# USE OF TARTARIC ACID FOR THE PRODUCTION OF SUSTAINABLE PORTLAND-FREE CSA-BASED MORTARS

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## ABSTRACT

The purpose of the study is to evaluate the effect of a tartaric acid-based set retarding admixture on rheological, elastic and physical performances of sustainable mortars manufactured with calcium sulfoaluminate, anhydrite and Supplementary Cementitious Materials replacing totally OPC. Experimental results indicated that the tartaric acid acts as superplasticizer and it is effective to extend the pot-life of mortars up to about 2 hours. On the other hand, the set-retarding admixture provides a strong retardation of binder hydration resulting in a reduction of initial expansion and compressive strength at early ages. However, this retarding effect disappears at long ages.

## KEYWORDS

Calcium sulphoaluminate cement; supplementary cementitious materials; tartaric acid; set-retarding admixtures; sustainability

## HIGHLIGHTS

- Sustainable OPC-free mortars with CSA and SCMs were investigated
- Tartaric acid acts as superplasticizer and set-retarding admixture
- Shrinkage and mechanical properties are influenced by tartaric acid addition
- About 60% reduction in Gross Energy Requirement and $CO_2$ emissions was achieved

# INTRODUCTION

The topics of sustainability and environmental protection in construction have become very important when Kyoto protocol was adopted in 1997 and, particularly, after the Paris Agreement (COP21, 2015) which was aimed to limit the temperature increase even further to 1.5°C above pre-industrial levels.

In this context, a sharp reduction of $CO_2$ emissions and in consumption of natural resources in production of construction materials is needed.

In 2016, about 4.2 billion tons of Portland-based hydraulic cement were used globally – about 2.4 billion tons in China – (1), and $CO_2$ emissions from the cement industry exceeded 7% of global anthropogenic greenhouse gases emission (2). Concrete industry is not eco-friendly since it consumes great amount of cement, aggregates and water.

In order to reduce the environmental impact of concrete industry, several authors (3,4) have identified different strategies: a) using alternative fuels and raw materials to reduce greenhouse gases emissions to produce Portland cement (5–7); b) replacing Portland cement clinker with low-carbon supplementary cementitious materials (SCM) (8–11); developing alternative low-carbon binders, such as alkali-activated materials, geopolymers and calcium sulphoaluminate cements (12,13); c) reducing natural resource consumption through to waste management and waste recovery (14–21); increasing durability of concrete structures by means of high-performance admixtures (22,23).

Between these strategies, calcium sulphoaluminate cements (CSA) are actually receiving increasing attention because they promise to provide a low-$CO_2$ and low-embodied energy alternative to Portland cement. In fact, compared to alite, which releases 0.578 $CO_2$ g/g, emissions of greenhouse gases, calcium sulphoaluminate clinker contributes only for 0.216 $CO_2$ g/g. In addition, the maximum kiln temperature to produce CSA clinker is typically 1250 °C, about 200°C lower than

50  that used for Portland cement clinker. Finally, the grinding process requires lower energy due to the

51  lower hardness of CSA clinker compared to Portland clinker (24–26).

52  In general, about 15-25 wt. % of calcium sulfate, in form of gypsum (G) or anhydrite ($C\bar{S}$), is

53  blended with CSA-clinker to control setting time, strength development and volume stability.

54  Several authors (27–29) have shown a close correlation between the main properties of CSA-based

55  composites and calcium sulfate dosage. Nowadays, the use of calcium sulphoaluminate cement is

56  widespread for calcium sulphoaluminate – ordinary Portland cement – calcium sulfates ternary

57  binders in which OPC is present up to 60% with respect to binder mass (30,31).

58  One of the main issues related to the use of CSA for the production of concrete is the setting time;

59  indeed, it is well known that mixtures containing calcium sulphoaluminate cement are characterized

60  by a short pot-life and a pronounced workability loss over time (32–34). In order to face this

61  practical problem, several set-retarding admixtures were proposed by different authors.  Sugama

62  proposed the use of citric acid as a set retarder (35). Velazco et al. (36) showed that the addition of

63  citric acid increased the setting time, modified the morphology of the ettringite needles, changed the

64  microstructural configuration and prevented the decreasing in compressive strength caused by

65  delayed ettringite formation. Moreover, Bishop et al. synthetized a novel retarding admixture based

66  on calcium nitrilotris(methylene)-triphosphonate (37) and investigated mechanisms responsible for

67  set and hardening retardation promoted by sucrose, tartaric acid and lignosulfonate in CSA-based

68  mortars (38). Results indicated that tartaric acid is the most effective in retarding $C_3A$ hydration and

69  ettringite formation.

70  The purpose of the present study is to evaluate the effect of addition of a tartaric acid-based set

71  retarding admixture on rheological, elastic and physical performances of sustainable mortars

72  manufactured with CSA, anhydrite and supplementary cementitious materials (fly ash, metakaolin

73  and ground granulated blast furnace slag) replacing totally OPC.

74

# MATERIALS AND METHODS

## Materials

A ternary binder based on ordinary Portland cement CEM I 52.5R (OPC: according to EN 197-1), commercial CSA clinker and technical grade anhydrite ($C\overline{S}$) was used to manufacture the reference mortar (CSA:OPC:$C\overline{S}$ = 40:40:20). Ground granulated blast furnace slag (S: according to EN 15167-1), metakaolin (MK: according to ASTM C618), V class fly ash (FA: according to EN 450-1 and EN 197-1) and hydrated lime CL90-S class (CH: according to EN 459-1) were employed to replace totally OPC in sustainable mortars (CSA:SCM:CH:$C\overline{S}$ = 40:35:5:20). CH was added to the mix in order to improve the pozzolanic reaction of SCM amount not consumed in the reaction with CSA; furthermore, sand/binder ratio was fixed equal to 3 (maximum diameter of natural siliceous aggregates equal to 2.5 mm). Tartaric acid-based set-retarding admixture was added up to 1.2% with respect to binder mass, while the mixing water was adjusted in order to attain, in absence of set retarding admixture, the same workability at the end of the mixing procedure, equal to 160 mm $\pm$ 10 mm spreading.

**Table 1 –** Physical properties of binders

|  | OPC | CSA | $C\overline{S}$ | CH | S | FA | MK |
|---|---|---|---|---|---|---|---|
| $D_{50}$ [μm] | 5.19 | 8.18 | 2.93 | 3.00 | 5.48 | 11.1 | 2.70 |
| Specific surface [cm$^2$/g] | 3`175 | 2`722 | 4`837 | 4`678 | 3`049 | 2`283 | 3`990 |
| Specific mass [kg/m$^3$] | 3`150 | 2`650 | 2`670 | 2`120 | 2`730 | 2`010 | 2`240 |

**Table 2** – Composition of mortars

| Composition [kg/m³] | CSA | CEM I 52.5 R | C$\bar{S}$ | CH | GGBFS | FA | MK | Aggregates | Water | Tartaric acid |
|---|---|---|---|---|---|---|---|---|---|---|
| **REF 40/40** | 183 | 183 | 91 | | | | | 1`370 | 279 | |
| **REF 40/40 0.4** | 183 | 183 | 91 | | | | | 1`370 | 279 | 1.82 |
| **REF 40/40 0.8** | 183 | 183 | 91 | | | | | 1`370 | 279 | 3.65 |
| **REF 40/40 1.2** | 183 | 183 | 91 | | | | | 1`370 | 279 | 5.48 |
| **S 40/35/5** | 183 | | 90 | 25 | 156 | | | 1`355 | 275 | |
| **S 40/35/5 0.4** | 183 | | 90 | 25 | 156 | | | 1`355 | 275 | 1.81 |
| **S 40/35/5 0.8** | 183 | | 90 | 25 | 156 | | | 1`355 | 275 | 3.61 |
| **S 40/35/5 1.2** | 183 | | 90 | 25 | 156 | | | 1`355 | 275 | 5.43 |
| **FA 40/35/5** | 170 | | 85 | 24 | | 147 | | 1`277 | 298 | |
| **FA 40/35/5 0.4** | 170 | | 85 | 24 | | 147 | | 1`277 | 298 | 1.70 |
| **FA 40/35/5 0.8** | 170 | | 85 | 24 | | 147 | | 1`277 | 298 | 3.41 |
| **FA 40/35/5 1.2** | 170 | | 85 | 24 | | 147 | | 1`277 | 298 | 5.11 |
| **MK 40/35/5** | 165 | | 82 | 23 | | | 142 | 1`234 | 329 | |
| **MK 40/35/5 0.4** | 165 | | 82 | 23 | | | 142 | 1`234 | 329 | 1.65 |
| **MK 40/35/5 0.8** | 165 | | 82 | 23 | | | 142 | 1`234 | 329 | 3.29 |
| **MK 40/35/5 1.2** | 165 | | 82 | 23 | | | 142 | 1`234 | 329 | 4.95 |

## Tests on mortars

At the end of the mixing procedure, workability was measured by means of flow table according to EN 1015-3. In addition, specific mass was evaluated on fresh mortars according to EN 1015-6 standard. Moreover, the pot-life of the mixture, which corresponds to time during which workability by flow table is higher than 140 mm, was also detected. Specimens 40x40x160 mm³ were produced and cured under water at 20°C; in addition, only for mixture containing 0.8% of tartaric acid, specimens were cured both under water at 20°C and in a climatic chamber at 20°C and R.H. 60%. Specific mass, compressive and flexural strength at 1, 7 and 28 days were also determined (EN 1015-11). Moreover, drying shrinkage was measured over time on specimens stored in dry environment (20°C, R.H. 60%) both in plastic and hardened (according to EN 12617-4) phase. Finally, SEM observation were performed on 28-day specimens cured under water.

## RESULTS AND DISCUSSIONS

The amount of water to achieve the target workability (160 mm spreading) is, in the absence of set retarding admixture, variable due to the different specific surface, texture and shape of binders

107   (Tables 1 and 2). In particular, replacing OPC with GGBFS, no change in terms of mixing water

108   was noticed. On the contrary, the use of FA determines an increase in water demand equal to 7%

109   due to the high unburnt carbon content (L.O.I. = 4.9% according to EN 196-2 and ISO 10694),

110   while employing MK in place of OPC water amount rise up about 18% respect to reference mortars

111   due to the higher fineness of metakaolin compared to Portland cement. Furthermore, tartaric acid-

112   based set-retarding admixture acts as a superplasticizer (Figure 1). The super-plasticizing effect is

113   more pronounced in fly-ash based mortars (+45% spreading with respect to mixture without set-

114   retarding admixture), while is almost the same for mortars manufactured with the other binders

115   employed (+20%).
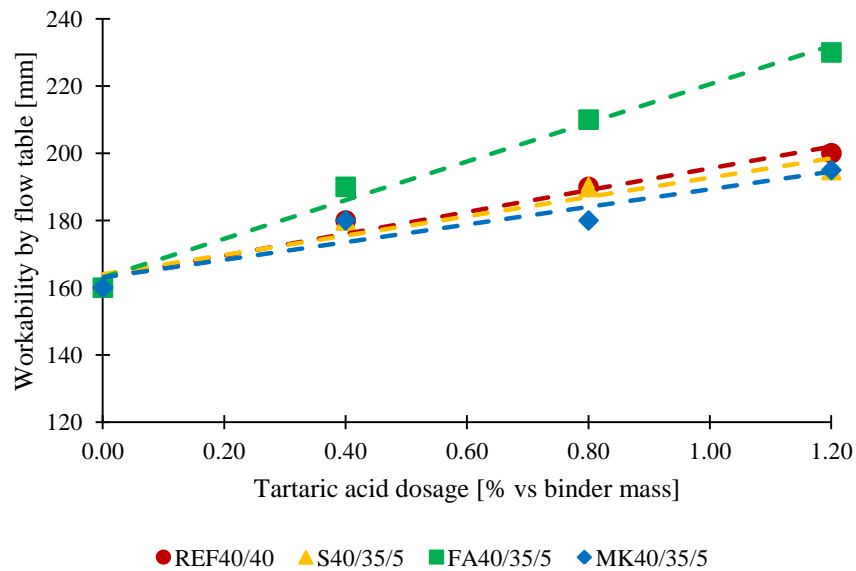


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117   *Fig. 1 – Workability by flow table of mortars vs set-retarding admixture dosage*

118   Tartaric acid addition does not produce any abnormal air entrapment; in fact, regardless of set-

119   retarding admixture dosage, specific mass of mortars is substantially the same both in fresh and

120   hardened state (Figure 2). On the contrary, the total substitution of OPC with SCMs modifies

121   density of mortars; in fact, FA and MK-based mixtures showed specific mass (both in fresh and

122   hardened state) lower than that detected on reference (containing OPC) and S-based mortars as a

123   consequence of the increase of mixing water to achieve the target workability.

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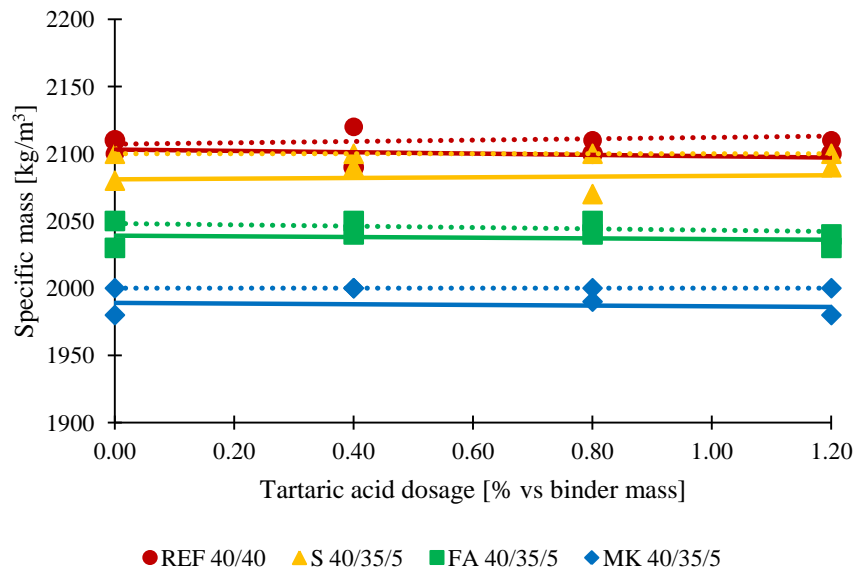
*Fig. 2 – Specific mass at fresh (continuous line) and hardened (dashed line) state of mortars vs set-retarding admixture*

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126

*dosage*

127 Figure 3 shows that the effectiveness of admixture with different binders is almost the same.

128 Regardless to the binder used, pot-life of mortars without tartaric acid is about 20 minutes, which is

129 not suitable for placing in the job-site; the addition of tartaric acid-based admixture extends the pot

130 life of mortars up to 110 minutes from mixing. The average time between mixing and placing a

131 mortar in the job-site is generally close to 60 minutes. Based on this target, it is possible to conclude

132 that the ideal set-retarding admixture dosage is equal to 0.8% vs. binder mass (Figure 3).
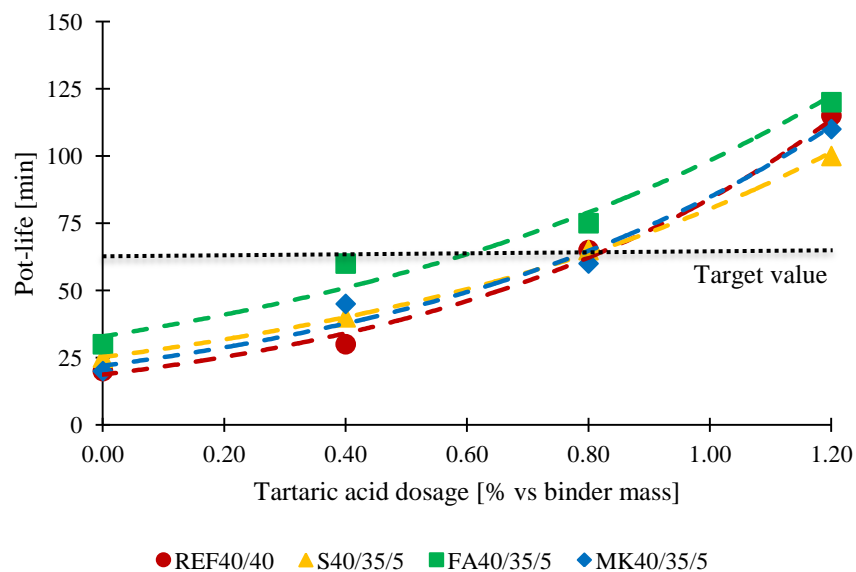


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*Fig. 3 – Pot-life of mortars vs set-retarding admixture dosage*

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Results (Table 3) indicate that addition of tartaric acid-based admixture determines a strong retardation of binder hydration and, consequently, a general reduction of 24-hour compressive strength of both reference and SCMs mortars, except for MK-mixtures. The higher the tartaric acid dosage, the stronger the decrease of compressive strength (Figure 4).

**Table 3** – Mechanical properties of hardened mortars wet cured

| Composition | w/b ratio | $R_f$ at 24 h [MPa] | $R_f$ at 7 days [MPa] | $R_f$ at 28 days [MPa] | $R_c$ at 24 h [MPa] | $R_c$ at 7 days [MPa] | $R_c$ at 28 days [MPa] |
|---|---|---|---|---|---|---|---|
| **REF 40/40** | 0.61 | 7.27 | 7.47 | 7.52 | 34.69 | 41.08 | 47.41 |
| **REF 40/40 0.4** | 0.61 | 4.69 | 5.02 | 6.86 | 21.53 | 39.13 | 44.06 |
| **REF 40/40 0.8** | 0.61 | 3.28 | 3.48 | 7.03 | 13.03 | 42.16 | 52.91 |
| **REF 40/40 1.2** | 0.61 | 0.82 | 2.11 | 7.03 | 2.22 | 27.84 | 47.81 |
| **S 40/35/5** | 0.61 | 5.09 | 5.29 | 5.39 | 30.50 | 32.59 | 35.56 |
| **S 40/35/5 0.4** | 0.61 | 5.16 | 5.19 | 5.25 | 26.22 | 31.44 | 36.69 |
| **S 40/35/5 0.8** | 0.61 | 4.69 | 4.69 | 5.16 | 21.94 | 30.22 | 34.13 |
| **S 40/35/5 1.2** | 0.61 | 0.96 | 2.29 | 4.99 | 19.98 | 24.12 | 34.98 |
| **FA 40/35/5** | 0.70 | 5.03 | 5.21 | 5.32 | 27.02 | 33.18 | 36.02 |
| **FA 40/35/5 0.4** | 0.70 | 4.92 | 4.92 | 5.25 | 23.50 | 31.52 | 35.86 |
| **FA 40/35/5 0.8** | 0.70 | 4.92 | 5.01 | 5.12 | 18.31 | 33.00 | 36.68 |
| **FA 40/35/5 1.2** | 0.70 | 1.12 | 2.53 | 5.33 | 14.69 | 22.13 | 35.82 |
| **MK 40/35/5** | 0.80 | 2.81 | 3.05 | 3.28 | 13.13 | 15.59 | 17.58 |
| **MK 40/35/5 0.4** | 0.80 | 3.52 | 3.75 | 3.75 | 12.50 | 17.94 | 20.06 |
| **MK 40/35/5 0.8** | 0.80 | 3.05 | 3.52 | 3.75 | 12.09 | 18.50 | 19.03 |
| **MK 40/35/5 1.2** | 0.80 | 0.56 | 1.88 | 3.19 | 10.06 | 13.09 | 18.42 |

Since the retarding effect of tartaric acid is more pronounced on OPC (39), the decrease of compressive strength in reference mortars, when the dosage of the set-retarding admixture increases, was significantly higher compared to slag and fly ash based mortars. Another effect responsible for the lower reduction of compressive strength of SCMs-based mortars should be attributed to a partial adsorption of tartaric acid by S, FA and MK particles. The lower amount of tartaric acid in the aqueous phase could justifies the lower retardation of these mortars.

This retarding effect totally disappears at 28 days for all mixtures (Figure 5). In general, the total replacement of OPC with SCMs causes a reduction in compressive strength ranging from 30% (for slag and fly ash) to 60% (for MK-based mortars). The effect of curing conditions was also investigated; specimens cured at 20°C under water evidenced compressive strength values about
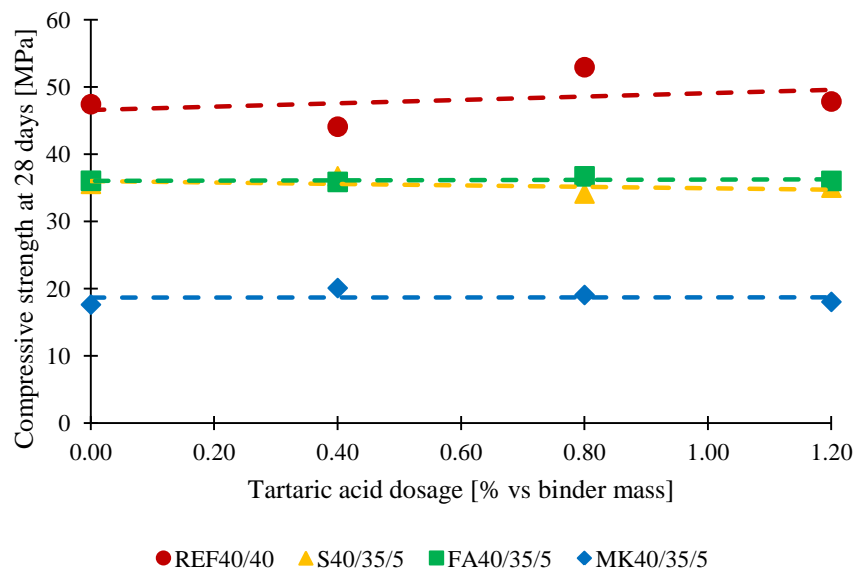
150  25% lower than that measured on mortars stored in dry environment (20°C, R.H. 60%),

151  independently of the age and the SCMs used (Figure 6).
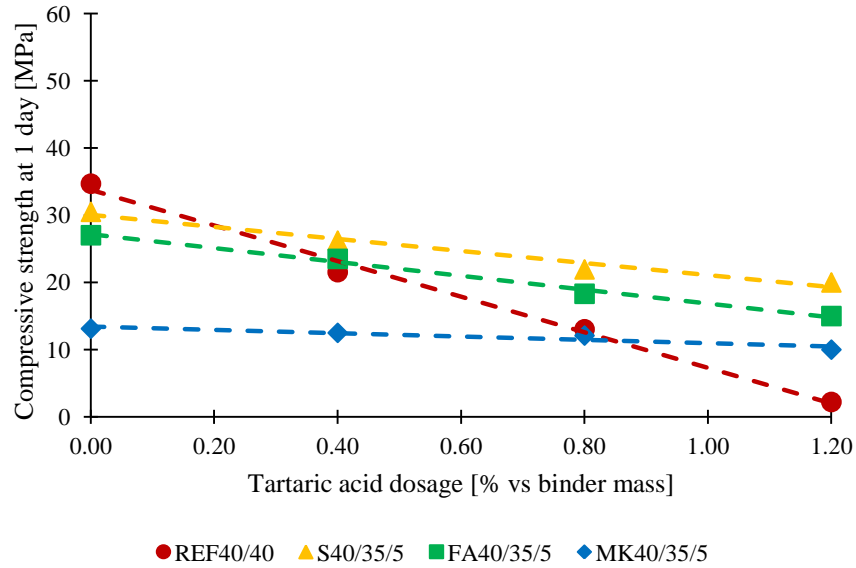
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153  ***Fig. 4** – Compressive strength of mortars after 24 hours vs set-retarding admixture dosage*
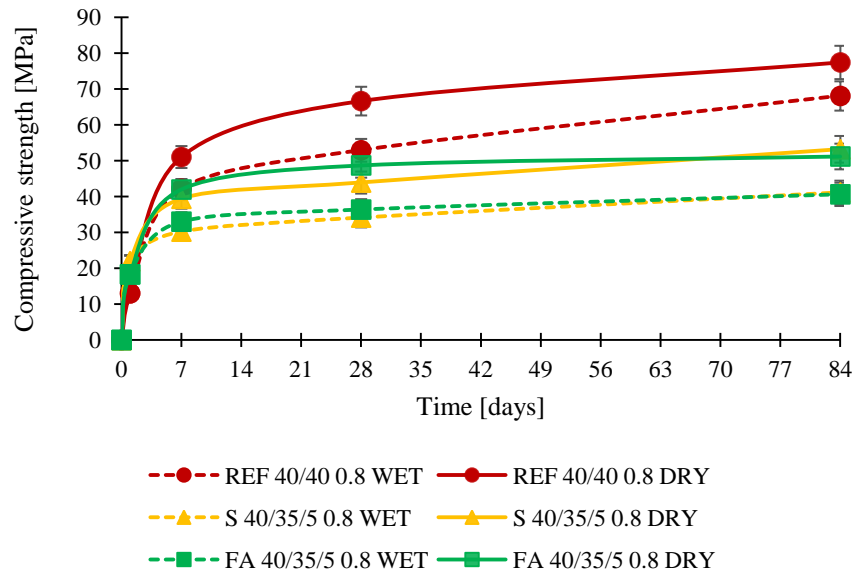
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155  ***Fig. 5** – Compressive strength of mortars after 28 days vs set-retarding admixture dosage (specimens under water at T*

156  *= 20°C)*

*Fig. 6 – Development of compressive strength over time with different curing: under water (WET) and on dry environment at R.H. 60% (DRY)*

The images collected by means of scanning electron microscope (SEM) on 28-day specimens showed a different microstructure between mortar containing Portland cement and those manufactured with SCMs (Figure 7 - 8). In particular, SCM-based mixtures are characterized by a homogeneous microstructure with rich amounts of needles covered by small Ca-rich particles of size 0.1-0.5 μm. The prismatic needles had a thickness of about 2-5 μm and a length approximately equal to 5-20 μm. On the contrary, the microstructure of CSA/OPC/C$\overline{S}$ mortar seems to be composed of denser crystals than those of SCM-based mixtures. In addition, the presence of Ca-rich particles highlighted in Portland-free mortars was not observed.
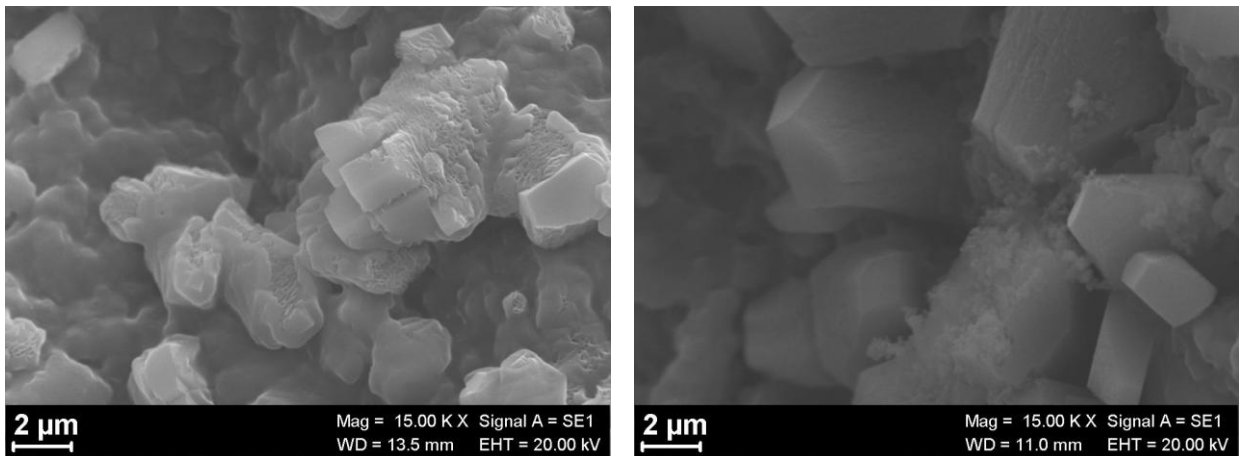


*Fig. 7 – SEM images of reference mortar (on the left) and S-based mortar (on the right)*
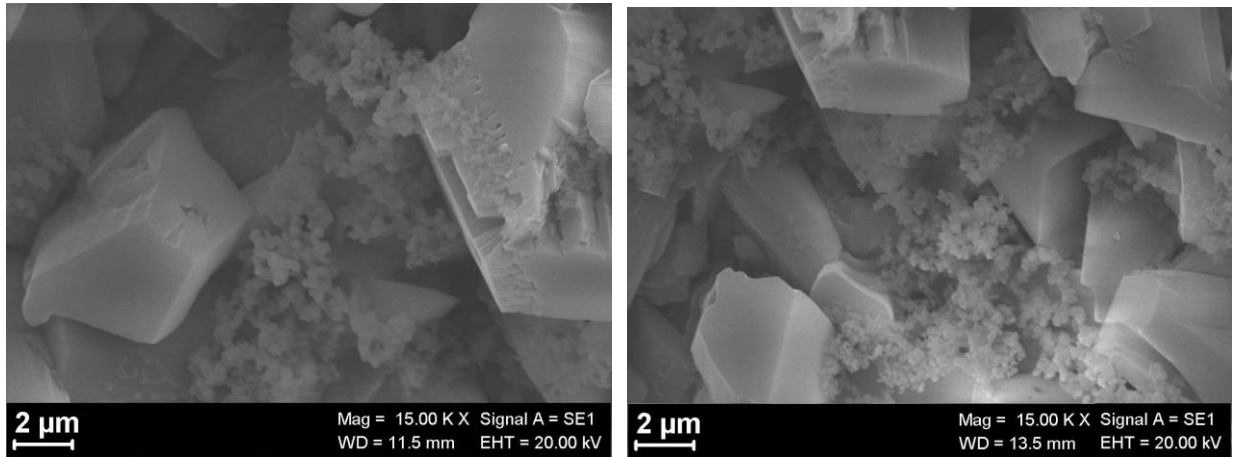
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Fig. 8 – *SEM images of FA- mortar (on the left) and MK-based mortar (on the right)*

Shrinkage tests were performed up to 270 days on prismatic 40x40x160 mm specimens stored at 20°C and R.H. 60% (Figure 9). Reference mortar manufactured without tartaric acid shows a marked expansive behavior (up to +800 μm/m at 24 hours from casting) followed by shrinkage (-400 μm/m at 270 days). Total replacement of OPC with SCMs and hydrated lime determines – in absence of set-retarding admixture – a sharp reduction of the initial expansion followed by shrinkage (about -500 μm/m after 270 days), independently of the nature of SCM replacing OPC.
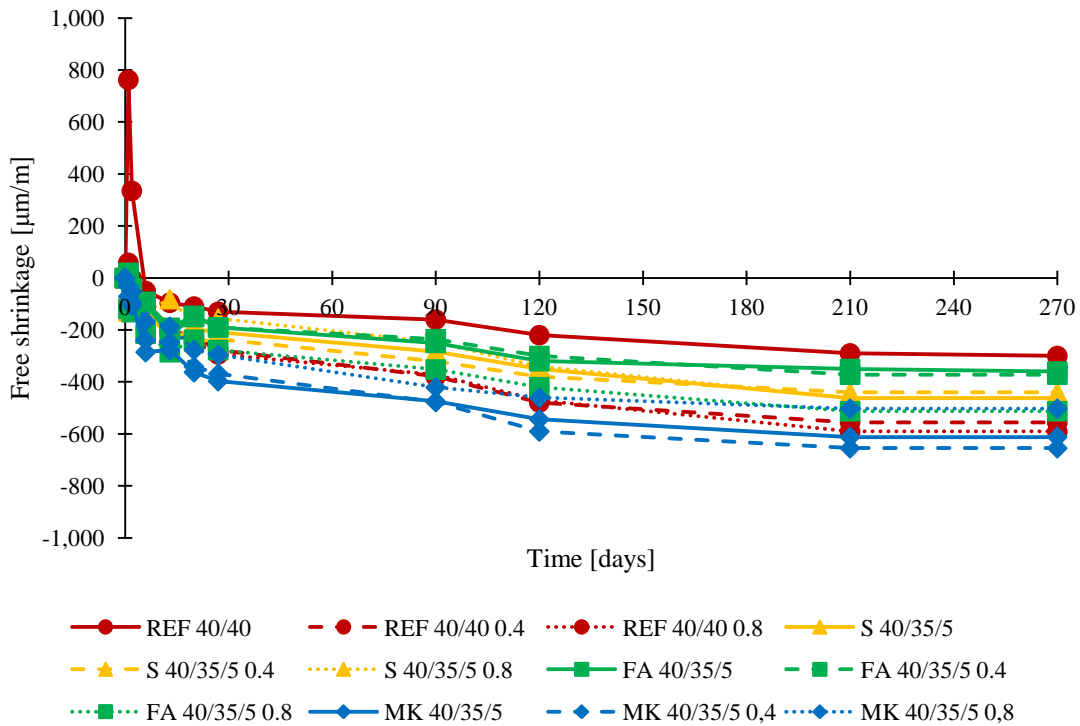


Fig. 9 – *Free shrinkage over time in dry environment (T = 20°C, R.H. 60%)*

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By using tartaric acid, CSA-based mortars (both that containing OPC and those manufactured with SCMs) did not evidenced the initial expansion, but they began to shrink just after the final setting time has occurred. This could be ascribed to the delay in the development of ettringite when the tartaric acid is used. These mixtures, however, despite the absence of initial expansion, present a quite stable behavior over time, with a free shrinkage lower than -500 μm/m after 270 days.

The role of tartaric acid is also evident on the expansive behavior in the plastic phase (Figure 10); reference mortar (containing OPC) manufacturing without set-retarding admixture achieves an expansion equal to 1`000 μm/m already after 6 hours from casting while the reference mortar manufactured with 0.2% set-retarding admixture is essentially stable over time. In general, use of tartaric acid-based set-retarding admixture, independently of the presence of OPC and the nature of SCM, eliminates the initial expansion typical of reference CSA-OPC-C$\overline{\text{S}}$ without admixture (Fig. 11). In other words, the "expansive/shrinkage" behavior of the mortar in the absence of tartaric acid is transformed in an "exclusively shrinkage" behavior. However, the final contraction detected for mortars containing set-retarding admixture was substantially the same of that measured in reference mortar (containing OPC) without tartaric acid.
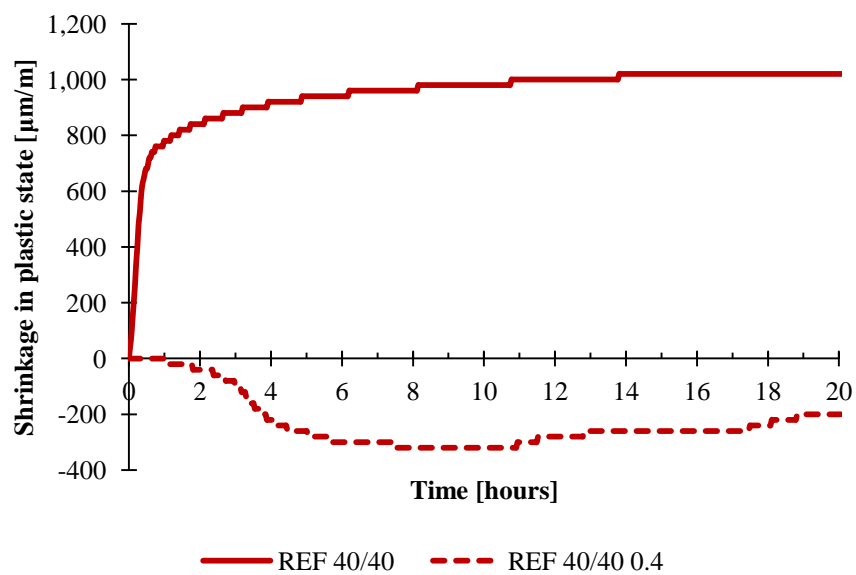
196 **Fig. 10** – *Shrinkage of reference mortars in plastic state over time in dry environment (T = 20°C, R.H. 60%)*



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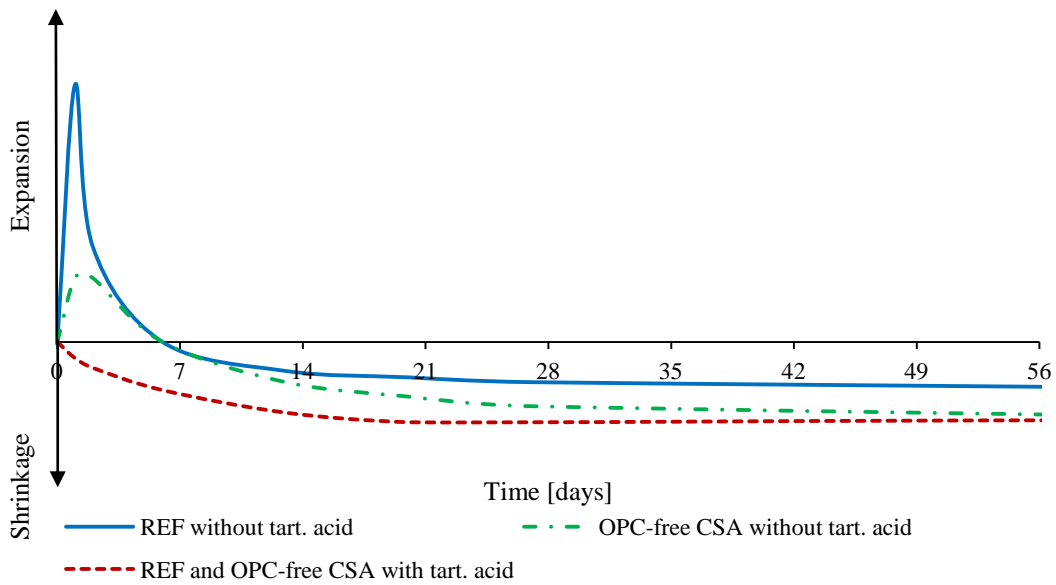
198 **Fig. 11** – *Expansive/shrinkage behavior of CSA-based mortars without tartaric acid compared to stable behavior of*

199 *mortars manufactured with set-retarding admixture*

200 From a practical point of view, mixtures with "exclusively shrinkage" behavior - at the same value

201 of 270-day shrinkage of expansive/shrinkage mortar - seems to be more promising in repair of

202 existing concrete structures since the tensile stress induced by restrained contraction is lower. As a

203 consequence of more stable behavior of SCM mortars manufactured with the tartaric acid, although

204 the sharp decrease detected for 28-days compressive strength when OPC is replaced by SCMs, FA-

205 and S-based mortars showed mechanical performances suitable for mixtures devoted to "cosmetic

206 repair" of existing reinforced concrete structures, where shrinkage is the main design parameter.  In

207 particular, CSA-Portland free mortar can be classified as R3 strength class ($R_c \geq 25$ MPa at 28 days)

208 according to EN 1504-3 and, hence, suitable for repair of existing concrete structures that present

209 corrosion of rebars and spalling of concrete cover. Furthermore, the worsening in mechanical

210 strength of SCMs mortars is fully offset by a marked improvement in environmental sustainability.

211 Indeed, at equal strength class, gross energy requirement (GER) and global warming potential

212 (GWP) parameters of Portland-free mortars are lower than those of both high volume fly ash

213 (HVFA) mortars (40), traditional mixtures manufactured with OPC and ternary binders based on

14

214    CSA. In particular, starting from data on $CO_2$ emissions and energy production of binders (CEM I,

215    CEM II/A-LL, CSA, $C\overline{S}$ and CH), supplementary cementitious materials (S, FA and MK) and

216    aggregates (Table 4), the reduction of GER and GWP deriving from the use of limestone Portland

217    cement, HVFA, CSA-OPC- $C\overline{S}$ ternary mixtures and CSA-SCMs-CH-$C\overline{S}$ blends in place of

218    Portland cement was determined. It is possible to conclude that, at the same strength class, the use

219    of traditional CSA-based ternary mixture in place of Portland cement or limestone Portland cement

220    determines a reduction in terms of GER and $CO_2$ emissions ranging from 25% to 35% while the

221    total replacement of OPC with SCMs slumps GER and GWP of about 60% (Figure 12). Finally,

222    GER and GWP of Portland-free CSA-based mixtures reach lower values than those shown by

223    HVFA mortars.

224         **Table 4 –** Environmental parameters of binders, SCMs and aggregates. Source: Ecoinvent 3.0 Database

|  | GER [MJ/kg] | GWP [Kg $CO_2$/ Kg] |
|---|---|---|
| **CEM I 52.5 R** | 5.50 | $9.8 \cdot 10^{-1}$ |
| **CEM II/A-LL 42.5R** | 3.60 | $8.8 \cdot 10^{-1}$ |
| **CSA** | 2.70 | $7.4 \cdot 10^{-1}$ |
| **$C\overline{S}$** | 1.30 | $2.4 \cdot 10^{-1}$ |
| **CH** | 4.50 | $4.2 \cdot 10^{-1}$ |
| **S** | 0.31 | $1.7 \cdot 10^{-2}$ |
| **FA** | 0.10 | $5.3 \cdot 10^{-3}$ |
| **MK** | 1.50 | $9.2 \cdot 10^{-2}$ |
| **Aggregates** | 0.13 | $2.4 \cdot 10^{-3}$ |

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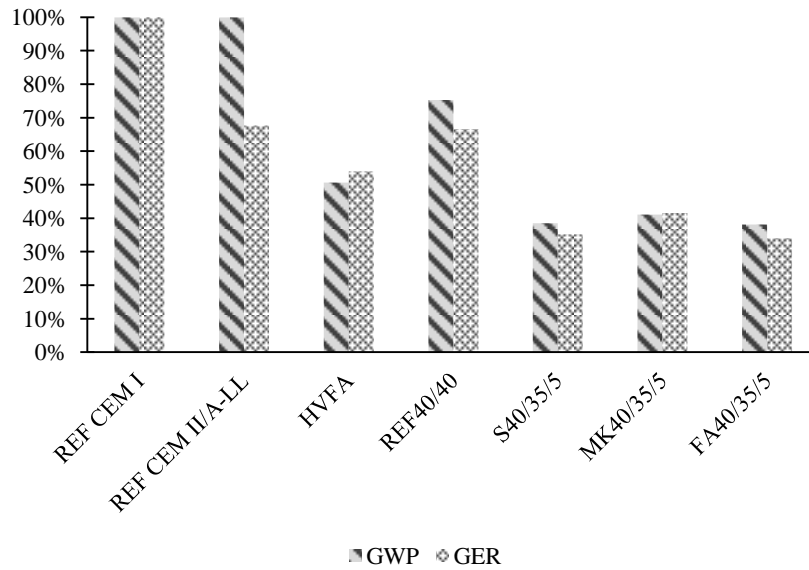
**Fig. 12** – *Global Warming Potential (GWP) and Gross Energy Requirement (GER) of mortars at the same strength class normalized by those of CEM I-based traditional mortar*

## FURTHER RESEARCH

Further experimentations are needed to measure Young modulus and the adhesion properties of these eco-friendly ternary binders. In addition, durability issues of mortars and concretes manufactured with CSA-based Portland-free binders have to be thoroughly investigated, especially in chloride and sulfate-rich environments or in presence of freeze and thaw cycles.

## CONCLUSIONS

In this paper, the influence of tartaric acid-based set-retarding admixture was evaluated on the performances of sustainable Portland-free CSA-based ternary mortars manufactured with supplementary cementitious materials. Results indicated that the tartaric acid, independently of the nature of SCMs replacing OPC, acts as superplasticizer and it is effective to extend the pot-life of mortars up to about 2 hours. No side-effects were detected on specific mass in fresh and hardened state by increasing the set-retarding admixture dosage; on the other hand, total substitution of OPC with fly ash or metakaolin cause a decrease in specific mass due to the higher water demand to attain the target workability at the end of the mixing procedure. The use of tartaric acid determines

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243    a strong retardation of binder hydration and, consequently, a reduction of compressive strength at

244    early ages, especially in reference mortars containing OPC. No retarding effect was detected at 28

245    days from casting. In general, the total replacement of OPC with supplementary cementitious

246    materials and hydrated lime determines a sharp reduction in terms of compressive strength ranging

247    from 30% (for mixture containing fly ash and slag) to 60% (for mortars manufactured with

248    metakaolin). In addition, as opposed to OPC-based mixtures, mortars containing CSA, SCM,

249    hydrated lime and anhydrite show higher compressive strength values when cured in dry

250    environment respect to that measured on specimens stored under water.

251    Mortars without tartaric acid showed an initial expansion during the first 5-7 days as a consequence

252    of the ettringite formation, than the mixtures shrink. When set-retarding admixture is used, the free-

253    expansion totally disappears and shrinkage begins immediately after final set has occurred.

254    However, after 270 days shrinkage is substantially the same for mortars with and without tartaric

255    acid. In other words, the "expansive/shrinkage" behavior of the mortar in the absence of tartaric acid

256    is transformed in an "exclusively shrinkage" behavior. However, the final contraction detected for

257    mortars containing set-retarding admixture was substantially the same of that measured in reference

258    mortar (containing OPC) without tartaric acid. Although the compressive strength of SCM-based

259    mortars is lower than the reference mixtures containing OPC, the more stable behavior evidenced

260    by these Portland-free materials makes them suitable for "cosmetic repair" of existing reinforced

261    concrete structures, where shrinkage is the main design parameter.  In particular, CSA-Portland free

262    mortar can be classified as R3 strength class ($R_c \geq 25$ MPa at 28 days) according to EN 1504-3 and,

263    hence, suitable for repair of existing concrete structures that present corrosion of rebars and spalling

264    of concrete cover.

265    Finally, CSA-SCM-CH-C$\overline{S}$ mortars are characterized by a reduction both in energy requirement

266    (GER) and greenhouse gases emissions (GWP) close to 60% respect to traditional OPC-based or

267    CSA-OPC-C$\overline{S}$ mortars at equal strength class.

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