

**CONCRETE CARBONATION
IN CANADIAN BUILDINGS**

Prepared for: THE RESEARCH DIVISION
CANADA MORTGAGE AND HOUSING CORPORATION
682 Montreal Road
Ottawa, Ontario
K1A 0P7

Submitted by: ROBERT HALSALL AND ASSOCIATES LIMITED
Consulting Engineers
6th Floor
188 Eglinton Avenue East
Toronto, Ontario
M4P 2X7

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Principal Consultants: Peter Halsall, M.A.Sc., P.Eng.
John Kosednar, B.A.Sc., P.Eng.

CMHC Project Manager: Alvin J. Houston

NOTE: DISPONIBLE AUSSI EN FRANÇAIS SOUS LE TITRE:

LA CARBONATATION DU BÉTON DANS LES BÂTIMENTS CANADIENS

Canada Mortgage and Housing Corporation, the Federal Government's housing agency, is responsible for administering the National Housing Act.

This legislation is designed to aid in the improvement of housing and living conditions in Canada. As a result, the Corporation has interests in all aspects of housing and urban growth and development.

Under Part IX of this Act, the Government of Canada provides funds to CMHC to conduct research into the social, economic and technical aspects of housing and related fields, and to undertake the publishing and distribution of the results of this research. CMHC therefore has a statutory responsibility to make widely available, information which may be useful in the improvement of housing and living conditions.

This publication is one of the many items of information published by CMHC with the assistance of federal funds. The analysis, interpretations and recommendations are those of the Consultant(s) and do not necessarily reflect the views of Canada Mortgage and Housing Corporation that assisted in the study and its publication.

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ABSTRACT

Carbonation is the reaction between atmospheric carbon dioxide and the cement paste that reduces the natural alkalinity of concrete. If the depth of carbonation in a reinforced concrete element reaches the level of the reinforcing steel it can result in corrosion of the steel.

This report estimates the extent of concrete carbonation in Canadian buildings, as well as the impact that carbonation will have on the existing building stock in this country. This report follows a previous CMHC-sponsored study⁽¹⁾, which examined the incidence of carbonation in the Toronto area.

This report concludes that carbonation of concrete, although locally active, is not presently causing widespread corrosion in reinforced concrete structures in Canada. Corrosion will exist in particular locations as a result of carbonation. It will be an increasing problem over time. The depth and quality of concrete cover are the most important factors in protecting reinforcing steel from carbonation-related deterioration. There is no simple method (e.g. on the basis of age, geographical location, visual appearance, etc.) of predicting the susceptibility of individual structures to carbonation.

The carbonation depth data gathered during this survey indicates that concrete sheltered from direct rainfall, but exposed to relatively high humidity and/or combustion exhaust (such as in some parking structures, boiler rooms and industrial facilities), may be particularly susceptible to carbonation induced corrosion.

KEY WORDS: Carbonation, Cement Content, Concrete Cover, Concrete Durability, Corrosion, Phenolphthalein Testing, Reinforcing Steel, Thermogravimetric Analysis.

EXECUTIVE SUMMARY

Introduction

Carbonation of concrete occurs when atmospheric carbon dioxide reacts with various hydrates within the cement paste to produce calcium carbonates. This process reduces the natural alkalinity of concrete. When the carbonation front reaches the level of the reinforcing steel it causes the steel to lose its passivity (immunity to corrosion). This permits corrosion of the steel and results in deterioration of the concrete.

The rate of carbonation is a function of the quality of concrete cover as well as local environmental effects such as relative humidity and concentration of carbon dioxide.

Concrete deterioration caused by carbonation has been widely reported in Europe and Australia. The incidence has not been studied in Canada. Therefore, Canada Mortgage and Housing Corporation (CMHC) commissioned a three phase study to assess the likely occurrence of future carbonation-induced decay of reinforced concrete in highrise residential structures in Canada. The first two phases were a literature review and analysis of other research, and an assessment of the likely impact of carbonation in Toronto.

This report presents the findings/conclusions from part of the third phase of the study that assesses the incidence and impact of carbonation in five cities across Canada.

A companion report entitled "Anti-Carbonation Coatings for Use on Canadian Buildings" presents preliminary findings from an assessment of anti-carbonation coatings.

Objectives

- a) Provide an estimate of the national incidence of carbonation in highrise residential buildings, and to assess the impact that carbonation will have on the durability of the existing building stock in Canada.
- b) Initiate a remedial measures test program limited to one building in Toronto.

Methodology

Local housing agencies and property owners in Halifax, Calgary, Edmonton, Vancouver and Victoria were contacted in order to identify a number of candidate buildings for physical examination. From these, four buildings in each city were selected for study on the basis of the availability of exposed reinforced concrete structural components.

A total of 204 cores were obtained from twenty (20) different buildings for phenolphthalein testing. Twenty (20) of these cores were selected for thermogravimetric testing to verify the phenolphthalein test results.

Following analysis of this data ten (10) of the buildings were selected for further study to determine the depth of concrete cover and to determine the level of corrosion activity.

Remedial measures assessments have been made and a treatment has been completed on one building, previously identified in the Toronto area pilot study. Arrangements have been made with Ontario Housing Corporation (OHC) to monitor the effectiveness of this surface treatment.

Findings

1. Concrete carbonation is generally progressing in all five cities that were included in this study. The rate of carbonation is clearly slower on the west coast (Vancouver/Victoria) than in the other cities included in this study.
2. Corrosion of embedded reinforcing steel in concrete, as a result of carbonation is not yet a major problem in Canada. However, there are localized situations within buildings where corrosion can occur. These localized situations are primarily related to areas where the depth or quality of concrete cover does not comply with the appropriate CSA A23.1 Standard, or in localized areas where an elevated level of atmospheric CO₂ contributed to an accelerated rate of carbonation.
3. The study findings confirm that concrete cover, and the quality of concrete in that cover, are the most important factors in controlling the rate of carbonation. Even if the carbonation front reaches the reinforcing steel depth, prompt initiation of corrosion does not necessarily result, but the potential for future corrosion is greatly increased.
4. Phenolphthalein testing is a cost effective method of determining the presence of carbonated concrete. However, using thermogravimetric testing, it was found that partially carbonated concrete may exist 10-20mm deeper than the level indicated by this test.
5. The reasons are unclear as to why concrete in Canada does not appear to have the same degree of carbonation-related corrosion as found in Europe. Although comparison with the European experience is beyond the scope of this study, explanations may rely on differences in the quality of construction, including the degree of consolidation of the concrete, the quantity and nature of the cementitious systems and, differences in the climate to which the external members were exposed.

A reduction in w:c ratio will reduce the bulk permeability of the concrete and make it less susceptible to carbonation. The Canadian climate may also be instrumental in mitigating concrete carbonation by maintaining the relative humidity in the concrete pore structure above the optimum level (70% RH) for significant periods of time. No comparative data was made available as a part of this study.

Conclusions

The study data provides CMHC and other property owners, such as members of the Canadian Institute of Public Real Estate Companies (CIPREC), with an early warning of the situation in Toronto, and in five other Canadian cities. An orderly approach can be chosen, where thought necessary by individual property owners, for further Canadian carbonation-related materials research and surface treatments.

CSA, in its current concern for writing concrete restoration standards guidelines or advisory documents, should find value in the information derived in this study.

1. Carbonation will have a relatively minor impact on the durability of the existing building stock in Canada. Localized repairs will become necessary, but widespread deterioration, due to severe carbonation in any given building, is not anticipated.
2. The depth of carbonation can be reliably measured as part of the investigation of concrete deterioration.
3. The current building and construction practices in Canada provide adequate protection from carbonation if the minimum requirements of CSA A23.1-M90 "Concrete Materials and Methods of Concrete Construction" are met.
4. There are many variables that determine the rate (and depth) of concrete carbonation within an individual building. The rate of concrete carbonation at any individual location is generally a function of the depth and quality of the concrete cover. However, there is no general or simple system for quantifying the susceptibility of a particular structure, in a particular geographical area, to carbonation.

The findings do indicate that the carbonation rate is dependent upon local environmental conditions. The relative humidity within the pore structure of the concrete, and the permeability of the concrete affect the carbonation rate; i.e. carbonation problems will not normally be experienced on the top surfaces of horizontal members exposed to rain but can be expected on vertical surfaces with reduced concrete cover and/or reduced quality of concrete (e.g. cracked or poorly consolidated concrete). An elevated concentration of atmospheric carbon dioxide also affects the carbonation rate.

1. INTRODUCTION

1.1 Objectives

The principal objectives of the study were to estimate the national incidence of carbonation in Canadian buildings, and to assess the impact that carbonation will have on the durability of the existing building stock. Tests were undertaken on buildings in Halifax, Calgary, Edmonton, Vancouver and Victoria. This report follows a previous CMHC sponsored study ⁽¹⁾ which examined the incidence of carbonation in the Toronto area.

A further objective is to assess the impact of building design and construction practices on the rate of concrete carbonation.

1.2 Investigators

The study was performed as a joint venture between various consultants in order to draw upon their knowledge of local construction practices and to reduce field sampling and laboratory testing costs.

The principal investigators in the study were Robert Halsall and Associates Ltd. of Toronto. Sub-consultants for this study included John A. Bickley Associates Ltd. (Toronto), W.S. Langley and Associates Ltd. (Halifax), HBT Agra Limited (Calgary) and B.H. Levelton and Associates Ltd. (Vancouver).

A parallel research programme, currently in progress in Toronto under the direction of Robert Halsall and Associates Ltd., is studying the long term effects of various coatings on the carbonation of highly permeable concrete.

1.3. Background

Carbonation is a process that reduces the natural alkalinity of concrete. This process involves the reaction of concrete (specifically calcium hydroxide and calcium silicate hydrates within the cement paste) with atmospheric carbon dioxide to produce calcium carbonates. The reaction requires sufficient water in the pores to dissolve the carbon dioxide. The consumption of hydroxyl ions causes the reduction in alkalinity.

Although a variety of concrete properties and environmental factors can contribute to carbonation, the mechanism that leads to deterioration of the reinforced concrete remains consistent. Steel immersed in an aerated, high pH electrolyte, such as concrete, initially exhibits passive behaviour, i.e. the availability of oxygen and high pH produce a film of ferric oxide ($\gamma\text{-Fe}_2\text{O}_3$) on the surface, which effectively acts as a barrier against corrosion⁽¹⁷⁾. Carbonation reduces the alkalinity of the concrete and the passive layer at the surface of the reinforcing steel becomes progressively less stable. At pH levels less than 11, passivity is generally destroyed and reinforcing steel becomes susceptible to corrosion⁽¹⁷⁾. The cross-sectional area of the reinforcing steel is reduced by corrosion which in turn reduces the capacity of the reinforced concrete element. In addition the resulting corrosion product occupies many times the volume of the original steel, causing the concrete to develop internal stresses. These stresses ultimately lead to concrete delaminations (or spalls). By separating the concrete from the reinforcing steel, the composite action between the two is broken down. This further reduces the capacity of the structural element.

The rate of carbonation is partially dependent upon the moisture level within the pore structure of the cement paste matrix. The pores must contain enough moisture to dissolve the atmospheric carbon dioxide but total saturation of the pores mitigates carbonation by slowing the diffusion of carbon dioxide from the exposed surface to the carbonation front. The maximum rate of carbonation occurs when the relative humidity (within the pores) is in the range of 50% to 70% ^(2,3,4). As carbonation is controlled by diffusion of carbon dioxide, it is generally accepted that the rate of carbonation is inversely related to the square root of time (following Fick's Law).

The rate of diffusion (and therefore carbonation) is also dependant upon the concentration of carbon dioxide in the local atmosphere, and the permeability of the concrete. Concrete may be exposed to elevated levels of carbon dioxide in the vicinity of exhaust from processes

involving combustion of hydrocarbons.

Permeability of concrete is a function of total cement content, water/cement (w:c) ratio, concrete placement practices (adequate vibration, degree of aggregate segregation, etc.) and curing along with other less significant variables. Many mathematical models of carbonation try to use concrete compressive strength as a single variable to represent the integral effect of all of these different properties on the rate of carbonation.⁽⁵⁾

Numerous studies have been conducted to determine the effect of different concrete admixtures/supplementary cementing materials on the rate of carbonation. There appears to be contradictory evidence on this issue⁽⁵⁾; some studies have arrived at the conclusion that the inclusion of granulated blast furnace slag or fly ash in a mix design makes concrete more susceptible to carbonation^(6,7,8,9,18), while other studies have found that these admixtures have very little impact on the rate of carbonation^(10,11,12). Still other reports are more specific; they conclude that supplementary cementing materials have a negative effect on carbonation resistance when used to replace portland cement content, but may be beneficial when added to the concrete mix to replace sand content^(13,14,15). Today's concrete mix designs are generally leaner (less portland cement for any given concrete strength) and therefore have higher w:c ratios (in the absence of water reducing agents). This results in concrete with a higher permeability; i.e. more susceptible to carbonation⁽¹⁶⁾.

Some researchers have suggested that carbonation is a self-limiting process⁽⁵⁾. The volume of the calcium carbonate byproduct is greater than that of the calcium hydroxide and calcium silicate hydrates that are originally present in uncarbonated concrete. This causes a reduction in bulk permeability of the concrete^(5,6,16). However, this may not be true for concretes containing granulated blast furnace slag^(6,23).

Such a reduction in permeability tends to reduce the diffusion rate of carbon dioxide from the exposed concrete surface to the carbonation front. It has been reported⁽⁵⁾ that carbonation can produce the following beneficial effects:

- i) increased compressive strength;
- ii) increased modulus of elasticity;
- iii) increased surface hardness; and
- iv) increased resistance to frost attack, sulphate attack and chloride penetration.

However, these beneficial effects are negated in terms of durability of reinforced concrete structures if the carbonation front reaches the level of the reinforcing steel, thereby making it susceptible to corrosion.

2. PROCEDURE

2.1 Methodology

This study includes buildings in five Canadian cities: Halifax, Calgary, Edmonton, Vancouver and Victoria. The buildings were selected on the basis of the availability of exposed reinforced concrete structural components.

The results obtained in this study are assumed to represent conditions in high rise residential construction in all subject cities except Victoria, where all subject buildings are "institutional" buildings; they are generally believed to have a higher quality of concrete construction, than residential buildings. Institutional buildings were included in the Victoria survey due to the lack of available residential highrise buildings with exposed reinforced concrete components.

The number of cores obtained in each city varies from 36 to 48 in accordance with the test protocol (Appendix A). Some of the local factors that could potentially affect the rate (and therefore depth) of carbonation were recorded during the field survey (age of structure, structural component, exposure to weather, height, orientation). The splitting tensile strength was measured for each of the 50mm diameter cores that were tested in order to be consistent with a previous study.⁽¹⁾

A phenolphthalein solution (pH indicator) was applied to the freshly exposed cross-section of each core specimen. The concrete surface generally turns red at pH levels greater than about 9; surfaces with a pH less than 9 remain uncoloured. Although this procedure does not define the exact depth of carbonation (i.e. the distance from the surface of the concrete to the boundary between uncarbonated and partially carbonated concrete), it does provide an indication of the progress of carbonation. It has been reported that the actual depth of the carbonation front can be up to 10mm deeper than that indicated by the phenolphthalein test⁽⁵⁾. Nevertheless, the low cost of this simple test makes it useful for collecting comparative data from a large number of samples.

Four cores from each city were further analyzed using a thermogravimetric test procedure. This laboratory test procedure measures the Ca(OH)_2 (lime) and CaCO_3 (carbonate) content of concrete core specimens to provide a direct measure of the degree of carbonation at various depths. The results are compared to the phenolphthalein test results to confirm the validity of the latter test.

Having assessed the carbonation depth data, two buildings from each city were selected for further corrosion-related investigation. The reinforcing steel in the vicinity of the core samples was located and the depth of concrete cover was documented. Half-cell potentials (with respect to a Cu/CuSO_4 reference electrode) were recorded along the length of reinforcing steel to assess the probability of corrosion activity.

2.2 Limitations

The test protocol (Appendix A) specifies the criteria for selecting buildings and core sample locations for inclusion in this study. Concrete pour records were not available to the field investigative teams. Therefore, depth of carbonation data cannot be correlated to variations in concrete mix design (cement content, w:c ratio, concrete admixtures), concrete placement methods, curing procedures, etc. Each of these factors can influence the rate of carbonation of the cover concrete, but are typically not available to inspectors in the process of assessing existing buildings.

Measurements of local carbon dioxide content and relative humidity were not included in this study, at least partially because there is no standard measure over time.

The splitting tensile strength of each 50mm diameter core was recorded as part of the phenolphthalein test procedure. (50mm cores were employed to minimize the intrusiveness upon building owners' who agreed to participate in this field study.) The absolute value of splitting tensile strength cannot be relied upon because of the disproportionate influence of the coarse aggregate in the 50mm diameter core specimen.

3. RESULTS

3.1 General Observations

All of the carbonation depth test results are tabulated in Appendix B.

General observations of the carbonation depths (as defined by phenolphthalein testing) in each city follow. It is noted that the 15mm depth of carbonation was selected as a reasonable depth beyond which steel could possibly be encountered and to illustrate differences between cities.

- a) **Halifax:**
 - 4 of 16 samples exhibited depth of carbonation (d_c) greater than 15mm
 - all four of these samples were obtained from vertical concrete surfaces
 - 3 of 4 buildings have at least one sample where d_c is greater than 15mm
- b) **Calgary:**
 - 7 of 16 samples exhibited d_c greater than 15mm
 - all seven of these samples were obtained from vertical concrete surfaces
 - 3 of 4 buildings have at least one sample where d_c is greater than 15mm
- c) **Edmonton:**
 - 5 of 12 samples exhibited d_c greater than 15mm
 - all five of these samples were obtained from vertical concrete surfaces
 - 3 of 4 buildings have at least one sample where d_c is greater than 15mm
- d) **Vancouver:**
 - 1 of 12 samples obtained from 4 different buildings exhibited d_c greater than 15mm
 - this sample was obtained from a vertical concrete surface
- e) **Victoria:**
 - 2 of 12 samples exhibited d_c greater than 15mm
 - both of these samples were obtained from a vertical concrete surface
 - the two samples were obtained from separate buildings

This macroscopic examination of the data suggests that carbonation is occurring in all of the subject cities, but is more prevalent in Halifax, Calgary and Edmonton than in Vancouver and Victoria. In comparison, a previous CMHC study⁽¹⁾ found that 38 of 116 samples obtained from buildings in Toronto exhibited $d_c > 15\text{mm}$.

Three cores comprise a sample; the third core was only tested in case of inconsistency in the results from the first two cores. Testing of all three core specimens was only necessary in 8 out of 68 samples in the study. The phenolphthalein test results for different core specimens of a common sample are fairly uniform.

A wide variation in depth of carbonation is noted between different samples (different components) at each of the buildings (Appendix B). This variability is examined in greater detail in the sections that follow.

The results from thermogravimetric analysis generally confirm the phenolphthalein test results.

Many of the buildings in this study were designed and constructed prior to 1970. For Building Codes in effect at that time⁽²²⁾ the minimum required concrete cover for structural components that are exposed to weather, was generally as follows:

- i) 2 inches (50mm) for bars larger than No. 5 (15M); and
- ii) 1½ inches (38mm) for No. 5 (15M) bars or smaller.

A pachometer survey performed at eight (8) of the sixteen (16) buildings included in this study revealed that the depth of concrete cover generally meets or exceeds the requirements of the Code for exposed reinforced concrete components. Refer to Section 3.4 for results from the pachometer survey.

Carbonation-related damage was not observed in any of the subject buildings.

3.2 Discussion of Results

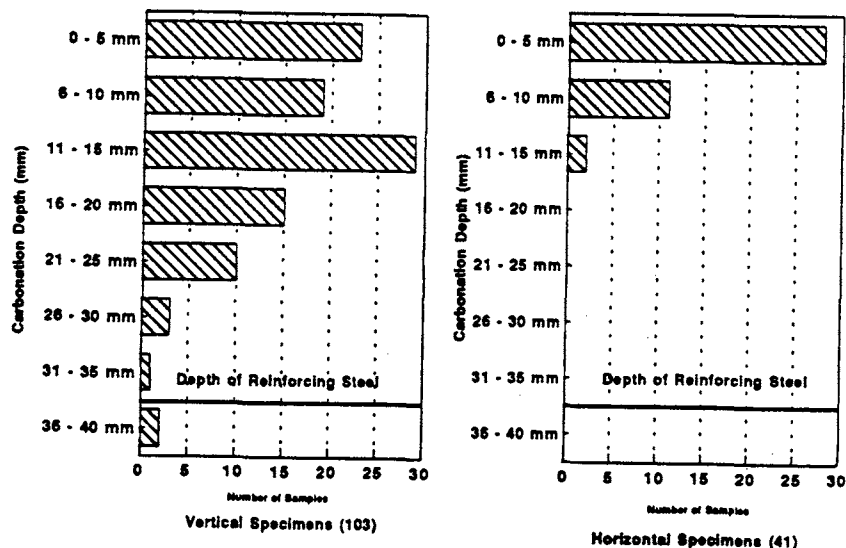
The carbonation data from phenolphthalein testing has been reorganized to examine the effect of various factors on depth of carbonation.

3.2.1 Type of Structural Component

The types of components available for sampling were either vertical (exposed columns, shear walls, foundation walls) or horizontal (top surfaces of balcony slabs or canopies).

The carbonation data has been recorded under these two categories and is summarized in Figure 1.

Figure 1
Distribution of Carbonation Depths - Summary



Carbonation depth results for each individual city are presented in Figures 1A to 1E - Appendix C.

In general, Figure 1 shows that vertical surfaces were found to have much greater average depths of carbonation than horizontal surfaces. Because this variability was anticipated, much fewer cores were obtained from horizontal surfaces than vertical surfaces in each city.

- i) In horizontal surfaces, only 2 cores out of 41 had an average carbonation depth over 10mm. One of the two locations (11mm; HT2 from Vancouver) was partially shielded from direct rainfall; the other one (11.52mm; E/SP/S-1 from Edmonton) was exposed to rainfall).
- ii) In vertical surfaces, the percentage of carbonation depths greater than 15mm ranged from 37% in Halifax to 20% in Victoria. No correlation to rainfall exposure conditions was noted for the vertical samples.

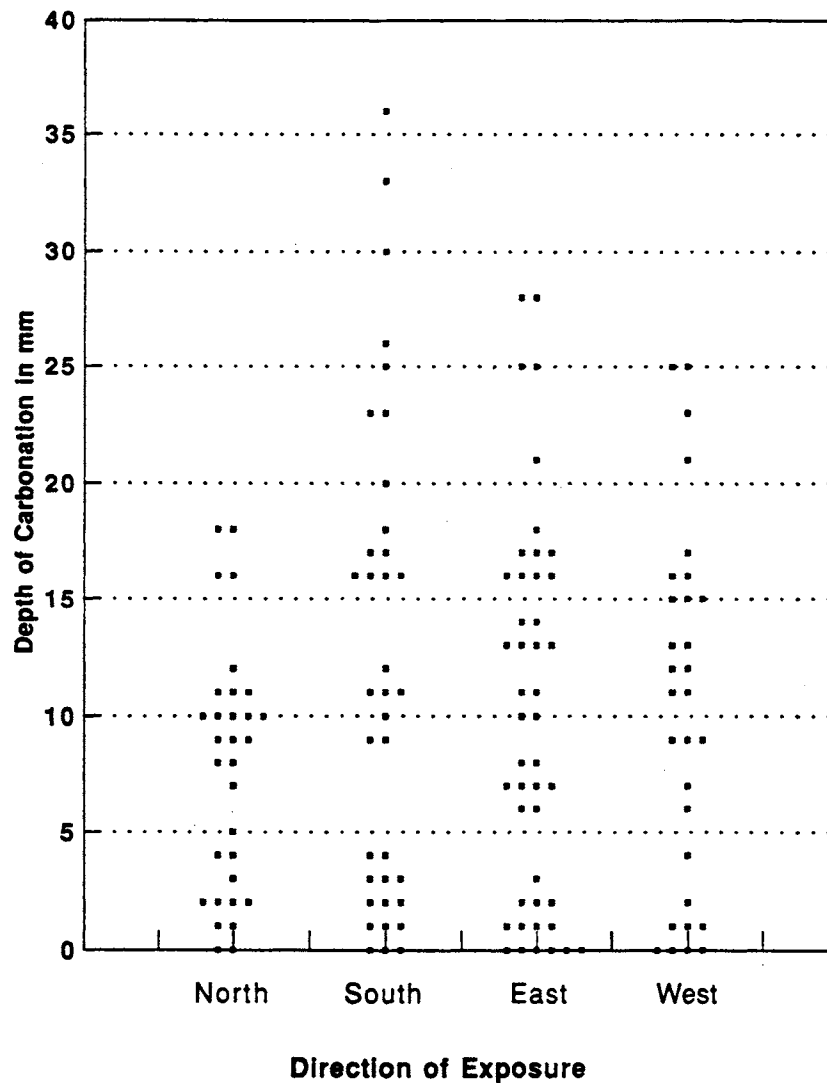
The rate of carbonation is maximized at relative humidities between 50% and 70%^(2,3,4). Previous field studies^(5,19,20) have found that the rate of carbonation was generally higher for drier exposure conditions (i.e. interior concrete or elements shielded from direct rainfall). The pore structure in horizontal concrete surfaces that are exposed to rainfall remains saturated much longer than vertical concrete surfaces with similar exposures. Diffusion of atmospheric carbon dioxide to the carbonation front is mitigated by excessive saturation levels. This reduces the carbonation rate, and explains the results noted in i) above. The carbonation depth on the underside of horizontal slabs was not included in this study; the carbonation rate should be higher on the underside because this surface is shielded from exposure to direct rainfall.

The trends observed in this study confirm that carbonation progresses at a slower rate on the top surface of horizontal elements. These results are consistent with previous studies.

3.2.2 Compass Orientation

The distribution of carbonation depth data has been organized relative to the orientation (direction of exposure) for the individual core specimens. The resulting data from each city is presented in Figure 2A to 2E - Appendix D. The aggregate summary of the data is provided in Figure 2 below. No pronounced trends in carbonation depth are apparent from the orientation of exposed elements in any individual city.

Figure 2
Depth of Carbonation vs. Direction
of Exposure - Summary

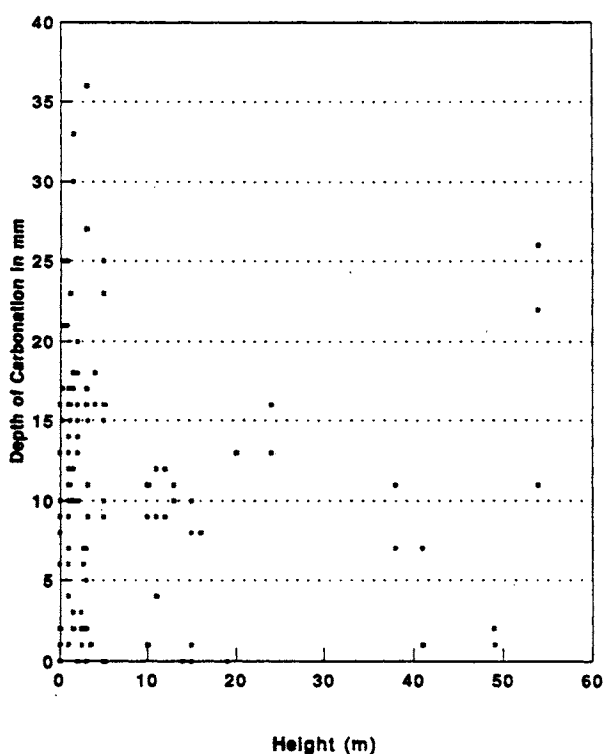


In general, it appears as if the rate of carbonation was the greatest on the south elevation and least on the north elevation. This could be related to differences in the relative humidity within the pore structure (presumably drier on the south elevation). The carbonation rate is dependent upon the microclimate in the pore structure, and this can be highly variable in different building components. For example, at a given moisture content in the concrete pores, if the temperature rises (e.g. due to solar gain on the south elevation), then the relative humidity will fall. Therefore, compass orientation alone cannot be used as a reliable predictor of carbonation rate.

3.2.3 Height

Carbonation rates may be elevated by increased exposure to carbon dioxide from automobile exhaust. The atmospheric concentration of exhaust gases is typically higher close to the base of a building. This may particularly apply to buildings that are located close to a busy street, or other sources of combustion byproducts. No industrial buildings were included in this survey, therefore the primary source of elevated CO₂ levels in this study would be automobile exhaust. Results for each city are presented in Figures 3A to 3E - Appendix E. The collected data are summarized in Figure 3 below.

Figure 3
Depth of Carbonation vs.
Height - Summary



The data supports the premise that the rate of concrete carbonation is generally inversely proportional to the height of the sample above grade. If we eliminate anomalies associated with two buildings from the carbonation test results, a clear relationship can be seen. The anomalies exist at sites N & S in Vancouver; the greatest depths of carbonation were noted in samples obtained from the roof. In one of these cases, a sample from a vertical surface (sample N1) was located in close proximity to a roof top exhaust fan ventilation duct. This may produce an elevated level of CO_2 in the local atmosphere.

On some specific buildings a definite relationship between carbonation depths and proximity to heavy automotive traffic (an elevated concentration of CO_2) was noted.

At site No.6653-B (Halifax) the west elevation is exposed to automotive traffic and the east elevation faces the harbour. The west elevation (exposed to automotive exhaust) exhibits greater carbonation (refer to Appendix B).

At site No.6653-C (Halifax), concrete columns in an open garage, at grade level, beneath the building exhibit significantly more carbonation than elsewhere on the same building.

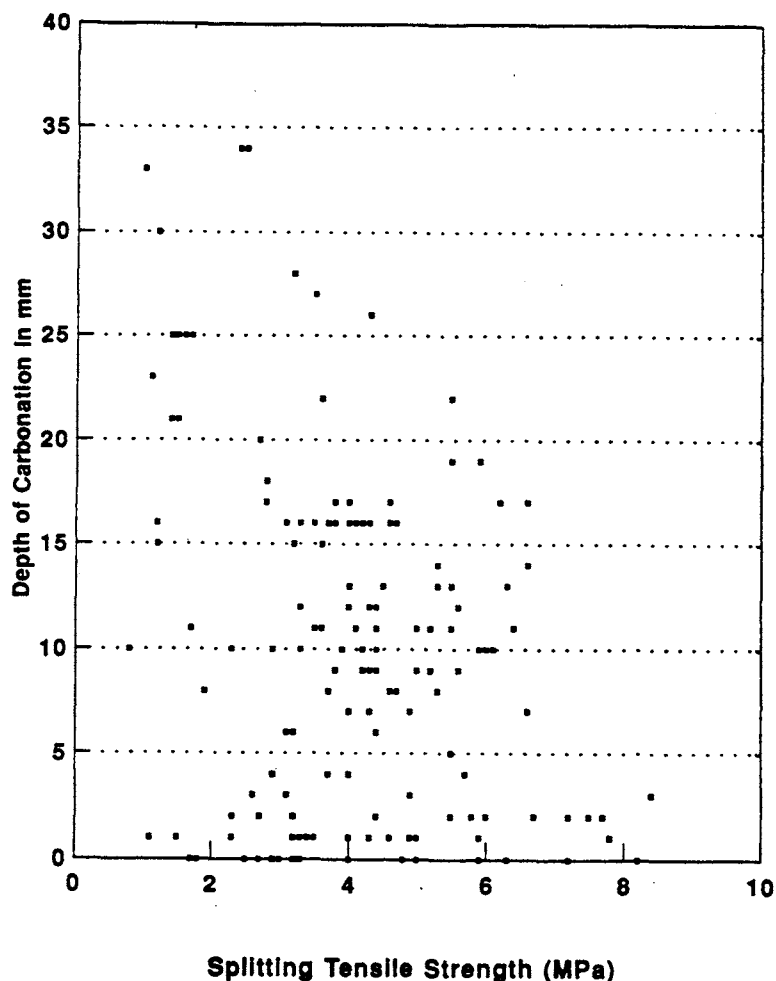
Similar behaviour was noted at Site No. C/E in Calgary (Appendix B). A column at grade level has a greater depth of penetration than samples obtained from vertical surfaces at greater height. (Splitting Tensile Strength variation may be a factor - refer to Section 3.2.4)

3.2.4 Concrete Properties

The concrete strength characteristics will provide a general indication of a combination of factors including cement content, w:c ratio, porosity, placement/curing procedures etc. The permeability of the concrete is dependent upon each of these factors. Therefore the carbonation rate can be affected by each of them.

The depth of carbonation is plotted versus splitting tensile strength in Figure 4 below. (Results for each individual city are given in Figure 4A to 4E in Appendix F).

Figure 4
Depth of Carbonation vs. Splitting
Tensile Strengths - Summary



The data from Halifax, Calgary and Edmonton appear to indicate a correlation between carbonation depth and strength. No such correlation was evident in Vancouver and Victoria.

There is a wide variation in measured carbonation depth at all values of splitting tensile strength. Cores with very little carbonation were observed at all values of splitting tensile strength indicating that all of the conditions required for carbonation were not present.

The maximum depth of carbonation generally declines with increasing splitting tensile strength. This trend is most evident in the case of the Edmonton data.

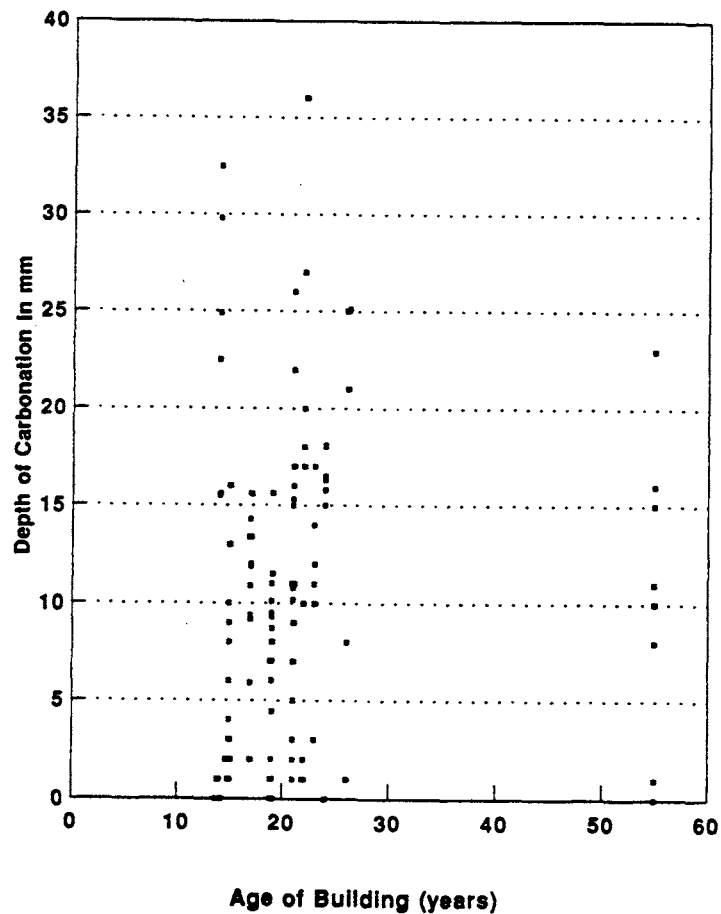
The values of splitting tensile strength are slightly higher in Vancouver and Victoria compared to other cities. Although the absolute accuracy of individual measurements is questionable, this sample does indicate a trend. The four buildings selected for this study in Victoria can be classified as institutional buildings; not below average construction quality as defined in the test protocol (Appendix A). Conversely, all four buildings selected for study in Vancouver are high-rise residential buildings. Despite the difference in the type of building samples, both sets of splitting tensile strength data are indicative of higher quality concrete in Vancouver and Victoria.

The concrete core specimens from Vancouver/Victoria exhibit less carbonation than those from the other three cities in this study. Only two cores from Vancouver (and none from Victoria) had measured carbonation depths greater than 20mm (at elevator penthouse wall - refer to 3.2.3).

3.2.5 Age

Carbonation depth is plotted as a function of building age in Figure 5. Results from different cities are given in Figures 5A to 5E - Appendix G.

Figure 5
Depth of Carbonation vs.
Age of Building - Summary



Examination of these figures demonstrates that time alone cannot be used as a predictor of carbonation. A structure cannot be classified as "prone to carbonation-related damage" simply on the basis of age. Nonetheless, it is well established that carbonation depth is a function of time; it appears that the size and distribution of our sample is inadequate to support this premise.

3.3 Thermogravimetric Test Results

Thermogravimetric testing gives a more accurate indication of the progress of the carbonation front through the cross-section of the concrete by measuring the variation in lime ($\text{Ca}(\text{OH})_2$) and carbonate (CaCO_3) contents, because lime is consumed and carbonates are produced during the carbonation process. The tabular data from carbonation depth testing by thermogravimetric means is presented in Appendix H and graphically presented in Appendix J. The solid lines in the figures in Appendix J illustrate the variation in lime and carbonate contents with respect to depth of concrete. The phenolphthalein test results are indicated by the dotted lines; they are representative of fully carbonated concrete. For the purposes of this study, the test results at the 65-70mm horizon are assumed to represent the lime content of the originally hydrated cement (uncarbonated "*peak lime content*").

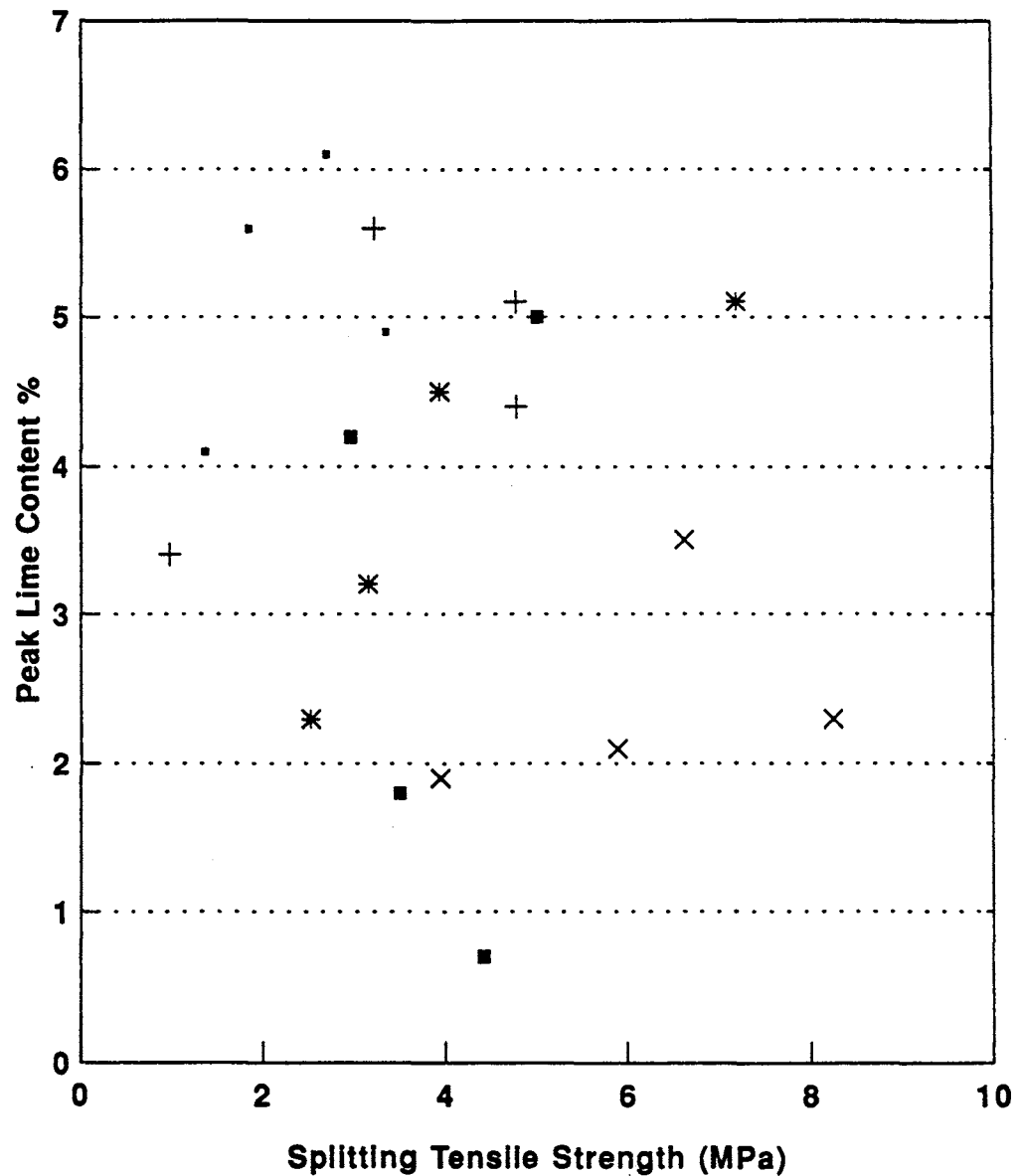
General observations are noted as follows:

- i) The depth of carbonation as determined by phenolphthalein testing corresponds to a lime ($\text{Ca}(\text{OH})_2$) content less than 1% (by weight of concrete). The exceptions are illustrated in Figures 6C, 6K and 6U.
- ii) The thermogravimetric test results generally verify that the phenolphthalein test results indicate the depth of *total* carbonation. The notable exceptions are illustrated in Figures 6C (phenolphthalein testing indicates a depth of carbonation of 20mm, whereas thermogravimetric test results indicate a depth of carbonation less than 15mm) and 6H (phenolphthalein testing indicates no measurable carbonation, whereas thermogravimetric test results indicate that at least 10mm of this core specimen is 100% carbonated).
- iii) In some cases, the depth of *partial* carbonation extends 10 to 20mm deeper than that indicated by the phenolphthalein testing. This is particularly evident in Figures 6A, 6E, 6F, 6G, 6H (see ii above), 6J and 6R.

- iv) The depth of *partial* carbonation generally corresponds to the zone where carbonate content increases. This in turn, corresponds to the zone where the lime content decreases.
- v) The carbonate contents in the "uncarbonated" zones of the cores are fairly uniform in each city. The data obtained from Calgary is the lone exception; the carbonate content from the Calgary concrete specimens is much higher than the other specimens obtained in this study.
- vi) The *peak lime content* of the core specimens varies greatly from building to building amongst all of the cities. The peak lime content may be related to the total cement content of the original mix design, the degree of hydration of the cement, and/or the type of aggregate. Each of these factors can affect the rate of carbonation.
- vii) If the peak lime content is related to the total content of hydrated cement, then this maximum (uncarbonated) lime content should also be directly related to the strength of the concrete. An exception to this would occur where supplementary cementing materials (pozzolans, granulated blast furnace slag, silica fume) have been incorporated into the mix design; however, the use of these materials was not prevalent in Canada when most of these buildings were constructed.
- viii) The carbonation depth *is not* a function of the absolute value of peak lime content. However, the absolute value of lime content near the surface of the concrete *is* important because it reflects reserve lime capacity.

Since the compressive strength and original mix design are not known for any of the concrete specimens, the maximum lime content has been plotted with respect to splitting tensile strength for four (4) cores from each city in Figure 7 on the following page.

Figure 7
Peak Lime Content vs Concrete Splitting
Tensile Strength - Summary



• Halifax + Calgary * Edmonton ■ Vancouver X Victoria

Definitive interpretation of Figure 7 is limited since the individual split tensile strength results are not reliable, and because the maximum lime content cannot be verified as uncarbonated. Nonetheless, the following observations are noted:

- a) for the Edmonton core specimens, the split tensile strength increases with higher lime content; this would be expected since the lime content should be indicative of the content of hydrated cement;
- b) for the Vancouver core specimens, the split tensile strength does not appear to be related to lime content; two of these specimens represent the lowest lime contents in the survey;
- c) the Victoria core specimens generally have a lower lime content than those of other cities, although the split tensile strength results are generally higher;
- d) the Halifax results are the inverse of those from Victoria - the lime content is generally higher than those of other cities, yet the split tensile strength results are generally lower.

The Halifax core specimens exhibited a higher value of carbonation (as a whole) than the Victoria core specimens; this seems to indicate that concrete strength (as it relates to permeability) is a more significant factor than free lime content (cement content) in determining rate of carbonation.

3.4 Pachometer and Half-Cell Potential Survey

None of the exposed reinforced concrete components that were included in this study exhibit visible signs of deterioration.

The phenolphthalein test results, as well as the results of the pachometer and half-cell potential surveys (to measure the depth of reinforcing steel and level of corrosion activity) in each city are summarized in Table 1 below.

Table 1 - Pachometer and Half-Cell Potential Survey Results

City/Sample #	Depth of Carbonation (mm) ₍₁₎	Range of Concrete Cover (mm)	Range of Half-Cell Potentials (mV) ₍₂₎
Halifax			
A1	21 to 25	105 to 120	-98 to -154
A2	None	76 to 120	-122 to -242
A3	21 to 25	90 to 105	-21 to -152
B1	None	60 to 70	-37 to -296
B2	8 to 10	60 to 70	-168 to -278
B3	15 to 23	0 to 20	-326 to -359
B4	10 to 16	6 to 32	-295 to -339
Calgary			
C/E/SW	15.3 to 15.6	35 to 50	-115 to -245
C/E/BW	22.5 to 24.9	30 to 45	-103 to -222
C/E/C	29.8 to 32.5	35 to 65	-159 to -300
C/R/EW	13.35 to 14.27	> 90	-97 to -256
C/R/WW	11.92 to 13.16	45 to 82	-6 to -327
C/R/S	9.16 to 9.69	60 to 75	-321 to -486
Edmonton			
E/V/W-S	35.9 to 36.0	50 to 61	-31 to -52
E/V/W-E	27.0 to 27.4	31 to 46	-95 to -280
E/V/W-N	17.0 to 17.2	48 to 61	-10 to -32
E/V/A/C	15.60 to 15.64	48 to 60	-20 to -48
E/V/A/N	8.68 to 10.13	32 to 45	-44 to -84
E/V/A/S	None	*none located	n/a
Vancouver			
N1	11 to 26	27 to 45	-65 to -132
N2	5 to 7	> 100	-30 to -150
N3	9 to 15	*none located	n/a
HT1	1 to 2	30 to 80	-125 to -225
HT2	7 to 11	60 to 67	-42 to -105
HT3	~8	12 to 35	-180 to -370
Victoria			
CO1	~11	37 to 90	-351 to -487
CO2	1 to 9	69 to 90	-202 to -260
CO3	16 to 17	66 to 150	-120 to -176
CS1	10 to 11	4 to 85	-123 to -325
CS2	3 to 12	60 to 91	-127 to -320
CS3	14 to 17	75 to 89	-134 to -186

1. Dc was measured by phenolphthalein testing
2. All half-cell potentials recorded with respect to copper-copper sulfate (Cu/CuSO₄) reference electrode.

In general, the lack of concrete deterioration can be attributed to the fact that the depth of carbonation (as indicated by phenolphthalein testing) has not yet reached the level of the reinforcing steel. The exceptions where carbonation has reached the level of the reinforcing steel are noted as follows:

- a) Halifax Sample Nos: B3, B4; and
- b) Victoria Sample No: CS1

According to the ASTM test method⁽²¹⁾ that governs interpretation of half-cell potential surveys for steel in concrete, a potential more negative than -350mV (wrt Cu/CuSO₄ [CSE] ref) indicates over 90% probability of active corrosion of the embedded steel in that area.

Both of the aforementioned Halifax samples exhibit potentials more negative than -350mV (CSE) but no visible concrete deterioration was observed. In both cases the walls in this building, constructed circa 1930, were reinforced with wire mesh. The mesh was located very close to the surface of the concrete, but it does not occupy enough volume to create a delamination plane.

The Victoria sample (CS1) has half-cell potentials ranging from -315 to -325mV (CSE) on a rebar whose concrete cover ranged from 39 to 51mm. These potentials may indicate active corrosion. Concrete carbonation has only penetrated to a depth of 10 to 11mm at this location. It was noted that an adjacent length of rebar with only 4mm of concrete cover, was still passive (i.e. not corroding).

Of the remaining 29 samples where half-cell potentials were recorded, only 3 samples have potentials more negative than -350mV (CSE); they are listed as follows:

- a) Calgary Sample No: C/R/S
- b) Vancouver Sample No: HT3; and
- c) Victoria Sample No: C01

²¹This test method is presently being revised by ASTM. The empirical criteria included in this test method are being reviewed because there is documented evidence to demonstrate that the criteria are not absolute.

In each case, the depth of total carbonation (as defined by phenolphthalein testing) had not reached the level of the reinforcing steel. The thermogravimetric analysis indicates that the zone of *partial* carbonation can extend 10 to 20mm deeper than that indicated by phenolphthalein tests (refer to Section 3.3). This argument can be used to explain the corrosion of a short section of rebar at Sample No.HT3 in Vancouver. The depth of carbonation was about 8mm. The concrete cover on this section of reinforcing steel was about 12mm, and the half-cell potential was -370mV (CSE) (actively corroding). The concrete cover 500mm away, along the same bar, was 30mm and the corresponding half-cell potential was -180mV (CSE) (passive).

Sample No.C/R/S from Calgary exhibited active corrosion potentials. The depth of carbonation (as defined by phenolphthalein testing) was only about 9.5mm, while the concrete cover on the reinforcing steel exceeds 60mm. In this case, it appears as if the aggressive corrosion potentials are the result of chloride ion penetration. During the initial field work it was not apparent to the field investigators that this local area was subjected to deicing salts in winter; the field investigators subsequently confirmed this to be the case.

Sample No.C01 from Victoria also exhibited active corrosion potentials. The depth of carbonation was about 11mm, while the concrete cover exceeds 37mm. The most active corrosion potential (-487mV) was recorded in an area where the cover concrete is cracked. This area was about 300mm away from the core locations. It is likely that the depth of carbonation is much greater in the immediate vicinity of this crack. One other length of reinforcing steel within the sample area had 90mm of concrete cover but it was also actively corroding. This wall is 10m above grade, and would not be subjected to deicing salt application; we cannot explain this behaviour without checking the concrete for background chloride content (i.e. chlorides included in the original concrete mix design).

Sample No.N1 obtained from a penthouse wall in Vancouver exhibits opposite behaviour. The depth of carbonation has penetrated within 1mm of the minimum depth of the reinforcing steel at this sample location, yet the half-cell potentials indicate that the surface of the reinforcing steel remains passive (not corroding).

3.5 Time to Corrosion

Having established the age of the building, the present depth of carbonation and the depth of the reinforcing steel, it is possible to estimate time before carbonation reaches the level of the steel, using the following relationship:

$$d_c = k\sqrt{t}$$

where t , is the age in years, and k is a factor [$\text{mm}(\text{years})^{-1/2}$] that represents all of the variables that affect rate of carbonation (refer to Section 1.3).

The results from this are presented in Table 2. The estimated time to corrosion, t_{corr} (years), represents the time (from the date of construction) for the carbonation front, as defined by phenolphthalein testing to reach the shallowest layer of reinforcing steel.

Table 2 - Estimated Time to Corrosion

City Sample #	Year of Construction	D _a (max) mm	k mm/yr	Concrete Cover (min) mm	t _{corr} years (est)
Halifax					
A1	1964	25	4.81	105	476
A2	1964	0	0	76	∞
A3	1964	25	4.81	90	350
B1	1930	0	0	60	∞
B2	1930	10	1.28	60	2200
B3	1930	23	2.94	0	0
B4	1930	16	2.05	6	9
Calgary					
C/E/SW	1976	15.6	4.03	35	75
C/E/BW	1976	24.9	6.43	30	22
C/E/C	1976	32.5	8.39	35	17
C/R/EW	1973	14.3	3.36	90	717
C/R/WW	1973	13.2	3.10	45	210
C/R/S	1973	9.7	2.28	60	693
Edmonton					
E/V/W-S	1968	36.0	7.51	50	44
E/V/W-E	1968	27.4	5.71	31	30
E/V/W-N	1968	17.2	3.59	48	178
E/VA/C	1971	15.6	3.50	48	188
E/VA/N	1971	10.1	2.27	32	200
E/VA/S	1971	0	0	n/a	∞
Vancouver					
N1	1969	26	5.54	27	24
N2	1969	7	1.49	100	4500
N3	1969	15	3.20	n/a	∞
HT1	1971	2	0.45	30	4500
HT2	1971	11	2.46	60	600
HT3	1971	8	1.79	12	45
Victoria					
CO1	1969	11	2.35	37	250
CO2	1969	9	1.92	69	1290
CO3	1969	17	3.62	66	330
CS1	1967	11	2.35	4	3
CS2	1967	12	2.56	60	550
CS3	1967	17	3.62	75	430

The data in Table 2 demonstrates that carbonation of concrete may contribute to isolated corrosion of reinforcing steel within the service life of buildings in all of these cities. However, the potential development of widespread problems was only identified in two buildings:

- a) Calgary: Building C/E; and
- b) Edmonton: Building E/V/W

The rapid rate of carbonation on these two buildings is occurring in exposed walls/columns with a southerly or easterly exposure. Samples obtained from the north elevations of both buildings exhibit a slower rate of carbonation (refer to Appendix B).

The data from the remainder of the buildings included in this study indicates that carbonation is only a problem in isolated areas where the depth of cover is obviously inadequate. (i.e. does not meet minimum requirements for concrete cover as specified in CSA Standard ⁽²²⁾)

Building B from Halifax (constructed circa 1930), where two samples were obtained from a foundation wall reinforced with mesh demonstrates the relationship between concrete cover and susceptibility to carbonation - related deterioration. In both foundation wall samples, the mesh is located very close to the surface and the carbonation depth extends well beyond the level of the mesh. Half-cell potentials indicate active corrosion in both samples, however, no concrete deterioration was apparent at the time of our survey. Two other samples were obtained from horizontal surfaces elsewhere on the building and the estimated time to corrosion exceeds 2200 years (refer to Table 2).

Building HT from Vancouver, where all of the samples were obtained from sheltered balcony slabs (horizontal surfaces), exhibits similar behaviour. In one sample area (HT3), the depth of carbonation is projected to reach the level of the reinforcing steel within 45 years, however this is directly attributable to the lack of adequate concrete cover. Carbonation should not cause any durability problems within the service life of this structure at the other two sample areas at this building, because the depth of concrete cover is greater (refer to Table 2).

In areas with adequate depth of concrete cover in the remaining buildings, the estimated time required for the carbonation front (as defined by phenolphthalein testing) to reach the reinforcing steel, exceeds 200 years.

4. CONCLUSIONS

Concrete carbonation is generally progressing in all five cities that were included in this study.

The measured rate of carbonation varies greatly. Significant variation was noted between cities; Vancouver and Victoria tend to exhibit slower carbonation than Halifax, Calgary and Edmonton. A previous study⁽¹⁾ reported carbonation rates in Toronto that are comparable to those found in Halifax, Calgary, and Edmonton in this study. Different structural elements on individual buildings also display a variability in carbonation rate; it was observed that concrete elements in which the pores are saturated for any significant length of time tend to have slower carbonation elements. Examples are as follows:

- a) The top surfaces of exposed horizontal elements (e.g. balconies) carbonate slower than exposed vertical surfaces (e.g. columns, shear walls);
- b) Elements that are exposed to direct rainfall carbonate slower than elements that are sheltered;
- c) Exposed elements on the north side of buildings may carbonate at a slower rate than similar elements elsewhere on the same building.

No visible signs of concrete deterioration due to carbonation-related corrosion of reinforcing steel were observed during this survey. The test results indicate that the depth of the carbonation front has generally not reached the level of the reinforcing steel. This can be partially attributed to the fact that the position of the reinforcing steel generally meets Code requirements; the specified minimum depth of concrete cover has been provided for the reinforcing steel. This increases the amount of time before the carbonation front reaches the level of the reinforcing steel. Other factors that may be contributing to superior resistance to carbonation include degree of concrete consolidation at time of placement, degree of curing, etc.

On this basis, it is concluded that current building and construction practices in Canada provide adequate protection from carbonation if the minimum requirements of CSA A23.1-M90 "Concrete Materials and Methods of Concrete Construction" are met.

However, active corrosion of the reinforcing steel in localized areas was noted in four of the cities that were included in this study (Edmonton was the exception). In most of these isolated areas the depth of carbonation has reached the level of the reinforcing steel because an individual bar, or a short section of a bar, was not positioned properly (too close to the surface of the concrete). Another possible cause of premature corrosion, identified during this study, would be isolated exposure to elevated levels of CO₂; generally caused by any process that involves combustion of hydrocarbons. Such an exposure can contribute to an accelerated rate of carbonation.

When the rate of carbonation is extrapolated into the future, using the very basic relationship:

$$d_c = k\sqrt{t}$$

where: d_c is depth of carbonation at time (t)

t is the age of the structure in years; and

k is a constant that accounts for various concrete/environmental factors in one specific area,

it is anticipated that carbonation-related corrosion of the reinforcing steel can be anticipated in localized areas of most buildings in Canada within their anticipated service life. However, this corrosion will generally be restricted to areas with reduced depth of concrete cover and/or reduced quality of concrete cover (e.g. cracked or poorly consolidated concrete), or localized areas exposed to elevated levels of CO₂.

On the basis of this study, it appears that carbonation will have a relatively minor impact on the durability of the existing building stock in Canada. Repair of carbonation-related concrete deterioration in isolated areas of a building will become necessary, however large scale repairs to rectify (or mitigate) widespread problems in a building are not anticipated.

In terms of monitoring progress of concrete carbonation, phenolphthalein testing is a cost-effective method of determining the presence of carbonated concrete. It gives an indication of the depth of carbonation from the exposed concrete surface. The results from corresponding thermogravimetric tests show that the actual depth of partially carbonated concrete can be 10 to 20mm deeper than that indicated by phenolphthalein testing.

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APPENDIX 'A'

TEST PROTOCOL

PHASE III CARBONATION IN CANADIAN BUILDINGS

CMHC FILE NUMBER 6711-5

Test Protocol:

1. Scope of Work

The work shall be limited to testing core samples obtained from buildings selected in accordance with prescribed criteria. Five cities were selected for the follow-up to the Phase II CMHC Carbonation Study ⁽¹⁾ that was conducted in Toronto. The selection of these cities was based upon their potential for carbonation, as reported in Phase I ⁽²⁾, their geographical distribution and the inventory of CMHC buildings in each city. The five cities are:

- a) Halifax
- b) Calgary
- c) Edmonton
- d) Vancouver
- e) Victoria

The extent of carbonation in the core samples shall be tested using phenolphthalein and thermogravimetric test methods.

Concrete strength testing shall be included as a means of comparing concrete properties between sites.

2. Building Selection

The subject buildings shall have these characteristics:

- .1 Constructed prior to 1975;
- .2 Exterior cast-in-place concrete components accessible for coring as described in Section 4.0;
- .3 Below average construction quality (i.e. the work shall include structures that are judged to have significant potential for carbonation on the basis local knowledge of construction practices and on the basis of visual examination of concrete quality).

3. Site Selection

The selection of core locations shall be based on the following requirements. The core samples from each city shall be:

- .1 Obtained from locations where the external surface has not been previously damaged or repaired (no visible delamination or patches);
- .2 Obtained from locations remote from salt splash;
- .3 Obtained from the top surfaces of balconies and exposed reinforced concrete columns and shear walls. Distribute the cores among these components as evenly as possible;
- .4 Distributed among all physical directions as evenly as possible (N, S, E and W).

4. Coring Procedure

Three cores shall be obtained at each location to constitute a valid scientific sample in accordance with the following procedure:

- .1 50mm dia. x 75mm deep cores shall be obtained by diamond drill bit cooled with water; core locations shall be repaired to the satisfaction of the building Owner;
- .2 The cores shall be identified and immersed in distilled water for transportation to the lab;
- .3 The following information shall be recorded for each set of core samples:

- Date
- Location: Street Address
 Type of Component
 Elevation
 Orientation (N, S, E or W)
- Exposure to Weather (i.e. exposed or shielded)
- Age of Structure

- .4 The total number of cores obtained in Victoria, Vancouver and Edmonton shall be thirty-six (36):

	4	Buildings/City
x	3	Samples/Building
x	3	Cores/Sample
<hr/>		
=	36	Cores/City

- .5 The total number of cores obtained in Calgary and Halifax shall be forty-eight (48):

	4	Buildings/City
x	4	Samples/Building
x	3	Cores/Sample
<hr/>		
=	48	Cores/City

5. Laboratory Procedure

- .1 The approximate tensile strength of two concrete specimens shall be calculated according to ASTM C406-86. Two of the three 50mm dia cores/sample shall be split along the longitudinal axis for this purpose.
- .2 Following the splitting of each core, the unmarked half-core shall be identified and returned to storage in distilled water for future testing.
- .3 The two remaining half-cores shall be tested to determine the depth of carbonation using standard phenolphthalein indicator solutions in accordance with the test procedure given in ISO Standard DOC N77E, except that only four depth measurements shall be made.

- .4** The third core of each sample shall remain in storage for future testing UNLESS the results obtained from 6.3 are inconsistent (i.e. variance greater than $\pm 3\text{mm}$). In this case, the third core would also be split and tested as described in 6.3 of this procedure.
- .5** The two most carbonated and two least carbonated specimens from each City, as determined by phenolphthalein testing, shall be selected for further testing as follows;
- a)** The specimens shall be removed from the distilled water and packaged in sealed, air tight, plastic bags for transportation to Ottawa by courier;
 - b)** The depth of carbonation shall be independently tested by the Institute for Research in Construction (IRC/NRC) using thermogravimetric analysis.

APPENDIX 'B'

CARBONATION DATA

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Victoria, B.C.

Date Tested: Dec. 20/90

Building: CS

Year of Construction: 1967

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)		Comments
						D avg.	D max.	
CS 1.	Wall	13 m above ground. Suburban university area	East, exterior, protected from South only	a	6870	10	12	
				b	6420	11	16	
				c				Not tested
CS 2.	Wall	Ground level, 1.5 m above ground	North, exterior, exposed	a	4940	3	18	
				b	4380	12	19	
				c	7070	10	16	
CS 3.	Wall	1 m above ground	East, exterior, protected	a	6550	14	19	
				b	6630	17	20	
				c				Not tested
4.								

Tested By: DMS/DG

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Victoria, B.C.

Date Tested: Dec. 20/90

Building: (X)

Year of Construction: 1969

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)		Comments
						D avg.	D max.	
CO1.	Wall	10 m above ground Suburban university area	Exterior, North, exposed	a	3300	11	17	
				b	3460	11	13	
				c				Not tested
CO2.	Column	Ground level, 1 m above ground	Exterior, West, exposed	a	5890	1	1	
				b	5520	9	13	Split tensile test invalid
				c	---	7	10	
CO3.	Column	Ground level, 1 m above ground	Exterior, protected, East	a	4590	16	18	
				b	3950	17	23	
				c				Not tested
4.								

Tested By: DMS/DG

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Victoria, B.C.

Date Tested: Dec. 20/90

Building: F

Year of Construction: 1976

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)		Comments
						D avg.	D max.	
F 1.	Slab on grade	Ground level. Suburban industrial/ commercial area	East, exterior, exposed	a	5840	0	0	
				b	8250	0	0	
				c				Not tested
F 2.	Slab on grade	Ground level	West, exterior, exposed	a	7800	1	1	
				b	7320	0	0	
				c				Not tested
F 3.	Suspended slab	Second Floor, 5 m above ground	Southwest, exterior, exposed	a	4920	0	0	
				b	6340	0	0	
				c				Not tested
4.								

Note: This building is located on a salt water foreshore. South side is exposed to the foreshore. Ground

Tested By: DMS/DG

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Victoria, B.C.

Date Tested: Sept. 28/90

Building: 1.

Year of Construction: 1975

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)		Comments
						D avg.	D max.	
1. 1.	Wall	Parapet wall at main entrance, ground level. Rural area	South, exterior, exposed	a	7730	2	2	
				b	7450	2	2	
				c				Not tested
1. 2.	Wall	Stairwell, ground level	East, exterior, protected	a	4610	8	13	
				b	4400	6	11	
				c				Not tested
1. 3.	Column	Ground level	West, exterior, exposed	a	4000	13	14	
				b	2960	16	18	
				c				Not tested
4.								

Tested By: DMS/DC

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Vancouver, B.C.

Date Tested: Dec. 20/90

Building: RT

Year of Construction: 1971

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm) D avg. D max.		Comments
RT1.	Balcony slab	16th Floor. Suburban residential/ commercial area	East protected, exterior	a	4910	1	5	4" in 5" slab
				b	4450	7	11	
				c	3440	1	2	
RT2.	Balcony slab	8th Floor	East protected, exterior.	a	2970	0	0	
				b	2760	0	0	
				c				Not tested
RT3.	Balcony slab	2nd Floor	East protected, exterior	a	4000	7	11	
				b	3100	6	8	
				c				Not tested
4.								

Tested By: DMS/DG

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Vancouver, B.C.

Date Tested: Dec. 20/90

Building: IIT

Year of Construction: 1971

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)		Comments
						D avg.	D max.	
IIT1.	Balcony slab	19th Floor. Wall developed residential/commercial area	North, protected, exterior	a	5030	1	3	
				b	4390	2	6	
				c				Not tested
IIT2.	Balcony slab	15th Floor	East, protected, exterior	a	4070	11	15	
				b	4880	7	10	
				c				Not tested
IIT3.	Balcony slab	7th Floor	East, protected, exterior	a	5250	8	11	
				b	4720	8	15	
				c				Not tested
4.								

Tested By: DMS/DG

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Vancover, B.C.

Date Tested: Sept. 27/90

Building: N

Year of Construction: 1969

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)		Comments
						D avg.	D max.	
N 1.	Elevator penthouse wall	Roof above 21st Floor, downtown area	South, exterior, protected, open to above	a	4430	26	28	
				b	4410	11	14	
				c	5510	22	24	
N 2.	Parapet wall	Entrance Canopy above driveway	Exterior, North, exposed	a	5510	5	6	
				b	6520	7	9	
				c				Not tested
N 3.	Wall	3.2 m above ground	Exterior, West, exposed	a	3560	15	17	
				b	3840	9	11	
				c	5150	11	12	
4.								

Tested By: DMS/DG

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Vancouver, B.C.

Date Tested: Sept. 27/90

Building: S

Year of Construction: 1975

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm) D avg. D max.	Comments
S 1.	Elevator penthouse wall	Roof above 10th Floor, suburban resid- ential area	East, exterior, exposed	a	3510	16 20	
				b	3380	13 17	
				c			Not tested
S 2.	Wall	Ground Floor, 1.5 m above ground	North, exterior, sheltered from West	a	5490	2 4	
				b	6680	2 2	
				c			Not tested
S 3.	Topping on suspended slab	Ground level	Exterior, West side, exposed	a	5770	2 2	
				b	4590	1 1	
				c			Not tested
4.							

Tested By: DMS/DC

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Edmonton

Date Tested: 01/02/91

Building: E/VA - Non CMHC Building

Year of Construction: 1971

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)	Comments
1.	Column	5 m above ground	South Exposed	E/VA/C1			Stored
				E/VA/C2	3761	15.64	
				E/VA/C3	4525	15.60	
2.	Column	5 m above ground	North Exposed	E/VA/N1	4468	10.13	
				E/VA/N2			Stored
				E/VA/N3	3693	8.68	
3.	Slab	5 m above ground	Upward Exposed East Side	E/VA/S1	3366	0	
				E/VA/S2			Stored
				E/VA/S3	3941	0	
4.							

Tested By: Mel Schmidt
Hardy BBT Limited - Edmonton

CARBONATION IN CANADIAN BUILDINGS,
CMHC FILE NO. 6711-5

City: Edmonton

Date Tested: 18/01/91

Building: E-SP - Non CMHC Building

Year of Construction: 1971

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)	Comments
1.	Roof Slab	12 m above ground	Upward Exposed South Side	E/SP/S-1	4518	11.52	
				E/SP/S-2	5130	9.25	
				E/SP/S-3			Stored
2.	Shear Wall	11 m above ground	West Exposed	E/SP/SW-1	3938	11.86	
				E/SP/SW-2			Stored
				E/SP/SW-3	4193	9.24	
3.	Column	11 m above ground	North Exposed	E/SP/C-1			Stored
				E/SP/C-2	5691	4.36	
				E/SP/C-3	5014	4.24	
4.							

Tested By: Mel Schmidt
Hardy BBT Limited - Edmonton

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Edmonton

Date Tested: 19/09/90

Building: E/V - Non CMHC Building

Year of Construction: 1968

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)	Comments
1.	Shear Wall	3 m above ground	South Exposed	E/V/W-1S	2525	36.0	Stored
				E/V/W-2S			
				E/V/W-3S	2456	35.9	
2.	Shear Wall	3 m above ground	East Exposed	E/V/W-1E	3553	27.0	Stored
				E/V/W-2E	3162	27.4	
				E/V/W-3E			
3.	Shear Wall	3 m above ground	North Exposed	E/V/W-1N	4575	17.0	Stored
				E/V/W-2N	2953	17.2	
				E/V/W-3N			
4.							

Tested By: Mel Schmidt
Hardy BBT Limited - Edmonton

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Edmonton

Date Tested: 19/09/90

Building: E/CH - Non CMHC Building

Year of Construction: 1969

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)	Comments
1.	Column	1.2 m above ground	South Exposed	E/CH/C-1S			Stored
				E/CH/C-2S	5183	10.8	
				E/CH/C-3S	5934	10.2	
2.	Column	2.4 m above ground	East Exposed	E/CH/C-1E	7208	2.0	
				E/CH/C-2E			Stored
				E/CH/C-3E	8392	3.0	
3.	Foundation Wall	0.3 m above ground	South Exposed	E/CH/W-5S	3799	17.0	
				E/CH/W-6S			Stored
				E/CH/W-7S	4156	15.3	
4.							

Tested By: Mel Schmidt

Hardy BBT Limited - Edmonton

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Calgary

Date Tested: 22/01/91

Building: C/R - Non CMHC Building

Year of Construction: 1973

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)	Comments
1.	Wall	2 m above ground	East Exposed	C/R/EW-1	4614	13.35	
				C/R/EW-2	5333	14.27	
				C/R/EW-3			Stored
2.	Column	10 m above ground	North Exposed	C/R/C-1	5332	9.29	
				C/R/C-2	5532	10.86	
				C/R/C-3			Stored
3.	Wall	1 m above ground	West Shielded	C/R/WW-1			Stored
				C/R/WW-2	5563	13.16	
				C/R/WW-4	5573	11.92	
4.	Slab	Ground level	Upward Exposed North Side	C/R/S-1	4223	9.69	
				C/R/S-2	4485	9.16	
				C/R/S-3			Stored

Tested By: Yoga Yodendran

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Calgary

Date Tested: 21/01/91

Building: C/F - Non CMHC Building

Year of Construction: 1973

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)	Comments
1.	Slab	3 m above ground	Upward Exposed Ease Side	C/F/S-1	6002	1.98	Stored
				C/F/S-2			
				C/F/S-3	3346	1.71	
2.	Column	1 m above ground	West Exposed	C/F/FW-1	3233	5.87	Stored
				C/F/FW-2			
				C/F/FW-3	3692	4.19	
3.	Shear Wall	20 m above ground	East Exposed	C/F/EW-T1	5136	13.08	Stored
				C/F/EW-T2			
				C/F/EW-T3	6489	12.65	
4.	Wall	3 m above ground	East Exposed	C/F/EW-2	3726	15.57	Stored
				C/F/EW-3			
				C/F/EW-4	4787	15.81	

Tested By: Yoga Yogendran
Hardy BBT Limited - Calgary

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Calgary

Date Tested: 21/09/90

Building: C/E - CMHC Building

Year of Construction: 1976

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)	Comments
1.	Shear Wall	5 m above ground	North Exposed	C/E/SW-1N	3351	15.6	
				C/E/SW-2N			Stored
				C/E/SW-3N	4012	15.3	
2.	Balcony Wall	5 m above ground	South Shielded	C/E/DW-1S	1603	24.9	
				C/E/DW-2S	3682	22.5	
				C/E/DW-3S			Stored
3.	Balcony Slab	14 m above ground	Upward Exposed North Side	C/E/BS-1	3226	0	
				C/E/BS-2			Stored
				C/E/BS-3	3023	0	
4.	Column	1.5 m above ground	South Exposed	C/E/C-1S	221	32.5	
				C/E/C-2S			Stored
				C/E/C-3S	1188	29.8	

Tested By: Yoga Yogendran
Hardy BBT Limited - Calgary

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Calgary

Date Tested: 21/09/90

Building: C/P - Don CMHC Building

Year of Construction: 1966

Sample No.	Component	Sample Location/ Elevation	Exposure	Core No.	Splitting Tensile Strength (KPa)	Depth of Carbonation (mm)	Comments
1.	Column	2 m above ground	West Exposed	C/P/C-1W	3218	15.0	
				C/P/C-2W	4118	16.3	
				C/P/C-4W			Stored
2.	Balcony Wall	4 m above ground	South Shielded	C/P/BW-1S	5910	18.1	
				C/P/BW-2S			Stored
				C/P/BW-3S	4213	15.8	
3.	Balcony Slab	2 m above ground	Upward Exposed West Side	C/P/S-1			Stored
				C/P/S-2	3271	0	
				C/P/S-4	4788	0	
4.	Shear Wall	1.5 m above ground	East Exposed	C/P/SW-1E	6176	16.7	
				C/P/SW-2E			Stored
				C/P/SW-3E	5447	18.0	

Tested By: Yoga Yogendran

Hardy BRT Limited - Calgary

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Halifax, Nova Scotia

Date Tested: 91/01/08

Building: 6653-D

Year of Construction: 1975

SAMPLE NO.	COMPONENT	SAMPLE LOCATION/ ELEVATION	EXPOSURE	CORE NO.	SPLITTING TENSILE STRENGTH (kPa)	DEPTH OF CARBONATION (mm)	COMMENTS
1	Wall	8m above grade West Elevation	Exposed Vertical Surface	1	3360	1	
				2	3510	1	
2	Parapet Wall	4.5m above grade South Elevation	Exposed Vertical Surface	1	2600	3	
				2	2960	4	
3	Wall	0.9m above grade, South Elevation	Exposed Vertical Surface	1	4300	9	
				2	3190	10	
4	Wall	0.9m above grade, North Elevation	Exposed Vertical Surface	1	2640	2	
				2	3070	3	

Tested By: W.S. Langley & Associates Limited

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Halifax, Nova Scotia

Date Tested: 90/09/25

Building: 6000 C

Year of Construction: 1968

SAMPLE NO	COMPONENT	SAMPLE LOCATION/ ELEVATION	EXPOSURE	CORE NO.	SPLITTING TENSILE STRENGTH (kPa)	DEPTH OF CARBONATION (mm)	COMMENTS
1	Column	2m above grade North End of Building	Sheltered Exterior Exposure	3	3880	10	
				4	2970	10	
2	Column	2m above grade South End of Building	Sheltered Exterior Exposure	6	2870	18	
				7	2710	20	
3	Spandrel Beam	3.5m above grade, South Elevation	Exposed Vertical Surface	1	4220	1	
				2	3990	1	
4	Spandrel Beam	2.5m above grade, North Elevation	Exposed Vertical Surface	2	2260	2	
				3	3260	1	

Tested By: W.S. Langley & Associates Limited

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Halifax, Nova Scotia

Date Tested: 90/09/20

Building: 6651 B

Year of Construction: 1930 - 1935

SAMPLE NO.	COMPONENT	SAMPLE LOCATION/ ELEVATION	EXPOSURE	CORE NO.	SPLITTING TENSILE STRENGTH (kPa)	DEPTH OF CARBONATION (mm)	COMMENTS
1	Parapet Wall Cap	15m above grade	Exposed Horizontal Surface	1	2310	1	
				2	2530	None	
2	Parapet Wall Cap	15m above grade South Elevation	Exposed Horizontal Surface	1	1900	8	
				2	1770	10	
3	Foundation Wall	1.2m above grade, West Elevation	Exposed Vertical Surface	1	1200	15	See below.
				2	1150	23	
				3	1220	16	
4	Foundation Wall	1.0m above grade, East Elevation	Exposed Vertical Surface	1	1680	11	
				2	2190	10	

Carbonation indicated to a depth of 40 mm along one side of core which appeared to be located immediately above a construction joint not visible prior to coring.

Tested By: W.S. Langley & Associates Limited

CARBONATION IN CANADIAN BUILDINGS
CMHC FILE NO. 6711-5

City: Halifax, Nova Scotia

Date Tested: 90/09/19

Building: 66's } A

Year of Construction: 1964

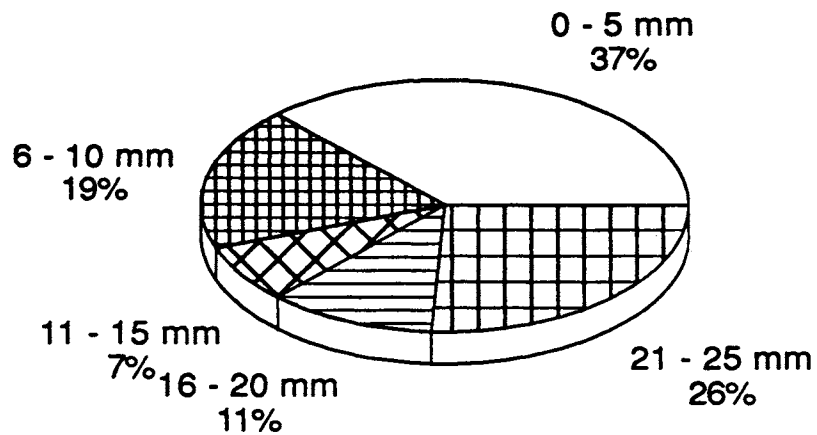
SAMPLE NO.	COMPONENT	SAMPLE LOCATION/ ELEVATION	EXPOSURE	CORE NO.	SPLITTING TENSILE STRENGTH (kPa)	DEPTH OF CARBONATION (mm)	COMMENTS
1	Foundation Wall	0.8m above grade West Elevation	Exposed	1	1380	25	
			Vertical	2	1380	21	
			Surface	3	1380	25	
2	Cast in place Concrete Doorway Canopy	3.0m above grade West Elevation	Exposed	1	1780	None	
			Horizontal	2	1850	None	
			Surface				
3	Foundation Wall	0.3m above grade East Elevation	Exposed	1	1530	21	
			Vertical	2	1690	25	
			Surface	3	1380	25	
4	Balcony	5th storey, East Elevation	Exposed	1	1130	1	
			Horizontal	2	1530	1	
			Surface				

Tested By: W.S. Langley & Associates Limited

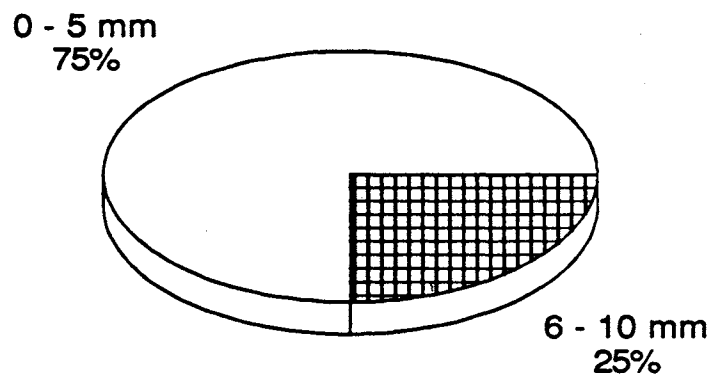
APPENDIX 'C'

DISTRIBUTION OF CARBONATION DEPTHS FOR HORIZONTAL/VERTICAL SPECIMENS

Figure 1A
Distribution of Carbonation Depths - Halifax

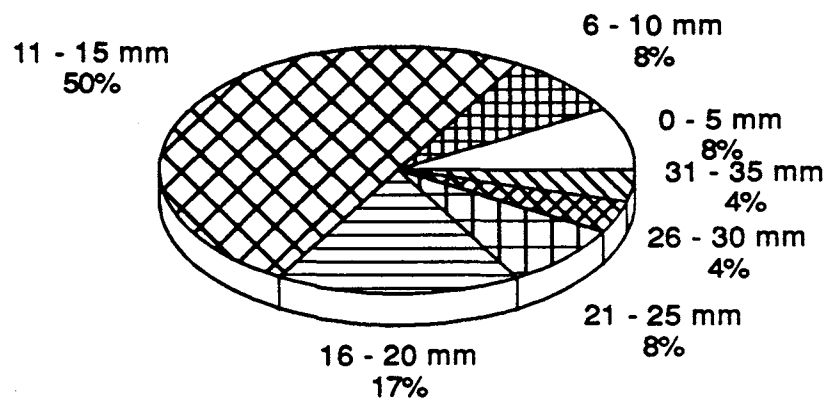


Vertical Specimens (27)

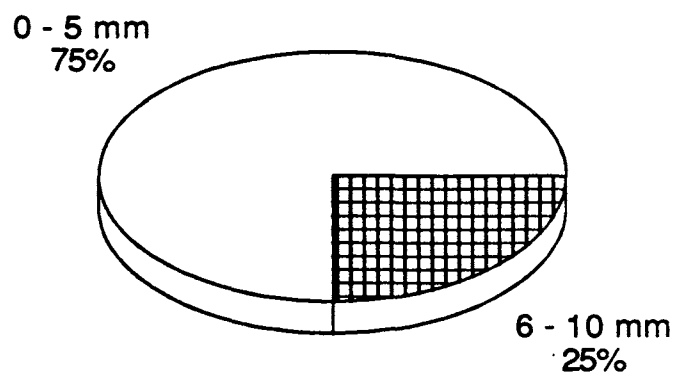


Horizontal Specimens (8)

Figure 1B
Distribution of Carbonation Depths - Calgary

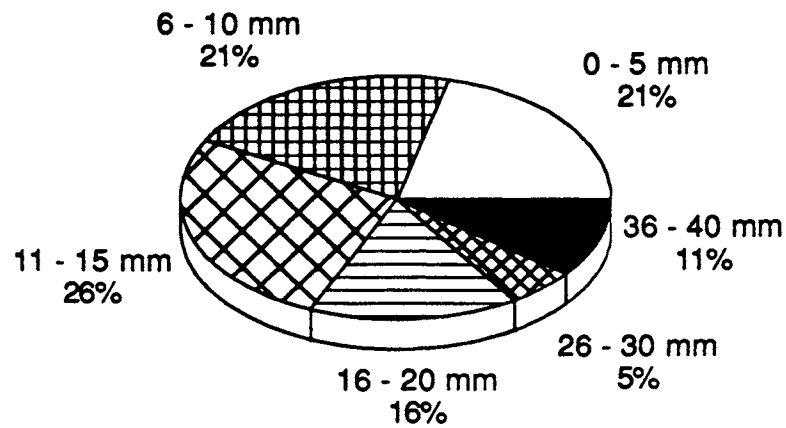


Vertical Specimens (24)

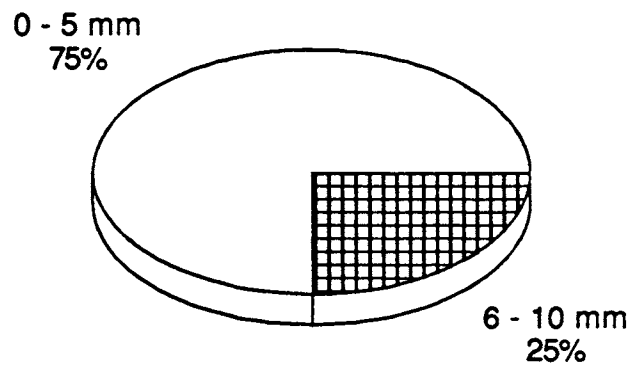


Horizontal Specimens (8)

Figure 1C
Distribution of Carbonation Depths - Edmonton

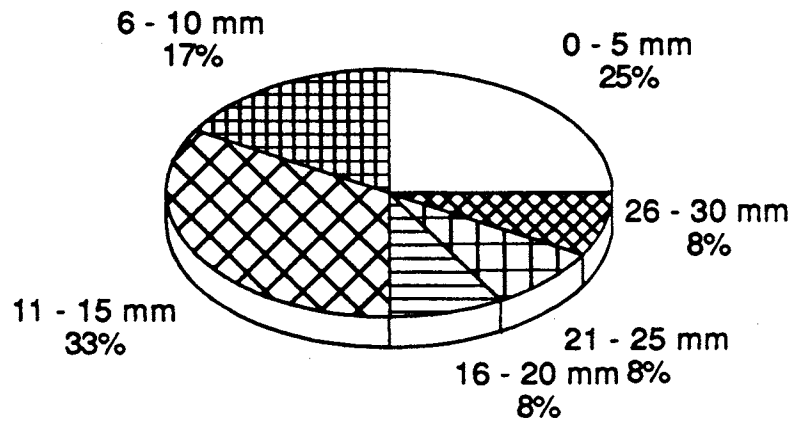


Vertical Specimens (20)

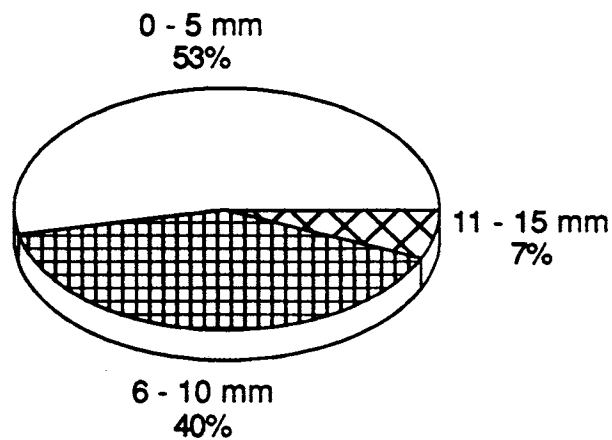


Horizontal Specimens (4)

Figure 1D
Distribution of Carbonation Depths - Vancouver

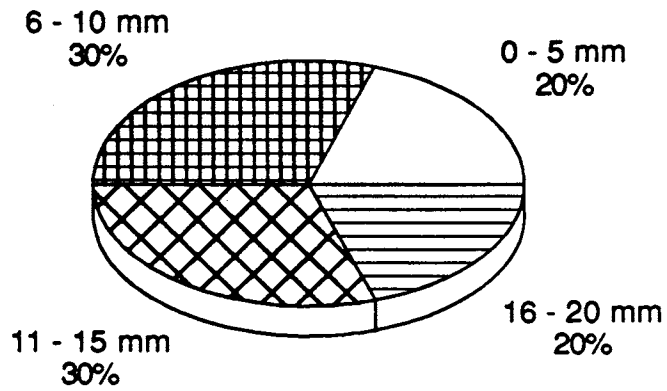


Vertical Specimens (12)

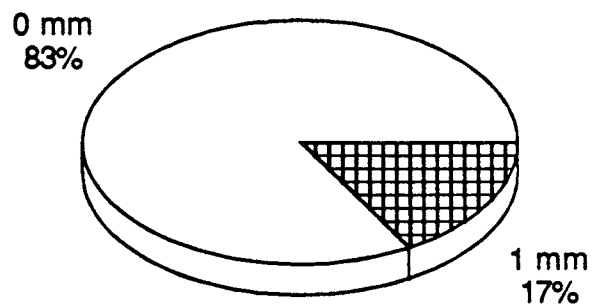


Horizontal Specimens (15)

Figure 1E
Distribution of Carbonation Depths - Victoria



Vertical Specimens (20)



Horizontal Specimens (6)

APPENDIX 'D'

DEPTH OF CARBONATION VS DIRECTION OF EXPOSURE

Figure 2A
Depth of Carbonation vs. Direction
of Exposure - Halifax

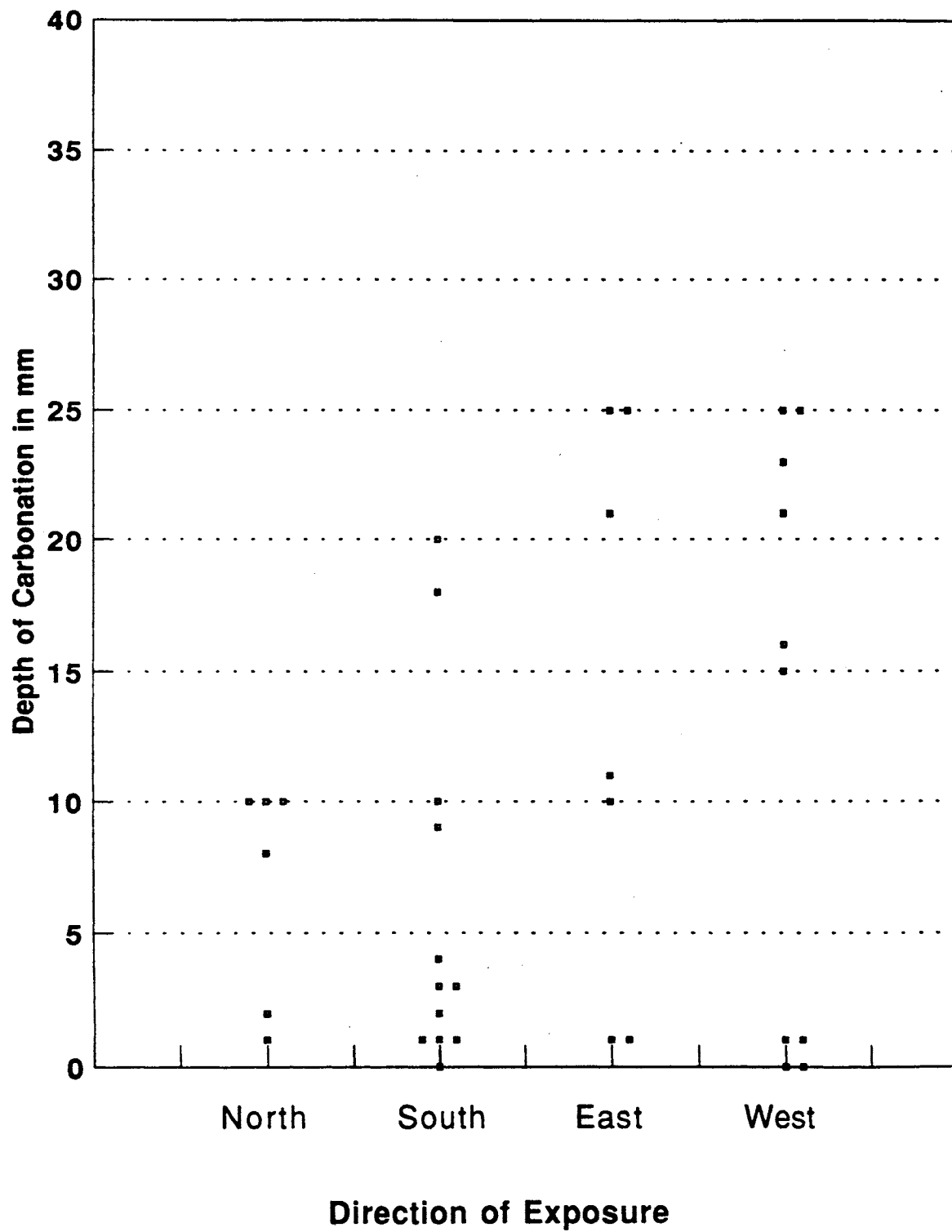


Figure 2B
Depth of Carbonation vs. Direction
of Exposure - Calgary

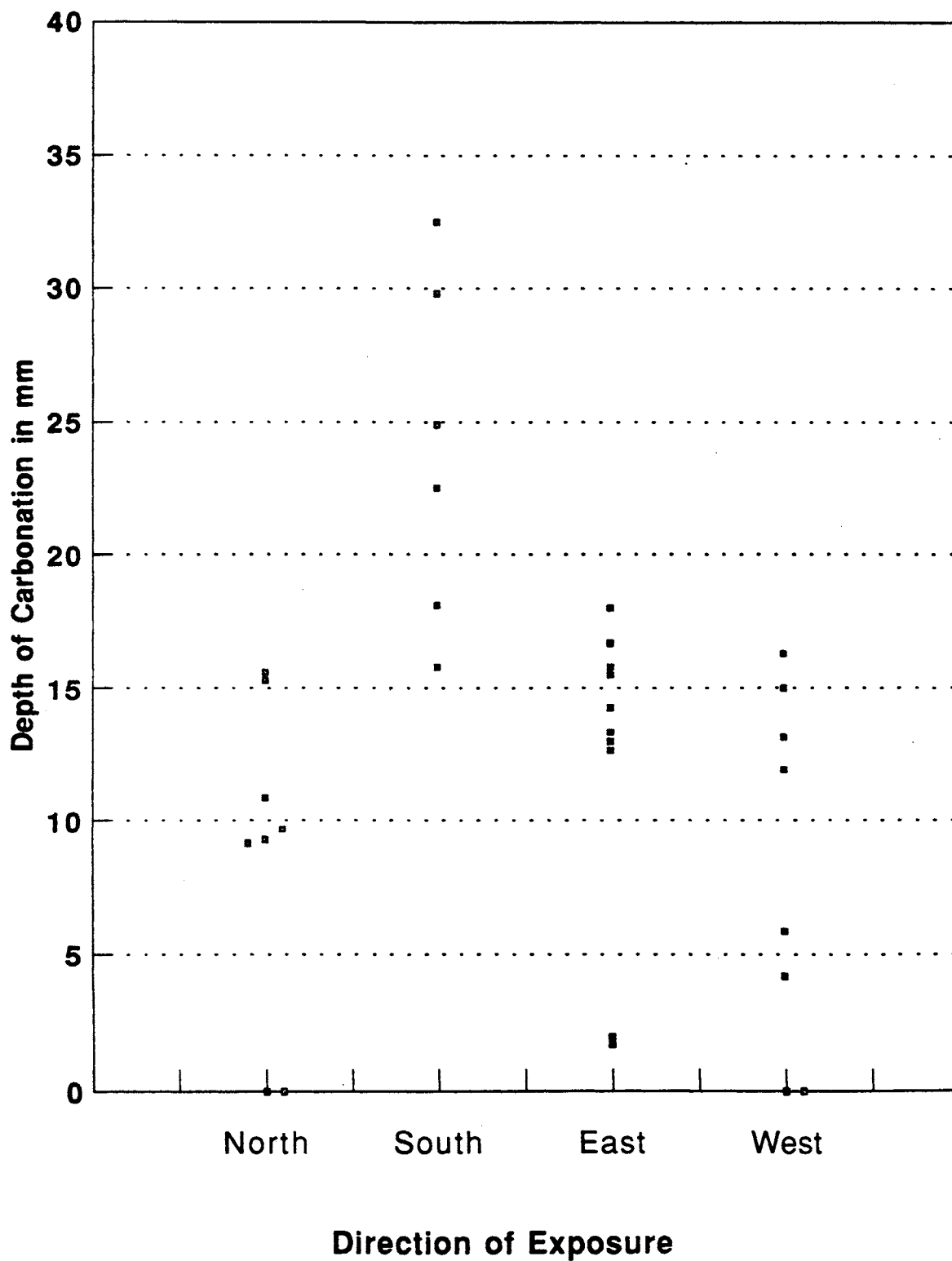


Figure 2C
Depth of Carbonation vs. Direction
of Exposure - Edmonton

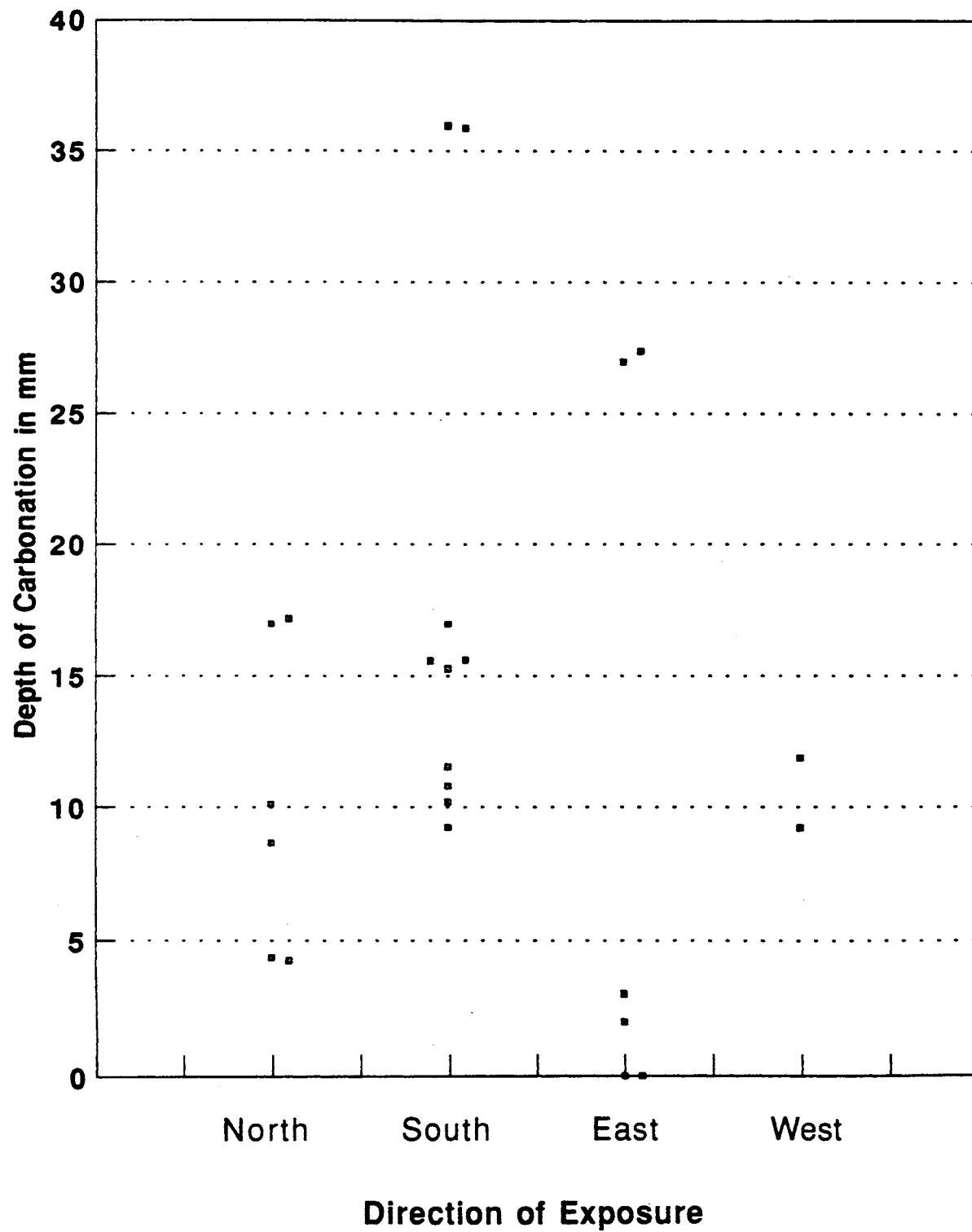


Figure 2D
Depth of Carbonation vs. Direction
of Exposure - Vancouver

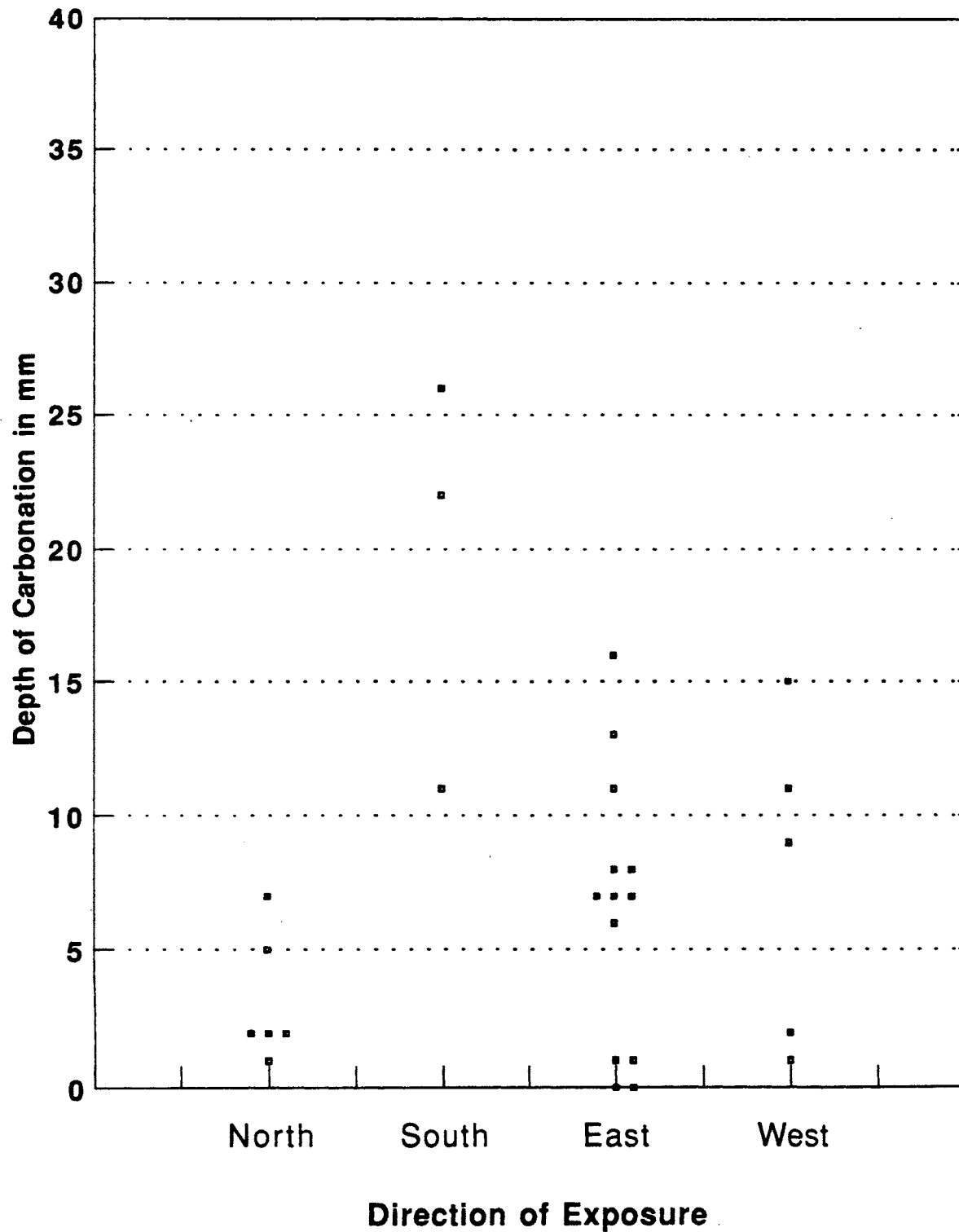
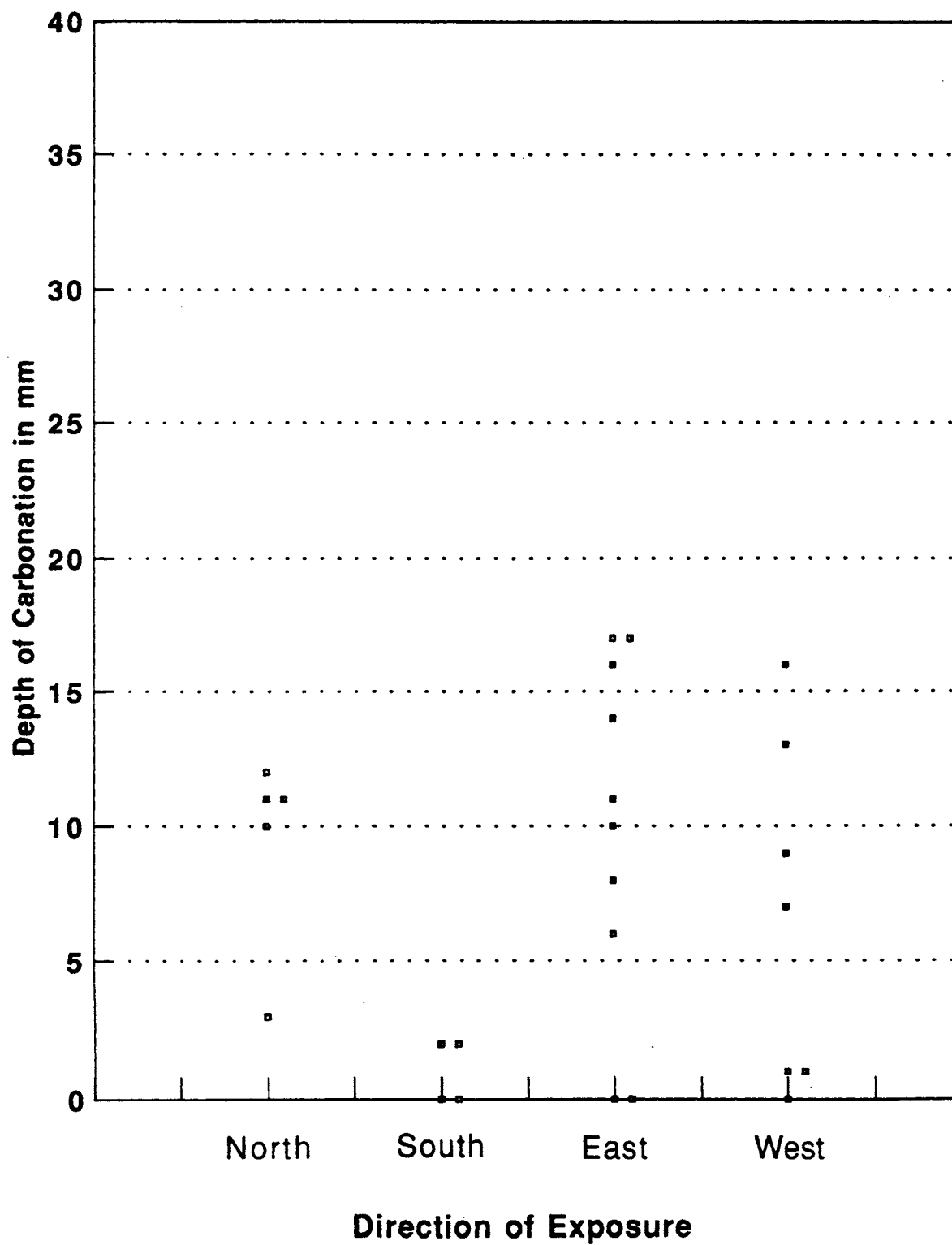


Figure 2E
Depth of Carbonation vs. Direction
of Exposure - Victoria



APPENDIX 'E'

DEPTH OF CARBONATION VS HEIGHT

Figure 3A
Depth of Carbonation vs.
Height - Halifax

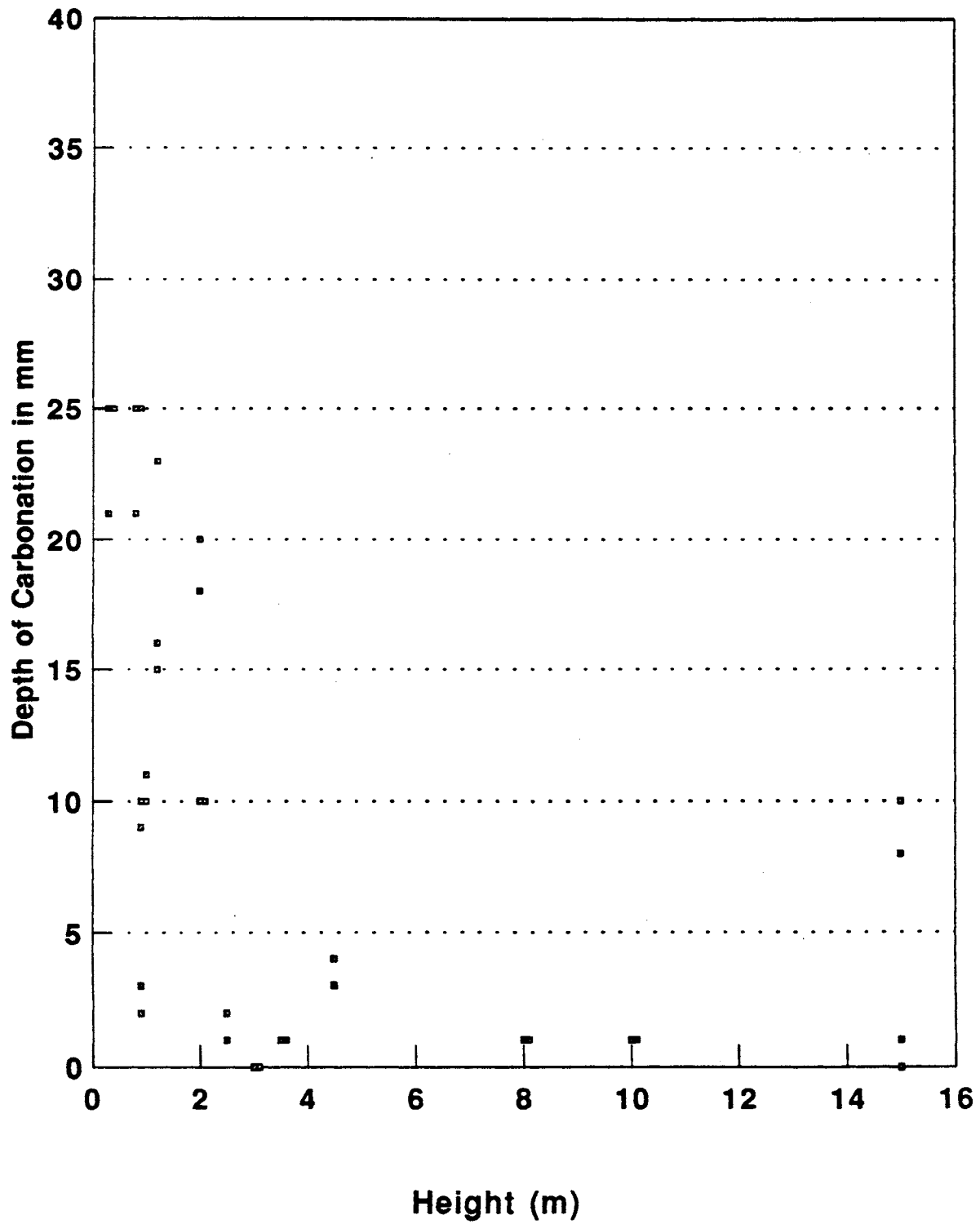


Figure 3B
Depth of Carbonation vs.
Height - Calgary

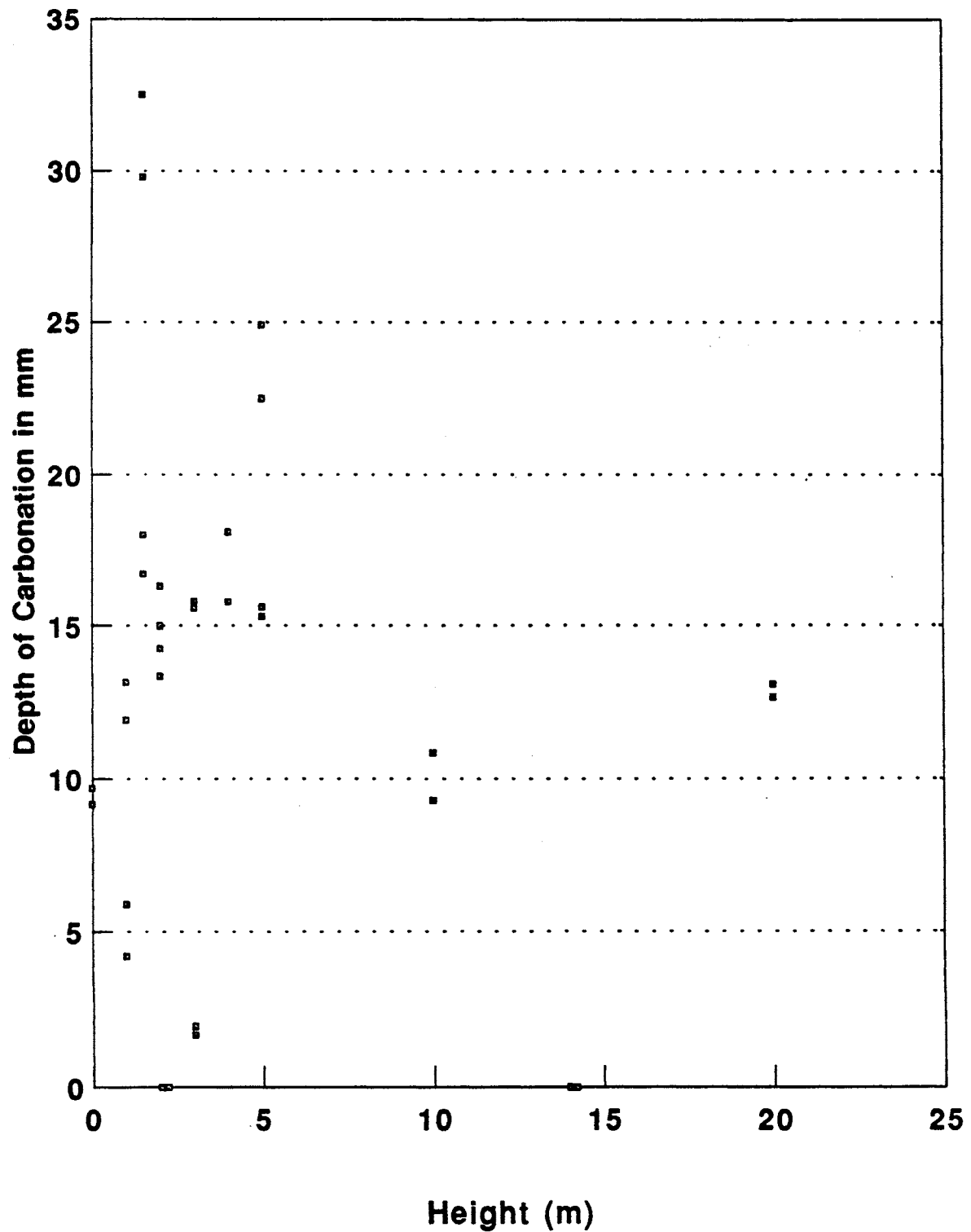


Figure 3C
Depth of Carbonation vs.
Height - Edmonton

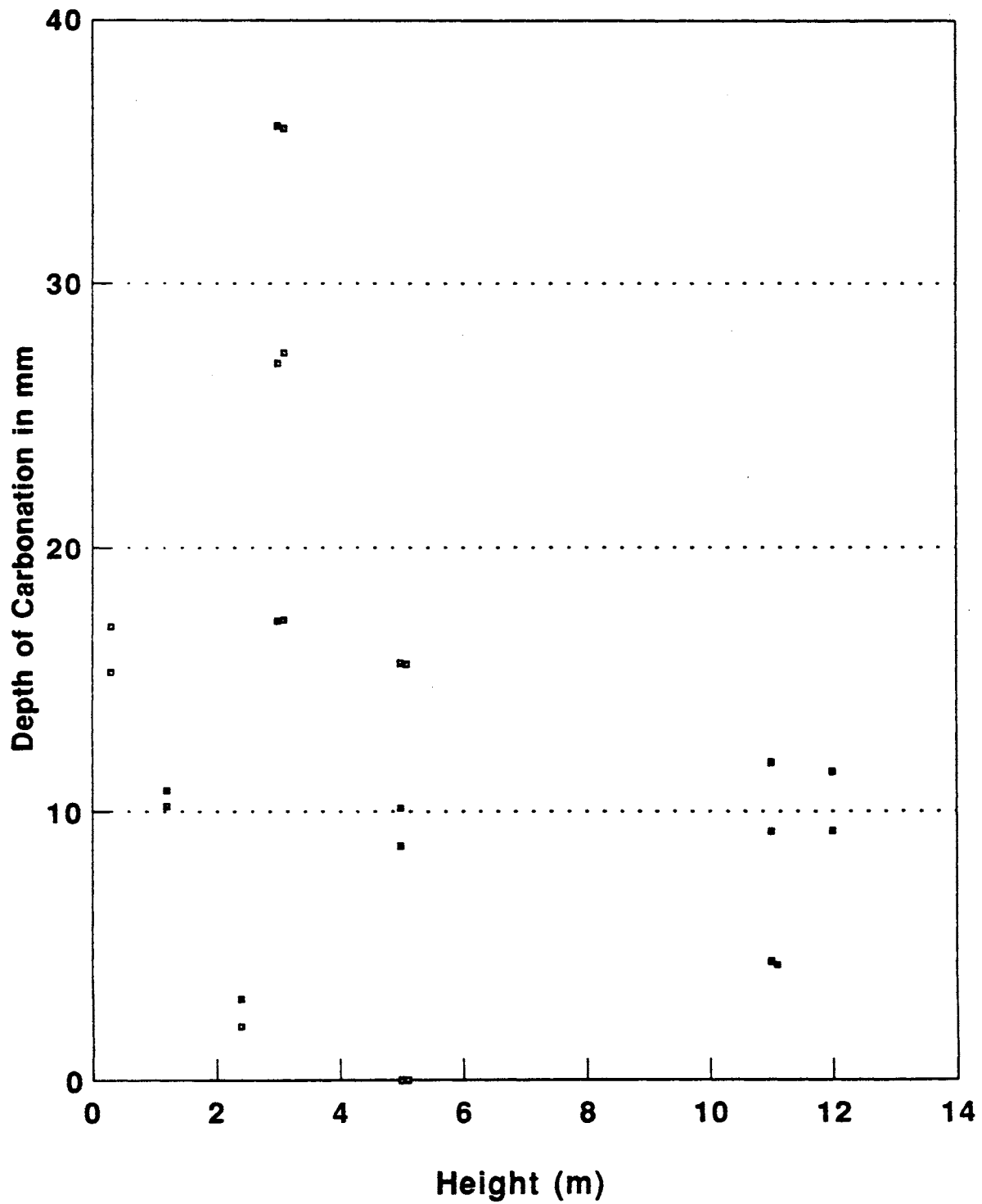


Figure 3D
Depth of Carbonation vs.
Height - Vancouver

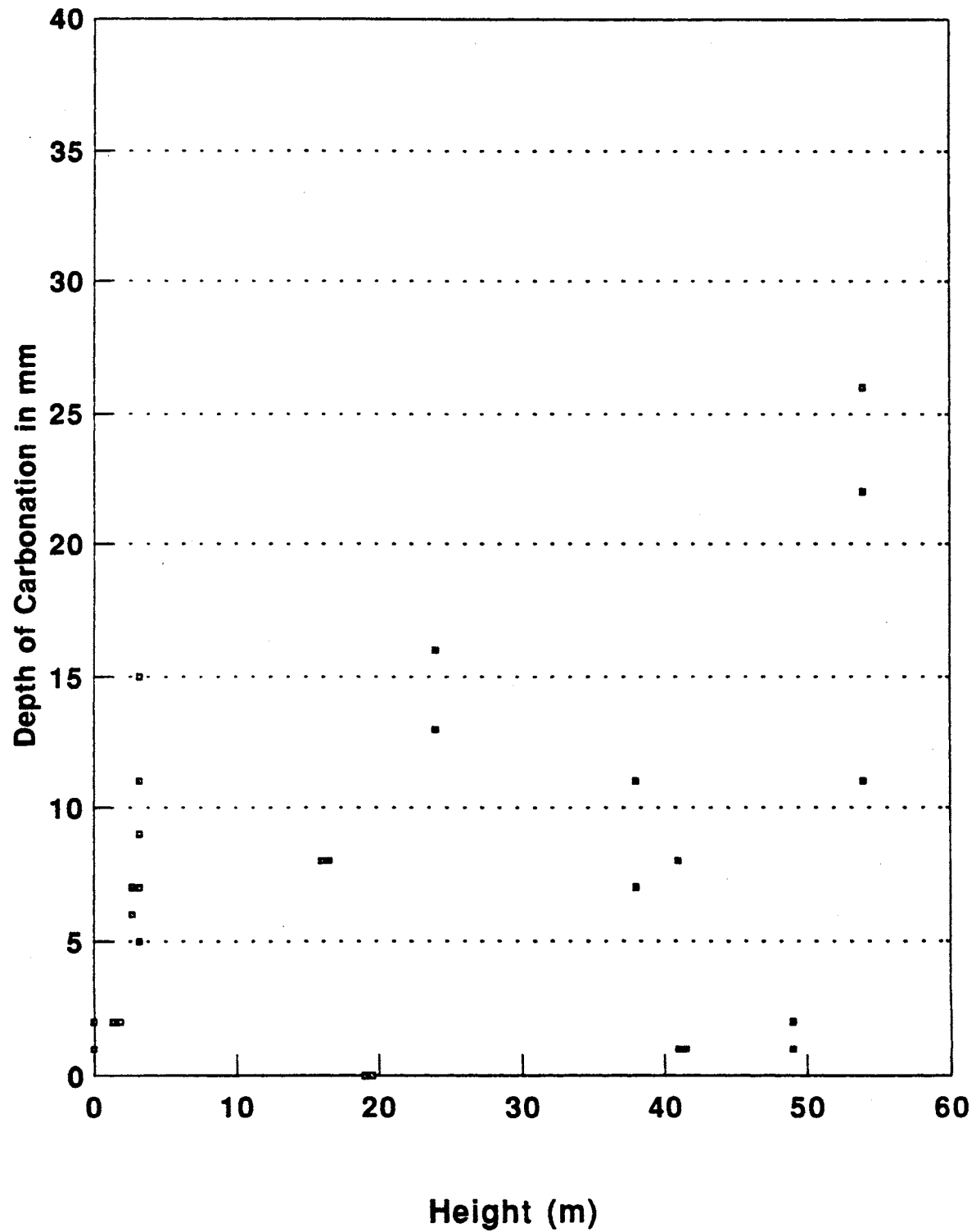
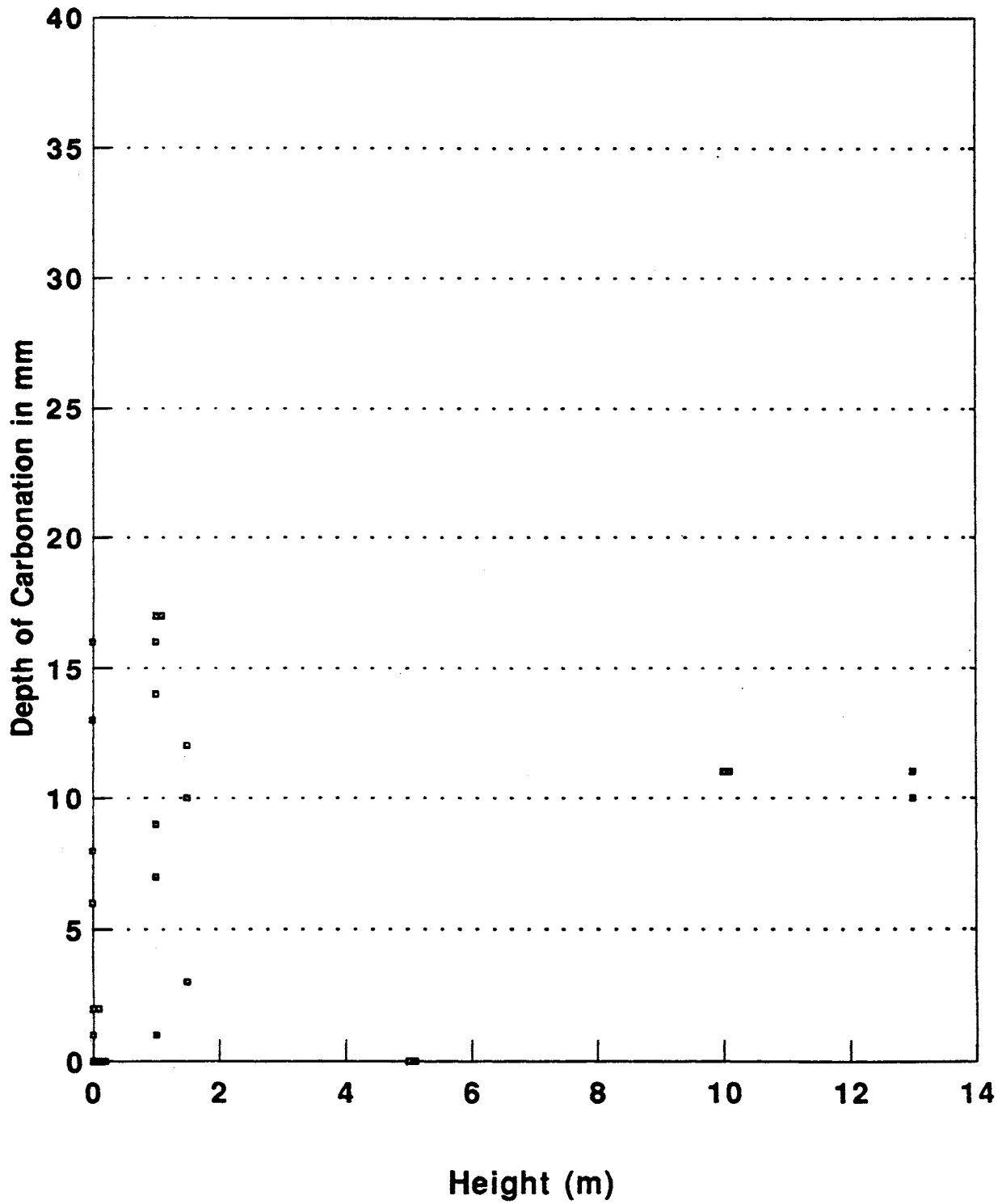


Figure 3E
Depth of Carbonation vs.
Height - Victoria



APPENDIX 'F'

DEPTH OF CARBONATION VS SPLITTING TENSILE STRENGTH

Figure 4A
Depth of Carbonation vs. Splitting
Tensile Strengths - Halifax

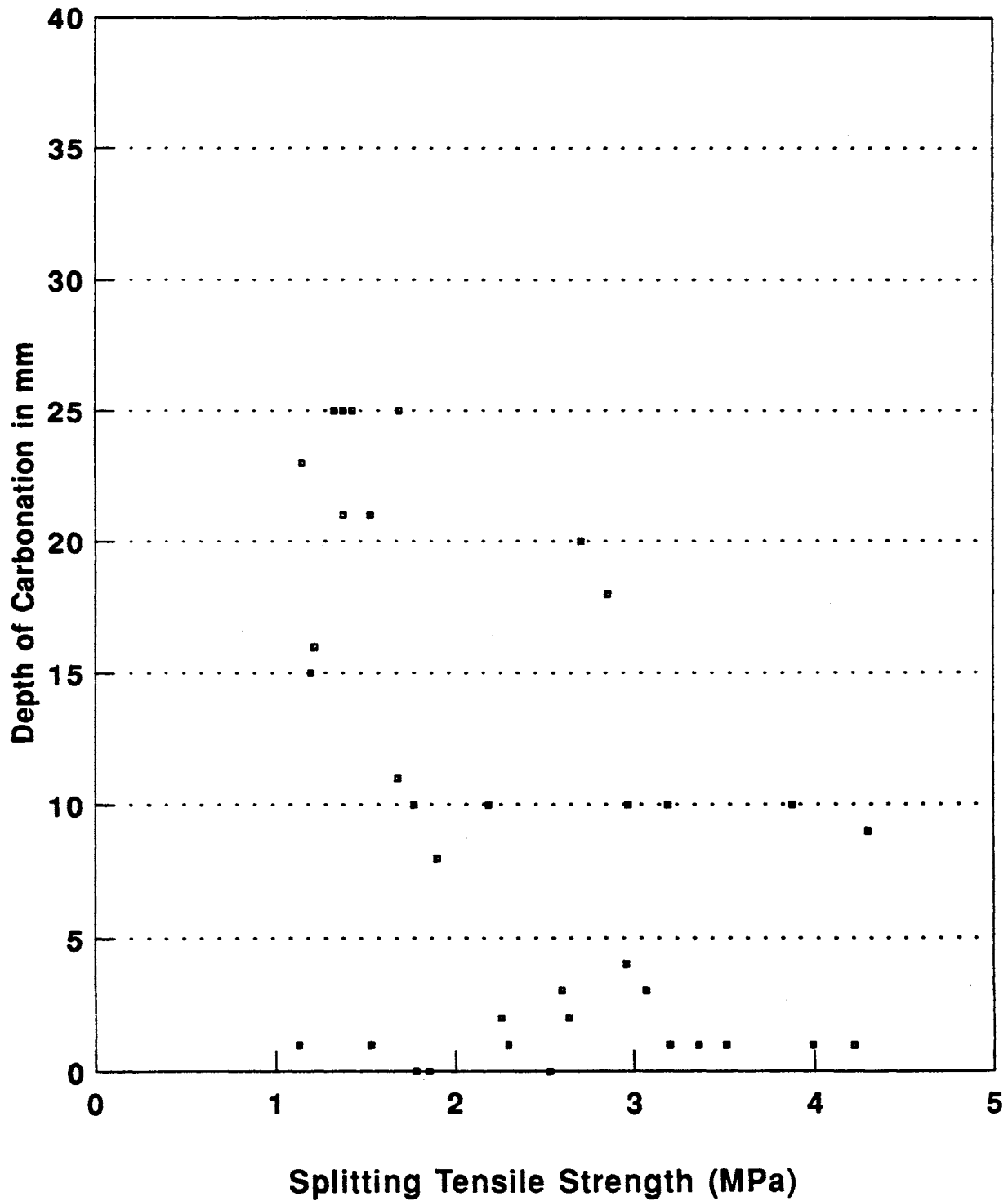


Figure 4B
Depth of Carbonation vs. Splitting
Tensile Strengths - Calgary

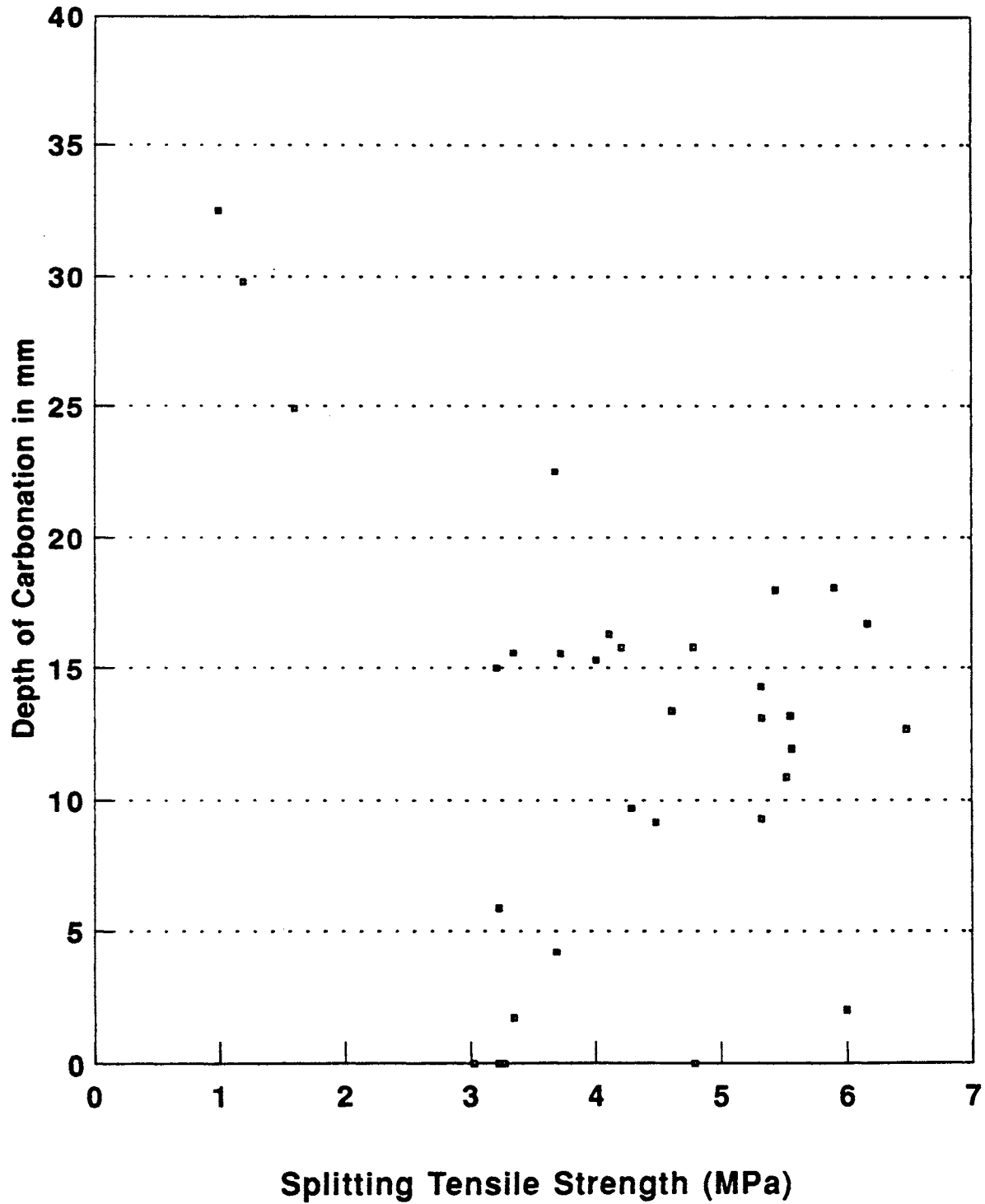


Figure 4C
Depth of Carbonation vs. Splitting
Tensile Strengths - Edmonton

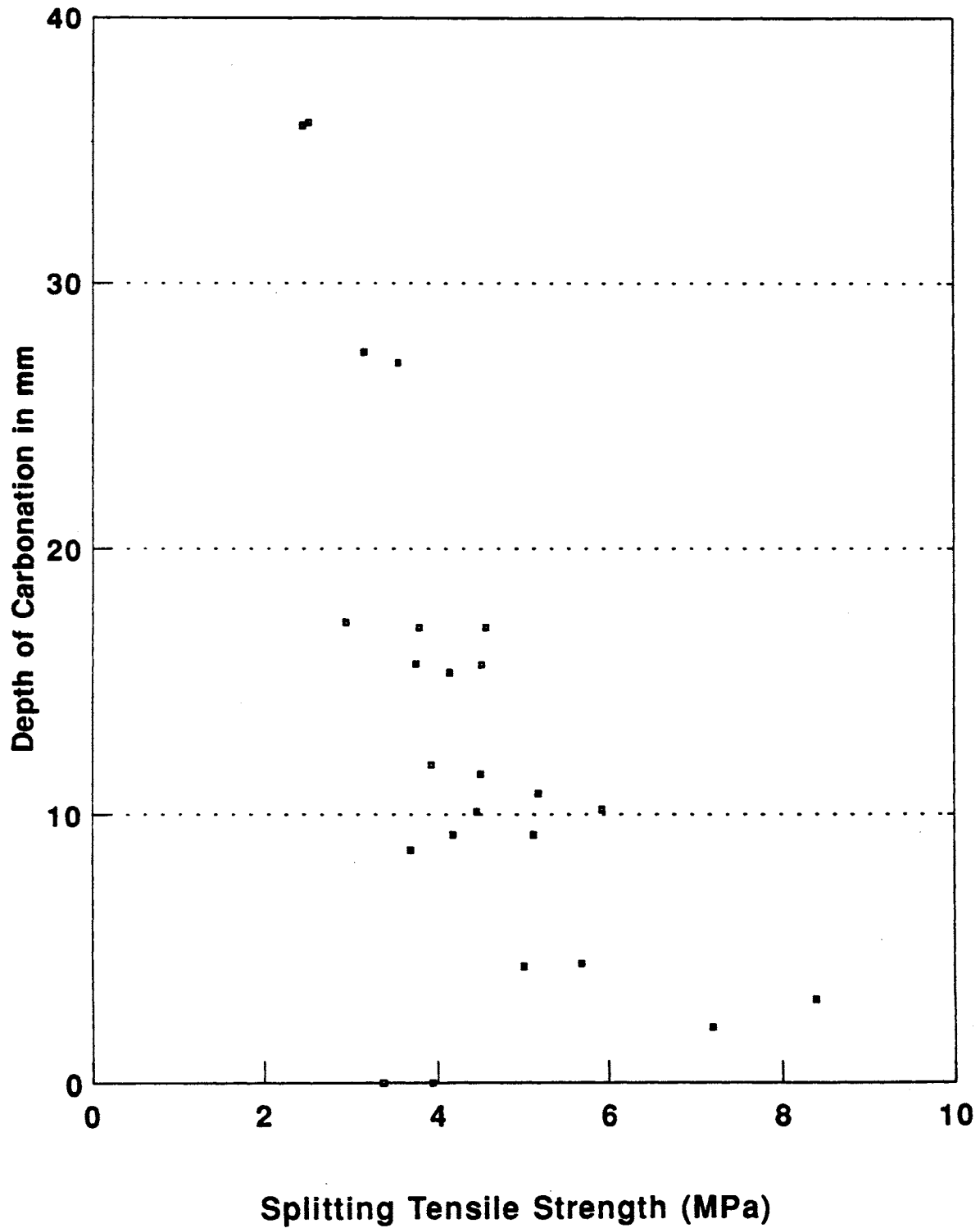


Figure 4D
Depth of Carbonation vs. Splitting
Tensile Strengths - Vancouver

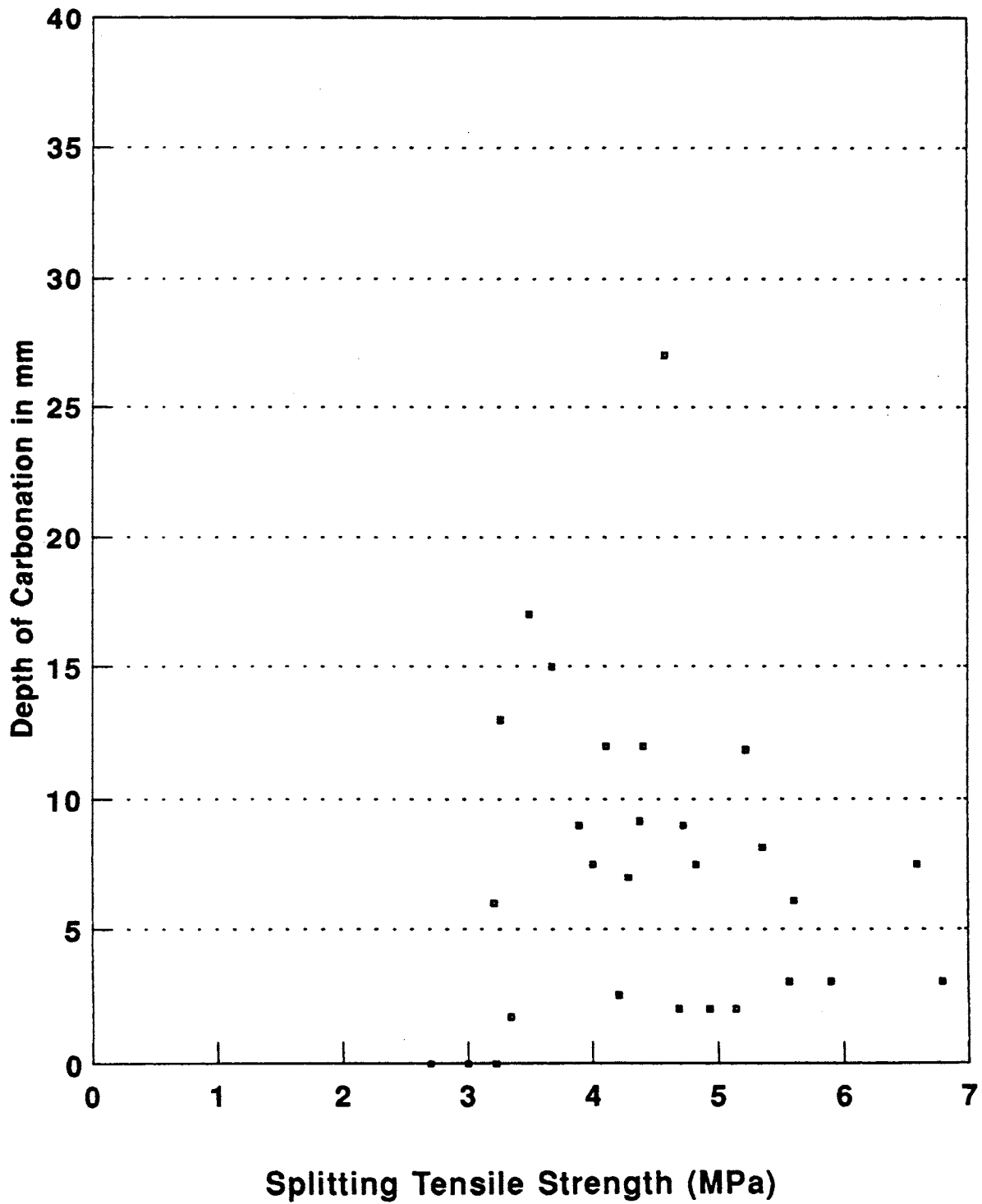
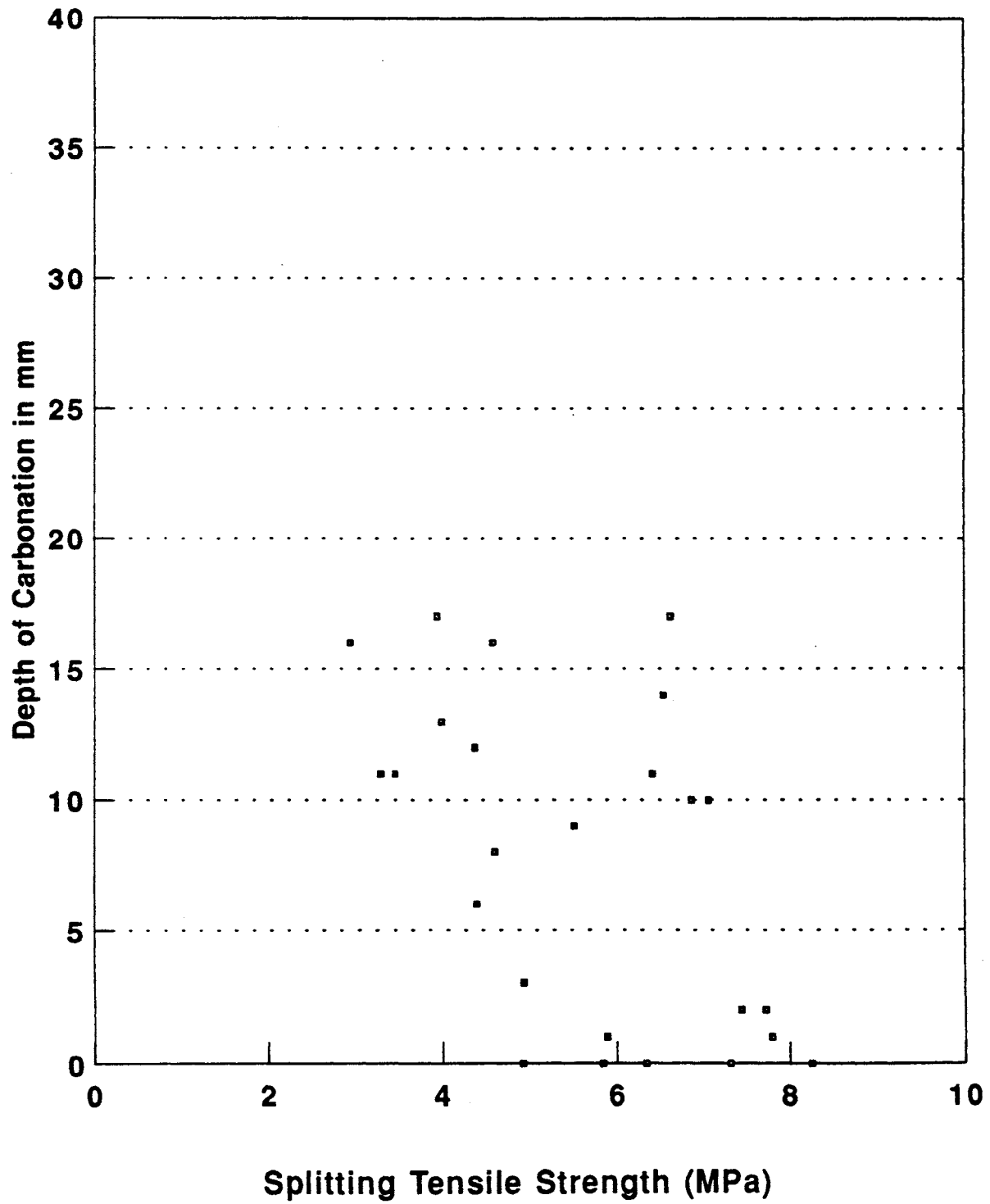


Figure 4E
Depth of Carbonation vs. Splitting
Tensile Strengths - Victoria



APPENDIX 'G'

DEPTH OF CARBONATION VS AGE

Figure 5A
Depth of Carbonation vs.
Age of Building - Halifax

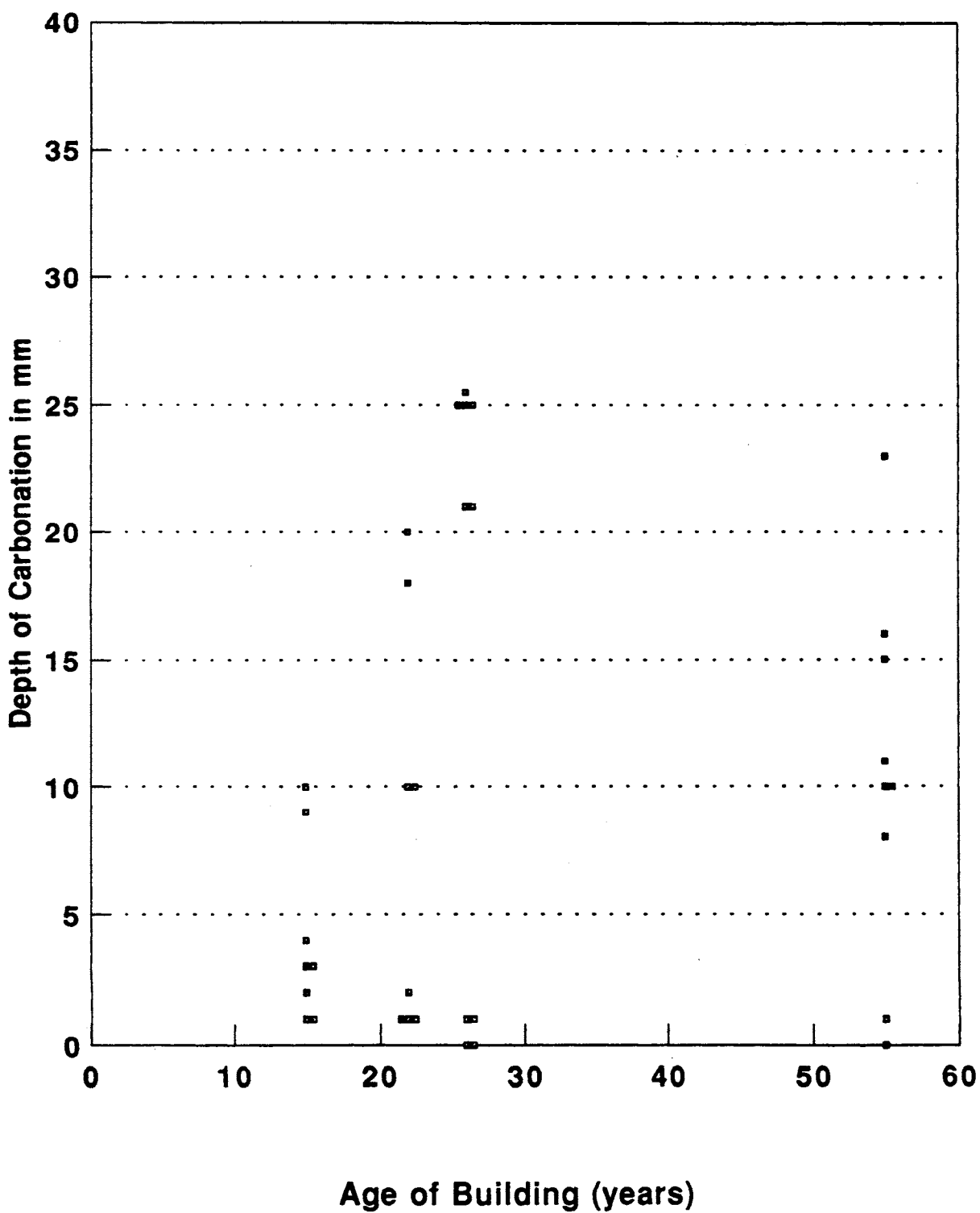


Figure 5B
Depth of Carbonation vs. Age of Building
Age of Building - Calgary

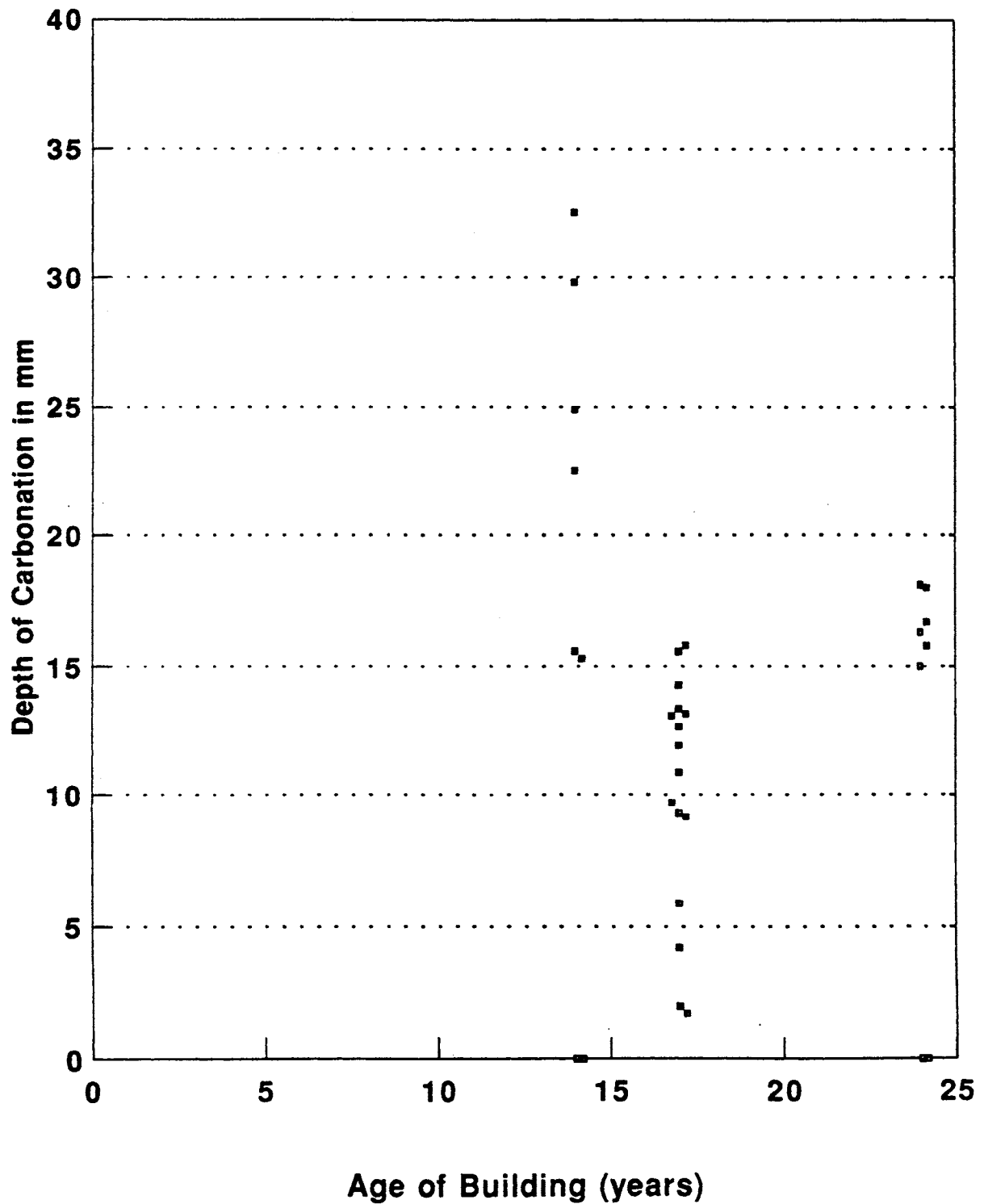


Figure 5C
Depth of Carbonation vs.
Age of Building - Edmonton

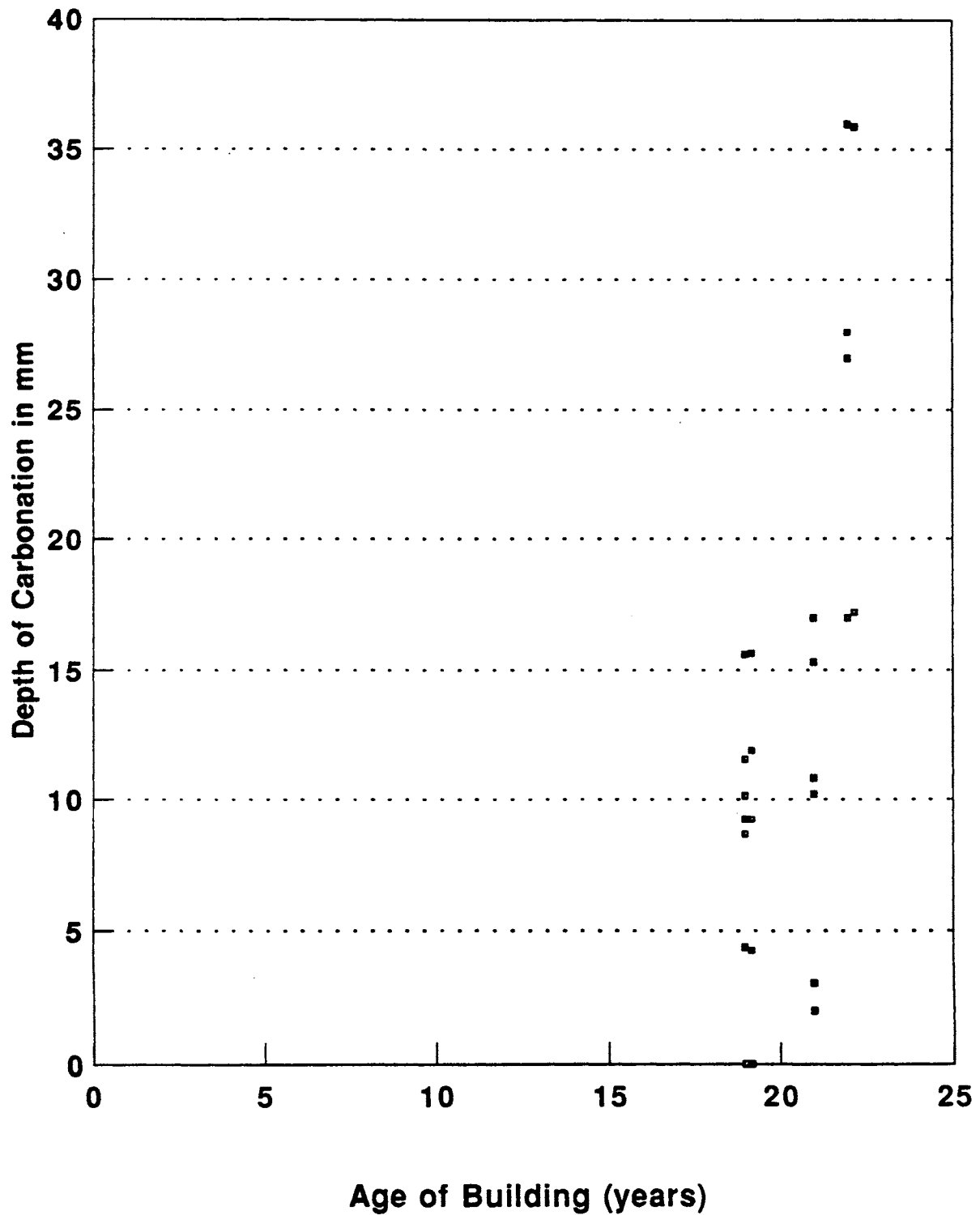


Figure 5D
Depth of Carbonation vs.
Age of Building - Vancouver

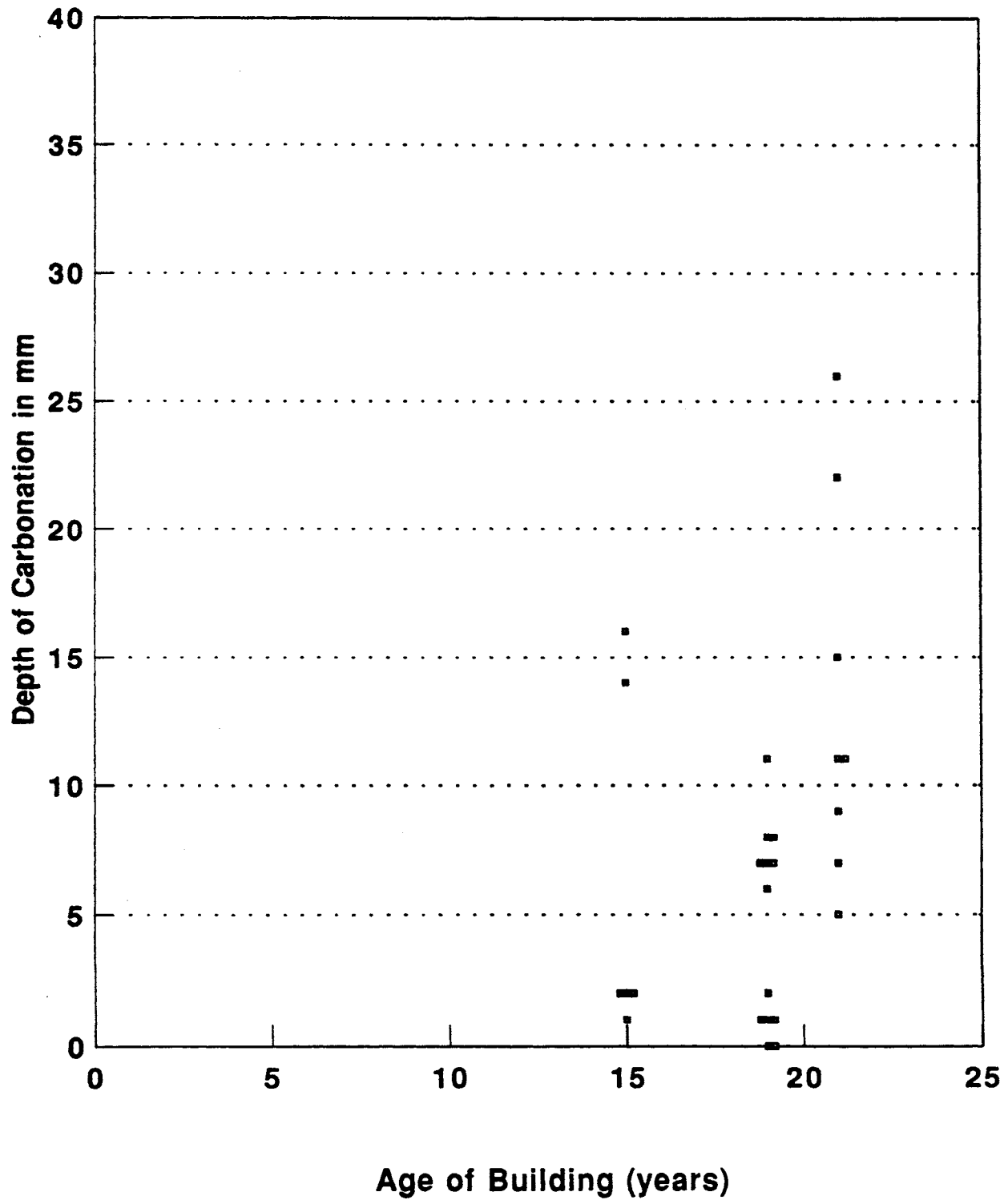
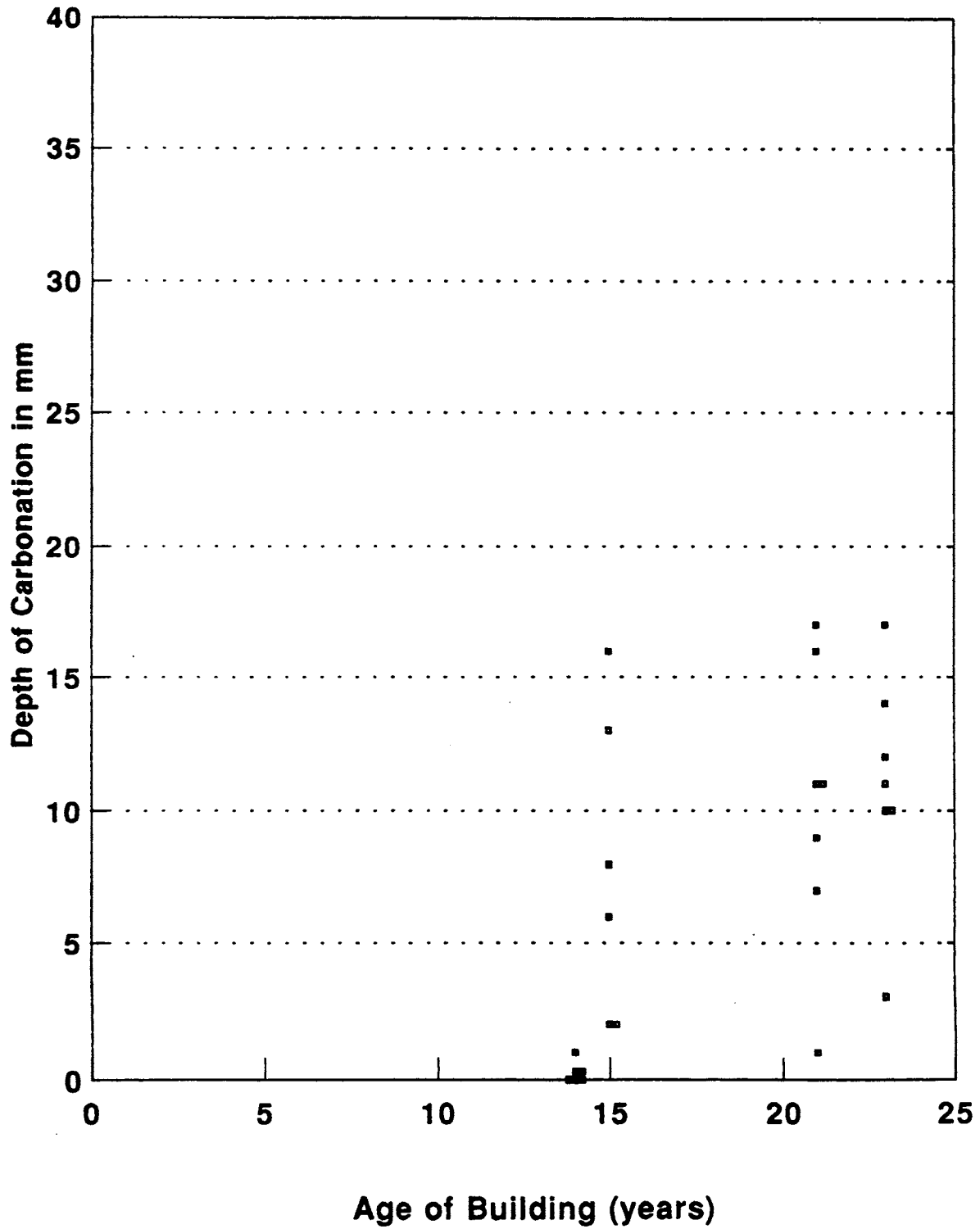


Figure 5E
Depth of Carbonation vs.
Age of Building - Victoria



APPENDIX 'H'

THERMOGRAVIMETRIC TEST RESULTS (TABULAR FORMAT)



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construction

CLIENT REPORT

for

Robert Halsall and Associates Limited
188 Eglinton Avenue, East, 6th Floor
Toronto, Ontario M4P 2X7

Determination of the Lime and Carbonate Content of Concrete Core Specimens

Author(s)

G.G. Litvan

H. Schultz

Approved

J.J. Beaudoin
Section Head

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Section: Materials

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Canada

Determination of the Lime and Carbonate Content of Concrete Core Specimens

Introduction

The lime and carbonate content of concrete core specimens received from R. Halsall Associates were determined by thermogravimetric analysis.

Specimens

The cores received were registered in our laboratory as follows:

<u>IRC Code Number</u>	<u>Original Code Number</u>
D190	CO2a
D191	CO3b
D192	CS3b
D193	F/b
D194	HT/a
D195	N1a
D196	RT2a
D197	S1a
D198	C/E/Bs-1
D199	C/E/C-2s No test required
D200	C/E/C-1s
D201	C/F/EW-4
D202	C/P/s-4
D203	E/CH/C-1e
D204	E/V/W-1s
D205	E/V/W-2e
D206	E/VA/s3
D207	6653 A-1-1
D208	6653 A-2-2
D209	6653 C-2-7
D210	6653 D-1-1

Specimen Preparation

The cores were received in wet condition sealed in plastic bags. Care was taken to maintain the wet condition during cutting and storage. With a water cooled diamond saw 4 mm thick slices were cut off from the samples at horizons requested in the letters of transmittal. Before testing, the specimens were dried at 105°C for an hour, and crushed using a hammer, and a mortar and pestle. Efforts were made to remove all coarse aggregate fragments. The specimens were then stored in nitrogen atmosphere.

Thermogravimetry

Specimens, 100 mg in weight, were heated in DuPont Model 9900 instrument at 20°C/min in a stream of nitrogen gas (30 mL/min).

Results

The results of the thermogravimetric analysis are shown in graphical form (File CO2.01 through CO2.73). The absolute weight loss percent (ordinate on the left hand side) as a function of temperature and, the first derivative of the weight percent lost (ordinate on the right hand side) as a function of temperature are given.

The peak of the derivative that occurs between 450 and 550°C is due to decomposition of lime Ca(OH)_2 in hydrated tricalcium silicate. The peak at approximately 780°C indicates the decomposition of CaCO_3 .

The areas below the peaks were integrated and the obtained values are directly proportional to the Ca(OH)_2 and CaCO_3 concentrations in the specimens.

The results are presented also in tabular form (Table 1).

On sample D201 the outer surface was not indicated, when received, and the outer surface was assumed to be the one with the high CaCO_3 content. Sample D201 at 10 mm horizon was rerun to ascertain the correctness of the assumption.

The outer surface on Core D203 appears to have been incorrectly marked, because according to the marking the high carbonate content occurred at 70 mm horizon. The horizon values indicated in Table 1 were given by assuming the other core surface to be the outer one. In this case an extra slice was cut to verify the correctness of the designation.

Comments

Because there is no method available to completely remove from the concrete all the coarse aggregate which may contain CaCO_3 , the values given in Table 1 comprise carbonate not only resulting from carbonation of lime but possibly also carbonate of the small aggregate fragments.

The extent of carbonation can be estimated from the weight losses at around 450°C . As a first approximation one may assume that the peaks obtained by testing samples at the 65 mm horizon represent the lime content of, or close to, that originally present in the hydrated cement. Accepting the lime content of the 65 mm horizon specimens as reference, the decrease at other horizons is a measure of the extent of carbonation.

Table 1
Values obtained from testing concrete cores for extent of carbonation

Sample	Horizon, mm	Lime, %	Carbonate, %	H ₂ O from lime	CO ₂ from carbonate	Ignited wt. at 1000 deg.	File No.
D190	0 mm	0.6	7.8	0.14	3.44	90.6	CO2.01
	8 mm	1.7	2.2	0.41	0.95	90.1	CO2.02
	65 mm	2.1	0.3	0.52	0.15	91.3	CO2.03
D191	10 mm	0.2	13.1	0.04	5.76	89.4	CO2.04
	23 mm	2.3	0.5	0.56	0.2	92	CO2.05
	23 mm	1.9	0.3	0.47	0.15	92.3	CO2.08
	35 mm	1.7	0.5	0.41	0.22	92.8	CO2.06
	65 mm	1.9	0.4	0.45	0.17	91.8	CO2.07
D192	10 mm	0.0	20.6	0	9.08	86.3	CO2.09
	23 mm	3.4	0.8	0.83	0.36	92.2	CO2.10
	35 mm	3.3	0.5	0.8	0.2	91.9	CO2.11
	65 mm	3.5	0.2	0.86	0.09	91.7	CO2.12
D193	0 mm	1.6	6.3	0.38	2.75	91.7	CO2.13
	8 mm	2.3	1.0	0.57	0.43	93	CO2.14
	65 mm	1.6	0.5	0.38	0.22	93.5	CO2.15
D194	0 mm	2.8	4.4	0.69	1.93	92	CO2.16
	8 mm	5.0	0.2	1.21	0.1	93	CO2.17
	65 mm	5.0	0.2	1.22	0.08	91.2	CO2.18
D195	20 mm	0.0	14.4	0	6.35	87.2	CO2.19
	35 mm	0.7	0.8	0.18	0.35	93.8	CO2.20
	48 mm	0.6	1.0	0.14	0.42	93.6	CO2.21
	65 mm	0.6	0.7	0.15	0.3	92.4	CO2.22
D196	0 mm	2.4	2.4	0.58	1.07	93.3	CO2.23
	8 mm	3.9	0.4	0.95	0.18	92.6	CO2.24
	65 mm	4.2	0.0	1.02	0	93.8	CO2.25

Table 1
Values obtained from testing concrete cores for extent of carbonation

Sample	Horizon, mm	Lime. %	Carbonate, %	H2O from lime	CO2 from carbonate	Ignited wt. at 1000 deg.	File No.
D197	10 mm	0.0	16.4	0	7.2	89.6	CO2.26
	23 mm	0.6	3.3	0.14	1.44	93	CO2.27
	35 mm	1.0	0.4	0.24	0.16	93.6	CO2.28
	65 mm	1.8	0.2	0.43	0.1	93	CO2.29
D198	0 mm	2.4	26.7	0.58	11.76	81.1	CO2.30
	8 mm	3.7	24.6	0.9	10.82	80.9	CO2.31
	65 mm	5.6	20.3	1.35	8.93	80	CO2.32
D200	25 mm	0.0	28.2	0	12.41	82.9	CO2.33
	35 mm	1.0	17.3	0.24	7.63	86	CO2.34
	48 mm	2.1	13.1	0.5	5.78	85.5	CO2.35
	65 mm	3.4	10.3	0.82	4.52	88.3	CO2.36
D201	10 mm	0.0	37.2	0	16.38	77.6	CO2.40
	41 mm	4.8	14.3	1.17	6.29	85.3	CO2.39
	53 mm	5.1	15.2	1.25	6.7	84.1	CO2.38
	66 mm	5.1	17.0	1.23	7.48	82.8	CO2.37
D202	0 mm	0.0	33.3	0	14.65	76.7	CO2.41
	8 mm	0.0	31.8	0	13.97	78.5	CO2.42
	65 mm	4.4	18.5	1.07	8.13	82.1	CO2.43
D203	0 mm	0.2	15.6	0.06	6.86	88.1	CO2.46
	8 mm	4.1	6.1	0.99	2.67	88.2	CO2.72
	62 mm	5.1	4.7	1.25	2.05	88.2	CO2.45
	70 mm	5.0	2.1	1.21	0.92	89.1	CO2.44
D204	30 mm	0.3	9.4	0.08	4.13	90.6	CO2.47
	39 mm	2.3	1.3	0.56	0.57	93.8	CO2.48
	48 mm	1.9	1.8	0.47	0.8	92.5	CO2.49
	65 mm	1.9	1.6	0.46	0.69	92.8	CO2.50

Table 1
Values obtained from testing concrete cores for extent of carbonation

Sample	Horizon, mm	Lime. %	Carbonate, %	H2O from lime	CO2 from carbonate	Ignited wt. at 1000 deg.	File No.
D205	23 mm	0.0	10.9	0.01	4.81	90.7	CO2.51
	35 mm	3.2	1.6	0.78	0.71	92.1	CO2.52
	48 mm	2.8	2.4	0.68	1.04	92.1	CO2.53
	65 mm	2.1	2.9	0.51	1.26	91.5	CO2.54
D206	0 mm	0.3	26.3	0.08	11.58	83	CO2.55
	8 mm	4.5	2.7	1.09	1.19	90.3	CO2.56
	65 mm	4.2	2.2	1.01	0.97	90.3	CO2.57
D207	23 mm	0.2	16.2	0.04	7.13	87.2	CO2.58
	35 mm	3.2	0.9	0.77	0.39	93.3	CO2.59
	48 mm	3.9	0.3	0.95	0.14	93	CO2.60
	65 mm	4.1	0.3	0.99	0.13	91.2	CO2.61
D208	0 mm	2.9	4.4	0.7	1.95	90.9	CO2.62
	8 mm	5.6	0.5	1.35	0.2	90.2	CO2.63
	65 mm	5.2	1.6	1.26	0.71	90.4	CO2.64
D209	15 mm	6.0	1.6	1.46	0.69	89.9	CO2.65
	23 mm	6.1	0.7	1.48	0.31	90.4	CO2.66
	35 mm	6.1	0.6	1.49	0.26	89.9	CO2.67
	65 mm	6.1	0.5	1.48	0.24	89.7	CO2.68
D210	0 mm	1.1	15.8	0.27	6.97	87.5	CO2.69
	8 mm	4.9	2.4	1.19	1.04	89.4	CO2.70
	65 mm	4.7	1.0	1.15	0.45	89.7	CO2.71

APPENDIX 'J'

THERMOGRAVIMETRIC TEST RESULTS (GRAPHICAL FORMAT)

Figure 6A
Phenolphthalein vs Thermogravimetric
Test Results - Halifax (Core 6653A1-1)

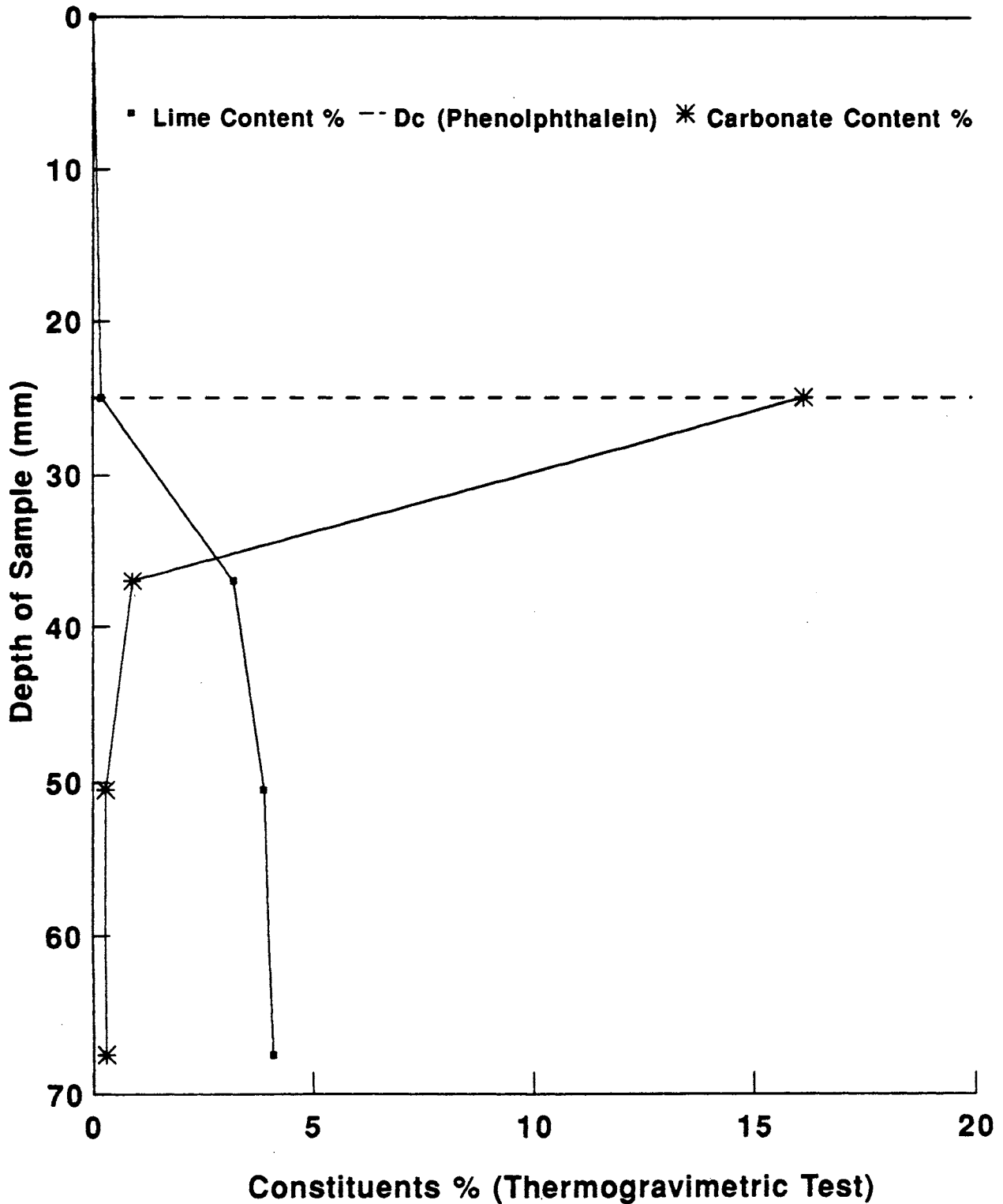
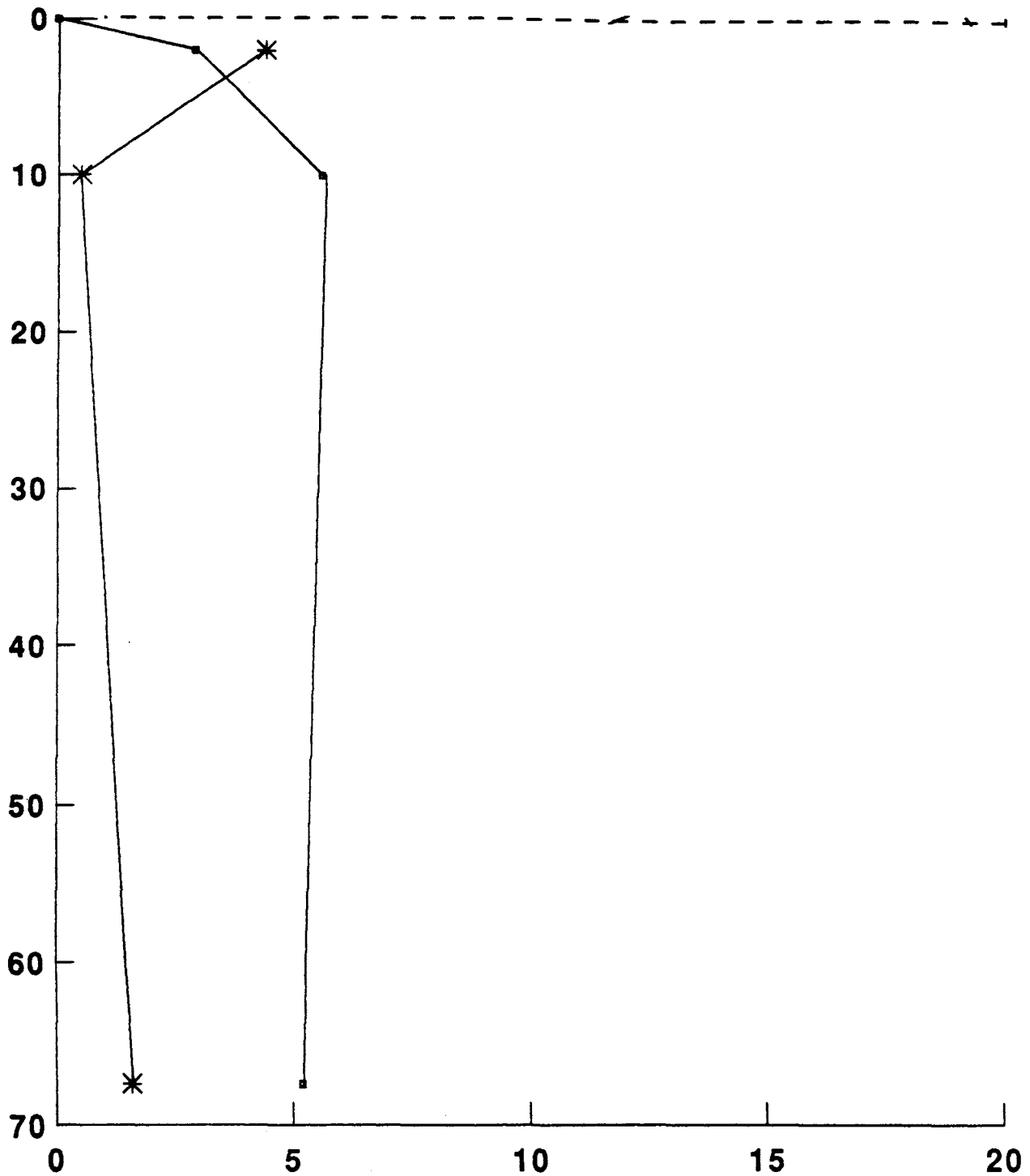


Figure 6B
Phenolphthalein vs Thermogravimetric
Test Results - Halifax (Core 6653A2-2)



Constituents % (Thermogravimetric Test)

▣ Lime Content % -- Dc (Phenolphthalein) * Carbonate Content %

Figure 6C
Phenolphthalein vs Thermogravimetric
Test Results - Halifax (Core 6653C2-7)

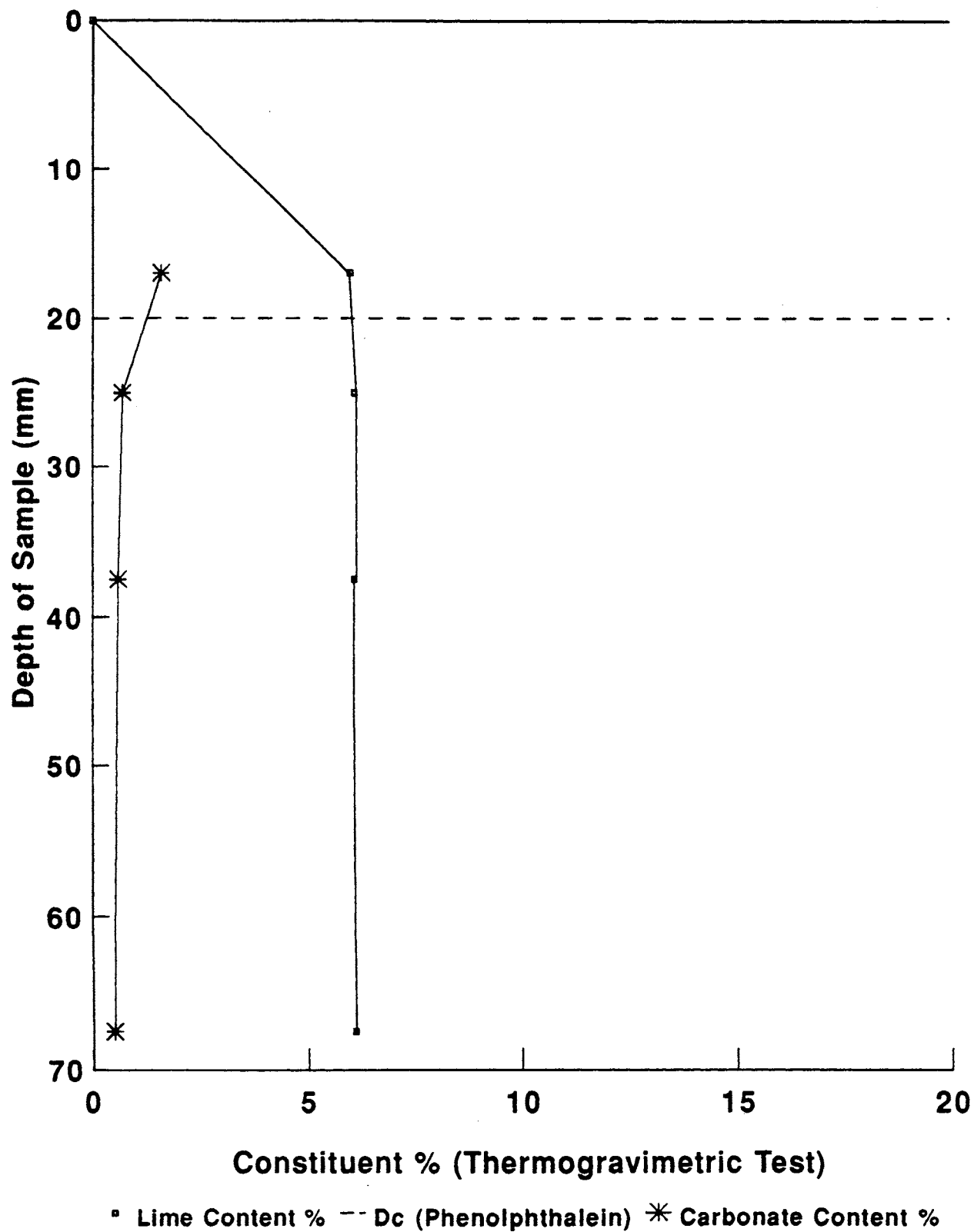
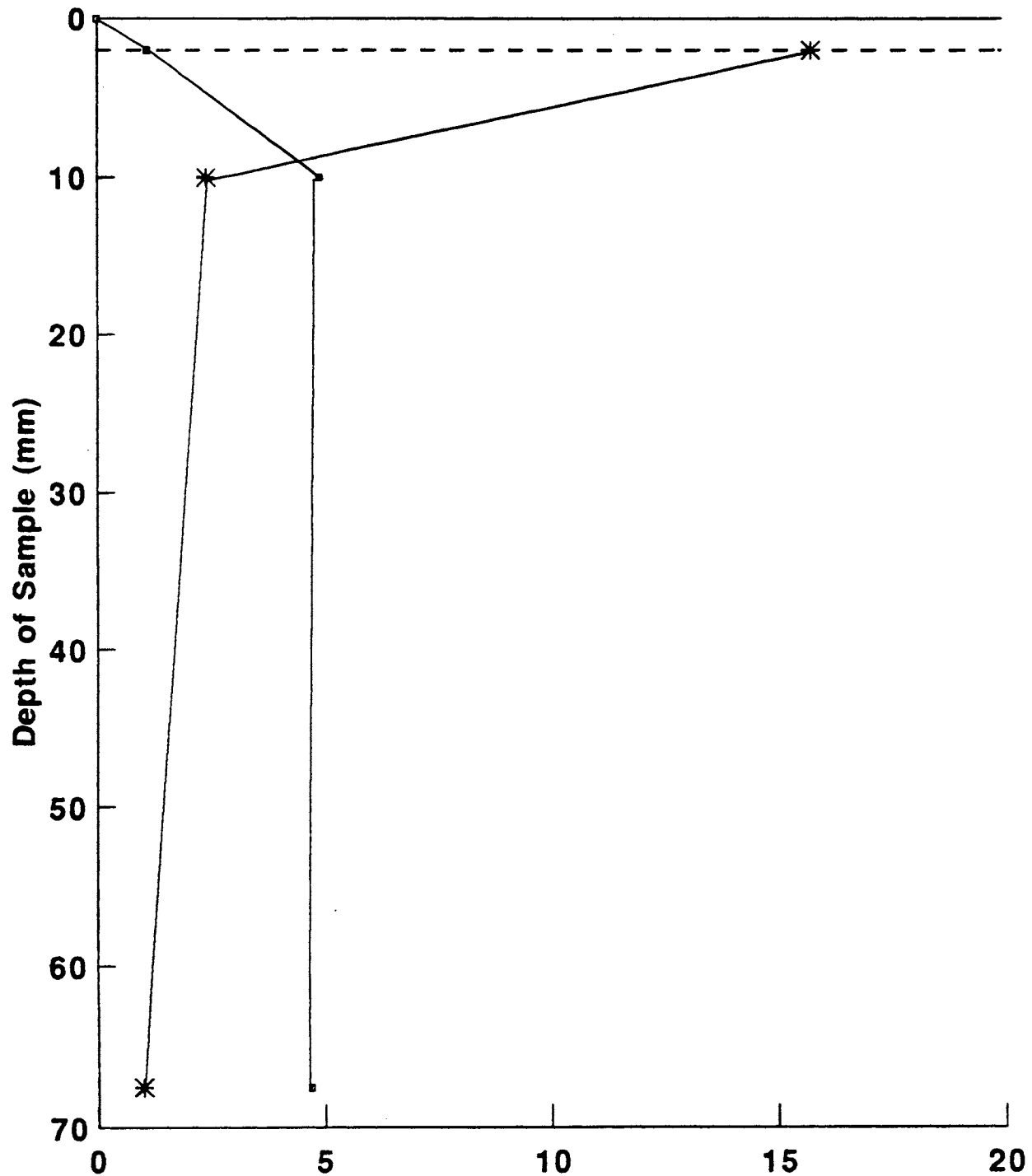


Figure 6D
Phenolphthalein vs Thermogravimetric
Test Results - Halifax (Core 6653D1-1)



Constituents % (Thermogravimetric Test)

□ Lime Content % -- Dc (Phenolphthalein) * Carbonate Content %

Figure 6E
Phenolphthalein vs Thermogravimetric
Test Results - Calgary (Core C/E/BS-1)

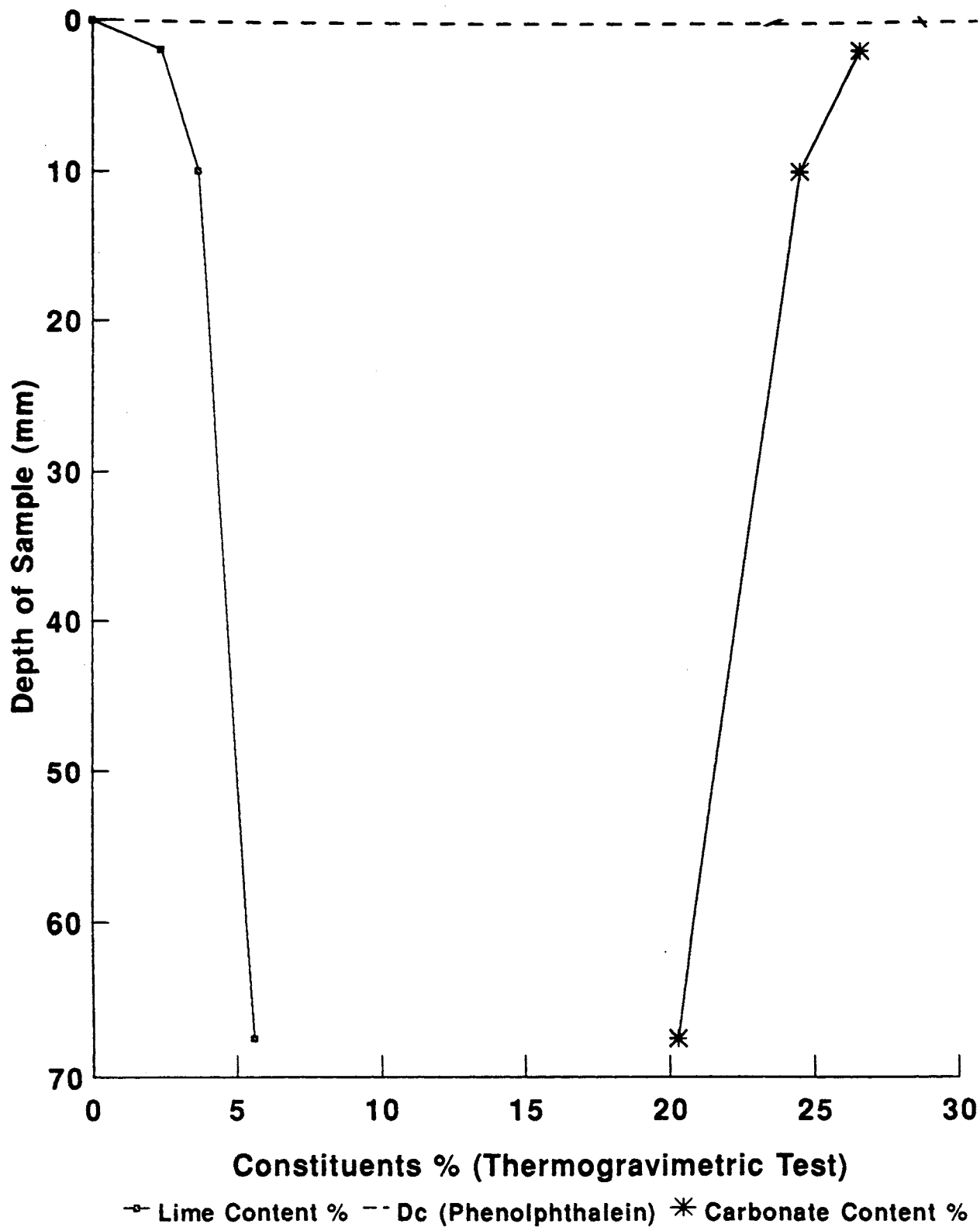


Figure 6F
Phenolphthalein vs Thermogravimetric
Test Results - Calgary (Core C/E/C-1s)

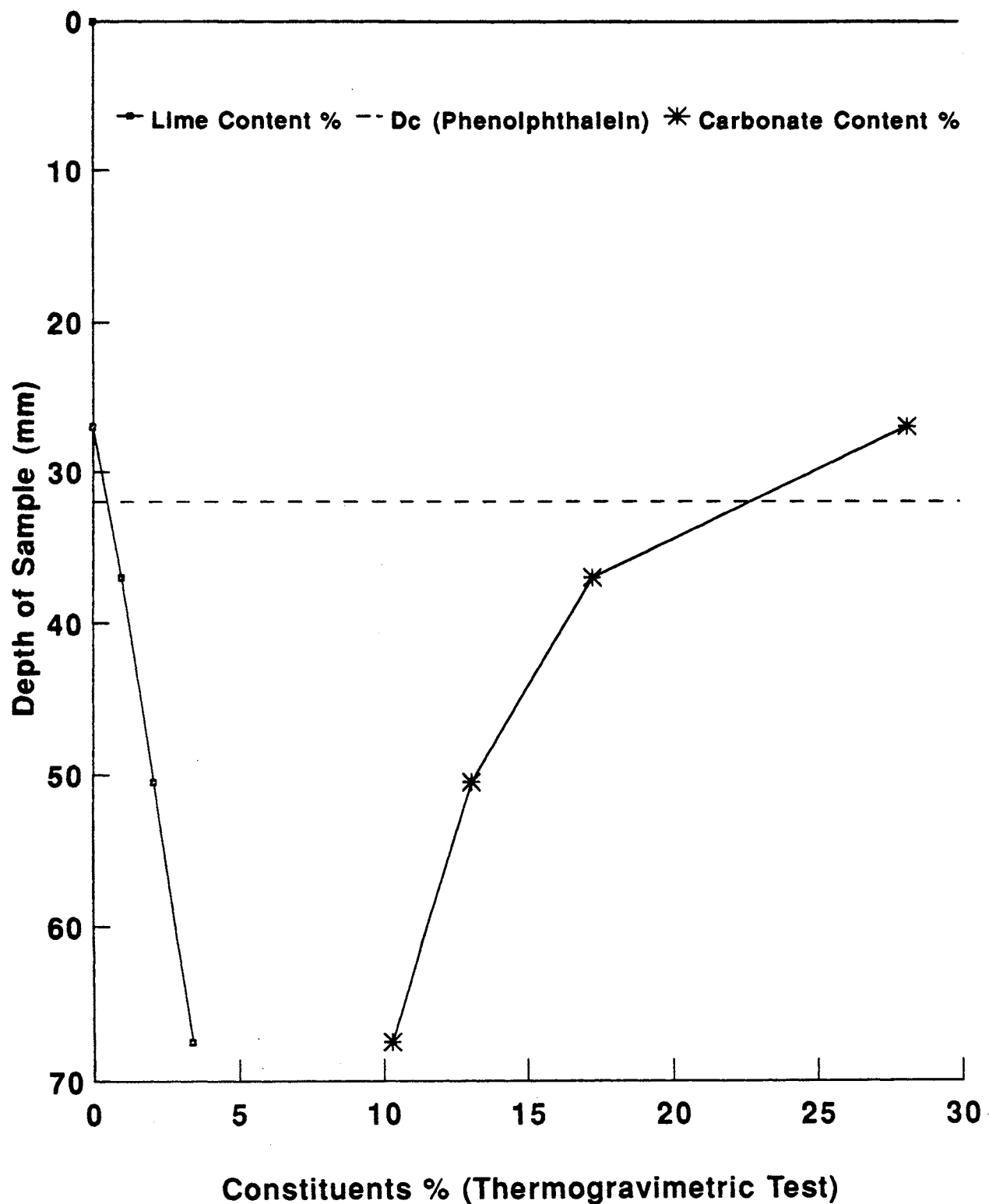


Figure 6G
Phenolphthalein vs Thermogravimetric
Test Results - Calgary (Core C/F/EW-4)

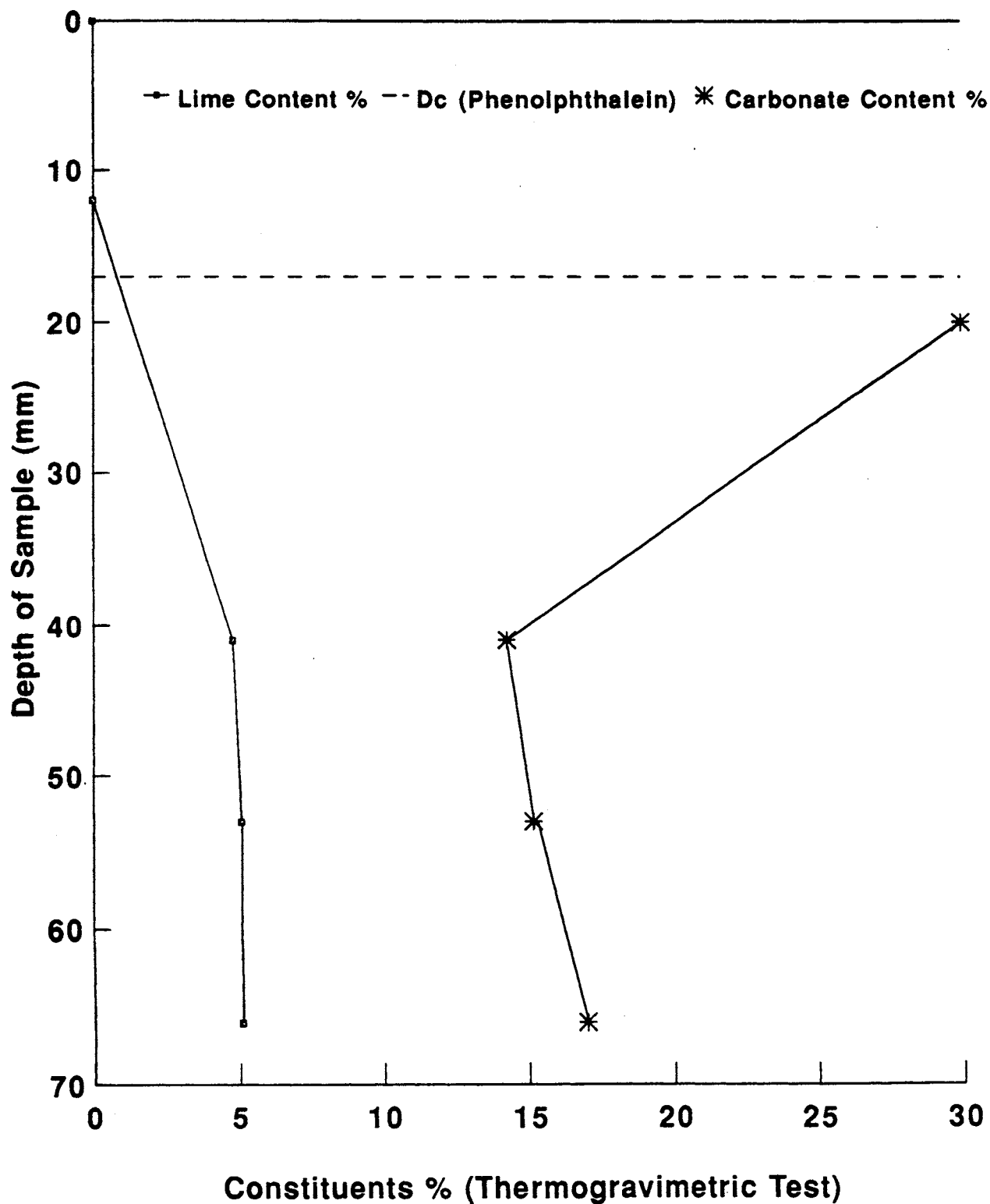


Figure 6H
Phenolphthalein vs Thermogravimetric
Test Results - Calgary (Core C/P/S-4)

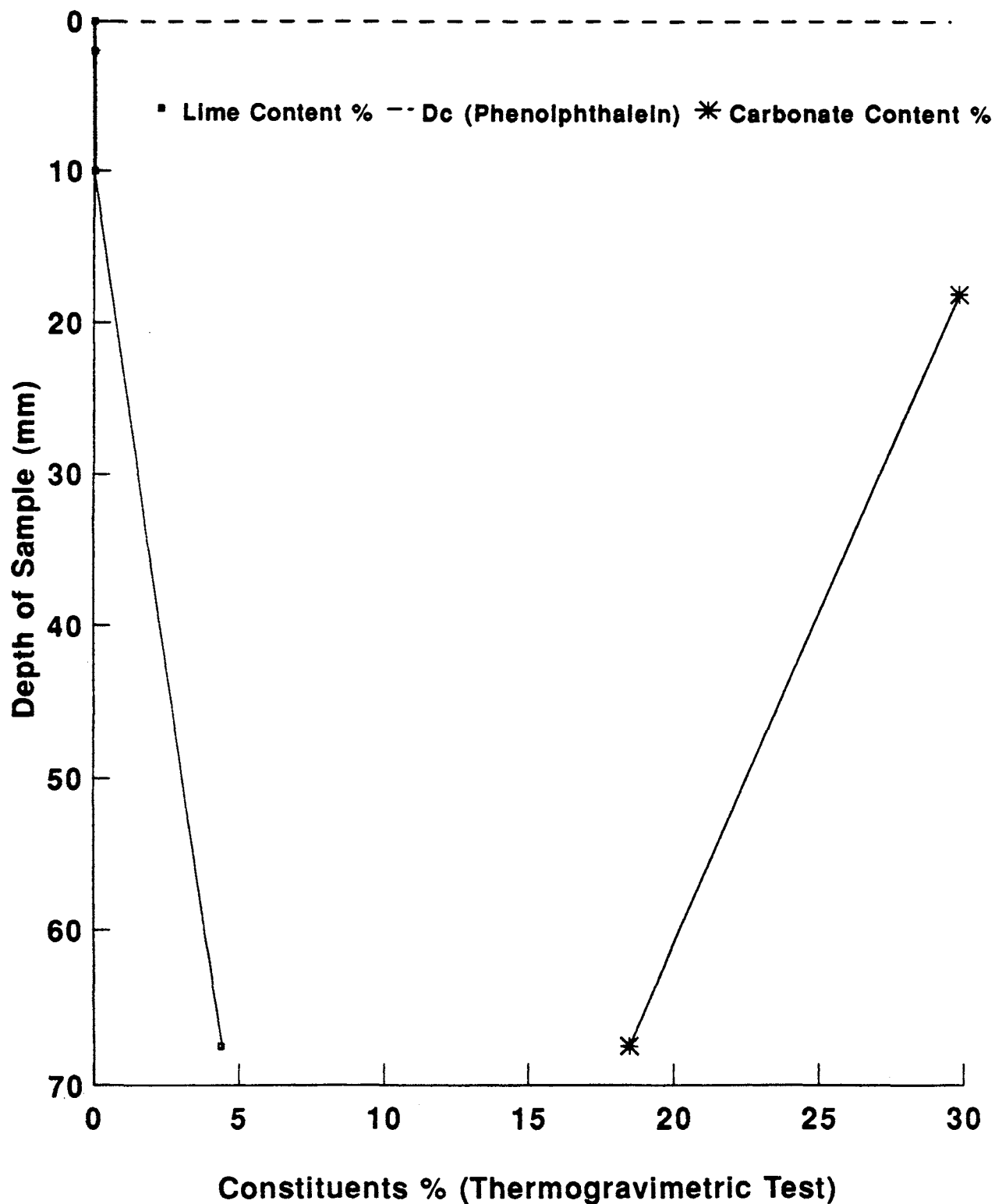
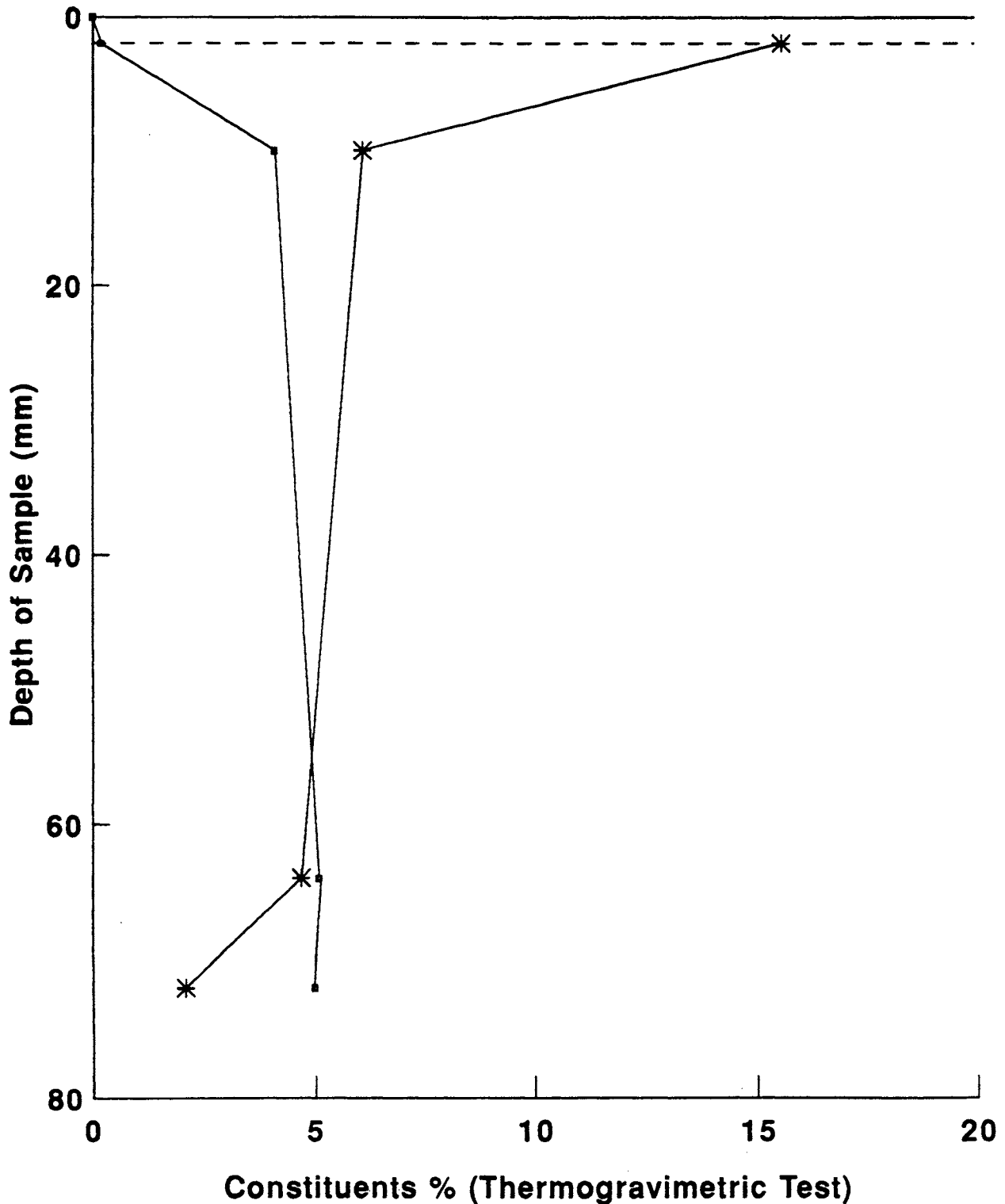


Figure 6J
Phenolphthalein vs Thermogravimetric
Test Results - Edmonton (Core E/CH/C-1E)



▪ Lime Content % -- Dc (Phenolphthalein) * Carbonate Content %

Figure 6K
Phenolphthalein vs Thermogravimetric
Test Results - Edmonton (Core E/V/W-1S)

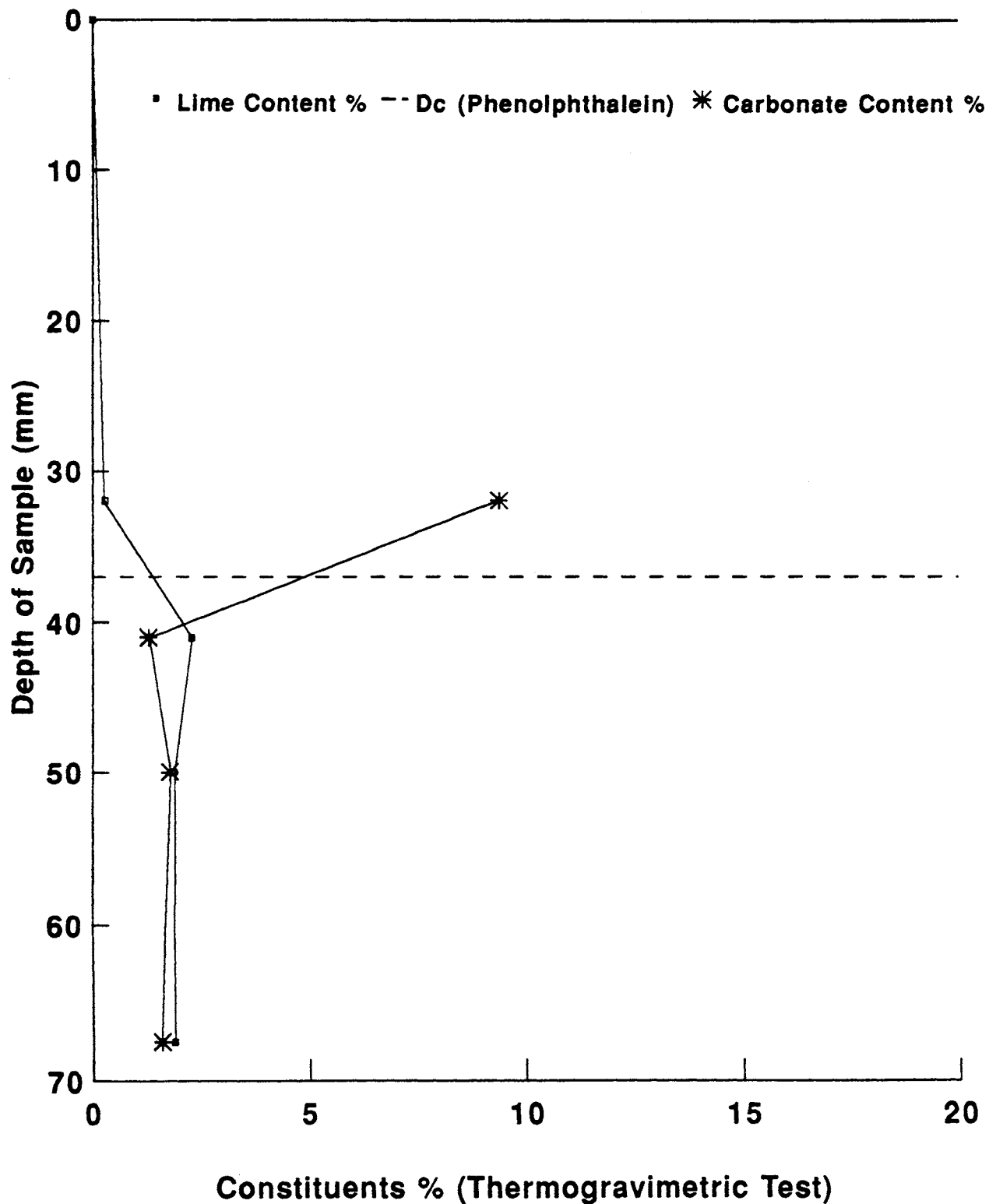


Figure 6L
Phenolphthalein vs Thermogravimetric
Test Results - Edmonton (Core E/V/W-2E)

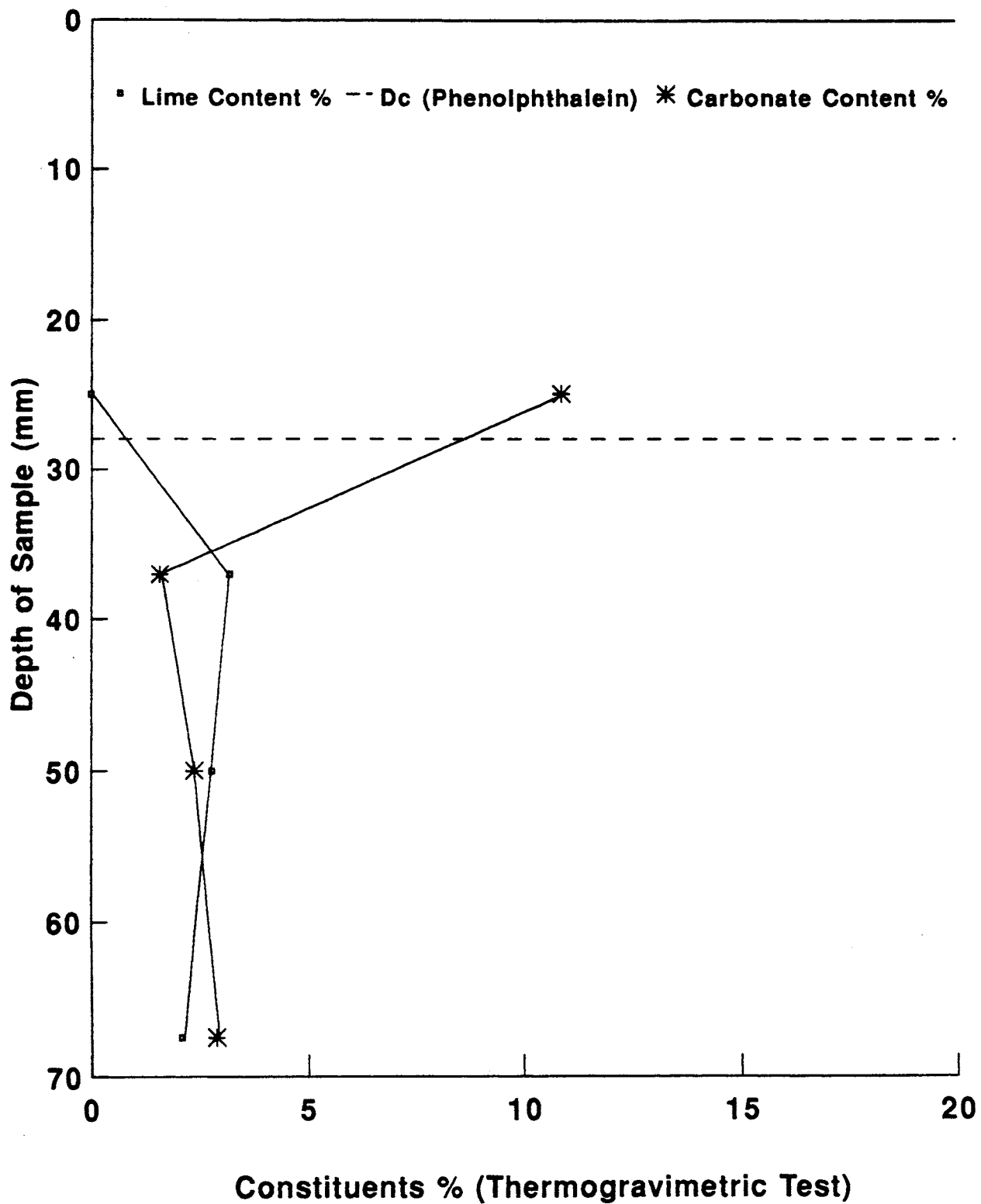
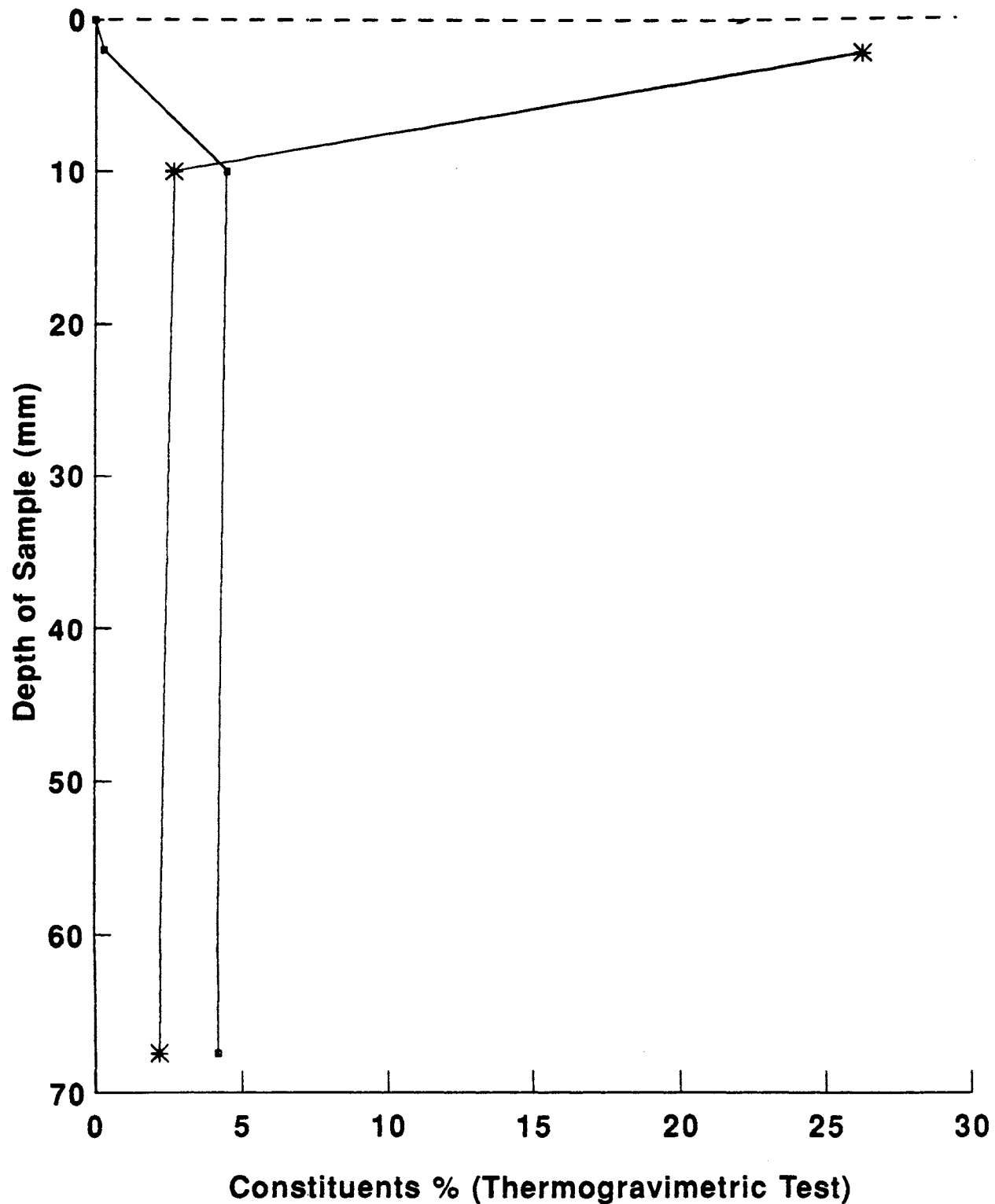
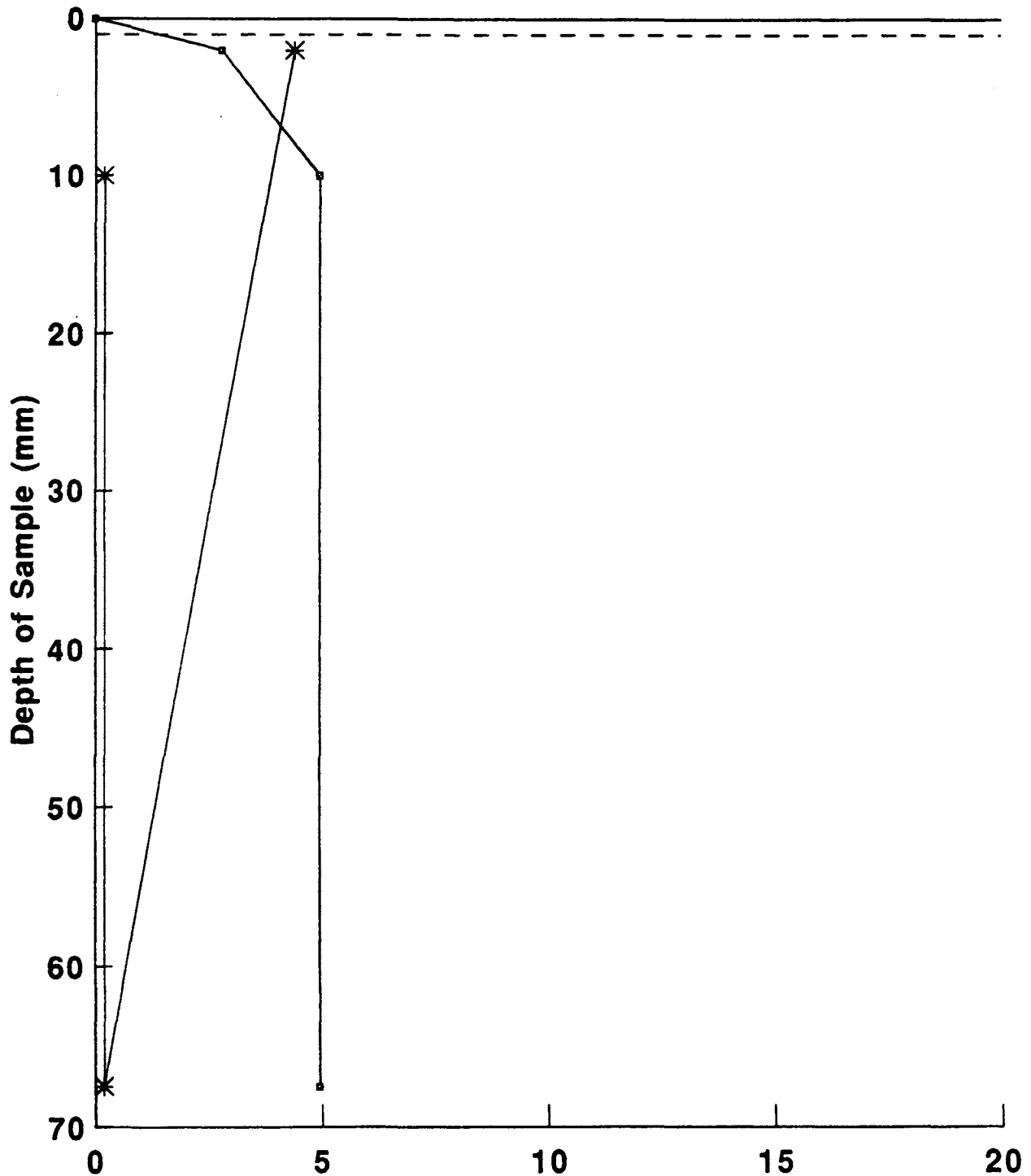


Figure 6M
Phenolphthalein vs Thermogravimetric
Test Results - Edmonton (Core E/VA/S3)



□ Lime Content % --- Dc (Phenolphthalein) * Carbonate Content %

Figure 6N
Phenolphthalein vs Thermogravimetric
Test Results - Vancouver (Core HT1a)



○ Lime Content % -- Dc (Phenolphthalein) * Carbonate Content %

Figure 6P
Phenolphthalein vs Thermogravimetric
Test Results - Vancouver (Core N1a)

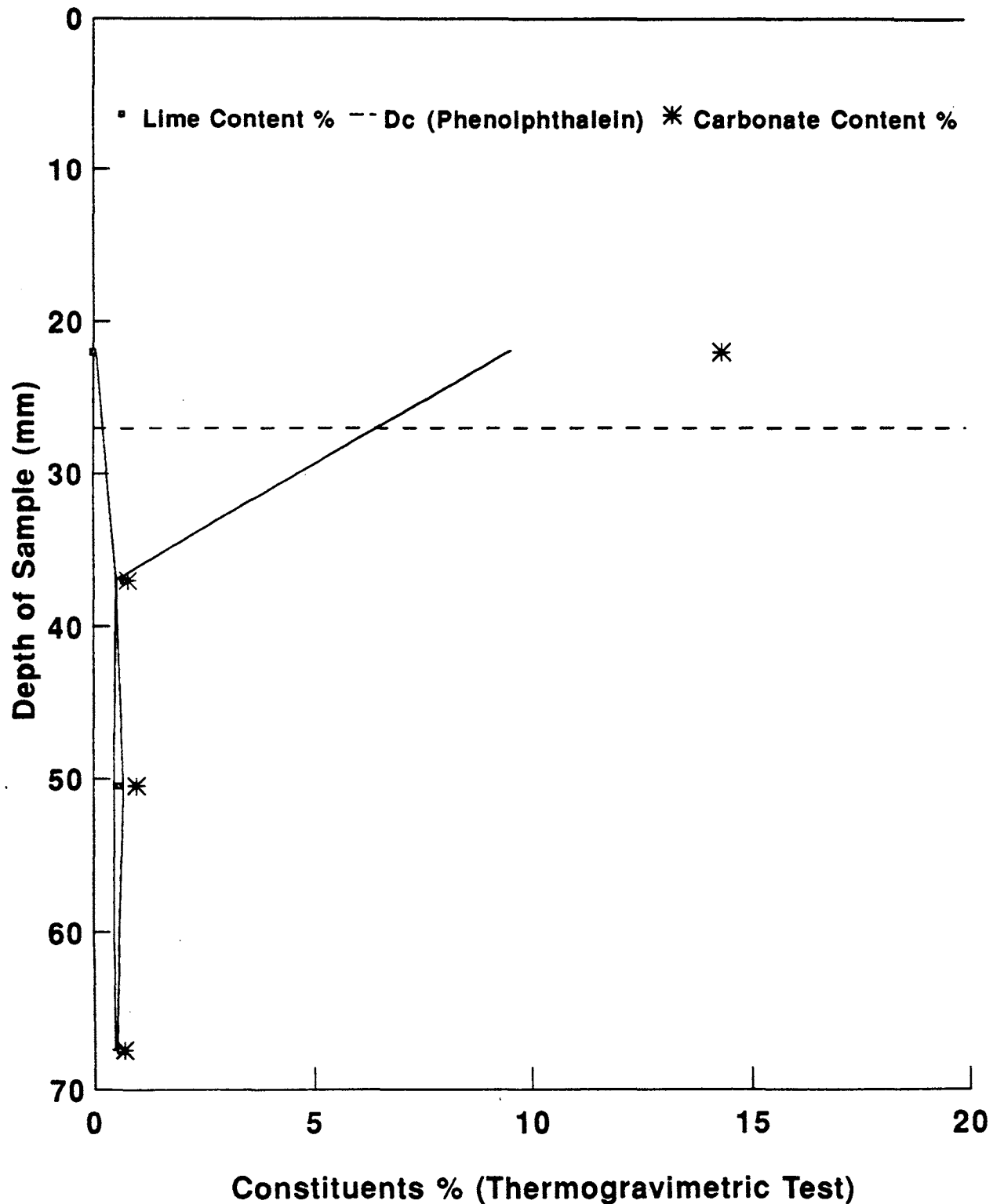


Figure 6Q
Phenolphthalein vs Thermogravimetric
Test Results - Vancouver (Core RT2a)

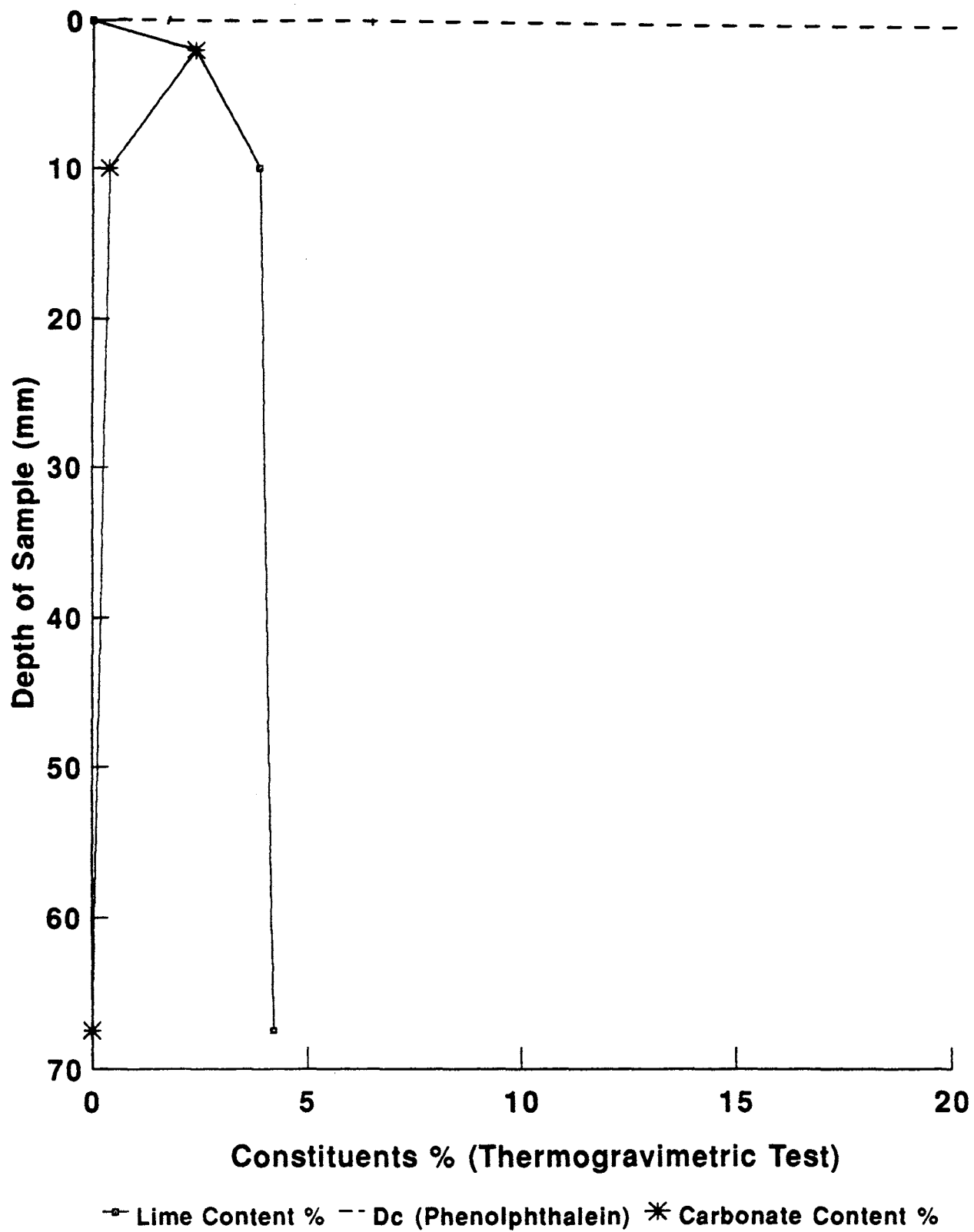


Figure 6R
Phenolphthalein vs Thermogravimetric
Test Results - Vancouver (Core S1a)

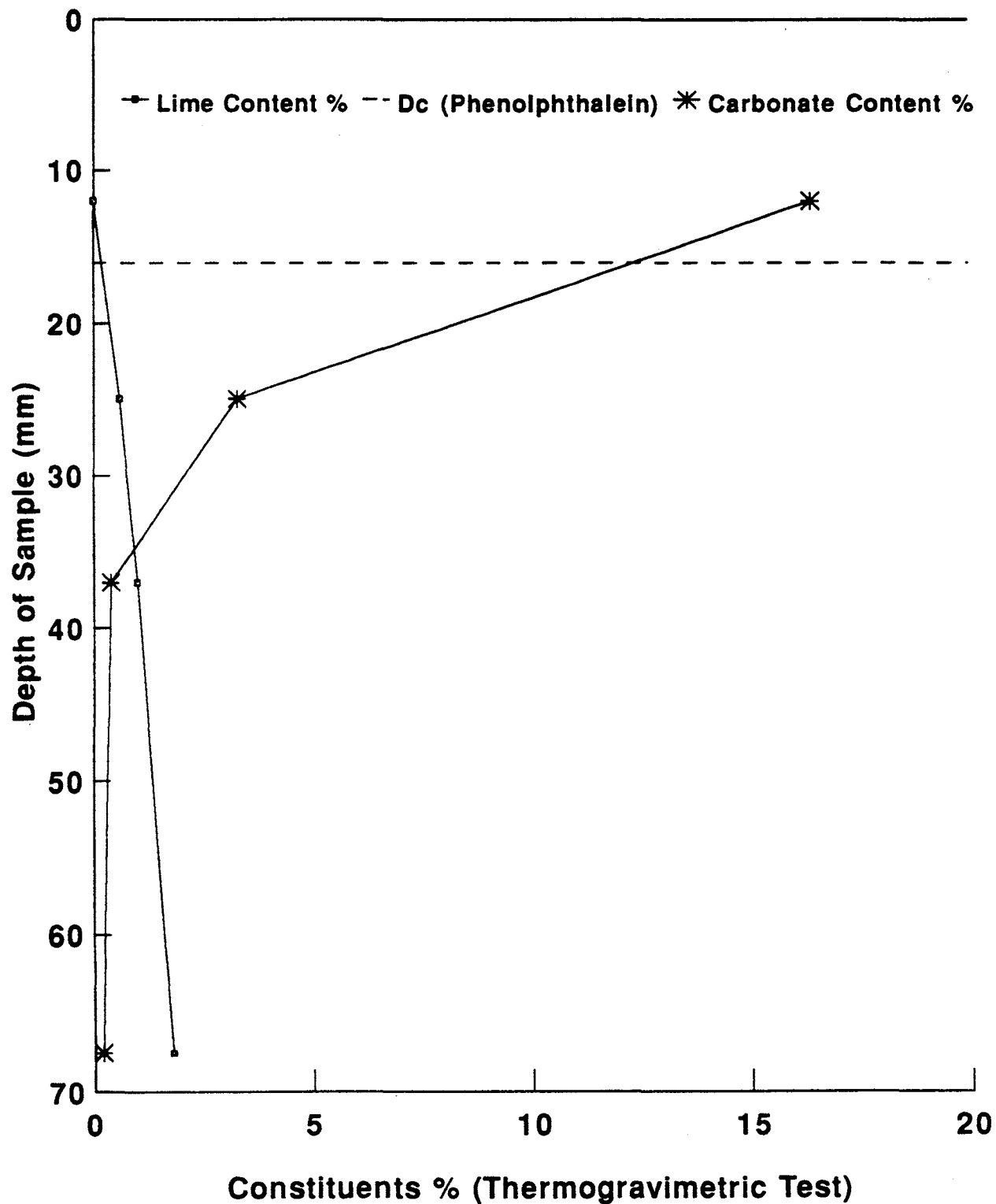


Figure 6S
Phenolphthalein vs Thermogravimetric
Test Results - Victoria (Core CO2a)

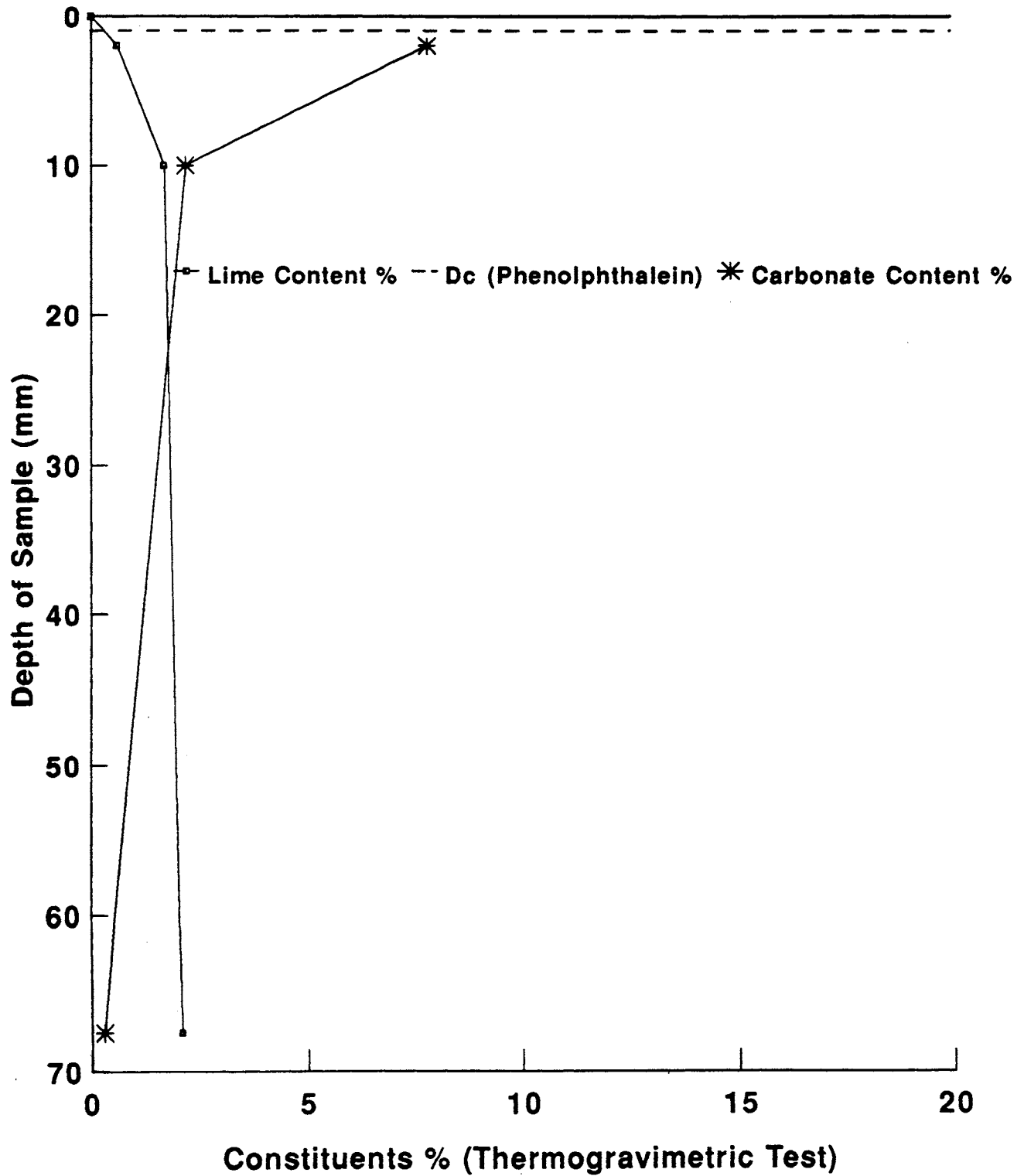


Figure 6T
Phenolphthalein vs Thermogravimetric
Test Results - Victoria (Core CO3b)

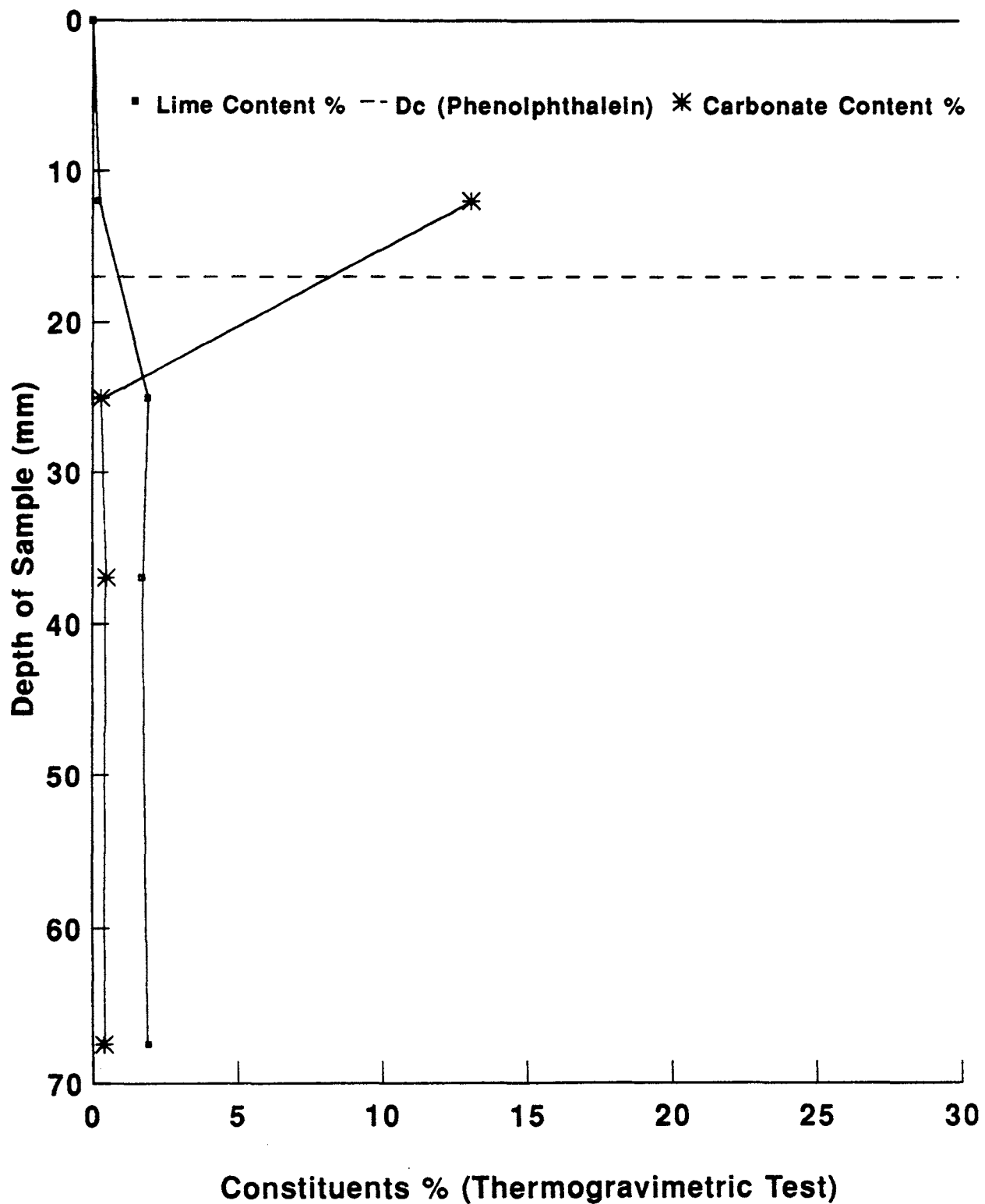


Figure 6U

**Phenolphthalein vs Thermogravimetric
Test Results - Victoria (Core CS3b)**

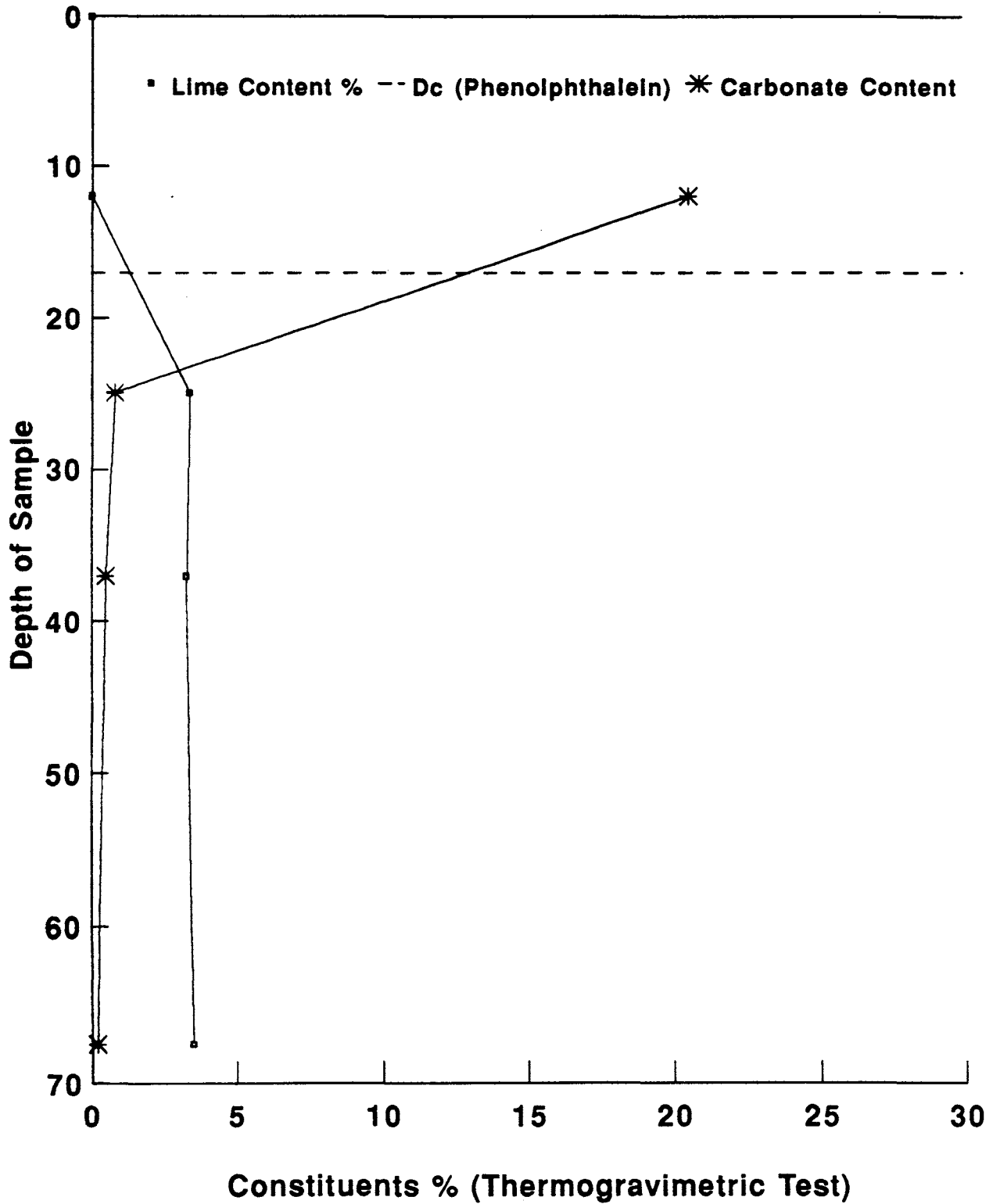


Figure 6V
Phenolphthalein vs Thermogravimetric
Test Results - Victoria (Core F1b)

