Effects of Different Expansive Agents on the Properties of Expansive Cementitious Materials

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Abstract. Cracking happens in the case of restricted volumetric shrinking in cementitious materials which has a negative influence on the mechanical characteristics and longevity of concrete materials and hence, reduces the life of concrete structures. Many techniques have been developed to reduce the shrinkage cracking of concrete among which, usage of expansive agents (EA) has been utilised for decades. Different types of EA creates divergence due to its chemical characteristics. In this paper, three main categories (CaO, MgO & Sulphoaluminate based) EA have been reviewed based on four criteria of concrete structures, such as strength, expansibility, durability and flowability. The review clearly indicates that CaO-based EA boosts the strength but unable to control the temperature rise, which results in thermal cracking in the long run. While MgO-based EA is vastly used in China and Sulphoaluminate based EA have been industrially used worldwide for decades, both of these agents can successfully compensate thermal shrinkage while maintaining adequate mechanical strength and durability. Beside all this differences, all types of EA have been reported to decelerate the flowability of the concrete.

1. Introduction

Exposure to unsaturated environment by a cement-based system leads to a drying shrinkage due to water evaporation [1]. One major reason for mortar and concrete defects such as curling, cracking and de-bonding is shrinkage. These cracks are mentioned as the largest drawback of concrete structures, as they lower the durability due to the water entering to trigger the corrosion of steel bars, allow the leakage of rain, and spoil the aesthetic appearance [2]. It is thus critical for the concrete industry to manage shrinkage deformation as a cause of cracks in concrete in order to extend the structural applications of concrete [3]. To overcome this weakness, different techniques have been adopted such as surface treatments, e.g. prestressed technology, admixture surface treatment [4], shrinkage reducing admixtures (SRA) [5], temperature and humidity in curing condition [6], hybrid fibers [7] and expansive agents. Among the various solutions to control shrinkage, expansive agents can increase the volume of concrete due to specific chemical reactions and can be partially replaced with Ordinary Portland Cement (OPC) [8]. Expansive cement is an additive, industrially sold as powder, which is generally used to reduce concrete drying shrinkage and avoid the formation of cracks while enhancing...
high early strength and concrete hardening process. A concrete, consisting of expansive agent (EA) is also known as expansive concrete or shrinkage compensated concrete. Different EA that causes expanding hydrates after reaction occurs with water can be used to introduce internal expansion. It is important to note that the majority of these reactions lead to less voluminous products than reactants. An EA-containing concrete has an initial bulging bigger than the identical concrete that does not contain any EA. During the water curing of concrete this expansion happens. The maximum expansion is attained between the 2nd and 7th day of water curing, which varies on the type of expansion agent. Then, as soon as the water curing is done, drying shrinkage occurs.

Although EA are massively applied for compensating the drying shrinkage of concrete, it triggers thermal shrinkage and cracking. Because the heat of cement hydration is poorly conducted, its temperature may greatly rise and hence induce substantial thermal shrinking during cooling, which is critical for the shrinkage crack of subsequent ages. The temperature of the concrete may grow dramatically. Preventing thermal shrinkage cracking in mass cement through traditional methods such as the use of cement with low hydration heat, the use of mixtures with high volumes of additional cement materials as cement replacements, precooling raw materials and/or aftercooling concrete by incorporating cooling pipes are all widely used. However, these methods are both expensive and time consuming. [9]. Moreover, despite of the increment of mechanical strength and concrete volume, the harmful side-effects are not considered in the past or present researches. This paper will accumulate the primary categories of EA and find out the important factors that has not been addressed for future investigations.

2. Mechanism and usage of EA
During early concrete hardening the expansion agent is employed to provide a volumetric expansion that entirely or partially mitigates the volumetric contraction generated by various kinds of shrinkage according to distinct chemical processes [10]. Indifference to the type of EA, the expanding mechanism is the same.

![Figure 1](image)

Figure 1. Illustration of the expansion and shrinkage in respect with moist and dry curing period of two concretes, one with an expanding agent and another without [10].

Gagné [10] has illustrated the difference in principle of concrete containing EA and vice versa. In figure 1, it can be analyzed that although the cement without EA has little expansion during the moist curing period, there is a drastic increase in shrinkage that stabilizes after a long period of time. Whereas, the cement with EA dramatically expands during wet curing condition and results in less shrinkage in dry curing condition.
Figure 2. Illustrated the development of concrete strains with or without an expanding agent when volumetric fluctuations are limited [10]

Figure 2 portrays the stress variations in a concrete that is restrained to volumetric variations. For concrete with no EA, a restricted shrinking drying effect leads to tensile tension while shrinkage is developing. Crack occurs if the restrained shrinkage tensile stress is larger than the tensile strength of concrete [11]. Concrete expansion, which contains an EA, is also restricted, so that during moist curing, it produces internal tension of compression (chemical prestressing). The internal compression is reduced when the drying shrinkage begins to form after the curing phase. Lastly, the final tensile stress is less than the former scenario and can greatly minimise or reduce the likelihood of cracking (figure 2).

EA-containing concrete is mostly utilised for building bridge decks and ground decks [12][13]. Repairs and thin bonded concrete overlays are potential sectors where EA's can also be employed [10]. The decrease of the shrinkage in bridge decks is especially significant since the deck is attached to the main or secondary beams. Friction on the ground is the main cause of shrinkage for the plates. The lack of shrinking cracks is particularly crucial for long-term endurance for all these constructions.

3. Different types of EA
Though various EA have been produced over time, the major components of expansive cement include: CaO-based, MgO-based and Sulphoaluminate-type.

The expansive CaO-based agent contains dead-burner calcium granules (CaO) which, on entering into contact with water, create portlandite crystals (Ca(OH)$_2$). Commercial products are poured straight into the mixer; Portland cement, where they are frequently dissolved. According to the ACI 223 Committee report, these EA are Type G.

MgO-based expansive grout contains MgO from the clinker (calcined at 1450 °C), creating chemically stable hydration product, named Mg(OH)$_2$, comparatively less water required for MgO hydration, and specifically its designable expansion properties. Experiments from both experimental and industrial applications showed MgO's benefits in neutralizing concrete shrinkage and improving concrete durability.

Sulphoaluminate-type EA consists largely of a calcium sulphoaluminate (C$_4$A$_3$S) and dead-burn lime (CaO) combination which results in the quick development of ettringitis during water curing. This type of expansion is also applied in United States cements of Type K. A type K component is immediately added to concrete during batching and marketed in the form of a powder. The EA is mixed in some Portland Cement, which is to be removed from the cement dose [10]. Nevertheless, the negligible amount effects greatly in terms of expansibility and mechanical strength.

4. Properties of expansive grouts
Expansive cement can cause volume expansion and does not reduce but expand to some amount in the process of hydration. The usage of expansive cement can help to overcome and strengthen some of the
flaws in regular cement concrete (typically used cement shrinks during the hardening process), allowing the structure to endanger permeability and create cracks, can enhance flexural, compressive and tensile strength and also the concentration of cement concrete structures and the integrity of concrete. The authors can be classified as follows.

| Table 1. Main categories of Expansive Agent. |
|---------------------------------------------|
| Different types of EA | Authors |
| CaO-based | [7][15][17] |
| MgO-based | [9][19][20][21][24][26][27][28] |
| Sulphoaluminate-based | [22][23][29][30][31] |

4.1. Effects on Flowability
An EA can lead to a quick reduction in concrete workability due to the substantial water consumption initially involved [12]. To cater the decreased workability, additional superplasticizer is utilized. Anshuang et al. [14] conducted a research on Ultra High Performance Concrete using CaO, MgO and Sulphoaluminate based Chinese Expansive Grout. The results indicated that the fluidity decreased with the addition of EA. But very few research have been conducted examining the flowability of fresh grout thus, proper examination and methodology should be followed in order to examine the flowability of expansive mortar.

4.2. Effects on Strength
CaO-based expansive grouts are industrially produced in powder form so that it can be added in a small amount (3-10% of the cement mass) to the total mixture. Corinaldesi & Nardinocchi [15] investigated the effects of CaO-based EA in compliance with hybrid fibre reinforcement. He found that although different amounts of EA did not influenced compressive strength values, increased dosages of CaO-based EA were able to significantly increase flexural strength of cement-based composites reinforced by metallic fibre. Usage of Shrinkage Reducing Agent (SRA) alone decreases the compressive strength of the mixture [16]. On the other hand, Nardinocchi and Corinaldesi [17] findings show that addition of polyethylene glycol as Shrinkage Reducing Agent (SRA) to the mixture of CaO-based EA and fibre reinforced concrete penalizes the flexural strength of the concrete. The mechanism may be explained as follows: the cement matrix tends to be expanded because of the use of higher dosages of CaO-based EA and because of the adherence at the interface and the high elastic module, the metallic fibre refinement [18] may be used to prevent this expansion.

The EA from MgO causes slower expansion than the EA from CaO due to the comparatively slower MgO hydration. However, Mo et al. [9] have demonstrated, by modifying calcination and residence duration, the expansion characteristics of an EA based on MgO can be engineered. Additionally, Shen et al. [19] showed that the expansion of MgO caused densification of the concrete under restricted circumstances and, in turn, contributed to the improvement in mechanical strength. In even restricted conditions, nevertheless, the microstructure of the concrete can always be destructed when excessive expansion is achieved by an excessive addition of MgO and then mechanical strength and strength drop [20]. The use of a relevant kind and the right additional dosage of MgO-based EA to achieve the necessary expansion is therefore important to avoid degradation of the microstructure or loss of mechanical strength in concrete. MgO-based expansive grout is known to increase the tensile strength. Qian et al. [21] found out that the ultimate tensile strength increases to a greater extent compared with the compressive strength. This effect is considered as a “scattered prestress effect”.

This EA is comprised primarily of a blend of calcium sulphoaluminate (Ca$_2$Al$_2$S) and dead-burn lime (CaO) that quickly generates ettringite, also known as Type K cement. The amount of aluminate creates different types of Sulphoaluminate based expansive cement. Concrete's compressive strength is unaffected by Type K cement, but it significantly increases the tensile strength of the mixture when fully replaced for Ordinary Portland Cement (OPC) [22]. The presence of expansive cement in Fibre Reinforced Concrete (FRC) resulted in a better bond between fibers and cement matrix over time due
to self-stressing. He also found that, although the flexural strength is same with the OPC cement, addition of steel fibre creates a radical increase to the flexural strength. A high mortar ratio of sulphaaluminate cement, alminate cement, and gypsum results in strong early compressive strength while the late strength of the grouts grows slowly, according to Li & Hao [23]. But it lacks the practicality of usage on site.

4.3. Effects on expansibility

CaO-based expansive grouts have early shrinking resisting effect due to hydration with water. Increment of CaO dosage causes decrement in total porosity. Sun et al. [7] found that the fibres prevented fracture initiation and propagation, decreased crack source size and quantity, and compensated with each other at different scales, improving the pore structure of concrete matrix. A self-prestress effect occurs due to the stress exchange between expanding cementitious paste and steel fibre, allowing a 30% decrease in 56-day drying shrinkage strains [17].

Moreover, Zhang et al. [24] conducted his research on industrially produced MgO-based expansive agent (MEA) and found out that the curing temperature of the expansive grout affects the expansion rate of the mixture. The combination of SRA and MEA cured at 850°C to 950°C could successfully counteract the cement paste shrinkage [24]. The presence of SRA lowered MEA hydration, and as cure age progressed, MEA hydration with or without SRA tended to be the same. It was because SRA breakdown decreases the polarity of water and SRA molecules absorb on MEA particles surface. Mo [25] said that MEA with increased responsiveness results in faster and bigger concrete expansion at an early age, but slower and less late expansion. Mo et al. [9] long-term research on MgO concrete samples or in-build surveillance on dam concrete shows that, once MgO hydration has been finished, the extension curve of MgO concrete is being stabilised. This is due to Mg(OH)$_2$, which have extremely poor solubility and which is 200 times less than Ca(OH)$_2$’s stable chemical characteristics. According to Chen and Ma [26], Gao et al. [27] and Ye et al. [28], as fly ash has moderating effects on the expansion of MgO, increasing the amount of fly ash added to cement pastes will result in a reduction in the expansion of MgO in the paste.

The expansion caused by the ettringite agent is significantly more than the regular grout [29]. Wu et al. [30] found a clear early expansion effect during standard curing, due to calcium sulphaaluminate hydrate-calcium hydroxide EA, compared to the basic cement mortar. But, CaO & MgO based EA have more expansive characteristics in comparison with Sulphaaluminate Expansive Cement. The results found in Afroughsabet et al. [22], also demonstrate that the use of Type K cement in place of OPC may compensate for shrinkage in concrete, and the length change remain relatively constant even after 56 days of exposure.

China has developed sulphaaluminate expansive cement of their own, known as United Expansive Agent (UEA). According to Sun [7], integration of EA with fibre on high strength grout improved the interface between fiber-matrix and aggregate-matrix, allowing fibres of varying sizes and types to resist shrinkage and cracking on a range of different scales. As a result, the shrinkage resistance of cement and fibers functioned earlier. Dong et al. [31] experimented using a Chinese Expansive agent from Nanjing Tejian Co. which is Low-alkali UEA. He found out that mineral admixtures remarkably influence the expansion characteristics of EA in grout. When the dosage of mineral admixtures is increased appropriately, the application impact of EA in grout is increased and the shrinkage effect of the grout is compensated for it. However, compared with curing conditions, mineral admixture has a minor influence on ettringite production.

4.4. Effects on durability

Durability of a compound is measured by examining its water permeability using different EA. Sun et al. [7] found out concrete reinforced with steel fiber has provided better improvement for the impermeability and durability. In fact, different sizes of steel fibers are providing different outcomes. Moreover, it had a considerably greater impact than that created by adding UEA or steel fibre alone when united expansive Agent (UEA) and steel fibre had. When three or two types of fibres are appropriately combined and integrated into the concrete, the relative coefficient of water permeability of the concrete might fall by 56% - 70% [7]. Usage of EA in hydraulic structures are less likely used in
practical life due to lack of enough research, including chlorine attack. Unfortunately, many research have not been focused on the durability of structures and future probes are to be conducted to diversify the usage of EA.

5. Conclusions and recommendations
This study summarized all different types of EA that has been used around the world and correlated each other based on the intended outcomes. Although sulphoaluminate-based expansive cement have been widely used for the past six decades, China has over 40 years of experience in using MgO-based expansive cement in their structures. Furthermore, usage of EA alone is not sufficient due to its own inexpediency. Thus addition of external additives such as shrinkage reducing agent (SRA), steel fibre, hybrid fibre, polyvinyl alcohol (PVA) fibers, polyethylene terephthalate (PET) fibres, pozzolans etc. have shown better results in terms of material strength, expansibility, durability and flowability. The factors that effects the expansibility of different EA are dosage, curing condition and temperature.

However, very few research has been conducted on the vast usage of expansive cementitious composite in modern days. Despite of simple and easy usage of EA due to its powder form, the traditional expansive additives have many drawbacks. For example, their hydration and expansion rates are too fast to control. The expansive hydration components do not work well in water (a low thermal stability). Although atmospheric conditions can be controlled during the experiment, usage of this EA on site. Table 2 also shows that very few research focused on the flowability of the expansive cement which tends to be the matter of utmost importance during construction. In addition, the water content necessary for hydration processes is excessively high. But until now only MgO-based EA have partly succeeded to compensate this limitations. It is recommended that further research using new cementitious components are to be conducted to bring more versatility into the process, including research on fresh cement flowability and early high-strength.

Table 2. Research summary.

| Parameters          | Sun et al. [7] | Corinaldesi & Nardinocchi [15] | Mo et al. [9] | Li [20] | Qian et al. [21] | Afroughsabet et al. [22] | Wu et al. [30] | Anshuang et al. [14] |
|---------------------|----------------|--------------------------------|---------------|---------|-----------------|--------------------------|----------------|---------------------|
| Strength            | -              | ✓                              | -             | ✓       | ✓               | ✓                        | -             | X                   |
| Expansibility       | ✓              | ✓                              | ✓             | -       | ✓               | ✓                        | ✓             | ✓                   |
| Durability          | ✓              | -                              | -             | -       | -               | -                        | -             | -                   |
| Flowability         | -              | -                              | -             | -       | -               | -                        | -             | X                   |

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