Technical Report

Effects of thermal and mechanical activation methods on compressive strength of ordinary Portland cement–slag mortar

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1. Introduction

Generally, the cement–slag mortars can be divided into three groups as: ordinary Portland cement (OPC) mortars (OMs), Ordinary Portland cement–slag mortars (OSMs), and slag mortars (SMs). Based on other researches, it can be said that among the activation methods, Chemical (C), Thermal (T), and Mechanical (M) are the most usual activation methods. However, for activation of the OSMs, the combinational methods of activation such as Chemical–Thermal (CT), Chemical–Mechanical (CM), Thermal–Mechanical (TM), and Chemical–Thermal–Mechanical (CTM) can be used. It is well known that for the mortars with cement particles like OMs and OSMs, the use of activation methods, including activators, are not effective [1,2], and then in this research work, only T, M, and TM methods were used. Not much research has been reported on the combinational activation methods of OSMs. The addition of alkalis to Portland cement results in a reduction of strength after 3 or 7 days, because hydration chemistry and the morphology of the hydration products are changed due to the presence of alkalis. OPC/slag mixes activated by alkalis showed a lower strength than the slag alone activated by an alkali [3].

Generally, it can be said that the SMs have both a low early and then ultimate strengths. The OMs have high early strengths and also relatively high ultimate strengths. Finally, the OSMs have low early and high ultimate strengths. However, some activation methods can be used to improve the strengths at early ages. Based on the results reported by other researches [4,5], it has been observed that by using chemical activators, early strength of the SMs can be improved.

Chemical activation refers to the use of some chemical substances to activate the potential reactivity of cementitious components. Some chemical activators are Na2SiO3, NaOH, KOH, and Na2CO3 [6]. The activator(s) can be added during the milling of cement/slag or can be dissolved in the mixing water and added during the mixing of cement/slag pastes, mortars, and concrete. The technology is very simple and does not need extra equipment. Raising temperature is more helpful to the reaction processes for higher reaction activation energies than those with lower reaction activation energies. Many researches [7] have shown that Portland-cement slag has higher hydration activation energy than Portland cement and the higher the replacement of cement with slag, the higher the apparent hydration activation energy. Under normal conditions, blast-furnace slags show a higher reactivity with lime than other glassy pozzolans. Hardened cement pastes and concretes can reach their maximum strength within several hours through elevated temperature curing. However, the ultimate strength of hardened cement pastes and concretes has been shown to decrease with curing temperature. Other researchers have indicated that slag was more sensitive to heat than Portland cement due to its high apparent activation energy [8,9]. Roy and Idorn [8] even suggested that the combined effect of alkalis and heat may be synergetic during early hydration.

Heat curing is commonly used in the production of precast concrete elements to increase the rate of hydration and accelerate early age strength development. High elevated temperatures
Laboratory research demonstrates that many Portland cements can be made to expand if cured at sufficiently high temperatures and then subjected to moist environments. In practice, the most effective method of controlling expansion is to avoid exposure to high temperatures during curing for a prolonged period of time. Curing temperature is the most important factor determining the potential for deleterious expansion of Portland cement products exposed to moist storage.

Prolonged grinding not only increases the surface area of a material, but it also increases the number of imperfections or active centers which exist at the edges, corners, projections, and places where the inter-atomic distances are abnormal or are embedded with foreign atoms. These centers are in a higher energy state than in the normal structure. The more such centers, the higher is the reactivity. If grinding is sufficiently prolonged, an upper limit of activity is attained; beyond which a continued increase in surface area does not produce any further increase in pozzolanic reactivity.

This paper considers the results of an investigation about OPC mortars and OPC–slag mortars which were studied after two curing regimes. These included water curing (wc) and curing at room temperature (ac). Five groups of mortars as: OM-ac and OSM/50-ac mixes (first group – G1), OM-wc and OSM/50-wc mixes (second group – G2), OM-T-ac and OSM/50-T-ac (third group – G3), OMM-wc and OSM/50-M-wc mixes (fourth group – G4), and OMTM-ac and OSM/50-TM-ac mixes (fifth group – G5) were also used. Each group included two mixes: one was OM and the other was OSM/50 with the same conditions of casting and material properties. It was noted that groups 1, 3, and 5 were cured in room temperature and groups 2 and 4 cured in the water. However, it should be noted that the selection of curing regimes type depends on the strength results obtained from prior parts of the study.

The objective of the research is to study the compressive strength of OMs and OSMs/50 cured in room temperature and water regimes. Moreover, it is well known that OSMs/50 have low early strengths, and it is desired to improve by using the thermal, mechanical, and thermal–mechanical activation methods. Finally, the effects of the aforementioned activation methods are studied on the early and ultimate strengths of OMs and OSMs/50 and the results are compared. Also based on the results obtained, the optimum activation method is recommended. In addition, based on the initial and ultimate strengths view points, the best mix/group of the mortars is introduced. It is noted that in this case the loss of strength is an important factor.

### 2. Mix proportions, curing, and testing

Table 1 represents the mix proportions of the mixes. In all mixes $W/B = 0.33, S/B = 2.25$ and silica sands were used. At first, based on particle size analysis (PSA), five groups of silica sands were mixed. Two min after that, cement was put into the mixture, followed by 2 min of mixing. Firstly, the mixing water was added to the mix and mixing was continued for two extra min, after which the required amount of super plasticizer was added. This mixing process was continued for 2 min. Finally, the moulds were filled with two layers of fresh mortar. Each layer was then made compact with 10 impacts by using a rod of 16 mm in diameter. Twenty-four hours after casting, the specimens were demoulded and cured in room temperature with $28 ± 4^\circ C$ and $65 ± 20$% relative humidity (RH) or in water $23 ± 2^\circ C$ with time needed for breaking the specimens.

#### 2.1. Materials

The properties of the materials that have been used in the study are described as follows:

**2.1.1. Cement**

The cement used in all mixes was OPC. ASTM C109/C109M-08 [13] was used for the determination of the compressive strength of hydraulic cement mortars by using 50 mm side cubes as specimens. The specific gravity of cement used is about 3.14. Based on particle size analysis (PSA) tests, the specific surface area (SSA) for OPC was determined to be $1893.9$ m$^2$/kg. The PSA diagram for the cement used in the study without use of grinding and with the use of duration of 6 h grinding is shown in Figs. 1 and 2. The chemical compositions of OPC used in this research have been determined by the X-ray fluorescence spectrometer (XRF) test. The results are given in Table 2.

**2.1.2. Slag**

The specific gravity GGBFS is approximately 2.87, with its bulk density varying in the range of 1180–1250 kg/m$^3$. The color of the slag is normally white (off-white). Based on the PSA test, SSA for slag has been determined at $3597.2$ m$^2$/kg. It can be seen that the $SSA_{slag} = 1.90 \times SSA_{OPC}$, which means that particles of slag are 90% finer than those of OPC. The compositions of slag are given in Table 2. As with all cementing materials, the reactivity of the slag is determined by its SSA. The PSA diagram for the slag used in the study without use of grinding and with use of duration of 6 h grinding is shown in Figs. 1 and 2.

In general, increased fineness results in better strength development, but in practice, fineness is limited by economic and performance considerations, and factors such as setting time and shrinkage. For better performance, the fineness of slag must be greater than that of cement. Based on the definition of the slag

### Table 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Mix name</th>
<th>Curing regime</th>
<th>OPC (g)</th>
<th>Slag (g)</th>
<th>Water (g)</th>
<th>Flow (mm)</th>
<th>SP (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OM-ac</td>
<td>Air</td>
<td>1800</td>
<td>0.0</td>
<td>632.0</td>
<td>230</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>OSM/50-ac</td>
<td>Air</td>
<td>900</td>
<td>0.0</td>
<td>632.0</td>
<td>220</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>OM-wc</td>
<td>Water</td>
<td>1800</td>
<td>0.0</td>
<td>632.0</td>
<td>230</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>OSM/50-wc</td>
<td>Water</td>
<td>900</td>
<td>0.0</td>
<td>632.0</td>
<td>230</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>OM-T-ac</td>
<td>Air</td>
<td>1800</td>
<td>0.0</td>
<td>632.0</td>
<td>225</td>
<td>26</td>
</tr>
<tr>
<td>6</td>
<td>OSM/50-T-ac</td>
<td>Air</td>
<td>900</td>
<td>0.0</td>
<td>632.0</td>
<td>230</td>
<td>43</td>
</tr>
<tr>
<td>7</td>
<td>OM-M-wc</td>
<td>Water</td>
<td>1800</td>
<td>0.0</td>
<td>632.0</td>
<td>230</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>OSM/50-M-wc</td>
<td>Water</td>
<td>900</td>
<td>0.0</td>
<td>632.0</td>
<td>235</td>
<td>28</td>
</tr>
<tr>
<td>9</td>
<td>OM-TM-ac</td>
<td>Air</td>
<td>1800</td>
<td>0.0</td>
<td>632.0</td>
<td>225</td>
<td>25</td>
</tr>
<tr>
<td>10</td>
<td>OSM/50-TM-ac</td>
<td>Air</td>
<td>900</td>
<td>0.0</td>
<td>632.0</td>
<td>230</td>
<td>50</td>
</tr>
</tbody>
</table>

In all mixes: $W/B = 0.33, S/B = 2.25$; wc = water cured, ac = room temperature cured. PSA for silica sand used in the mixes is as: 12% mesh 50/100, 18% mesh 30/60, 30% mesh 16/30, 20% mesh 8/16, and 20% mesh 4/6.
activity index (SAI) [12] in ASTM C989 [14], it can be seen that
SAI = (SP/P)/C3100; where SP = average compressive strength of
slag-reference cement mortar cubes, P = average compressive
strength of reference cement mortar cubes; both the mentioned
strengths are in MPa. Based on this definition the slag used in
the tests is classified into Grade 120. A sample calculation is shown
in the bottom of Table 2.

2.1.3. Grinding of cement and slag
OPC and GGBFS used in the tests should be subjected to grind-
ing. For this purpose the grinder machine shown in Fig. 3 was used.
At first, OPC and GGBFS were weighed by a balance with ±0.1 g
accuracy, and then put in the cylinders of the grinder machine.
The machine used for the grinding of the materials has three cylin-
der boxes. Each cylinder is filled by four spherical steel balls. The
diameter of each ball is 50.6 mm and it has a mass of 533.3 g. Six

\[
\frac{\text{SSA Slag}}{\text{SSA OPC}} = 1.90
\]

\[
\frac{\text{SSA Slag}}{\text{SSA OPC}} = 1.35
\]

Fig. 1. Particle size analysis diagram of OPC and slag without use of grinding (SSA ratio = 1.90).

Fig. 2. Particle size analysis diagram of OPC and slag with use of duration 6 h grinding (SSA ratio = 1.35).

Table 2
Compositions of cementitious materials (% by mass).

<table>
<thead>
<tr>
<th></th>
<th>For OPC</th>
<th></th>
<th>For slag</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>18.47</td>
<td>31.21</td>
<td></td>
</tr>
<tr>
<td>Al2O3</td>
<td>4.27</td>
<td>12.96</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>2.08</td>
<td>4.27</td>
<td></td>
</tr>
<tr>
<td>Fe2O3</td>
<td>2.06</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>64.09</td>
<td>41.47</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.05</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>K2O</td>
<td>0.28</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>TiO2</td>
<td>0.11</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>SO3</td>
<td>4.25</td>
<td>2.04</td>
<td></td>
</tr>
<tr>
<td>CO2</td>
<td>4.20</td>
<td>6.00</td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>0.02</td>
<td>0.11</td>
<td></td>
</tr>
</tbody>
</table>

For 7 days; SAI = 47.57/47.76 = 1.00 > 0.95; for 28 days; SAI = 62.83/50.26 = 1.25 > 1.15; \( K_b \) (basicity index) for slag = \( \frac{41.47 + 4.27}{31.21 + 12.96} \) = 1.03 > 1.00 then the slag
is basic. 1.30 < CaO/SiO2 = C/S = 1.33 for slag < 1.40 [10].

2.1.3. Grinding of cement and slag
OPC and GGBFS used in the tests should be subjected to grind-
ing. For this purpose the grinder machine shown in Fig. 3 was used.
At first, OPC and GGBFS were weighed by a balance with ±0.1 g
accuracy, and then put in the cylinders of the grinder machine.
The machine used for the grinding of the materials has three cylin-
der boxes. Each cylinder is filled by four spherical steel balls. The
diameter of each ball is 50.6 mm and it has a mass of 533.3 g. Six

Fig. 3. Photograph of grinder machine and steel balls (a) – SSA variations vs.
grinding time for OPC and slag (b) – the best curve fitting for SSA values – binomial curves.
hundred and fifty gram of materials are poured in each box. Following that, the machine is turned on for a period of 6 h. The pacing rate of the grinder machine is around 110 rpm.

2.1.4. SSA of binders and r diagrams
PSA tests were conducted for slag and OPC and SSAs were determined. SSA for slag and OPC vs. grinding time can be fitted according to binomial relations. SSA diagrams are shown in Fig. 4.

As the size of the particles decreases during the process of grinding, the particles are strongly subjected to attractive inter-particle forces, leading to an aggregation phenomenon that generates an increase of the suspension viscosity [15]. Grinding is an effective way to obtain active powders. In order to study the relationship between the grinding process and activation, seeking the optimum grinding efficiency is one of the most important research fields in mechano-chemistry [16]. A maximum SSA was reached in duration of 6 h for OPC and 9.5 h for slag. Continued grinding causes extra surface energy and surface electric charge which results in an agglomeration and an aggregation of the finer particles. Particle size distributions show that the number of particles with a size greater than 42 μm increases with a longer grinding time. Slag is harder than clinker and is therefore more difficult to grind. Generally, for better performance, slag should be finer than OPC [12]. From Figs. 5 to 6 it can be seen that both diagrams are increasing, but decrease suddenly after 9.5 h and 6 h, respectively. This shows that whenever grinding time is more than 9.5 h for slag and 6 h for OPC, agglomeration occurs for slag and OPC particles. Therefore, it can be said that the optimum grinding period for OPC and slag is 6 and 9.5 h, respectively. For the optimum duration of grinding, the SSA ratio, i.e. \( r \) value is 1.41 \((r = 4374.1 / 3098.7 = 1.41)\) and for finely ground slag and OPC particles, the \( r \) value of binders used in the M and TM methods was 1.35 \((r = 4180.6 / 3098.7 = 1.35)\).

2.1.5. Aggregates
The fine aggregates used in the mixes are graded silica sands with specific gravity, fineness modulus (FM) [17,18] and water absorption (BS812: Clause 21) 2.68%, 3.88% and 0.93%, respectively. The maximum size of aggregate is 4.75 mm. PSA are given in Table 3 and the grain size distribution diagram is shown in Fig. 6.

2.1.6. Super plasticizer
In order to have appropriate consistency with low \( W/B \) ratio, super plasticizer (SP) is used. The SP used in this investigation is Rheobuild 1100. The specific gravity of the SP is approximately 2.68%, 3.88% and 0.93%, respectively. The consumed amount of SP in the mortar depends on the levels of cement and replaced slag. Rheobuild 1100 is a chloride-free product. Meet ASTM C494 [19]. The basic components are synthetic polymers which allow mixing water to be reduced considered. The dosage of R1100 generally varies from 0.8 to 1.2 l/(100 kg) of cement. Other dosages may be recommended in special cases according to specific job conditions. It is compatible with all cements and admixtures meeting ASTM and UNI standards.

2.1.7. Water (mixing and curing)
The water used in all mixes and curing of the specimens was potable water from the pipeline of the lab.

2.2. Testing procedure
2.2.1. Workability test of fresh mortar
In order to have appropriate workability and consistency for each mortar mix after casting, a flow table test was done. The range of flow amounts was 220–235 mm. In the test procedure after casting, some mortar was put in the truncated brass cone in two layers. Each layer was compacted by 10 impacts using a 16 mm diameter steel rod. The cone was then lifted and the mortar was collapsed on the flow table. Following this, both the table and the mortar were
jolted 15 times in a 60 s period. The jolting of the flow table enabled the mortar to consequently spread out, with the maximum spread to the two edges of the table being recorded. The average record was calculated as flow in mm. Flow table tests were done according to ASTM C230/C230M-08 [20]. The photograph of the test equipment is shown in Fig. 7.

2.2.2. Compressive strength test of hardened mortar

Three cubic samples with lengths of 50 mm were used for each stage. The samples produced from the fresh mortar were demoulded after 24 h, and then cured in water with a temperature of 23 ± 2 °C, and in the room with a temperature of 28 ± 4 °C and 65 ± 20%RH. The samples were then used for compressive strength tests at 1, 3, 7, 28, 56, and 90 days. Compressive strength measurements were carried out using an ELE testing machine press with a capacity of 2000 kN, and a pacing rate of 0.5 kN/s. Compressive tests were done according to BS 1881, Part 116, 1983.

3. Results and discussion

3.1. Study of mortar groups’ behavior

The first group of mortars (G1) included two mixes, which were OM-ac and OSM/50-ac. The variations of compressive strength vs. the age of curing for G1 are shown in Fig. 8.

The comparison between the results of the strength obtained for the mixes showed that OSMs/50 have a greater sensitivity to curing regimes compared to OMs. It was observed that the ultimate strength of OSMs/50 at later ages is less than those of OMs by about 14.3% at the same ages. This reality has been previously confirmed by the ACI 308 committee. The ACI 308 committee recommends 7 days of moist curing for most structural concretes. However, the period of curing should be extended to 14 days whenever the cement contains supplementary cementitious materials such as slag and fly ash, owing to the slow hydration reaction between the supplementary cementitious materials and the calcium hydroxide. The process of this reaction requires the presence of water to produce the cementing compounds to contribute for the filling of the capillary voids.

The second group of mortars (G2) included two mixes, which were OM-wc and OSM/50-wc. The variations of the compressive strength vs. age of curing for G2 are shown in Fig. 9.

In contrast to curing in the air, whenever both the mixes of G2 which were cured in the water, it was seen that at 90 days, the ultimate strength of the OSMs was much more than that of the OMs. The amount was more by about 13%. Additionally, it was seen that after 28 days, the growth of strength of the OSMs/50 was much more and faster than that of the OMs. It seems that this is due to the fact that the slag particles have much latent potential compared to cement particles at long ages. After 28 days, it appeared that this increase was ultimately stronger nearby water.

The third group of mortars (G3) included two mixes which were OM-T-ac and OSM/50-T-ac. The variations of the compressive strength vs. age of curing for G3 are shown in Fig. 10.

The activation of both mixes by heating (H60 °C – 20 h) [22] and a comparison of ultimate strengths reveal that the OSMs/50 have a

Table 3

<table>
<thead>
<tr>
<th>Sieve size (μm)</th>
<th>Sieve no.</th>
<th>WSS + WS (g)</th>
<th>WS (g)</th>
<th>WSS (g)</th>
<th>Ret. %</th>
<th>Cumul. Ret. %</th>
<th>Cumul. pass. %</th>
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<tbody>
<tr>
<td>4750</td>
<td>3/16 in.</td>
<td>409.9</td>
<td>408.3</td>
<td>1.6</td>
<td>0.32</td>
<td>0.32</td>
<td>99.68</td>
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<td>2360</td>
<td>NO.7</td>
<td>462.3</td>
<td>375.7</td>
<td>86.6</td>
<td>17.33</td>
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<td>1180</td>
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<td>437.2</td>
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<td>63.50</td>
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<td>90.99</td>
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<td>NO.200</td>
<td>309.9</td>
<td>275.2</td>
<td>34.7</td>
<td>5.94</td>
<td>97.92</td>
<td>2.08</td>
</tr>
<tr>
<td>Pan</td>
<td>–</td>
<td>250.8</td>
<td>240.4</td>
<td>10.4</td>
<td>2.08</td>
<td>–</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>499.7</td>
<td>–</td>
<td></td>
<td>388.31</td>
</tr>
</tbody>
</table>

FM = 388.31/100 = 3.88 [17,18]; SS absorption is 0.93%.
higher strength at 90 days compared to the OMs by about 12.3%. It was also observed that until 7 days, the strengths of both mixes were approximately the same, but the strength of the OSMs/50 at 28 days was higher than that of the OMs by about 6%.

The fourth group of mortars (G4) included two mixes which were OM-M-wc and OSM/50-M-wc. The variations of the compressive strength vs. age of curing for G4 are shown in Fig. 11.

Fig. 8. Variations of compressive strength vs. age of curing for G1.

Fig. 9. Variations of compressive strength vs. age of curing for G2.

Fig. 10. Variations of compressive strength vs. age of curing for G3.

Fig. 11. Variations of compressive strength vs. age of curing for G4: (a) at 120 days and (b) at 145 days.

The fourth group of mortars (G4) included two mixes which were OM-M-wc and OSM/50-M-wc. The variations of the compressive strength vs. age of curing for G4 are shown in Fig. 11.
The use of the mechanical method for the activation of G4’s mixes shows that both mixes have the same strength levels at 90 days as 76 MPa. At 7 days, the strength levels of the OMs and the OSMs/50 are 57.5 and 65.5 MPa respectively. These results revealed that by using finely grounded cement and slag particles, it can significantly improve the strength levels of OMs at both short and long ages whenever the specimens are cured in the water. While the strength growth of the OSMs/50 is higher than that of the OMs at the early ages; there is, however, some strength loss at the later ages of the OSMs/50. Since there is no strength loss at the later ages for the OM-M-wc mix, it seems that the strength loss of the OSM/50-M-wc mix is due to the finely grounded slag particles mixed by the finely ground cement particles. It was observed that even though the strength level of the OSM/50-M-wc at 28 days was 80 MPa, it dropped to 76 MPa at 90 days. This means a 6% strength loss at 90 days. It was noted that there was no strength loss for the OM-M-wc at any age, and the strength growth was in a steady state at all ages.

The reason for the loss of strength can be due to internal or external reasons. The internal reasons are those linked to the chemical composition of the reacted products. The external reasons are due to the variability of specimens, testing procedures, and flatness of testing procedures. One other factor that has an important effect is the temperature. The initial curing temperature has an important effect and can reduce or increase strength at long curing times, i.e. at an advanced age. In this study, it seems that the main cause of strength loss is attributed to phase separation. Fig. 12 shows this reality. It is evident that whenever phases are separated, there is not enough interlocking on the boundary layer (inter-facial zone), permitting two phases to either slide against each other or intrude, which leads to strength loss. Fig. 13 shows the energy dispersive X-ray spectroscopy (EDX) results. It can be seen that there are two separate phases in the specimen that are Si and Ca. Based on the standard, Si and Ca indicate SiO₂ and Wollastonite, respectively.

The fifth group of mortars (G5) included two mixes, which were OM-TM-ac and OSM/50-TM-ac. The variations of their compressive strength vs. their age of curing for G5 are shown in Fig. 14.

The use of the mechanical method for the activation of G4’s mixes shows that both mixes have the same strength levels at 90 days as 76 MPa. At 7 days, the strength levels of the OMs and the OSMs/50 are 57.5 and 65.5 MPa respectively. These results revealed that by using finely grounded cement and slag particles, it can significantly improve the strength levels of OMs at both short and long ages whenever the specimens are cured in the water. While the strength growth of the OSMs/50 is higher than that of the OMs at the early ages; there is, however, some strength loss at the later ages of the OSMs/50. Since there is no strength loss at the later ages for the OM-M-wc mix, it seems that the strength loss of the OSM/50-M-wc mix is due to the finely grounded slag particles mixed by the finely ground cement particles. It was observed that even though the strength level of the OSM/50-M-wc at 28 days was 80 MPa, it dropped to 76 MPa at 90 days. This means a 6% strength loss at 90 days. It was noted that there was no strength loss for the OM-M-wc at any age, and the strength growth was in a steady state at all ages.

The reason for the loss of strength can be due to internal or external reasons. The internal reasons are those linked to the chemical composition of the reacted products. The external reasons are due to the variability of specimens, testing procedures, and flatness of testing procedures. One other factor that has an important effect is the temperature. The initial curing temperature has an important effect and can reduce or increase strength at long curing times, i.e. at an advanced age. In this study, it seems that the main cause of strength loss is attributed to phase separation. Fig. 12 shows this reality. It is evident that whenever phases are separated, there is not enough interlocking on the boundary layer (inter-facial zone), permitting two phases to either slide against each other or intrude, which leads to strength loss. Fig. 13 shows the energy dispersive X-ray spectroscopy (EDX) results. It can be seen that there are two separate phases in the specimen that are Si and Ca. Based on the standard, Si and Ca indicate SiO₂ and Wollastonite, respectively.

The fifth group of mortars (G5) included two mixes, which were OM-TM-ac and OSM/50-TM-ac. The variations of their compressive strength vs. their age of curing for G5 are shown in Fig. 14.

In this group of mortars, it was seen that the strength of the OSM/50-TM-ac mix at 90 days was higher than that of the
OM-TM-ac mix at the same age by about 9.6% (72.84/66.49 = 1.096) but the strength of the OSM/50-TM-ac at 1 day was less than that of the OM-TM-ac at the same age. This is a reality and it is well known that whenever a 50% of the cement is replaced by finely grounded slag, it will lead to a strength decrease at an early age and an increase at long ages because the slag has latent potential at later ages and can improve its strength. It is seen that at 3 and 7 days, the strength levels of the OSMs/50 are higher than those of the OMs by about 15.8% (62.00/53.55 = 1.158) and 4.1% (67.60/64.95 = 1.041), respectively. Usually, a latent potential in slag appears after 7 days and results in strength improving of the OSMs/50. At 28 days, both mixes of the G5 had approximately the same strengths as 69 MPa. After 28 days, the OSMs/50 had strength growth, but there was some strength loss for the OMs at 56 days by about 6% compared to their strength at 28 days. It seems that this is due to a majority of the cement particles' potential being released at the early ages, and there is no water available in the room temperature curing regime to release the remained potential, and then strength loss takes place.

As it is seen from Fig. 15, it is clear that the worst mix is the OSM/50-ac included in the G1. It seems to be due to the slag which is a pozzolan activated by the near water. The cement particles can have a hydration progression with the water, and whenever the mix is cured in room temperature, the strength will not be improved at both the early and later stages. There is no strength loss at the early ages because the cement is replaced by the slag, and the remaining cement does not have enough potential to improve the strength. Due to there being unavailable enough water to progress the hydration of the slag and the cement particles at later ages; therefore, improving the strengths cannot be expected.
3.2. Comparison between the effects of TM, M, and T activation methods on OPC–slag mortars

3.2.1. For OPC mortars

The effects of T activation method on the OMs at 3 and 7 days were higher than those of the M activation method. It was seen that at 28 days and above, the aforementioned statement was reversed. It means that the effects of the M activation method are higher than those of the T method. It was noted that there was no strength loss for the OM-M-wc mix, while there was for the OSM/50-M-wc mix at some long ages.

3.2.2. For OPC–slag mortars

The effects of T activation method on the OSMs/50 were higher than those of the M activation method at 3 days, but at 7 days and above the aforementioned statement were reversed, and then the strength at 28 days reached to 80 MPa. At 56 days, for both the T and M activation methods there was strength loss about 2.2% and 6.2%, respectively. It is seen that the amount of strength loss due to the M activation method was about 2.8 times of the loss of strength obtained due to the T activation method.

Comparison between the effects of TM, M, and T activation methods on compressive strengths of OSMs/50 and OMs are shown in Fig. 16. It can be seen that except at 1 day, at the other days ages of OSMs/50 the strength obtained by TM, M, and T activation methods are higher than those of OMs at the same ages. This shows that if 50% of OPC is replaced by slag, the strengths at early and long ages will be improved, whenever the TM, M, and T activation methods are used. It is noted that the highest effects are attributed to the TM activation method.

3.3. Determination of the worst and the best groups of mortars

Among the five groups of the mortars studied in this research work, it can be said that the G1 group was the worst. This was due to the mixes which were included in the G1 group having the least ultimate strengths, and there were also strength losses at 56 and 90 days, respectively. The two mixes, which were the OM-ac and OSM/50-ac in the G1 mortar group, had strength loss at 56 and 90 days by about 1.3% and 6.72%, respectively. Generally speaking, a study on the G1 group showed that whenever the mixes were cured in the room temperature, not only were their strengths restricted, but also a strength loss occurred. Moreover, it was observed that the strength levels at 7 days of the OM-ac and OSM/50-ac are 95% and 88% of the ultimate strengths, respectively. This showed that the OMs had higher initial strengths compared to the OSMs/50. It seems that this is due to the more hydration progress by using the internal water of the specimens at early ages, but after 7 days there is unavailable enough water for hydration progress, and then the hydration will be slowed and/or may be stopped. Finally, strength loss will occur. Additionally, it can be said that due to tensile micro cracks, strength growth is slowed and/or the strength is even dropped.

A comparison among all the groups of mortars showed that it cannot absolutely recognize one group as the best. There is not a specific group with both high early and later strengths and without strength loss.

A comparison among all the groups revealed that G4 is the best group from the point of view that its strength grew at 28 days and above (long ages), whilst G5 is the optimum group at 3 and 7 days (short ages). It seems that whenever the cement and slag particles were finely grounded and also when the specimens are cured in the water, which were ideal conditions to progress fully hydration, strength growth at 28 days and above (for G4) was expected. In G5, due to the heat treatment, the early strengths were fully improved. However, there was some strength loss at later ages. Anyway, this is an accepted idea by other researchers. Several investigators [23–25] reported that high temperature improves strengths at early ages. At a later age, the important number of formed hydrates had no time to arrange suitably, and this engendered a loss of ultimate strengths. This behavior had been called the crossover effect [26,27].

Generally speaking, it can be said that there is actually no best group of mortars. This is because some mortars have higher early strengths, others have a higher ultimate strength and additionally, some of the others have strength loss at later ages.

Basically, it is impossible to introduce a specific group of mortars as the best. This is because it depends on the uses of the mortars. Whenever the use of the mortar is due to strength growth at early ages, G5 is recommended, and when the objective is to improve strengths at 28 days and above, G4 is introduced.

It is noted that both G4 and G5 have some strength loss at 56 days. The maximum contents of strength loss of G4 and G5 are by about 6.2% and 5.8%, respectively.

3.4. Comparison between the strength growths of OMs activated by different activation methods

Based on the results of this experimental work, as seen in Table 4, the following points can be noted:

(a) At 1 day, activation methods do not have significant effects on strength growth. It is noted that the thermal activation method affects the specimens after 1 day age due to the heating which is applied on the specimens after demoulding (24 h).
Relative strength growth of OSMs/50.

Table 4
Relative strength growth of OMs.

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>OM-wc mix is assumed as control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>T</td>
<td>-</td>
</tr>
<tr>
<td>M</td>
<td>0.782</td>
</tr>
<tr>
<td>TM</td>
<td>-</td>
</tr>
</tbody>
</table>

Different activation methods

3.5. Comparison between strength growths of OSMs/50 activated by different activation methods

(b) Among the activation methods, the thermal method is the best until 3 days. From Table 4, it is clear that the thermal effect on the specimens is by about 1.9 and 1.1 times of the effects of the mechanical and the thermal–mechanical methods, respectively.

(c) At 7 days, the effect of a combined thermal–mechanical activation method is the best. It is seen that TM’s effect is by about 1.5 and 1.8 times of the effects of the thermal and mechanical methods, respectively.

(d) It is evident that at 28 days and above, the effect of the mechanical activation method is better than those of the thermal and thermal–mechanical methods, especially at 90 days. It is observed that at 90 days, the effect of the mechanical activation method is 6.6 and 4.4 times of the effects of thermal and thermal–mechanical methods. It seems this is due to the fact that there is strength loss at later ages, whenever heat treatment is used to activate mortars and concretes at early stages.

3.6. Comparison between the relative strength coefficients of different activation methods on OPC–slag mortars

Based on the results obtained in this investigation, as seen in Table 6, the following points were noted:

(a) According to row 4 of Table 6, it is clear that the OSMs/50 has lower strengths than those of the OMs until 3 days, but at 7 days and above they will achieve more strength growth compared to the OMs at the same ages. It can be averagely said that the OSMs/50 have a higher strength gain compared to the OMs by about 9% in duration of 7–90 days. This is due to the fact that the replacement slag particles with a 50% level instead of cement particles have a latent potential that will be released after 7 days, and then results in strength growth compared to the OMs. Hence, since the OSMs/50 have proper mechanical properties such as a high resistance against sulphates, chloride intrusion, environmental friendliness, and high durability, it is accepted that whenever a fast loading of the structures is not needed, the OSMs/50 are recommended to the OMs.

(b) It is evident from Table 6, whenever any of the three activation methods are used, the OSMs/50 are activated so that they will find a strength growth that is higher than that of the OMs at 3 days. The most increasing effects are attributed to TM, M, and T methods, respectively. At 3 days, the strength of the OSMs/50 is 16% more than those of the OMs, whenever the OSMs/50 are activated by the TM method. This shows that the combined activation method has the most effect in activating the OSMs/50. The second effect is attributed to the mechanical activation method by about 7%, and this shows the high effect of the finely grounded of slag and cement particles on strength growth.

(c) It is seen that the T activation method has a positive effect in duration of 3–90 days on the strength growth of the OSMs/50 compared to the OMs. This effect at 90 days is maximized by about 13%. From Table 6, it is clear that the relative strength coefficient is by about 1.00 and this shows that there is some strength loss at 56 days compared to 28 days for the OSMs/50. However, this is an accepted idea around strength loss due to heat treatment at long ages.

(d) The results obtained by the M activation method shows that the highest strength growth is attributed to 28 days age by about 14%; at 56 days there is strength loss that was discussed in the prior section of the paper. In this method, the relative strength coefficients are 1.06 and 1.00 at 56 and 72% at 3 days and 44.3% and 17.6% at 7 days, respectively.

(c) At 28 days and above, the M activation method is the best, especially at 90 days age. At this age, it is seen that the M’s effects on the ultimate strength growth compared to the effects of T and TM’s methods are 2.2 and 3.5 times, respectively. It seems that this is due to the fact that heat treatment reduces the strengths at long ages.

Relative strength coefficient is defined as OSM/50’s strength/OM’s strength.

Table 5
Relative strength growth of OSMs/50.

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>OSM/50-wc is assumed as control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>T</td>
<td>-</td>
</tr>
<tr>
<td>M</td>
<td>1.488</td>
</tr>
<tr>
<td>TM</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6
Comparison between relative strength coefficients of different activation methods on OMs and OSMs/50.

<table>
<thead>
<tr>
<th>No.</th>
<th>Activation method</th>
<th>Relative strength coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 Day</td>
</tr>
<tr>
<td>1</td>
<td>T</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>TM</td>
<td>0.65</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Based on the results obtained in this investigation, as seen in Table 6, the following points were noted:

(a) According to row 4 of Table 6, it is clear that the OSMs/50 has lower strengths than those of the OMs until 3 days, but at 7 days and above they will achieve more strength growth compared to the OMs at the same ages. It can be averagely said that the OSMs/50 have a higher strength gain compared to the OMs by about 9% in duration of 7–90 days. This is due to the fact that the replacement slag particles with a 50% level instead of cement particles have a latent potential that will be released after 7 days, and then results in strength growth compared to the OMs. Hence, since the OSMs/50 have proper mechanical properties such as a high resistance against sulphates, chloride intrusion, environmental friendliness, and high durability, it is accepted that whenever a fast loading of the structures is not needed, the OSMs/50 are recommended to the OMs.

(b) It is evident from Table 6, whenever any of the three activation methods are used, the OSMs/50 are activated so that they will find a strength growth that is higher than that of the OMs at 3 days. The most increasing effects are attributed to TM, M, and T methods, respectively. At 3 days, the strength of the OSMs/50 is 16% more than those of the OMs, whenever the OSMs/50 are activated by the TM method. This shows that the combined activation method has the most effect in activating the OSMs/50. The second effect is attributed to the mechanical activation method by about 7%, and this shows the high effect of the finely grounded of slag and cement particles on strength growth.

(c) It is seen that the T activation method has a positive effect in duration of 3–90 days on the strength growth of the OSMs/50 compared to the OMs. This effect at 90 days is maximized by about 13%. From Table 6, it is clear that the relative strength coefficient is by about 1.00 and this shows that there is some strength loss at 56 days compared to 28 days for the OSMs/50. However, this is an accepted idea around strength loss due to heat treatment at long ages.

(d) The results obtained by the M activation method shows that the highest strength growth is attributed to 28 days age by about 14%; at 56 days there is strength loss that was discussed in the prior section of the paper. In this method, the relative strength coefficients are 1.06 and 1.00 at 56 and 72% at 3 days and 44.3% and 17.6% at 7 days, respectively.

(c) At 28 days and above, the M activation method is the best, especially at 90 days age. At this age, it is seen that the M’s effects on the ultimate strength growth compared to the effects of T and TM’s methods are 2.2 and 3.5 times, respectively. It seems that this is due to the fact that heat treatment reduces the strengths at long ages.
and 90 days, respectively. It is seen that the relative strength coefficient at 90 days is less than that of 56 days, and this shows not only there is strength loss of OSMs/50 at 90 days, but also there is some strength growth for OMs at the same age (70.88 MPa at 56 days is raised to 75.91 MPa at 90 days).

(e) For the TM activation method, it was observed that the most strength growth of the OSMs/50 occurred at 3 days age. The reason is clear due to the sum total effects of the finely grounded binder particles and also the heat treatment. This integrated effect has caused more progression of the hydration process. The relative strength coefficient at 3 days is by about 1.16, but in the duration of 7–28 days, it has reduced to 1.00. This coefficient reduced to 1.04 at 7 days because the strength growth of the OMs in duration of 3–7 days is higher than that of the OSMs/50. This is well known due to the cement particles which have more hydration progress at early ages compared to the slag particles. Moreover, the relative strength coefficient is reduced once again from 1.04 at 7 days to 1.00 at 28 days. This is due to the aforementioned reason above too. But, it is suddenly seen that the coefficient is increased to 1.05 at 56 days due to their strength loss by about 5.8% of OMs at 56 days. This is a well known result because the OMs’ specimens have been cured in room temperature, and then the hydration process of cement particles cannot progress in room temperature, and also the OSMs/50 will gradually release latent potential until 90 days age, whilst the OMs have approximately constant strength by about 65 MPa in duration of 56–90 days. Therefore, the relative strength coefficient will be increased to 1.10 at 90 days.

(f) Comparison between the relative strength coefficients in Table 6 shows that the best feasible and efficient activation method is TM at short ages, but at long ages none of the three activation methods is recommended, due to there being some strength loss at long ages. In this case, the use of OSMs/50 is only recommended without using any activation method due to its strength growth at later ages is significantly high and also there is no strength loss at long ages. Hence, none of the three aforementioned activation methods is suggested at long ages.

The study of variations of compressive strength vs. the age of specimens shows that the best curve fitting for the variations of strength vs. the age of specimens for both the OMs and the OSMs/50 is a logarithmic relationship as: $CS = a + b \times \ln(t)$, where $CS$ and $t$ is compressive strength and age of curing in MPa and days, respectively. It is noted that the coefficient values $a$ and $b$ for each mix are specific and constant. The values of $a$, $b$, and $R^2$ are shown in Fig. 17. The results of the best curve fitting of all the mixes are also shown in Fig. 17.

4. Conclusions

Based on the results obtained in this investigation work, the following conclusions can be drawn:

(a) The results obtained show that the worst group of mortars is G1, but it cannot absolutely recognize one particular group as the best. This is due to there not being a specific group with both early and later high strengths and without strength loss.

(b) A comparison between the relative strength coefficients shows that the best feasible and efficient activation method is the TM at early ages, but at later ages none of the three studied activation methods is recommended because there is some strength loss at long ages.

(c) According to the results obtained from the SEM images and EDX analysis, it seems that the main cause of strength loss is attributed to phase separation. It is well known that whenever the phases are separated, there is not enough interlocking on the inter-facial zone. Permitting two phases to either slide against each other or intrude results in strength loss.
Generally speaking, it was observed that the OSMs have more sensitivity to curing regimes compared to the OMs. It could be seen that the ultimate strengths of the OSMs/50 at later ages are less than those of the OMs by about 14.3% at the same ages, whenever the specimens are cured in the air under room temperature, but the above statement is reversed if the specimens are cured in the water.

The best curve fitting for the variations of compressive strength vs. the age of specimens for both the OMs and the OSMs/50 is a logarithmic equation as: $CS = a \cdot \ln(t) + b$ with $R^2$ as coefficient of correlation. The results of the best curve fitting of all the mixes are shown in Fig. 17.

References

[21] ACI Committee 308. Recommended practice for curing concrete. MCP, American Concrete Institute, Farmington Hills, USA; 1998.