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NEW GENERATION OF CHEMICAL ADMIXTURES FOR SUPERIOR CONCRETE RHEOLOGY

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SUMMARY

High performance concrete and mixes containing manufactured sands can be harsh, sticky and tenacious requiring more effort, energy and time to mix, handle, pump, place, trowel and finish. This paper describes a novel and newly developed class of admixtures. These admixtures are designed to lower plastic viscosity, improve rheology, stability, robustness and address some of the issues related to the characteristics of fresh and hardened concrete.

Keywords: Modified polyether, rheology, viscosity, wet out time, pumpability, robustness

INTRODUCTION

Chemical admixtures like plasticisers and superplasticisers facilitate the production of concrete. These types of admixtures function as cement dispersants making it possible to achieve the required consistency despite a lower water content in the mix. Consequently, less water in concrete equates to better strength development or in other words the strength of hardened concrete is inversely proportional to the water/binder ratio.

Superplasticisers play an important role in this context as they can significantly increase concrete strengths after hardening. Self-compacting or self-consolidating concrete (SCC), super-workable concrete (SWC), high strength concrete (HSC), ultra-high strength concrete (UHSC) and reactive powder concrete (RPC) are prime examples of superplasticiser applications. Conventional polycarboxylate ether (PCE) polymer chemistry based superplasticisers are used to achieve high flows and strengths in mixes with low water/binder ratios. Some PCE admixtures however tend to impart characteristics such as an increase in viscosity, thixotropy and stickiness which in most cases are less desirable in concrete.

In recent years there have been concerted efforts to reduce global warming through reduction in carbon dioxide (CO_2) emissions. One major source of human CO_2 emission is the production of Portland cement (Hargreaves 2013). For every tonne of Portland cement produced, approximately 900 kg of carbon dioxide are released into the atmosphere (Mahasenan et al. 2003).

Concrete is the single most widely used material in the world and it has a carbon footprint to match. It is therefore of little surprise that modern concrete technology strives towards minimising the need for Portland cement without sacrificing the strength of concrete. A simplistic solution would be to use superplasticisers, midrange water reducers and plasticisers to achieve the same strength with less cement in the mix. A more scientific approach and prevalent counter practice offered by the concrete industry to reduce global warming has been the replacement of cement with supplementary cementitious materials (SCMs). The replacement of cement however, leads to a reduction in early strength that is usually compensated for by lowering the water/binder ratio. Often the resultant mixes are higher in viscosity which negatively affect its mixing, handling, pumpability, placeability, trowel ability and even surface finish.

A new and novel class of admixtures based on modified polyether (MPE) nano-chemistry has recently been developed with an aim to counter the issues described earlier in the paper.

MECHANISM OF ACTION

Chemical admixtures based on modified polyether (see Figure 1) differ from conventional PCE superplasticisers in the chemical nature of their polymer backbones. Like conventional PCE admixtures (see Figure 2), the polymers exhibit a comb-like structure with polyether side chains. However the acrylate-free backbone of MPE consists of an aromatic rather than aliphatic character that is considered to be more rigid. The presence of aromatic units in combination with a very high density of negative charges is thought to increase its affinity to the surface of the cement particle. The presence of side chains also adds steric hindrance to the electrostatic component of the inter-particle repulsion forces. These aromatic comb-like polymers combine some of the beneficial properties of sulphonated naphthalene and melamine formaldehyde condensates (SNFC & SMFC) with the high performance of PCE.

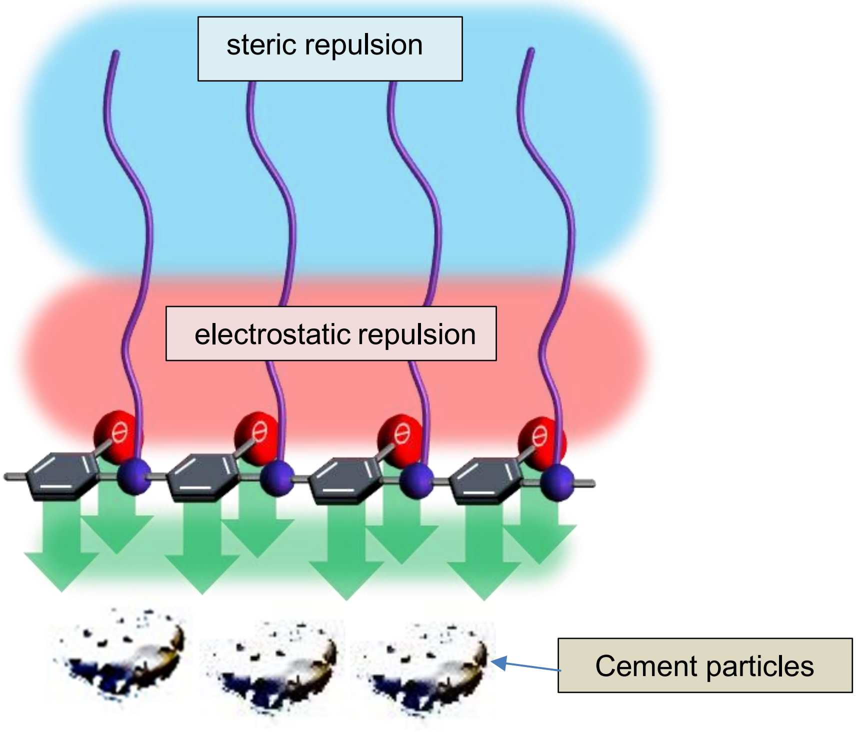

Figure 1. Schematic representation of the aromatic comb-like structure of MPE

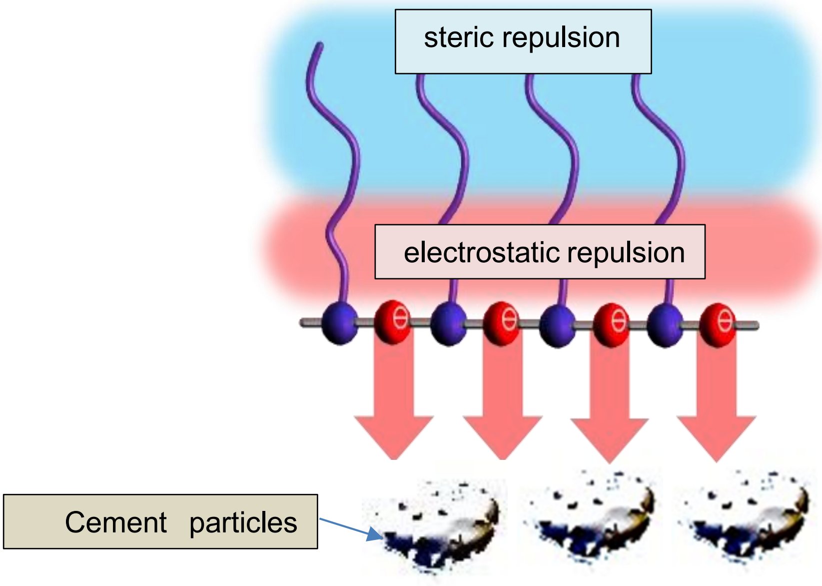

Figure 2. Schematic representation of a conventional PCE

RHEOLOGY AND IMPACT OF VISCOSITY

The rheology of fresh concrete has a major impact on the way it is mixed, transported, pumped, placed and finished. Traditional test methods of slump or slump flow measurement are not capable of characterizing the fundamental rheological properties of fresh concrete. Workers often observe a significant difference when handling concrete even if the mixes exhibit similar slump and slump flow values. The situation in the field of concrete technology was so unsatisfactory that Tattersall wrote in 1976 that “at present, the most reliable method of measurement of workability is subjective judgement by an experienced operator….it remains common experience for two concretes giving identical slump or other test values to behave quite differently” (Banfill 2006).

With modern concrete technology this behaviour can be quantified by comparing rheology, thixotropy, yield values and plastic viscosities using single point tests like the V-funnel and two-point tests using instruments such as a rheometer.

Fresh concrete can be considered as a fluid which means that it will flow under the action of shear forces. The Bingham type relation (equation 1) is used to describe the flow characteristics of fresh concrete at low and intermediate shear rates. It describes a linear dependency of shear stress τ in relation to the applied shear rate $\dot{\gamma}$:

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{1}$$

In the Bingham model (see Figure 3), the yield stress τ_0 determines the value when concrete begins to flow under its own mass. The type, shape, size and amounts of solid materials used as ingredients can have an independent impact on yield stress. The same holds true for viscosity modifying agents (VMA), air entraining agents (AEA) and dispersants such as superplasticisers (HWR). Wallevik and Wallevik (2011) have summarized these influences in a rheograph and report that superplasticisers improve the flowability of concrete mainly by lowering its yield stress.

Plastic viscosity μ of a fluid is the ratio of shear stress to the shear rate. It determines the flow time or the speed with which concrete can be placed or pumped. The flow behaviour of concrete is influenced by many parameters. Firstly, the water content in the mix plays an important role. Higher the water content in the mix, the lower the yield stress and plastic viscosity.

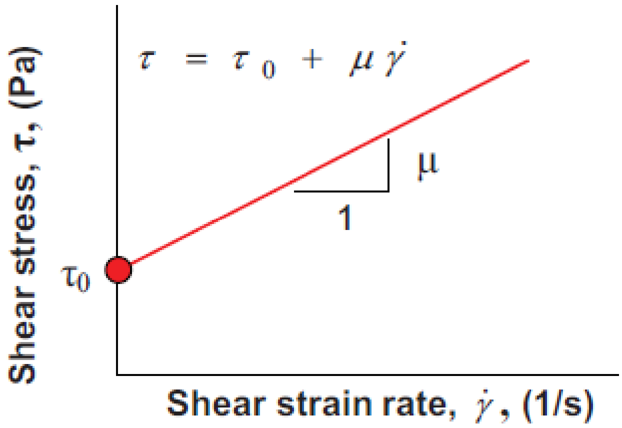

Figure 3. Bingham model

An ICAR rheometer has been used to measure, compare and study the fundamental flow properties of concrete containing admixtures based on MPE and PCE. Extensive laboratory and field testing confirm a dramatic reduction in plastic viscosity coupled with an improvement in the rheology of concrete mixes with MPE admixtures. Comparative data of reduction in the plastic viscosity in grades 50, 80 and 100 MPa of concrete with similar slump flow values containing SCMs is shown in Table 1. The causes and effect of plastic viscosity on segregation potential are discussed later in the paper.

Table 1. Plastic viscosity reduction in grades 50, 80 & 100 MPa concrete

Concrete grade (MPa)	**Slump flow (mm)**		**Viscosity (Pa.s)**	
	PCE	**MPE**	**PCE**	**MPE**
50	590	580	45	36
80	620	600	87	65
100	630	640	108	78

Wet out time reduction and its benefits

Wet out time as defined by the author is the time taken for concrete to achieve fluid consistency after the addition of water and admixtures to the mix. Concrete with MPE consistently shows a substantial reduction in wet out time in comparison to PCE. This inherent reduction in wet out time with MPE is in the order of 25 to 60% compared to PCE or for that matter SNFC. The wet out time is substantially reduced because the adsorption of the MPE polymer on the cement or binder particles within the cementitious matrix is provided by a chemical bond that does not impede the flow of concrete. Comparative test data is presented in Table 2.

A decrease in wet out time reduces the time taken for a concrete agitator or wet batch mixer to achieve uniform consistency. A faster or shorter mixing time for a given mix design and load size translates to increased production output and savings not only in terms of time but also costly inputs like fuel, resources and manpower. Better fleet optimization can also be achieved with a quicker turnaround of trucks, especially when larger mixing bowls are preferred for increased delivery capacity. The difference in wet out times is far more noticeable in low water/binder ratio and high SCM mixes probably due to the higher initial plastic viscosities of such mixes.

T_{500}, slump flow and V-funnel tests

T_{500}, slump flow, L-box and V-funnel tests have established that the lower plastic viscosity property imparted to concrete by the MPE admixture reduces the high degree of cohesion and stickiness. With improved rheology, it becomes easier to mix, discharge, handle and work with a concrete mix that is less viscous and less sticky. More importantly, concrete manufactured with MPE can be placed, pumped and finished faster with less effort and energy. Additionally, in most cases a better off-form finish has been reported with concrete containing MPE.

The impact of viscosity reduction with MPE versus PCE admixtures in a commercially available 50 MPa piling mix using a laboratory tilt drum mixer with 440 kg binder content (280 kg cement + 140 kg slag + 20 kg silica fume) and w/b = 0.40 is summarized in Table 2.

Table 2. Comparative test performance in a 50 MPa piling mix

Mix	Wet-out time (sec)	T_{500} (sec)/Slump flow (mm)	V-funnel time (sec)
PCE	120	4.5/580	15.0
MPE	60	3.0/550	7.7

PUMPABILITY

Transport of fresh concrete by pumping through pipes to the point of placement has been used since the 1930s and, given current trends towards greater mechanization of site work, interest can only increase (Banfill 2006). Concrete pumping technology has become an essential element for high speed construction, and the use of high performance pumps has also increased. Continuous pumping, be it vertical or horizontal remains a challenge as we continue to build taller and longer structures such as super-tall buildings, bridges and dams.

The slump test is no longer sufficient to evaluate the pumpability of high strength and highly fluid concrete. Since complicated factors affect concrete when fresh concrete is passing through a pump line it is essential to use the rheology approach to evaluate and predict pumpability in regard to fluidity, viscosity, resistance to slip and segregation (Kwon et al. 2011).

Browne and Bamforth (1997) described concrete movement within a pipeline as “plug flow” where a “plug” of concrete is separated from the pipe by a lubricating layer of paste and finer aggregate particles in the outer few millimetres.

In another approach developed in the early 2000’s, the lubrication layer properties are reproduced in a tribometer. This device is similar to a concrete rheometer, but while in a rheometer, the formation of the lubrication layer must be prevented, a tribometer has a smooth surface to provoke the dynamic segregation of the coarse aggregate (Feys et al. 2015).

Successful examples of long span horizontal single stage pumping of concrete through 1.36 km upstream 2.432 km downstream sections in a major hydropower project in India have been reported (Hazare and Mahadevan 2015).

Predicting the expected pumping pressure is a vital part of pumping concrete up super-tall buildings. The pressure required will depend on frictional losses within a concrete pipeline and the pressure head. The use of high performance concrete in tall reinforced buildings is dependent on the ability to pump. With the advent of powerful pumps, such as the Putzmeister 14000 SHP-D used on the Burj Khalifa, the ability to conduct single stage pumping to heights of 600 metres or more has been established. Hydraulic and maximum concrete pressures for the C80-20 mix used in core walls for the Burj Khalifa project are shown in Figure 4. The pumping pressure also increases with increasing elevation (Aldred 2007).

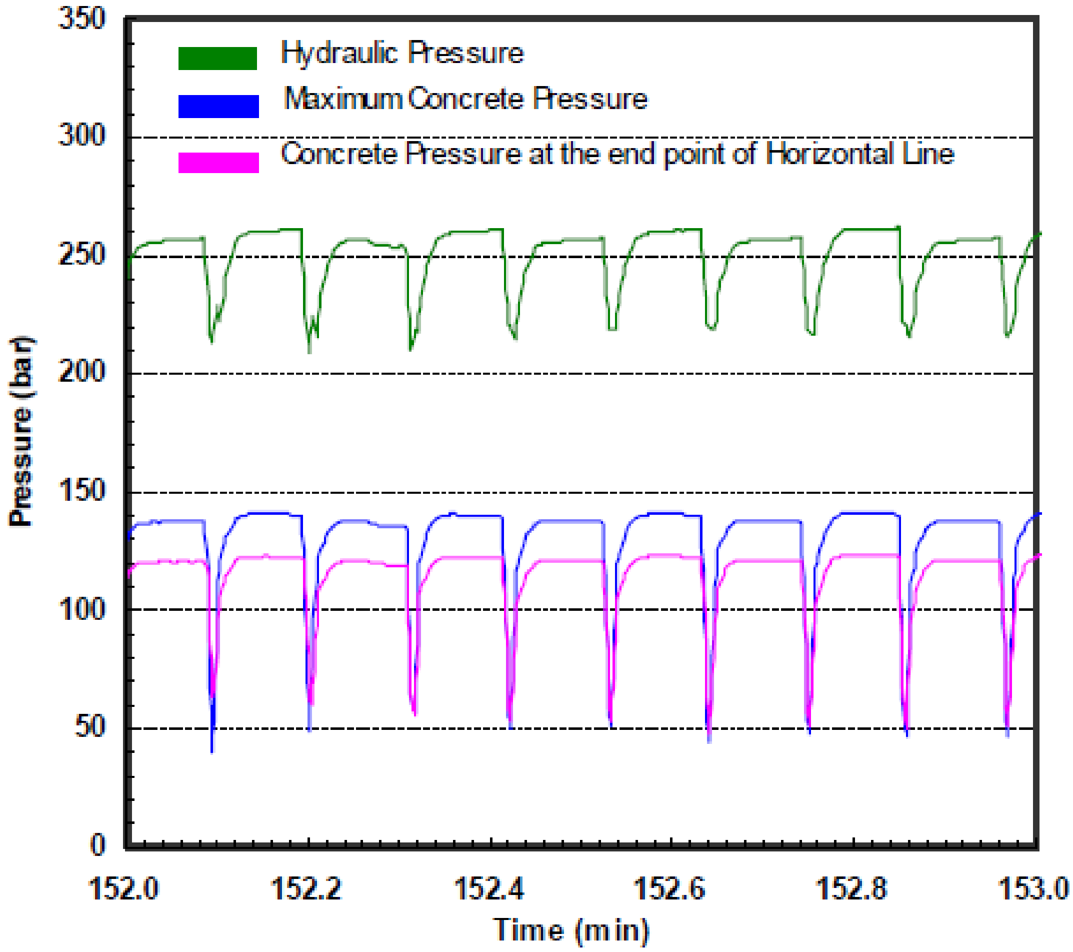

Figure 4. Pressure data for C80-20 (Output 26 m^3/hr)

Feys et al. (2015) state that concrete viscosity is not only a good indicator for the pressure loss for SCC mixtures, it also appears to be a good indicator for highly workable concrete (HWC), non-SCC mixtures and even for conventional vibrated concrete (CVC).

Comparative studies have been conducted by BASF technical personnel at job sites in various countries across Europe and the Asia Pacific region where concrete was pumped using static and boom piston-type pumps. In most cases the hydraulic pressure reduced by 15-24% in mixes with MPE admixtures, irrespective of the concrete grade and mix design. Furthermore, the calculated friction factor at some sites using MPE mixes also decreased by 15-20% compared to PCE thereby increasing pumping efficiency.

It is the author’s understanding that the reduction in pumping pressure observed with MPE is derived from the lower yield stress and plastic viscosity values of the mix including the slip or lubricating layer present in the pump line (Figure 5).

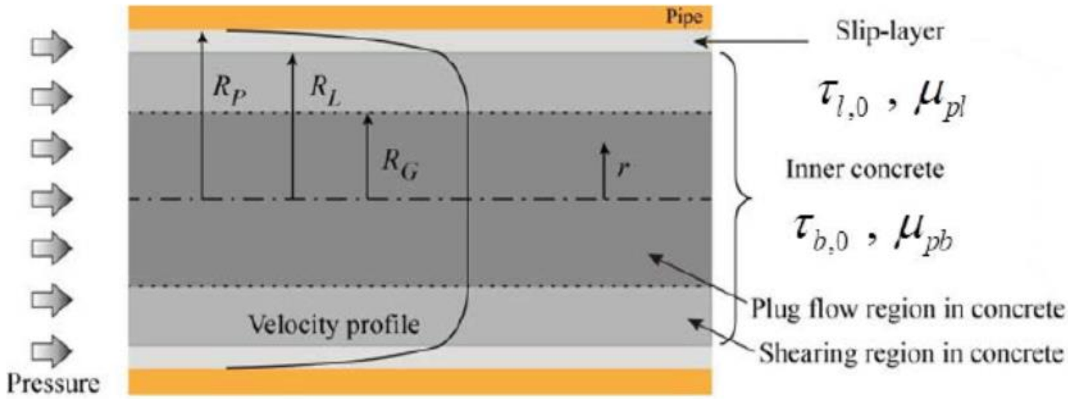

Figure 5. Profile of flow of concrete in a pipe (Choi et al. 2015)

STABILITY AND ROBUSTNESS

Segregation can be defined as the separation of the constituents of a heterogeneous mixture so that their distribution is no longer uniform (Neville 1981). According to Aitcin (1998) the causes of segregation are many, from the presence of washing water left within the ready-mix drum by the truck driver to an error in the water or superplasticiser dosage or a sudden increase in the water content in the sand. Generally speaking, increasing the viscosity of the concrete enhances its stability and hence reduces segregation.

Contrary to the last statement above regarding the relationship between viscosity, stability and segregation, our experimental laboratory work and field experience have shown that concrete produced with MPE admixtures is less sensitive to additional or accidental water and not prone to segregation in spite of the lower viscosity. High resistance to segregation and reduced bleeding characteristics with MPE have been observed in conventional vibrated concrete (CVC) with high proportions of manufactured sands, highly workable (HWC) and self-compacting concrete (SCC) type mixes. This phenomenon may be explained and attributed to the interaction of the MPE molecule with cement particles, whereby the MPE has a greater affinity to the surface of cement compared to PCE.

UNIFORM MIXING AND CONSISTENCY

The goal of mixing concrete is to obtain a uniform mixture with no lumps or agglomeration of materials. Lumps, material balls or agglomerated materials jeopardize structural integrity of a concrete by forming weakened zones and by increasing the permeability. Florida Department of Transportation (FDOT) Standard Specifications for Roads and Bridges Construction (2000) Section 346-7.4.1 requires that concrete should be free from lumps and balls of cementitious material. Hence, when lumps are found, concrete batches are rejected. The consequences are disruption of work, costly rework, and loss of valuable time. A study was performed to determine the root causes and the remedies of the formation of lumps and balls in high-slump truck-mixed concrete. It was found that inadequate mixing and poor batching procedures caused concrete lumps (Amziane et al. 2006).

PCE admixtures take longer to disperse cement and achieve consistency because of the less rigid polymer backbone as discussed earlier. In field work carried out by the author, MPE has been used in similar high-slump truck-mixed concrete and circumstances to alleviate the problems associated with inadequate mixing and consequential formation of lumps and balls which were discharged on to the grate of the concrete pump hopper (see Figure 6).

Figure 6. Lumps & material balls retrieved from grate of pump hopper

CONCLUSIONS

1. Modified polyether (MPE) chemistry can reduce yield stress and plastic viscosity values resulting in superior rheology.
2. A shorter wet-out time can offer the concrete producer potential savings in time, manpower and other resources.
3. Stickiness of concrete can be reduced making the mix more user-friendly.
4. Pumpability and pumping efficiency can be improved.
5. Utilization of MPE technology can benefit the construction industry by accelerating the construction process and reducing overall project costs.

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