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# The characteristics and engineering properties of dry-mix/steam-injection concrete

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## Abstract

This study aims to investigate the characteristics and engineering properties of the dry-mix/steam-injection method (DMSIM) which was developed to overcome difficulties involved in vacuum conditions of the lunar environment. A comparison was made to examine the differences in the hydration process, mechanical properties and the composition of hydration products between DMSIM and the normal-temperature wet-mix method (NTWMM). In DMSIM, when dry cement particles come in contact with steam, heat immediately transfers from the steam to the cement, with part of the steam being forced into the inner regions of the cement particles via the micropores. As cement particles gain activation energy and moisture condensed from steam, they undergo rapid and complete hydration. Test results showed that the optimal steaming temperature for dry-mix samples of cement and standard sand is 180–200°C and the optimal steaming scenario for 10 $cm^3$ samples of concrete is at 200°C for 18 h. The present DMSIM has advantages of lower cement content, shorter hardening time and higher concrete strengths, as compared to NTWMM.

*Keywords:* Concrete; Steam; Dry mixture; Compressive strength

## 1. Introduction

The dry-mix/steam-injection method (DMSIM) is a novel technology specially developed for concrete mixing on the moon. The hydration process involved in the traditional normal-temperature wet-mix method (NTWMM) is rendered impossible due to the almost vacuous lunar environment [1,2]. This difficulty calls for the present dry-mix method. In DMSIM, cement and aggregate are mixed first. The resulting dry mixture is placed in a steam boiler or autoclave. Then saturated steam of 105–200°C is introduced to induce hydration of concrete, which completes the DMSIM. The processes involved in DMSIM is outlined in Fig. 1. Despite being originally designed for lunar concrete synthesis, DMSIM has advantages such as less cement content, shortened hardening time and enhanced concrete strength. These merits of DMSIM make it as attractive as (if not more than) NTWMM in terrestrial precast concrete member production [3].

Under normal temperature, the hydration reaction of water with cement involves the following five phases: (1) the initial reaction, (2) the induction period, (3) the acceleratory period, (4) the deceleratory period, and (5) a period of slow, continued reaction. The reaction time and reaction products vary with the temperature, the moisture content and the reaction environment. When cement particles collide with water molecules, many $Ca^{+2}$, $OH^-$ and $H_3SiO_4^-$ ions are released and calcium hydroxide (CH) as well as calcium silicate hydrates (C-S-H gel) are formed [4,5]. However, the exact duration of the initial reaction and the induction period depends on the temperature and the moisture content. At elevated temperatures, $Ca^{+2}$ reaches the saturation level sooner and $H_3SiO_4^{-4}$ dissolves faster. As a result, the duration of the initial reaction becomes shorter and the C-S-H gel, CH, etrringite and calcium sulfoaluminates thus formed will have a hydrate structure different from those obtained under normal temperature. This study aims to investigate the characteristics and engineering properties of DMSIM as well as the

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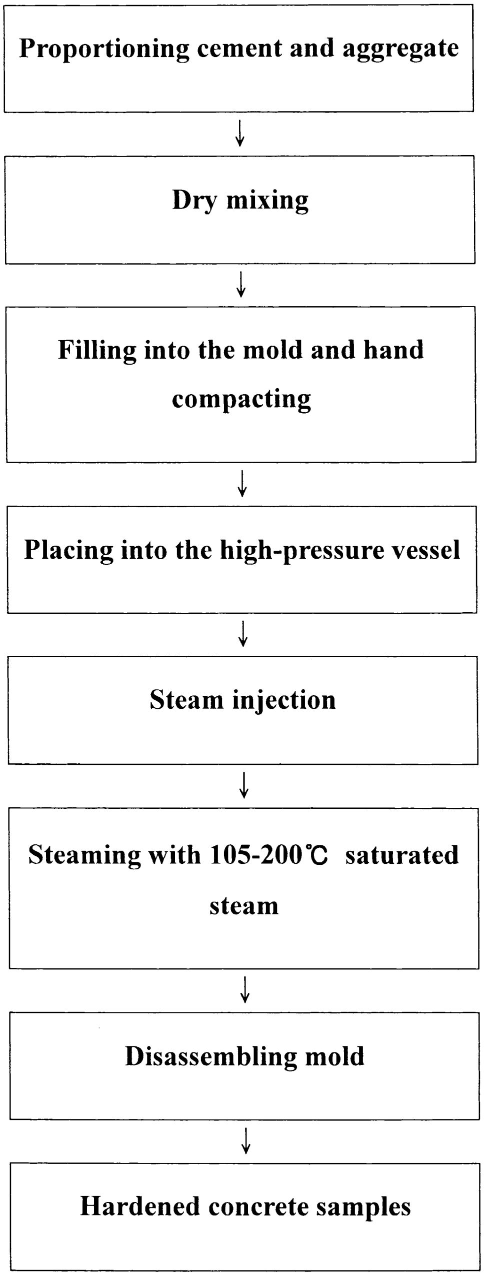


Fig. 1. Steps of DMSIM.

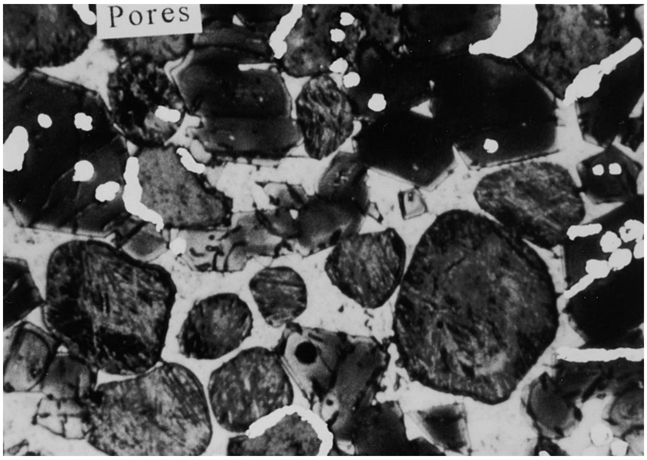


Fig. 2. Micropores in cement compounds ( × 1000).

differences in the hydration process, mechanical properties and the composition of hydration products between DMSIM and NTWMM.

## 2. Characteristics of steam hydration

From a physicochemical point of view, the permeation and the hydration of steam within the dry sample of cement and aggregate have the following features [6].

1. The penetration depth of steam within the dry sample depends on the steaming method, the permeation path as well as the composition, the mixing proportion, the degree of compaction and the size of the sample.

2. The concrete strength is affected by the steam temperature, the steam pressure and the steaming time [7].

3. The degree of hydration of the sample is affected by the material, shape, porosity and dimensions of the mold used to contain the dry sample, as well as the surface area of the sample exposed to steam [8,9].

4. Fig. 2 shows the size of micropores in the cement compounds is much larger than the diameter (about 2.75 Å) of steam molecules. The steam molecules, pushed by steam pressure, will diffuse into the core of the cement particles quickly; this furnished the energy and moisture required for the hydration of cement [10].

5. When colliding with dry cement particles, steam molecules will confer part of their thermal and kinetic energy to the cement particles, resulting in an increase in the energy level of the latter. When the energy of the cement particles is high enough, exothermic hydration reaction will take place [11].

6. In essence, the hydration process in DMSIM is the same as that in NTWMM. However, the different stages of the hydration process in DMSIM will shorten at elevated temperatures. For example, the hydrolysis reaction and

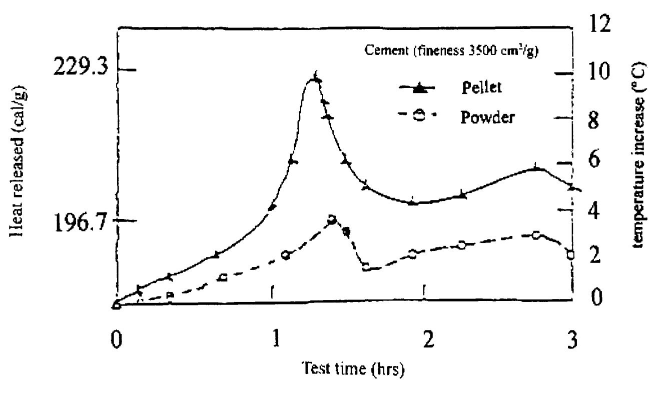
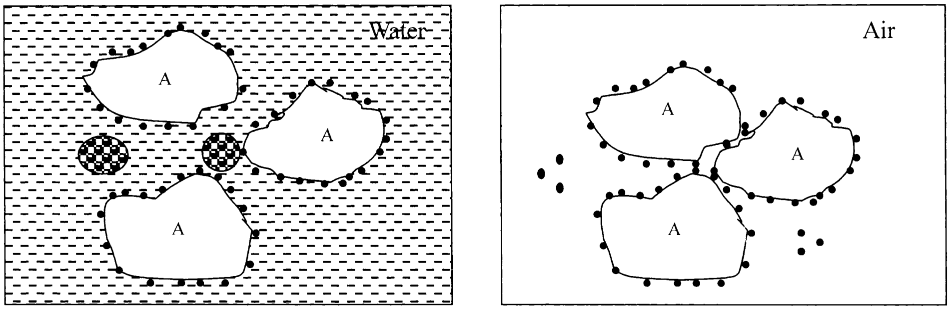
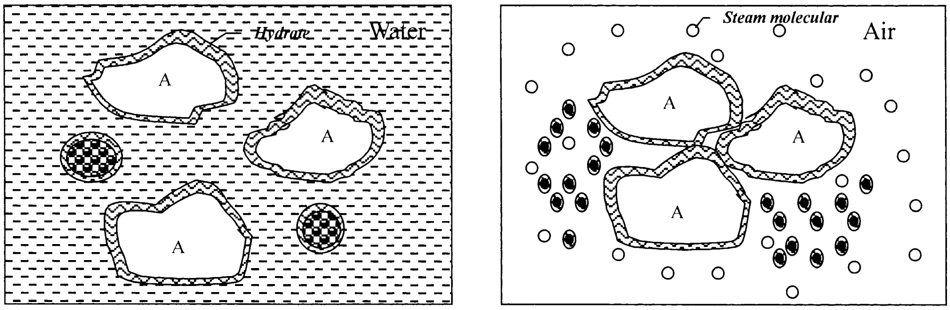


Fig. 3. Thermal history of dry-mix cement exposed to 180°C steam.



(a) Initial phase in NTWMM

(c) Initial phase in DMSIM



(b) After hydration (early stage)

(d) After steam hydration in DMSIM

*A : aggregate ● : unhydrated cement ▨ : hydrate*

Fig. 4. Schematic illustration of hydrates for NTWMM and DMSIM samples.

induction period will hasten or even disappear completely, as demonstrated in Fig. 3, due to the decrease in the surrounding moisture [12]. Furthermore, the chance that CaO peels off from $C_3S$ particle surface and dissociates into $Ca^{+2}$ is less in DMSIM. Therefore, less calcium hydroxide is formed in the steam hydrate.

7. Fig. 4 shows dry mixing cement and aggregate can eliminate the conglomerate group of cement matrix wetting by water in the space of aggregate. Furthermore, the dispersion of cement matrix around neighbor would be more compactly in DMSIM than in NTWMM.

8. During the hydration process, the surface of the dry sample will hydrate first and a barrier film is formed. This barrier film will block the entrance of the incoming steam causing incomplete hydration in the core region of large-sized products [13].

From the above-mentioned, it can be seen that the hydration features of DMSIM and NTWMM are dramatically different. Therefore, it is important to understand their differences such as the hardening characteristics of concrete, the concrete strength and the micromorphology, to name a few.

## 3. Research significance

The newly developed DMSIM method in this study has advantages of shorter hardening time and higher concrete strength than the NTWMM. With the innovative DMSIM technology, it is believed that in situ materials for making concrete on the Moon becomes possible and DMSIM may also be applied to the manufacturing of precast concrete on earth.

## 4. Test program

The main focus of this study is to measure the compressive strength of mortar and concrete and investigate the optimal water–cement ratio. Samples are taken from DMSIM products to analyze the hydrate composition and the degree of hydration to reveal the microscopic structure. Also, slices are cut from the concrete samples to determine the void.

### *4.1. Test materials*

#### *4.1.1. Cement*

The cement used in the test program is Type I Portland Cement manufactured by Taiwan Cement with quality meeting the ASTM C150 standard.

#### *4.1.2. Standard sand*

Imported from Illinois, USA, the standard sand employed to produce mortar is the Ottawa grade silicate sand with quality meeting the ASTM C778 standard.

#### *4.1.3. Coarse and fine aggregates*

The coarse and fine aggregates used to synthesize concrete are domestic products from the Ta-An River located in

Table 1
Physical properties of aggregate

| Property | Coarse aggregate | Fine aggregate |
|---|---|---|
| Specific gravity (S.S.D) | 2.66 | 2.67 |
| Absorption (%) | 0.7 | 1.76 |
| Unit weight (kg/m$^3$) | 1569 | – |
| Fineness modulus | – | 2.67 |

Table 3
Mixing proportions of dry mixtures

| | Mix proportions, kg/m$^3$ | | | |
|---|---|---|---|---|
| Materials | M1 | M2 | M3 | M4 |
| Cement | 250 | 325 | 400 | 475 |
| Fine aggregate | 780 | 750 | 720 | 690 |
| Coarse aggregate | 1170 | 1125 | 1080 | 1035 |

central Taiwan. Their physical properties and grading are listed in Tables 1 and 2, respectively.

### 4.1.4. Water

The water used is tap water supplied by the Hsin-Chu plant of Taiwan Water.

## 4.2. Samples

### 4.2.1. Mortar samples

The mortar sample is made in the following way. First, 1 part of cement with 2.75 parts of standard sand (weight ratio) are dry-mixed together. After being hand-packed compactly, the dry mixture is filled into a $5 \times 5 \times 5$-cm iron mold in three layers. Then the mold is placed in an autoclave and steamed with saturated steam at (1) 105–120°C (steam pressure 0.12–0.24 MPa), (2) 140–150°C (0.36–0.48 MPa) and (3) 160–180°C (0.62–1.0 MPa) for 6, 12, 18, 24, 31, 38, 46 and 57 h, respectively, to yield the DMSIM mortar samples. These steaming durations include the 2-h temperature-raising period, but not the cooling period.

### 4.2.2. Concrete samples

Cement, fine aggregate and coarse aggregate are mixed together in four different proportions as displayed in Table 3. After being hand-packed compactly, the mixture is filled into a $10 \times 10 \times 10$-cm iron mold in three layers. Then the mold is placed in a medium-sized boiler. Finally, the mixture is steamed under eight steaming scenarios as detailed in Table 4 for 5, 18, 22.5, 30 and 37.5 h, respectively, to yield the DMSIM concrete samples. These steaming durations include the 5-h temperature-raising period, but not the cooling period.

Table 2
Aggregate grading

| Coarse aggregate | | | Fine aggregate | | |
|---|---|---|---|---|---|
| Sieve size | Percent passing | ASTM C33 requirement (%) | Sieve size | Percent passing | ASTM C33 requirement (%) |
| 1 in. | 100 | 100 | 3/8 in. | 100 | 100 |
| 3/4 in. | 95 | 100–90 | #4 | 95.2 | 100–90 |
| 1/2 in. | 37.5 | 55–20 | #8 | 81.8 | 100–80 |
| 3/8 in. | 7.5 | 15–0 | #16 | 70.9 | 90–50 |
| #4 | 0 | 5–0 | #30 | 55.6 | 60–25 |
| | | | #50 | 16.8 | 30–10 |
| | | | #100 | 3.9 | 10–2 |

### 4.2.3. Control samples

Water, cement and standard sand are wet-mixed at a weight ratio of 0.485:1:2.75. The wet mixture is then placed into a $5 \times 5 \times 5$-cm iron mold, remains there for 24 h and cured for another 27 days to yield the NTWMM mortar samples. Also, cement, fine aggregate and coarse aggregate are mixed in proportions prescribed in Table 3 with water added at a water–cement ratio of 0.485. The resulting wet mixture is cured for 28 days to yield the NTWMM concrete samples. A comparison is to be made between the NTWMM samples and DMSIM samples to highlight the differences between these two methods.

## 4.3. Steaming equipment

The equipment required in DMSIM consists of: (1) the dry mixing machines, (2) the molds, (3) the compacting and troweling tools, and (4) the boiling system, as described in detail below. [5]

1. Dry-mixing machines: The Hobat mortar mixing machine and Atika concrete mixing machine are used.

2. Specimen molds: A three-coupled $5 \times 5 \times 5$-cm iron mold is used to contain the dry mixture of cement and standard sand. A five-coupled $10 \times 10 \times 10$-cm iron mold is used to hold the dry mixture of cement and sand.

3. Compacting and troweling tools: A steel rod 60 cm in length, 1.6 cm in diameter and 0.84 kg in weight with hemispherical ends is used to tamp the three-layered dry mixture 25 times for each layer. Then a 0.94-kg rubber hammer is used to strike the outside wall of the mold to compact the mixture. Finally, a trowel polishes the dry mixture on the topside of the mold.

4. The boiling system: The boiling system is composed of a small autoclave and a medium-sized steam boiler. The small autoclave utilized is a vertical autoclave, cylindrical in shape, 220 mm in inside diameter and 530 mm in height. It is a product of ELE, UK and has a maximum pressure of 4 MPa. The medium-sized steam boiler includes the steam generator, the high-pressure vessel, the soft-water equipment as well as steam and water pipes. The steam generator with a maximum pressure of 1.76 MPa is an electrically heated type. Steam is injected from the steam generator into the high-pressure vessel to steam the dry sample to yield the hardened product.

Table 4
Steaming scenarios

| Steaming curve | Phase | Temperature-raising period | Constant-temperature period | Temperature-decreasing period |
|---|---|---|---|---|
| 1[a] | Temperature (°C) | 20 → 105 | → 130 → 155 | → 180 → 100 → 20 |
| | Time (h) | 5 | 6, 9 | 10, 7, 10 |
| | Pressure (kg/cm$^2$) | 0.02 → 1.28 | → 2.9 → 5.2 | → 10.14 → 1.0 → 0.02 |
| 2 | Temperature (°C) | 20 → 180 | 180 → 180 | 180 → 100 → 20 |
| | Time (h) | 5 | 25 | 7, 10 |
| | Pressure (kg/cm$^2$) | 0.02 → 10.14 | 10.14 → 10.14 | 10.14 → 1.0 → 0.02 |
| 3 | Temperature (°C) | 20 → 180 | 180 → 180 | 180 → 100 → 20 |
| | Time (h) | 5 | 17.5 | 7, 10 |
| | Pressure (kg/cm$^2$)[b] | 0.02 → 10.14 | 10.14 → 10.15 → 15 | 15 → 15 → 0.02 |
| | Time (h) | | 14.5, 3 | 16.9, 0.1 |
| 4 | Temperature (°C) | 20 → 180 | 180 → 180 | 180 → 100 → 20 |
| | Time (h) | 5 | 10 | 7, 10 |
| | Pressure (kg/cm$^2$) | 0.02 → 10.14 | 10.14 → 10.14 | 10.14 → 100 → 0.02 |
| 5 | Temperature (°C) | 20 → 180 | 180 → 180 | 180 → 100 → 20 |
| | Time (h) | 5 | 25 | 7, 10 |
| | Pressure (kg/cm$^2$) | 0.02 → 10.14 | 10.14 → 10.14 | 10.14 → 1.0 → 0.02 |
| 6 | Temperature (°C) | 20 → 200 | 200 → 200 | 200 → 100 → 20 |
| | Time (h) | 5 | 17.5 | 7, 10 |
| | Pressure (kg/cm$^2$) | 0.02 → 15.9 | 15.9 → 15.9 | 15.9 → 1.0 → 0.2 |
| 7 | Temperature (°C) | 20 → 200 | 200 → 200 | 200 → 100 → 20 |
| | Time (h) | 5 | 17.5 | 7, 10 |
| | Pressure (kg/cm$^2$) | 0.02 → 15.9 | 15.9 → 15.9 | 15.9 → 1.0 → 0.02 |
| 8 | Temperature (°C) | 20 → 200 | 200 → 200 | 200 → 100 → 20 |
| | Time (h) | 5 | 13 | 7, 10 |
| | Pressure (kg/cm$^2$) | 0.02 → 15.9 | 15.9 → 15.9 | 15.9 → 1.0 → 0.02 |

[a] Saturated steam pressure was maintained for all curves except no. 3.

[b] Additional pressure was applied.

### 4.4. Testing quantities and instrument

#### 4.4.1. Compressive strength

The compressive strengths of mortar and concrete samples are measured according to the ASTM C39 standard using the Shimadzu 100-ton Universal Testing Machine.

#### 4.4.2. Water–cement ratio

The weight of the steamed, hardened mortar or concrete sample is measured first, then minus the weight of the dry sample to determine the weight of water. The weight of water thus obtained is then divided by the weight of the dry sample to yield the DMSIM water–cement ratio.

#### 4.4.3. Degree of hydration and calcium hydroxide content

The thermogravimetric analysis instrument and differential thermogravimetric analysis instrument, products of TA Instruments, were employed to determine the degree of hydration and the content of calcium hydroxide of the concrete sample using the ignition method. The degree of hydration of concrete and calcium hydroxide content of concrete are based on Eqs. (1) and (2):

$$\alpha = \frac{(W_{105} - W_{580}) + 0.41(W_{580} - W_{1007})}{nW_{1007}} \times 100\% \qquad (1)$$

where $\alpha$: degree of hydration, %. $n$: evaporate water in cement paste with completed hydration, the $n$ equals to 0.24 for the ordinary cement paste. $W_{105}$, $W_{580}$, $W_{1007}$: weights of specimens at 105°C, 580°C and 1007°C, respectively. 0.41: the mass ratio of 1 mol $H_2O$ to 1 mol $CO_2$.

$$W_{CH} = \frac{4.11(W_{440} - W_{580}) + 1.68(W_{580} - W_{1007})}{W_{1007}} \times 100\% \qquad (2)$$

where $W_{CH}$: the weight ratio of $Ca(OH)_2$ in the cement paste. $W_{440}$, $W_{580}$, $W_{1007}$: weights of specimens at 440°C, 580°C and 1007°C. 4.11: the mass ratio of 1 mol $Ca(OH)_2$ to 1 mol $H_2O$. 4.11: the mass ratio of 1 mol $Ca(OH)_2$ to 1 mol $CO_2$.

#### 4.4.4. Density

The density is determined by first measuring the weight of the 10 × 10 × 10-cm hardened concrete which is then divided by the volume of the concrete.

#### 4.4.5. Void

A steamed, hardened concrete sample is cut and covered with a transparent plastic film. The porous portion is painted black and the void is determined.

#### 4.4.6. Porosity

A mercury intrusion porosimeter, product of Quanta Chrome, USA is used. A 1-g sample is taken from the mortar and is evacuated. Then air is introduced so that the sample is surrounded by mercury. Finally, mercury is forced to penetrate into the sample by the application of 0–412 MPa pressure and the porosity is determined.

### 4.4.7. Micromorphology of hydration products

Observation and photographs are made by Hitachi S-2500 type Scanning Electronic Microscope (SEM).

## 5. Results and discussion

### 5.1. Compressive strength of mortar

Table 5 shows that the mortar with a water–cement ratio of 0.348 and a compressive strength of 23.1 MPa can be obtained by steaming the dry sample with 105–120°C saturated steam for 6–57 h. When the dry sample is steamed with 140–150°C saturated steam for 6–46 h, the mortar strength is 39.6 MPa. If the saturation temperature of steam is further increased to 160–180°C, the mortar strength will also rise to 54.7 MPa. This can be explained by the fact that at 180°C the steam molecules have higher kinetic energy and greater mobility, therefore it is easier for steam molecules to diffuse into the core region of the dry sample and collide with the cement particles, thus favoring the hydration process. As a result, the mortar strength is enhanced. It is also found that if the dry sample is steamed with saturated steam of 225°C for 18–48 h, the mortar strength will not be increased, contrary to expectations. This is because at such a high temperature, the gelation of the pure cement compounds deteriorates and the mortar loses strength. Therefore, the optimal steaming temperature is 160–180°C.

### 5.2. Compressive strength of concrete

Fig. 5 illustrates the different concrete strengths under different steaming scenarios as shown in Table 4. Four sets of dry samples with various proportions of cement are steamed using Curve 2 (steaming at 180°C for 40 h), Curve 3 (steaming at 180°C for 22.5 h with pumping), Curve 4 (steaming at 180°C for 22.5 h), Curve 7 (steaming at 200°C for 22.5 h) and Curve 8 (steaming at 200°C for 18 h) to yield concrete of average strengths of 65.3, 67.6, 67.2, 71.5 and 77 MPa, respectively. The relatively lower strengths of 34.7 and 46.1 MPa obtained by Curves 1 (increasing to 180°C from 105°C gradually) and 6 (steaming at 150°C for 15 h) are due to low streaming pressures. Moreover, since the steaming time is too short, the strength of concrete produced by Curve 5 (steaming for 15 h at 180°C) is only 52.8 MPa. It is worthy to note that if the rates of temperature and pressure reduction before the samples are removed from the steam boiler are too high, the steam trapped in the pores of the samples will vaporize and escape, causing cracks to develop on the surface of the samples. In addition, cracks can also develop after the sample is removed from the steam boiler due to inhomogeneous cooling. In this regard, the overall damage incurred by steaming needs further investigation. Nonetheless, the above results reveal that the optimal scenario for a $10 \times 10 \times 10$-cm sample is either steaming at 180°C for 22.5 h or cooking at 200°C for 18 h.

### 5.3. Water–cement ratio and density

The water–cement ratios of the concrete produced by steaming scenarios prescribed in Table 3 range from 0.126 to 0.425 with an average of 0.236, far less than those produced by NTWMM. Whether steam molecules can penetrate through the hardened layer on the surface of the hydrated dry samples and reach the core region is a determining factor of concrete strength. Therefore, as shown in Fig. 6, concrete strength is proportional to the water–cement ratio in DMSIM. Test results show that the density of 2.30–2.40 g/cm$^3$ of DMSIM concrete is very close to that of 2.32–2.39 g/cm$^3$ of 28-day NTWMM concrete with a water–cement ratio of 0.485. This is because in DMSIM the reduction in density due to the decrease in capillary water offsets the density increment due to greater compaction between cement and aggregate. As a result, concrete produced by these two methods has approximately the same density.

### 5.4. Effect of cement content on concrete strength

Fig. 7 illustrates the relationship between cement content and concrete strength. Cement content of 250, 325, 400 and 475 kg/m$^3$ yield strengths of 59.9, 62.4, 61.8

Table 5
Measured compressive strength and water–cement ratio of mortar (unit: MPa)

| | Steaming time (h) | | | | | | | | Average compressive strength |
|---|---|---|---|---|---|---|---|---|---|
| Steaming temperature | 6 | 12 | 18 | 24 | 31 | 38 | 46 | 57 | |
| 105–120°C | 13.8 | 19.4 | 19.9 | 21.2 | 29.0 | 27.4 | 27 | 27 | 23.1 |
| Water–cement ratio | 0.301 | N.A. | 0.346 | 0.369 | 0.421 | 0.336 | 0.329 | 0.336 | 0.348 |
| 105–120°C | 21.5 | 25.3 | 26.6 | 36.1 | 49.1 | 51.1 | 67.3 | N.A. | 39.6 |
| Water–cement ratio | 0.327 | 0.324 | 0.323 | 0.341 | 0.366 | 0.344 | 0.363 | N.A. | 0.341 |
| 105–120°C | 27.9 | 39.5 | 68.9 | 68.9 | 68.6 | N.A. | N.A. | N.A. | 54.7 |
| Water–cement ratio | 0.248 | 0.276 | 0.352 | 0.35 | 0.337 | N.A. | N.A. | N.A. | 0.315 |

N.A.: not available

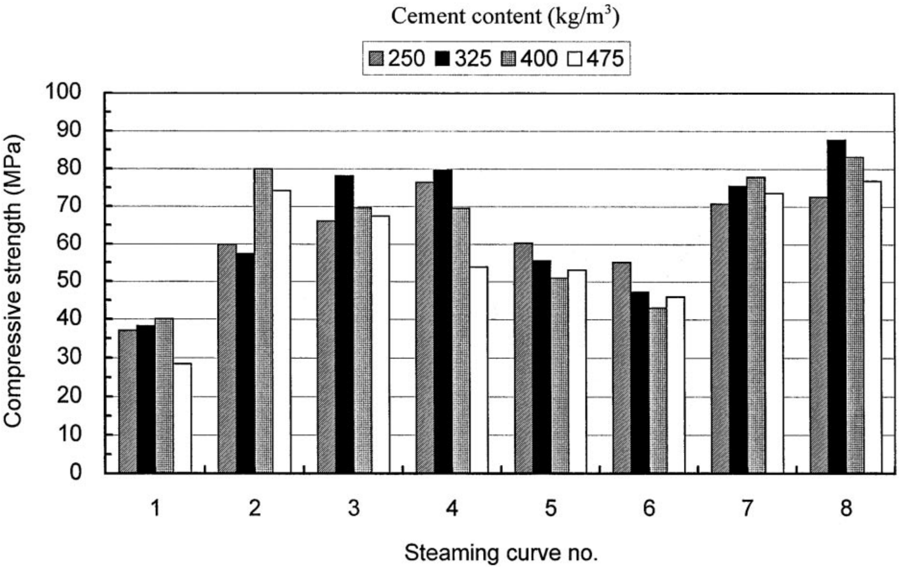


Fig. 5. Strength of concrete made through eight steaming scenarios.

and 56.9 MPa, respectively. It reveals that dry samples with 325 and 400 kg/m$^3$ yield concrete of higher strength. With 250 kg/cm$^3$ cement content, the concrete possesses a high void of 27.7% due to deficient cement. With 475 kg/m$^3$ cement content, there exist lots of barrier films that hinder the penetration of steam molecules, thus affecting the hydration process. In NTWMM, 475 kg/m$^3$ (W/C = 0.32) usually produces concrete of strength of 61.8 MPa. However, the present study finds that in DMSIM cement content at 250, 325 and 400 kg/m$^3$ are enough to produce concrete of strengths of 59.9, 62.4 and 61.8 MPa, respectively. The cement cost of high-strength concrete will be saved about 20–47% by using DMSIM.

### *5.5. Void in concrete*

That concrete produced by 28-day NTWMM with a water–cement ratio of 0.485 and cement content at 250, 325, 400 and 475 kg/m$^3$ has voids of 27.7%, 5.9%, 1.12% and 0.5%, respectively. Apparently, the higher the cement content, the less the void will be. This is because water bleeding and aggregate segregation in NTWMM lead to formation of void. With a low cement content such as 250 kg/m$^3$, NTWMM causes the materials to segregate. To make things worse, hand-packing dislocates aggregate and results in high void percentage and concrete of strength of only 19.4 MPa. In contrast, the void in concrete by DMSIM is almost 0%. Hence, a low cement content of 250 kg/m$^3$ is

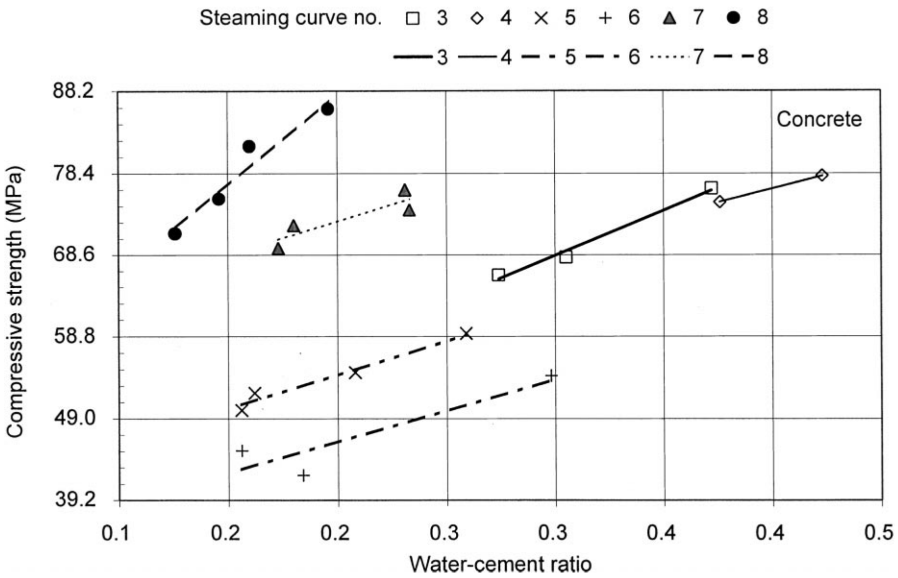


Fig. 6. Water–cement ratio vs. concrete strength.

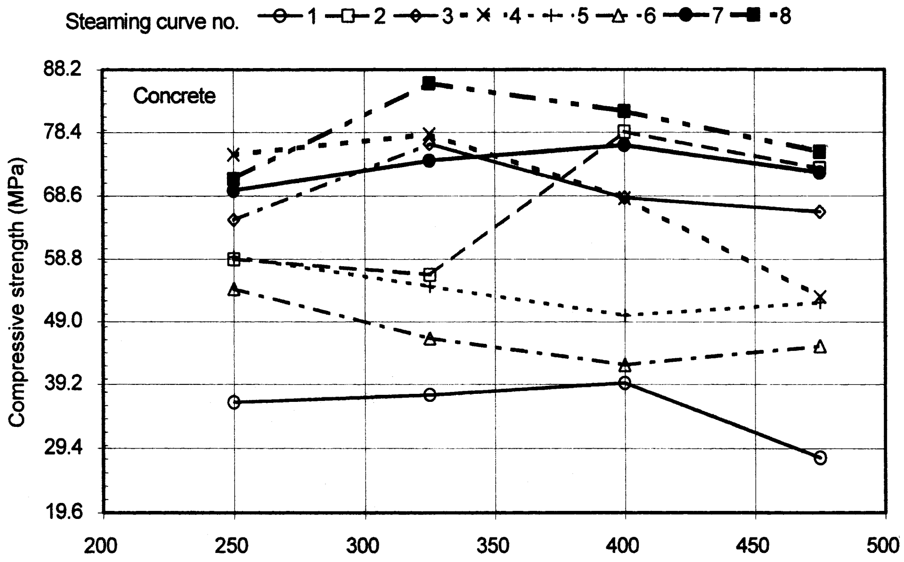


Fig. 7. Cement content vs. concrete strength.

able to produce concrete of strength of 59.9 MPa. Thus, so long as an appropriate steaming scenario is employed, DMSIM can produce concrete of high compressive strength.

### 5.6. Mortar porosity

Fig. 8 shows the mortar porosity as measured by the mercury intrusion porosimeter. The porosity is 0.0102 cm$^3$/g for NTWMM products. On the other hand, a sample steamed by DMSIM (160–180°C saturated steam for 12–34 h) has a porosity of 0.021–0.044 cm$^3$/g. In NTWMM, the hydrate forms and grows under the normal temperature with a slower growth rate, giving rise to a more compact structure. In contrast, the hydrate in DMSIM is less homogeneous due to high temperatures. Also C-S-H gel particles tend to become larger in size, which results in higher porosities. In other words, as the high temperature steam reacts with the dry sample, many nuclei are formed suddenly during the initial phase of hydration, which leads to the rapid growth of hydrates. Therefore, the gel conglomerate and crystal have a looser structure and a higher porosity.

### 5.7. Micromorphology of the hydrate

The micromorphology of the hydrate of hardened mortar produced by NTWMM with a water–cement ratio of 0.485 possesses many large pores with diameters ranging from 0.081 to 0.25 mm, as shown in Fig. 9(a) (dark

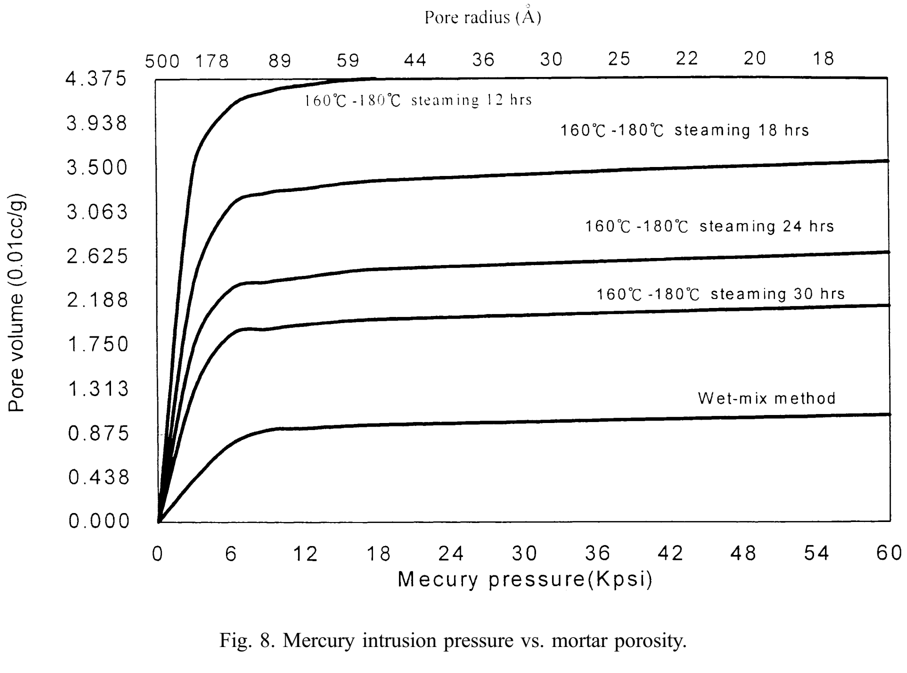
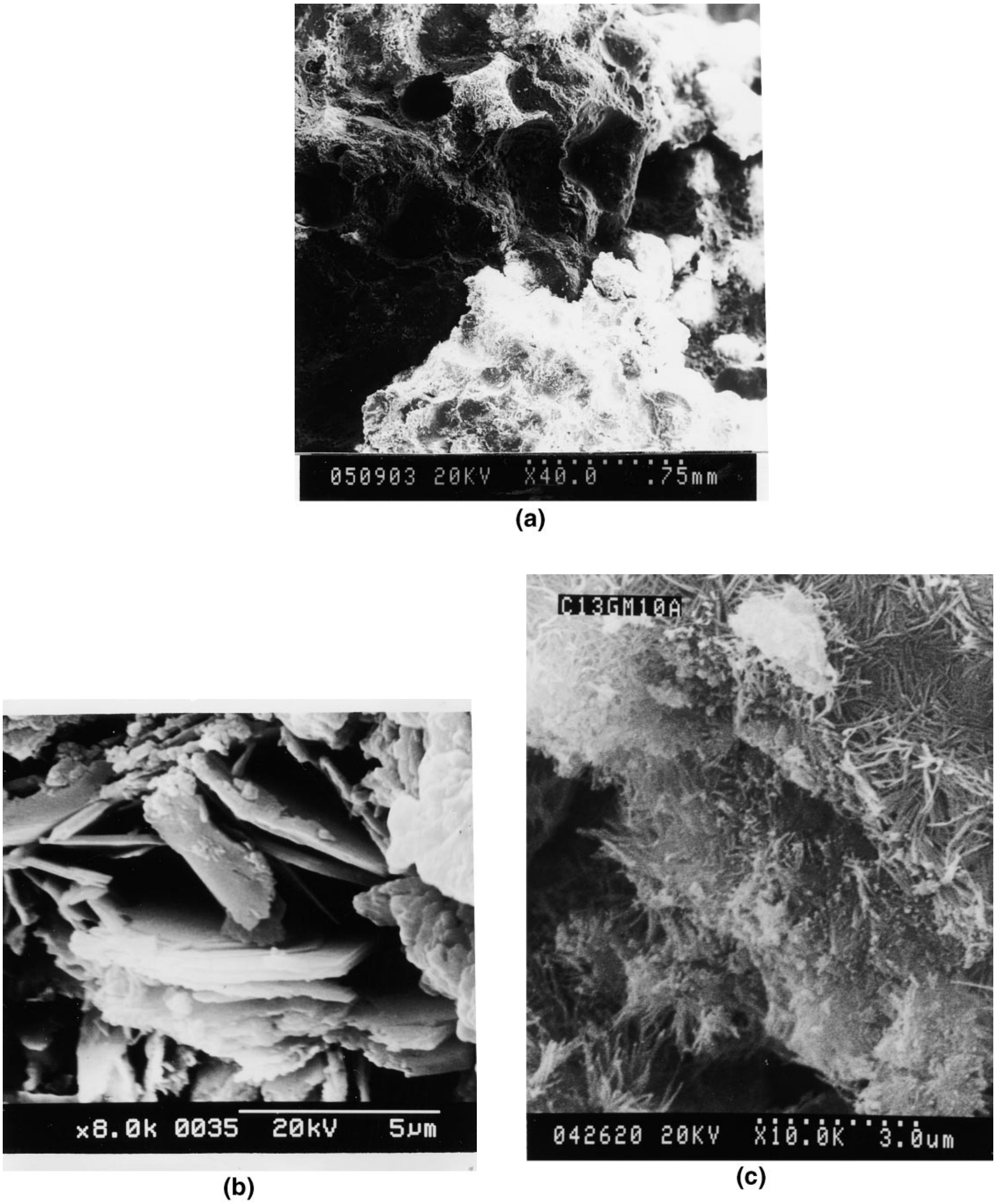


Fig. 8. Mercury intrusion pressure vs. mortar porosity.



(a)

(b)

(c)

Fig. 9. Micromorphology of mortar hydrates. (a) Large pores in NTWMM mortar. (b) Abundant calcium hydroxide in NTWMM mortar. (c) Abundant C-S-H gel with small amount of calcium hydroxide in DMSIM mortar.

region), and abundant large calcium hydroxide crystals, as shown in Fig. 9(b) (light region). The compressive strength of mortar is only 22.8 MPa for NTWMM products. On the contrary, mortar produced by DMSIM contains only a handful of calcium hydroxide crystals (the light region in Fig. 9(c), but has more compact C-S-H gel structure than mortar yielded by NTWMM. DMSIM mortar has more C-S-H gel as well. As a consequence, DMSIM mortar has higher strengths as seen in Table 5. This SEM observation is consistent with the hydration characteristic mentioned in Section 2. It is worthy to note that the key ingredient of standard sand in the dry sample is $SiO_2$, which has a higher dissolution rate and is involved in the hydration process yielding a mixed structure of C-S-H (I) or Tobermorite gel at elevated temperatures.

### 5.8. Degree of hydration

Table 6 reveals that the average degree of hydration in the core region is 87% for concrete prepared by the six different steaming scenarios. However, for the NTWMM concrete of 28-day age, the degree of hydration is only 59%. Obviously, DMSIM increases the degree of hydration. Table 6 also indicates that steaming with 180°C steam for 22.5–30 h results in higher degree of hydration (Scenarios 2, 3 and 4). If the temperature is raised to 200°C while the steaming time is shortened, a high hydration level is still possible (Scenarios 7 and 8). However, if the temperature is reduced to 150°C but the steaming time is prolonged to 37.5 h, the degree of hydration will become lower. With 325 or 400 kg/m$^3$ of cement content, the resulting porous structure makes it easier for steam to permeate. The outcome is higher degree of hydration and enhanced strength. If the cement content is increased to 475 kg/m$^3$, the overdose of cement becomes detrimental to the penetration of steam molecules due to the presence of copious barrier films, resulting in a lower degree of hydration.

### *5.9. Calcium hydroxide content*

The calcium hydroxide content in DMSIM hydrate is 22.4–35.6%, with an average of 28%, as shown in Table 7, far less than the 36% of its 90-day age NTWMM counterparts. This is because in NTWMM CaO tends to peel off from the $C_3S$ surface and hydrolyze to yield $Ca^{2+}$, which subsequently reacts with $H_2O$ to yield excessive $Ca(OH)_2$. On the other hand, the absence of abundant moisture in DMSIM shortens the initial reaction of the hydration process (or such reaction disappears completely). Therefore, the hydration process proceeds from the induction period to the acceleratory period directly, and the steam molecules liquefy partially while colliding with cement particles and are forced to enter the lattice of pure cement compounds and accelerate the hydration process. Thus, more C-S-H and less CH hydration structure are present as shown in Fig. 9(c).

### *5.10. Effects of sample dimensions*

It is also of interest to study whether ‘steaming failure’ will occur in case of larger molds in DMSIM. To this end, dry samples with a cement content of 325 kg/m$^3$ are placed into cylindrical iron molds with dimensions of 7.5 × 15, 10 × 20 and 15 × 30 cm, respectively, and steamed at 180°C for 37.5 h. The results show that the strengths thus obtained are only 29.9, 24.8 and 12.1 MPa, respectively, far less than the 10 × 10 × 10-cm mold because steam cannot penetrate into the central region of the mold. When the sample is cut using the saw with diamond cutting edge, a closer examination reveals that insufficient hydration occurred in the core region of the sample. This phenomenon is more pronounced as the sample gets larger. In this regard, whether a different scenario is required for a larger sample merits further investigation.

Table 6
The degree of hydration (unit: %)

| | Cement content, kg/m$^3$ | | | | Average of four mixes |
|---|---|---|---|---|---|
| Steaming curve | 250 | 325 | 400 | 475 | |
| 3 | – | – | 95 | – | 95 |
| 4 | 85.0 | 97.5 | 90.7 | 82.6 | 89 |
| 5 | – | 95.6 | 93.1 | – | 94 |
| 6 | 97.8 | 79.0 | 77.0 | 64.0 | 77 |
| 7 | 81.6 | 97.0 | 82 | 84.0 | 84 |
| 8 | 80.6 | 97.7 | 85.8 | 76.3 | 83 |
| Average of all steaming scenarios | 84 | 97 | 87.2 | 76.3 | 87 |
| Wet-mix | 59 | | | | |

Table 7
The calcium hydroxide content (unit: %)

| | Cement content, kg/m$^3$ | | | |
|---|---|---|---|---|
| Steaming curve | 250 | 325 | 400 | 475 |
| 3 | 25.9 | 30.6 | 26.6 | 20.8 |
| 4 | – | 33.0 | 32.5 | – |
| 5 | – | – | – | – |
| 6 | 28.9 | 25.6 | 25.7 | 22.2 |
| 7 | 30.3 | – | 26.6 | 33.8 |
| 8 | 30.6 | 22.4 | 35.6 | 26.8 |
| Wet-mix | 36.0 | | | |

## 6. Conclusions

A summary of our findings is as follows.

1. DMSIM can inhibit the chance of calcium oxide peeling off from tricalcium silicate and dissociating into calcium ions, thus suppressing the formation of calcium hydroxide and enhancing the production of C-S-H gel.
2. The mixing proportion, the steaming scenario and the sample dimensions will affect the compressive strength of DMSIM concrete.
3. The steaming scenario and the dimensions of sample also influence the degree of hydration of DMSIM concrete.
4. The void of DMSIM concrete is less than that of NTWMM concrete.
5. Hot steam molecules enable rapid growth of hydrates, resulting in looser hydrate structure and higher porosity than concrete produced by NTWMM.
6. Dry samples with low cement content are able to yield concrete of high strength.
7. The optimal steaming temperature for dry-mix sample of cement and standard sand is 180–200°C.
8. The optimal steaming scenario depends upon the dimensions of sample, e.g. for 10 × 10 × 10 cm samples, the optimal steaming time is 22.5–30 h; the optimal steaming duration corresponding to 200°C is 18 h.

9. The strength of DMSIM concrete is proportional to the water–cement ratio and the degree of hydration.
10. The present DMSIM has advantages of lower cement content, shorter hardening time and higher concrete strengths, as compared to NTWMM.
11. The steaming scenario for larger samples needs further investigation.

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