete gains strength, durability, and decreased permeability. By using less water, the water content also helps to make the concrete more sustainable.
- Enhancing workability: Due to their capacity to improve flow and decrease viscosity, these SPs greatly improve concrete's workability. Concrete's enhanced workability facilitates its placement, shaping, and finishing, particularly with complex architectural designs and intricate forms.
- Improved strength development: SPs containing PCE encourage concrete's long-term and early strength development. They lead to higher compressive strengths, which strengthen and preserve the concrete by lowering the water content while ensuring adequate hydration over time.
- Adaptability in design: PCE SPs offer enhanced workability and flowability, hence facilitating increased design and construction flexibility. The fluidity and simplicity of concrete placing make it possible to achieve complex architectural designs, thin sections, and fine details.
- Reduced cracking and shrinkage: PCE SPs minimize drying shrinkage and the risk of cracking in the finished concrete by improving workability and

lowering water content. This is particularly crucial for guaranteeing the durability and structural soundness of the completed project.

- Energy efficiency: The process of making concrete frequently uses a lot of energy. PCE SPs help reduce the amount of cement in concrete mixtures by allowing for the use of lower W/C ratios. Thus, the carbon footprint connected to the manufacture of concrete is reduced.

Two alternative ways to synthesize PCE super-plasticizers are: (1) Gradient polymers produce a higher side-chain density because of aqueous free radical copolymerization. (2) Esterification, a random copolymer with a predictable distribution is created (Gelardi et al., 2016; Karakuzu et al., 2021; Aicha, 2020; Sakai et al., 2006; Ran et al., 2015).

The following factors primarily affect a PCE polymer's properties:

- The chemistry of the backbone (maleic, methacrylic, acrylic, etc)
- The quantity of anionic groups (commonly salts or carboxylic acids) in relation to the side chains and the backbone.
- The length of side chains and the backbone's length (degree of polymerization)
- The number of side chains in relation to the ionic groups and the backbone.
- The stability of the type of bond between the backbone and the side chains.
- Polymers charge density.

Even though PCE technology is no longer thought of as cutting edge, the PCE sector is constantly expanding and has never leased attempting to enhance its technology. Currently, a wide range of PCE SPs are available in the market with varying chemical compositions falling into the following categories: Methacrylate ester-based PCE (MPEG PCE), Maleic Anhydride, and ω-methoxy-α-allyl poly (ethylene glycol) macromonomer (APEG PCE), Vinyl ether-based PCE (VPEG PCE), 2-hydroxyethyl poly(ethylene glycol) vinyl ether (EPEG PCE), diethylene glycol vinyl ether and ethylene oxide (GPEG PCE), Methallyl (C_4) ether macromonomer (HPEG PCE), isoprenyl (C_5) oxy vinyl ether (IPEG PCE), phosphate SPs, and cationic SP.

MPEG PCEs

The mainstay of the SPs business in Europe continues to be PCEs based on methacrylate ester, which were first made commercially available in Japan in 1987 by Nippon Shokubai Co., ltd. There are two techniques to create MPEG PCEs; (a) by performing an acid-catalyzed grafting reaction at approximately 150 to 175^{0}C under vacuum while methoxy poly (ethylene) glycol with poly (methacrylic acid) backbone (Guicquero et al., 1999). This process yields a regular (statistically) copolymer with a fairly uniform side chain distribution along the main chain; (b) as an alternative, this PCE can be made by free radical copolymerizing methacrylic acid at 75ºC with ω-methoxy poly (ethylene glycol) methacrylate ester macromonomer (Plank et al., 2008).

This method creates a gradient polymer that is considered by the change in the side chain arrangement in addition to the polymer's main chain. This is due to the limited availability of the macromonomer, in the making of MPEG PCEs by free radical copolymerization (Weekwerth et al., 2021). One of their key drawbacks is the poor stability of MPEG-PCEs, which results from the ester connection between the main and side chains hydrolyzing. The raw materials' diol or diester content must be maintained below 1% to prevent undesired crosslinking. Some PCE makers go around this problem by esterifying ethylene glycol with a methacrylic acid anhydride to generate the macromonomer locally. MPEG PCEs are now believed to be less effective at dispensing than new-generation PCEs, such as IPEG or HPEG polymers. MPEG PCEs, on the other hand, are reportedly less susceptible to producing segregation and bleeding in concrete. As a result, the concrete will be more cohesive or sticky due to its lower hydrophilic-lipophilic balance (HLB) value (Lange et al., 2014).

APEG PCEs

Maleic anhydride and the macromonomer of ω-methoxy-α-allyl poly (ethylene glycol) can be combined to create this form of PCE, which Nippon oil and fats initially patented in 1987, either in aqueous solution or even in bulk (for nEO $\leq$ 34) (Akimoto et al., 1987). According to Fig 1, APEG PCEs regularly exhibit a stiff A-B-B-B monomer sequence by an alteration between maleic acid and the APEG macromonomer. According to numerous studies, APEG PCEs are more effective than MPEG PCEs in their non-neutralized form. The "star shape" of the substance's molecules, resulting from resonance stabilization's comparatively low propensity to copolymerize the allyl ether radical, is credited with this higher performance (Plank and Sachsenhauser, 2006). The two main benefits of APEG PCEs are their potential for bulk polymerization, which enables the creation of PCE solutions with relatively low viscosities at solid contents of up to 70%, and their high acid form efficacy. However, only a small number of industries have used APEG PCEs thus far, namely the precast industry. The spectrum for producing APEG PCEs, including those with higher anion-city, has recently been greatly expanded by the introduction of a new process that allows the copolymerization of the allyl macromonomer with acrylic acid (Sun et al., 2012).

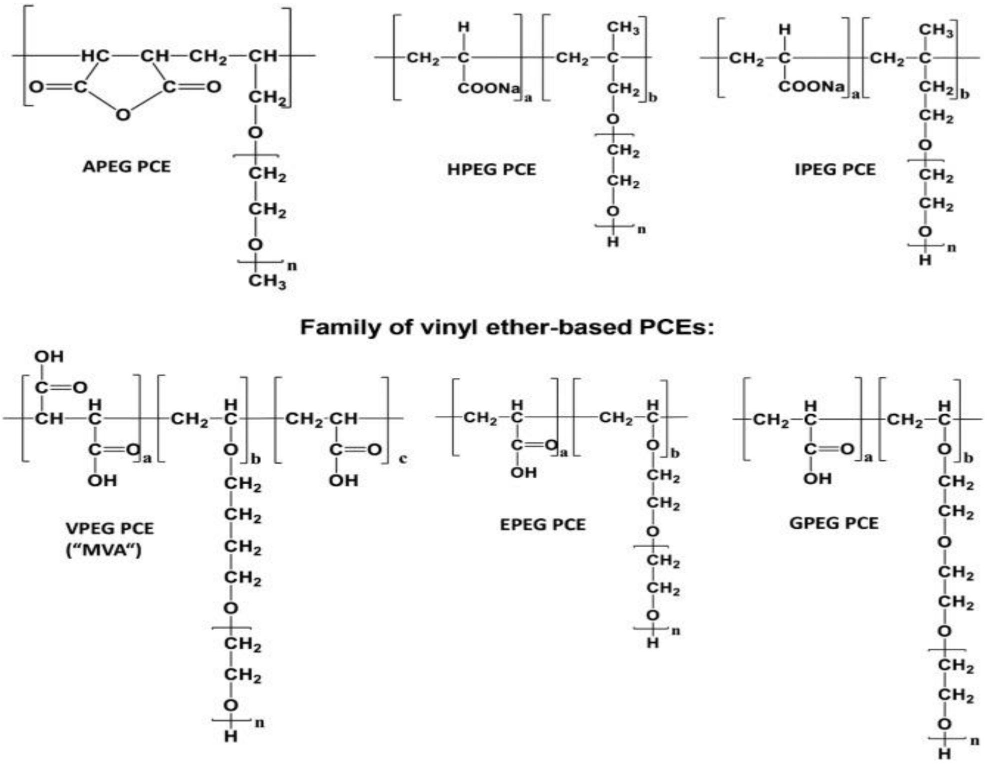


Figure 1. Chemical structures of different types of PCE SPs (Lei et al., 2022a).

APEG-PCEs were initially known to cause delayed plasticization, which is when concrete slumped further over 30 minutes to reach its maximum and then began to decrease. Such conduct is strongly discouraged since it frequently leads to PCE overdose and subsequent concrete hemorrhage. However, this issue has been resolved in the interim. For instance, certain comonomers, such as styrene, have been used as spacer molecules to adjust the conformational flexibility of the trunk chain. Higher values of the hydrodynamic radius indicate that this approach imparts significant stiffness to PCE molecules. According to time-dependent adsorption studies, these modified APEG-PCEs can adsorb more quickly, preventing the effects of delayed plasticization (Akimoto et al., 1992; Sun et al., 2013).

VPEG PCEs

Since their initial development in Germany in the 1990s, vinyl ether-based PCEs have expanded into a broader group of copolymers. The "classic" VPEG PCE (sometimes called "MVA" PCE), which was patented in 1995, is made up of a vinyl ether (C_2) macromonomer, acrylic acid, and a terpolymer of maleic anhydride (Albrecht et al., 1996). To prevent the 4-hydroxy butyl poly (ethylene glycol) vinyl ether from producing harmful breakdown products such as acetaldehyde, its synthesis requires room temperature (ideally $<25^{o}$C). Due to its higher reactivity than vinyl ether, the allyl ether can attain a larger range of molecular compositions and create PCEs with both slump-retaining and water-retaining properties during a low-temperature synthesis. Two unique vinyl ether PCEs, EPEG and GPEG, were made available in China. The vinyl oxy ether is chemically constructed differently from the "classic" VPEG PCE. The "classic" VPEG PCE is sometimes referred to as "VOPEG" PCE as it comprises vinyl oxy ether (Albrecht et al., 1996; Liu et al., 2020).

EPEG and GPEG PCEs

In EPEG PCE, the acrylic acid-copolymerized side chain bearing macromonomer 2-hydroxyethyl poly (ethylene glycol) vinyl ether is presented (in Fig 1). This vinyl ether is created in the first ether synthesis because of the increased reactive nature of ethylene glycol in VOPEG compared to butane diol, but ethylene diol is poisonous (Liu et al., 2020).

A new macromonomer from ethylene oxide and diethylene glycol vinyl ether is incorporated into GPEG PCEs (in Fig 1). There is currently little field experience available because it is a new product on the market. The group of VPEG PCEs has several benefits, such as a wide range of variability in the molar ratio of $–COO^{-}$ to the side chain, allowing it to be adapted for various field applications. The "classic" VOPEG PCE's extremely exothermic polymerization reaction requires expensive apparatus to maintain control temperature (Dong et al., 2018).

HPEG PCEs

In contrast to the allyl ether (C_3), macromonomer in APEG PCEs, the methallyl (C_4) ether macromonomer in HPEG PCEs has a significantly higher degree of reactivity (see Fig 1). Even at room temperature, this macromonomer readily copolymerizes with the more adaptable acrylic acid as opposed to maleic anhydride (Wang et al., 2013). Changing the corresponding molar compositions makes it simple to produce high-range HPEG PCEs that maintain slump or reduce water (Hamada et al., 2001).

The highest dose effectiveness of all currently available PCE types is demonstrated by HPEG PCEs, notably in their capacity to reduce water. Because of this quality, simple room-temperature preparation, and an affordable macromonomer cost (which represents the PCEs primary cost element due to its substantial weight percentage), HPEG PCEs have quickly risen to the top of the PCE market worldwide, particularly in Asia. In addition, remarkable performance has been observed in innovative calcined clay blended composite cement (low-carbon binders). So, it is reasonable to assume that their consumption will continue to rise in the future (Schmid and Plank, 2021).

IPEG PCEs

The unsaturated macromonomer employed in constructing IPEG PCEs (also known as TPEG PCEs in China; see Fig 1) isoprenyl (C_5) oxyvinyl ether. IPEG PCEs can be produced using free radical copolymerization of acrylic acid and isoprenyl oxy poly (ethylene glycol) macromonomer at room temperature, much like HPEG polymers. Despite having a marginally lower water-reducing capacity than HPEG PCEs, IPEG PCEs exhibit slump retention effects that are comparable to or perhaps significantly superior, according to recent field research (Yamamota et al., 2004). However, their ability to break down into isoprene, water, and glycol is a drawback of IPEG-PCEs. The IPEG PCE and mono-monomer should always be stored in an aqueous solution to avoid this undesirable reaction. The current global shortage of good-grade isoprene, which raises the cost of this essential raw material, has a negative impact on the application of IPEG PCEs. The availability of more isoprene capacity in Thailand is expected to change this situation starting in 2022 (Lei et al., 2022a; Lei et al., 2022b).

Phosphated superplasticizers

To solve problems like lowering air entrainment or increasing concrete flow, phosphate-functionalized comb polymers with phosphate functionalities (exclusively or partially) in place of the carboxylate groups generally present in PCEs have been developed. Combining these phosphate copolymers with the generally available class of SPs with phosphonate functions is not recommended. Fig 2 shows the chemical composition of a commercially available MPEG poly carboxylate-phosphate. At low w/c ratios, it was noted that adding phosphate groups with strong anchoring groups than carboxylates, improves adsorption, thereby enhancing dispersion. It should be emphasized that the slump flow (or spread), which typically relates to yield stress, is simply one indicator of cementitious material's fluidity (or workability). Contrarily, the flow rate (sometimes referred to as "stickiness" or "viscous appearance of a concrete") exclusively depends on the hydrodynamic viscous diffusion that occurs in the flowing suspension (Stecher and Plank, 2019). Additionally, a new polyphosphate comb polymer has been made available in commercial form. It is produced by poly-condensing phenol, formaldehyde, phenol-ethoxylate, and an ester of phenol-ethoxy phosphate. Since they offer additional benefits that standard polycarboxylates do not like, such as high sulphate resistance, improved cementitious compatibility, and lower stickiness of concrete, phosphorylated PCEs have experienced great market success. They also work very well in $CaSO_4$ binders, outperforming PCEs in α-hemihydrate formulations, for example, by a wide margin.

The drawback is that the phosphate-containing building block is more expensive. The cost can be significantly reduced by substituting a fraction of the carboxylate groups with phosphates, which produces effects almost identical to those of completely phosphate copolymers. Unfortunately, due to their PEG side chains and their resistance to impurities of clay found in aggregates, they behave similarly to conventional PCEs when exposed to these impurities (Hot et al., 2014; Wieland et al., 2011; Plank et al., 2020).

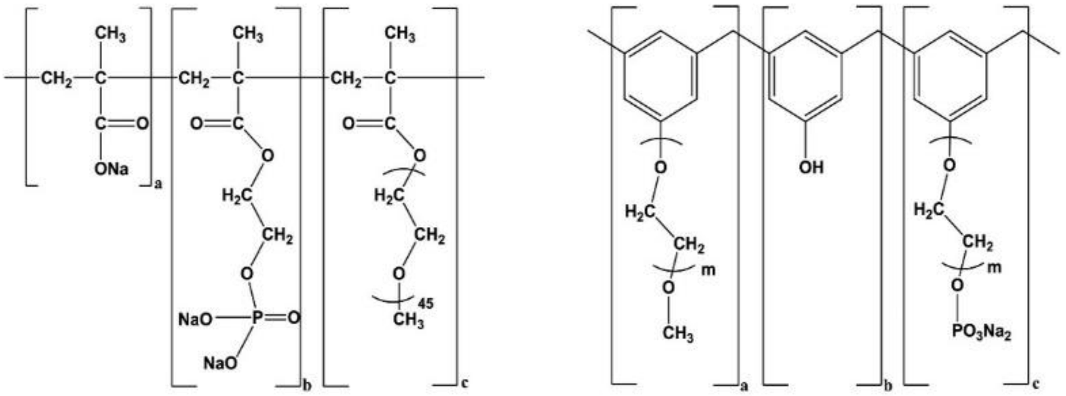
Zwitterionic PCEs (amphoteric PCEs)

The heterogeneous charge distribution in the hydrating products of cement has been hypothesized to be represented by a mosaic charge structure, in which positively and negatively charged adsorption sites coexist on the outer layer of the hydrating cement particle, with the latter being dominant and

DOI: https://doi.org/10.52756/ijerr.2024.v38.007

allowing anionic SPs to dock onto them. This method suggests that zwitterionic PCE polymers with negatively charged groups, such as carboxylates, and positively charged functionalities like cationic activities, can work as effective cement dissolvents. As early as 2006, the first instance of this type of polymer exhibiting mixed charges was given. Due to their higher price, amphoteric PCEs initially received little attention; however, more recently, this has changed due to their outstanding performance in calcined clay blended-type cement. Zwitterionic PCE chemical composition is shown in Figure 3 (Hsu et al., 2006; Amaya et al., 2000).

Several initiatives have been taken to develop a highly reactive cement dissolvent based on cationic (comb) polymers; some examples are shown in Figure 4 (Schmid et al., 2017). No cationic SP has yet to be commercialized, despite some encouraging results. This is primarily because cationic monomers are more expensive and require far greater dosages than their anionic equivalents. Because negatively charged surface sites are more dominant than positively charged ones on cement. Hence, a commercial marketplace may eventually develop for these given in the industry to adopt cutting-edge binder systems, such as ternesite, α-C_2SH, and or belite-ye'elimite-ferrite (BYF) (Gartner et al., 2018).



partially phosphated MPEG PCE

phosphated phenol ethoxylate

Figure 2. Chemical structures of phosphate comb polymers (Lei et al., 2022a).

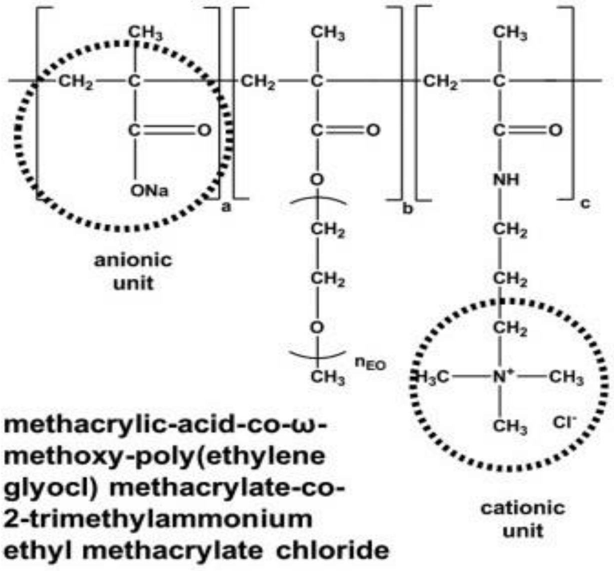


Figure 3. Chemical structure of zwitterionic PCE (Lei et al., 2022b).

Cationic Superplasticizers

Positively charged (cationic) polymers, as opposed to the more popular anionic ones, can disperse cement particles very well due to their uneven surface charge.

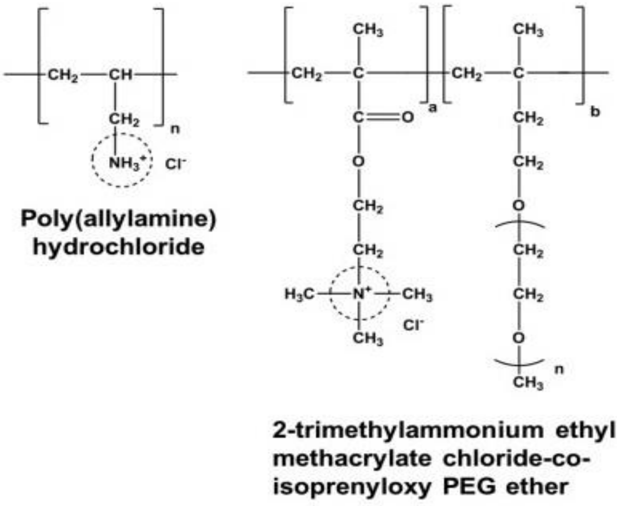


Figure 4. Chemical structure of cationic superplasticizer (Lei et al., 2022b).

Action mechanisms of SPs with cementitious products

SP addition modifies cementitious systems' setting times and improves their rheological characteristics. The main function of SPs is to reduce the required water quantity for mixing the concrete, also called water

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Table 1. Basic elements that can affect the interaction of cement and SP (Yamada, 2011).

Category	Basic Elements
Physical factors	Morphology of particles and their size distribution
Chemical factors	Steric chemical structure of PC (e.g., main chain length or side chain length) SPs charge density. Absorption capacity of SP into the hydrated products. Type of surfaces and mineral phase.

reduction, while enhancing or retaining the workability of fresh concrete and delaying agglomeration. When there is excess water content in the fresh concrete, porosity develops in the hardening process through water evaporation and consumption. This may reduce the longevity and strength of concrete. The w/b ratio and type of cement determine the appropriate SP dosage. Incompatibility is the aggregate term for the conditions that result from improper combinations, which include low fluidity, quick or delayed setting, segregation, bleeding, etc. The mortar influences concrete's cohesiveness and its ability to flow. The qualities of both the additive and the cement signify the compatibility factor.

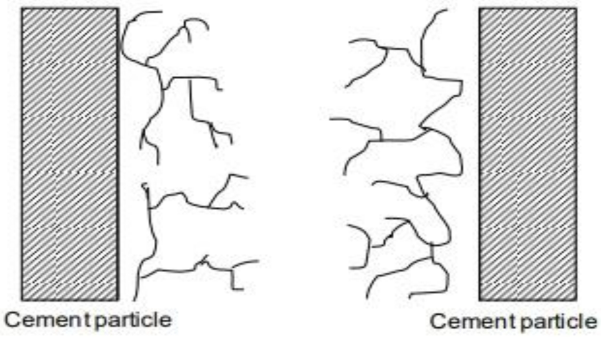

Figure 5. Mechanism of steric hindrance in PCE admixture (Ajay et al., 2020)

PCE's side chains are carboxylate and ether groups, with a linear hydrocarbon backbone chain. Steric repulsion is produced by the persistence of long ether group chains, and this leads to cement dispersion. The combined action of the electrostatic repulsion mechanism and steric hindrance displaced by the PCE admixture is shown in figure 5 (Ajay et al., 2020). A greater rate of adsorption occurs on the cement grains when PCE admixtures with shorter side chains, lower density, and high molecular weight. Its adsorption increases with the amount of carboxylate present in the mixture. Variations in fluidity can be attributed to cement type, grade, and adding time. Calcium ions are present in the interface of the solution and the cement particles, which causes SPs to adsorb by the cement particles' surface (Aicha, 2020; Nkinamubanzi et al., 2016; Yamada, 2011). The basic elements that can affect the interaction of cement and SP are shown in Table 1.

It is commonly recognized that the slow flow and stickiness of concrete made with a low w/c ratio can be resolved as follows: it was discovered that whether the concrete prepared with polymers exhibits fast or slow flow depends on the HLB value of the PCE molecule used (Lange et al., 2014). Research data indicates that PCE molecules should have an HLB value greater than 18.5 and be as hydrophilic as feasible. Such PCEs, ideally of the APEG and/or IPEG types, provide cement matrix with remarkably low plastic viscosities and free flows. Such rheological-optimized concrete represents a significant advancement in enhancing the fresh properties of different types of concretes at low w/c ratios since it is simpler to pump, distribute, and compact.

Recent applications have noted that, in contrast to poly-condensates, PCE SPs show marked sensitivity to silt and clay impurities (Jeknavorian et al., 2003; Atarashi et al., 2004). They consequently perform much worse or the PCEs stop working altogether. The 2:1 smectite clay montmorillonite is more toxic than muscovite, kaolinite, and other clay minerals. More hydrated and viscous cement pastes result from clays' ability to absorb water and smell. That impact alone, without the presence of an SP, leads to an increase in water content or a reduction in workability (Lie and Plank, 2014).

In a cement matrix, calcium adsorption onto the negative aluminosilicate layers causes the top layer of bentonite clay particles to become positively charged. The pore solution partially loses SPs because of Ca^{2+} adsorption of polyanionic SPs, like poly-condensates or polycarboxylates, onto these surfaces. In this sense, SP molecules are competed with clay in cement. The PCE polymers chemically intercalate into the interaction zone between the separate aluminosilicate layers of some clay minerals, particularly bentonite. This creates an additional layer commonly known as the organo-mineral phase in which the poly side chains (ethylene glycol) of the PCE polymers occupy the interlayer space. XRD tests clearly showed that this clay-specific reaction is unique to every individual PCE and is a result of their PEO side chains. So, although poly-condensates like BNS are only destroyed by surface contact, PCEs can be depleted by clay through both surface adsorption and chemical sorption. For this reason, clay has a much greater effect on PCEs than on poly-condensates (Ng and Plank, 2012a; Jardine et al., 2002; Ng and Plank, 2012b).

To lessen the detrimental impacts of clay on PCEs, the industry has created several solutions. The usage of sacrificial agents is part of concept number one. Individual PCE constituent sorbed amounts were analyzed using poly (ethylene glycol), and the results showed that the polymer trunk is used up significantly less (nearly 30 mg PMA/g clay) while the side chain sorbs in considerable amounts (nearly 400 mg MPEG/g clay). This indicates that the PEO side chain primarily interacts with clay and PCE. It also provides a solution to the issue wherein pure MPEG or PEG are used as sacrificial agents to fill the interaction zones, preserving the PCE molecule, which has a lesser inclination to intercalate due to its anionic charge and enabling it to interrelate with the cement particles to achieve dispersion (Ng and Plank, 2012). Cationic polymers, which completely prevent clay from expanding, have been suggested as an additional treatment (Jacquet et al., 2006). Since the clay will not hydrate at all, this approach has the benefit of requiring no water. Furthermore, the PCEs will not have access to the interlayer spacing.

A new PCE structure devoid of PEO side chains would undoubtedly be the best way to address the incompatibility issue between clay and PCE. These polymers have recently been synthesized as side chain-bearing macromonomers from vinyl ethers or hydroxy alkyl methacrylic acid esters (Lei and Plank, 2012). These new polycarboxylates were discovered to adsorb in tiny amounts (about 25 mg polymer/g clay) and do not suffer side chain intercalation using XRD analysis. As such, even with clay impurities present, they function quite well. This behavior fully validates the idea of using non-PEO side chains to solve the issue of conventional PCEs intercalating into clay formations.

SPs made of PCEs are frequently used in ready-mix concrete (RMC) and precast concrete. Reducing the water content of precast concrete is the primary goal to increase its early strength, which permits quick removal of formwork while maintaining high fluidity for quick placement. PCEs with a strong anionic nature (high carboxylate groups, like acid: macromonomer ratio = 6:1) and the ability to retain long chains (having η_{EO} greater than 45, ideally 65-120) are responsible for these features. On the other hand, PCEs that are frequently used in RMC have a somewhat low anionic nature (e.g., a molar ratio of 2-3:1) and short to medium-length side chains (having η_{EO} value between 25 to 45) (Yamada et al., 2000). When it comes to PCE, the RMC needs far larger dosages (about 0.2-0.5% by cement weight) than the precast variety. To maximize the cost-performance connection, commercial PCE admixtures frequently consist of a mixture of two or more PCEs, which should be emphasized. To obtain high initial fluidity in RMC applications, PCEs are frequently formulated to contain approximately 80% water-reducing PCE and nearly 20% of slump-maintained PCE. In recent years, slump-retaining PCEs were created, in which the PCE molecule is combined with a fast-hydrolyzing ester (like hydroxyethyl acrylate) as a third monomer (Gao et al., 2017). The ester then gradually hydrolyzes in the alkaline cement matrix, resulting in PCE species with a higher anionic nature and more persistent adsorption that enhances the workability of RMC. In practice, clay contamination is usually a bigger issue for RMC since less emphasis is placed on the purity of the sand and other aggregates because of the material's large volume and affordability.

The remarkable capabilities of commercially available PCE products have allowed us to construct amazing concrete constructions. One notable example is the Burj Khalifa, which is now the world’s tallest skyscraper at 820 meters, built in Dubai. Its structure is made of high-strength concrete with retarder and PCEs of the VPEG type up to 650 meters. This combination produced a formulation that exhibited slump retention for three hours at temperatures as high as 50ºC and was pumped up to a height of 650 meters. This kind of formulation was unimaginable before developing PCE polymers (Amberg et al., 1998; Plank et al., 2015).

PCE SPs are now widely utilized in the production of gypsum wallboards in addition to concrete. There, the PCE products enable a significant decrease in the volume of water used for the gypsum slurry during mixing. Since the density of the boards is maintained, the wet gypsum body has more air and can be dried with significantly less energy, which lowers costs (Plank et al., 2015; Hampel et al., 2013). Therefore, the main driver for using PCE in this situation is the decrease in energy costs, with the resulting increase in strength coming in second. For this application, particular PCE materials with incredibly quick (in a matter of seconds) adsorption have been developed. Europe and the United States, the two biggest markets for gypsum wallboards, have also seen a rise in the popularity of this technology.

The main binding phases and hydration products (about 50% by mass) of hydrated cement products are CSH. The commercial development of CSH-based materials to speed up hydration has begun after laboratory studies. According to Owens et al., adding 2% by weight, CSH increased the early strength development with a 50% reduction in the initial and final setting times. It was discovered that adding CSH seeded the hydration process, increasing the amount of hydration and speeding up the primary hydration rate peak times. Because CSH particles agglomerate and do not preserve their initial size during synthesis, a low surface area may be the reason for the modest acceleration effect.

A relatively new development is utilizing calcium silicate hydrate (CSH)-PCE nanocomposites in the form of seed crystals to hydrate the C_3S and C_2S silicate phases. The nanocomposites can be made by mixing a PCE solution with aqueous solutions of calcium formate and sodium silicate. Instantaneous precipitate with surface adsorbed and perhaps intercalated PCE nano foils of CSH are present in the resultant mixture. The silicate hydration is substantially accelerated because the nano foils eliminate the crystallization's free activation energy. This barrier must be removed to start CSH formation in cement. This means early strength development is significantly improved without compromising ultimate strength, especially after 6-12 hours of hydration (Nicoleau et al., 2011; Nicoleau et al., 2013).

The level of acceleration and formation often depends on the surface area of tiny particles of cement matrix. By using the right chemical structure, synthesized circumstances, and PCE concentration, the particle size of the CSH can be regulated to the nanoscale. Owing to the coated silicate structure, polymer/CSH nanocomposites provide great candidates for the intercalation of organic molecules to manipulate and control their properties. Synthetic PCE/CSH nanocomposites can notably improve the early strength of cement matrix, accelerate early hydration, and optimize the pore structure, even at small dosages, according to research by Sun et al. (2012). It is also possible to control the size of CSH/PCE nanocomposites by adjusting the volume of the PCE solution. Plank et al. (2015) concluded that PCE polymers, as opposed to CSH, created lower particle sizes for PCE/CSH nanocomposites. The nanocomposites can significantly increase the early strengths of the mortar.

The PCE-CSH nanocomposite significantly speeds up the reactive nature of the mineral admixtures, accelerating the hydration of the silicate compounds found in the clinker. To understand the impact of the synthesis conditions on the particle size of CSH/PCE nanocomposites, more thorough investigations are necessary. Furthermore, additional investigation is necessary to determine how synthetic PCE/CSH nanocomposites affect the long-term characteristics of the cement matrix. PCE/CSH nanocomposites are also most likely to be used in prefabricated concrete and winter construction, where the colder weather helps the concrete's early age strength. Therefore, it will also be required to study the mechanism and effect of nanocomposites at various temperatures.

Admixtures containing polycarboxylic acid are currently often utilized in concrete. It is a common structural component. Concrete performance can be effectively enhanced by polycarboxylic acid due to its high water reduction rate and great flexibility. In real-world uses, it expedites transit and raises the caliber and pace of development. Consequently, the use of PCE SP representatives not only significantly increases the financial benefits but also boosts the strength and quality of contemporary structural structures in practical applications. SPs with bases in polycarboxylic acid, naphthalene, fatty acids, etc., are frequently utilized in contemporary concrete. Every SP has benefits and drawbacks of its own. The qualities of SPs that are frequently utilized in concrete applications in contemporary buildings and examined in the following manner:

1. Naphthalene-based admixtures typically have a 17% SP property and very narrow compatibility with matrix materials compared to larger compatibility with sand and gravel materials. Their water retention is low, their slump and expandability losses are comparatively high, and their fluidity performance is mediocre. Additionally, performance is not so great in terms of adhesion, characteristics, or climatic adaptability (Qian and Schutter, 2018; Osuji and Ikogho, 2018).
2. Fatty acid collection's SP home is typically 20%, and it shares a common adaptability with admixtures of the naphthalene series. While its adhesion and climate adaptability are good, its fluidity is ordinary, and with usage, its slump and expandability losses are minimal.
3. PCE SP typically has a 25% SP property. It is compatible with a wide range of matrix materials, but not with sand and gravel materials. There is no less and very little expandability and slump losses during use. Although there is a lot of fluidity and good water retention, adhesion, and climate adaptation, there is a greater technology demand.

Due to rapid economic and technological development, PCE SPs, which have effective SP capabilities, are frequently utilized in construction engineering concrete. Typical examples are maleic acid, methyl propionic acid, and polypropylene hydrochloric acid. Acid poly-maleic, polymers, etc. When used in real applications, polypropylene hydrochloric acid SP has been found to work well with various kinds of cement. The monomer acrylic acid, which acts as the matrix in use, is combined with polyoxymethylene to yield a product with a higher molecular weight. Methyl propionic acid-maleic acid polymers block SP polymers composed of methyl propionic acid and maleic anhydride as monomers. They are combined with additional SPs to ensure better fluidity and adsorption qualities. A polymer-reactive fine-particle SP that is insoluble in water is maleic acid. Intramolecular lipids, acid anhydride, and other groups are present in the main chain of its molecular structure. Due to the alkaline component, these molecular groups will hydrolyze when concrete is ready-mixed. This is a practical method of converting the water-insoluble polymer into a soluble one. It might simultaneously gradually penetrate the solution due to the dispersant's effect. Slow dispersion of the hydrolysis phenomena on the concrete's surface prevents slump loss of the structure. This phenomenon happens gradually and slowly (Ma et al., 2022; Fang et al., 2022; Swartz et al., 2023).

Discussion on the use of PCE superplasticizers in concrete

The cement matrix influences concrete's cohesiveness and capability to flow. Incompatibility is the aggregate term for the conditions of fresh concrete that result from improper combinations, which include low fluidity, quick or delayed setting, segregation, and bleeding. Products like concrete admixtures and admixtures have attracted much interest since they can improve the mechanical residential qualities, building efficiency, and toughness of concrete. SP addition modifies cementitious systems' setting times and improves their rheological characteristics. The type of cement and the w/b ratio determine the appropriate SP dosage.

The development of chemical admixture PCE SPs in 1981 has resulted in several technological advancements that are essential to the contemporary concrete industry. In the market of PCEs, more efficient products, such as HPEG and IPEG PCEs are used for the longer workability of concrete and are rapidly replacing the MPEG PCE, which represents the comb polymers of first generation, produced 40 years ago in Japan (Liu et al., 2019). Simultaneously, new versions of VPEG PCEs, such as EPEG and GPEG, have also appeared. Some of the projects constructed using PCE SPs are presented in Table 2.

In recent years, SPs made of PCE have been employed extensively in modern construction projects. The criteria for external functional additives in modern concrete are considerable. Consequently, the following crucial technologies need to be considered while incorporating the PCE SP into a concrete system.

1. Compatibility technology based on polycarboxylic acid. High-performance SPs based on polycarboxylic acid have a unique structure that prevents them from being kept or used in conjunction with other SPs, particularly those based on naphthalene. Cross-contamination must be prevented by thoroughly cleaning the appropriate containers for the various SP kinds that must be used interchangeably to maintain the concrete's exceptional quality. The effectiveness of SPs in adsorption varies depending on the kind of cement. Poor compatibility is unavoidable because PCE SPs have a limited range of compatibility with cement. As a result, either the dosage must be increased or other kinds of cement must be used to tackle this issue.
2. Technology for PCE SP retardation. The use of the retarder can effectively extend the malleability of concrete during the construction process because of how long it takes for it to take effect. To prevent the decline of tangible performance, it is necessary to consider the incompatibility between the two.
3. Control over air content. Because of its good air-entraining effect, the polycarboxylic acid SP can be employed in conjunction with deforming agents, air-entraining agents, etc. Concrete's air web content can be controlled, improving its workability and durability by first removing and then adding.

Reduction of mud content in gravel and sand. The amount of mud in sand and gravel can affect the efficacy of high-performance SPs based on polycarboxylic acid. If the mud content of the sand and gravel is more than 2%, the structure between the clay layers will absorb a lot of SP molecules, which would lower the concrete's flow performance. When building, if there is a lot of mud involved, you might want to use a clay-resistant PCE SP.

Effect of cement on PCE superplasticizer

Ordinary lignosulfate-based, water-reducing, polycarboxylic acid-based, and naphthalene-based agents differ significantly from one another. Water-reducing compounds based on polycarboxylic acid are commonly employed due to their great slump retention, high water-reducing rate, non-hazardous nature, and environmental friendliness. While this type of water-reducing agent does have some drawbacks, such as low adaptation, this is also a typical flaw in regular water-reducing agents. For instance, the cement slurry could not be very fluid or effective at decreasing water when using a specific cement. The main cause of this feeling stems from the materials' molecular makeup. It also influences cement

Table 2. Some of the projects constructed using PCE SPs.

Sl. No.	Name of the Project/Location	Type of PCE used	Requirements of project
1.	Happy Valley Race Course, Hong Kong	4th generation PCE SP.	Water proofing effect and reduction of shrinkage in concrete
2.	Pune Metro Pune.	PC-based admixture	To resolve problems of high retention, slump drop, pipeline chocking and optimizing the cost per meter cube of M60 and M50 grades concrete.
3.	Oasis Towers Worli, Mumbai.	PC-based admixture	To retain excellent workability retention for over 3 hours without compromising the durability and strength of M40, M50, and M80 grades concrete.
4.	Chennai Metro Rail, Chennai.	PC ether polymer with a long lateral chain	Improving durability with a rapid chloride permeability test value as low as 600 Coulombs at 56 days. Further, early strength attainment of 13.5 MPa at 14 hours with good retention.
5.	Redi-Rock System, Goole.	Newly developed PC based ether polymers.	To promote strength gain whilst still providing the workable concrete.
6.	Felixstowe Docks, Suffolk	Admixture based on 3rd generation PCE polymers.	To enhance the workability, durability and aesthetics of the concrete.
7.	Aviva Stadium, Dublin, Ireland.	Admixture based on modified PCE polymers	Reduced water permeability and penetration, air permeability and water absorption.
8.	i360 Tower, Brighton.	Admixture based on 3rd generation PCE polymers to replace lignosulphonate-based water reducer.	To obtain a high-quality concrete mix with good early and late strength achievement and extended workability without delay in setting characteristics.
9.	Harburnhead Wind Farm, West Lothian.	Admixture based on PCE polymers.	To facilitate easier placing and improved concrete surfaces that met the requirements of BS EN 206-1.
10.	Harestances Windfarm Extension	SP based on PCE polymers and 2nd generation SP based on PCE polymers are used.	To achieve unachievable degree of concrete performance that is customized for a unique solution, while maintaining early strength development and allowing for significant water savings and extended workability retention.
11.	Queensferry High Sports Complex, West Lothian.	Admixture-based 3rd generation PCE polymers.	To produce concrete with a low w/c ratio without loss of workability that meets EN 206-1.
12.	Ineos Ethane Tank, Grangemouth.	3rd generation SP-based PCE.	To produce the highest durability and t ensure consistent strength, quality and speed of cure.
13.	Liverpool 2 Dock Extension, Liverpool.	SP based PCE ether polymers.	To produce high-quality ready-mixed concrete with high water reductions and extend the workability period.
14.	Queensferry Crossing, Fife.	SP based on PCE polymers.	To prolong workability retention and permit high water reduction levels without interfering with the early stages of strength growth.

DOI: https://doi.org/10.52756/ijerr.2024.v38.007

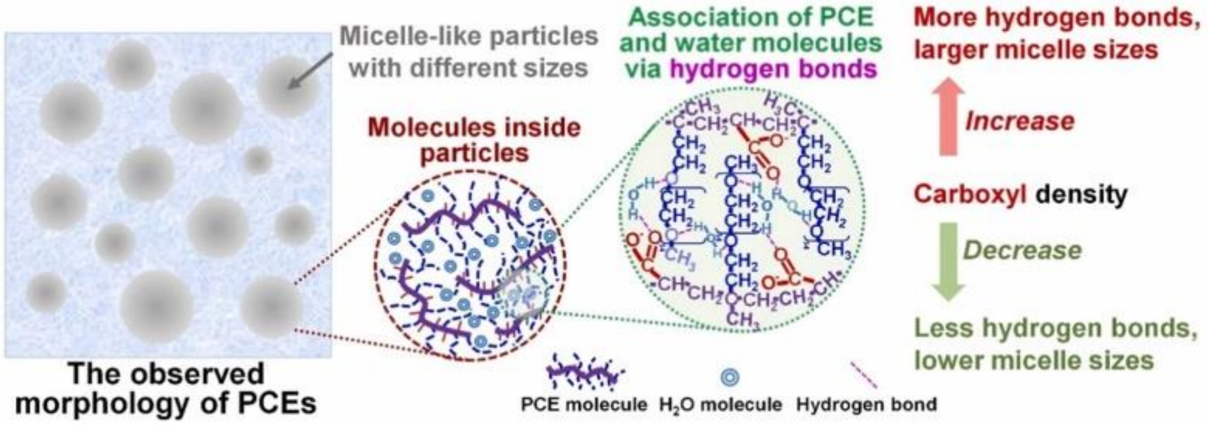

Figure 6. Diagrammatic depiction of PCE form by TEM (Wang et al., 2024).

quality, surface characteristics, and composition (Ma et al., 2023). A diagrammatic depiction of PCE form as seen by transmission electron microscopy (TEM) is shown in Figure 6 (Wang et al., 2024). A transmission electron microscope (FEI Company, America) was used to examine the PCE's morphology. The TEM's schematic representation of PCE morphology shows how PCE forms different micelle-like particles when hydrogen bonds with water molecules form. Greater micelle sizes with rising carboxyl density would result from the successful production of PCEs (Sahin et al., 2023).

Effect of fine aggregate on PCE superplasticizer

One of the basic components needed to prepare concrete is industrial and natural sand, which are commonly utilized as excellent aggregates. Sea, hill, and river sand are the three categories of fine aggregate. Nevertheless, it should be mentioned that an excessive amount of water-reducing agent PCE should not be used when producing concrete. The addition of fine aggregate will undoubtedly react as soon as it becomes excessive, influencing both the slump of the concrete. It impacts the intensity adversely. Moreover, the amount of stone powder in the sand significantly determines how adaptable concrete and PCE water-reducing agents are. When sand with a high concentration of stone powder is used to prepare concrete, the concrete's fluidity will most likely be affected in various ways (Wo et al., 2023; Naaman et al., 2020).

Furthermore, other characteristics of fine accumulations, including sand density, will also affect the adaptability of concrete and polycarboxylic acid-based water-reducing agents. Generally, concrete will lose its fluidity quickly if the quality of the sand is lower than its average value. In addition, the water reduction of the polycarboxylic acid system will be influenced by the sand rate as well as the remaining sulphates and chloride ions in the sea sand. Specifically, the agent's degree of adaptability will matter. Apart from the previously mentioned elements, the degree of silt present in sand and gravel will also impact the flexibility and efficacy of the PCE water-reducing agent. This is typically because of the silt's strong adsorption force, which affects the water and lowers the cost of the water decreasing representative. The silt content will also vary for various materials. Generally, PCE water-reducing agents will be greatly impacted by the soil composition in the sand and gravel. Even applying the right amount of mixture will not increase the flow of concrete when the silt content in the gravel and sand surpasses 3%. This will considerably reduce the water-reducing agent's efficacy (Patowary et al., 2023; Jiang et al., 2023; Khupsare et al., 2023).

Effect of coarse accumulation on PCE superplasticizer

Coarse aggregate is another important factor influencing PCE SPs. The stones' sharp and needle flake content is the primary display of this performance. The flow velocity of concrete will unavoidably slow down if the needle flake substance of the stones rises, even for stones with the same gradation. This drop in development may result in bleeding or partition. Different coarse aggregates will undoubtedly absorb water at different rates depending on their densities. The water absorption of excellent aggregate is often higher than that of tough material. The intended outcome cannot be accomplished even if the water-reducing agent dosage is changed. The amount of concrete can be changed simply by changing the concrete mixture. Because of this, it's essential to continuously modify the sand's silt content and stone gradation during the building process to find the optimal solution given the real raw material conditions (Dash et al., 2022; Patowary et al., 2023; Olowofoyeku et al., 2019).

Effect of PCE superplasticizers on impermeability of concrete

DOI: https://doi.org/10.52756/ijerr.2024.v38.007

The pore structure and porosity of concrete are related to its impermeability. Based on pore diameter, concrete pores can be categorized into four degrees: >100 nm, 50-100 nm, 5-50 nm, and <4-5 nm. Concrete's strength and impermeability will suffer if the pore volume fraction rises larger than 50 nm. Conversely, concrete's power, impermeability, and resistance to deterioration will all improve if the volume portion of pores smaller than 50 nm rises (Plank et al., 2019; Dong et al., 2017; Chica et al., 2022). In addition, concrete's pore framework will be strengthened, and its water-cement ratio will be reduced when combined with the high-efficiency PCE water-reducing agent. By doing this, the internal structure of the concrete will become more compact and there will be fewer bleeding channels, which will improve the concrete's impermeability (Plank et al., 2019; Chen et al., 2022).

Effect of PCE superplasticizer on freeze and thaw resistance

SPs containing polycarboxylic acid have a similar effect to regular water-reducing chemicals on the capability of concrete to resist freeze-thaw cycles. The high-efficiency water-reducing action of the PCE high-efficiency water-reducing agent, which does not impede airflow, can efficiently lower the concrete's w/c ratio when combined with it. In addition, it increases the concrete's impermeability, which helps to improve freeze-thaw resistance because there is less free water in the structure that can freeze (Silva et al., 2021; Sahin et al., 2023). This is primarily because when concrete is combined with the required amount of air-entraining and either a non-air-entraining and or air-entraining PCE high-efficiency water-reducing representative and admixture, the air-entraining impact of the admixture causes the concrete, a certain amount of tiny, independent, stable bubbles will be introduced into the concrete. These bubbles will help to alleviate the concentration of expansion pressure induced by freezing and super-cooled water migration (Li et al., 2023; Sahin et al., 2023; Han et al., 2023).

Effect of PCE superplasticizer on resistance to sulfate and chloride resistance

According to experimental studies, there is no discernible difference between the corrosion resistance of concrete mixed with PCE SP and concrete mixed with regular admixtures when it comes to sulfate and chloride salts. While some sulfate will be present in the PCE SP, the strong web content is typically less than 10% and does not affect the freeze-thaw resistance of concrete when used in the recommended dosage. Regular use of PCE SP won't cause the steel bars in reinforced concrete to corrode (Fekry et al., 2022; Han et al., 2023; Sahin et al., 2023;).

Discussion and Conclusions

As a result of ongoing innovation, the market for SPs is currently exhibiting robust dynamics. PCEs with higher charge density show better adsorption adhesion nature on the external layers of cement, resulting in good preliminary distribution but low slump retention in concrete or cement-based products. Generally, the viscosity of the slurry will be significantly decreased when PCE SP is added to concrete. Simultaneously, the concrete is susceptible to delamination and segregation, even with optimal dosage and water consumption of the PCE SP and no bleeding. This is mainly confirmed by the large quantities of coarse aggregate interacting with the cement paste and pure paste phase. In addition to being extremely evident in terms of delamination and segregation, this kind of concrete mixture does not vibrate when concrete is poured.

Long side chain PCE often exhibits greater slump retention. However, big molecular weight PCE yields extremely flowable concrete. In actuality, cement paste performance may be affected synergistically, restricting, crossing, or colliding by the charge density, side chain length, and the main chain length of PCE. A PCE with a greater charge density, short main chains, and long side chains can disperse extremely well. PCE can greatly enhance concrete's ability to withstand cold and retain bubbles with imide/amide groups on the side chain, dramatically lowering the solution's surface tension. The hydrophobic and hydrophilic groups on the side chains of PCE can also be tailored to produce highly flowable concrete. Because PCE with a hyperbranched structure absorbs more strongly on cement particle surfaces, it has a better diversification effect. Compared to comb-PCE, it exhibits stronger steric hindrance, which aids in its dispersion.

In comparison to ordinary PCEs, phosphate PCEs show greater resistance to sulfates. A few minutes after adding PCE, the quick consumption of the additive during the early hydration phase is significantly reduced in mixes with high tricalcium aluminate content. A cement's hydration rate and competitive adsorption with PCE are both regulated by the type and quantity of sulfate present in the combination, which warrants careful consideration. The amount of water needed by the cementitious mixture could decrease if enough PCE is present. Anionic charge density and high molecular weight PCEs are used to improve the fresh characteristics of cementitious systems incorporating mineral admixtures. Furthermore, zwitterionic polymers have emerged as a potential substitute for calcined clay blended types of cement; still, substantial enhancements are required before they can be commercialized.

Conventional SPs such as sulfamates, lignosulfonates, aliphatic series, and naphthalene series can be combined in any ratio to satisfy different needs for concrete preparation. In addition to being highly soluble in water, these conventional SPs can provide good superposition effects when combined. There are many restrictions with PCE SPs. It is not very compatible with other traditional SPs and can only be used in conjunction with lignosulfonate, a typical SP. When combined with other traditional SPs, the concrete will become harder to produce a superposition effect, be much less fluid, require a lot more water, lose a lot of slumps, become dry and difficult to unload, and lose strength and durability.

In conclusion, PCE SPs have significantly transformed the field of current concrete technology. Furthermore, to get a comprehensive grasp of the variables influencing concrete microstructure and to apply PCE SPs to create more durable concrete, more quantitative micro-analytical methodologies, and modeling tools are required. More intriguingly, it would be possible to regulate the consistency (fluidity) of the concrete during delivery by using an energy-dependent PCE dosage and the spinning container of the concrete truck. The present chemical admixture products will surely undergo additional refinement to enhance their effectiveness and customize them to specific applications.

Conflict of Interest

The authors declare that there is no conflict of interest.

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How to cite this Article:

Uppala Venkata Narayana Rao, Namepalli Venkata Sairam Kumar, Chagarlamudi Kavitha, Yellinedi Madhavi and Ponduri Samatha Chowdary (2024). Polycarboxylate superplasticizers used in concrete: A review. *International Journal of Experimental Research and Review*, *38*, 69-88.

DOI : https://doi.org/10.52756/ijerr.2024.v38.007