Influence of ground perlite on the hydration and strength development of calcium aluminate cement mortars

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HIGHLIGHTS

- Calcium aluminate hydrate conversion is stopped using ground perlite and sodium sulfate.
- Stratlingite formation requires 50 % or more perlite, humidity, and sodium sulfate.
- Perlite replacement reduces strength less than dilution amount for W/CM = 0.4.
- Perlite addition accelerates hydration but reduces heat evolved.

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ABSTRACT

Calcium aluminate cement (CAC) concretes are desirable owing to their rapid strength development and resistance to high temperatures, sulfates and acids. They suffer two drawbacks, however, high cost and strength loss due to conversion of water-rich hydration products to more stable structures, resulting in a drop in strength. Although its rate is dependent on temperature and moisture, the conversion process is thermodynamically inevitable but can be prevented by adding sufficient quantities of supplementary cementing materials (SCMs) to form an alternate, stable hydrate, Stratlingite (C_2ASH_8). Based on this premise, natural pozzolans could mitigate conversion, also reducing cost. This study investigated the influence, on hydration, of replacing 25–75% of CAC with ground perlite (GP), an inexpensive and abundant natural pozzolan. Paste and mortar mixtures with water-to-binder ratios of 0.40 and 0.60 were cured in air at 23 °C or in water at 40 °C. The influence of adding Na_2SO_4 to promote Stratlingite formation was also investigated. A multi-method approach comprising X-ray diffraction (XRD), isothermal calorimetry, thermal analysis, and compressive strength development was used. Stratlingite formation was confirmed in many mixtures containing GP. Wet-cured mortars with $\geq 50\%$ GP and 1% Na_2SO_4 contained Stratlingite and showed continuous strength increases up to 90 d. Rapid-, or slow-progressing drops in strength were observed in air-cured mixtures or wet-cured mixtures containing $< 50\%$ GP. Mortars with 75% GP did not experience conversion but their ultimate strengths were much lower than even the converted strength of the pure CAC mortar. Heats of hydration of pastes decreased linearly with GP replacement of CAC despite their setting times being shortened.

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1. Introduction

Calcium aluminate cement (CAC) concrete has been available for over a hundred years [1]. Despite a decline in its popularity following some widely-heard of problems involving its use in pre-stressed beams in the 1970 s [2], there has been a renewed interest in CAC due to its ability to gain strength rapidly even at low temperatures, its high chemical and abrasion resistance, and its refractory properties [3,4;5;6;7;8]. The two main drawbacks of

CAC are its high cost (nearly 10x the cost of portland cement [PC] in Turkey for CAC with ~ 40% alumina) and the chemical “conversion” of its metastable hexagonal aluminate hydrates, CAH_{10} and C_2AH_8 , into the stable cubic aluminate hydrate C_3AH_6 , accompanied by the formation of AH_3 gel. The release of water and formation of porosity (since the stable hydrates are denser) due to conversion causes a significant decrease in strength [9,10]. CAH_{10} is favored to form at < 15 °C, and C_2AH_8 and AH_3 at > 30 °C, due to the hydration of the main clinker phase CA. At 15 to 30 °C, both CAH_{10} and C_2AH_8 will form slowly. Above 45–50 °C, C_3AH_6 and AH_3 predominate [11,12]. Although the rate of conversion is dependent on the amount and nature of the

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particular hydrated phase, ambient temperature, and moisture, it is thermodynamically inevitable. Conversion takes place faster/sooner at higher temperature and moisture [13,12]. Water-to-cementitious materials ratio (W/CM) also influences the rate of conversion and an upper limit of 0.40 is often recommended.

Although hydration of CAC does not produce any $\text{Ca}(\text{OH})_2$ like PC hydration does, CAC can also be partially replaced with suitable supplementary cementing materials (SCMs) in order to both lower the cost of the concrete and reduce the strength loss resulting from conversion. Depending on the particular SCM used, the effect may be physical, chemical or both. Various studies have used fly ash, ground, granulated blast furnace slag, silica fume, ground limestone, gypsum, etc. [14,11;15,16,17]. The addition of a source of silica can lead to the formation of a stable hydrate, Stratlingite (C_2ASH_8). Kirca et al. [17] reported a continuous increase of compressive strength up to 90 d for CAC mortars containing 40% or greater slag, cured at 20 to 50 °C. Stratlingite was formed instead of calcium aluminate hydrates below 40 °C; whereas at higher temperatures C_3AH_6 was formed more rapidly than Stratlingite, leading to lower strengths than at lower temperatures. Stratlingite has also been observed in CAC mixtures with pozzolans such as metakaolin and silica fume [18,14]. The amount of Stratlingite that can form appears dependent on the capacity of the SCM to release silica [19]. Sodium salts like sodium sulfate and sodium silicate have also been reported to promote the formation of Stratlingite in blended CAC systems. The additives increase the pH and the alkali ions act as catalysts to accelerate the dissolution of silica from the SCM and Stratlingite forms topochemically on the CAC particle surfaces. Addition of 1–2% of a sodium salt was able to prevent conversion in some cases where the SCM alone was not able to [20,21;22].

Natural pozzolans typically contain higher than 60–70% silica but their effectiveness in controlling conversion has not been studied like the influence of artificial pozzolans. Natural pozzolans show low variability in their oxide compositions and are widely available in several countries. One such natural pozzolan is perlite, a volcanic glass abundant in cement-producing countries like Turkey, China, Greece, the US, and Italy [23]. Perlite is best known for its use in the expanded state as a lightweight aggregate. However, it has also been shown that both unexpanded and expanded ground perlite are effective pozzolans to partially replace PC [24,25;26] and can even be activated with alkaline solutions to form geopolymeric binders [27,28;29,30]. This study investigated the influence of partially replacing CAC with ground perlite on the hydration, heat evolution, and strength development paste and mortar mixtures.

2. Experimental

2.1. Materials

The CAC used (ISIDAÇ 40, the only high-alumina cement produced in Turkey) was obtained from Çimsa Cement Factory in Mersin, Turkey. The natural, unexpanded ground perlite (GP) was obtained from a quarry in Erzincan, Turkey. Oxide compositions of the powder binders, determined with X-ray fluorescence spectroscopy, are given in Table 1.

The “low grade” (38–40% Al_2O_3) CAC was dark gray in color with typical low SiO_2 and high Fe_2O_3 contents. Its specific surface area and specific gravity were $3000 \text{ cm}^2/\text{g}$ (Blaine), and 3.25, as reported by the manufacturer. The light gray perlite, with a measured specific gravity of 2.43, was ground in a ball mill to $\sim 5500 \text{ cm}^2/\text{g}$. Its high SiO_2 and very low CaO contents are typical of a natural pozzolan. The typical high alkali content of perlite ($\sim 7\% \text{ Na}_2\text{O}_e$), which could influence hydration reactions, is also noteworthy.

Table 1

Oxide compositions of the powder binders used.

Oxide*	Mass (%)	
	CAC	GP
CaO	34.9	1.5
SiO_2	4.0	69.5
Al_2O_3	38.1	13.6
MgO	0.64	0.36
Fe_2O_3	15.7	1.6
Na_2O	0.14	4.0
K_2O	0.16	4.7
SO_3	0.08	0.11
TiO_2	2.0	–
CO_2	4.2	4.6
Loss on ignition	0.5	2.9

*oxides with mass < 0.1% are not shown.

thy. Reagent grade (>99%) anhydrous Na_2SO_4 was chosen to promote the dissolution of the perlite since Ding et al. [21] had shown that sodium sulfate addition provided both high early and late strengths in zeolite-blended CACs. The Na_2SO_4 dosage was selected as 2% of the CAC in a mix (hence decreased with increasing GP content). Continuously graded silica sand conforming to TS EN 196–1 [31] and deionized water were used to prepare the mortar mixtures.

2.2. Methods

Several experimental methods were employed to evaluate the influence of GP addition on hydrated phase composition as well as mechanical and thermal properties. Table 2 summarizes the mixtures prepared. Mortar mixtures were used for determination of strength and paste mixtures (with the same compositions as in Table 2 less the sand) were used for the other tests.

2.2.1. Measurement of heat evolution

Heat of hydration evolution of the mixtures were measured using paste samples with the same CAC/GP ratios as in the strength testing mortar mixtures (Table 2) but only with W/CM = 0.4 to avoid bleeding. An eight channel isothermal microcalorimeter (TA Instruments Tam Air) with precision of $\pm 20 \mu\text{W}$ was used to monitor heats of hydration at 23 °C. The pastes were mixed by hand and immediately placed in the calorimeter. Samples weighing 10 g each were tested up to 48 h.

2.2.2. Mineralogical investigations

The types and amounts of hydration products were investigated with X-ray diffraction (XRD, Olympus BTX-II) between 5° and 55° 2 θ , with a resolution of 0.05°. Cu K α radiation was used at a voltage of 30 kV and a current of 330 μA . The analysis was performed on powder samples, at ages 12 h, 24 h, 7 d, 28 d, and 90 d. The nature of the hydration products was also investigated using differential thermal/thermogravimetric analysis (DTA/TGA) (TA Instruments Discovery SDT 650) on hydrated pastes cured for 28 d. Samples were heated in an N_2 environment to 1100 °C, at a rate of 20 °C/min, and heat flow and mass loss were recorded. Pastes with W/CM = 0.40 and 0.60, cured in air at 23 °C and under water at 40 °C were analyzed with XRD and pastes with W/CM = 0.40, cured in water at 40 °C were analyzed with thermal analysis.

2.2.3. Measurement of water requirement and setting time

The effect of replacing CAC with GP on the initial and final setting of the pastes was investigated using ASTM C 187 [32]. The water requirement to reach normal consistency was determined using ASTM C 191 [33].

Table 2
Mixtures prepared for various tests.

W/CM,curing	Cementitious powders		Silica sand (% by mass of total cementitious powder)	Na ₂ SO ₄ (% by mass of CM)
	CAC (%)	Ground perlite (%)		
0.4, 23 °C air	100	0	275	0
	75	25		
	50	50		
	25	75		
	100	0		2.0
	75	25		
	50	50		
	25	75		
0.6,23 °C air	100	0	275	0
	75	25		
	50	50		
	25	75		
	100	0		2.0
	75	25		
	50	50		
	25	75		
0.4,40 °C water	100	0	275	0
	75	25		
	50	50		
	25	75		
	100	0		2.0
	75	25		
	50	50		
	25	75		
0.6,40 °C water	100	0	275	0
	75	25		
	50	50		
	25	75		
	100	0		2.0
	75	25		
	50	50		
	25	75		

2.2.4. Measurement of strength development

Compressive strength was determined on 50-mm mortar cubes, at 3 h, 6 h, 24 h, 48 h, 7 d, 28 d, and 90 d. The reported strength at each age is the average of three specimens. Since previous studies [34,11] indicated that high cement replacement levels can be needed for effective control of conversion, 25, 50, or 75% GP was used to replace CAC. Two different W/CM were chosen; one conducive to “slow conversion” or none at all (0.40), and one conducive to “quick conversion” (0.60). For the same reason, two very different curing conditions were chosen: conducive to “slow conversion” (23 °C air curing) and conducive to “quick conversion” (40 °C wet curing). After casting, the specimens were cured for 24 h under a damp cloth, demolded, and then subsequently kept in a curing room at ~ 60% RH for air curing or under water in a curing chamber for wet curing, until the test day.

3. Results and discussion

The influence of varying mixture proportions and curing conditions on the nature of the hydration products, setting behavior, heat evolution, and mortar strength development of the CAC/GP mixtures was investigated.

3.1. Influence of mixture proportions on setting behavior

Table 3 gives the amount of water needed to bring the CAC/GP pastes to normal consistency and their measured setting times.

As the GP is finer than the CAC used, W/CM needed for normal consistency increases with increasing GP content. The initial setting time increases noticeably upon addition of 25% GP but is lower than the control at higher replacement levels. The final setting time is consistently shortened with increasing replacement. This is

Table 3
Water requirement and setting times for the CAC/GP pastes.

CAC content (%)	W/CM	Initial setting time (min)	Final setting time (min)
100	0.23	185	345
75	0.26	229	256
50	0.28	157	202
25	0.32	82	167

likely due to the finer GP particles promoting the hydration of CAC as well as the change in the hydration products formed (Section 3.4). These results are unlike the influence of GP addition to PC pastes, in which it has been reported to delay setting [25].

3.2. Influence of mixture proportions and curing conditions on strength development

Fig. 1 shows the influence of GP addition on compressive strength development of mortars.

At W/CM = 0.40, the 23 °C/air-cured CAC-only mortar reaches > 65 MPa strength in as little as 3 d (Fig. 1a). Replacement of CAC with GP decreases both early (1–3 d) and later-age strengths, in percentages related with the replacement level. The 14 d strengths for the 25, 50, and 75% GP-containing samples are roughly 88, 61, and 22% of the CAC-only specimen. No sudden loss of strength is apparent, as would be expected due to any conversion. However all mortars, particularly those rich in CAC, show a steady loss of strength beyond 14 to 28 d. No measurements were made after 90 d but it is likely that the strength loss continues. This is a clear example of slow-proceeding conversion. The same general behavior is observed for the mortars with W/CM = 0.60 (Fig. 1b). The main differences are the lower maximum strength

Fig. 1. Effect on strength development of replacement of CAC with GP: a) W/CM = 0.4, air cured; b) W/CM = 0.6, air cured; c) W/CM = 0.4, wet cured; d) W/CM = 0.6, wet cured.

achieved by the CAC-only mortar and the greater relative drop in strength up to 90 d. The latter is indicative of a greater amount of conversion for these mortars with a greater starting water content. Hence, the replacement of CAC with 25–50% GP does not appear to prevent conversion, even in the low temperature/air-cured case. At higher GP replacement levels, the relative drop in strength with time is lower but the maximum strength reached is also much lower, especially for W/CM = 0.60.

For the case of wet curing, a lower maximum strength (than with air curing) is achieved for all mortars (Fig. 1c). A drop in strength from 3 to 14 d is observed, quite significant (~50%) for the CAC-only and 25% GP samples. The drop, a clear example of rapid conversion, is even greater for the W/CM = 0.60 samples (~75%). Once again, the strength reduction is less for the high GP mortars but is accompanied by low strengths (<10–20 MPa). Noticeable for the converted samples (such as the samples with 100% or 75% CAC) is a slight increase in strength, on the order of 5–6 MPa, beyond ~14 d. This is due to continued hydration of remaining clinker phases, under the favorable curing conditions. At W/CM = 0.4, replacement of CAC with GP is “efficient” in that it decreases the 90-d strengths of mortars with respect to the CAC-only mortars less than the percentage of GP (Fig. 2). This is not the case at W/CM = 0.6 and these curves remain below the “line of dilution”.

Although Fig. 2 shows that air-cured mortars are relatively stronger than their wet-cured counterparts, it is important to note that the 14–91 d portions of the strength-time curves are decreasing for the air-cured mortars (Fig. 1a) but increasing for the wet-cured ones (Fig. 1c). Converted or not, since the early and ultimate strengths of the mortars containing 75% GP are quite low, the strength development of these mixtures is not discussed further. Since even 50% replacement of CAC with GP can not (adequately) prevent conversion in samples wet/warm-cured at 40 °C, the influ-

Fig. 2. Change in 90-d strength of mortars as a function of CAC dilution with GP.

ence of sodium sulfate addition on strength development was investigated (Fig. 3).

Fig. 3a shows that the addition of 2% Na_2SO_4 does not have a positive influence on the strengths of CAC-only mortars. Since the system doesn't contain a source of soluble silica, the slow conversion in the low temperature/air-cured case and the rapid early conversion in the wet/warm-cured case are still observed. In fact, the early and ultimate strengths of the added sulfate-bearing specimens are lower. The effect of Na_2SO_4 seems to be quite negative also for the 25% and 50% GP mortars air-cured at 23 °C (Fig. 3c and 3e). Early strengths are reduced by 25–30 % and the gradual drop in time is not prevented. However, the situation for the wet/warm-cured cases is different. For 25% GP and W/CM = 0.4, the rapid drop in strength from 3 to 14 d is replaced by an increase of strength directly to the “converted” value. This does not mean conversion is avoided but rather that it happens very early on.

Fig. 3. Effect of Na_2SO_4 on strength development: a) 100% CAC, W/CM = 0.4; b) 100% CAC, W/CM = 0.6; c) 75% CAC, W/CM = 0.4; d) 75% CAC, W/CM = 0.6; e) 50% CAC, W/CM = 0.4; f) 50% CAC, W/CM = 0.6.

For the wet/warm-cured 50% GP mortars (Fig. 3e), the mortar with Na_2SO_4 shows a steady increase in strength up to 90 d, unlike its no-sulfate counterpart which experiences a significant strength drop (~30%) from 2 to 28 d. More importantly, the ultimate strengths of the sulfate-bearing mortars are ~30% higher than that of the no-sulfate mortar. In Fig. 3, it is seen that, of all the CAC/GP mortars with sodium sulfate as additive, the 50% GP mortar gives the highest ultimate (90 d) strength for the 40 °C wet-cured case. This mortar is slower to gain strength than a CAC-only mortar (it reaches ~55% of its 90-d strength at 2 d) and although it does not attain the high ultimate strength of pure CAC systems, it is stable and would be significantly less expensive.

The strength development of the W/CM = 0.60 mortars is similar. Addition of sodium sulfate doesn't prevent gradual conversion for most of the low temperature/air-cured mortars with the exception of the 50% GP mortars. For the wet/warm-cured mortars, Na_2SO_4 addition doesn't seem to provide any benefit up to 50% GP addition. The 50% GP mortars with 2% Na_2SO_4 of their CAC contents show a continuous increase in strength, up to a 90 d value > 200% of the strength of the no-sulfate mortar, even higher than the

strength of the no sulfate 25% GP mortar. Nevertheless, the ultimate strengths of the stable GP-bearing mortars with W/CM = 0.6 are quite low and the general recommendation of the use of W/CM = 0.4 as a maximum appears suitable.

3.3. Influence of mixture proportions on heat evolution

The changes over time in the rate of heat evolution of the different CAC/GP pastes, cured inside the calorimeter (in air but sealed) at 23 °C, are compared in Fig. 4.

The peak in the first few minutes seen for all mixtures is affected by the thermal disturbance of the calorimeter measurement channel while placing the sample inside, and can be ignored. The hydration of the CAC-only paste shows one main hydration peak, at ~9 h. This peak is due to the reaction of CA. The heat flow at this time is much greater, ~4–5 times that of a PC paste, partly explaining the rapid strength gain. Replacement of CAC with GP shifts this main peak to earlier times, by about 1.5–2 h for every 25% GP. The total heat evolved up to 48 h is reduced, in accord with the lower strength gain (Section 3.2). Most of the total heat is

Fig. 4. Effect on heat flow rate and cumulative heat evolution of air-cured W/CM = 0.4 pastes: a, b) replacement of CAC with GP; c, d) addition of Na₂SO₄.

evolved until the end of setting, similar to a large fraction of the ultimate strength being gained at early ages. The addition of Na₂SO₄ has a retarding effect, delaying setting by about 4 h (compare Fig. 4a and Fig. 4c). The peak is slightly suppressed but the heat evolution up to 24 or 48 h decreases by <10%. The heat evolution of the GP-containing pastes with Na₂SO₄ is similarly slightly delayed. Remarkably, all pastes with GP give their main hydration peaks at roughly the same time (12–14 h). The peak heat flow rates are reduced nearly linearly with the addition of GP. The influence of GP substitution and Na₂SO₄ addition on the behavior of the pastes with W/CM = 0.6 (not shown) is quite similar, with slightly greater heat evolved in the first two days for the higher W/CM pastes, particularly for the pastes richer in CAC.

3.4. Mineralogical analysis

3.4.1. X-ray diffraction

The change, with ongoing hydration, in the x-ray diffractograms for the W/CM = 0.4 pastes incorporating only CAC or 50% GP, with or without Na₂SO₄, are given in Fig. 5.

The pure CAC paste air-cured at 23 °C shows peaks for CA, C₄AF, C₁₂A₇ as clinker phases and CAH₁₀ as the main hydration product. The peaks for the clinker phases clearly reduce in intensity from 24 h to 90 d while those of CAH₁₀ detectable after 24 h grow continuously. Wet curing at 40 °C gives C₃AH₆ and AH₃ as hydration products, accompanied by a reduction in CAH₁₀, consistent with the expected conversion at the higher curing temperature under humid conditions. This causes the dramatic reduction of strength measured (Fig. 1c).

For the 50% GP paste, CAH₁₀ is detected earlier, in the first measurement at 12 h, consistent with the accelerated hydration suggested by the calorimetry results. Small amounts of AH₃ also

appear beyond 28 d, in the low temperature/air-cured case, indicating conversion. Stratlingite (C₂ASH₈) is observed (from ~ 7 d) in the wet-cured paste (with the intensity of the corresponding peaks increasing beyond 24 h) suggesting, along with an absence of C₃AH₆, that conversion reactions must at least be partially stopped. In accordance with this, not much strength loss is recorded for this paste after 7 d. However, the amount of Stratlingite is limited, due probably to the limited dissolution of the GP.

Addition of Na₂SO₄ to the air-cured 50% GP paste appears to form some calcium carbonate (CC), particularly beyond 28 d, due to carbonation (hence disappearing CAH₁₀ peaks). Fernandez-Carrasco et al. [35] also reported formation of vaterite and aragonite in CAC pastes after several months. For the wet-cured 50% GP paste, Na₂SO₄ addition not only results in greater amounts of Stratlingite being formed (its peaks continuously increasing from 7 d to 90 d) but the peaks for CAH₁₀ are suppressed sooner and more completely. Stratlingite is the dominant phase in this hydrated paste, at 90 d (Fig. 5f). The mortar made with this paste shows continuous strength gain up to 90 d. Hence XRD shows that Stratlingite is formed only in the warm/wet-cured pastes. This is consistent with Gosselin[12] who reported no evidence of Stratlingite in CAC/slag mixtures cured up to 90 d at 20 °C but large amounts of it at 40 °C. While Stratlingite is detected in all wet-cured 50% GP pastes, its amount appears to be sufficient to prevent conversion (and the associated strength loss) only in the pastes containing Na₂SO₄. Similar hydration products are formed in the pastes with W/CM = 0.6. The main difference is that the amount of Stratlingite formed (as judged by relative peak intensities) is less than in the lower W/CM pastes. No C₂ASH₈ forms in the pure CAC paste with 2% Na₂SO₄, either in the air- or the wet-cured cases, suggesting that a significant source of soluble silica is necessary along with wet curing for Stratlingite to be produced.

Fig. 5. Change in time of the x-ray diffractograms for W/B = 0.4 pastes: a) air-cured CAC-only; b) wet-cured CAC-only; c) air-cured 50% GP; d) wet-cured 50% GP; e) air-cured 50% GP with 1% Na₂SO₄; f) wet-cured 50% GP with 1% Na₂SO₄.

3.4.2. Thermogravimetric/Differential thermal analyses

The presence of stratlingite in the wet/warm-cured 50% GP pastes with W/CM = 0.4 was further investigated by measuring changes in mass and heat flow, during heating to 1100 °C (Fig. 6).

The loss of mass of the pastes takes place over three distinct temperature ranges, up to 200 °C, around 300 °C, and around 700 °C (Fig. 6a). In hydrated CAC pastes, metastable phases like CAH₁₀ and C₂ASH₈ are known to decompose in the 100–200 °C range while stable phases like AH₃ and C₃ASH₆ decompose in the 250–350 °C range [36]; Kirca; 2006; [12]. Loss at 600–800 °C is typically indicative a decarbonation [37].

The thermal decomposition of C₂ASH₈ shows three consecutive water-loss events [38]; Gosselin, 2009) which overlap with

some of these ranges, hence is not easy to distinguish C₂ASH₈ from other hydrated phases. The heat flow peaks in Fig. 6b indicate that upon addition of Na₂SO₄ to the 50% GP paste, the loss between 100 and 200 °C shifts slightly to lower temperatures. The 50% GP paste with 1% Na₂SO₄ has peaks at ~ 120 °C and ~ 165 °C, characteristic peaks for the initial and intermediate water loss in Stratlingite [39,38]. In contrast, the peaks for the 50% GP paste without Na₂SO₄ (for which XRD suggests lower C₂ASH₈), are stronger at ~ 145 °C and ~ 180 °C. Also signaling the existence of some stratlingite is the small peak at ~ 420 °C, attributed to the decomposition of portlandite, which forms during the decomposition of stratlingite [40]. This peak is weaker for the no-sulfate paste. As such, thermal

Fig. 6. Change in: a) Mass loss; and b) heat flow, of warm/wet-cured W/CM = 0.4 pastes upon heating.

decomposition analysis also suggests the occurrence of Stratlingite in the 50% GP pastes with added Na_2SO_4 .

Both the 100% CAC and 50% GP pastes lose 1–2% mass at $\sim 700^\circ\text{C}$, due to decarbonation. In each, the loss is slightly more noticeable with the addition of Na_2SO_4 , probably because some of the additive forms sodium carbonate. The total mass loss of the 50% GP pastes is noticeably lower than that of the 100% CAC pastes. This is primarily due to the dilution of CAC with GP, and to a hydrated paste with less bound water. GP doesn't contain much water to lose and doesn't decompose up to high temperatures. GP may lose the small amount of water it contains and partially melt at $\sim 1000^\circ\text{C}$ or higher but at 50% replacement of CAC, the net effect is a reduction in total mass loss. Addition of Na_2SO_4 to the pure CAC paste does not affect the total mass loss but affects at what temperatures the losses take place. The paste without any added sulfate loses much mass at $\sim 125^\circ\text{C}$ (for CAH_{10}), while the paste with added sulfate shows loss centered around $\sim 185^\circ\text{C}$, $\sim 280^\circ\text{C}$ and $\sim 325^\circ\text{C}$ (for C_2AH_8 , AH_3 and C_3AH_6), suggesting that the addition of Na_2SO_4 to pure CAC pastes may influence conversion reactions, although this is not clear from the respective strength developments of the two pastes.

4. Conclusions

This study investigated the influence of partially replacing calcium aluminate cement with a natural pozzolan, ground perlite, on the hydration of pastes and mortars. The following conclusions were drawn:

- The conversion of unstable hydration products can be mitigated by partially replacing CAC with GP, to form Stratlingite, in the presence of sufficient humidity and Na_2SO_4 . Addition of GP can also reduce the high cost of CAC systems.
- No Stratlingite forms in samples cured in air at 23°C , with or without GP, at any age. Hence, slow conversion and an associated strength loss beyond ~ 14 d cannot be prevented.
- 40°C wet-cured samples with $<50\%$ GP or without any Na_2SO_4 experience sudden and significant drops in strength from 3 to 14 d due to quick conversion. Wet-cured mortars with $\geq 50\%$ GP and 1% Na_2SO_4 contain sufficient quantities of Stratlingite to prevent conversion, showing continuous strength gain up to 90 d. The 90-d strength is equal to or higher than mortars with less perlite or with no added Na_2SO_4 . Also, most of this strength gain happens within the first week.

- Replacement of CAC with GP decreases the strengths of mortars less than the percentage of GP used, particularly for W/CM = 0.4. Hydration is accelerated but total heat evolved decreases. Addition of Na_2SO_4 , however, has a retarding effect.

- W/CM does not strongly influence the behavior of mixtures. The strengths (before and after conversion) of the higher W/CM mortars are lower at all ages and conditions, despite their greater heat evolution at early ages, especially for higher CAC contents.

CRediT authorship contribution statement

Kemal Şengül: Methodology, Investigation, Writing - original draft. **Sinan T. Erdoğan:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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