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Influence of mechanoactivation of Portland cement on the hydration heat and mechanical properties of binders and mortars based on them

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Abstract: The issues considered in the article are related to determining the effect of mechanical activation in the presence of a superplasticising admixture on the properties of binders and mortars based on them. The activation of cement, in combination with the use of ground quartz sand (S = 250 m^2/kg) and the polycarboxylate superplasticising admixture (SP), is relevant for this study. The amount of quartz sand was adjusted in the range from 0 to 40% of the cement weight, and the superplasticiser from 0.15 to 0.5% of the cement weight or the weight of cement + ground sand. The presented data made it possible to evaluate the influence of factors on the fluidity of the binder. Activation, in combination with a reduced water-cement ratio (for cement and cement + ground sand) of the cement paste, helps to increase the intensity of its heating, as well as to increase the maximum temperature. The peak of the exothermic reaction for the mechanically activated binder occurs 3 hours earlier compared to the non-activated mixture. The increase in the strength of the mortar (without ground sand) on mechanically activated cement with the addition of a superplasticising admixture reached 80% compared to the control.

Keywords: mechanical activation, rotary high-speed mixer, plasticising admixture, exothermic heating, water-cement ratio

1. Introduction

One of the current methods for improving the properties of hardened cement paste and building composites based on it is the use of superplasticising and mineral admixtures. Activated concrete has several features that significantly impact the nature of concrete failure under load, affecting crack formation and durability [1,2]. Various methods exist for activating binder and concrete mixtures, including the addition of chemical admixtures, surfactants, grinding in a mill, liquid-phase mechanical activation, and others. Among these, liquid-phase mechanoactivation stands out for its ability to achieve a more complete hydration process and a concrete mixture with improved workability.

Among the existing methods for activating the hydration processes of binders, turbulent high-speed mixers of various designs are widely used [3,4]. All of them pursue a common technological goal – improving the physical and mechanical properties of composite materials [5]. The use of high-speed mixers helps address multiple issues, including enhancing the homogeneity of the freshly prepared mixture and increasing the strength of the hardened cement paste and mortar based on it [6].

A promising method for improving the physical and mechanical characteristics of building composites is the mechanoactivation of Portland cement in combination with ground quartz sand and a superplasticising admixture. A high degree of cement activation is achieved through the use of a high-speed forced-action activator. The degree of cement activation is significantly increased by the combined effect of high-speed mixing in the presence of a superplasticiser and ground quartz sand. However, mechanical activation requires specialised equipment and increased energy consumption due to grinding, which is a disadvantage of the method.

Quartz sand is an inexpensive fine aggregate, with grains that possess high strength and serve as a structural framework [7,8]. Ground quartz sand has a smaller pore size between the grains and increased chemical activity due to the larger adhesion area of the grains, which contributes to the enhanced strength of structural formations.

The use of superplasticising admixtures is crucial in the technology of manufacturing resource-efficient mortars. Such admixtures are often used both individually and in combination with other admixtures of synthetic or natural origin [9,10]. The application of superplasticisers reduces excess water during mortar preparation, leading to decreased porosity in the hardened concrete and increased strength [11,12]. However, the disadvantages of using superplasticisers include the higher production cost and the environmental impact of the activated binder compared to conventional binders.

The use of high-speed hydrodynamic mixing to activate cement, in combination with the efficient consumption of a plasticising admixture (significantly reducing the water-cement ratio) and an optimised amount of ground quartz sand (ensuring the most favourable balance between cement replacement and strength reduction), accelerates cement hardening, intensifies exothermic heating, and enhances mortar strength. This technology enables a significant reduction in the water-cement ratio, which, in turn, leads to an increase in mortar strength [13,14].

2. Objectives and methods of research

2.1. Objective of the study

The aim of this study is to determine the effect of high-speed mixing of binders in a specially designed forced-action mechanical activator (n = 1800 rpm) on their exothermic heating, water-cement ratio, and the compressive strength of cement-sand mortars.

2.2. Research methods

The activation of Portland cement alone and in combination with ground sand was carried out in an aqueous medium using a mechanical activator for 180 seconds (as a further increase in activation time had little effect). As a control, cement that was not subjected to mechanical activation was used. The combined effect of mechanical activation, superplasticiser dosage (maintaining a constant flow spread of cement paste at 120 ± 1 mm using a Suttard viscometer), and the specified quantity of ground quartz sand on the kinetics of exothermic heating was also analysed. The activation duration was chosen based on efficiency and ease of use of the activator. The flow spread was adjusted to reduce the fluidity of the samples while maintaining workability.

To measure the exothermic heating of the aqueous binder, a thermos – a glass flask with double walls containing a vacuum – was used. The temperature of the samples was recorded every 30 minutes during the hardening process until the subsequent temperature reading remained unchanged or was lower than the previous one (until a consistent decrease in temperature was observed).

To assess the effect of mechanical activation, the influence of ground quartz sand content (20% and 40%) and superplasticiser dosage (0.15% and 0.5%) on mortar strength was investigated. The samples were prepared in the form of beams measuring 4×4×16 cm. The mortar mix ratio used for sample preparation was 1:1 (binder:sand, where the binder was either cement or a mixture of cement and ground sand). The flow spread of mortars was determined by measuring the spread of the mixture cone after 30 shakes on a shaking table, which ranged from 105 to 110 mm.

3. Research results

3.1. Impact on water-cement ratio of binders

In the study, Portland cement CEM II/A-M(S-L) 42.5 R and a mixture of Portland cement with ground sand were used as binders. The Cement + ground sand binder was obtained by jointly grinding Portland cement with quartz sand in proportions of 20% and 40%. Quartz sand with an M_F of 2.2 was used as the aggregate for the mortar. For the Cement + ground sand binder, ground quartz sand with a specific surface area of 560 cm^2/g was used.

Table 1 presents the mixture proportions, including the content of ground sand in the binder, the dosage of the polycarboxylate superplasticising admixture, activation time, and the water-cement ratio (W/C) of the binders during the spreading of the cement paste on the Suttard viscometer. The measurements were taken at each experimental point within the flow spread range of D = 120 ± 1 mm.

Reducing the cement content in the binder by partially replacing it with ground quartz sand (Cement + ground sand) results in a smaller specific surface area and a lower water-cement ratio. The use of mechanical activation enables the production of a more homogeneous binder and improves its fluidity, thereby reducing water consumption.

Analysis of the experimental data presented in Table 1 indicates that high-speed mixing of the binder for 180 seconds allows achieving the required mixture flow spread (diameter 120 ± 1 mm) at reduced water-cement ratios. Specifically, high-speed mixing of the binder reduces the water-cement ratio from 0.387 (control—no activation) to 0.346 (activation for 180 s), representing a decrease of almost 12%. Notably, mechanical activation also reduces the water-cement ratio for Cement + ground sand.

Table 1. Mixture proportions, activation time, and water-cement ratio of the binding systems. *Source*: own study

#	Cement, %	Ground sand, %	Specific surface of binder, cm^2/g	Activation time, s	SP, %	W/C
1	100	0	5048	0	0	0.387
2	100	0	5048	0	0.15	0.28
3	100	0	5048	0	0.5	0.241
4	100	0	5048	180	0	0.346
5	100	0	5048	180	0.15	0.251
6	100	0	5048	180	0.5	0.233
7	80	20	4743	0	0	0.348
8	80	20	4743	0	0.15	0.25
9	80	20	4743	0	0.5	0.225
10	80	20	4743	180	0	0.313
11	80	20	4743	180	0.15	0.24
12	80	20	4743	180	0.5	0.217
13	60	40	4085	0	0	0.324
14	60	40	4085	0	0.15	0.24
15	60	40	4085	0	0.5	0.217
16	60	40	4085	180	0	0.284
17	60	40	4085	180	0.15	0.224
18	60	40	4085	180	0.5	0.203

For the binder containing 20% ground quartz sand (Table 1, entry 7), mechanical activation decreases the W/C ratio from 0.348 to 0.313, a reduction of more than 11%. Meanwhile, mechanochemical activation of the binder with 40% ground quartz sand (Table 1, entry 13) lowers the W/C ratio from 0.324 to 0.284, a decrease of nearly 14% compared to the control.

The effect of mechanical activation on reducing the water-cement ratio while maintaining a spread diameter of 120 ± 1 mm is also observed in the presence of a superplasticising admixture. Increasing the superplasticiser content to 0.5% reduces the water-cement ratio of the binder from 0.387 to 0.241 (control – without activation). The combined effect of mechanical activation and the presence of 0.5% superplasticiser further enhances the binder's fluidity, achieving the required flowability at a W/C ratio of 0.233.

The positive interaction between mechanical activation and the superplasticiser is also evident for binders containing ground quartz sand in amounts of 20% and 40%.

3.2. Effect on exothermic heating

High-speed mixing of binders also influences the kinetics of their exothermic heating over a 15-hour period (Fig. 1).

The experimental results indicate the presence of an induction period in the heating process of the binder, both with mechanical activation (A) and without it (C). The induction period for Portland cement without the addition of ground sand and without activation lasts approximately 4 to 6 hours from the moment of mixing with water. However, preliminary activation reduces this induction period to 2–3 hours. Following the induction period, a relatively sharp increase in the temperature of the hardening binder is observed.

For the non-mechanically activated binder, the maximum temperature did not exceed 51.7°C, with peak heating occurring no earlier than 11 hours after mixing the cement with water.

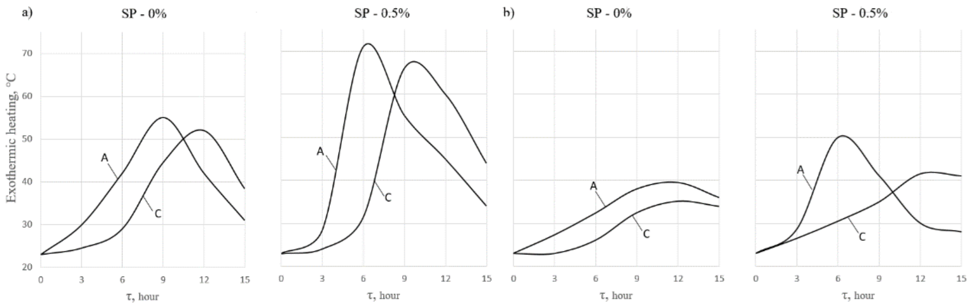

Fig. 1. Kinetics of exothermic heating of binders: a, b – content of ground quartz sand in the binder: 0% and 40%, respectively. *Source*: own study

Mechanical activation of the binder in the presence of a superplasticiser at a dosage of 0.5% reduces the consumption of mixing water, which in turn increases the hydration rate and raises the maximum heating temperature to 71.5°C (Fig. 1a).

The incorporation of ground quartz sand into the binder reduces its exothermic heating. Specifically, adding 40% ground sand to the binder (Fig. 1b) lowers the maximum heating temperature of the hardening binder from 59.4°C to 46.1°C, representing a reduction of nearly 23%.

3.3. Effect on compressive strength

The final stage of the study involved determining the effect of mechanochemical activation of cement and Cement + ground sand in the presence of a superplasticiser on the compressive strength of mortar at 3, 7, and 28 days of hardening (Fig. 2).

Analysis of the graphical data indicates that the combined effect of mechanical activation and the superplasticiser significantly enhances mortar strength compared to the control. At 3 days of hardening, the strength increased from 32 MPa to 63 MPa—almost doubling. By 7 days, the difference slightly decreased but remained above 70%. At 28 days of hardening, the strength difference was reduced to 60%.

Increasing the superplasticiser dosage from 0% to 0.5%, without mechanical activation, resulted in a strength increase of more than 50% for cement and over 40% for Cement + ground sand. Additionally, extending the mechanical activation time from 0 to 180 seconds, without the use of a superplasticiser, led to a strength increase of more than 20% across all samples.

The addition of 40% ground quartz sand to Portland cement significantly reduces strength. However, even in this case, mechanical activation in the presence of a superplasticiser increases the compressive strength of the mortar by 20–25% compared to the control samples.

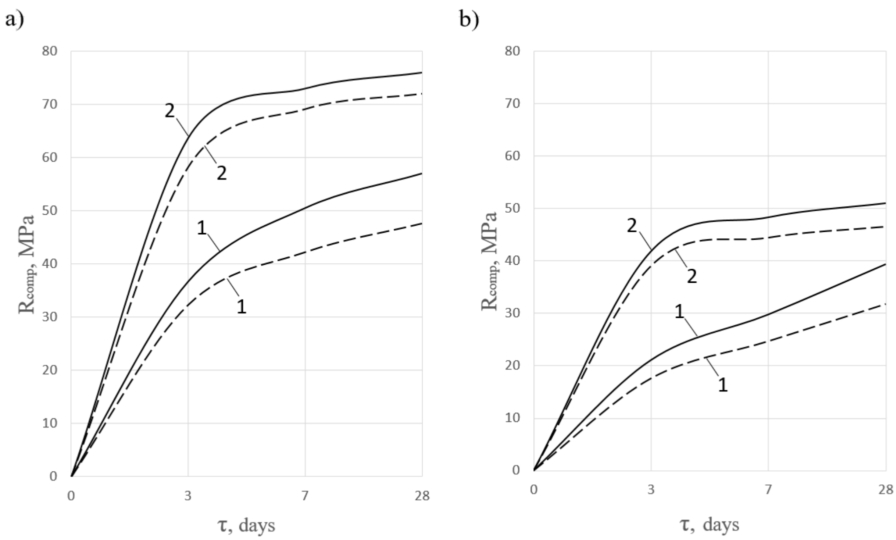

Fig. 2. Kinetics of strength gain of mortar during 28 days of hardening: continuous line – mechanically activated binder for 180 s.; dashed line – control (no mechanical activation of the binder); 1, 2 – superplasticiser content: 0% and 0.5% (by weight of cement), respectively; a, b – ground sand content in the binder: 0% and 40%, respectively. *Source*: own study

4. Conclusions

1. The use of mechanoactivation of binders in the presence of a superplasticiser (up to 0.5% of the cement weight) allows a reduction in the water-cement ratio from 0.387 to 0.241, i.e. by more than 60%.
2. Mechanoactivation of the binder (SP = 0%) significantly increases the exothermic heating temperature from 51.7°C (no activation) to 59.6°C (mechanoactivation for 180 s).
3. The use of 40% ground quartz sand and 0.5% superplasticiser allows achieving the strength of the control sample at the target age while ensuring a reduction in cement consumption.
4. The combined effect of mechanoactivation of the binder in the presence of a superplasticiser (0.5%) increases the strength of the mortar at 7 days of hardening by almost 70%. By 28 days of hardening, this difference decreases to 60% compared to the control.
5. Mechanical activation requires increased energy consumption due to milling, while the addition of a superplasticiser increases both costs and the environmental impact of the activated binder compared to ordinary Portland cement binders.

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