d) Minimum C/S of 1:2; and
e) Initial surface absorption test values of the hardened slab to have ISAT values less than:

Time (min)	10	30	60
ISAT Value (mi/m^2/s)	0.100	0.055	0.035

The preliminary study reported herein focuses on tests carried out to study the early age strength development and some quality control and durability-related characteristics of the mortar used and the precast ferrocement secondary roofing slabs, when subjected to microwave curing. This preliminary study is divided into two phases. The first phase involves casting and testing of mortar cubes using a domestic microwave oven. Several mixture proportions and methods of microwave application were used and surface temperatures were measured using infrared thermometers. The second phase involves casting and testing of prototype ferrocement secondary roofing slabs using an industrial microwave curing system. Several heating rates are employed. These preliminary tests were to:
a) Check suitability of typical mixture proportions;
b) Observe strength development at early ages up to 7 days;
c) Determine suitability of quality control tests involving cubes; and
d) Determine suitability of quality control tests using prototype precast slabs

<u>Microwave curing of specimens</u>

(1) Domestic microwave oven

Before actual tests were carried out, several preliminary trials were conducted. A domestic microwave oven was used. Due to its size only one cube specimen could be cured at a time. The oven was equipped with a turntable for uniform heating and has a constant power level of 900 W with a 0.07 m^3 curing chamber.

The maximum power level of the domestic microwave oven used is 900 Watts. However, this may be applied continuously or intermittently. For comparisons between duration of microwave curing, it is desirable to use total energy absorbed. Thus with 900 Watts microwaving continually for 4 minutes, the 100 mm mortar cube placed within the oven would consume 216 kJ energy. When the intermittent method of application is used, the microwave energy may be applied in cycles, say 11 seconds on and 14 seconds off followed immediately by another cycle of 11 seconds on and 14 seconds off and so on. This cycle could be continued until the desired time, say 9 min 10 sec (22 cycles) is reached. This would use up the same amount of energy (216 kJ) as before, but of course the total time duration for processing of the cube specimen is longer. Another regime of this intermittent method of application may also be used to allow the cube specimen to cool down before the next cycle begins. This would involve the removal of the cube from the oven between cycles to cool under indoor ambient conditions. In summary, the three regimes of microwave curing employed with the domestic microwave oven were:

a) Method D_1: Continuous application at 900 Watts for the desired time duration;
b) Method D_2: Intermittent application without cooling down period (900 Watts on for 11 seconds and off for 14 seconds. This cycle repeated for the desired number of times) with the specimen remaining inside the oven over the entire curing regime; and
c) Method D_3: Intermittent application with cooling down period. (Continuous application at 900 Watts for 3 minutes followed by air cooling of the specimen outside the oven for one hour. This cycle was repeated for two or three cycles).

(2) Industrial microwave curing system

A large 6 kW industrial microwave curing system with a 0.75 m^3 curing chamber was used for the second phase of testing (Fig. 1). The specimens to be subjected to microwave curing were fed into the oven one by one using a conveyor system. Appropriate power levels may be applied by operating the curing system at various power levels up to 6 kW for various time intervals as desired. The energy consumed would have to take into account the volume of the specimen placed within the chamber. The chamber can accommodate up to three 900 mm x 600 mm x 20 mm ferrocement slab specimens, but only one specimen was cured in the oven at any one time in the present study. An infrared thermometer was used to measure the surface temperature. Two methods of microwave applications were used as floows:

a) Method I_1: Microwave power level was kept constant at 5400 W and applied continually for various time duration up to 20 minutes.
b) Method I_2: Lower power levels were employed for different time durations such that the total absorbed energy consumed remained constant.

Compressive Strength Test

Testing was done to study the effects of curing time. Test specimens were microwave-cured for various times using Method D_1 from 3–6 minutes. Method D_3 was also used for two and three cycles of microwave application. The compressive strength tests were performed using 100 mm mortar cube specimens cast with a mortar mixture of 2.5 of sand and one of cement with a W/C of 0.42. Type I portland cement that is commonly available was used. The test specimens were cast using specially fabricated perspex moulds. The perspex moulds have good thermal stability up to about 100°C, and are transparent to microwave. The cube specimens were compacted using a vibrating table and left at ambient conditions in the laboratory for 30 minutes before first being exposed to microwave curing. Specimens not subjected to microwave curing were also tested for comparison. For compressive strength tests conducted at less than 7 days, all the specimens including the normal cured specimens tested were kept at indoor ambient laboratory conditions until they were tested. Specimens tested at 7 days were demoulded after 24 hrs, and left in water for 6 more days.

Modified Los Angeles Abrasion Test

As mentioned previously, breakage of corners during demoulding and handling may give rise to potential problems. It was decided to use the modified Los Angeles Abrasion Test to evaluate the susceptibility of microwave cured cubes to this problem by subjecting 100 mm cube specimens to surface and corner degradation by placing one cube specimen at a time in a rotating steel drum. The steel drum was adjusted to rotate at a speed of 30 to 33 revolutions/min with only one mortar cube placed inside. At the end of each 200 revolutions the specimen was retrieved. brushed to remove loose particles and weighed to determine the percentage weight loss. After weighing, the cube specimen was replaced and the drum rotated again. This was repeated until 1000 revolutions of the drum was completed. Six specimens were cast using the same mixture proportions. Three were microwave cured and the other normal cured. For microwave cured specimens, method D_2 was used with the cycle repeated continuous for total time duration of 9 min 10 sec. All specimens were demoulded after 24 hrs and cured in water for a further 6 days. After which they were air dried at indoor ambient laboratory conditions until they were tested at 28 days.

Initial Surface Absorption Test

One of the quality control tests used at present for conventionally precast ferrocement secondary slabs is the Initial Surface Absorption test (ISAT). This test is described in BS1881: Part 5:1970. The test was carried out directly on the surface of the slabs and served to indicate the rate of flow of water per unit area into the specimen through the surface after various time intervals from the start of the test under constant applied head (200 ± 20 mm of water) and at a temperature of 27 ± 2°C. The specimens were cast using a mortar mixture of two of sand to one of cement and a W/C of 0.45. The industrial microwave curing system was used for the microwave curing of the slab specimens. In the first series of specimens, ferrocement slabs were cured using a microwave power level of 5400 Watts (Method I_1). The mortar was mixed for 10 minutes using a planetary-type mixer and then placed into the moulds. The specimens were then vibrated for compaction. The application of microwave began 30 minutes after the water was added to the sand and cement mixture. The specimens used for the ISAT comprise 4 types, viz.,

a) Specimens subjected to method I_1 microwave curing;
b) Normal cured specimens;
c) Specimens subjected to method I_2 microwave curing; and

d) Specimens with commercially available powder curing compound (CC) had the compound sprinkled on the top of the slab after trowelling (1.5 kg/m^2) followed by microwave curing.

After microwave exposure the slabs were taken out of the chamber and covered with a thin plastic sheet to reduce further moisture loss from the surface of the slab. All slabs including the normal cured slab were demoulded after 1 day and were kept in the fog room for three days. Thereafter they were air-dried at indoor ambient laboratory conditions until the ISAT was performed after 28 days.

Patch Load Test

The patch load test has been used as a quality control test for precast ferrocement secondary roofing slabs. Previous use of the test involved ferrocement secondary roofing slabs of a slightly different size and design. A minimum ultimate load was specified and the ultimate loads of a number of slabs selected from each batch of precast ferrocement secondary roofing slabs tested, should not fall below this value. This quality control test is no longer being used. The ultimate load previously specified is also not applicable to the present design of ferrocement secondary roofing slab. However, for the present investigation it was decided to carry out this test on the prototype slab specimens cast using the industrial microwave curing system. Specimens used for the patch load tests were the same ones that were subjected to the ISAT. Thus the age of the specimens were about 30-32 days.

The slabs are simply supported at all four corners and tested to failure under a central patch load of size 125 mm x 125 mm. The corners were not restrained. The maximum load sustained by slabs was recorded. All the slab specimens tested have the same amount of reinforcement at nominally the same cover. After the patch load tests, the specimens were cut along the failure section and the actual position of reinforcement at this section noted. Slab thicknesses at the failure sections were also measured. From the slab thickness, effective depth of reinforcement and the 28-day compressive strengths of the mortar cube, the theoretical ultimate moment capacity of each slab was calculated.

RESULTS AND DISCUSSION

Early Age Strength Development

The results of the compressive strength tests are shown in Fig. 2. Each result is an average of 2 specimens. As expected the normal cured mortar cubes did not developed significant strengths when tested 3-7 hours after casting. It may be observed that except for the 3 minute microwave cured specimens, all the other specimens developed considerable strengths (>12 Mpa), only 5 hours after casting. All mortar cubes showed similar strengths one day after casting, but the 7-day strengths of all the microwave cured specimens are lower than that of normal cured specimens. This may be due to the heating rate used in the experiment which was relatively rapid compared to the method used by Wu *et al* (3). These results indicate that the 7-day strength is sensitive to very rapid heating at an early age particularly when the temperature reached by the mortar specimen is high. The surface temperature of all the mortar cubes tested exceeded 70°C except for the 3 min and 4 min microwave cured specimens. The temperature reached more than 90°C in some cases. Thus the 7-day strength obtained agrees with findings by Leong and Pheeraphan (7) who noted that when temperatures reach more than 65°C, cracks and fissures could be generated caused by the escape of steam from the surface of the specimens. It should be pointed out that in the present specimens no surface fissures were noted although a slight bulging of the trowelled surface of the specimen was noted.

The results also indicate that allowing the specimens to cool down in between short cycles of microwave application (Method D_2) yielded compressive strengths very similar to those achieved by specimens subjected to method D_1 (except for the specimen subjected to 3 min-continuous). The normal cured specimen showed dramatic strength increase beyond 1-day and showed the highest 7-day strength after being cured for a further 6 days under water. After microwave curing, the 6 days of water curing resulted in all the microwave cured specimens showing very similar compressive strength at 7-day age.

Modified Los Angeles Abrasion Test

Results obtained after subjecting 100 mm mortar cubes to corner and surface degradation by the modified Los Angeles Abrasion Test are shown in Fig. 3. The normal cured cube specimens show a distinct trend of increasing weight loss after 1000 revolutions of the drum as the W/C was increased from 0.42 to 0.55. The microwave cured specimens (method D_2), on the other hand, show generally the same amount of weight loss regardless of the W/C. This could be accounted for by the fact that free water loss from the cube specimen tested are roughly similar since all the specimens were subjected to the same microwave curing regime (method D_2) resulting in very similar pore structure on the surface and near surface zones. The marginally higher weight loss (1%) of the latter compared to the normal cured specimen could be easily reduced by using a method of microwave curing that causes less rapid temperature rise than the method employed here (method D_2).

Heating Rate and Surface Temperature variation

In the present investigation, an infrared thermometer was used to monitor only the surface temperatures of the specimens. It is generally agreed that too rapid a rise in temperature is detrimental to the mechanical properties of the specimen. For the ferrocement slabs tested when method I_1 was used for time durations of 10, 15 and 20 mins, the maximum surface temperature recorded reached 55, 60 and 65°C respectively (Fig.4). These temperatures were below those of cubes. Fig. 5 summarizes the results obtained for specimens subjected to method I_2 of microwave curing. The lower the power the lower the peak surface temperature attained.

Initial Surface Absorption

As shown in the Fig. 6, the ISAT values are higher than the specified values for the first set of ferrocement roofing slabs. This indicated that specimens subjected to method I_1 performed worse than normal cured specimens. This is caused by the relatively fast temperature rise and higher peak temperature attained probably causing a higher degree of porosity, coarser pore size distribution, or the formation of microcracks. It should also be noted that the heating rate for these slabs ranged between 115 and 175°C/hour. For specimens subjected to method I_2 when lower power was used and the microwave power and application time varied such that the total forward energy remained constant, ISAT values were significantly reduced. These are shown in the Fig. 7. As shown, the absorption values of all six slabs tested were lower than values specified for ferrocement secondary roofing slabs. It may be observed that the 2700W-30min slab and 4000W-20min slab show the lowest ISAT values. However the surface of the 4000W-20min slab was not fully set after completion of the microwave exposure and time had to be allowed for full set to occur before demoulding. Application of curing compound (CC) on the surface of the slab did have much effect on ISAT values compared to the normal cured specimen. In fact, marginally higher ISAT values were observed compared to the specimen without CC (Fig. 7). It can be observed from Fig. 7 that the 1800W-45min slab specimen showed the highest ISAT values for all the slabs tested in this series. Thus when the microwave exposure time is excessive, it is probable that more moisture will be lost from the exposed trowelled surface during microwave application. This would affect the quality of the exposed surface.

Ultimate Load-carrying Capacity of Prototype Slabs under Patch Load

Prototype slab specimens were subjected to patch load tests at ages of more than 28 days. The theoretical ultimate moment capacity of each slab was calculated and the results are summarized in Table 1 together with the experimental values of ultimate load. The theoretical values took into account the cube strength (28 day), position of the reinforcement and thickness of the slab. Typical load-deflections of each slab under patch load tests are shown in Fig. 8. Their first crack load ranged from 0.9 kN to 1.5 kN and ultimate loads ranged from 3 kN to 4.5 kN. The theoretical ultimate load capacities based on yield line analysis of the slabs supported on four unrestrained corners are much lower than the experimental values. All the specimens tested failed in flexure mode as modeled with high ductility.

Since secondary roofing slabs are used as non-structural elements when placed on rooftop, a typical value of the ultimate load (concentrated load applied at the centre of the slab) is 2.35 kN. This incorporates a live load factor of 1.6. It may be observed that all the specimens tested failed at ultimate load values well above this.

CONCLUSIONS

From the results obtained from this study it is concluded that microwave curing can enhance the early age strength development of mortars without affecting the long-term performance. Also from the modified Los Angeles abrasion tests carried out, it can be concluded that compared to the normal cured specimens the near-surface quality is marginally poor for microwave cured cube specimens. The ISAT and patch load tests show that the current mix design is suitable for microwave curing of ferrocement secondary roofing slabs, but heating regimes should be carefully selected for better performances.

REFERENCES

(1) Alunno-Rossetti, V., G. Chiocchio and M. Collepardi, Cement and Concrete Research, Vol. 6, 1974, pp 279 – 298.

(2) Alexanderson, J. "Behaviour of Concrete under Temperature Extremes" SP 39-7, ACI Special Publication, SP39, Detroit, Michigan, 1973.

(3) Wu, X., J. Dong, and M. Tang, "Microwave curing Technique in Concrete Manufacture", Cement and Concrete Research, Vol. 17, 1987, pp. 205-210.

(4) Mak, S. L., G. Shapiro, and T. Son, "Accelerated Heating of Concrete with Microwave Curing", Proc. 4th CANMET/ACI/JCI Int. Conf. on Recent Advances in Concrete Technology, Malhotra, V. M. (ed.), Tokushima, Japan, June 1998, pp.531-542.

(5) Mak, S.L. "Microwave Accelerated Processing for Precast concrete Production", Proc.4th CANMET/ACI Int. Conf. on Recent Advances in Concrete Technology, Malhotra, V. M. (ed.), Tokushima, Japan, June 1998, pp.709-720.

(6) Watson, A. "Curing of Concrete", Microwave Power Engineering, Okress, E.C. (ed.), Academic Press, New York, 1968.

(7) Leong, C.K. and T. Pheeraphan, "Microwave curing of Portland Cement Concrete: Experimental Results and Feasibility for Practical Applications", Construction and Building Materials, Vol. 9, No. 2, 1995, pp. 67-73.

(8) Della Bella, B., G. Della Bella, S. Lai, and M. Pinna, "Application of Microwaves for the Hyperaccelerated Curing of Concrete", Proc. Fourth International Symposium on Noteworthy Development in Prestressing & Precasting, Singapore, July 1997, pp.38-43.

(9) Donggy S. and D. Lynn, "Microwave Curing Effects on the 28-day Strength of Cementitious Materials", Cement and Concrete Research, Vol. 29, 1999, pp. 241-247.

Table 1 Theoretical and experimental ultimate load carrying capacities of ferrocement slabs under patch loading

Specimen	$P_{u,theo.}$ (kN)	$P_{u,exp.}$ (kN)	$P_{u,exp}/P_{u,theo}$
normal cured-1	1.93	3.78	1.95
precaster's-1	1.80	2.93	1.63
5400W-10min	1.65	2.93	1.78
5400W-15min	2.34	3.59	1.53
5400W-20min	1.98	3.26	1.65
normal cured-2	1.80	3.67	2.03
1800W-45min	1.92	3.47	1.81
2700W-30min	1.86	4.48	2.41
3000W-27min	1.86	3.73	2.01
4000W-20min	1.97	3.15	1.60

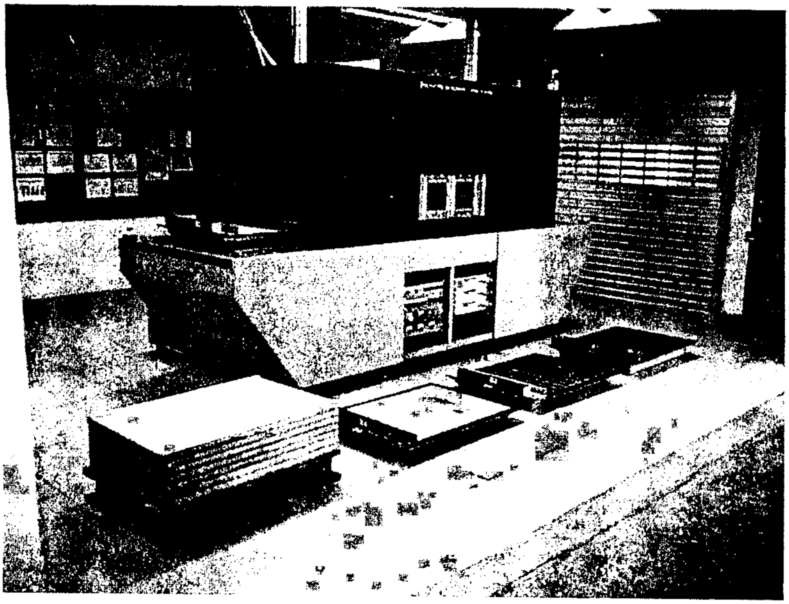

Fig. 1 Industrial microwave curing system

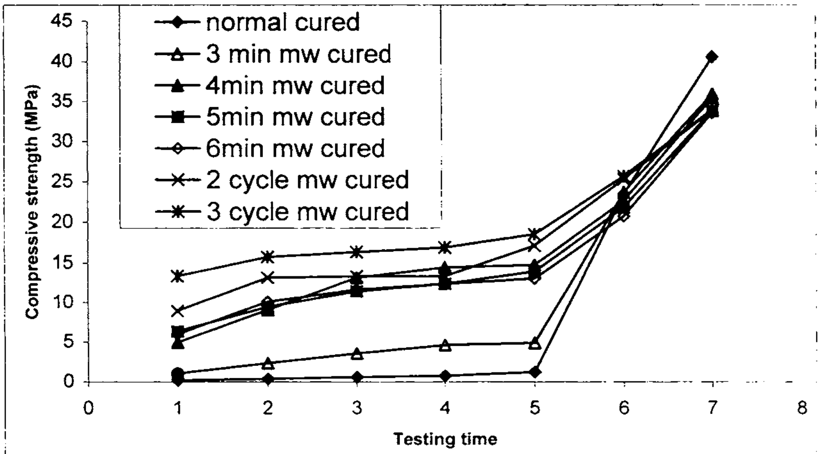

Fig.2 Compressive strength of mortar cubes

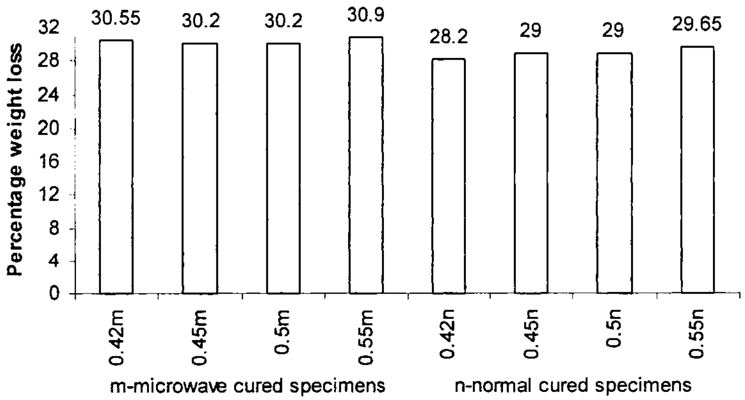

Fig.3 Percentage weight loss after 1000 revolutions
S/C = 2.0

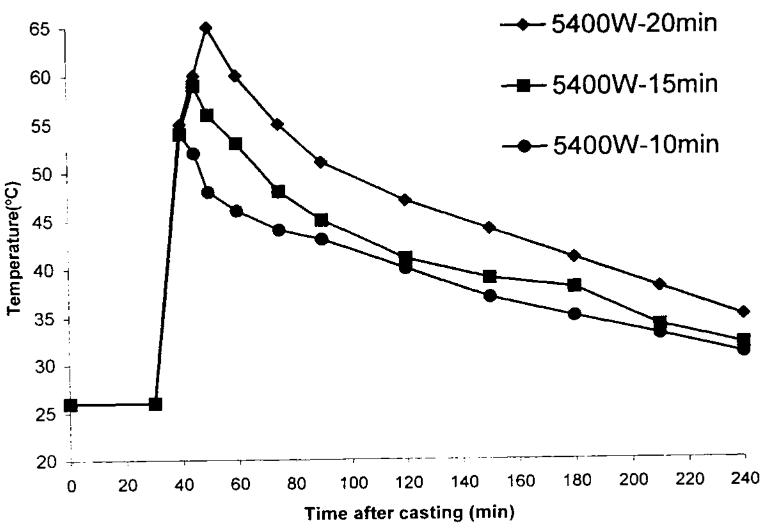

Fig.4 Variation of surface temperature with time for various microwave cured ferrocement slabs-1