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Prediction of later-age compressive strength of normal concrete based on the accelerated strength of concrete cured with microwave energy

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Abstract

Microwave energy can accelerate the hydration of cement, resulting in rapid strength development of concrete in an early period. In this paper, prediction of later-age compressive strength of normal concrete, made with rapid-hardening and ordinary Portland cement, based on the accelerated strength of concrete cured with microwave energy was investigated. To accelerate curing properly, the optimal microwave curing process for concrete was first determined and then was applied to concrete. The possible early ages for the strength prediction were found to be at 3.5 and 5.5 h for concrete made with rapid-hardening and ordinary Portland cement, respectively. For each cement type, a formula for the strength prediction was derived from the relationship between accelerated early-age strength of concrete cured with microwave energy and later-age strength of normally cured concrete. Predictions of strength at 7 days for concrete made with rapid-hardening Portland cement and 28 days of concrete made with ordinary Portland cement were within 15% agreement with actual test results.

Keywords: Microwave processing; Processing; Compressive strength; Properties; Portland cement; Composition

1. Introduction

Compressive strength of concrete is clearly the most important property for quality control in concrete production and construction. Therefore, knowing potential later-age concrete strength at the earliest possible time after concrete is produced, especially in a few hours, can be beneficial for necessary remedy or adjustment.

Several methods that were developed in Japan on the rapid test method for early-age prediction of concrete quality were reviewed and compared by Kasai [1]. The methods to predict 28-day concrete strength consisted of test methods for unit amount of cement, water, water/cement ratio in fresh concrete and the accelerated strength tests of fresh concrete and mortar that included hot water curing, high-temperature curing in a sealed, restricted mold and the rapid-hardening method, using set-accelerating admixture. These methods, however, were not used widely because of a number of shortcomings. To accurately predict the later-age strength, a relatively long curing period (more than 24 h) was still required before the early-age test was performed. Also, costly equipment might be required, and the tests were difficult to perform.

De Siqueira Tango [2] classified several methods to predict the strength of cementitious material, mostly at 28 days, as (1) accelerated curing methods by heating or using accelerating admixtures, (2) correlations with early-age strengths under standard curing conditions and (3) correlation methods using other characteristics such as chemical composition, cement fineness, heat of hydration, estimated porosity and early-age sonic pulse velocity. Most of these methods still required over 24 h before early-age tests could be performed. For example, the American standard test method, using the results of early-age compressive values obtained from conventional curing to project potential later-age strength, required an early-age strength test at no less than 24 h [3].

In this study, the accelerated curing method using the microwave heating technique for later-age strength prediction is illustrated. With this technique, early-age strength values measured within a few hours can be correlated to later-age strength values. Microwave heating is based on the internal energy dissipation associated with the excitation of molecular dipoles and ions in electromagnetic fields. It was

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shown to be effective to accelerate hydration and produce concrete with very high early strength with insignificant reduction in later-age strength [4,5]. Rapid early strength development of concrete not only favors construction operations, such as precasting and repairing, but can also be useful in later-age strength prediction.

2. Experimental program

Ordinary Portland cement and rapid-hardening Portland cement were used to produce concrete mixture. Limestone with a maximum size of 20 mm and local construction sand were washed and dried in a conventional oven for 24 h before use. No admixture was added to the mix in this study.

Seven $76.2\times$ 152.4 mm specimens were cast in polyethylene moulds for each batch. Thirty minutes after water was added, four of them were cured with microwave energy while the others were cured normally. The normally cured specimens were covered with plastic sheets after casting, removed from the moulds after 1 day and placed in water at room temperature until testing time. To obtain uniform heating, the moulds in the microwave oven were arranged in a circular pattern on the turntable. After microwave curing, each mould was removed from the cavity and covered with a plastic sheet to continue the curing process. To measure the accelerated early-age strength, the microwave-cured specimens were removed from their moulds with a piston, 30 min before the compression test and then capped with sulfur mortar. For later-age strength tests of the microwave-cured specimens and the normal-cured specimens, the specimens were demoulded after 1 day and cured in water at room temperature until testing time.

To perform microwave heating, a commercial kitchen microwave oven with internal cavity dimensions of 390 (width) $\times$ 268 (height) $\times$ 400 mm (depth) was used. Its output power could be adjusted from 10% to 100% of full output power, which was specified to be equal to 850 W based on the International Electrotechnical Commission (IEC) Publication 705 rating standard [6]. Thus, to refer to the microwave power level in this work, P# was used, where # represented the percentage number of the full output power. For instance, P40 represented the power level at 40% of full output power. Although the standard method in the IEC Publication 705 was used to measure microwave output power of the oven at its maximum microwave power setting, in this work, for comparison purposes, the same method was adopted to obtain the output powers in unit of watt at various power settings.

To obtain the formula for prediction of later-age compressive strength of normal-cured concrete (NCC), a two-step procedure was adopted for each type of cement. Firstly, the optimal microwave curing process was determined and used to accelerate hydration of concrete mixtures with several mix proportions. Then, the relationship between the accelerated early-age strength and the later-age strength of NCC was established to derive a formula for the strength prediction.

3. Results

3.1. Result of optimal microwave curing process

To obtain the optimal process for each cement type, the method of trial and error was used. The cement:sand:aggregate proportion of 1:1:1.5 and water/cement ratio of 0.50 were employed. The optimal process of microwave curing was defined as a microwave curing process that provided high early-age and later-age strength with a minimum amount of applied microwave energy [4]. The processing parameters affecting the optimal process were (1) application time after mixing, (2) duration of application, (3) early-age test time and (4) microwave power.

Leung and Pheeraphan [4] and Pheeraphan [5] found an optimal microwave curing process for concrete, cast with rapid-hardening Portland cement, to gain both high early-age and later-age strength, compared to later-age strength of concrete cured normally. The processing parameters included an application time after mixing of 30 min, an application duration of 45 min, an early-age test time of 4.5 h and an average microwave power below 400 W. However, since the number of specimens heated in the microwave oven and the type of microwave oven used in their works were different from those used in this study, some parameters affecting the optimal process needed to be modified. Here, for both cement types, the application time after mixing for 30 min and the application duration of 45 min were employed while the microwave power and the early-age test time needed be determined.

To determine both parameters, the method of trial and error was used. Firstly, the early-age test time was arbitrarily fixed, while the microwave power was varied, to determine the optimal power. This was because for each experimental setup, i.e., when different types/brands of microwave ovens or different sizes, shapes and numbers of heated specimens were used, the appropriate microwave curing power for concrete was more difficult to determine, while the early-age test time could be set approximately based on previous works. Then, using the determined optimal microwave power, the early-age test time was varied and the most appropriate time could be determined.

3.1.1. Concrete with rapid-hardening Portland cement

To determine the power, the early-age test time was fixed at 4.5 h as high early strength could be measured at 4.5 h in previous work (Leung and Pheeraphan [4] and Pheeraphan [5]). Five different microwave power levels were investigated and compared as listed below:

Case 1: power at P20 (198 W)
Case 2: power at P30 (275 W)

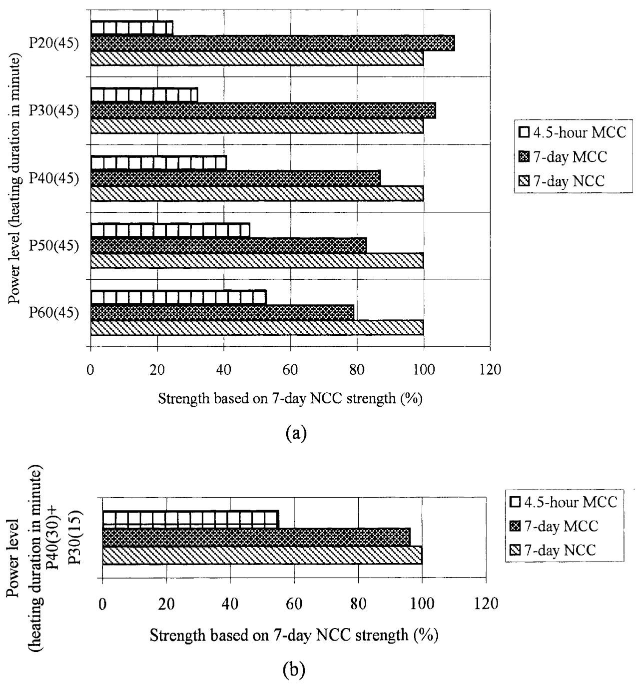

Fig. 1. Effect of microwave power application on compressive strength of concrete with rapid-hardening Portland cement; C:S:A = 1:1:1.5 and W/C = 0.50.

Case 3: power at P40 (362 W)
Case 4: power at P50 (396 W)
Case 5: power at P60 (543 W).

For each case, the early-age compressive strength (at 4.5 h) and the later-age strength (at 7 days) were measured and compared with the 7-day strength of normal-cured specimens. The results for all cases were shown in Fig. 1a. In the figure, it could be noticed that when the applied power level increased from P20 to P60, the 4.5-h accelerated strength increased from 25% to 53% of the 7-day strength of NCC, while the 7-day strength of microwave-cured concrete (MCC) decreased from 109% to 79% of the 7-day strength of NCC. The explanation could be that for microwave-cured specimens, high early strength could be obtained owing to the effect of accelerated cement hydration, but later strength could be reduced enormously due to the effect of the increased porosity and microcracking from overheating.

By the definition of the optimal process mentioned above, it was obvious that the optimal power should be between P40 and P30 for 45-min heating (see Fig. 1a). Therefore, to obtain the optimal power that consumed less power, the combination of power levels between P40 and P30 should be investigated. Pheeraphan [5] reported that for the microwave curing process, higher power should be applied during the early heating period because an application of relatively high heating power at the early period, especially during the plastic stage, could accelerate hydration advantageously. During the plastic stage, microwave application could remove free water before setting, leading to low permeability [7] and high early-age and later-age strength [4,5]. After this high-power application period, the network structure of concrete began to form so it was preferable to apply low heating power from this point forward. Hence, it should be advantageous to arbitrarily apply a combination of power levels at P40 and P30 power for 30 and 15 min, respectively, to determine the optimal power. The results in Fig. 1b showed that its 4.5-h accelerated strength was as high as 55%, while the 7-day strength of MCC was at 96% of normally cured concrete. It should be noticed that the hybrid heating power caused a higher percentage of early strength based on the 7-day strength of normally cured concrete, compared to the results of cases of single heating power at P30 and P40, which were at 32% and 40%, respectively. This is probably due to the effect of an application of relatively high heating power at the early period, followed by a lower heating power, as explained above. Therefore, the combination of P40 for 30-min heating and P30 for 15-min heating was considered to be optimal among the cases studied here.

The early-age test time was initially set at 4.5 h. After the optimal power was obtained, the best early-age test time needed to be determined. Using the determined power level at P40, for 30-min heating, and P30, for 15-min heating, four different early-age test time values were investigated and compared. Fig. 2 showed that the accelerated strength values at 3, 3.5, 4 and 4.5 h were about 24%, 40%, 44% and 55%, respectively, of the 7-day strength of concrete cured normally. It should be noticed that the rate of strength development was highest during the period of 3–3.5 h and became lower after 3.5 h. Since the strength at early age was very sensitive to small variations in time during the first few hours, it was therefore advantageous to select the early-age test time to be at the point whose rate of strength development was not too high. Thus, the earliest test time should be at 3.5 h among the cases studied.

To conclude, the optimal microwave curing process for rapid-hardening Portland cement consists of the processing parameters as shown in Table 1.

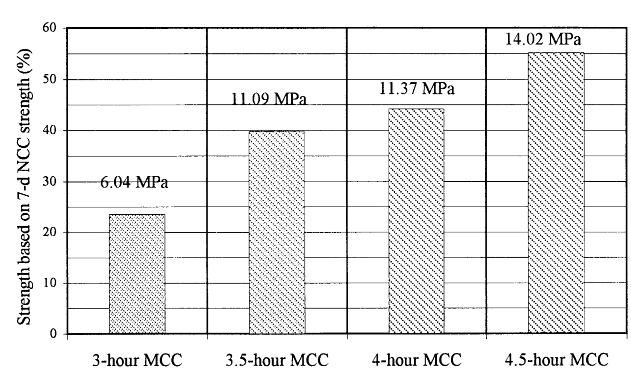

Fig. 2. Effect of microwave power at P40(30) + P30(15) on compressive strength of concrete with rapid-hardening Portland cement; C:S:A = 1:1:1.5 and W/C = 0.50 at different early ages.

Table 1
Determined processing parameters affecting the optimal microwave curing process for rapid-hardening Portland cement

Number	Processing parameters	Determined value
1	Application time after mixing	30 min
2	Duration of application	Total 45 min
3	Microwave power	P40 (for 30-min heating) + P30 (for 15-min heating)
4	Early-age test time	3.5 h

3.1.2. Concrete with ordinary Portland cement

To determine both microwave power and early-age test time for this cement type, a similar approach as in Section 3.1.1 was employed. It should be noted that due to the time limit here, the later age was set at 14 days instead of 28 days for determination of both parameters affecting the optimal process. This is truly valid because in order to determine these parameters, the accelerated early-age and later-age strength values of MCC are compared to the later-age strength value of NCC. Normally, for concrete produced with ordinary Portland cement, its 14-day strength is about 80% or more of the 28-day strength.

Since the preliminary test indicated that the strength of concrete made with ordinary Portland cement could be measured at 6 h, the early-age test time was fixed at 6 h. Five different microwave power levels (same as in Section 3.1.1) were investigated and compared. For each case, the early-age compressive strength (at 6 h) and the later-age strength (at 14 days) were measured and compared with the 14-day strength of normal-cured specimens. The results were shown in Fig. 3a. In the figure, it could be noticed that when the applied power level increased from P20 to P60, the 6-h accelerated strength increased from 18% to 40% of the 14-day strength of normal-cured specimens, while the 14-day strength of microwave-cured specimens decreased from 102% to 68% of the 14-day strength of normal-cured specimens. The explanation was similar to that for rapid-hardening Portland cement. Again, it was obvious that the optimal power should be between P40 and P30 for 45-min heating (see Fig. 3a). A similar combination of power levels at P40 and P30 power, for 30-and 15-min heating, respectively, was tested for optimal power. The results in Fig. 3b showed that its 6-h accelerated strength was at 39%, while the 14-day strength of MCC was at 96% of normally cured concrete. Therefore, the combination of P40, for 30-min heating, and P30, for 15-min heating, was considered to be optimal among the cases studied here.

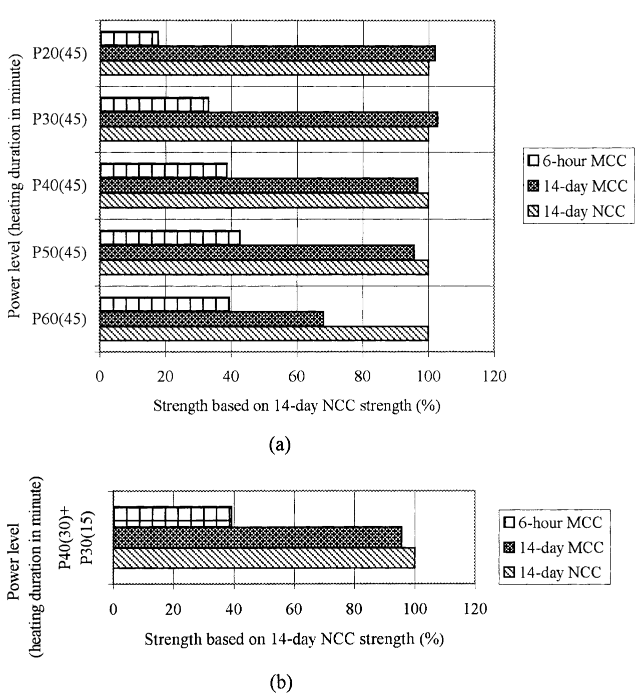

Fig. 3. Effect of microwave power application on compressive strength of concrete with ordinary Portland cement; C:S:A = 1:1:1.5 and W/C = 0.50.

Since the early test time was initially set at 6 h, the possible early test time needed to be determined after the optimal power was obtained. Using the determined power level at P40, for 30-min heating, and P30, for 15-min heating, three different early test time values were investigated and compared. Fig. 4 showed that the accelerated strength values at 5, 5.5 and 6 h were about 28%, 34% and 39%, respectively, of the 14-day strength of concrete cured normally. It should be noticed that the rate of strength

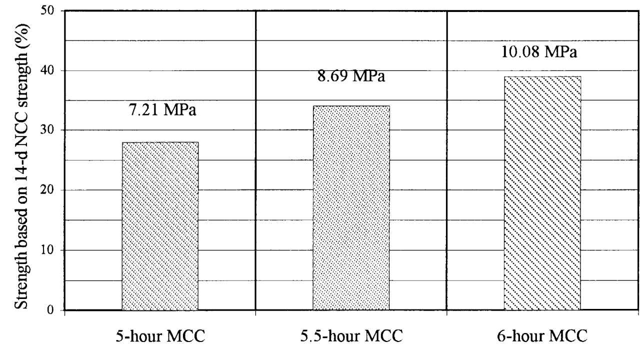

Fig. 4. Effect of microwave power at P40(30) + P30(15) on compressive strength of concrete with ordinary Portland cement; C:S:A = 1:1:1.5 and W/C = 0.50 at different early ages.

Table 2
Determined processing parameters affecting the optimal microwave curing process for ordinary Portland cement

Number	Processing parameters	Determined value
1	Application time after mixing	30 min
2	Duration of application	Total 45 min
3	Microwave power	P40 (for 30-min heating) + P30 (for 15-min heating)
4	Early-age test time	5.5 h

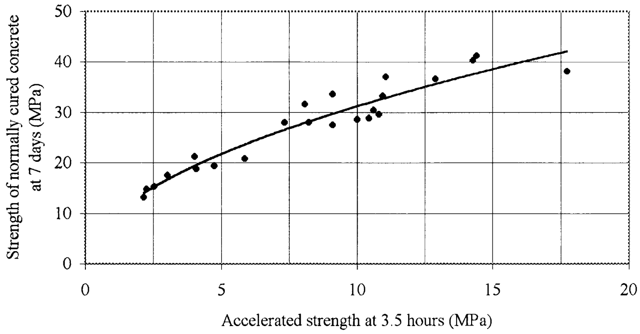

Fig. 5. A relation between strength determined by accelerated curing and 7-day strength of normally cured concrete with rapid-hardening Portland cement.

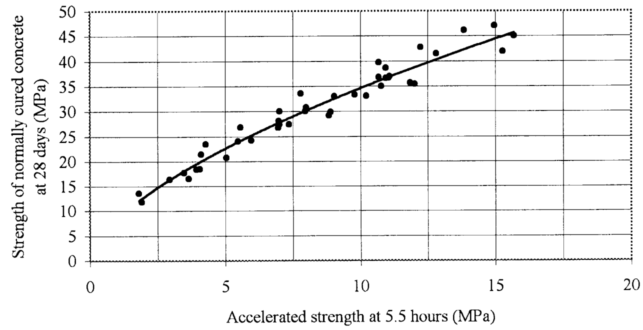

Fig. 7. A relation between strength determined by accelerated curing and 28-day strength of normally cured concrete with ordinary Portland cement.

development was highest during the 5–5.5 h among these cases and became lower after 5.5 h. Thus, the earliest test time was considered to be at 5.5 h among the cases studied.

To conclude, the optimal microwave curing process for ordinary Portland cement consists of the processing parameters as shown in Table 2.

3.2. Relationship between the accelerated early-age strength and the later-age strength of normally cured concrete for later-age strength prediction

After all processing parameters affecting the optimal microwave curing process for each cement type were determined, the optimal process was applied to several concrete mixtures with different mix proportions. The accelerated early-age strength and the later-age strength of normally cured concrete were then measured and compared to establish a relationship for later-age strength prediction.

An equation for later-age prediction was determined for each cement type. The applicability of the equation to later-age strength prediction was assessed by considering the difference between the predicted and the measured values.

3.2.1. Concrete with rapid-hardening Portland cement

The possible early testing age for this cement type was found to be at 3.5 h, while the later age was selected at 7 days. To derive an equation for later-age strength prediction, the accelerated strength at 3.5 h and the later-age strength at 7 days were plotted and compared.

Fig. 5 shows a plot of the accelerated strength at 3.5 h of MCC, and the 7-day strength of normally cured concrete. From the plot, the following equation can be obtained as:

$$S_{7d-NCC} = 9.3912*(S_{3.5h-MCC})^{(0.5220)} \tag{1}$$

where $S_{3.5h\text{-}MCC}$ is accelerated strength at 3.5 h (MPa) and $S_{7d\text{-}NCC}$ is strength of normally cured concrete at 7 days (MPa).

Once the accelerated strength at 3.5 h is measured experimentally, Eq. (1) is used to predict the 7-day strength of normally cured concrete. For the range of 7-day compressive strength between 13 and 41 MPa, it was found that the maximum percentage of error was within ±13%. Fig. 6 showed the measured and predicted compressive strength at 7 days.

3.2.2. Concrete with ordinary Portland cement

For ordinary Portland cement, the possible early testing age was found to be at 5.5 h, while the later age was set at 28 days. To derive an equation for later-age strength prediction, the accelerated strength at 5.5 h and the later-age

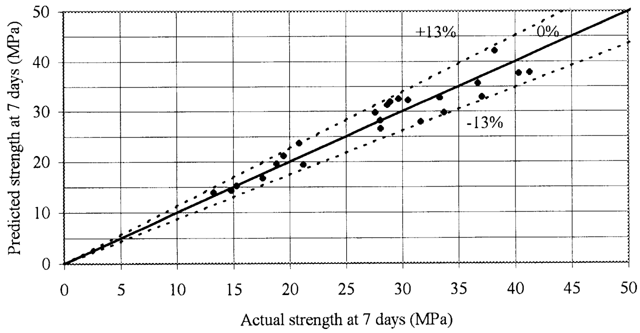

Fig. 6. Comparison of 7-day predicted compressive strength obtained from prediction vs. actual strength at the same age.

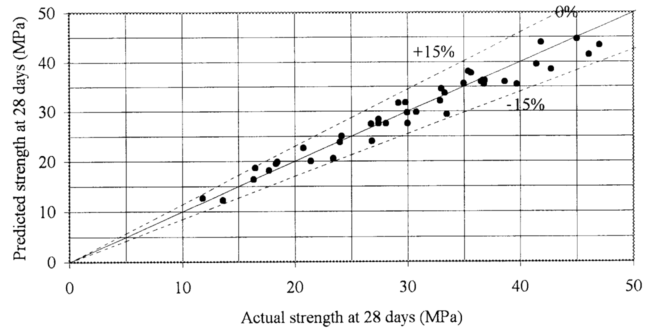

Fig. 8. Comparison of 28-day predicted compressive strength obtained from prediction vs. actual strength at the same age.

strength at 28 days were measured and plotted (Fig. 7). From the figure, the following equation can be derived as:

$$S_{28d-NCC} = 8.5459*(S_{5.5h-MCC})^{(0.6003)} \quad (2)$$

where $S_{5.5h\text{-}MCC}$ is accelerated strength at 5.5 h (MPa) and $S_{28d\text{-}NCC}$ is strength of normally cured concrete at 28 days (MPa).

Eq. (2) can be used to predict the 28-day strength of normally cured concrete once the accelerated strength at 5.5 h is measured. Similarly, it was found that the maximum percentage of error was within about ±15% for the range of 28-day compressive strength between 11 and 47 MPa. Fig. 8 showed the measured and predicted compressive strength at 28 days.

4. Discussion

The concept of using the microwave curing technique in later-age strength prediction is to apply an optimal microwave curing process to concrete mixture to achieve high strength in a short period of time, while minimizing the reduction in later-age strength. The formula for later-age strength prediction can be derived from the relationship between the accelerated early-age strength values and the later-age strength values. The accuracy of this prediction method significantly relies on several factors such as source of cement, type of aggregates and microwave curing process. Therefore, it is necessary to carry out the preliminary test to establish a formula to predict later-age strength for concrete made with known materials before using this prediction method.

It is obvious that the crucial task for this method is to determine the optimal microwave curing process. Four processing parameters affecting the optimal process were investigated for each cement type. It was found that the early-age test time was different for each type of cement, while the rest of the parameters were the same. For rapid-hardening Portland cement, the possible early-age test time was only 3.5 h after mixing, while it was 5.5 h for ordinary Portland cement. This is because concrete with rapid-hardening Portland cement can develop higher early strength during early age than concrete with ordinary Portland cement. For both cement types, the optimal power was at P40, for 30-min heating, and P30, for 15-min heating, and the application time after mixing was at 30 min.

After the determined optimal microwave curing process was applied to several concrete mixtures with different mix proportions, their accelerated strength values could be used to establish a relationship with the later-age strength values of concrete cured normally. The plots in Figs. 5 and 7 showed that a good relationship between the accelerated strength and the later-age strength could be obtained. A simple formula for prediction could then be derived for each cement type.

The results of the comparison of measured and predicted compressive strength in Figs. 6 and 8 showed that for the range of compressive strength between 11 and 47 MPa, the prediction yielded a percentage of error within about ±15%. It shows that the microwave curing technique has high potential for later-age strength prediction based on strength values measured at an early age.

A similar approach can also be applied to concrete with any chemical admixture, except that determination of processing parameters affecting optimal process must be carried out again. However, a new parameter must be introduced in place of an application time after mixing, since chemical admixture can significantly affect the setting and hardening time of concrete, resulting in different rates of strength development of concrete. Current work in developing such a technique is under investigation and the result will be available soon.

According to the American standard, the compressive strength at 28 days of 152.4 × 304.8 mm cylinder is usually required. It was found here that the average strength value of 76.2 × 152.4 mm cylinder used throughout this work was about 106.8%, compared to that of the standard-sized cylinder. Hence, the correction factor of 0.936 must be multiplied to the strength value obtained from a 76.2 × 152.4 mm cylinder to compare with the strength value of the standard-sized cylinder.

5. Conclusion

Using the microwave curing method, it is possible to predict the later-age strength of normal concrete from compressive strength test, performed as early as 3.5 and 5.5 h for rapid-hardening and ordinary Portland cement, respectively. For each cement type, the prediction using a formula derived from the relationship between the accelerated early-age strength and the later-age strength of NCC is within 15% of experimentally measured values.

Acknowledgments

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