PILOT STUDY ON USE OF INFRARED OVEN FOR DETERMINATION OF SOIL MOISTURE CONTENT

GEO REPORT No. 301

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THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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PREFACE

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H.N. Wong
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September 2014

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FOREWORD

A pilot study was initiated by the Public Works Central Laboratory (PWCL) to investigate the feasibility and practicability of using the infrared heating technique for carrying out routine moisture content tests. The results revealed that the moisture content tests of most of the common fill materials in Hong Kong could be completed within 3½ hours, which could facilitate the early determination of relative compaction and hence the progress of filling works. The findings indicate that the infrared heating technique appears to be promising as a possible alternative to the conventional method of using a convection oven.

The study was carried out by Mr Thomas H.H. Hui under the supervision initially of Mr Rick C.K. Tam and later Dr H.K. Tam. Mr Jeffrey K.S. Lau and Mr W.C. Leung assisted in designing the infrared oven and carrying out the calibration tests. All contributions are gratefully acknowledged.

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ABSTRACT

A pilot study was conducted in the Public Works Central Laboratory (PWCL) to investigate the feasibility and practicability of using the infrared heating technique for carrying out routine soil moisture content tests. A total of 180 moisture content tests involving ten different soil samples were undertaken using an infrared oven. A power control device was developed to regulate the temperatures of soil specimens within the oven throughout the drying process. Only one out of 1,400 measurements (< 0.1%) showed that the temperature of the soil specimen exceeded the threshold value of 110 ^{o}C by 1.5 ^{o}C for about 5 minutes in the drying process.

Two sets of comparative tests were carried out to investigate the accuracy of both the infrared drying method and the conventional method using a convection oven. The findings indicated that there was virtually no difference in the test results between these two methods.

The findings of the pilot study indicate that the moisture content test of the vast majority of the commonly used fill materials in Hong Kong could be completed within 3½ hours, which could facilitate the early determination of relative compaction and hence the progress of filling works. The infrared heating technique appears to be promising as a possible alternative to the conventional method of using a convection oven.

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CONTENTS

1. INTRODUCTION

Relative compaction (RC) is a compliance test for checking of the density of filling materials (HKSARG, 2006) and is a core service of the Public Works Regional Laboratories (PWRL). Moisture content is one of the key parameters for determining the RC. The standard testing method for determination of moisture content of soils in Hong Kong is given in Geospec 3 – Model Specification for Soil Testing (GEO, 2001). The method is based essentially on the use of a traditional convection oven operating at a temperature of 105±5 °C (or 45±5 °C, depending on the types of soil samples tested). A drying time of at least 20 hours is usually needed and in general, the results of RC tests would only be available on the following day of the sampling, which is considered to be too time consuming for some construction projects (e.g. fill compaction works). A quicker and sufficiently accurate alternative means of determining the moisture content of soil would greatly facilitate the progress of fill compaction works.

Chung & Ho (2006) completed a study of using a microwave oven, instead of a convection oven, for determination of soil moisture content. It was established that the drying process could be completed within one hour. In addressing the issue of potential over-heating of soil specimens (i.e. exceeding the threshold value of 110 °C) during the drying process by microwave, two preventive measures were recommended: (a) the time of each drying cycle was recommended to be 5 minutes, and (b) stirring/mixing test specimens thoroughly achieve a more uniform heating to be carried out during each drying cycle. Implementation of these two measures, however, would have meant a notable increase in the workforce required for a test. This is unlikely to be practical for routine tests which involve a large number of tests per day.

A pilot study was conducted in the Public Works Central Laboratory (PWCL) to investigate the feasibility and practicability of using the infrared heating technique for the determination of the moisture contents of the soil specimens. Based on the testing requirements and the operational needs of the PWRL, the indicators adopted for assessing the overall performance of the infrared heating technique are as follows:

(a) time required for a test,

(b) temperature of soil specimens (i.e. not to exceed the threshold value of 110 °C during drying),

(c) workforce required for conducting a test,

(d) complexity of the testing procedure (i.e. whether or not stirring of the soil specimens is required during the drying process), and

(e) costs.

2. PRINCIPLES OF INFRARED HEATING TECHNIQUE

The discovery of infrared radiation (IR) is ascribed to William Herschel (Hoskin, 2008)

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in the early 18th century. With the use of a prism to refract light from the sun, it was noted that there was an increase in temperature at locations beyond the red light zone of the spectrum.

IR comprises electromagnetic radiation. Unlike thermal conduction and convection, the radiation propagates through a vacuum and then converts to heat upon absorption by a material. The energy loss during the transmission is low and hence the energy efficiency in heating is much better than that of the conduction or convection method. In recent years, IR has been used as a popular heat source in a number of industrial processes, e.g. curing of coatings, forming of plastics, print drying, etc.

The intensity of the radiation and the bandwidth of the emission spectrum are related to the temperature of the heat source. Figure 1 shows the spectral distribution of an ideal infrared source (often referred to as 'blackbody'). The temperature increase of the heat source will cause a shifting of the peak radiation to the left of the electromagnetic spectrum (i.e. a shorter wavelength and a higher frequency). It should be noted, however, that the heat source is made up of thousands of point sources, among which the temperature may be different. Each point source will have a local spectral distribution, the combination of which will make up the entire spectral distribution.

For the purposes of heating, maximum energy efficiency can be achieved if the peak output wavelength of the infrared source matches with the selective absorption band of the material being heated (i.e. resonance). The natural wavelength of a water molecule is close to that of intermediate and far IR (i.e. wavelength of 1 μm to 10 μm), indicating that IR is an effective heat source for water heating. A summary of the theory of infrared heating is given in Appendix A.

3. REVIEW OF CURRENT STANDARDS AND PRACTICES INVOLVING INFRARED HEATING

In 2005, the Australian Standard published a testing method, AS1289.2.1.5, for the rapid determination of moisture content using an infrared heating source (AS, 2005). The operational procedure of this infrared oven method is basically the same as that of the standard method based on the use of a convection oven. However, stirring/mixing of the soil specimens would have to be carried out at regular intervals to facilitate the evaporation process. According to the above Australian Standard, soil specimens are deemed to be dry and the test could be terminated if the difference between successive weights at 10-minute intervals is less than 0.1% of the initial wet mass. Unlike the conventional method that requires the convection oven to be operated at 105±5 °C, the infrared oven method as proposed in AS1289.2.1.5 does not have any specific requirements on the temperature control of the oven or soil specimens. The above Australian Standard also stated that the infrared oven method is presumed to be less accurate than the standard method and that results obtained using an infrared oven should be corrected to the standard method.

Sample size, initial moisture content and energy output from the infrared lights are the key factors affecting the time required for the drying process. Similar to the conventional method, the infrared oven method is not recommended for soils containing gypsum, calcareous material or organic matters. Some recommendations on the design of the infrared

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system are given in the above standard, such as the infrared light should be mounted horizontally at about 150 mm above soil specimens and that the power output of the infrared emitter is preferably 250 Watts.

4. DESIGN OF INFRARED OVEN

4.1 Selection of Infrared Heating Source

Infrared heat sources that are commonly available in the market are metal sheath, quartz tube, quartz lamp, catalytic, flat-faced panel and ceramic. The properties of these materials are presented in Table 1.

Ceramic heating panel was selected in this pilot study. The considerations of this selection were as follows:

(a) The radiant efficiency of ceramic panels is about 96%, which is the highest among the various types of heat sources.

(b) Ceramic is a very durable material and the life expectancy of the heating panel is over 10,000 hours. The cost per panel is only about HK$400.

(c) More variety in the size and power output of ceramic panels is available in the market. This will facilitate the design of an infrared heating oven for achieving uniform heating of soil specimens.

(d) The operating temperatures of ceramic panel are much lower than that of other infrared heat sources. This allows cyclic heating and cooling at a shorter time intervals (i.e. < 10 minutes), which is important in maintaining the temperature of the soil specimens to be within the optimum range of 100 °C to 110 °C.

Concave-shape ceramic panels (Plate 1) of size 245 mm x 60 mm were selected for this pilot study. However, infrared panels of power output of 250 Watts were temporarily out of stock at the time of the study and only 400 Watts and 600 Watts panels were available.

Infrared is a very weak radiation and has been widely used as a household heat source. The intensity of radiation emitted by a 400 Watts infrared panel during the course of drying was checked by a radiation measuring sensor (see Plate 2). The level of radiation was found to be extremely low such that it could not be detected by the sensor. Therefore, infrared radiation is considered to be a safe heating source for use in laboratory.

4.2 Oven Design and Layout of Infrared Panels

A disused convection oven was used in this pilot study (Plate 3). The heating

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elements within the oven were dismantled and the oven was virtually a steel cabinet. Rusted surfaces within the oven were covered with aluminum foil as far as possible (Plate 4) to improve the reflectivity of infrared radiation.

The oven could house a maximum of ten containers in two rows (see Plate 4). Instead of using standard steel containers, 'microwave acceptable' glass containers were used, thus allowing the soil specimens to absorb infrared radiation from all directions. Therefore, both the rate of heating and temperature uniformity of the soil specimens would have been improved. Infrared panels were mounted both above and below the glass containers. The clearance distance between the upper infrared panels and the glass containers was about 150 mm to allow adequate room for handling the soil specimens, whereas the clearance distance of the glass containers to the lower infrared panels was about 50 mm.

During the drying process, vaporisation of water would cause an increase in relative humidity (RH) of the air within the oven. Under a high RH condition, the vaporisation process would be inhibited, which is not preferable for the drying of soil. In this pilot study, a small external fan had been installed at the rear side of the oven (Plate 5) to facilitate the removal of water vapor inside the oven. Owing to the poor sealing of the front doors of the oven, it was found that concentrated inflow of cool air from outside the oven had caused a reduction in the temperature of some of the containers near the front doors. This could be improved with the use of a proper oven in future.

The performance of a combined oven (i.e. integration of convection heating elements with ceramic infrared panels) was also tested (see Section 6.2.1).

4.3 Temperature Control

The energy transfer mechanism of infrared is by means of radiation, and the temperature of air within the oven may not necessarily be the same as that of the soil specimens. In addition, the temperatures of soil specimens in different compartments of the oven are likely to be different during the process of drying. Nevertheless, it is of utmost importance to ensure that the temperatures of soil specimens within the oven are below the threshold value of 110 ^{o}C, as stipulated in Geospec 3.

To facilitate the drying process, it is preferable to maintain the temperatures of the soil specimens to be within the optimum range of 100 ^{o}C to 110 ^{o}C. A power control device was developed to regulate the power supply to infrared panels, which in turn could control the temperature of the soil specimens within the oven. The device comprised two key components:

(a) a control soil specimen, and

(b) a power control device to regulate the power supply (i.e. on/off) to the infrared panels.

The control specimen was placed at the most critical location (Plate 6) within the oven where the temperature is the highest. As the soil mass of the control specimen was perfectly dry, the temperature sensor embedded in the control specimen which would give a quicker response to temperature change than that for other specimens. The temperature of the control specimen would be monitored closely by the power control device. If the temperature of the control specimen exceeds 100 °C (Plate 7), the power supply to infrared panels would be terminated automatically. In this pilot study, it was noted that the temperature of the control specimen would continue to increase to a maximum value of about 108 °C (i.e. less than the threshold value of 110 °C). The power supply to infrared panels would be resumed if the temperature of the control specimen falls below 100 °C. With the power control device, the temperature of the soil specimens could have maintained within the optimum range of 100 °C to 110 °C.

In this study, temperature sensors were installed in all soil specimens (Plate 4) for monitoring the temperature of individual specimens throughout the drying process. Detailed discussion of the performance of the power control device is given in Section 5.3.2.

5. TESTING PROGRAMME AND RESULTS

5.1 Testing Details

The operating procedure of an infrared oven and the method of sample preparation are very similar to that of the conventional moisture content test using a convection oven. Upon placement of soil specimens, power supply to both infrared panels and ventilation fan at the back of the oven would be switched on. It took less than 10 minutes for the oven to reach 100 °C from room temperature. The temperatures of the control specimen, together with all other test specimens, were recorded at half-hour intervals after commencement of the test.

The first record of the weight of soil specimen was taken at 2½ hours after commencement of the drying process. Successive weights were carried out at half-hour intervals thereafter. The soil mass would be considered as being 'dry' and the moisture content test terminated when the difference in successive weights is less than 0.1% of the initial wet mass, pursuant to the requirement of Geospec 3 (GEO, 2001).

In order to evaluate the appropriateness of the above termination criteria, after completion of drying in the infrared oven, further over-night drying of the soil specimens in a convection oven at 105±5 °C was carried out. Detailed discussion of the results is given in Section 5.4.

In this pilot study, two major improvements were made, namely, in respect of temperature control and requirement of workforce, as compared with the Australian Standard AS1289.2.1.5. The provision of the power control device helped to maintain the temperature of the soil specimens to be within the optimum range of 100 °C to 110 °C. In order to reduce the amount of workforce required for conducting a test, the need to stir the soil specimens at regular intervals was waived, although a correspondingly longer time would be expected for the completion of drying. This is considered justifiable in view of the large number of moisture content tests to be conducted by PWRL per day.

The total amount of time that the infrared panels were switched on during the moisture content test had also been recorded for a broad assessment of the energy consumption and costs per test (see Section 6.2.4).

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5.2 Sample Types and Moisture Contents

The soil type was considered to be a key factor affecting the time required to complete a moisture content test. Soil samples with higher fines content (i.e. silt and clay) would take a longer time to complete the test. A combination of medium-grained and fine-gained soil samples from different fill sources (either CDG or CDV origin), covering a wide range of particle size distribution (PSD), were selected for testing. The PSD results of all the samples tested in this pilot study are summarized in Table 2 and Figure 2. Three of the samples (samples G, N & O) have fines content exceeding 50%, with a maximum of about 63% (sample O). These samples probably represented the worst composition of materials in local filling works in practice.

The amount of soil mass used in each of the test would also affect the testing time required. Pursuant to Geospec 3, a minimum soil mass of 300 g and 30 g in weight will be needed for medium-grained soil and fine-grained soil respectively for moisture content test. In this study, about 350 g of soil mass was used for each test.

As the use of coarse-grained soils for filling works is uncommon in Hong Kong and that a minimum of 3 kg of soil mass would be needed for each moisture content test, the drying performance of coarse-grained soils in an infrared oven is not covered in this pilot study.

Other than the soil type, the initial moisture content of a soil sample is also an important factor in controlling the duration of a test. It is noteworthy that the moisture contents of soil samples collected from filling sites were all on the dry side of the respective optimum moisture content (OMC). This is a common arrangement in compaction operation of fill materials. Nevertheless, a conservative approach in specifying the moisture content of soil specimens (i.e. wetter than typical specimens) had been adopted in this study whereby the moisture contents were set either at OMC or at OMC+5% (Plate 8). Samples with moisture content at OMC+5% could be very wet (Plate 9) such that compaction may not be feasible in practice. According to the General Specification for Civil Engineering Works (HKSARG, 2006), fill materials should be compacted at the optimum moisture content, with a tolerance of ±3%.

5.3 Test Results

5.3.1 General

For each of the two initial moisture contents (i.e. OMC & OMC+5%), nine soil specimens were prepared to account for possible sample variability and other uncertainties. In addition, these specimens were placed at different locations within the oven for monitoring of temperature during the course of drying. A total of 180 moisture content tests involving ten different soil samples were carried out in this pilot study.

5.3.2 Temperature of Soil Specimens

Upon drying in the infrared oven for half an hour, the temperature of soil specimens were increased from room temperature to about 80 ^{o}C. This was followed by a further

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steady increase in temperature, but at a much lower rate, as drying proceeded. Approaching the end of drying, with the provision of the power control device, the temperature of the soil specimens was generally in the range of 100 °C to 110 °C. Among the nine soil specimens in the oven, the maximum difference in temperatures at any one time throughout the testing was less than 20 °C. Of the two rows of containers, the temperatures of soil specimens near the front side of the oven were consistently lower than that at the rear side. The non-uniformity in heating was probably due to the poor sealing of the front door of the old oven used in this study. This could be improved with the use of a new oven, together with a better design of the ventilation system and configuration of the infrared panels.

The temperature measurements of soil specimens taken during the tests are presented in Figures 3 & 4 and Table 3 respectively. Except for one out of about 1,400 measurements, the temperatures of all soil specimens during the drying process were lower than 110 °C. The isolated case was on sample 'K' and the maximum temperature exceeded the threshold value of 110 °C by 1.5 °C for only about 5 minutes.

5.3.3 Time Required for Moisture Content Test using Infrared Oven

According to the operation of the PWRL, it is preferable that the moisture content test could be completed within 3½ hours. Among the 180 tests on ten soil samples involving two different moisture contents (i.e. OMC and OMC+5%), 162 nos. (90%) could be completed within 3½ hours (i.e. difference in successive weights being less than 0.1% of the initial wet mass). The success rates for specimens at OMC and OMC+5% are 97% (i.e. 87 out of 90 nos.), and 83% (i.e. 75 out of 90 nos.), respectively.

Of the 'unsuccessful' 18 specimens, 15 (83%) involved soil samples with fines content (i.e. silt and clay) exceeding 50% (samples G, N & O). In addition, 13 out of 18 soil specimens were located at the front side of the oven where the temperature was lower than that at the rear side.

The success rate of specimens at OMC was up to 97% (87 out of 90 nos.) and the three 'unsuccessful' soil specimens all had fines contents exceeding 50% (samples N & O), which were located at the front side of the oven. The success rates of specimens at OMC and OMC+5% would have been increased to 100% and 97% respectively if 4 hours were allowed for the test.

After completion of drying in the infrared oven, all soil specimens were transferred to a convection oven for further drying over-night. The differences in moisture contents of all the specimens before and after drying in the convection oven were generally less than 0.3%, indicating that the test termination criteria (i.e. difference in successive weights less than 0.1% of the initial wet mass) were acceptable. Owing to the relatively small number of tests carried out in this pilot study, a more comprehensive testing programme is needed to further investigate the appropriateness of the test termination criteria. The rate of drying in the infrared oven, in terms of both the percentage of drying and differences in the successive weights, is given in Figures 5 to 8 and Tables 4 & 5.

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5.4 Comparative Tests

Taking cognizance of the differences in the principles of energy transmission between infrared and convection, there could be a concern about the possible removal of 'non-free' water molecules by infrared radiation, which would not be desirable.

A comparative test was carried out on 30 soil specimens from six different samples to investigate the possible significance of infrared radiation in removing 'non-free' water (which would not have been removed by a convection oven). Soil specimens were placed in a convection oven at a temperature of $105\pm5\,^{o}$C for drying over-night and then the drying of these specimens was continued in an infrared oven for six hours. All the free water in the soil mass should have been removed completely after drying in the convection oven. Further reduction in the water mass after drying in the infrared oven could be attributed to the removal of 'non-free' water by infrared radiation. The test results of all 30 soil specimens revealed that removal of 'non-free' water by infrared radiation, if any, was insignificant, with the differences in moisture contents before and after placement in the infrared oven being less than 0.1% (Figure 9).

The procedure was reversed in the second set of comparative tests (i.e. drying in an infrared oven for six hours, followed by drying in a convection oven). A total of 45 specimens involving five soil samples were tested. Similarly, the differences in moisture contents were less than 0.1% (Figure 10).

5.5 Immediate Weighing after Drying

Under the current working procedure of a moisture content test, the soil specimens would be transferred to a desiccator for cooling after drying in an oven. A simple test was carried out to investigate the differences in the soil mass between immediate weighing (viz. immediately after oven drying), and after proper cooling in the desiccator. The test results of 17 soil specimens revealed that the differences in moisture contents were less than 0.1% (see Figure 11), which were insignificant.

6. DISCUSSION

6.1 Implications of Using Infrared Oven in PWRL

According to WBTC No. 14/2000, RC tests of all public works projects have to be undertaken through PWL. In general, samples would be collected from works sites in two sessions each day (i.e. morning and afternoon) by staff members of the PWRL. The results of RC would normally not be available until at least the next day after sampling.

The infrared method appears to be promising in significantly reducing the amount of time required for drying soil specimens as compared to the conventional method. Further study is warranted to see if the drying time could be reduced to less than 3½ hours such that it would be possible for the test results of samples collected in the morning session to be available on the same day. This will help to expedite the progress of filling works on site.

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6.2 Factors to be Considered in Using Infrared Oven

6.2.1 Temperature Control within the Infrared Oven

The power control device would automatically terminate the power supply to the infrared panels should the temperature of the control specimen exceed 100 °C. The maximum temperature of the soil specimen would reach about 108 °C. Only one of about 1,400 temperature measurements exceeded the threshold value of 110 °C (i.e. 111.5 °C) for about 5 minutes. This was an isolated case and the implication should be minimal because the difference was only 1.5 °C and the duration was around 5 minutes. In general, the overall performance of the power control device was acceptable. Notwithstanding this, there are still rooms for further improvement of the setting.

The variation in temperature of soil specimens within the oven was generally less than 15 °C, and the temperature at the rear side of the oven was consistently higher than that at the front side. The lower temperature at the front side would prolong the time required for a test. It is noteworthy that 13 out of 18 'unsuccessful' soil specimens (see Section 5.3.3) were located at the front side of the oven, and the corresponding initial moisture contents were all at OMC+5%. A new oven with a better sealing of the front doors, together with an improved design of the ventilation system and configuration of infrared panels, would help to reduce the temperature variations.

In this study, the power output of the infrared panels was 400 Watts. A small-scale trial was also undertaken to compare the performance of 400 Watts and 600 Watts infrared panels. The results indicated that the performance of the 400 Watts panels, in terms of both the temperature control and time taken for a test, was better than that of the 600 Watts panels. A search of overseas suppliers indicated that infrared panels of 250 Watts are also available. It is possible that further improvement of the overall performance of the infrared oven could be achieved with the use of 250 Watts infrared panels.

A combined oven (i.e. integration of convection heating elements and ceramic infrared panels) had been assembled to compare the performance with that of an infrared oven. However, it was established that the idling time of infrared panels inside the combined oven was much longer than that of infrared oven, thus resulting in comparatively lesser emission of infrared radiation. In addition, the temperature control of the combined oven is not as good as that of the infrared oven and it was difficult to maintain the temperature of the oven to be within the optimum range of 100 °C to 110 °C. The performance of the combined oven was inferior to that of the infrared oven.

6.2.2 Time and Workforce Required for Moisture Content Tests Using Infrared Oven

In this study, drying of more than 97% of the tests on soil specimens at OMC could be completed within 3½ hours. The 'unsuccessful' cases were all located at the front side of the oven and the corresponding fines contents were over 50%. It is probable that the success rate could be further increased with the use of a new oven, incorporating improved control.

The test results indicated that with the use of an infrared oven, the time required for moisture content test (and hence the RC test) would be significantly reduced for most of the filling materials in Hong Kong.

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The results of the comparative tests confirmed that removal of the 'non-free' water by infrared radiation was insignificant. Also, there was virtually no difference in testing accuracy between the infrared drying method and the conventional method.

Since stirring of the soil specimens was not required in this study, the working procedure of a moisture content test using an infrared oven is simple and very similar to that of the conventional method using a convection oven (see Section 5.1). Therefore, the implications on workforce requirements should be minimal.

6.2.3 Need for Prior Cooling of Specimens in Desiccator before Weighing

It is a general practice of the PWCL and PWRL that the soil specimens would be transferred to a desiccator for cooling after drying in an oven. The test results given in Section 5.5 suggest that there may be room for streamlining the above procedure. However, as only a relatively small number of pilot tests had been undertaken, a more comprehensive testing programme is needed to further investigate this point.

6.2.4 Costs

Owing to the long testing time, it is a general practice to maintain the convection oven in operating mode (i.e. power switched on) 24 hours a day. Infrared oven, however, can be operated on a need basis and the power supply to the oven could be terminated after completion of drying, the duration of which is normally less than 4 hours.

The high efficiency of infrared radiation and the operational characteristics of infrared ovens may help to reduce the energy consumption per test. A preliminary estimate revealed that the energy consumption of moisture content tests on nine soil specimens was about 5 kWh. This corresponds to an equivalent energy cost of about HK$0.5/specimen.

The total cost of an infrared oven, including infrared panels and accessories, is about HK$20,000, which is much cheaper than that of a convection oven (about HK$50,000). This is largely attributed to the low cost of infrared panels (i.e. about HK$400/panel).

7. CONCLUSIONS AND RECOMMENDATIONS

The findings of this pilot study revealed that the infrared drying method appears to be promising as a possible alternative to the conventional method using convection ovens for carrying out moisture content tests for the determination of relative compaction. The drying process of most of filling materials in Hong Kong could be completed within 3½ hours.

It is recommended that a more comprehensive testing programme be launched to assess the applicability and practicability of using the infrared drying method in routine moisture content tests. The assessment should focus on key factors including the success rate, implications on the workflow, time and cost savings, calibration aspects (e.g. power, configuration of the oven and uniformity of the temperature distribution, etc.), safety precautions and checks, examining a wider range of soils (e.g. marine deposits, alluvial clay,

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alluvial sand, CDV, etc.), maintenance requirements, etc.

The recommended procedure for determination of moisture content using an infrared oven is as follows:

(a) Ensure that soil specimens in a given compartment of the infrared oven are from the same source as far as possible.

(b) Turn on the power supply to infrared panels and the ventilation fan after placement of soil specimens.

(c) Take the first record of soil mass three hours after drying.

(d) Take the second record of soil mass 3½ hours after drying.

(e) The soil specimen shall be deemed to be dry when the difference between the first and second records is less than 0.1% of the original wet mass.

(f) Otherwise, soil specimen shall be transferred to the convection oven at $105 \pm 5\,^{o}C$ to continue drying in accordance with the procedure of the conventional method as specified in Geospec 3.

Similar to the conventional method, infrared oven testing is not suitable for soil specimens containing gypsum, calcareous material or organic matters. Such soils should be dried in the convection oven at $45 \pm 5\,^{o}C$, as recommended in Geospec 3.

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Table 1 - Properties of Various Types of Infrared Heating Sources

	Metal Sheath	Quartz Tube	Quartz Lamp	Catalytic	Flat Faced Panels	Ceramic
Radiant Efficiency	56%	61%	86%	80%	88%	96%
Physical Strength	High	Low	Very Low	High	Medium	Medium
Heat-Up Cool Down	Slow	Fast	Very Fast	Very Slow	Slow	Slow
Max. Temp.	760°C	870°C	2200°C	420°C	870°C	700°C
Color Sensitivity	Low	Low	High	Low	Low	Low

Notes:

(1) Radiant Efficiency: Total amount of energy emitted from the source as infrared radiation. The balance of heat energy from the sources is transferred via convection and conduction.

(2) Physical Strength: The physical strength of each source, with a high rating denoting a very durable source that can withstand physical abuse, such as dropping a wrench on the source.

(3) Heat-Up/Cool Down: The amount of time required for the source to achieve the operating temperature and to cool down to room temperature.

(4) Maximum Temperature: Maximum operating temperature of the source.

(5) Color Sensitivity: This refers to the ability of a typical material to absorb the spectral radiation emitted from a source based on the color of the material. The shorter the wavelength emitted from a source the more color sensitive a material will be to the sources spectral radiation.

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Table 2 - Particle Size Distribution of the Ten Different Soil Samples

Sample No.	Gravel	Sand	Silt	Clay
F	23.0%	55.6%	13.6%	7.8%
G	17.5%	34.4%	25.2%	22.9%
H	36.8%	31.0%	24.2%	8.0%
I	48.9%	30.6%	16.0%	4.5%
J	26.0%	41.7%	19.8%	12.5%
K	36.5%	48.0%	10.5%	5.0%
L	21.8%	65.9%	7.5%	4.8%
M	25.1%	36.2%	22.3%	16.4%
N	13.0%	31.0%	37.1%	18.9%
O	7.0%	30.0%	40.1%	22.9%

Table 3 - Records of Temperature Monitoring of Soil Specimens during Testing (Sheet 1 of 5)

Sample No. F	Hour	Specimen No. (Temperature ^oC)								
		A	C	D	E	F	G	H	I	J
OMC = 10%	0.5	83.7	81.6	85.3	82.7	75.8	79.1	82.0	77.4	75.2
	1.0	93.8	93.8	96.6	93.3	85.3	90.6	94.6	87.6	83.8
	1.5	91.4	94.7	96.2	92.8	86.6	91.8	96.1	90.2	86.1
	2.0	86.9	92.1	94.2	91.8	88.4	91.3	93.3	90.0	88.3
	2.5	102.7	107.2	109.7	107.1	101.5	105.1	107.4	103.5	102.7
	3.0	101.8	105.3	106.2	102.9	98.1	102.2	102.6	100.2	99.3
	3.5	95.3	98.3	99.6	95.4	95.3	100.7	99.3	99.0	94.7
	4.0	98.8	103.9	107.3	103.8	100.5	103.9	104.2	99.4	98.3
OMC + 5% = 15%	0.5	80.3	76.7	78.3	82.5	82.7	77.7	79.4	70.6	70.8
	1.0	81.2	81.5	81.9	85.8	80.1	80.8	83.4	73.8	74.9
	1.5	84.8	86.7	87.9	89.7	82.6	87.6	89.8	81.2	80.7
	2.0	96.2	99.0	102.9	99.0	94.4	100.3	101.5	94.4	92.0
	2.5	99.2	102.8	106.1	100.8	99.5	104.5	104.6	99.6	96.9
	3.0	95.0	98.9	97.8	94.6	95.2	97.9	95.4	83.8	88.9
	3.5	98.8	98.6	98.8	98.8	94.3	96.6	96.5	82.0	95.5
	4.0	99.4	99.4	99.5	99.4	97.7	99.6	99.7	98.0	97.5

Sample No. G	Hour	Specimen No. (Temperature ^oC)								
		A	C	D	E	F	G	H	I	J
OMC = 17%	0.5	80.7	84.1	81.7	83.8	77.4	83.9	82.2	73.8	77.5
	1.0	86.6	88.8	86.2	88.2	82.2	87.9	87.5	77.4	81.4
	1.5	83.8	89.4	84.2	85.8	81.0	85.8	86.5	78.1	82.7
	2.0	97.7	103.9	100.4	103.3	94.5	102.9	103.6	91.5	96.3
	2.5	99.6	103.9	103.2	103.1	96.3	101.8	102.4	92.8	98.9
	3.0	101.1	102.3	103.6	99.3	98.5	103.7	103.5	90.2	100.6
	3.5	104.3	106.6	104.6	101.3	103.8	106.3	106.3	87.1	99.9
	4.0	102.6	104.1	104.3	101.2	100.6	101.5	102.8	84.4	97.9
OMC + 5% = 22%	0.5	81.5	79.8	78.0	81.5	77.1	75.2	74.8	73.3	75.0
	1.0	82.9	83.0	78.9	83.2	77.6	76.6	77.2	74.8	75.7
	1.5	85.9	87.0	81.8	86.1	79.9	79.3	80.3	78.8	78.2
	2.0	90.4	92.2	85.7	90.5	83.7	83.1	86.6	84.0	82.2
	2.5	95.7	100.3	90.1	96.4	89.0	87.2	95.0	89.1	88.1
	3.0	99.9	104.7	96.2	99.9	97.3	92.6	100.9	99.0	92.4
	3.5	104.0	104.7	105.6	105.1	102.0	102.2	104.9	100.3	99.2
	4.0	105.9	107.7	107.5	106.0	103.6	104.2	105.8	103.8	102.6

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Table 3 - Records of Temperature Monitoring of Soil Specimens during Testing (Sheet 2 of 5)

Sample No. H	Hour	Specimen No. (Temperature ^{o}C)								
		A	C	D	E	F	G	H	I	J
OMC = 12%	0.5	82.5	79.3	81.5	81.8	78.4	80.9	83.9	75.1	77.1
	1.0	86.7	84.7	89.3	88.3	83.6	86.5	92.0	80.5	81.4
	1.5	90.2	88.6	95.8	92.1	86.8	89.9	97.2	84.2	85.1
	2.0	96.5	93.8	102.6	97.4	92.4	95.8	101.4	89.3	90.4
	2.5	101.4	101.3	105.8	101.1	98.3	102.5	103.3	96.9	96.5
	3.0	104.1	105.1	106.8	103.1	103.5	106.0	106.2	97.3	96.4
	3.5	98.7	98.4	100.3	96.4	95.1	96.1	97.0	89.7	92.9
	4.0	96.4	96.1	98.9	96.0	98.4	97.7	98.8	92.9	95.8
OMC + 5% = 17%	0.5	82.8	85.9	78.0	88.7	103.8	104.3	102.0	99.8	94.5
	1.0	85.2	88.8	81.3	87.6	93.5	95.7	93.7	91.9	86.5
	1.5	88.7	97.2	89.8	95.3	109.1	109.2	109.3	104.8	100.0
	2.0	92.1	93.4	95.7	93.2	96.9	100.6	101.7	99.5	99.7
	2.5	102.7	100.2	105.1	101.6	96.2	98.1	98.0	95.5	88.9
	3.0	99.3	98.5	101.0	98.0	94.8	98.6	98.2	90.4	92.3
	3.5	99.4	100.9	102.9	100.2	100.0	100.9	101.0	94.7	96.6
	4.0	99.4	102.4	102.9	100.5	98.6	100.0	101.5	92.8	95.2

Sample No. I	Hour	Specimen No. (Temperature ^{o}C)								
		A	C	D	E	F	G	H	I	J
OMC = 12%	0.5	89.3	91.0	86.7	91.4	87.8	85.9	87.7	87.2	82.6
	1.0	86.9	88.0	85.7	87.3	84.3	83.0	86.1	84.2	80.0
	1.5	-	-	-	-	-	-	-	-	-
	2.0	96.8	96.5	94.6	95.2	92.9	90.2	95.5	92.1	89.2
	2.5	101.9	103.9	103.5	102.4	99.5	97.8	103.0	101.0	98.0
	3.0	102.1	103.9	102.8	101.7	100.0	101.7	101.6	100.9	100.6
	3.5	102.7	105.0	-	103.5	103.8	105.9	105.4	101.2	103.7
	4.0	98.6	100.7	106.4	101.0	101.1	103.7	102.1	97.1	99.1
OMC + 5% = 17%	0.5	82.5	80.2	76.7	79.8	78.0	75.2	78.1	68.4	70.9
	1.0	84.3	83.2	80.1	81.3	79.7	79.3	80.2	80.6	75.9
	1.5	95.8	93.4	95.2	93.4	92.2	93.2	93.8	87.9	85.3
	2.0	95.1	95.1	101.1	95.4	93.6	96.1	96.1	92.6	90.9
	2.5	100.6	103.0	108.2	101.7	98.3	101.7	100.6	98.0	95.0
	3.0	103.0	107.5	107.7	100.7	101.3	104.6	104.3	97.0	92.4
	3.5	106.0	109.0	-	103.0	105.6	105.0	106.8	95.4	101.3
	4.0	103.2	107.6	107.5	102.8	108.1	108.1	109.4	101.0	97.2

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Table 3 - Records of Temperature Monitoring of Soil Specimens during Testing (Sheet 3 of 5)

Sample No. J	Hour	Specimen No. (Temperature °C) A	C	D	E	F	G	H	I	J
OMC = 12%	0.5	79.8	88.4	77.9	82.6	75.2	74.4	80.3	81.5	74.5
	1.0	83.3	91.0	82.4	84.4	77.9	76.3	83.1	84.8	80.6
	1.5	89.7	97.7	88.6	88.7	84.1	82.2	89.1	88.8	90.1
	2.0	96.4	100.3	94.7	91.4	88.7	92.5	98.0	97.6	95.7
	2.5	97.8	101.5	99.1	95.5	91.7	97.5	101.3	99.1	100.8
	3.0	102.2	108.2	106.0	102.0	97.4	102.0	105.5	103.5	101.1
	3.5	97.5	101.9	102.4	99.5	96.0	96.0	100.4	99.5	94.7
OMC + 5% = 17%	0.5	91.9	89.5	70.7	82.1	78.1	63.5	74.1	83.4	76.5
	1.0	92.9	93.1	82.7	86.7	82.1	68.4	71.7	84.5	81.7
	1.5	94.4	98.4	94.2	90.3	87.2	80.2	89.9	89.3	86.4
	2.0	93.3	100.5	98.1	94.8	89.0	92.1	94.9	94.4	89.4
	2.5	97.0	105.4	102.9	100.2	91.9	100.1	100.3	99.3	90.7
	3.0	98.2	99.2	99.9	99.4	93.2	91.6	95.3	97.9	92.3
	3.5	100.4	101.5	102.7	101.2	94.8	102.2	102.9	102.3	96.0

Sample No. K	Hour	Specimen No. (Temperature °C) A	C	D	E	F	G	H	I	J
OMC = 9.4%	0.5	82.8	86.4	94.0	91.6	98.7	89.8	84.3	79.5	79.6
	1.0	88.4	93.3	104.7	97.5	103.3	95.5	82.6	85.1	86.4
	1.5	96.4	99.1	109.0	104.5	104.1	101.4	98.9	91.1	94.7
	2.0	103.2	102.5	107.5	103.4	101.8	100.8	101.2	96.9	97.8
	2.5	107.1	106.7	111.5	107.1	105.3	103.1	103.4	98.6	99.3
	3.0	107.3	106.5	108.4	105.5	99.3	99.5	100.1	96.2	96.8
	3.5	102.9	105.9	107.4	103.4	97.7	96.0	98.0	94.5	92.8
	4.0	103.4	103.9	107.3	103.8	99.1	98.4	98.5	96.4	96.4
OMC + 5% = 14.4%	0.5	74.9	76.5	79.1	81.3	71.8	71.7	79.8	68.4	69.7
	1.0	84.4	83.6	89.6	87.2	79.0	83.5	85.9	74.6	69.1
	1.5	95.8	94.1	98.4	93.8	88.0	93.3	92.5	84.2	77.4
	2.0	101.6	103.9	105.5	102.2	102.8	103.7	103.1	95.6	89.1
	2.5	102.2	105.5	107.1	103.0	104.1	104.8	104.5	96.6	96.3

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Table 3 - Records of Temperature Monitoring of Soil Specimens during Testing (Sheet 4 of 5)

Sample No. L	Hour	Specimen No. (Temperature ^{o}C)								
		A	C	D	E	F	G	H	I	J
OMC = 15%	0.5	75.7	75.5	78.5	69.2	77.3	76.0	79.7	62.2	73.0
	1.0	76.5	82.8	83.0	80.6	80.3	79.4	83.4	68.2	75.2
	1.5	84.3	93.6	94.6	90.3	97.4	90.8	92.5	82.0	85.4
	2.0	96.1	98.7	102.8	94.8	93.4	97.4	94.9	86.3	90.5
	2.5	102.2	104.3	106.4	99.8	100.2	103.6	101.7	95.0	97.2
	3.0	101.0	103.4	104.2	102.1	101.1	103.5	102.2	94.0	98.8
	3.5	98.5	96.6	100.1	95.9	94.6	96.7	97.8	90.9	91.4
	4.0	93.4	87.6	87.0	86.2	96.7	100.1	101.6	96.6	93.7
OMC + 5% = 20%	0.5	68.8	74.9	71.6	70.7	71.0	72.4	71.0	75.4	69.5
	1.0	68.4	78.9	71.9	69.7	70.1	72.1	70.7	74.5	69.0
	1.5	78.1	96.7	90.9	82.0	83.1	89.3	83.7	89.8	83.3
	2.0	93.3	103.9	103.4	98.5	94.8	99.6	99.0	102.3	96.9
	2.5	96.7	105.0	105.3	102.2	97.3	101.9	102.4	105.8	99.6
	3.0	97.5	103.0	101.8	101.6	94.2	95.1	95.0	97.6	97.3
	3.5	94.8	102.3	101.3	99.8	92.4	94.4	98.0	97.0	96.6

Sample No. M	Hour	Specimen No. (Temperature ^{o}C)								
		A	C	D	E	F	G	H	I	J
OMC = 15%	0.5	86.6	83.1	83.6	83.9	80.9	85.6	85.1	79.2	77.4
	1.0	89.8	85.7	86.5	86.9	85.1	87.8	87.6	81.1	80.8
	1.5	95.1	89.9	91.1	92.9	91.8	93.8	93.9	87.1	86.2
	2.0	101.1	94.7	98.4	99.3	98.3	99.3	100.2	91.6	91.1
	2.5	104.6	101.5	104.4	102.8	101.6	104.1	103.7	94.9	98.4
	3.0	102.1	104.0	107.0	100.7	100.6	105.4	103.2	92.5	98.9
	3.5	100.8	106.6	103.7	99.5	100.9	103.5	104.2	97.5	98.8
	4.0	96.1	99.8	100.6	94.4	94.1	95.9	97.5	90.9	88.7
OMC + 5% = 20%	0.5	74.7	73.9	78.9	69.4	72.8	68.6	72.2	62.3	64.4
	1.0	75.0	77.4	78.6	70.7	72.6	68.7	71.7	64.4	65.0
	1.5	80.4	85.5	85.8	79.8	80.8	78.6	79.2	73.8	73.6
	2.0	84.3	91.4	91.5	85.4	88.7	84.6	84.4	80.2	79.9
	2.5	90.7	97.0	98.6	90.8	95.2	91.7	88.6	81.5	86.6
	3.0	100.9	105.3	100.7	98.8	99.3	102.1	103.1	98.0	98.6
	3.5	102.9	108.1	105.9	100.5	98.5	103.9	99.1	95.7	98.6
	4.0	101.2	108.4	106.0	101.1	99.6	105.2	101.6	95.4	95.2

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Table 3 - Records of Temperature Monitoring of Soil Specimens during Testing (Sheet 5 of 5)

Sample No. N	Hour	Specimen No. (Temperature ^{o}C)								
		A	C	D	E	F	G	H	I	J
OMC = 16%	0.5	84.9	84.4	90.0	89.6	84.4	89.7	84.0	78.4	81.1
	1.0	86.8	85.5	90.6	89.7	84.7	89.0	85.3	78.0	81.8
	1.5	90.7	89.6	96.8	93.7	88.7	92.6	89.4	81.2	85.4
	2.0	94.3	95.3	101.9	97.9	92.2	96.8	95.9	84.2	88.3
	2.5	95.9	98.9	102.1	96.9	93.1	98.5	97.0	83.2	89.4
	3.0	97.0	102.0	98.5	96.2	95.2	96.9	97.3	90.0	85.5
	3.5	96.2	104.2	95.3	97.2	92.1	93.0	92.3	80.4	84.2
	4.0	100.3	106.5	101.4	99.7	101.2	102.7	105.2	100.9	96.2
OMC + 5% = 21%	0.5	74.9	80.6	80.7	77.3	80.9	82.7	77.1	63.7	73.8
	1.0	76.0	81.5	80.8	76.6	79.7	80.2	76.5	67.3	72.7
	1.5	81.3	87.3	86.6	81.0	83.6	83.8	83.6	75.0	79.2
	2.0	86.9	95.9	95.9	88.8	92.3	90.8	92.6	82.6	88.8
	2.5	95.0	102.6	102.7	95.6	96.5	98.1	98.4	86.1	96.8
	3.0	100.4	106.4	104.5	101.8	98.9	101.3	102.2	91.5	96.0
	3.5	101.3	103.8	98.4	96.6	96.3	99.1	102.0	85.3	86.0
	4.0	102.8	107.7	105.9	102.0	99.6	98.4	98.3	77.4	88.4

Sample No. O	Hour	Specimen No. (Temperature ^{o}C)								
		A	C	D	E	F	G	H	I	J
OMC = 17%	0.5	85.7	87.6	82.3	83.4	79.8	82.5	80.5	71.9	71.3
	1.0	89.0	91.3	86.9	86.3	83.3	85.9	82.1	75.5	75.3
	1.5	91.8	96.2	92.8	91.6	87.9	91.8	88.7	81.0	81.2
	2.0	100.6	104.5	100.5	97.8	83.2	96.4	94.1	85.5	85.7
	2.5	103.7	108.8	105.0	103.6	98.1	101.6	99.0	89.5	89.8
	3.0	93.8	98.6	92.4	89.9	91.3	92.0	89.9	83.7	84.2
	3.5	98.1	102.5	97.8	95.9	96.1	97.2	98.3	-	86.8
	4.0	98.5	104.6	98.6	97.7	98.5	99.6	97.4	-	87.9
OMC + 5% = 22%	0.5	80.2	82.2	80.6	83.4	76.9	78.4	75.3	75.8	64.4
	1.0	77.5	81.1	79.7	79.5	75.1	76.7	70.7	75.9	65.2
	1.5	80.1	82.4	81.9	80.1	77.4	79.0	75.6	78.2	70.0
	2.0	84.9	86.7	87.0	83.0	83.0	83.1	82.2	80.8	78.4
	2.5	100.8	91.1	89.0	89.9	91.7	92.3	87.0	87.6	87.7
	3.0	96.5	104.5	101.4	100.2	95.7	99.0	98.4	84.4	91.9
	3.5	100.7	107.9	100.9	98.4	99.1	100.7	103.0	92.1	93.1
	4.0	96.8	103.7	95.9	95.5	93.6	97.4	97.8	88.2	88.8

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Table 4 - Progress of Moisture Content Test in terms of Percentage Completion of Drying (Sheet 1 of 3)

Sample No. F	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 10%	2.5	99.9%	100.0%	99.9%	100.0%	99.9%	99.9%	100.0%	99.9%	99.9%
	3.0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 15%	2.5	99.1%	99.9%	99.8%	99.9%	99.9%	99.8%	100.0%	99.9%	99.8%
	3.0	99.8%	100.0%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Sample No. G	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 17%	2.5	98.5%	99.4%	99.2%	97.6%	97.1%	99.1%	98.8%	99.2%	98.8%
	3.0	99.6%	99.7%	99.8%	99.6%	99.4%	99.8%	99.7%	99.9%	99.6%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 22%	2.5	91.1%	93.9%	91.2%	92.8%	87.5%	90.0%	93.2%	90.5%	88.6%
	3.0	97.7%	98.3%	97.4%	98.3%	95.3%	96.0%	98.0%	97.0%	95.7%
	3.5	99.5%	99.6%	99.4%	99.5%	98.9%	98.8%	99.4%	99.3%	99.0%
	4.0	99.9%	99.9%	99.9%	99.9%	99.8%	99.7%	99.8%	99.9%	99.8%

Sample No. H	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 12%	2.5	99.3%	99.7%	99.8%	99.9%	99.6%	99.8%	100.0%	99.5%	99.7%
	3.0	100.0%	100.0%	99.9%	100.0%	100.0%	100.0%	100.0%	99.8%	100.0%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 17%	2.5	100.0%	99.9%	100.0%	99.8%	99.9%	99.9%	99.8%	100.0%	99.9%
	3.0	100.0%	99.9%	100.0%	99.9%	99.9%	100.0%	99.8%	100.0%	100.0%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Sample No. I	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 12%	2.5	98.1%	99.1%	98.8%	98.9%	98.2%	98.2%	99.1%	98.5%	98.5%
	3.0	99.5%	99.8%	99.8%	99.9%	99.7%	99.6%	99.9%	99.8%	99.7%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 17%	2.5	99.4%	99.6%	99.8%	99.6%	99.7%	99.7%	99.7%	99.8%	99.7%
	3.0	99.7%	99.8%	99.9%	99.7%	99.9%	99.9%	99.9%	99.9%	99.8%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

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Table 4 - Progress of Moisture Content Test in terms of Percentage Completion of Drying (Sheet 2 of 3)

Sample No. J	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 12%	2.5	99.8%	100.0%	99.8%	99.7%	99.4%	99.8%	100.0%	99.8%	99.8%
	3.0	99.9%	100.0%	99.9%	99.9%	99.8%	100.0%	100.0%	99.9%	99.9%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 17%	2.5	97.3%	99.5%	99.6%	99.6%	98.2%	99.7%	99.1%	99.6%	99.3%
	3.0	99.6%	99.8%	99.9%	99.9%	99.7%	99.9%	99.7%	99.9%	99.9%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Sample No. K	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 9.4%	2.5	100.0%	99.8%	100.0%	100.0%	99.8%	100.0%	100.0%	100.0%	100.0%
	3.0	100.0%	100.0%	100.0%	100.0%	99.9%	100.0%	100.0%	100.0%	100.0%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 14.4%	2.5	99.7%	100.0%	99.8%	99.9%	99.9%	99.9%	100.0%	99.9%	99.8%
	3.0	100.0%	100.0%	99.9%	99.9%	99.9%	100.0%	100.0%	100.0%	100.0%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Sample No. L	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 15%	2.5	99.8%	99.9%	99.9%	99.7%	100.0%	99.7%	99.7%	99.6%	99.7%
	3.0	99.9%	100.0%	100.0%	99.9%	100.0%	99.8%	99.9%	99.8%	100.0%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 20%	2.5	98.0%	99.8%	99.9%	99.4%	99.7%	99.9%	99.5%	99.9%	99.7%
	3.0	99.7%	99.9%	99.9%	99.8%	99.9%	100.0%	99.8%	100.0%	99.9%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Sample No. M	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 15%	2.5	99.8%	99.7%	99.5%	100.0%	99.3%	99.7%	99.8%	99.6%	99.4%
	3.0	100.0%	100.0%	100.0%	100.0%	99.9%	99.9%	100.0%	99.9%	99.8%
	3.5	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 20%	2.5	98.6%	98.7%	99.4%	97.1%	98.8%	98.5%	94.9%	93.4%	98.5%
	3.0	99.7%	99.8%	99.8%	99.1%	99.7%	99.6%	98.5%	97.3%	99.7%
	3.5	99.9%	100.0%	99.9%	99.8%	99.9%	99.9%	99.8%	99.5%	100.0%
	4.0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

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Table 4 - Progress of Moisture Content Test in terms of Percentage Completion of Drying (Sheet 3 of 3)

Sample No. N	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 16%	2.5	98.0%	98.1%	99.3%	96.2%	96.1%	99.3%	97.3%	98.8%	95.0%
	3.0	99.3%	99.4%	99.7%	99.4%	99.0%	99.6%	99.4%	99.6%	98.6%
	3.5	99.6%	99.7%	99.8%	99.7%	99.6%	99.8%	99.6%	99.6%	99.4%
	4.0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 21%	2.5	98.9%	99.0%	97.9%	97.9%	96.5%	99.3%	98.7%	99.7%	99.1%
	3.0	99.7%	99.8%	99.7%	99.7%	99.0%	99.8%	99.6%	99.9%	99.8%
	3.5	99.9%	99.9%	99.9%	99.8%	99.8%	99.9%	99.9%	99.9%	99.9%
	4.0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Sample No. O	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 17%	2.5	97.2%	98.3%	97.5%	97.7%	97.5%	97.6%	95.1%	97.5%	95.6%
	3.0	99.2%	99.5%	99.3%	99.3%	99.1%	99.2%	98.7%	99.3%	98.7%
	3.5	99.7%	99.8%	99.7%	99.7%	99.7%	99.8%	99.8%	99.9%	99.9%
	4.0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
OMC + 5% = 22%	2.5	96.4%	97.6%	96.6%	95.8%	96.1%	98.3%	97.1%	95.7%	96.2%
	3.0	99.5%	99.7%	99.5%	99.4%	99.4%	99.8%	99.6%	99.4%	99.3%
	3.5	100.0%	100.0%	100.0%	99.9%	99.9%	99.9%	99.9%	100.0%	99.9%
	4.0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Note: OMC denotes the initial moisture contents of the soil specimens are at optimum moisture content.

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Table 5 - Difference in Successive Weights at Different Time Intervals after Testing (Sheet 1 of 2)

Sample No. F	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 10%	3.0	0.00%	0.00%	0.01%	0.00%	0.00%	0.01%	0.01%	0.01%	0.01%
	3.5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
OMC + 5% = 15%	3.0	0.10%	0.01%	0.00%	0.02%	0.01%	0.03%	0.01%	0.03%	0.02%
	3.5	0.03%	0.00%	0.02%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%

Sample No. G	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 17%	3.0	0.17%	0.04%	0.09%	0.28%	0.34%	0.09%	0.14%	0.10%	0.13%
	3.5	0.05%	0.05%	0.03%	0.06%	0.09%	0.03%	0.04%	0.02%	0.05%
OMC + 5% = 22%	3.0	1.14%	0.78%	1.08%	0.96%	1.37%	1.06%	0.85%	1.16%	1.26%
	3.5	0.31%	0.23%	0.34%	0.22%	0.65%	0.51%	0.25%	0.41%	0.58%
	4.0	0.07%	0.05%	0.08%	0.06%	0.15%	0.15%	0.06%	0.10%	0.14%
	4.5	0.01%	0.02%	0.02%	0.02%	0.04%	0.05%	0.04%	0.03%	0.04%

Sample No. H	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 12%	3.0	0.07%	0.04%	0.02%	0.02%	0.05%	0.02%	0.01%	0.03%	0.03%
	3.5	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	0.02%	0.00%
OMC + 5% = 17%	3.0	0.00%	0.00%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.02%
	3.5	0.00%	0.01%	0.00%	0.01%	0.01%	0.01%	0.03%	0.00%	0.00%

Sample No. I	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 12%	3.0	0.13%	0.08%	0.10%	0.11%	0.16%	0.15%	0.08%	0.13%	0.12%
	3.5	0.05%	0.02%	0.02%	0.01%	0.03%	0.04%	0.01%	0.02%	0.03%
OMC + 5% = 17%	3.0	0.04%	0.03%	0.02%	0.01%	0.01%	0.03%	0.03%	0.01%	0.01%
	3.5	0.04%	0.03%	0.01%	0.05%	0.02%	0.02%	0.02%	0.01%	0.03%

Sample No. J	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 12%	3.0	0.01%	0.01%	0.01%	0.02%	0.05%	0.02%	0.00%	0.01%	0.01%
	3.5	0.01%	0.00%	0.01%	0.01%	0.02%	0.00%	0.00%	0.01%	0.01%
OMC + 5% = 17%	3.0	0.32%	0.05%	0.04%	0.05%	0.21%	0.02%	0.09%	0.04%	0.08%
	3.5	0.06%	0.03%	0.02%	0.01%	0.04%	0.02%	0.05%	0.02%	0.01%

Sample No. K	Hour	Specimen No.								
		A	C	D	E	F	G	H	I	J
OMC = 9.4%	3.0	0.00%	0.01%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%
	3.5	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%
OMC + 5% = 14.4%	3.0	0.03%	0.01%	0.01%	0.00%	0.00%	0.01%	0.00%	0.02%	0.02%
	3.5	0.01%	0.00%	0.01%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%

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Table 5 - Difference in Successive Weights at Different Time Intervals after Testing (Sheet 2 of 2)

Sample No. L	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 15%	3.0	0.01%	0.01%	0.01%	0.03%	0.00%	0.01%	0.02%	0.03%	0.03%
	3.5	0.01%	0.00%	0.00%	0.01%	0.00%	0.02%	0.02%	0.02%	0.01%
OMC + 5% = 20%	3.0	0.29%	0.02%	0.00%	0.07%	0.03%	0.01%	0.05%	0.01%	0.04%
	3.5	0.05%	0.01%	0.01%	0.03%	0.01%	0.00%	0.03%	0.01%	0.01%

Sample No. M	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 15%	3.0	0.02%	0.04%	0.06%	0.00%	0.08%	0.02%	0.02%	0.03%	0.05%
	3.5	0.00%	0.00%	0.01%	0.00%	0.01%	0.02%	0.01%	0.01%	0.02%
OMC + 5% = 20%	3.0	0.19%	0.17%	0.06%	0.34%	0.15%	0.19%	0.59%	0.64%	0.18%
	3.5	0.03%	0.03%	0.02%	0.11%	0.03%	0.06%	0.21%	0.37%	0.05%
	4.0	0.01%	0.01%	0.02%	0.04%	0.01%	0.01%	0.04%	0.07%	0.01%

Sample No. N	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 16%	3.0	0.18%	0.19%	0.06%	0.43%	0.43%	0.05%	0.28%	0.11%	0.49%
	3.5	0.04%	0.04%	0.01%	0.05%	0.07%	0.02%	0.03%	0.00%	0.11%
	4.0	0.05%	0.04%	0.03%	0.04%	0.07%	0.03%	0.06%	0.06%	0.09%
OMC + 5% = 21%	3.0	0.15%	0.14%	0.30%	0.32%	0.44%	0.09%	0.15%	0.03%	0.11%
	3.5	0.03%	0.02%	0.03%	0.01%	0.14%	0.02%	0.04%	0.01%	0.02%
	4.0	0.01%	0.02%	0.02%	0.03%	0.03%	0.02%	0.02%	0.01%	0.02%

Sample No. O	Hour	Specimen No. A	C	D	E	F	G	H	I	J
OMC = 17%	3.0	0.27%	0.17%	0.26%	0.23%	0.23%	0.23%	0.53%	0.27%	0.44%
	3.5	0.07%	0.04%	0.05%	0.06%	0.08%	0.09%	0.16%	0.09%	0.18%
	4.0	0.04%	0.03%	0.04%	0.04%	0.04%	0.03%	0.03%	0.01%	0.01%
OMC + 5% = 22%	3.0	0.58%	0.39%	0.52%	0.64%	0.60%	0.26%	0.46%	0.68%	0.56%
	3.5	0.08%	0.05%	0.09%	0.08%	0.09%	0.03%	0.05%	0.11%	0.11%
	4.0	0.01%	0.00%	0.01%	0.02%	0.02%	0.01%	0.02%	0.01%	0.01%

Note: OMC denotes the initial moisture contents of the soil specimens are at optimum moisture content.

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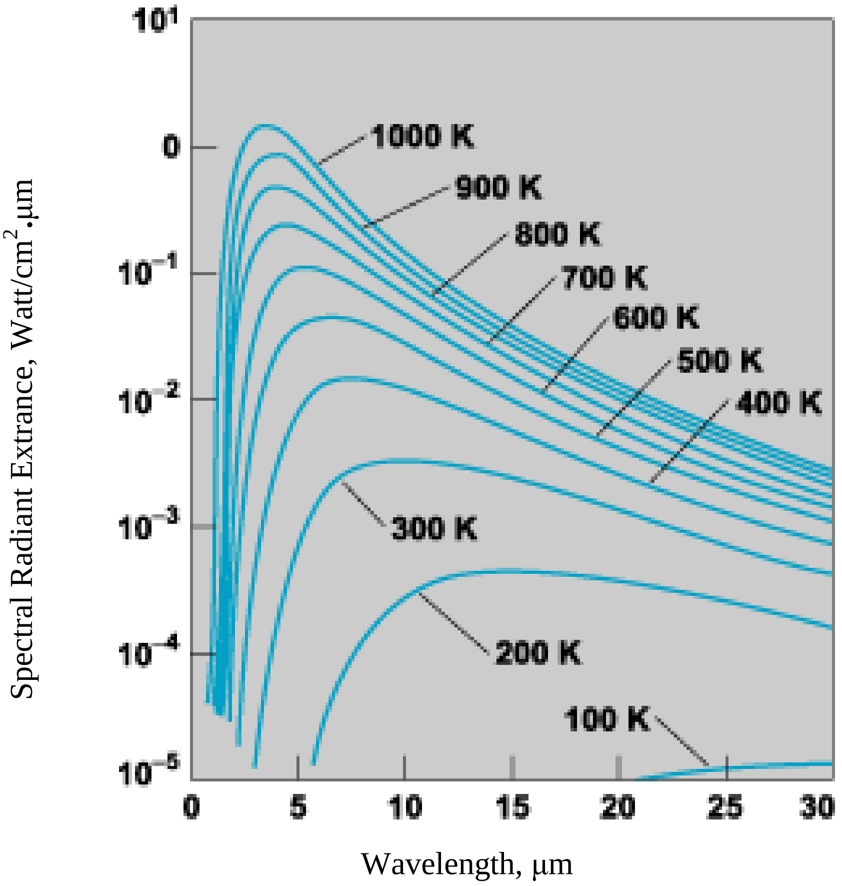

Figure 1 - Electromagnetic Output Spectrum of an Ideal Infrared Heating Source at Different Temperatures

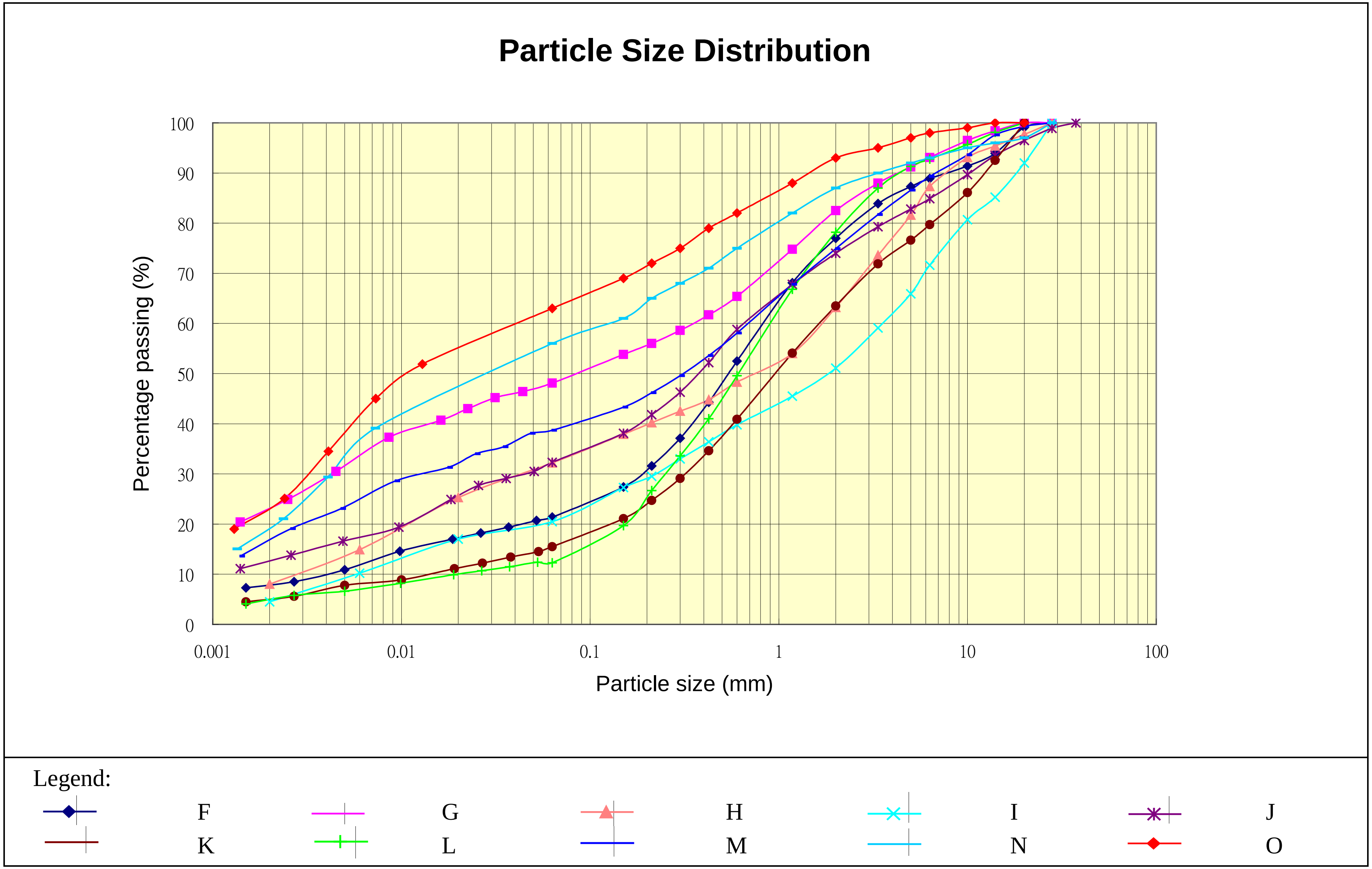

Figure 2 - Particle Size Distribution Curves of the Ten Soil Samples

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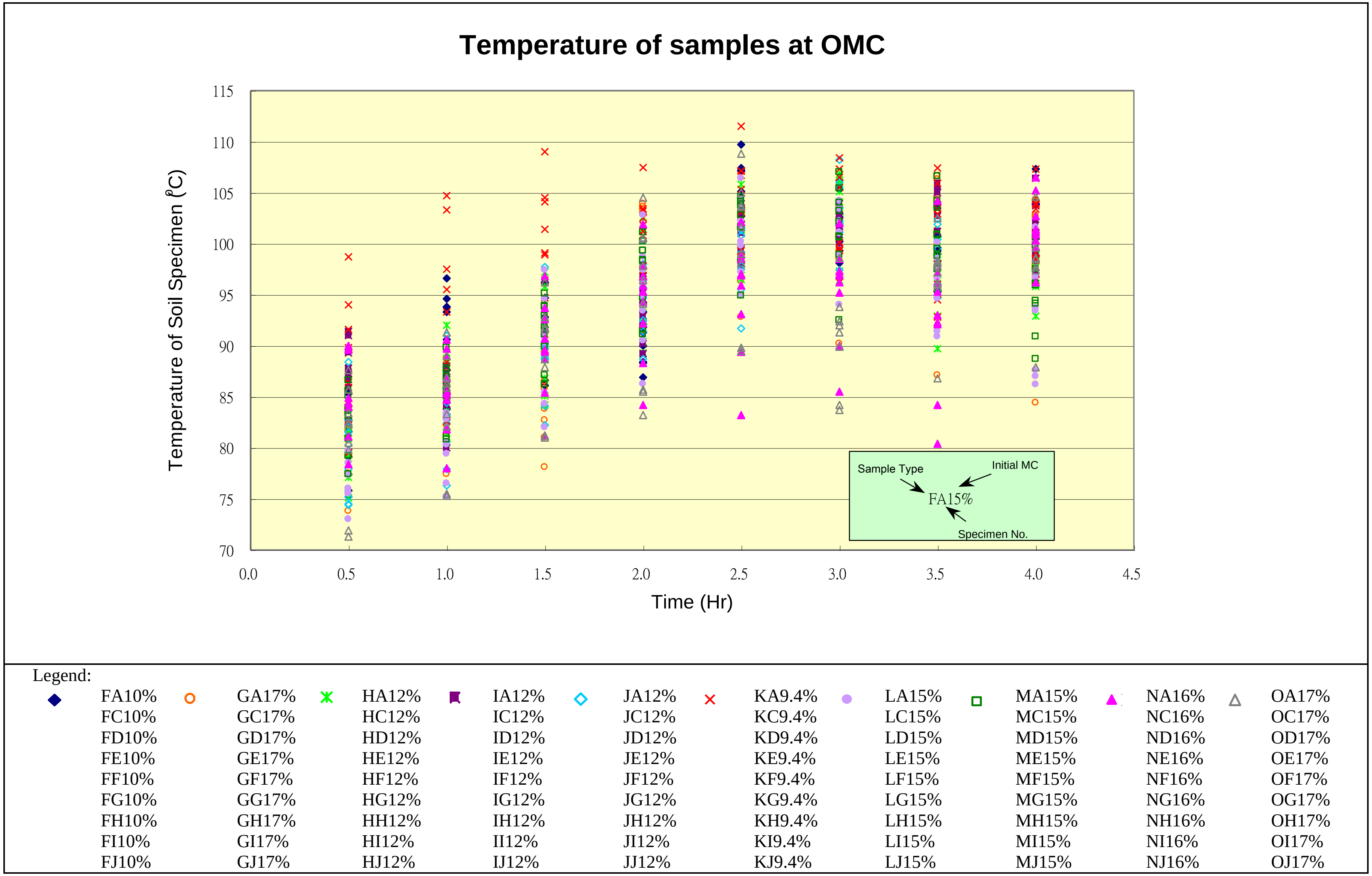

Figure 3 - Temperature Monitoring Records of Soil Specimens with Initial Moisture Content at OMC

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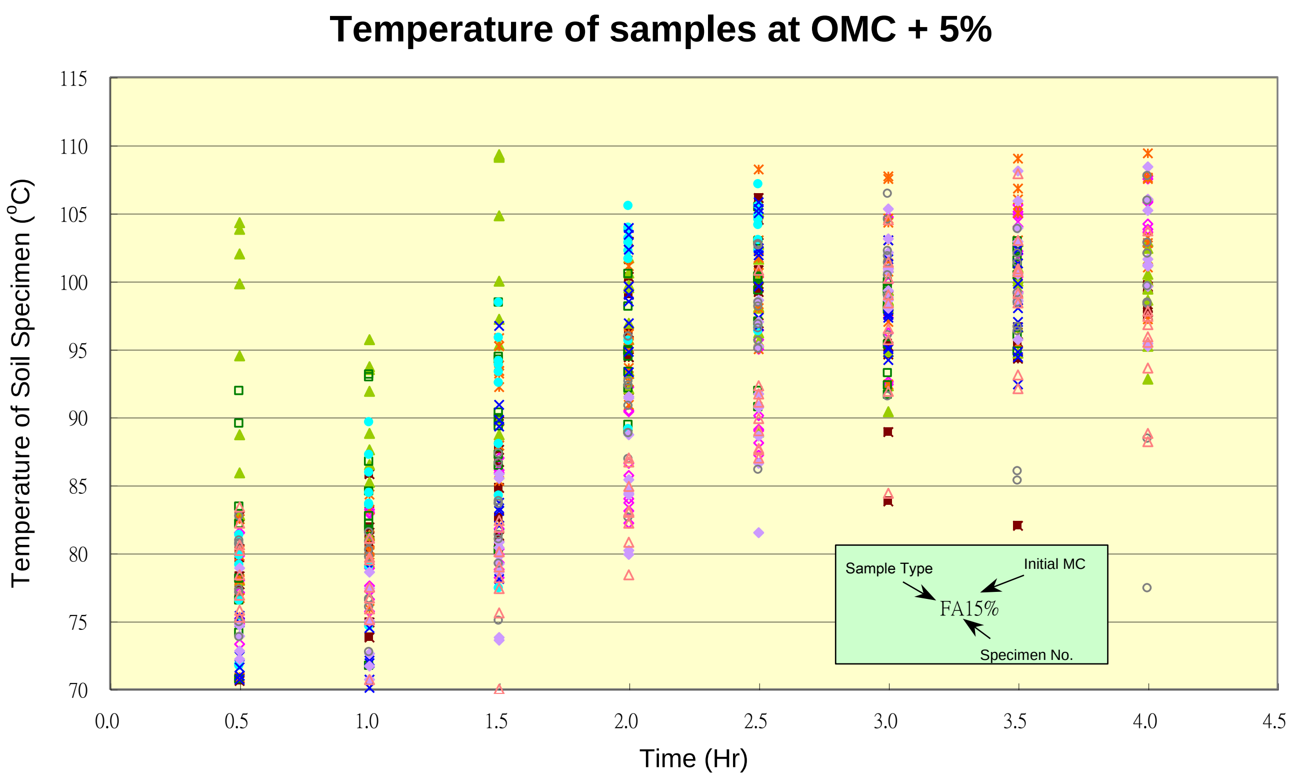

Legend:

FA15%	GA22%	HA17%	IA17%	JA17%	KA14.4%	LA20%	MA20%	NA21%	OA22%
FC15%	GC22%	HC17%	IC17%	JC17%	KC14.4%	LC20%	MC20%	NC21%	OC22%
FD15%	GD22%	HD17%	ID17%	JD17%	KD14.4%	LD20%	MD20%	ND21%	OD22%
FE15%	GE22%	HE17%	IE17%	JE17%	KE14.4%	LE20%	ME20%	NE21%	OE22%
FF15%	GF22%	HF17%	IF17%	JF17%	KF14.4%	LF20%	MF20%	NF21%	OF22%
FG15%	GG22%	HG17%	IG17%	JG17%	KG14.4%	LG10%	MG20%	NG21%	OG22%
FH15%	GH22%	HH17%	IH17%	JH17%	KH14.4%	LH20%	MH20%	NH21%	OH22%
FI15%	GI22%	HI17%	II17%	JI17%	KI14.4%	LI20%	MI20%	NI21%	OI22%
FJ15%	GJ22%	HJ17%	IJ17%	JJ17%	KJ14.4%	LJ20%	MJ20%	NJ21%	OJ22%

Figure 4 - Temperature Monitoring Records of Soil Specimens with Initial Moisture Content at OMC + 5%

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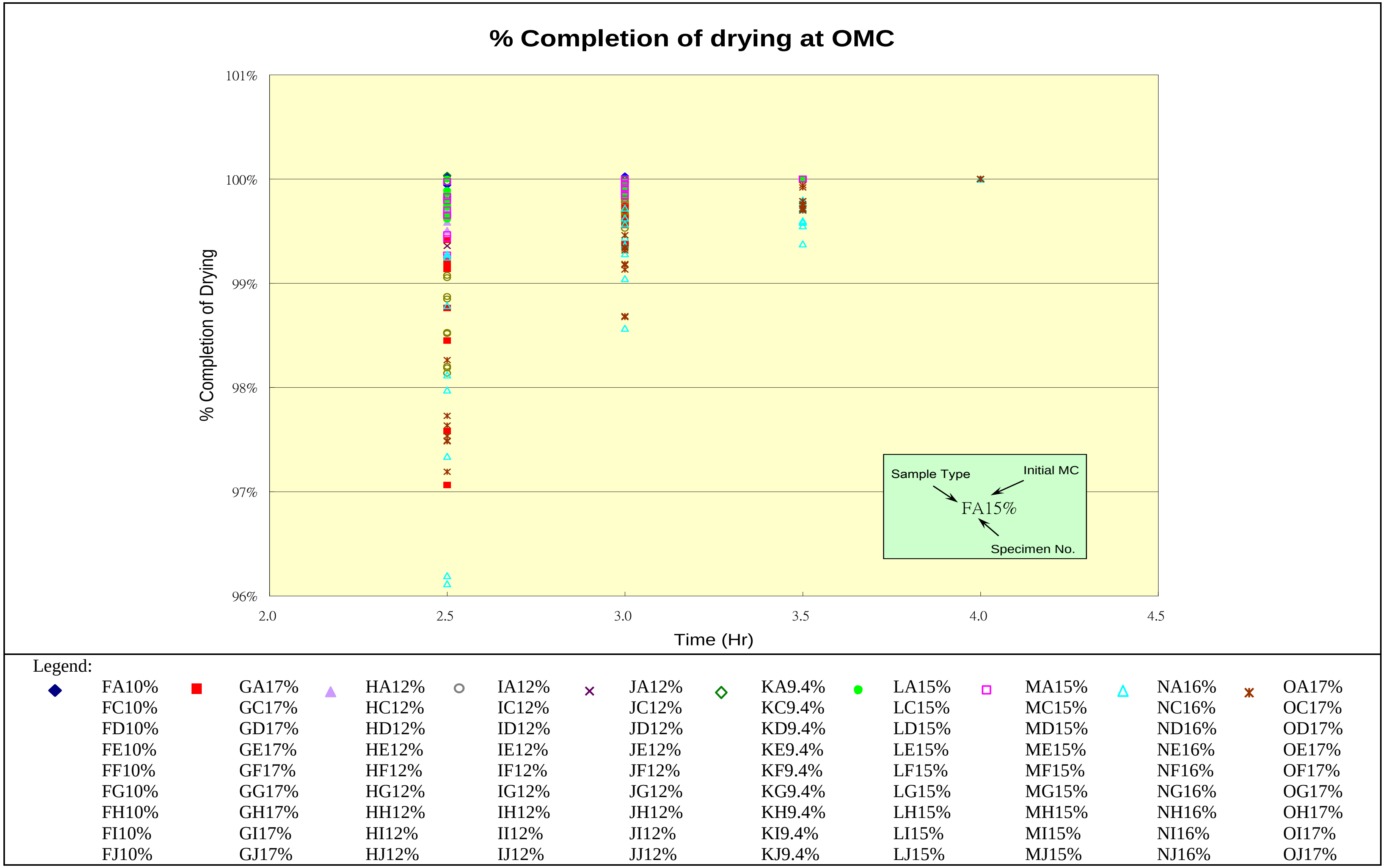

Figure 5 - % Completion of Drying of Soil Specimens with Initial Moisture Content at OMC

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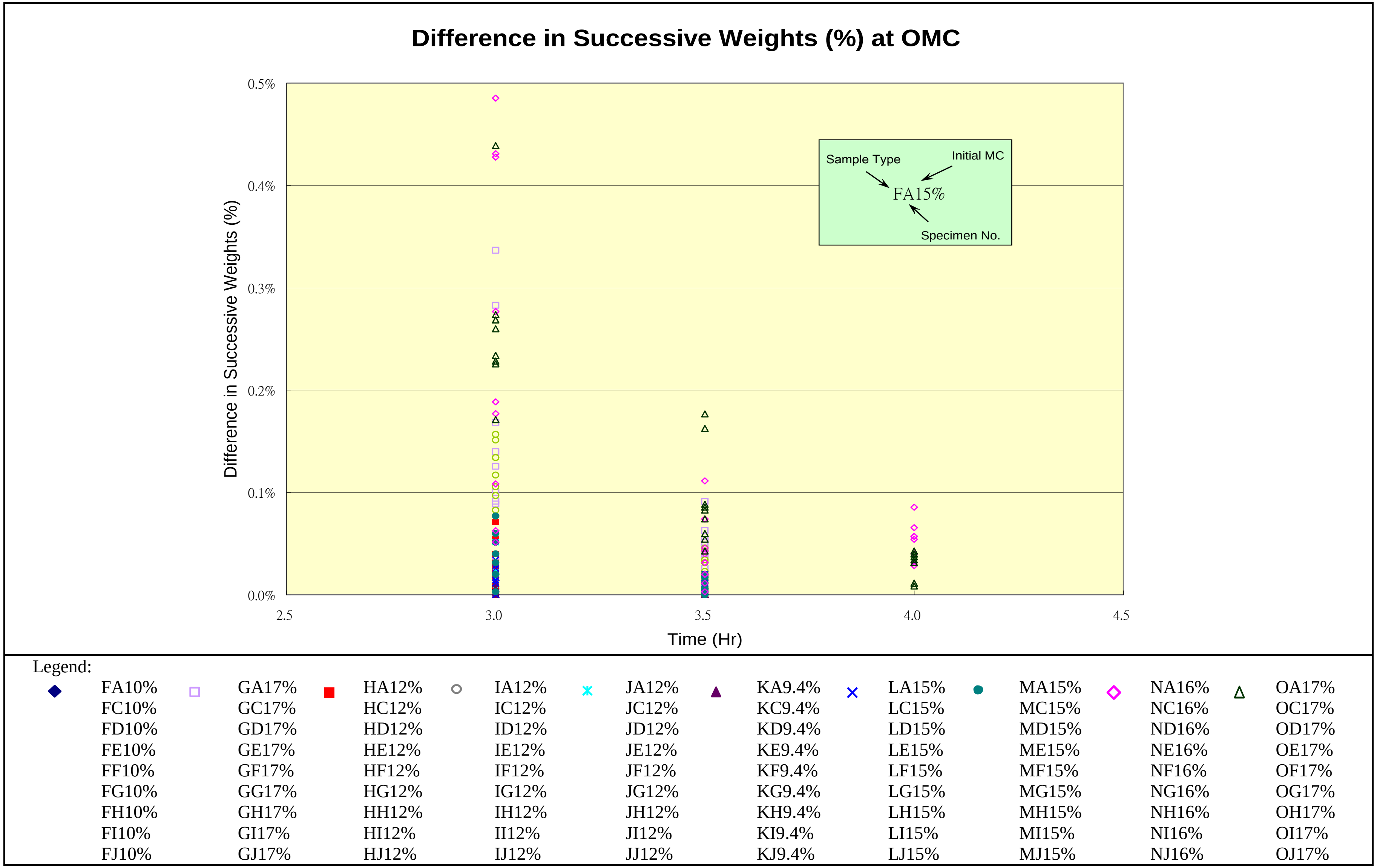

Figure 6 - Difference in Successive Weights of Soil Specimens with Initial Moisture Content at OMC

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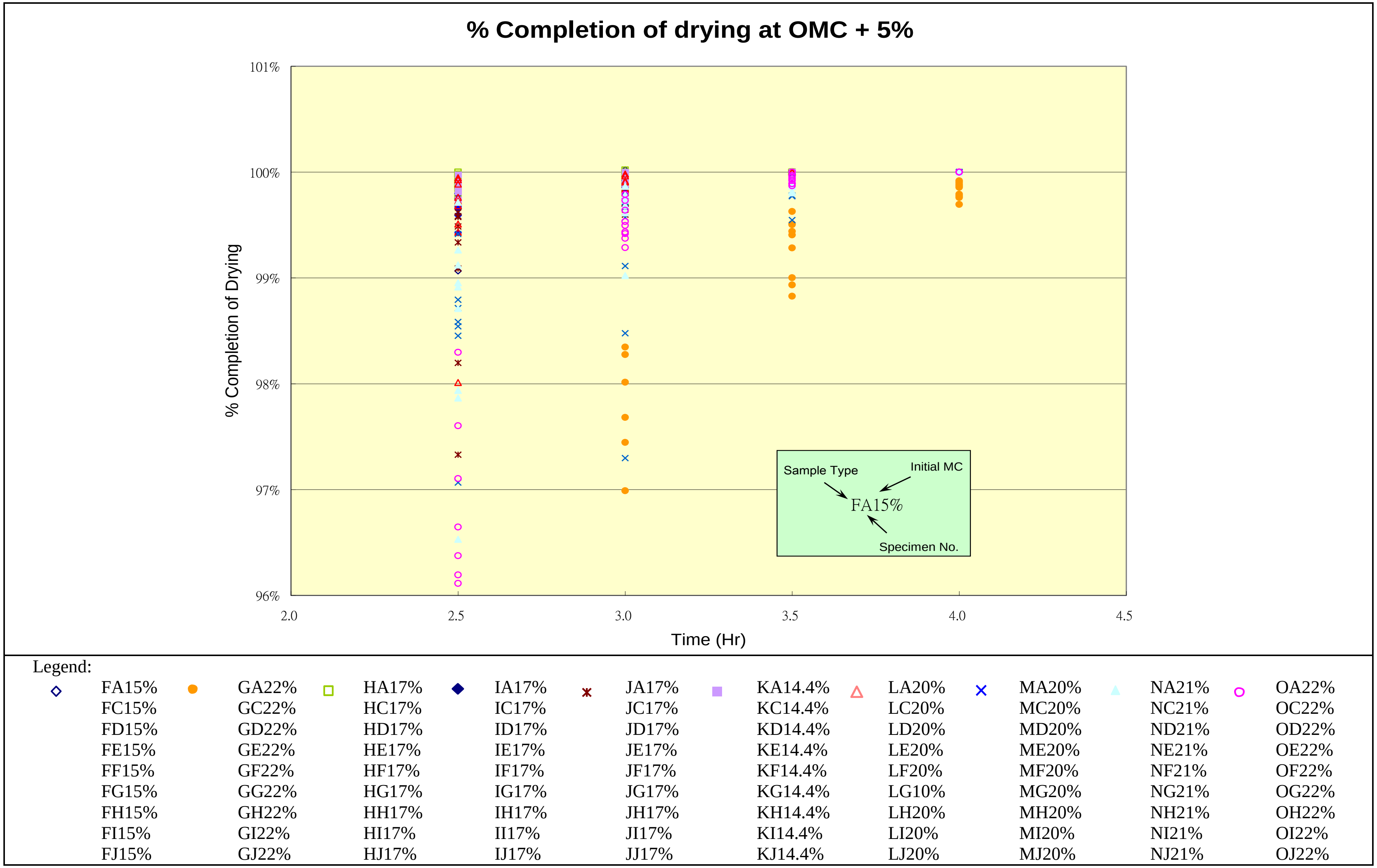

Figure 7 - % Completion of Drying of Soil Specimens with Initial Moisture Content at OMC + 5%

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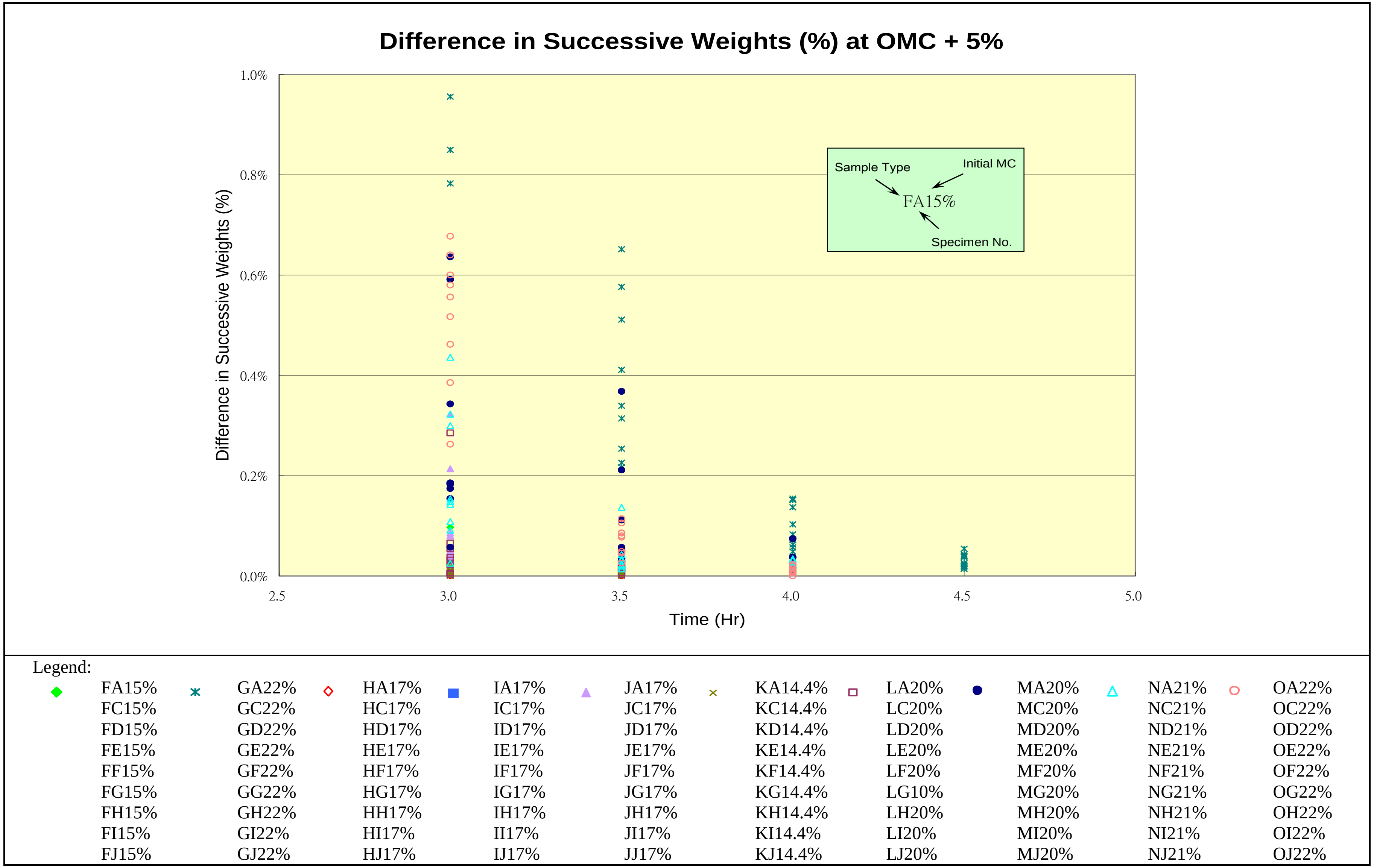

Figure 8 - Difference in Successive Weights of Soil Specimens with Initial Moisture Content at OMC + 5%

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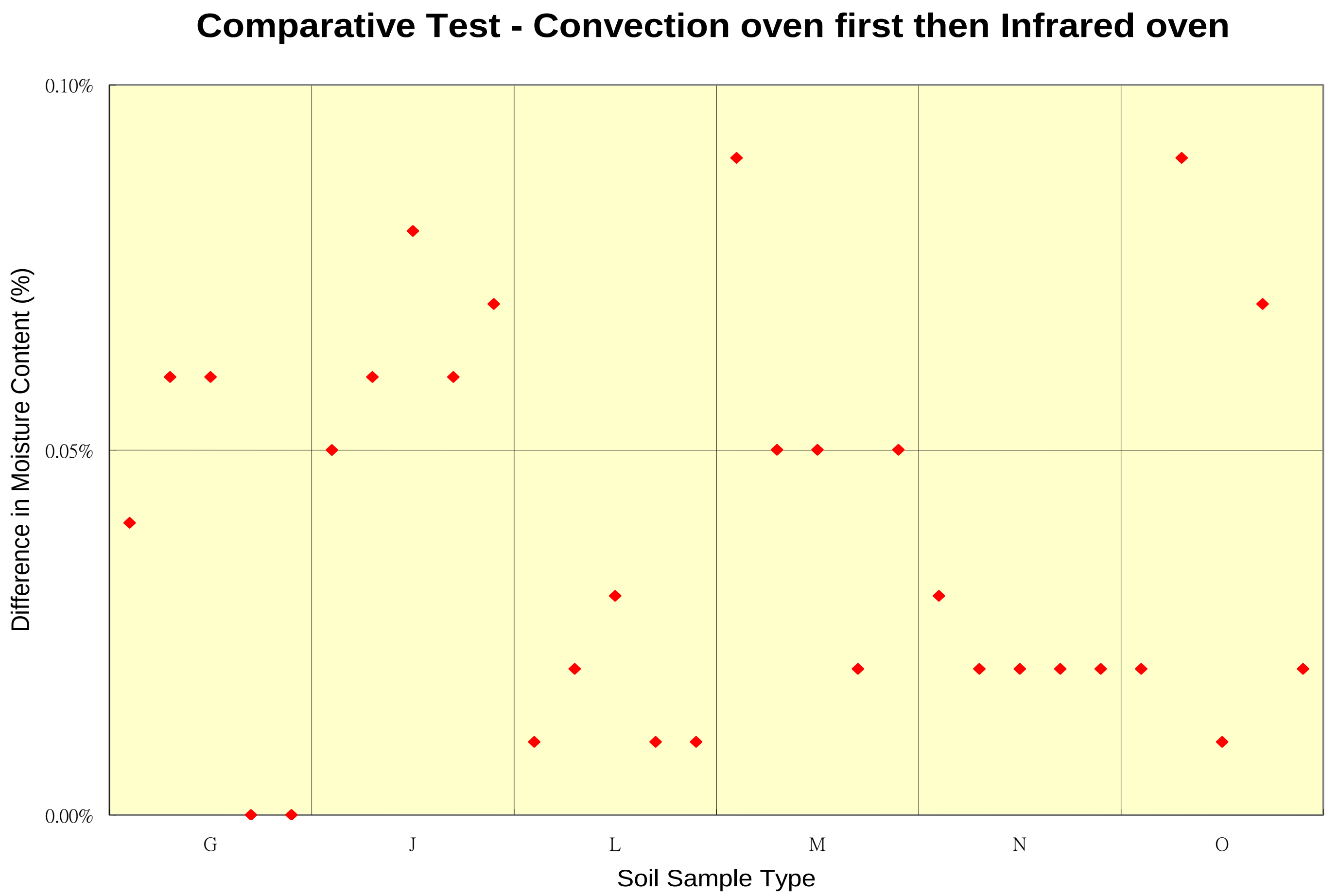

Legend:

◆ Drying done using convection oven first, subsequently drying was continued in an infrared oven

Figure 9 - Difference in Moisture Content for Specimens Dried in Convection Oven First and Followed by Infrared Oven

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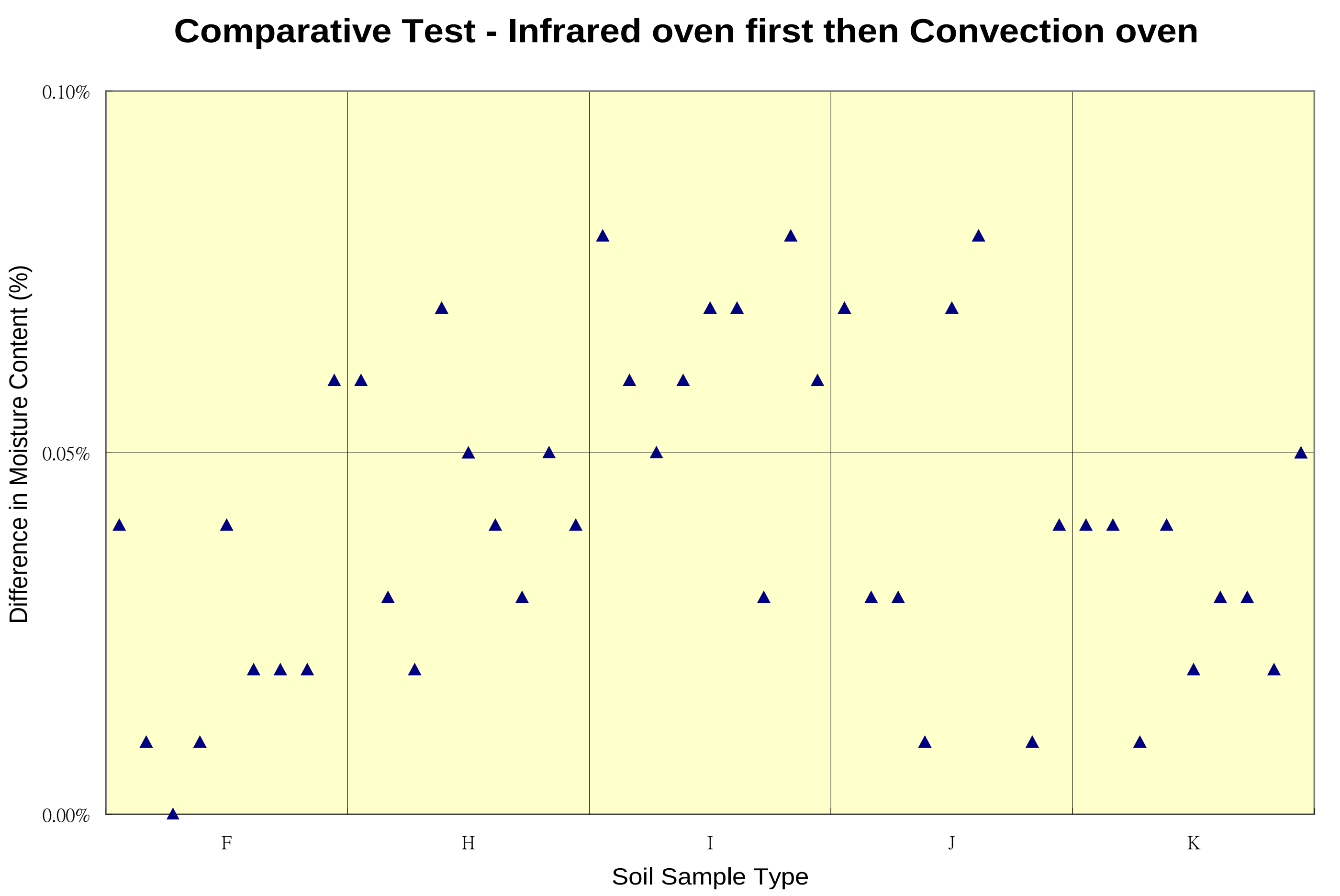

Legend:

▲ Drying done using infrared oven first, subsequently drying was continued in an infrared oven convection oven

Figure 10 - Difference in Moisture Content for Specimens Dried in Infrared Oven First and Followed by Convection Oven

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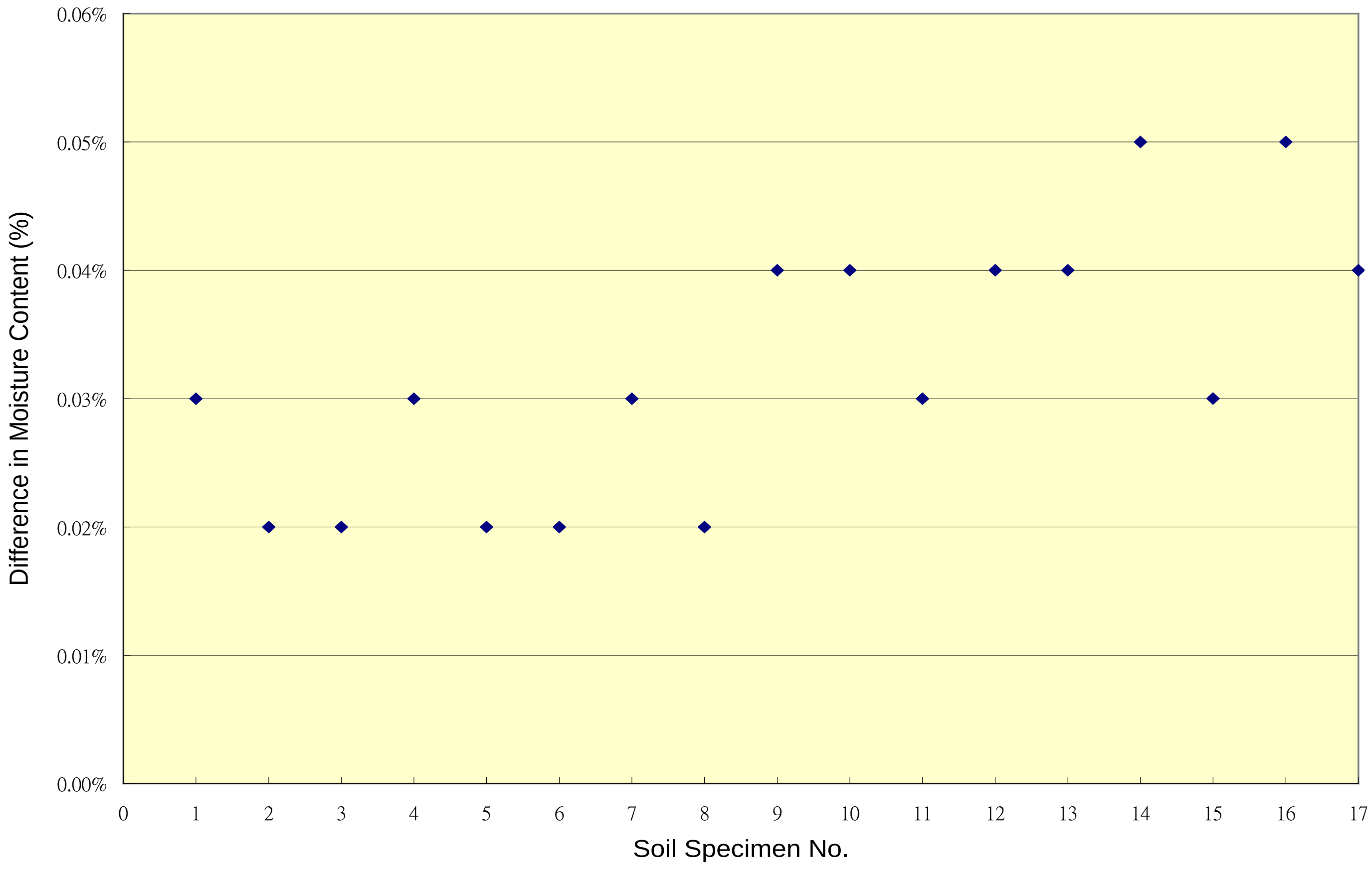

Legend:

◆ Between immediate weight and after cooling in desiccator

Figure 11 - Difference in Moisture Content of Specimens Between Immediate Weight and After Cooling in Desiccator

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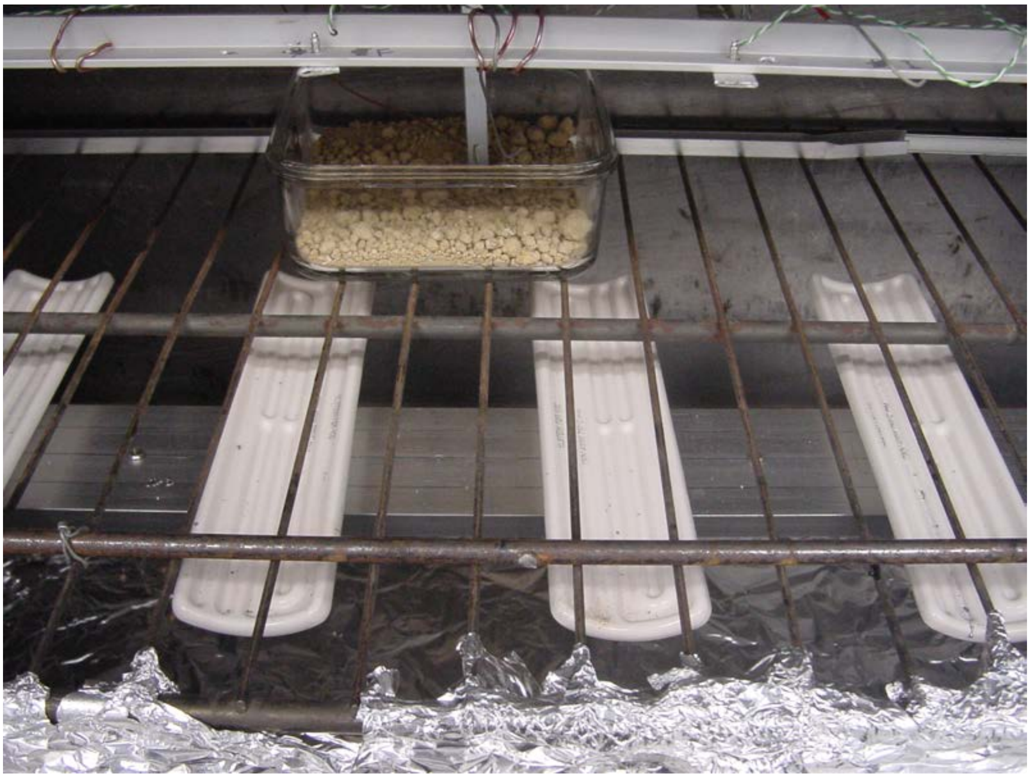

Plate 1 – Concave-shape Infrared Heating Panels Used in this Study

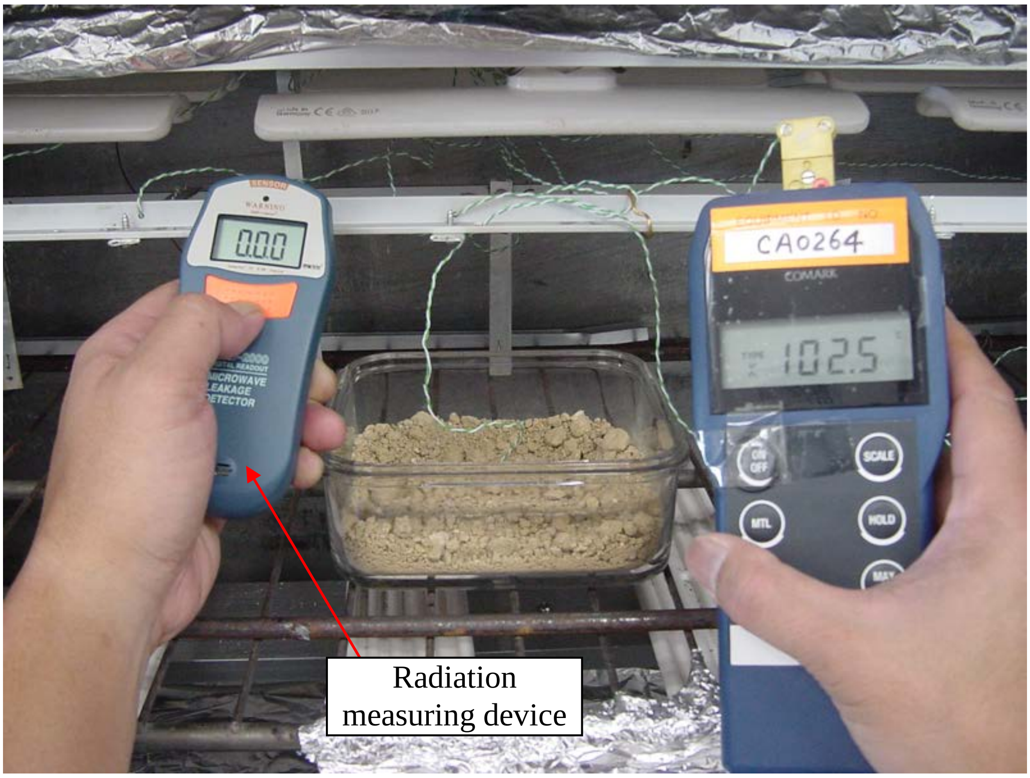

Plate 2 – Measurement of Radiation Emitted by Infrared Panels

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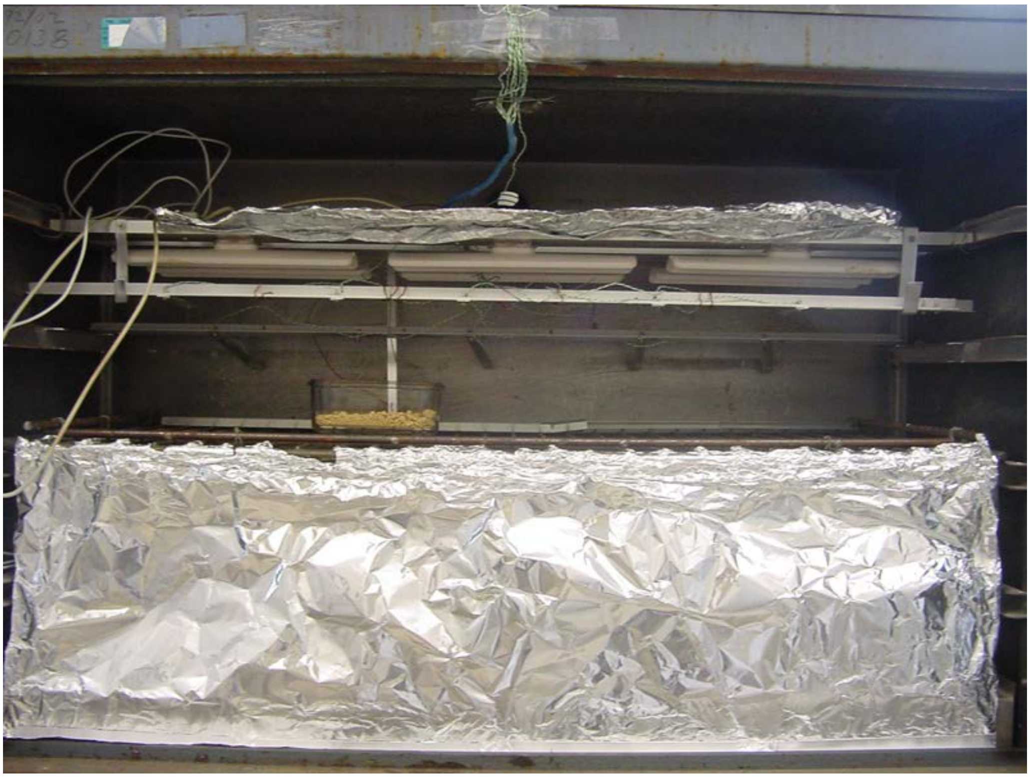

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Plate 8 – Conditions of Selected Samples with Moisture Content at OMC and OMC + 5%

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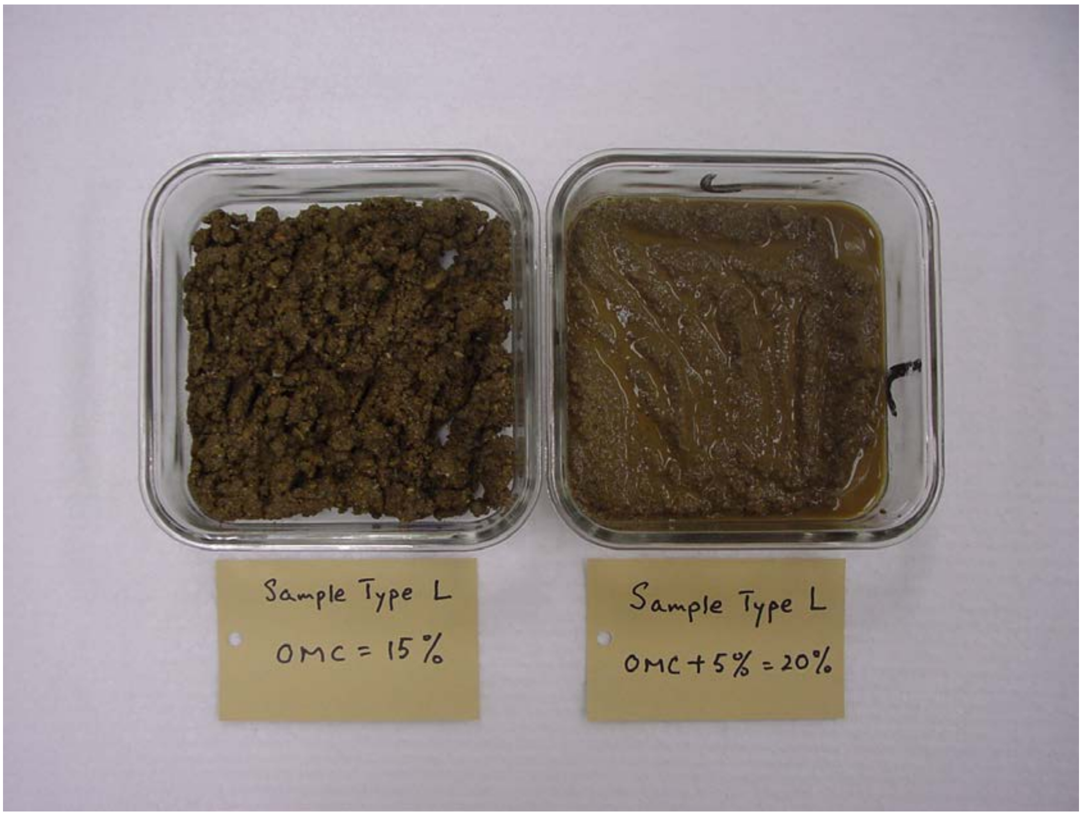

Plate 9 – Sample Very Wet at Moisture Content of OMC + 5%

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APPENDIX A

SUMMARY OF THE THEORY OF INFRARED HEATING

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A.1 INTRODUCTION

When infrared energy strikes an object, it may be absorbed, transmitted or reflected from the surface. The sum of the amount of energy absorbed, transmitted and reflected must equal the total incident energy. An object is called a "blackbody" if it absorbs (or emits) 100% of the incident infrared radiation.

$$\text{Total incident energy} = \rho + \alpha + \tau \quad \ldots\ldots\ldots\ldots \quad (1)$$

where ρ = proportion of energy reflected
α = proportion of energy absorbed
τ = proportion of energy transmitted

Example: If a certain amount of infrared energy strikes an object that reflects 30% of the energy and is 20% transparent to the total incident energy, then the amount of energy absorbed by the object is:

$$\alpha = 1 - 0.3 - 0.2$$
$$= 0.5 \text{ (i.e. 50\% of the total incident energy)}$$

A.2 EMISSIVITY

A true blackbody source for industrial applications has not yet been developed. However, various radiant heating elements are available with a wide range of radiant efficiencies. The efficiency of a radiant heater is given by its emissivity value. Emissivity is defined as the ratio of the radiant energy emitted by an object at a given temperature and the radiant energy emitted by a blackbody at the same temperature.

$$e = W_s / W_{bb} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where e = emissivity of source
W_s = Total radiant energy emitted from a source at a given temperature
W_{bb} = Total radiant energy emitted from a blackbody at a given temperature

A.3 PLANCK's LAW

In order to understand the spectral distribution of infrared radiation from a source, we must first understand Planck's Law. This law gives us the spectral distribution of radiation from a blackbody source. That is, a source that emits 100% infrared radiation at a given single temperature. It is important to understand that in practice, infrared sources are made up of thousands of point sources that are all at different temperatures. Each point source will have a different spectral distribution and the combination of point sources will make up the entire spectral distribution (Figure A1). Therefore, we can only approximate the spectral distribution using an average surface temperature and emissivity value.

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$$R(\lambda) = \frac{e \times (2.416069 \times 10^{-25})}{(\lambda)^5 [\exp^{0.014408/\lambda T} - 1]} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where R(λ) = spectral radiancy
e = emissivity of source
λ = wavelength in metre
T = temperature in K (Kelvin)
K = °C + 273.15

As the temperature of the source increases, the peak wavelength of the source becomes shorter. When the temperature of the source becomes too high, a noticeable amount of energy is emitted from the source as light, i.e. a portion of the energy emitted from the source falls within the wavelengths associated with light. The infrared spectrum starts at 0.7 µm and extends to 1,000 µm. The useful range of wavelengths for infrared heating applications falls between 0.70 µm to 10 µm.

The spectral absorption curve given in Figure A2 shows the range of wavelengths that water molecules will absorb as well as the percentage of absorption. The curve can be used to give a general idea of the range of infrared radiation in which water molecules will absorb.

A.4 REFERENCES

National Plastic Heater (2000). Ceramic Infrared Emitters Technical Manual. National Plastic Heater Sensor & Control Co., Canada, 20 p.

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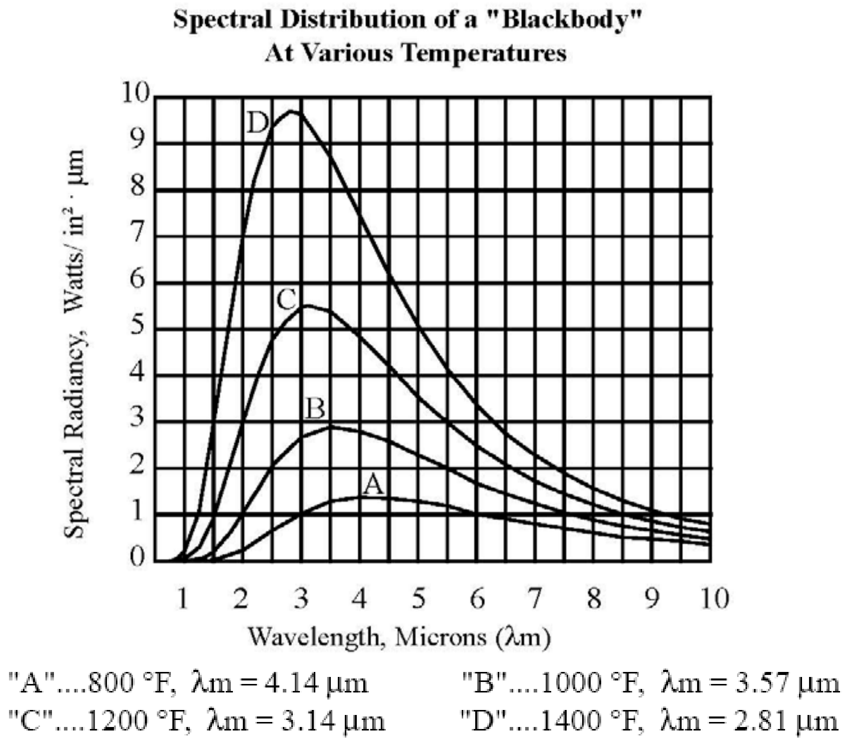

Figure A1 – Spectral Distribution of a Blackbody at Various Temperatures

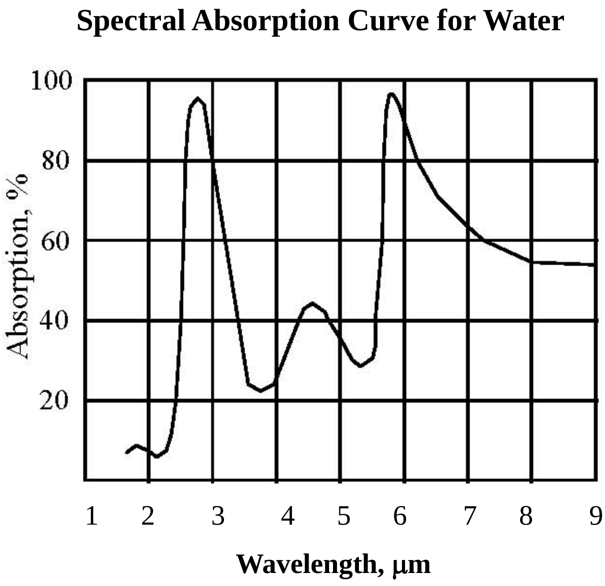

Figure A2 – Spectral Absorption Curve for Water

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Highway Slope Manual (2000), 114 p.

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