PREDICTING ENVIRONMENTAL PERFORMANCE OF FAÇADE GEOMETRY

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To all those who taught me everything I know about Building Science and Architecture.

ABSTRACT

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One of the main objectives of designers and builders is to develop building facades that do not deteriorate to cause aesthetic or structural damage due to environmental forces. The aim of this research is to assess the influence of different geometrical configurations on a facade's performance. Particular consideration is given to panelized facades using precast concrete or similar materials.

The analysis of the impact of weathering factors - especially pollution, rain and wind - in interaction with facade geometry and materials is presented. Extensive site observations have been undertaken in the Montreal area to evaluate the seriousness of weathering problems and help understand the mechanisms involved. The observed facade surfaces are classified into main and sub categories according to their sectional profiles. The weathering patterns likely to occur within each category are illustrated in a comprehensive taxonomy. An analysis of the additional factors that aggravate or minimize weathering is also present. Investigations for a preliminary model of water behaviour over different facade surfaces exposed to a variety of rain and wind conditions are carried out.

The results of the study form a set of pragmatic recommendations for building designers. Both large and small scale design issues related to weathering are rationalized. The findings aim to provide a reliable guide to achieve a better long term performance of building facades.

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CHAPTER I

INTRODUCTION

1.1 NATURE OF THE PROBLEM

The performance of building facades is a major concern to designers and inhabitants. In many buildings, facade surfaces have failed dismally in resisting the negative effects of the external environment. This is a rapidly growing problem, too important to be ignored [1.2].

The environmental performance of building facades can be defined as "the ability of a facade to perform a set of required functions in a given environment over the building life span". Generally, three main factors determine the performance of any building facade, and cause undesirable aesthetic and structural deterioration:

(i) Local weather conditions
- Air pollution
- Precipitation (rain, snow)
- Wind
- Temperature and humidity
- Atmospheric radiation

(ii) Geometric configuration of facade
- Overall geometry and form
- Incorporated details

(iii) Materials properties
- Absorbtivity
- Surface texture and finish

Numbers in Brackets [ ] designate the appended references.

- Chemical composition
- Solubility

These three factors, being substantially inter-related, make it difficult to attribute any single defect of a building facade to one isolated factor. An underestimation of the climatic influences, inadequate design of geometric configuration and incompatible materials may all be present in facade deterioration.

The problem with externally exposed materials is that they undergo visual as well as compositional changes when they interact with atmospheric pollution, water, water-soluble salts, ultra-violet radiation, organic growth, etc. The interaction with water in liquid or gaseous state, however, is the single most important factor affecting the deterioration processes in both porous and non-porous materials [1, 2, 18]. In porous materials, the problem is aggravated by the fact that the chemical action of water proceeds rapidly from the external to the internal depth of the material. By contrast, in non-porous materials the serious deterioration is usually encountered on the external surface.

When building facades are located in highly polluted environments and are subjected to varying rain and wind conditions, the question of performance and durability becomes more complex. Examples of those buildings are numerous in the downtown area of any big city subjected to the above weather characteristics. This problem is best illustrated on the facades of the building pictured in figure 1.1. It is noted that :

(i) the differential staining of facade surfaces has caused an undesirable disfigurement.

(ii) The degree of such disfigurement varies from a facade to another.

This unsuccessful performance of building facades gives rise to issues that warrant further investigation:

- On the macro-climate scale, the influence of facade orientation and the surrounding buildings.
- On the micro-climate scale, the implications of the designed geometry and the selected materials on aggravating or minimizing the resulting disfigurement.

In general, it is the movement of rainwater over the surface contours of facades that causes the uneven - i.e. partial - washing action and the concentration of deposited dirt and pollutants in the dispersed locations. This process is referred to as 'weathering' and is mainly associated with the visual changes and deterioration in the appearance of buildings.

Apart from the undesirable changes in the facade appearance, weathering usually results in an unforeseen increase of the cost of maintenance. Generally, removing the deposited pollutants from facade surfaces - particularly in highly polluted atmospheres - is desirable in order to avoid the chemical reaction between the deposits and the underlying material. These reactions can lead to serious disintegration and decay of the facade materials [1, 2]. Furthermore, if the cleaning process is not periodically carried out, the continuous deposition of pollution could hide other potential defects.

1.2 REVIEW OF PREVIOUS WORK

Some attempts have been made during the past two decades to approach the problem of facade weathering. In 1967, White prepared an up-to-date study on the visual effects of weathering on buildings [29], most of which had been previously published in the digests of the British Research Establishment in England. The study stressed the need for greater attention to be given to weathering problems merely through photographs of the observed defects. The study did not conclude any design recommendations.

Later in 1970, Simpson and Horrobin published their research on weathering and performance of building materials [27]. In this study they discussed the basic deterioration processes that different materials may be subjected to. The visual and compositional changes that occur at the facade surfaces were examined as a part of the total performance of a building. Emphasis was mainly given to the influence of material properties on resisting the negative effects of weather. The extent to which the geometrical configuration of building facades affects their performance was not included.

In 1972, Addleson published two volumes [1, 2] in a series of studies titled "Materials for buildings". In these two volumes the main concern was the analysis of water effects on materials. The influence of wind-driven rain on facade weathering was noted on a macro-climate scale for a building complex located in a polluted atmosphere. Though the percentage frequency of wind-driven rain from all directions was considered, the amounts of rain and the accompanying wind speed were not mentioned. Both factors have a substantial effect on the resulting weathering of any facade surface. Limiting the investigations to one building put a constraint on further analysis and comparison of different applications. On the micro-climate scale of building facades, Addleson followed the same line previously presented in White's study [29]. Dependence was mainly on pictorial presentation of observed defects to demonstrate their effects on performance. Emphasis was placed on the fact that rain-water moving over facade contours can bring about undesirable visual changes and deterioration of materials. The performance of porous and non-porous materials was examined with the intention of establishing the faults of the previous applications. However, no conclusions or recommendations were drawn for designers and builders.

Recently, in 1975, Robinson and Baker reported a study [25] dealing with weathering of facades due to dirt making. The influence of driving rain interacting with facade surfaces was examined. Analysis of weather records including frequency, direction, and speed of wind during rain was presented for most Canadian cities; the same analysis for Montreal was not included. Consideration of the amounts of rainfall was generally omitted. The study was based on site observations of building facades in Ottawa. Further extensive research on the problems associated with water migration and dirt marking on facade surfaces was recommended.

The growing interest in evaluating facade performance was expressed in a recent RILEM/ASTM/CIB symposium held in Helsinki, Finland,

1977. Current research results in the area of 'facade weathering' were presented. Among those researches is the one carried out by Carrié, et al, [6] on soiling of surfaces due to pollution deposits. The coefficient of soiling for different building materials - porous and non-porous - was experimentally determined. Fluctuation in the rate of dust and dirt deposition due to varying the surface inclination and its physico-chemical nature was also measured. Furthermore, the influence of the ambient temperature and humidity conditions on the material soiling was discussed.

In another research project prepared by Beijer [5], weathering of concrete walls was studied. His analysis was based on the hypothesis that uneven soiling is mainly caused by the driving rain; rain redistributes air-borne impurities which were originally - relatively - evenly distributed over the facade surface. Both laboratory investigation and measurements on external walls with flat surface were carried out to examine the distribution of driving rain and water run-off. Despite the thorough analyses included, the study did not establish guides for designers to avoid weathered facades.

The extent of shelter from driving rain provided by projections on external walls was the main concern of a study conducted by Ishikaw [15] in Tokyo, Japan. The shape and size of the stained wall area below horizontally projecting elements were measured on existing buildings. The results were analyzed together with the frequency distribution of wind velocity during rainfall. The study did not furnish specific recommendations so as to how stains at these particular locations could be eliminated.

1.3 SCOPE AND OBJECTIVES OF THE PRESENT RESEARCH

The review and analyses of the previous attempts dealing with weathering problems show that pollution deposition and driving rain movement over facade surfaces are the central issues in determining the degree and consequences of weathering. The resulting 'partial washing' induced by the action of water run-off over different profiled surfaces is considered the main area where further studies are necessary. The present work will therefore examine the influence of pollution, rain, and wind on facade performance on both the macro- and micro-climate scales. The extent to which the rest of weather factors such as temperature, humidity, and atmospheric radiation are likely to affect the facade weathering will be noted where relevant, but detailed consideration is generally omitted.

The role played by facade geometry and material in resisting or aggravating weathering is discussed. Particular emphasis is given to the effects of the geometric configuration of a facade on its performance, an area that still needs more integrated investigations. Only the surfaces of porous materials such as concrete, stone, and bricks are considered.

The literature review also shows that weathering of building facades in the Montreal area as a result of their exposure to local climatic conditions, has not yet been explored. The present study presents the first attempt to evaluate the seriousness of weathering problems in the city. The planned site observation will mainly be concerned with the performance of the building facades in the downtown area particularly those using precast concrete panels. Through a classification of the observed facade surfaces, the weathering mechanism involved and the possible remedies are investigated for each category.

The ultimate purpose of this research is to provide designers and builders with a reliable and rational guide to strengthen their ability to predict weathering failures. By so doing, the inevitable consequences of weathering can either be eliminated or at least minimized. The results of this work will contribute to establish an important tool with which a better long-term performance of building facades can be achieved.

1.4 LAYOUT OF THE THESIS

The study has been organized as follows:

Chapter II deals generally with weathering of building facades due to the interaction of their surfaces with atmospheric pollution, rain and wind. A diagnostic study of the main casual factors involved in the mechanism of weathering is also included.

Chapter III is designed to demonstrate the results of an extensive field observation of weathering problems in the Montreal area. The analysis of local climatic characteristics and their influences are also presented. These influences are examined on both the macro- and micro-climate scales. On the macro-climate scale the effects of orientation and location of a building on the weathering of its facades are shown. On the micro-climate scale, the effects of different geometric configurations and common building details are presented in a comprehensive taxonomy.

In Chapter IV, a preliminary model of water behaviour over facade surfaces is investigated. A method of estimating the quantity of rain run-off is developed for different materials when exposed to a variety of rain and wind conditions.

Finally, in Chapter V a set of recommendations are established to aid designers and builders to avoid the consequences of undesirable weathering and achieve a better performance of building facades.

(i)

(ii)

An example of a building in downtown Montreal showing:

(i) the differential staining of the facade surfaces has caused an undesirable disfigurement.

(ii) the degree of such disfigurement varies from a facade to another.

CHAPTER II

MECHANISM OF WEATHERING

2.1 INTRODUCTION

In this chapter, it is proposed to examine the weathering problem of building facades and to assess the complex mechanism involved. The principal factors are related to:

(1) Atmospheric pollution deposits.

(2) Rain movement over facade surfaces.

(3) Wind-driven rain effect on facade wetting.

(4) The geometric configuration of facades.

(5) Materials nature and surface characteristics.

These factors, it should be emphasized, are strongly interrelated; therefore, the present work will integrate them all in analyzing the weathering problem. Particular emphasis, however, is given to the implication of different geometric configuration of facade surfaces on the resulting weathering.

2.2 WEATHERING OF BUILDING FACADES

As briefly explained in the first chapter, the interaction of weather with facade surfaces usually results in unique patterns of water flow, thereby determining the location and degree of washed and unwashed areas. The differential staining is very much dependant on the quantities of accumulated dirt as well as quantities of rain water moving over facade surfaces. A building in a suburban area, for example is less subjected to weathering problems when compared with a compatible building in the downtown area exposed to greater quantities of atmospheric pollution. Furthermore, the degree of exposure to driving rain that has a particular orientation, frequency and duration, will substantially affect the resulting weathering patterns. A building facade totally exposed to increased wetting due to free driving rains may normally be subjected to enough periodic washing to keep its surfaces clean. This washing action, however, is usually complex and far from uniform, and it results in most cases in undesirable changes in facade appearance.

The overall configuration of a facade geometry whether in a high or low rise building is responsible for the resulting wetting patterns. In tall buildings, wetting of facades is highly dependent on the wind condition in the surrounding environment and its effect on the accompanied rainfield. In low rise buildings, wetting is comparatively uniform due to the wind flow patterns which usually permit a more steady rainfield than that on tall buildings. Moreover, the individual details of a facade surface such as ribs, window sills, drips in soffits, substantially influence water movement, and consequently the resulting washed and unwashed areas.

Weathering problems are generally associated with porous building materials such as concrete, stone, and brick. The performance of non-porous materials (eg. glass, metal, etc.) is totally different due to their smooth surfaces where dust will not usually deposit or adhere. Moreover, rainwater that hits these surfaces will immediately run off taking with it any lodged impurities.

Different materials, depending mainly on their porosity and surface texture, react differently under the same climatic conditions. For example, the soiling of brick facades due to dirt accumulation has been observed to be substantially less evident when compared with concrete or stone work. Colour of materials is also related to the weathering of surfaces. It affects absorption and reflection of atmospheric radiation and hence the rate of evaporation of rain water from building facades. The quantities of rain run-off will then be affected and hence the resulting washing pattern. Generally, dark toned finishes are practically less susceptible to weathering.

2.3 MAIN FACTORS AFFECTING WEATHERING

As mentioned above, facade weathering is mainly attributed to the deposition of atmospheric pollution coupled with the effects of rainwater that often results in differential washing action. The issue of water presence, deposit, and movement over building surfaces has recently been referred to as 'surface hydraulics' [25]. Assessing the complexity of surface hydraulics is then inseparable from studying the mechanism of weathering that involves mainly two sets of variables. The first set is less controllable and is related to the weather factors, pollution, rain and wind. The second is associated with more controllable variables pertaining to the facade geometry and its materials.

2.3.1 ATMOSPHERIC POLLUTION DEPOSITS

In analyzing the weathering mechanism, a primary consideration should be given to the air quality around buildings. The chemical agents contained in the polluted atmosphere are often deposited on and interact with facade surfaces. Dust particles, soot containing carbon particles, sulpher dioxide and many other pollutants are all present in different intensities in any big city. These pollutants contribute to the formation of three dust layers in the atmosphere [13]. The first, i.e the lowest, lies between houses and open spaces and is caused by street traffic and railway smoke. A second layer exists about 20 meters from the ground and is continuously fed by the smoke resulting from chimneys above the houses. Above this, at a height of 50-60 meters, is the third which is caused principally by chimneys of the industrial and commercial establishments. Pollution intensities within these three layers can be substantially enhanced depending on the sources of pollution and their potential emition of smoke.

The vertical mixing of the three layers and the resulting deposition on building facades are strongly dependent on the other atmospheric conditions such as wind, rain, fog and the temperature gradient [23]. Strong wind for example increases the mixing of dust layers, however, it usually cleans out the city pollution and hence the risk of dirt deposition is decreased. Rain and fog increases the pollution level in the street air with pollutants from the upper dust layers. Vertical transportation can also occur in the summer days when the ground temperature is relatively higher than the upper layer. In winter little mixing is encountered and hence pollutants are likely to be dispersed and swept away [23]. Worse conditions can then occur if long periods of light winds prevail since they favour the accumulation of dust and soot particles on building surfaces.

Weathering problems practically start when the rain water moving over facade surfaces redistributes the deposited dirt and soot. Particles deposition will then become relatively uneven resulting in undesirable change in the building appearance. Moreover, some pollutants such as sulpher dioxide and carbon dioxide react with the surface material forming a layer of foreign products. The chemical reaction is enhanced in the presence of rainwater, and, in many instances, causes deterioration and decay of the surface material. Consequences of such chemical reactions are further elaborated in Appendix I.

2.3.2 RAIN MOVEMENT OVER FACADE SURFACES

Rain is usually characterised by four basic features which determine the quantities of precipitation that will strike and flow over a building facade:

- Angle of falling rain.
- Intensity and duration of rain.
- Range of droplet size.
- The prevailing wind conditions.

Once deposited, rain drops are always subjected to other actions that affect their ultimate movement over the surface [18]. These actions are:

(1) The force exerted on the rain droplet as its kinetic energy is transformed by contact with the building face.

(2) Gravity, acts on water drops to move them into any passage that leads downward. The velocity of downward movement - will depend on the surface profile, texture, and irregularities that is friction forces.

(3) Air pressure difference across the enclosure, exerts a force that can cause inward movement of water. Wind pressure, stack effect, and ventilation all contribute to the resultant pressure difference.

(4) Capillary action draws and holds water in small capillaries. Upon material saturation the suction force approaches zero.

The resultant of these forces acting on the deposited rain drops might cause the water to penetrate the surface, be absorbed by the wall material or run off the building face. Depending on the rain quantity, the run off water induces either a complete or partial washing of the deposited dust and soot over facade surfaces.

2.3.3. WIND-DRIVEN RAIN EFFECT ON FACADE WETTING

In presence of wind, the falling rain is never vertical and is always driven at an angle striking the buildings facades. Wind is a random and complicated phenomenon and until very recently building designers were unaware of its serious implications on the built environment. Recent advances in the techniques of measuring wind pressure have permitted a more accurate analysis and prediction of the influence of wind on facades.

An example of such studies [10] was carried out on a 34 storey building located in downtown Montreal (see figure 2.1). It was concluded that fluctuations in wind direction is an important factor in determining the induced pressure and suction on the building envelope, and in establishing their local peak values.

Another study [11] was conducted in Toronto on an existing 57 storey building to measure the induced pressure and suction in different regions of flow. The reported results indicated a satisfactory agreement between the mean wind pressures measured on the building facades and those previously measured on the scale model during wind tunnel tests. In line with this study, the air flow pattern around a high rectangular building and the resulting distribution of mean pressures are presented in figures 2.2, 2.3 (based on Robertson's investigations, [26]).

The incident pressure distribution causes a secondary airflow along the windward facade surface from high pressure to low pressure regions as illustrated in figure 2.4 [21]. Suction at the leeward facade, roof and side walls, causes other patterns of secondary airflow. At the leeward wall, for example, air tends to flow upward in the direction of high suction regions toward the roof. At the side walls, air flows in a reverse direction back towards the wall edges where the main flow separates from the windward facade.

A similar study was reported by Baines [4] where he determined the secondary airflow pattern over the surfaces of a simple cube. The results are illustrated in figure 2.5.

These different airflow patterns over building surfaces affect water movement and concentration at certain areas, thereby determining the potential washing action and the consequent results of facade weathering. Generally, two cases of wetting patterns of facades can be distinguished; the first is associated with low-rise buildings - up to 4-5 storeys, the second with tall buildings.

Considering the performance of low-rise buildings, their facades are subjected to a wind-driven rain field that is subjected to high turbulence and unsteady conditions. As a result, the wetting of low-rise building facades is generally more uniform due to the increased randomness of the rain field of those low heights. The falling rain striking any of the building facades will tend to migrate down the surface causing a certain washing action that will depend on both the water quantities and surface material. The basic effects of wind-driven rain on a hypothetical low-rise building is illustrated in fig. 2.6.

In tall buildings, the incident wind-driven rain permits a 'turbulent' flow* with mean velocity (and pressure) increasing with height. Generally, this flow rolls up into a standing vortex system near the building base (recall figure 2.4) causing high wind speeds in this region. At the same time, a pressure difference is created between the low pressure wake regions (leeward and side faces) and the relatively high pressure region at the base on the windward side [3]. This difference accounts for the increasing flow of air carrying water, and hence wetting of the building corners. The increased wetting - whether on the corners or top areas, is also attributed to compression of the stream lines of flow that causes concentration of the accompanied rain field. A typical generalized wetting pattern of a tall building subjected to wind-driven rain is illustrated in figure 2.7. The contract between the washed areas - subjected to increased wetting and the less washed surfaces causes undesirable change in the building appearance.

At stronger wind-driven rain, the induced washing action may result in erosion of the surface layers of facade materials (such as lime-stone). The erosion is attributed mainly to the density of each raindrop which is about 1000 times larger than the density of the surrounding air [26], though the velocities of wind and rain may be nearly equal.

* It is the type of flow in which the particle behaviour may be entirely random, with individual particles and groups of particles spinning and rotating and moving first in one direction then in another with no order or method except that the whole aggregate is proceeding in the streaming direction [14].

Despite the advancement in wind studies, the exact patterns of air flow around buildings and the resulting effects of wind and wind-driven rain - both on the macro and micro-climate scale are still not completely defined. Difficulties arise because of the complexity of the aerodynamic behaviour of buildings and the interaction between the infinite variety of geometrical configuration they have with the surrounding context.

2.3.4 THE GEOMETRIC CONFIGURATION OF FACADES

Whereas it is possible to get a reliable weather data pertaining to the basic exposure condition of a given site to rain and wind, the extent to which this exposure is further changed by the facade geometry will be subjected to substantial modifications. The geometric configuration of a facade may cause wetting to be increased at certain locations while complete sheltering is given to other nearby areas. Though it is not an easy task to classify all variations in a facade geometry, it would still be possible to study the effect of most common architectural details on the surface hydraulics of facades.

- VERTICAL PROJECTIONS

In case of a vertically projecting mass (eg. huge column, staircase shaft, etc.) the facade surfaces are subjected to different degrees of exposure to driving rain. Sheltered areas are less washed than other surfaces and hence display more stains and dirt accumulation.

A vertical projection such as a rib or a louver, can direct rainwater to be concentrated in downward streams and hence prevent it from moving laterally or diagonally. Concentration of water increases the washing action over the inside corners of vertical projection.

In contrast, deposits remain over the exterior flat of the projecting element since the surface tension prevents water from moving in great quantities on such narrow surfaces.

When vertical surfaces are not interrupted with projections or recesses, water and dirt will be allowed to move comparatively freely. Risk of weathering will then depend on the surface area, its absorption capacity, and the quantities of the moving rain. Generally, the rate of flow at the commencement and end of any rainfall is usually less than that which occurs during the fall. Water will continue to flow at a progressively slower rate for sometime after the fall is ceased and the evaporation is started. The resulting drying out process often influences the pattern of streaking which manifests itself in the contrast between clean and dark stained areas.

- HORIZONTAL PROJECTIONS

Sheds, canopies, balconies, eaves, window sills, etc. are ideal horizontal surfaces for dirt and pollutants to deposit. They are also likely to receive the greatest rain quantites for all angles of rainfall varying from 0.0° to 45° to the vertical. Horizontal projections are normally designed to either throw water away clean of the wall surfaces or collect it to be drained in any designed vertical paths. Beside preventing local concentration, projections also provide a certain degree of protection from rain to the surfaces below. However, when rainwater is not controlled, localized increased wetting occurs and consequently differential weathering between washed and unwashed surfaces.

A positive control of rainwater moving over building façades would substantially be affected by the design considerations given to:

(a) The slope and profile of the projecting elements.

(b) Drips in soffits.

The slope of any projecting surface has a direct relation with the quantities of rainwater it receives. For a constant angle of rainfall (eg. 10 degrees to the vertical), increasing the surface inclination to the vertical will result in increasing its exposure to the rainfield [20]. Figure 2.8 illustrates schematically the changing exposure conditions for different wall surfaces. Whatever the quantities of water received by a projecting surface, still their potential paths will be affected by the profile of the front edge. Examples of a variety of profiles and their influence on water flow are illustrated in figure 2.9.

The drip incorporated in soffits of projections prevents the flow of water from returning through the soffits to the facade surface. Omission of drips may result in a complete deterioration of soffits due to the resulting wetting. When such decay is repeated in the soffits of a facade balcony, for example, substantial change in its overall appearance will soon occur. If drips are improperly dimensioned, the moving water will be allowed to bridge them and again deterioration will take place. Extending the drip horizontally and - if possible - vertically down the building face would contribute to guide the accumulated water into controlled drains.

2.3.5 MATERIALS NATURE AND SURFACE CHARACTERISTICS

As previously mentioned, weathering problems are mainly associated with porous building materials rather than with non-porous materials. The differing characteristics of each group, such as absorptivity, surface texture, solubility, chemical composition, etc., substantially affect their interaction with weather.

Porous materials - especially when externally used - allow particles of air pollution to accumulate more readily especially when their surface roughness (ie. cavities) is of the same order of the particles dimension. On a microscopic scale, the behaviour of the deposited particles usually involve a set of complex factors related to:

- The size of the capillaries
- The degree of interconnection of pores in the material
- The internal pore surface
- The ambient humidity level

Particles of dirt can move into capillaries with water molecules and hide at some distance from the surface layer of the material as the case with some types of bricks [6]. In materials with less surface porosity, accumulation of dirt particles will mainly be expected at the material face. Evaporation of water molecules usually causes pollutants to adhere closely to the material.

Generally, the surfaces of most materials exert certain forces of attraction on water vapour molecules. They adhere to the surface in a state of equilibrium with the ambient water vapour conditions. Accordingly, in humid environments, the material surface will attract more water vapour molecules with which particles of dirt will more easily adhere. This fact has been confirmed experimentally in a study done by Carrié [6] for cement-based materials, lime stone and bricks. Granite and aluminum on the other hand, have showed less sensitivity to soiling (ie. dirt accumulation) when the humidity level fluctuates. Carrié has also developed a relation between the surface temperature and the soiling rate. It was reported that the colder the surface the more readily it retains dirt. Conclusions of this study are in a good agreement with what was reported by White, 1967 [29], that is, hot and dry climates are less susceptible to soiling problems than cold and humid environments.

Time is an important factor in the deposited quantities of pollutants over building surfaces and hence weathering rate. Generally, facade surfaces, unless subjected to periodic washing in enough quantities, tend to accumulate dirt deposits that alter their appearance. Water run-off patterns over building surfaces are then the key issue in determining weathering.

Run-off water is directly related to both the quantities of driving rain arriving to the surface and the absorptivity of the wall material. Under the same climatic conditions, a more absorptive material such as brick, displays lesser quantities of run-off than concrete for example. This behaviour of the material will limit the movement of rainwater carrying dust and pollutants and hence the possible weathering. (More elaborate investigations are included in Chapter IV).

Generally, brick facades are considered to have less weathering problems because of:

- The size of the pore structure sometimes permits particles of the deposited pollutants to be hidden in the material pores [6].
- The relatively greater absorptivity with which less quantities of water run off the building face minimizing the risk of dirt redeposition or concentration at localized areas.

- The small scale pattern of brick work does not show the normal accumulation of dirt to the same extent as large plain surfaces of concrete [20].
- The comparatively dark colour of bricks causes more absorption of the atmospheric radiation that increases the evaporation rate of water present over the surface. This directly results in decreasing run-off quantities and hence minimizing the risk of migration and redeposition of dirt.

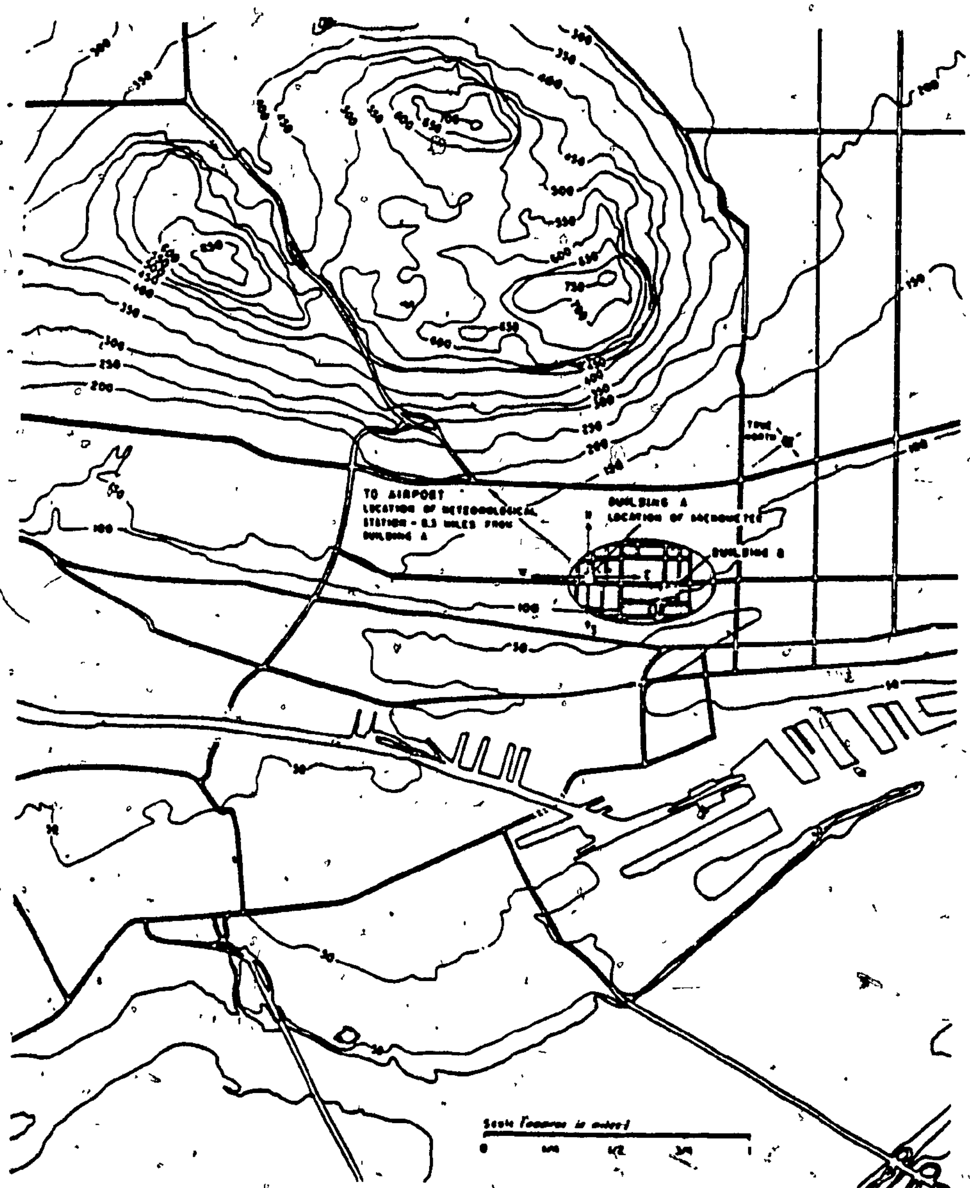
The performance of stone facades are not so different from that of concrete. Solubility of some types of stones, especially those containing lime, allows a set of complex chemical interactions to take place with the acidic gases of the atmosphere such as carbon dioxide (CO_2) and sulpher dioxide (SO_2). The resulting compounds* deposit and adhere to the surface forming a layer of different characteristics from the underlying material (ie. insoluble and less porous). This situation is likely to occur on surfaces that are not subjected to periodic washing; continuously washed surfaces, on the other hand, are kept fairly clean.

In essence, it can be concluded that rain water arriving to a building facade of porous material - either windward or leeward - will first be absorbed then upon material saturation, the unabsorbed quantities will accumulate and start running off. As a result, a water film develops and tends to run down the surface taking with it any impurities lodging or adhereing on the facade. The film thickness at any

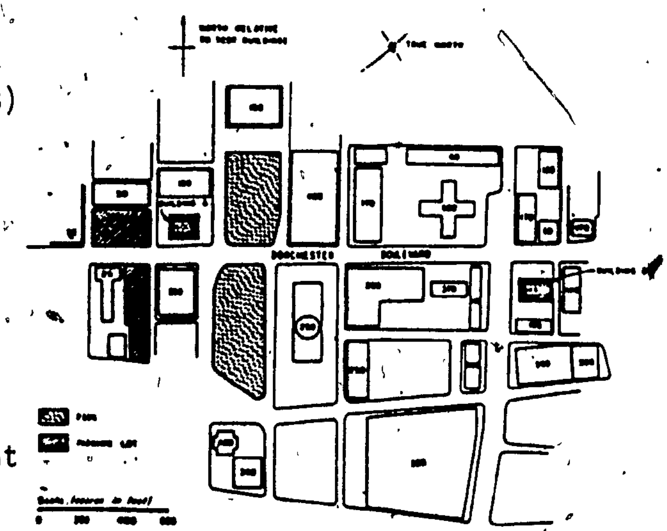
* Detailed discussions pertaining to the resulting compounds of carbonates and sulphates are presented in Appendix I.

height will determine the degree of the washing action that occurs on the facade surface. Accordingly, different rates of dirts concentration will take place causing undesirable differential weathering of the facade.

More detailed investigations pertaining to simulation of the behaviour of water over concrete, stone and brick facades are illustrated in Chapter IV. Variety of exposure conditions to driving rain with varying intensities and durations is also considered.



(A)



(B)

FIG. 2.1:

(A) Contour map of the terrain surrounding the 34 storey building under consideration. [ie. building B]

(B) Close-ups showing the building location and the heights of adjacent building.

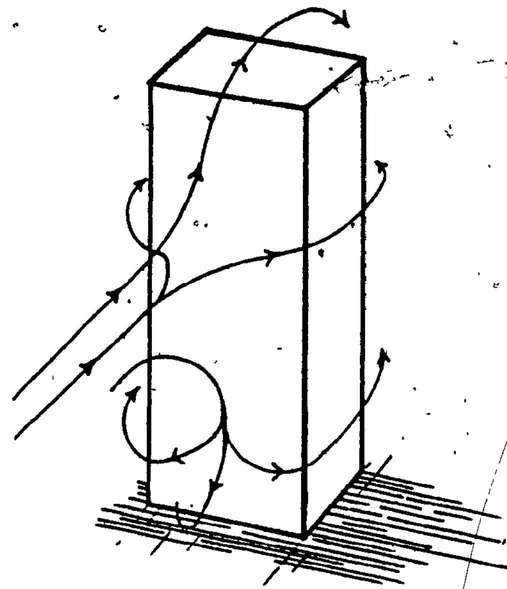


FIG. 2.2:

Typical air flow pattern around a high rectangular building as a result of exposure to wind perpendicular to the building facade. (After Robertson [26]).

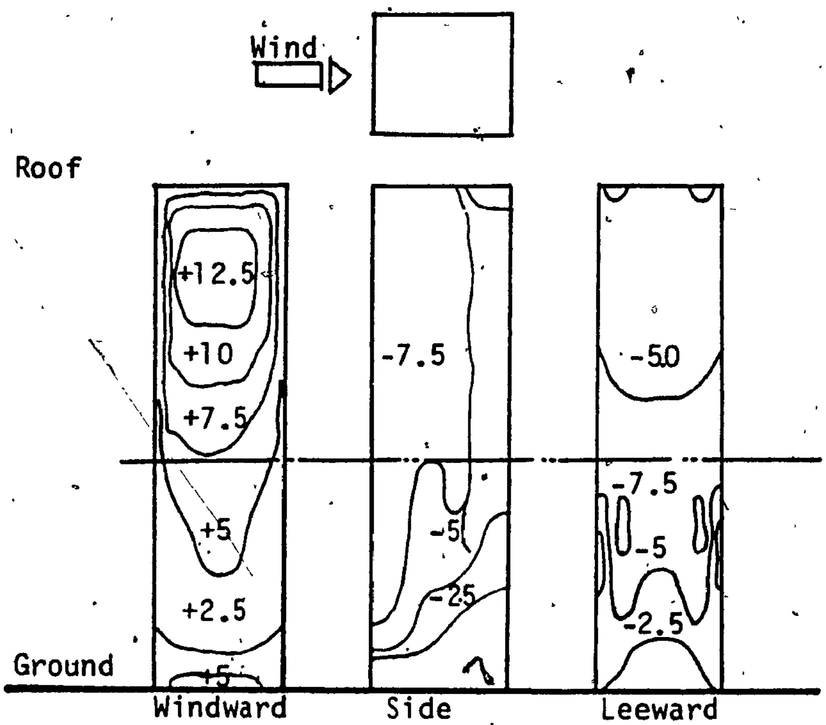


FIG. 2.3: The incident pressure distribution on the facades of a hypothetical building. (mean wind pressures (PSF) V = 72 m.p.h. at roof level. (After Robertson [26]).

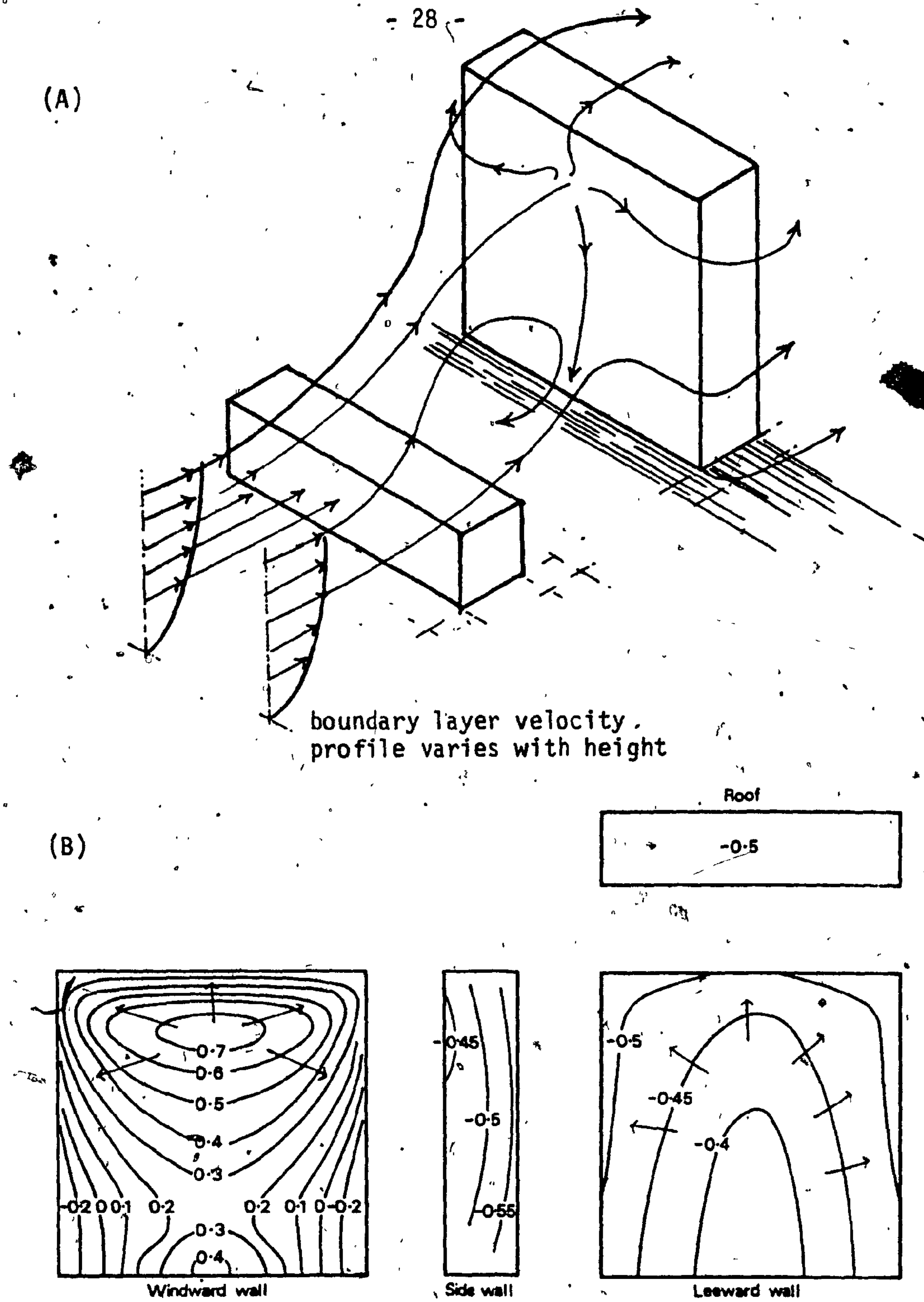


FIG. 2.4:

(A) Flow pattern around a tall building with a low rectangular building to windward.

(B) The incident pressure/suction distribution causes a secondary air flow (close to the facade surface) from the high to low pressure regions at the windward facade and from low to high suction regions at the other facades and the roof. (After Penwarden and Wise [21]). Numbers represent pressure coefficients referenced to building height.

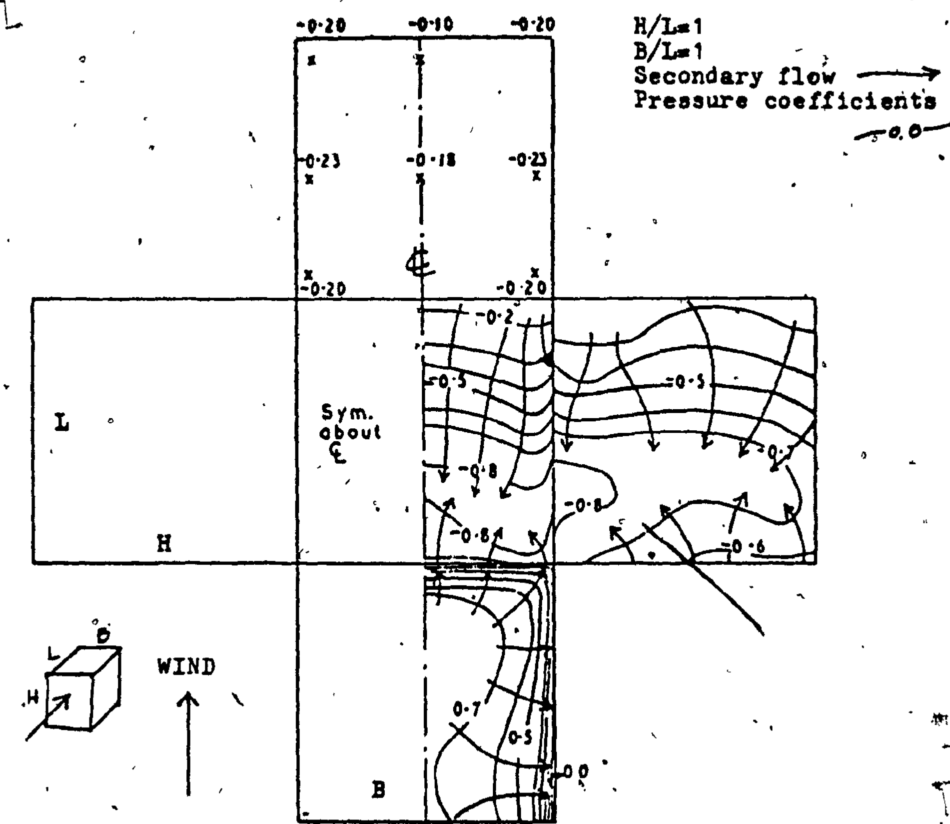


FIG. 2.5: Pressure distribution and resultant secondary flow on a cube in a boundary layer wind velocity field. (After Baines [4]).

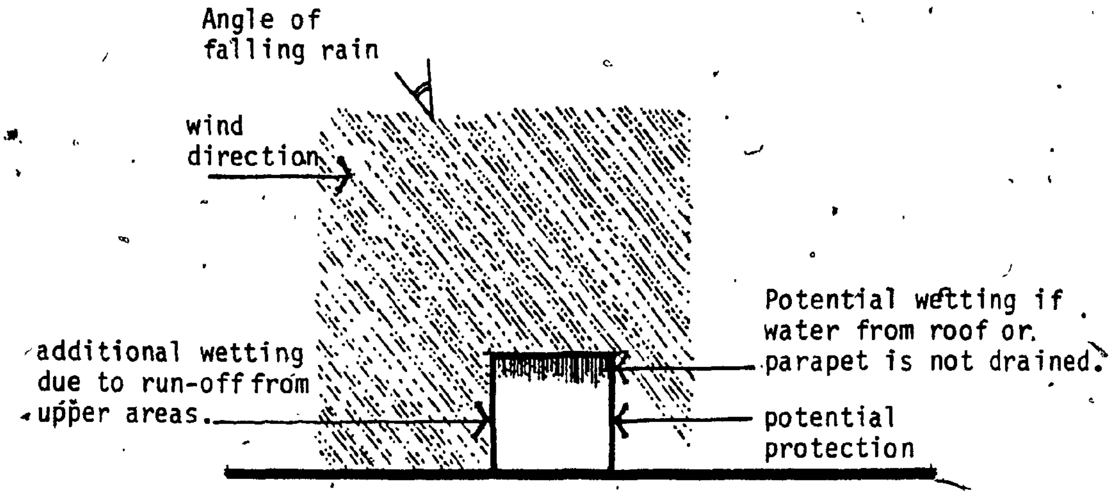


FIG. 2.6: Basic effects of wind-driven rain on a hypothetical low-rise building.

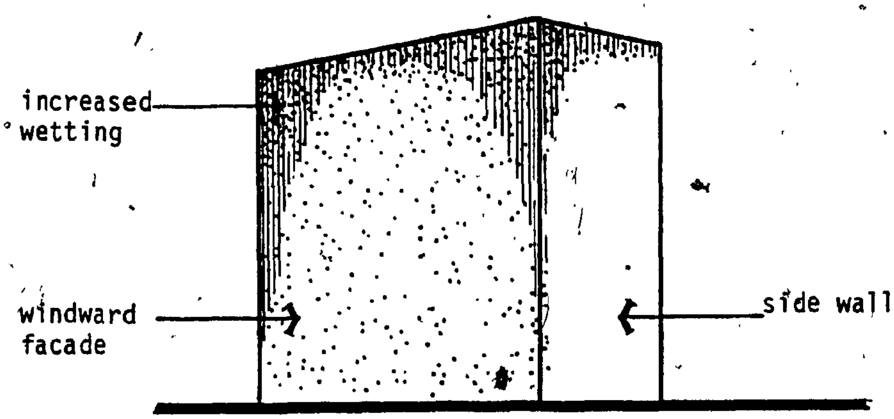


FIG. 2.7: A typical generalized wetting pattern of a tall building subjected to wind-driven rain (Based on Couper [9]).

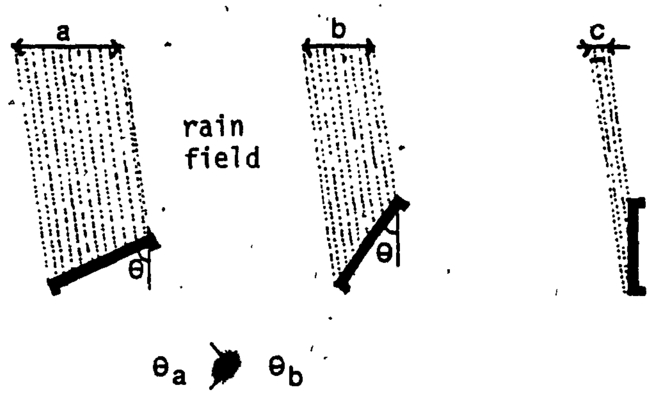


FIG. 2.8: The volume of rainwater likely to strik wall surfaces having different inclination θ° to the vertical. Increasing θ increases the exposure to rain. (After PCI [20]).

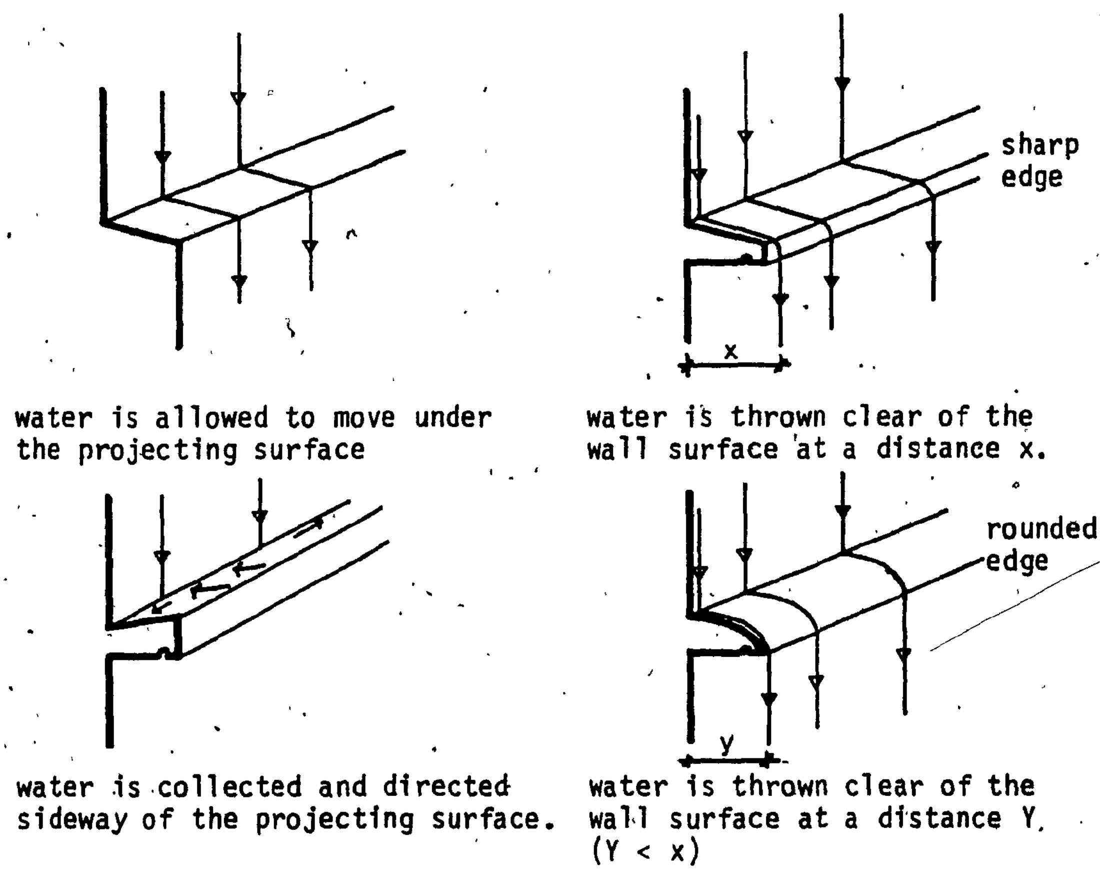


FIG. 2.9: Diagrammatic illustration of the effect of the profile of the front edge of a horizontal element on the water flow.

CHAPTER III

AN ANALYSIS OF FACADE WEATHERING PATTERNS

3.1 INTRODUCTION

Despite the difficulties involved in illustrating photographically the variable patterns of water flow over building facades, it is still possible to depict generally the final results in the form of localized concentrations that indirectly indicates the way water moves and migrates over surfaces. Photographic examples of most commonly found weathering patterns - both on the macro and micro-climate scales are classified and presented in this chapter. Accompanied analysis and interpretation of the causal mechanism are included and as a prerequisite study, the influence of Montreal climate on facade weathering is also discussed.

The analysis of the selected examples assists in appreciation of the mechanism of surface hydraulics as well as in reinforcing the ability of designers and builders to evaluate and predict, the behaviour of rainwater moving over building facades and the resulting weathering patterns.

3.2 INFLUENCE OF MONTREAL CLIMATE ON FACADE WEATHERING

Montreal is located about two thirds of the way up the St. Lawrence River valley giving it a continental climate. The city is situated between 45° N and 46° N lattitude (see figure 3.1). As previously mentioned, the climatic influence on weathering of building facades is mainly dependent on pollution levels, rain and wind patterns.

3.2.1 POLLUTION FACTOR

Air pollution is an important feature of the Montreal climate.

Compared with other cities, records showed Montreal city to have the highest dust fall of any city in Canada and to approach the values recorded in some of the worst areas in the United States [23].

Many types of pollution are produced in the city, including dust, smoke, carbon dioxide (CO_2) and such dangerous chemical gases as sulpher dioxide (SO_2) and carbon monoxide (from automobiles). Measurements of pollution level are mainly concerned with a parameter called 'Soiling Index'*. Observation using smoke samplers has shown that air pollution can vary with location and the time of the year. Figure 3.2 illustrates the seasonal cycle of the Soiling Index at three sites.

(a) A residential-commercial downtown area near the corner of Crescent and deMaisonneuve Boulevard (see figure 3.3)

(b) Another residential-commercial area near the campus of McGill University (about a half mile away from (a)).

(c) On the top of Mount Royal at the CBC transmitter.

It can be noticed that site (a) has the highest levels of air pollution and that peak values are usually recorded during the heating season from November to April.

Deposition of dust and soot particles carrying contaminants such as SO_2, CO_2 and other dangerous substances over building facades can bring about harmful effects when interacts with the facade material. The interactions are enhanced in the presence of rainwater and can lead not only to weathering but also to more serious decay and disintegration of the surface material. The consequences of such interacitons are elaborated in Appendix I.

3.2.2 RAIN FACTOR

According to the climatic data of Montreal [8], there are

* Soiling Index is the presence of soot in the air.

approximately one hundred and eighteen rainy days expected every year with considerable variations in intensity, duration and the accompanied wind velocity. Despite the fact that precipitation in winter is in the form of snow, there are on the average three to six rainy days per month in the period between December and March. (ie. the period of increased pollution levels). The mean total amount of rain (average of 30 years measurements) is 43 inches (105cm) per year and 3.5 inches (8.75cm) per day [7]. The seasonal variation in precipitation recorded at Dorval Airport from 1957 to 1966 is presented in figure 3.4. More details about duration of rainfalls together with the intensity-frequency are illustrated in table 3.1 and figure 3.5 [23]. It can be noticed from figure 3.5, that the greatest rainfall quantity for a duration of 60 minutes has the value 0.95 inches for an expected return period of two years.

Of more importance is the consideration of the average rainfall quantity that occurs most often. Therefore, the recorded weather data of the measured rain intensities per hour was further analyzed. The results of this analysis, presented in figure 3.6, show that rain intensity of 0.2 inch/hr (5mm/hr)* is the most frequent intensity that occured during the period of 1970-1975.

The movement of rainwater over the building facades causes either a partial or a complete washing action of the deposited pollutants. Generally, the washing process is uneven and hence results in differential staining of the facade surfaces leading to disfigured appearance.

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* The quantity 5.0mm indicates the depth of the accumulated rainwater on a horizontal unit area. As explained in Chapter IV, designers can convert such quantity to its equivalent that will strike a vertical unit area (ie. one square meter of a vertical wall) for any given speed of the accompanying wind.

3.2.3 WIND-DRIVEN RAIN FACTOR

Variations in wind direction and speed present another important factor to be considered. To illustrate the wind condition in Montreal, some selected mean wind speed values with the highest wind speed and its direction for each month is presented in table 3.2. It can be noticed that there is not sudden fluctuation in wind speeds over the year and the dominant pattern indicates long periods of almost a steady speed. Such prolonged periods of light winds is quite a significant feature, especially in a polluted climate such as Montreal since they favour the accumulation process of air pollution over building surfaces. Table 3.3 gives the average frequency of such long periods of light winds (8 m.p.h or less) over an 18 year period.

A study [23] of the mean frequency of hourly occurences of winds in all months of the year has been carried out at Dorval and St. Hubert Airports for the period of 1957-1966. The outcome of this study pertaining to the wind patterns is presented in figures 3.7 to 3.10. It can be concluded that winds from the sector SW to W at Dorval occur most frequently in all months of the year. Such winds at St. Hubert Airport favour the direction WSW to WNW. During the colder months of the year at both airports, there is a large incidence of winds from NE to NNE sector, in some months about 20%.

A third significant wind frequency maximum from the southeast was recorded at St. Hubert Airport as shown in figures 3.9 and 3.10. This is not noticeable at Dorval. The period of southeasterly winds is often followed by a wind shift to the southwest.

As a conclusion, the general wind pattern of most moderate to strong surface winds expected in the Montreal area will generally favour the direction of St. Lawrence valley flowing from high to low pressure [23]. During periods of rising pressure, the winds will blow from a southwesterly sector. During periods of falling pressure the winds will blow from the north-northeast. Percentage frequency rose of wind from all directions is illustrated for a hypothetical square plan building in figure 3.11.

Of more importance is to consider the prevailing conditions of wind during rain, since the resulting combinations affect the weathering of building facades. For Montreal, such conditions of wind during rain have not yet been investigated. Therefore, as a part of the present research, the climatological data of wind and rain were further examined to determine whether or not there is a predominant direction from which wind-driven rain originates. The procedure followed was based on analyzing the monthly data recorded at Dorval Airport for a period of five years (1970-1975). The wind direction - while hours of rain - for each rainy day was noted, the sums were taken and percentages calculated. Conclusion of this analysis is illustrated in figure 3.12 for a hypothetical square plan building subjected to wind-driven rain expressed as percentage frequency compass rose. It can be noted that:

- No particular direction of wind-driven rain dominates.
- SW to WSW, NE to NNE and SE to SSE are the most frequent directions.

The analysis of the weather data has also shown that the occurence of wind during rain having a speed of 0 and 9 m.p.h. (ie. 0 to 14.4 km/hr) is 47.2% of the raining time. For a wind speed varying between 10 to 19 m.p.h. (ie. 14.5 to 30.4 km/hr) the percentage occurence is 46.2%. Figure 3.13 illustrates a comparison of the frequency of different wind speeds while raining.

In actual practice, it should be emphasized, these findings are frequently modified by both (a) exposure conditions determined by orientation and the building's surroundings; (b) the architectural massing of the building and the geometric configuration of its facades.

3.3 SITE OBSERVATION OF WEATHERING PROBLEMS IN MONTREAL

An extensive field observation was planned and carried out in the Montreal area to evaluate the seriousness of weathering problems. The observations were planned in two main phases. The first considers the facade weathering on the macro-climate scale and the influence of orientation and the surrounding buildings on the problem. In the second phase, particular emphasis was given to weathering of facade surfaces on the micro-climate scale and the effects of different geometrical configuration on the surface hydraulics and hence, on the resulting staining patterns. Particular consideration is given to panelized facades using precast concrete panels and the effect of their sectional profiles on weathering.

To achieve the intended merits of such observations, the following systematic strategy was followed:

- Choosing specific examples of new/old residential and commercial buildings in similar site conditions in the downtown area as the case studies required for subsequent analysis and comparison.
- Identifying each observed building (ie. its location, age, materials used in facades, etc.) whenever needed.

- Categorizing the weathered facades so as to establish relationships between the casual factors on the one hand, and to emphasize their impact on the required performance on the other.
- Analyzing the sensitivity of each factor in aggravating or minimizing the resulting weathering.

3.3.1 WEATHERING OF FACADES ON THE MACRO-CLIMATE SCALE

Considering the facade as one surface, exposure to driving rain presents the main issue in its weathering. The general observations suggest that much of the differential staining and disfigurement of facades are attributed to the partial wetting and hence the partial washing of surfaces. The problem is further aggravated by the fact that the various elevations of a building receive markedly different amounts of driving rain according to orientation and location.

An example of such a situation observed in the downtown area is illustrated in figure 3.14. This 18 storey building is almost free from all sides and the surrounding buildings are generally low-rise. It can be noted that the north-east and south-east facades have substantially altered their original appearance due to the partial washing of deposited pollutants. Only the top and side edges are kept clean in contrast with the middle areas that display the accumulated unwashed pollution. The degree of disfigurement is less on the other two facades, particularly the north-west, however, the stained pattern having a bell shape form can still be traced.

In another example pictured in figure 3.15, similar bell shaped staining pattern has characterised the main facades of the corner building. On both the north-east and north-west facades the driving rain has washed only the top and edges. The same situation is repeated on the north-east and south-east facades of the building pictured in figure 3.16.

Among the observed buildings that show similar staining patterns is the one pictured in figure 3.17. The north-east facade of this building was observed during driving rain coming from different directions. The aim has been to study the relation between the different wetting patterns likely to occur and the resultant stained and washed pattern. In cases of exposure to driving rain as a wind-ward side, the induced facade wetting varies from partial to total depending on rain intensity and duration as well as on the wind speed. In most cases, however, wetting was usually limited to the top and side edges as illustrated in figure 3.18 (a). When the facade is subjected to a driving rain field as a side wall, wetting - unless in heavy rainstorms - is usually experienced only at the top areas and the corner towards the wind direction (see figure 3.17). Even in cases of exposure as a leeward face, wetting is encountered only at the top parts as illustrated in figure 3.18 (b). Depending on the rain quantity and the surface absorptivity, the wetted area may expand toward lower levels. The diagrammatic illustration of the different wetting patterns discussed above is presented in figure 3.17. Superimposing the results of all possible exposure conditions gives the final weathering - ie. the continuously washed and unwashed surfaces. It can be noticed that washing is more likely to occur at the top four storeys and near the corners (recall the influence of wind flow patterns on the resulting weathering as explained in section 2.3.3). The remaining surfaces receive substantially less washing action and hence display greater amounts of dirt particles resulting from the originally deposited and those migrating with the downward flow of water increasing the rate of disposition.

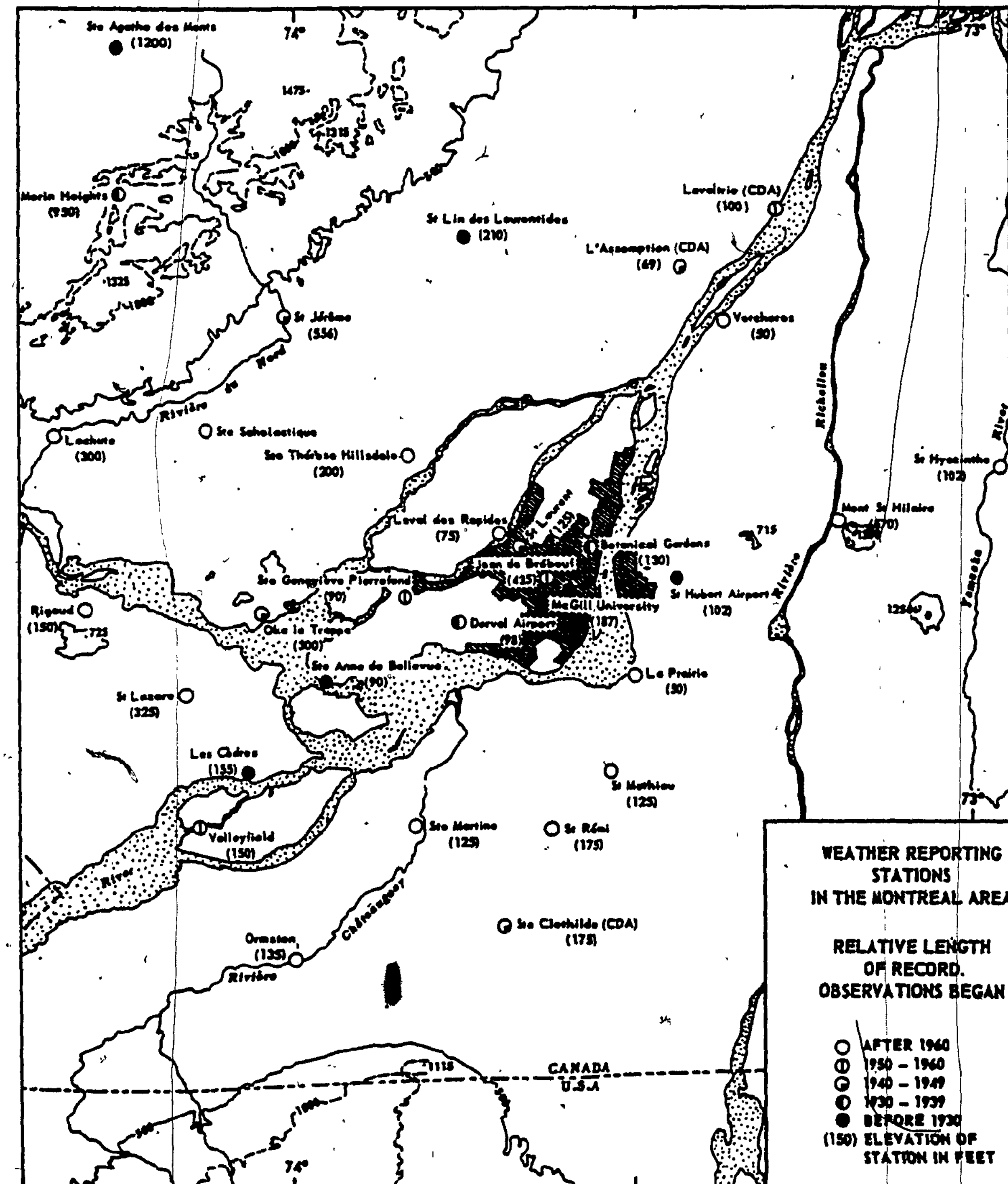
It was also observed that the long term exposure to driving rains aggravates the contrast between the continuously washed and unwashed stained areas. This can result in more severe disfigurement; figure 3.19 pictures a 50 year old building that illustrates clearly such an undesirable situation. It can be noted that the heavily accumulated pollutants form the same bell shape staining pattern observed on many other facades.

When the building is attached to another side building, the driving rain flow will be eliminated at this particular corner and the increased wetting will be limited to the other corner of the building facade and the top storeys. Figure 3.20 illustrates the resulting pattern on a concrete facade in central Montreal. The change in appearance is also attributed to the increasing quantities of dirt accumulation on the surfaces near the street level. Alike and more severely affected, is the stone facade pictured in figure 3.21. It can be noted that the free corner is subjected to more wetting and hence washing action if compared with the other corner.

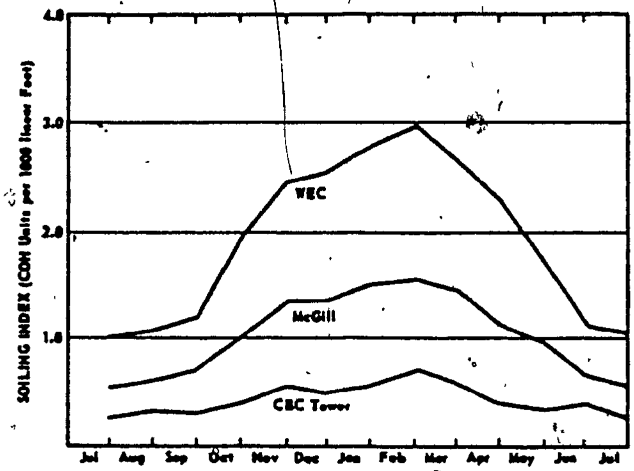
Staining the facade surfaces near the street level can be further aggravated when the facade is surrounded by taller buildings that minimize wetting at the lower storeys and limit it only to the top areas. An example that illustrates this situation is pictured in figure 3.22. The five storey facade is surrounded by taller facades from almost all directions. This causes wetting to occur mainly at the top levels in contrast with the other surfaces that receive substantially less amounts of rain. In another example, wetting and hence washing action is more pronounced at the upper three storeys of the facade pictured in figure 3.23. The panels of the other storeys display unwashed - stained - surfaces due to lack of enough rainwater. The fifteen storey building across the street (see the accompanied map in figure 3.23) help aggravating the resulting differential staining by giving shelter to lower storeys from driving rain.

3.3.2 MAIN FINDINGS OF THE MACRO-CLIMATE EFFECTS

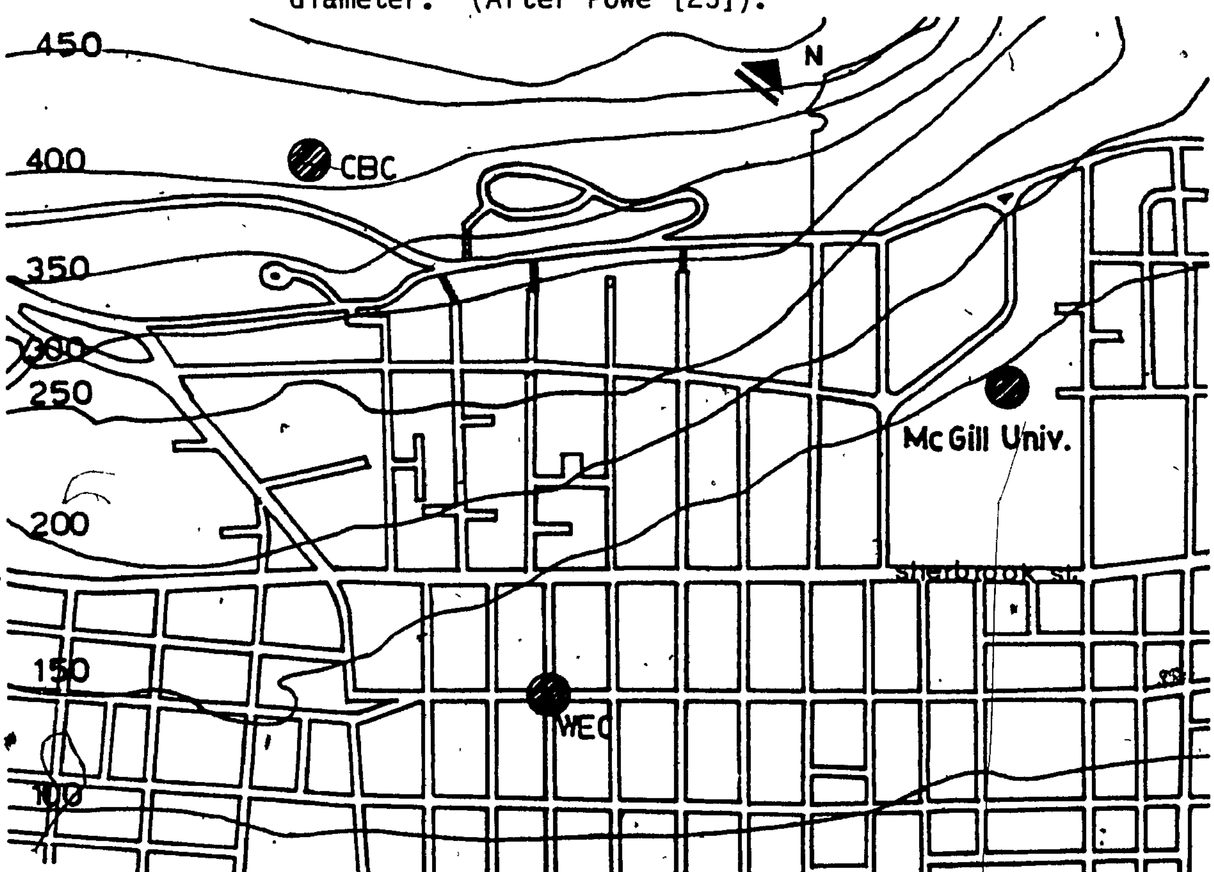
In essence, all building facades are subjected to driving rain whether as a windward, leeward or side face. The resulting wetting patterns - superimposed each other - determine the final washed and unwashed pattern. Regardless of the facade orientation, the top and side edges of the observed facades were usually cleaner than the remaining surfaces. For materials that are more susceptible to retain dirt, such as limestone and sandstone, the differential staining was more pronounced. Relative to stone facades, concrete usually display less differential staining. Exposure to direct driving rain aggravates weathering of facades. Based on the wind-driven rain rose - figure 3.12 - there is not any particular direction dominating the others, and the driving rain on the south-east, north-east and south-west facades have almost that same frequent occurence. Driving rain on the north-west facade is comparatively less frequent. These findings when correlated with the observed weathering on facade surfaces are found to be in a good agreement. When given almost the same site conditions, the facades are less subjected to driving rain - ie. the north-west facades showed less differential staining on their surfaces. On the other hand, the contrast between the washed and unwashed areas is generally enhanced on those facades exposed to more frequent driving rain - ie. SE, NE, and SW facades. This contrast can be further aggravated when the surrounding buildings influence the resulting wetting to be limited only to the top storeys. The final weathering pattern however, still depends on other variables such as the surface geometry and its material characteristics particularly absorbitivity and texture. The effects of these factors are elaborated in the following sections.



<u>FIG. 3.1</u>: A map showing the location of the city of Montreal and the weather reporting stations in the area. (After Powe [23]).



<u>FIG. 3.2</u>: Seasonal cycle of soiling index at Montreal. COH - coefficient of haze - indicates the capacity of air in a cylinder 1000 feet long and 1 inch in diameter. (After Powe [23]).



<u>FIG. 3.3</u>: A map showing the location of the three stations where the measurements of soiling index were recorded. (Numbers indicate the altitude in feet).

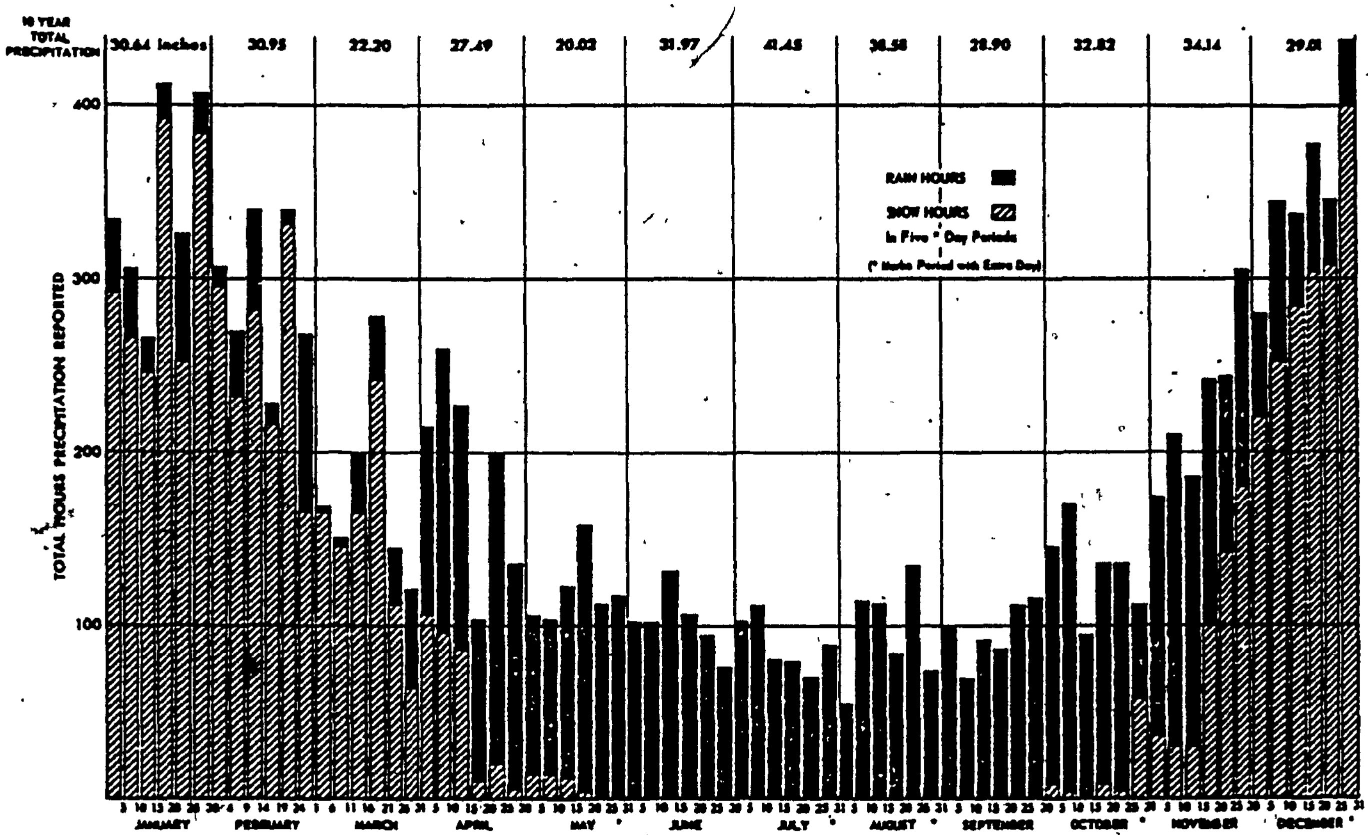


FIG. 3.4: Seasonal variation in precipitation hours at Dorval Airport based on the period 1957-1966. (After Powe [23]).

TABLE 3.1

RECORD SHORT DURATION RAINFALLS AT DORVAL AIRPORT 1942-1968

Greatest Rainfall	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
in 5 minutes	.10	.60	.60	.37	.50	.33	.16	.13
	9/67	22/45	24/62	10/66	16/66	27/51	25/59	23/53
in 10 minutes	.19	.61	.90	.52	.76	.38	.31	.17
	4/63	22/45	6/63	10/66	16/66	2/52	25/59	23/53
in 15 minutes	.26	.63	1.20	.65	1.06	.41	.37	.19
	4/63	22/45	6/63	8/58	16/66	4/66	25/59	23/53
in 30 minutes	.33	.67	1.39	.86	1.45	.61	.67	.26
	4/63	22/45	6/63	1/56	16/66	4/66	25/59	23/63
in 60 minutes	.40	.74	1.58	1.07	1.57	.84	1.10	.40
	4/63	22/45	6/63	22/60	16/66	12/63	25/59	4/50
in 24 hours	1.29	1.48	2.67	2.85	2.71	2.76	2.16	2.17
	6/49	4/45	15/43	5/58	21/52	12/63	25/59	4/50

(After Powe [23]).

TABLE 3.2

AVERAGE MONTHLY AND ANNUAL WIND SPEEDS: DORVAL AIRPORT
Period 1942 to 1968

	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.	Annual
27 Year Average	12.4	12.4	12.2	12.0	11.4	10.3	9.5	9.1	9.7	10.8	11.8	11.7	11.1
Highest Average	15.2	14.6	15.1	13.9	15.5	11.6	10.8	10.2	11.6	12.9	14.4	14.4	11.9
Year with Highest Average	1950	1945	1943	1943	1947	1950	1960	1964	1962	1955	1963	1946	1945
Lowest Average	9.9	9.7	8.4	10.3	6.0	5.8	5.7	4.4	5.7	7.6	9.1	9.4	9.3
Year with Lowest Average	1955	1955	1967	1966	1968	1968	1968	1967	1968	1948	1966	1958	1967
Maximum Speed for 1 Hour	SW 51	NE 50	NE 46	NE 39	SW 46	SW 42	NE 33	N 35	SW NE 42	SW 37	NE 46	NE 51	
	14th	26th	1st	8th	9th	29th	6th	31st	2nd	31st	26th	12th	
	1950	1961	1942	1956	1964	1957	1948	1954	1963	1951	1950	1944	
Maximum Speed for 10 Mins.	SW 60	NE 60	SW 54	W 50	SW 54	SW 46	NW 44	S 49	S 52	SW 46	NE 48	W 58	
	14th	26th	20th	5th	9th	29th	4th	9th	27th	27th	4th	2nd	
	1950	1961	1943	1945	1964	1957	1955	1966	1942	1942	1965	1942	
Maximum gust	SW 75	SW 86	S 110	SW 63	W 77	SW 69	NW 67	S 65	S 64	SW 62	SW 63	W 74	
	19th	25th	5th	18th	22nd	29th	1st	9th	27th	24th	21st	2nd	
	1943	1956	1964	1945	1945	1957	1946	1966	1942	1957	1956	1942	

(After Powe [23]).

TABLE 3.3

DORVAL AIRPORT 1951 TO 1968 INCLUSIVE
PROLONGED PERIODS OF LIGHT WINDS (Under 8 mph)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Number of Periods that Lasted at Least												
6 Hours	11	15	12	11	12	12	15	14	12	11	10	11
12 Hours	5.1	6.1	5.4	3.5	5.2	5.4	6.8	7.6	6.0	6.9	5.9	5.4
24 Hours	1.4	1.4	1.8	.9	.9	1.1	1.8	2.1	1.7	2.9	2.1	1.4
36 Hours	.6	.3	.8	.3	.4	.3	.9	.9	.9	1.9	1.2	.6
2 Days	.1	.1	.3	.1	.2	.1	.5	.3	.3	.7	.6	.3
3 Days	*						.1	.2	.1	.2	.3	
4 Days							*	.1	.1	*	*	
5 Days								.1	*	*		
Percentage of Hours Winds are less than 8 mph	30	31	35	35	37	40.	46	49	44	38	34	39

*Less than .05

(After Powe [23]).

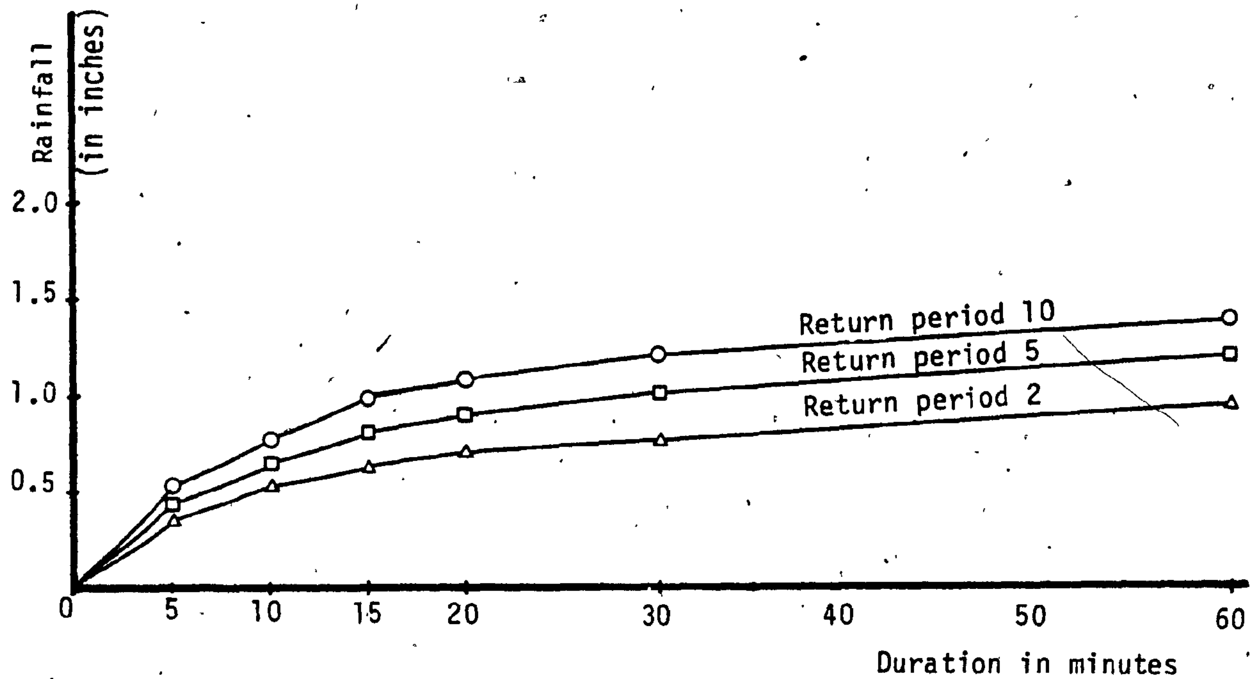


FIG. 3.5: Greatest rainfall intensities that are likely to occur during short durations for a return period of 2, 5, and 10 years. (Based on weather data [23]).

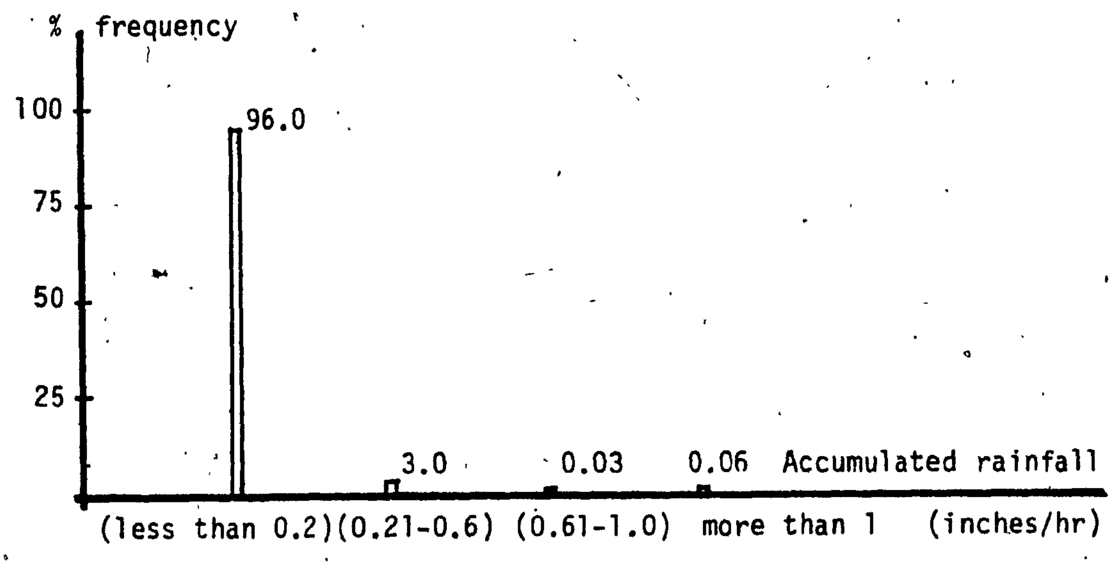


FIG. 3.6: % frequency of rainfall in different intensities (Based on the author's analysis of recorded data for the period 1970-1975).

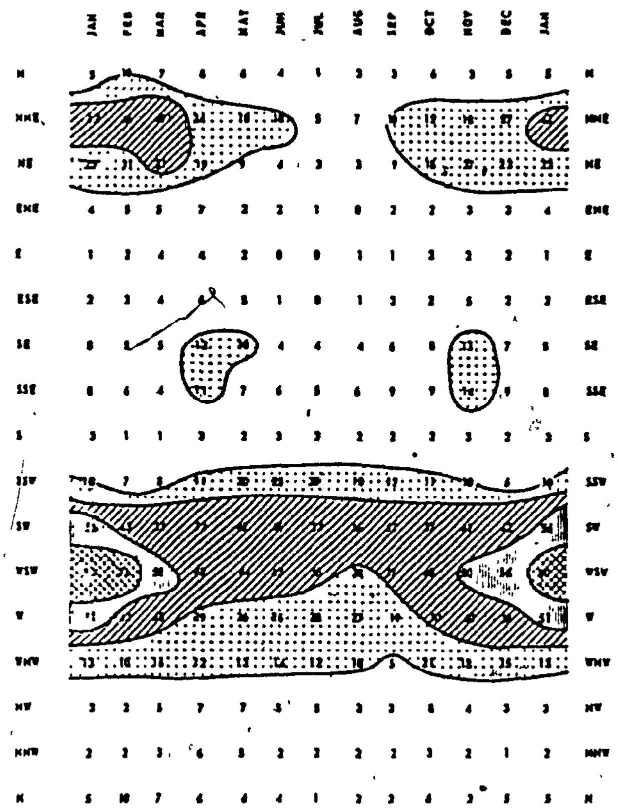


Figure 3.7 Mean hourly frequency per month of winds over 12 mph at Dorval Airport, 1957-1966

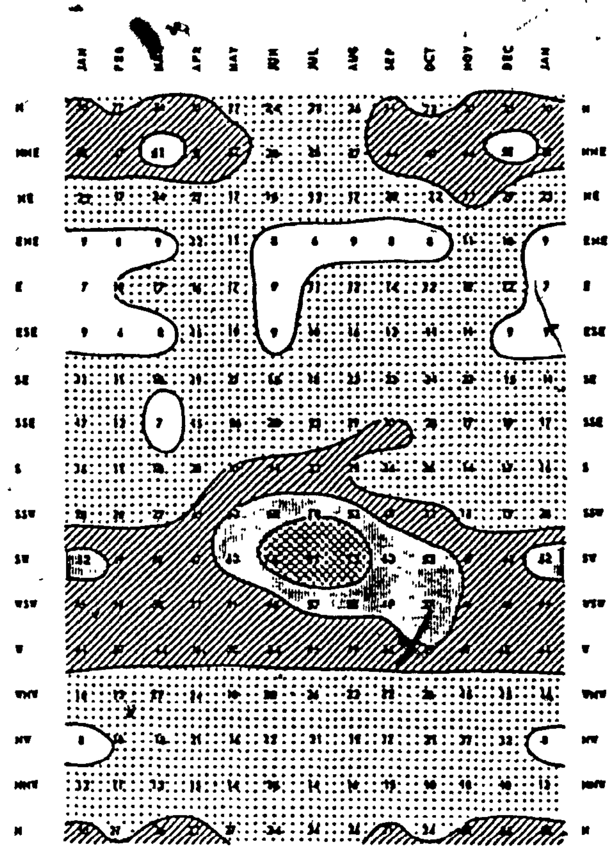


Figure 3.8 Mean hourly frequency per month of winds speeds from 4 to 12 mph at Dorval Airport, 1957-1966

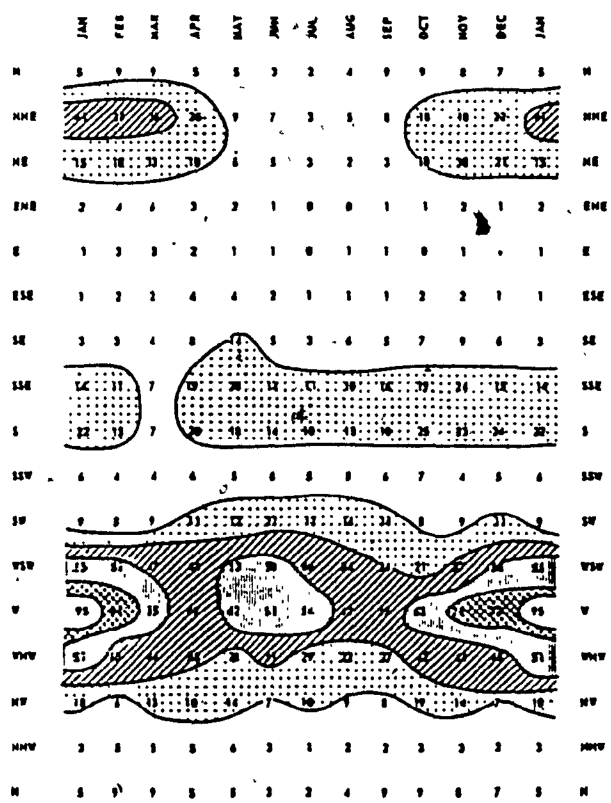


Figure 3.9 Mean hourly frequency per month of winds over 12 mph at St Hubert Airport, 1957-1966

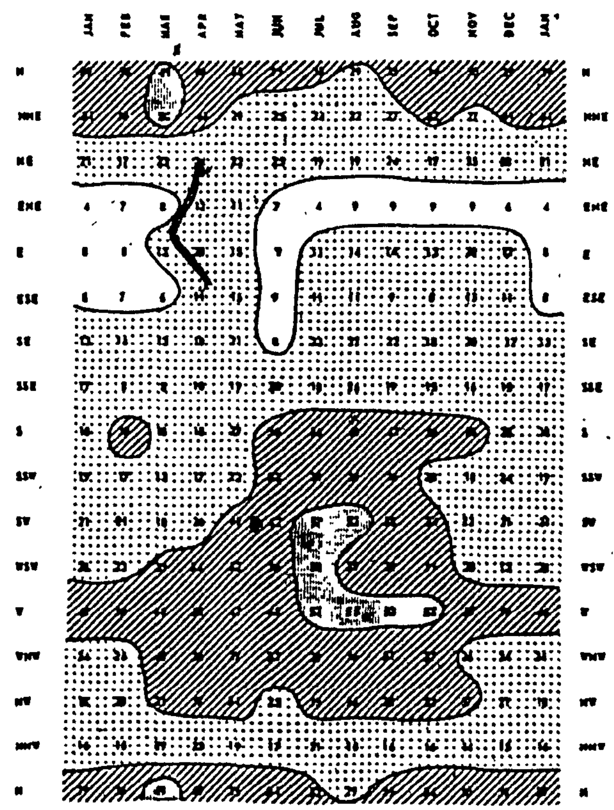
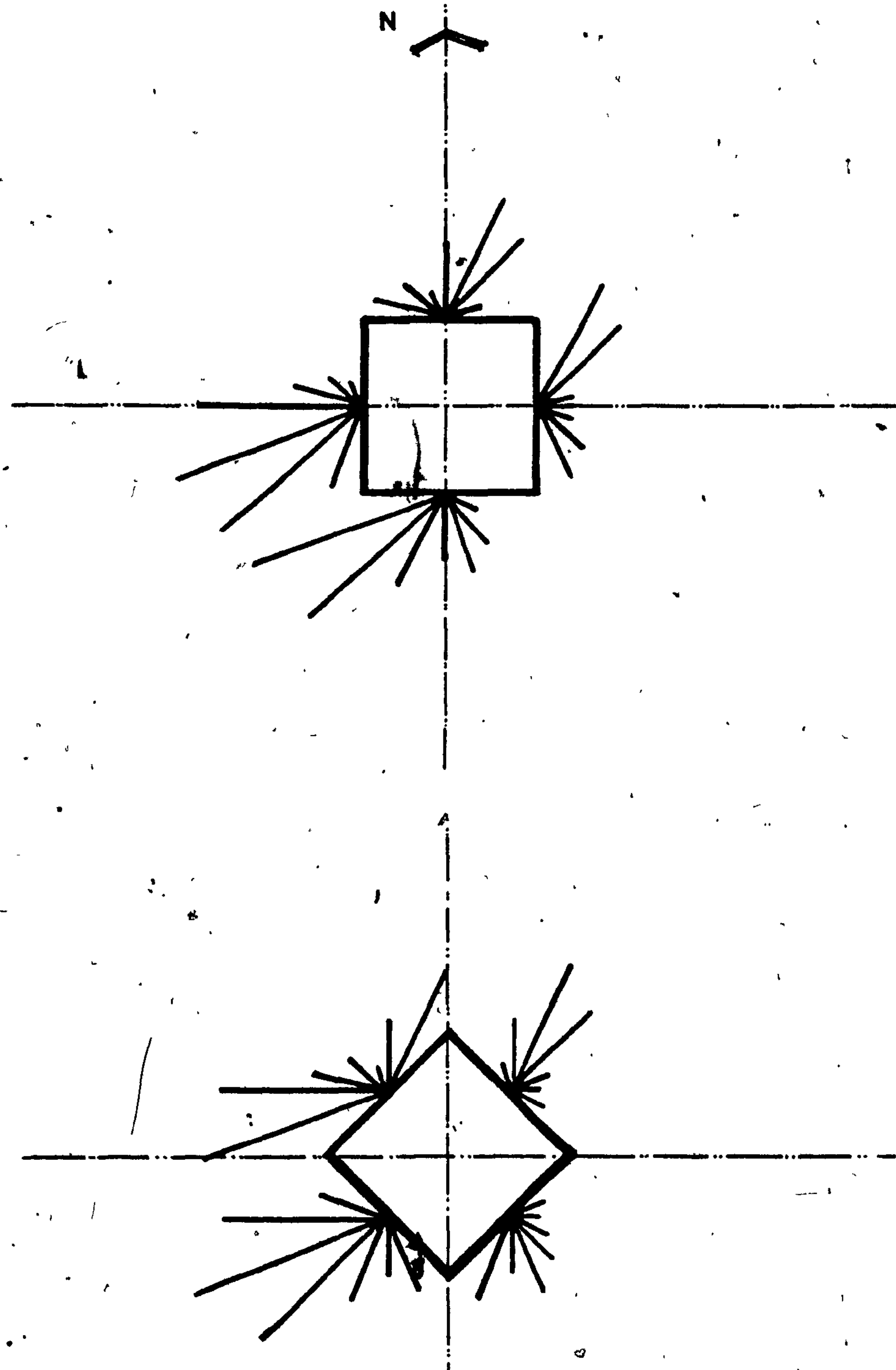


Figure 3.10 Mean hourly frequency per month of winds at speeds of 4 to 12 mph at St Hubert Airport, 1957-1966



Direction	Frequency %
N	5
NNE	9
NE	7
ENE	2
E	2
ESE	2
SE	4
SSE	5
S	4
SSW	7
SW	13
WSW	14
W	11
WNW	5
NW	3
NNW	2

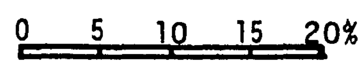
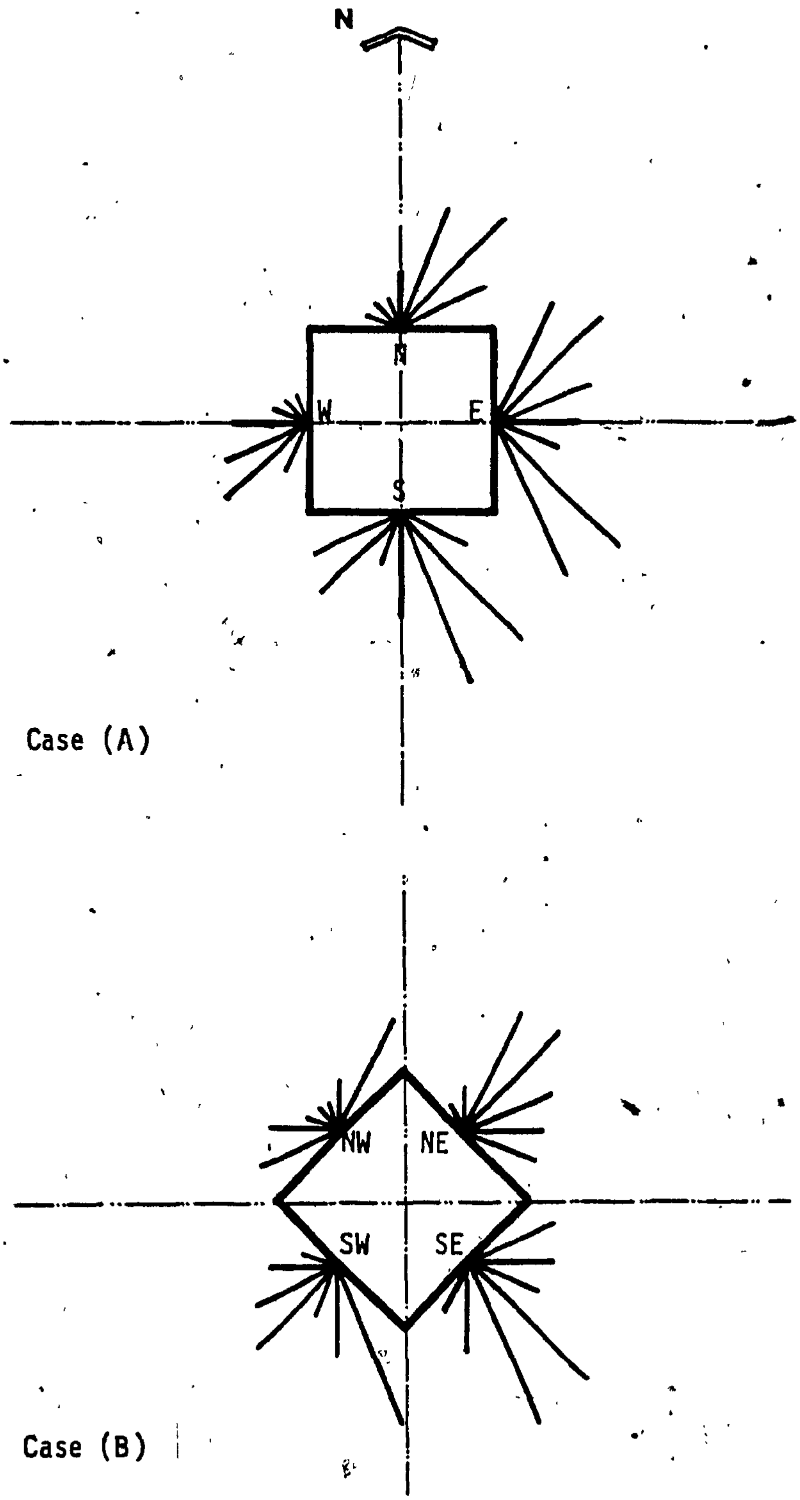


FIG. 3.11: Percentage frequency rose of wind at all hours*
(Based on tabulated data recorded at Dorval Airport, Montreal, in the period 1955-1972).
*wind speeds below 5 m.p.h. are neglected.



Direction	Frequency %
N	3.8
NNE	8.2
NE	9.5
ENE	6.3
E	5.8
ESE	4.6
SE	11.6
SSE	11.6
S	6.3
SSW	3.8
SW	7.9
WSW	6.1
W	4.7
WNW	2.5
NW	1.9
NNW	2.1

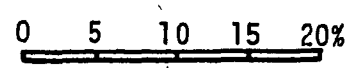


FIG. 3.12: Diagrammatic illustration of a hypothetical square plan building subjected to wind-driven rain: (A) if oriented towards the compass points (B) if oriented towards the mid points.
Calm winds below 1 m.p.h. having a percentage frequency of 3.3 are not shown on this wind-driven rain rose.

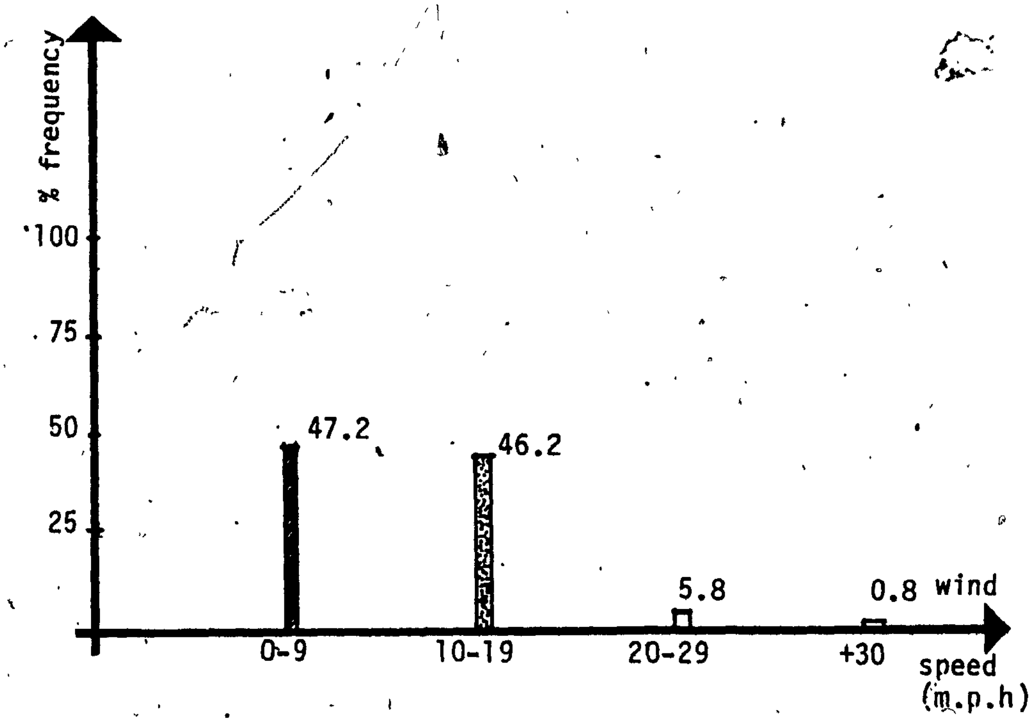


FIG. 3.13: % frequency of wind occurrence (during rain) in different speeds,
(Based on the author's analysis of recorded data for the period 1970-1975).

Building name : Northern Telecom

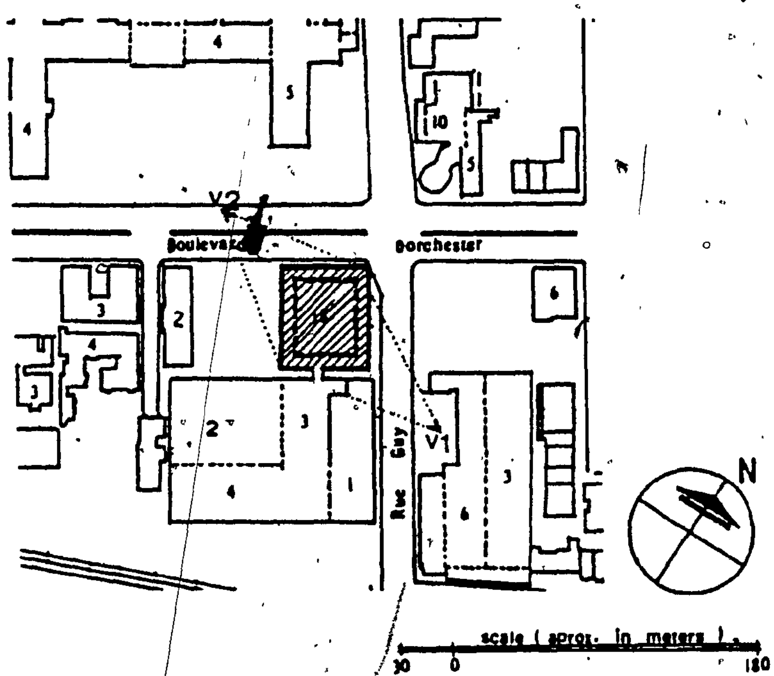
Age in years : 21

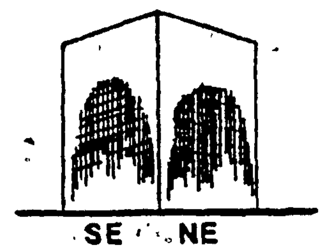
Facade material : Cut lime stone

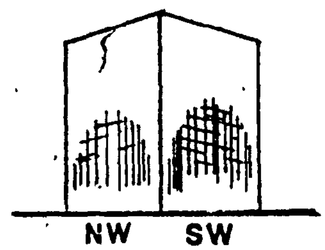
o Residential

ø Commercial

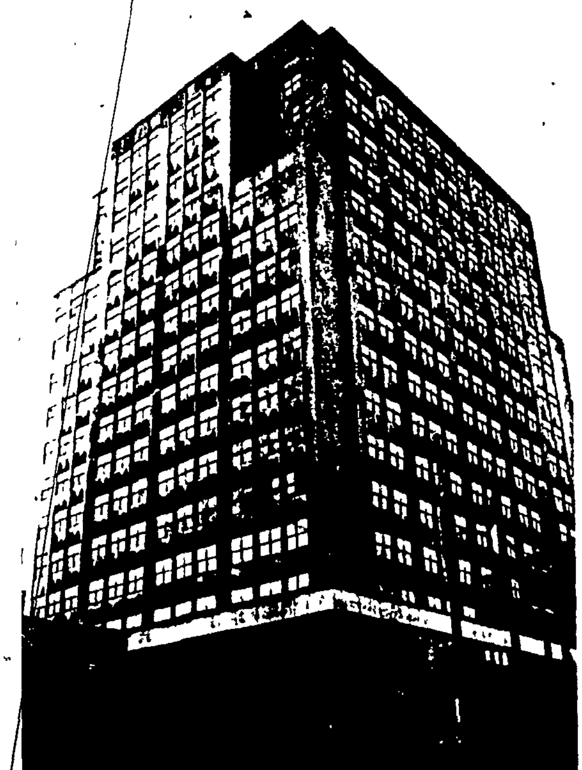
o Others



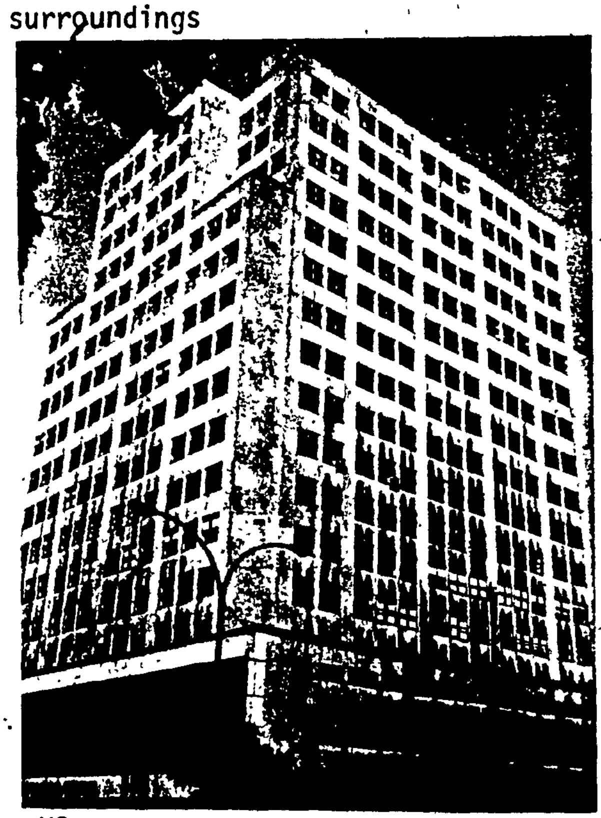




Location/nature of the surroundings



V1



V2

FIG. 3.14: The increased wetting of the facade top and side edges, limits the washing action to these areas. The unwashed surfaces form a bell-shape staining that is more pronounced in the SE, NE facades of this building.

Building name : Le permenant

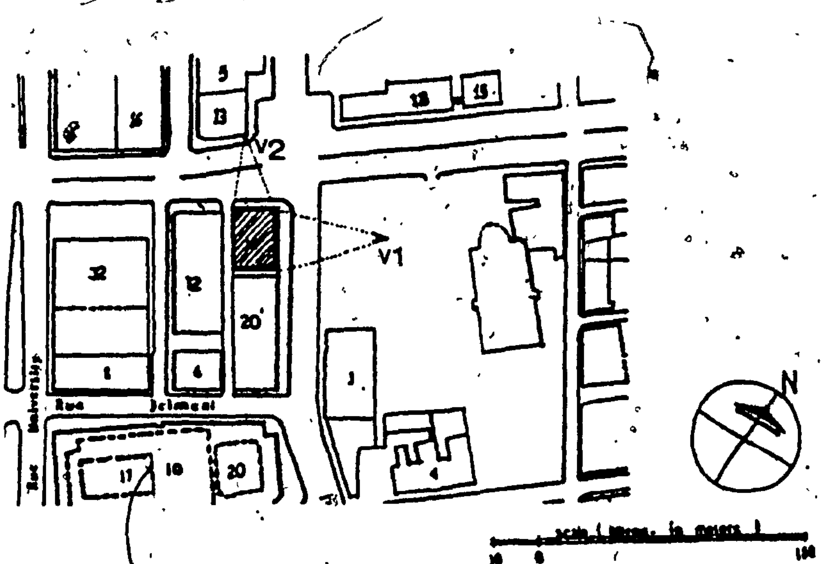
Age in years : 25

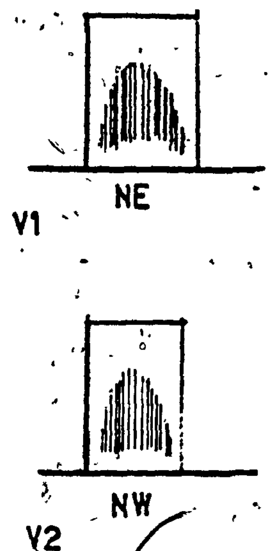
Facade material : Cut lime stone

o Residential

ø Commercial

o Others





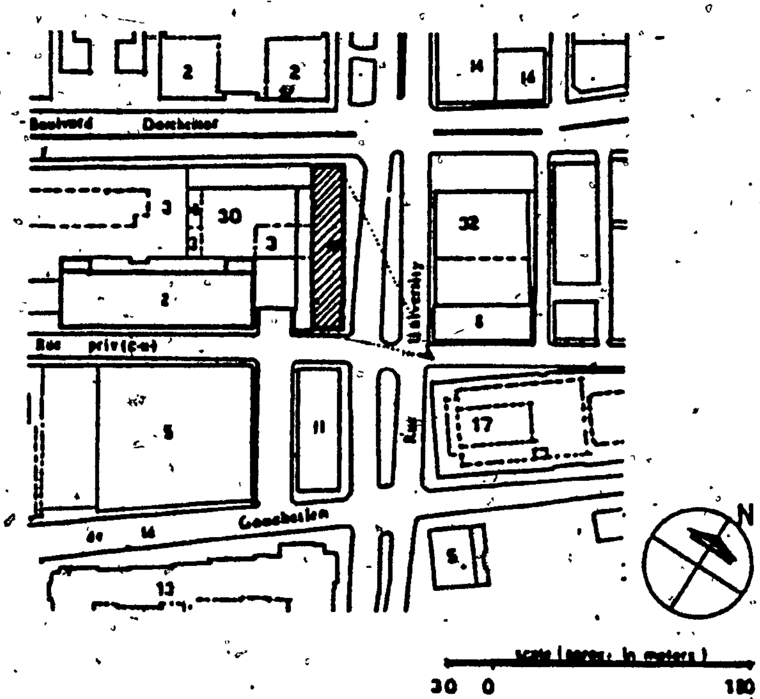
Location/nature of surroundings

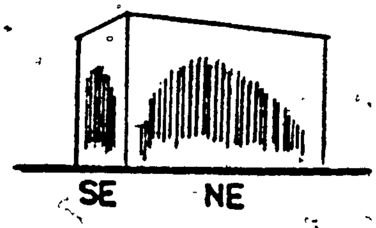
V1 V2

FIG. 3.15: The same bell-shape staining pattern is repeated on the NE, NW facades of this building.

Building name : International Aviation (ICAO)
Age in years : 31
Facade material : Cut lime stone

o Residential
ø Commercial
o Others





Location/nature of the surroundings

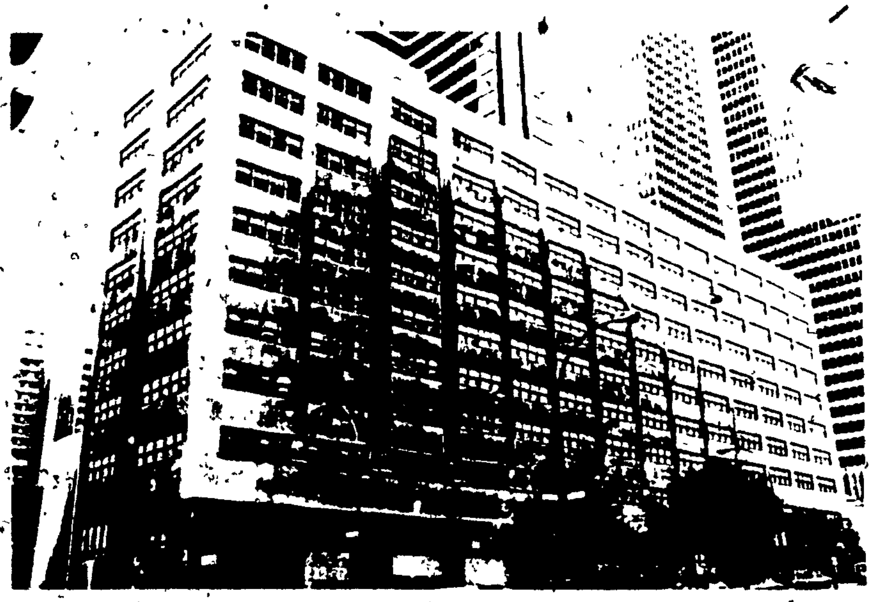


FIG. 3.16: An example illustrates the bell-shape staining pattern of the building facades.

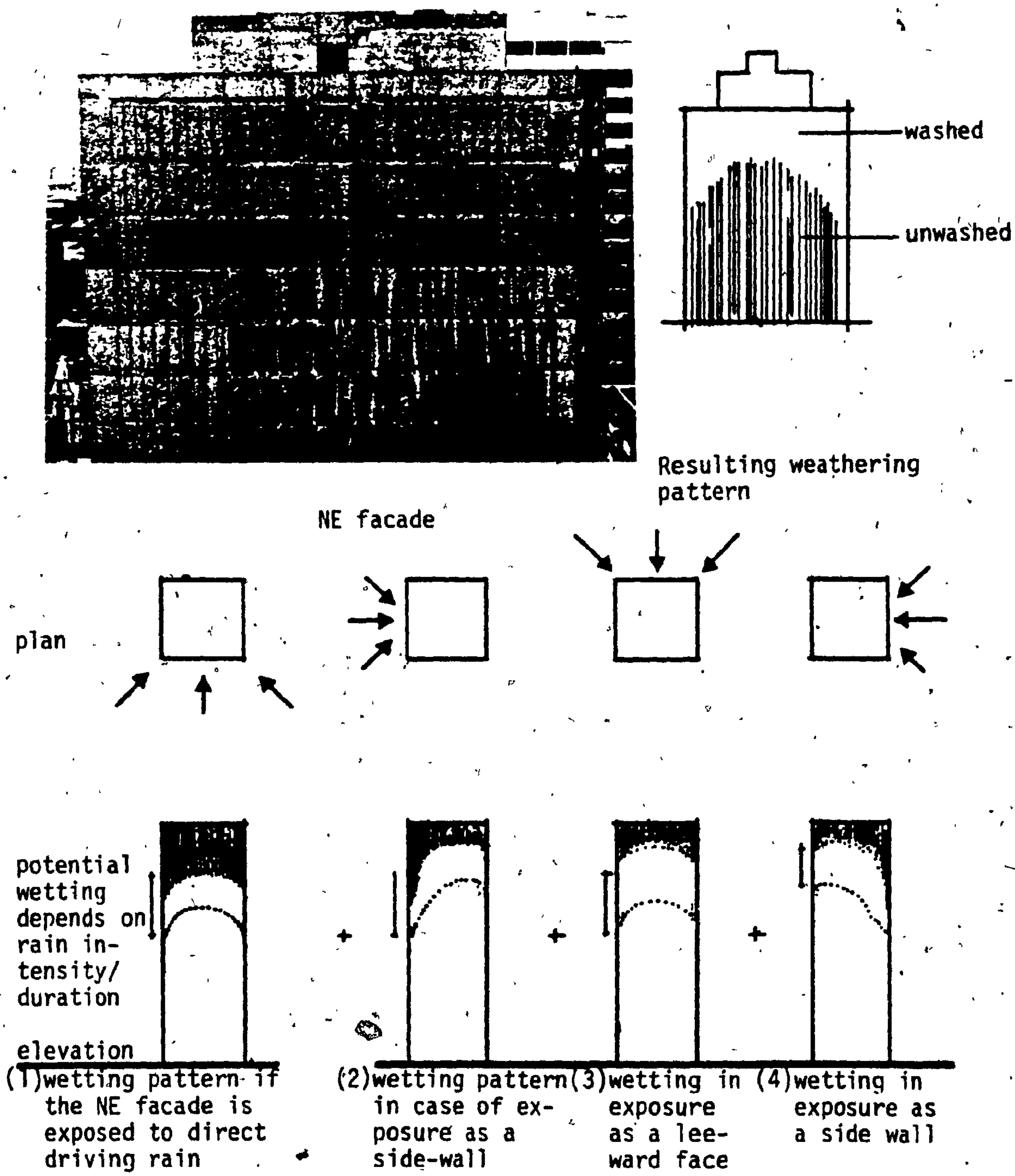
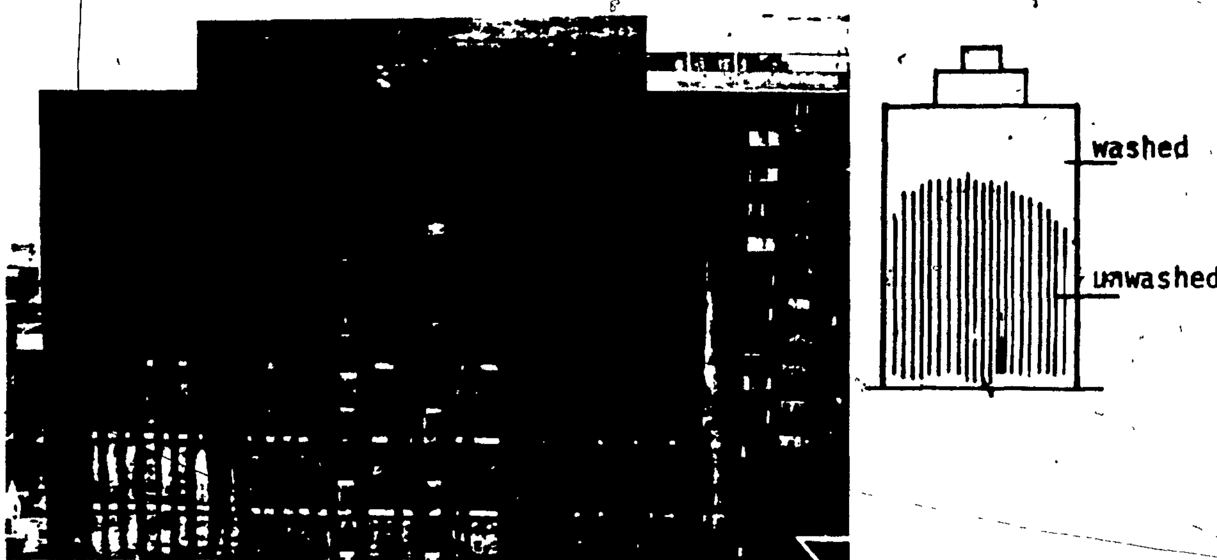


FIG. 3.17: The final weathering pattern of any facade results from superposition of all possible wetting patterns induced when the facade is subjected to driving rain coming from different directions.



(a)

(b)

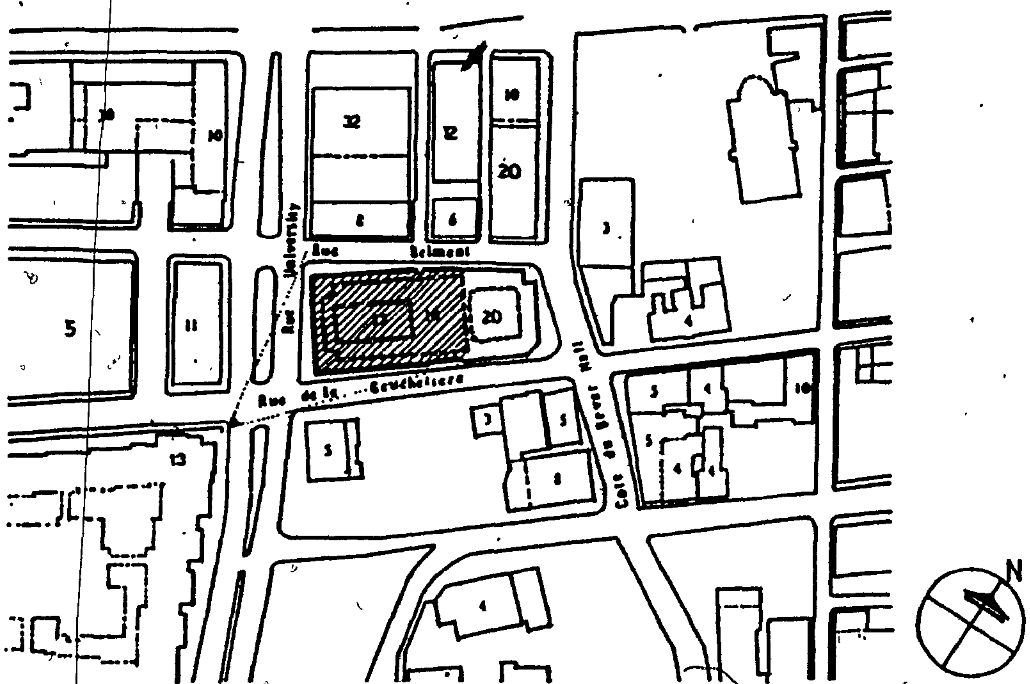
<u>FIG. 3.18</u>: Wetting of the facade surface

(a) if subjected to direct driving-rain (ie., as a windward facade)

(b) if subjected to driving-rain as a leeward facade

Building name : Bell Canada
Age in years : 50
Facade material : Cut lime stone

o Residential
ø Commercial
o Others



Location/nature of the surroundings

SW Facade SE Facade

FIG. 3.19: Example showing the effect of the long term exposure to driving-rain in aggravating the contrast between washed and unwashed surfaces. The result is a serious disfigurement of the building appearance.

Building name : Hotel 'le sherboure'

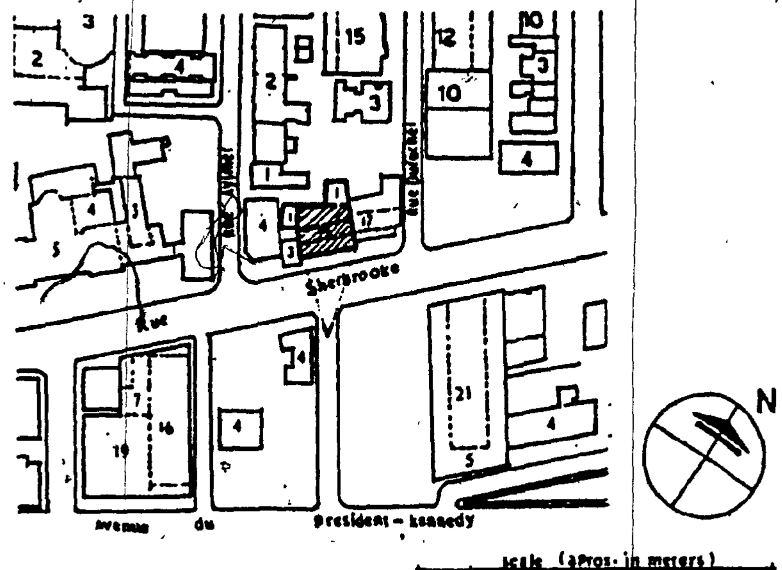
Age in years : 10

Facade material : Precast concrete

o Residential

ø Commercial

o Others



Location/nature of the surroundings 30 0 180

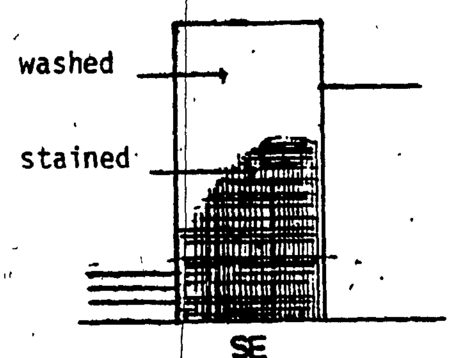


FIG. 3.20: An example of the staining pattern when the building is attached to another side one.

Building name : C.N. Headquarters

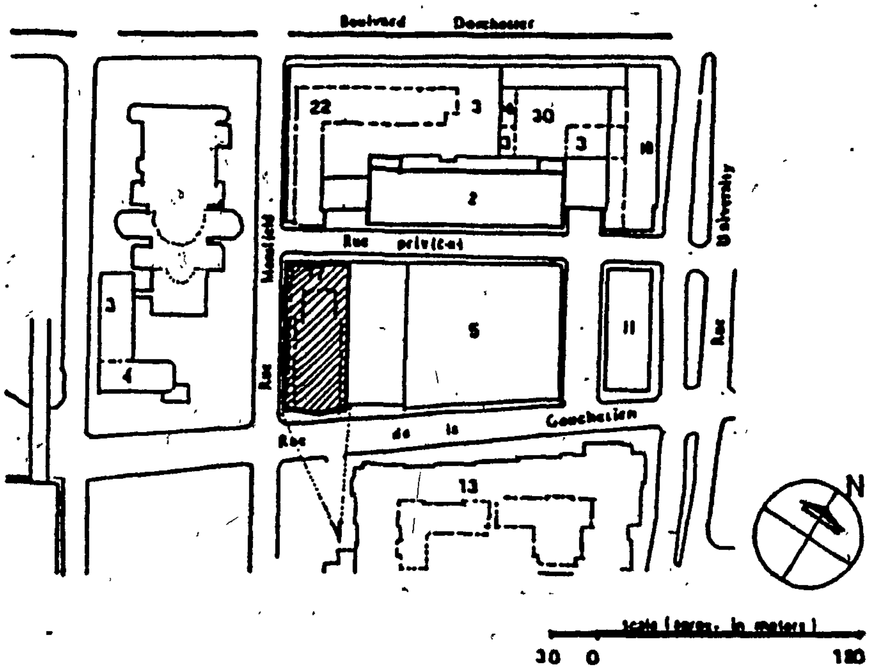
Age in years : 18

Facade material : Cut lime stone

o Residential

● Commercial

o Others



Location/nature of the surroundings

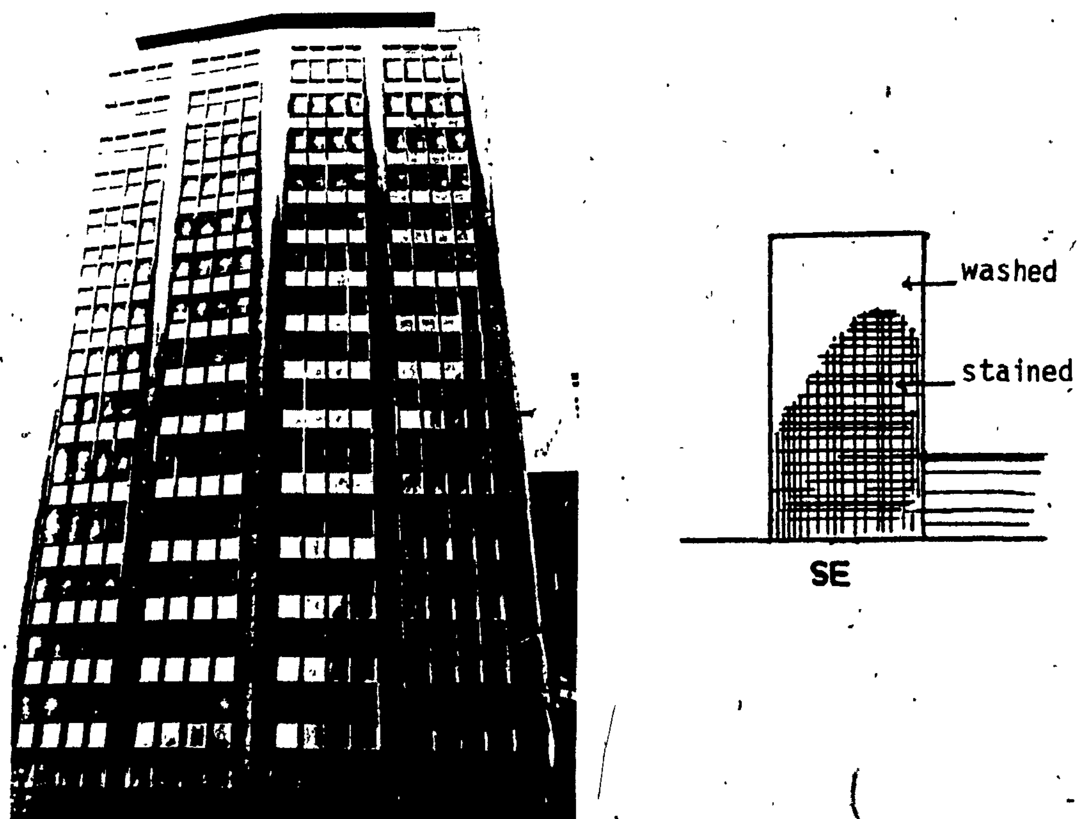


FIG. 3.21: Wetting is enhanced at the free corner and hence the resulting bell-shape staining pattern is modified.

Building name : Central Station

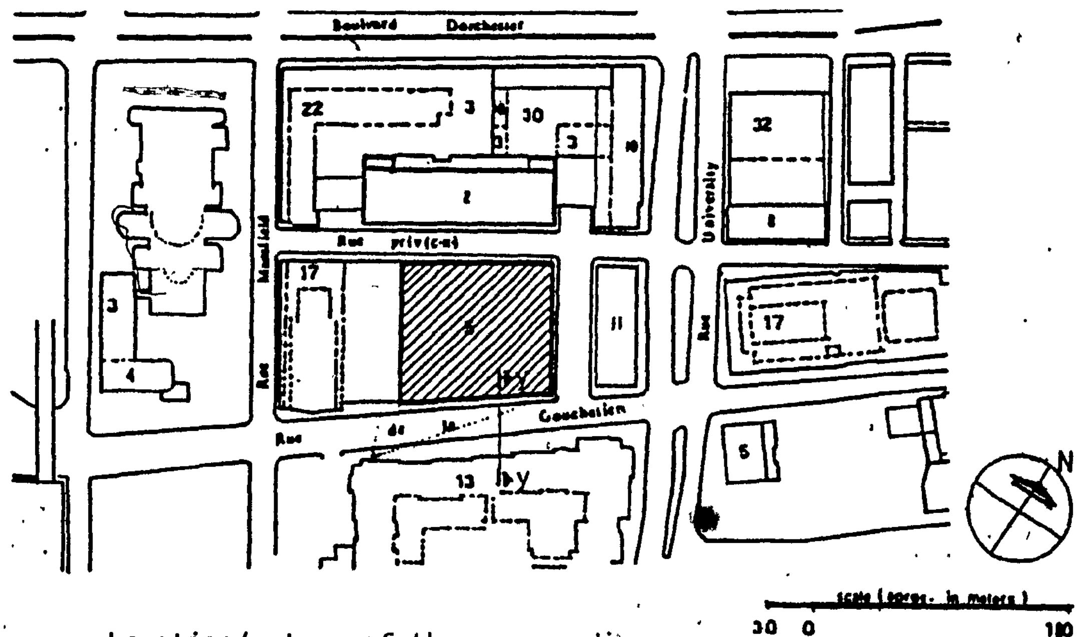
Age in years : 35

Facade material : Cut lime stone

o Residential

● Commercial

o Others

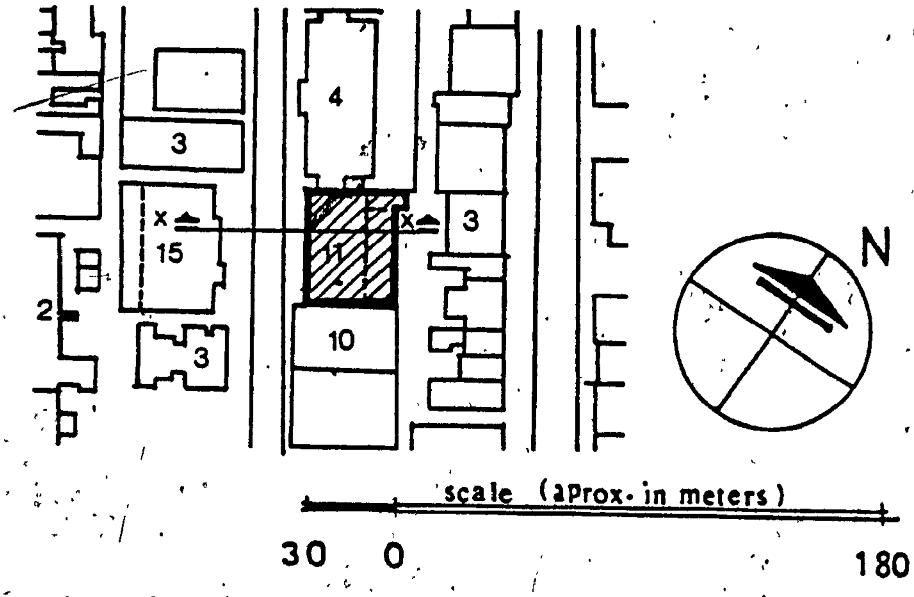


Location/nature of the surroundings

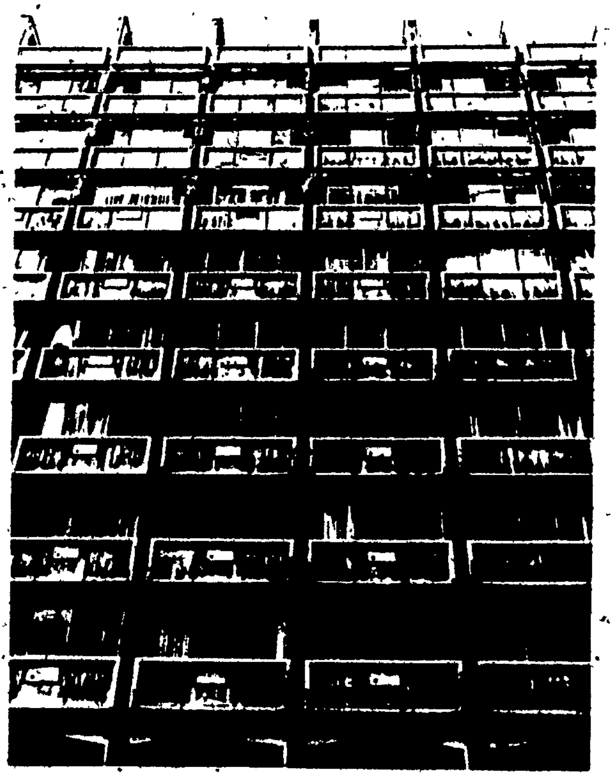
FIG. 3.22: An example showing the influence of the surrounding taller building in minimizing wetting of the lower storeys of this facade. The differential staining is then increased.

Building name : The Ellsworth
Age in years : 11
Facade material : Precast concrete

☑ Residential
● Commercial
o Others



Location/nature of the surroundings



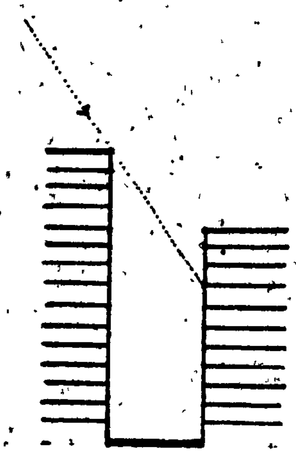


FIG. 3.23: Wetting by driving-rain, and hence washing action, is limited to the top storey of this facade.

3.3.3 WEATHERING OF FACADE SURFACES ON THE MICRO-CLIMATE SCALE

In this section, the influence of different geometrical configurations of a facade on its weathering is investigated. Generally, most of the observed examples are medium or high rise buildings located in the downtown area of Montreal city and are assumed to have similar exposure condition to pollution deposits and to driving rain. All the case studies are facades using porous materials particularly concrete and cut stone. Emphasis is given to precast concrete panels and the effect of the sectional profiles to aggravate or minimize weathering.

In this study, the observed facade surfaces are classified on an abstract level into three main categories:

(I) Moderately sculptured surfaces

(II) Heavily sculptured surfaces

(III) Plain surfaces

Emphasis is given to the first category as it contains most of the observations. The main groups and the architectural details defining each one are illustrated in the chart presented in figure 3.24. Sub groups are also established with diagrammatic sketches showing the characteristic staining patterns. The final level in the chart includes typical examples of the observations. When more than one example are of the same type, the group will be arranged in a vertical series from better weathering to poor weathering top to bottom. The detailed analyses and comparisons of case studies are illustrated in figures 3.25 to 3.52.

(I) MODERATELY SCULPTURED SURFACES:

(1.1) Vertical Projections

The observed examples having vertical projections are divided in two main sub groups. The first comprises big scale projecting masses, the second contains all other small scale projections such as ribs, mullions, etc.

(1.1.1) Big Scale Projections:

The vertically projecting masses cause protection of the inside corners from driving rain at any angle other than the one perpendicular to the wall. Accordingly, the protected areas will be less washed than other nearby surfaces and hence, more susceptible to weathering. Figure 3.25 illustrates a typical example of such a situation. The vertically projecting masses of the north-east facade have protected the inside corners (as shown in the figure) from the north-east driving rain that has a considerable frequency (recall the driving rain rose figure 3.12). The result is localized stains on all the sheltered areas. The width of the stained area is approximately half the extent of projection. Stains are generally more pronounced near the street level.

In some cases, the projecting masses can cause staining to occur at both inside corners. Such a situation was observed on the south-east facade of the same building (figure 3.26). This facade has fronting on a main downtown street, its exposure to driving rain modimodified due to the local wind conditions. The tunneled air flow system does not permit rain to wash the inside corners of the projecting masses. The probable trajectories of rain and wind are presented in the same figure based on Couper's investigations [9].

(1.1.2) Small Scale Projections:

Considering other vertically projected elements such as mullion, ribs, etc., the associated wetting pattern may be somewhat different to that discussed above of a projecting mass. Run off water will be concentrated in a downward movement increasing its potential washing action at the inside corners. In contrast, water can not move in great quantities over the exterior flat surface or over the side surfaces of the vertically projecting elements. Staining, due to the accumulated dirt deposits is much more likely to occur over these surfaces. Figure 3.27 illustrates two examples of the resulting weathering in such a situation. It can also be noted that when the concentrated run-off is allowed to move freely over the wall surface under projections, differential staining occurs.

(1.2) Horizontal Projections:

The examples observed in this group are mainly of big scale masses or small scale elements such as belt courses, spandrels, balconies, etc. Generally, horizontal projections give shelter from driving rain to the surfaces below. The projected zones will be less washed if compared with other nearby surfaces, accordingly, differential staining is likely to occur. Staining is further enhanced if the surface material is more susceptible to retain dirt deposits. Figure 3.28 illustrates two examples; in the first, dark stains are displayed below each projecting mass. In the second, stains occur over the concrete surface of the projecting mass due to partial washing. The surface under this projecting mass is glass panels (ie. non-porous) and hence displays no staining.

Generally, horizontal projections are characterized by their lack of adequate detailing to control rainwater movement over wall surfaces. Figure 3.29 illustrates three examples of projections, all have failed to control the falling rain over their horizontal surfaces. In the first example, water is directed sideways and hence the stone surface under the projection seldom gets wet. In the second example, water arriving to the projecting belt course is allowed to move freely causing irregular staining of the stone surfaces around it. The third example shows similar disfigurement of a projecting spandrel due to differential staining resulting from uncontrolled water flow over such white concrete surface.

In another example, figure 3.30, the projecting spandrel shows uneven and discontinuous staining pattern. The clean areas are sheltered from rain by the projecting balconies of the above storey reversing the staining effects of figure 3.29. On the other hand, the unprotected surfaces allow water to carry deposited pollutants and redeposit them over the surfaces of the spandrel. Without the large scale protection the washing action becomes the primary staining mechanism.

If the minute details such as drips in soffits are overlooked when designing horizontally projecting elements, weathering will be more likely to occur. Omission of drips or improper dimension*, results in undue wetting of soffit surfaces. As illustrated in figure 3.31, wetting can lead not only to changes in appearance but also in deterioration of the material. The problem is much more serious when echoed on soffits of projecting balconies since the excess wetting affects the

* Drips less than 15 x 15mm repeatedly failed to prevent water bridging.

deterioration of the reinforcing steel bars (see figure 3.32(a)).

If rainwater accumulated over the horizontal surface of a projection is not controlled in a vertical channel or a reveal, streaks due to increased wetting will be likely to occur. An example of such a situation is pictured in figure 3.32(b).

(1.3) <u>Combination of Vertical/Horizontal Projections</u>:

This group is characterized by combined vertical and horizontal projecting elements in a frame shape having a certain thickness 't' and a projection 'V' (see figure 3.33). Most of the staining patterns discussed in (1.1), (1.2) are likely to occur with this group. If the projecting frame is repeated on the facade surfaces, the weathered surfaces around such projections are accordingly increased. Figure 3.33 pictures two examples of the resulting weathering patterns on the facades of two buildings in the downtown area. In both buildings, the same pattern is repeated under each projecting frame on the stone surfaces of each facade.

Generally, the observed examples can be classified into two main sub-groups. In the first, the projecting frames are separated, whereas in the second they are attached.

(1.3.1) Separated Projecting Frames:

Observation and comparisons of the different projecting frame panels belonging to this sub-group have indicated that detailing of panel profiles can aggravate or minimize the resulting disfigurement. Increasing the thickness 't' of the projecting frame increases the exterior flat surface that is stained as illustrated in figures 3.34 and 3.35. Increasing the extent of projection V results in maximizing the side areas of the frames that are also susceptible to weathering.

The resulting uneven staining is illustrated in figure 3.36.

The horizontal and vertical spacing between frames (x, Y) in relation to the projection V presents another factor to be considered since these locations often display localized dirt accumulation. When $\frac{X}{V}$ or $\frac{Y}{V} \leqslant 1$ the potential weathering between projections is more masked due to the effects of shades and shadows (as shown in figures 3.34 and 3.35). If the ratio $\frac{X}{V}$ or $\frac{Y}{V} > 1$ weathering will be more pronounced (as shown in figure 3.37).

When the spandrel surface below the projecting frames is splayed inwards, weathering is further aggravated because:

- The downward movement of rainwater is interrupted.
- The washing action induced between projections is reduced.
- Water is allowed to move on the top surface of the horizontal projections and carry the deposited pollutants. This process causes redeposition of such pollutants on the vertical surfaces between projections.

Another common problem is the lack of adequate vertical channels to control rainwater. In all the observed cases the design of the frame corners allows a horizontal sideway movement of rain between frames. This interruption of the downward flow is usually accompanied by localized deposition of dirt particles around the frame corners (as illustrated in figure 3.38)

Furthermore, when the vertically channeled water from above is released to move freely over the spandrel surfaces near ground level, differential weathering is commonly found (as illustrated in figure 3.39). Increasing the length of the spandrel (Z) results in maximizing the areas subjected to weathering. On spandrals with smooth and light colour material the contrast between stained and unstained surfaces is more pronounced.

(1.3.2) Attached Projecting Frames:

If the projecting frames are attached with no spacing in between (ie. x = Y = 0), the weathering problems will be more likely to occur over the soffits and the side surfaces of the vertically projecting elements. Omission of drips allows the rainwater carrying the deposited dirt particles to move over the glass window causing probable staining and etching. Figure 3.40 illustrates two examples of the resulting weathering pattern. Staining can be generally aggravated if the downward flow of water over the projecting ribs is interrupted. An example of such a situation is pictured in figure 3.41.

In summary, the weathering patterns associated with the facade elements having projecting frames are related to:

- The basic dimensions t, v, x, Y, Z of the frame profile. Increasing t, V, or the values of x, Y, Z relative to V to more than 1:1 increases the potential weathering.
- The interruption of the downward flow of water allowing horizontal sideway movement between projections.
- The uncontrolled movement of rainwater over the spandrels near the street level.
- The omission of drips in soffits of horizontal projections.

(1.4) Flush/Punched Openings:

The facades of this group are characterized by the lack of projections that usually causes more exposure of their surfaces to rainwater. Windows in a facade develop comparatively more run-off than the surrounding wall material; accordingly, increased wetting occurs below windows. The resulting weathering patterns are directly related to the window design and its control of rain run-off. When the rain-water is directed sideways on the horizontal plane of the sill, the resulting pattern of washed and unwashed areas will be different from that usually occuring below the sill. Figures 3.42 and 3.43 illustrate typical examples showing the resulting weathering pattern in each case.

Further observation of numerous examples shows that correct detailing of window sills to control water movement is generally overlooked. Figure 3.44 depicts three different examples.

(1.4.1). Flush Openings:

One of the important factors that affects the sill weathering is its recessed depth 'R'. Windows with narrow sills (ie. R ≈ 0) allow less dirt and soot deposits and at the same time receive less rain quantities than deep sills. Below sill weathering, however, can still occur as illustrated in figure 3.45. The resulting pattern is further modified below each window mullion as shown in the same figure. The reason is attributed to the concentration of the randomly moving rain drops into downward streams at the vertical mullions.

(1.4.2) Punched Recessed Openings:

Recessed openings are more susceptible to weathering than the flat ones. Observation has showed that increasing the recessed depth 'R' substantially aggravates the problem*. Comparative examples of window sills having different recessed depths are presented in figure 3.46.

---

* Serious changes in the desired appearance of buildings (particularly in panelized facades) occur when the same disfigured pattern below recessed windows is repeated. Few chosen examples illustrating the final weathering are presented in figure 3.47.

The vertical sectional profile of the facade elements present another major factor in aggravating or minimizing weathering. Generally, two main profiles belonging to this group can be identified:

1. A profile that allows continuous downward flow of water over the facade panels from any storey to the one below (as shown in figure 3.48).
2. A profile that interrupts such a flow at each storey (as shown in figure 3.49).

The comparison between the performance of both profiles showed that the weathered surface in the first profile is extended under each window sill to the window head of the lower storey. With the second profile, weathering is limited only below window sills. Furthermore, glass staining is more likely to occur with the first profile since run-off experiences a continuous uncontrolled flow.

Considering the horizontal sectional profile of the facade elements, observation has indicated that piers between panels are not designed to guide water into vertical channels or any other intentioned paths. Accordingly, streaks due to irregular water flow was a common feature.

Generally, three main profiles of piers can be distinguished:

1. A profile with a plain surface as shown in figure 3,45 and 3.48 example a.
2. A profile with outward projection as shown in figure 3.47, examples b, c and figure 3.48 example b.
3. A profile with inward recess as shown in figure 3.49 example a.

The comparison of these different examples presented in figure 3.50 shows that weathering is more pronounced in the first type since water is allowed to move freely. The degree of disfigurement of facade appearance is directly related to the width of the piers. Light colour and smooth surfaces aggravate the contrast between washed and unwashed areas (as shown in figures 3.45 and 3.47 example c).

The second type also does not control water flow and thus the projecting surfaces are susceptible to weathering. The splay of the piers presents and important factor. Varying the angle θ between any two planes (θ < 90°, θ = 90°, θ > 90°) as shown in figure 3.50, affects water migration from one surface to another. Increasing the angle θ maximizes the effect. Continuity of water flow between surfaces is also enhanced when the corners between them have rounded edges instead of sharp edges.

The third type performs better since run-off water is controlled into recessed channels. Shadows on recesses usually help masking any streaks or weathering particularly when the recessed depth 'd' is equal or greater than the channel width 'C' (see figure 3.50). The streaks can also be masked when the channel surfaces have a darker tone colour than the rest of the surrounding surfaces or when the overall colour of the panel is dark.

The final weathering pattern of facade panels is also dependant on the exposure condition to atmospheric pollution and driving rain as well as on the surface characteristics of the wall material.

In summary, the weathering patterns associated with recessed windows without projections are due to:

(1) Uncontrolled water run-off under window sills.

(2) Lack of drips in the vertical sectional profiles causing water to flow from one storey to another increasing the

weathered surfaces.

(3) Window heads are not designed to stop the water flowing from upper surfaces.

(4) Horizontal profiles and splays of vertical piers that do not guide run-off water vertically in designed recesses or channels.

(II) HEAVILY SCULPTURED SURFACES:

Generally, in recently completed buildings the use of heavy detailing, cornices, sculptures, etc. are rare. Figure 3.51 illustrates two different sculptured designs that are characterized by their multi-planed surfaces having different compositions of projections and recesses. Pollution deposition over these surfaces is usually uneven. Moveover, the rainwater movement over the surface contours is always in complex and irregular patterns. The resulting weathering can be a combination of all staining patterns explained in the first category of moderately sculptured surfaces. In short, the more sculptured a facade surface is, the more complex the surface hydraulics is and consequently the more localized stain is likely to be.

(III) PLAIN SURFACES:

Comprising this category are facade surfaces without the geometrical configurations discussed above. The partial washing of the facade surfaces and resulting differential staining is due to the material characteristics and their interaction with rain, wind and the ambient atmosphere. Generally, for the three categories studied in this chapter, the selection and use of the exposed surface material affects pollution deposition and rain run-off. Many of the previously illustrated examples could have avoided the partial staining had their surfaces allowed less dirt accumulation and more rain run-off. This is strongly dependant on the material absorptivity and its surface properties (as elaborated in Chapter IV).

A typical example that clearly illustrates the important effect of surface absorptivity on facade weathering was observed at the two-storey base of 'Place Ville Marie'. The 47 storey office tower, completed in 1962, is considered one of the significant projects in the centre of Montreal's business district. Unfortunately, most of the facade surfaces of the two-storey base display severe dirt concentration because of the partial washing action. The resulting weathering pattern is illustrated in figure 3.52. The combed surface of the sandstone facade units increases the susceptibility to dirt accumulation. Moreover, the surface absorptivity of this wall material does not allow the periodic washing to develop enough water run-off that can perform a complete washing action. As shown on the accompanied map (figure 3.52), the surrounding tall buildings help minimize the rainwater quantities received at lower storeys.

Similar unattractive appearance is being repeated on the facade panels of Montreal's cultural and art centre 'Place des Arts'. The vertically grooved concrete panel allow dirt to accumulate in great quantities between the grooves. The downward movement of rainwater causes redeposition and concentration of dirt particles at the lower level of the panels. Lack of enough rainwater flowing over the panel surfaces has resulted in the weathering pattern shown in figure 3.53. In the same figure, it can be noted that the building is located among taller buildings that increase its shelter from the driving-rain.

A third example that illustrates the phenomenon of partial washing on a plain surface was observed on the concrete brick facade of 'Complex Desjardins' completed in 1976. The two-storey surface (pictured in figure 3.54) allows dirt to accumulate more readily due to its rough texture. Despite the open site around the building, the driving rain quantities arriving to the facade surface do not perform a complete washing action. The result is differential weathering similar to that shown in figures 3.51 and 3.53.

It should be emphasized that lack of available data pertaining to surface absorptivity of the observed examples has handicapped a subsequent correlation between the driving rain quantities arriving to a facade and the water run-off developed over its surface. The problem is further complicated when considering facades of tall buildings in a variety of site conditions. This is due (as explained in 2.3.3) to the implications of wind flow patterns on the accompanying rain field and consequently on the resulting wetting.

These findings give rise to the importance of wind-tunnel studies now being done on a wider scale for buildings at the planning and design stages. If these studies are further developed to account for the influence of air flow patterns on the induced wetting, more accurate predictions of the behaviour of rainwater over facade surfaces would then be feasible.

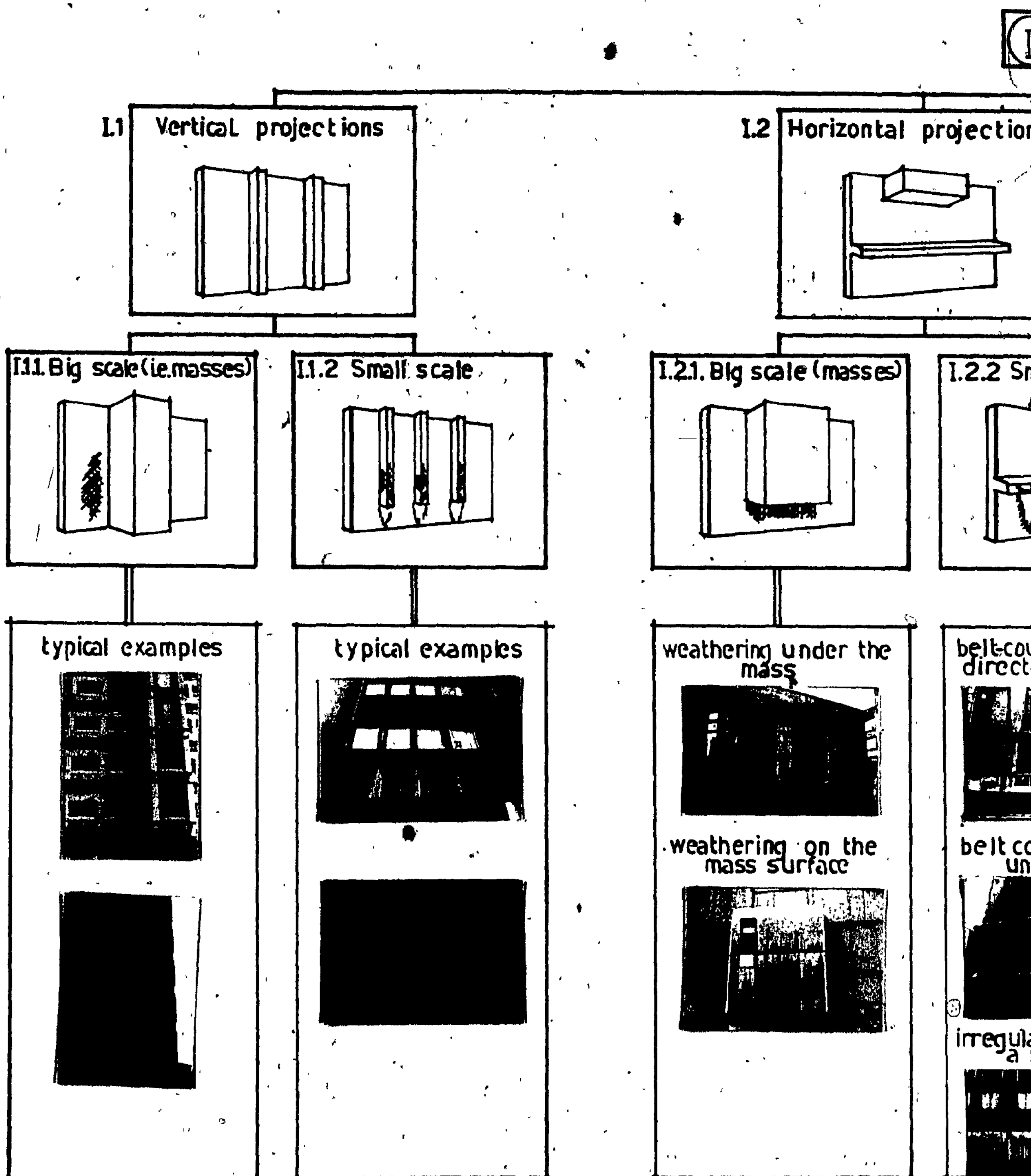
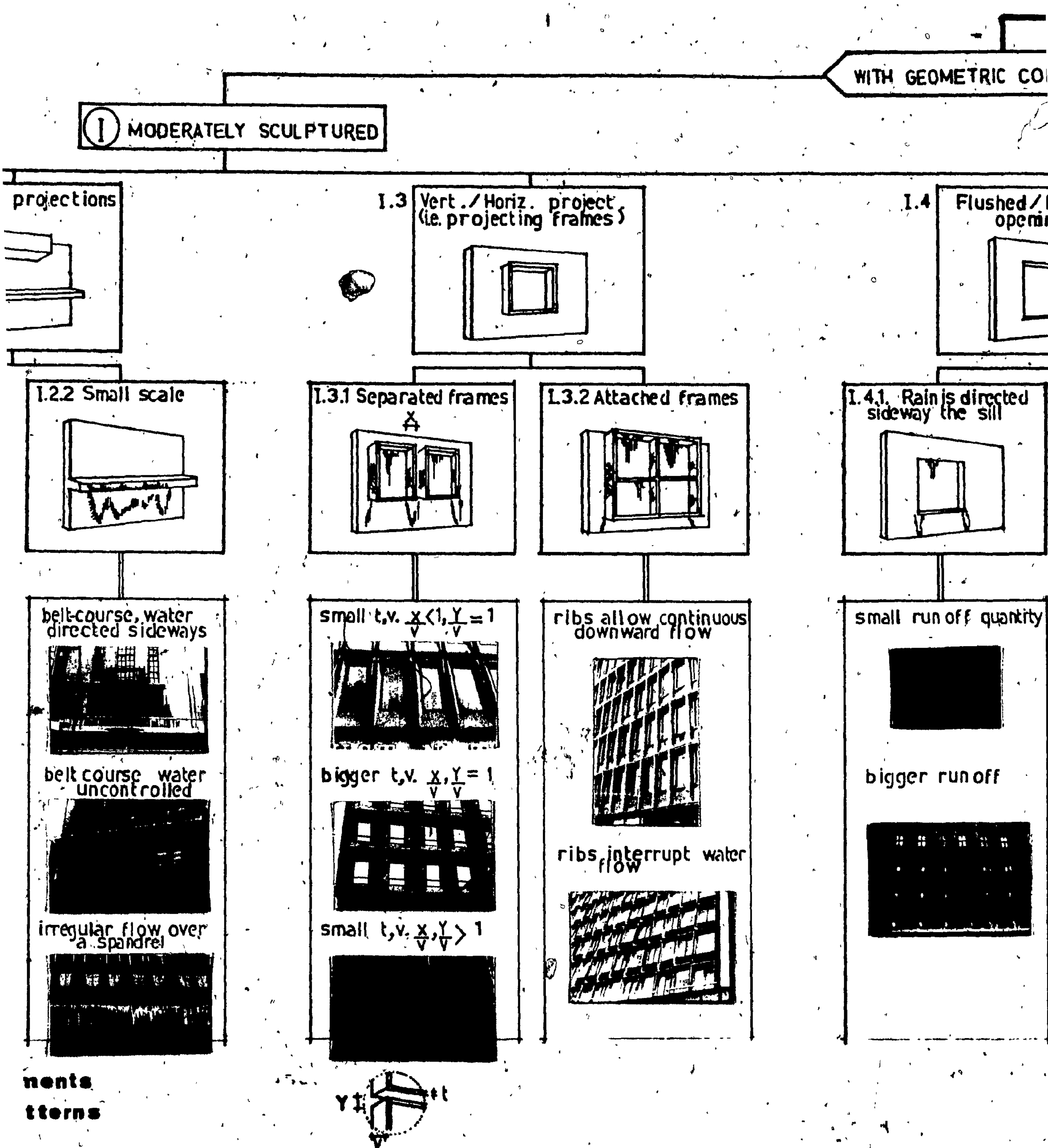
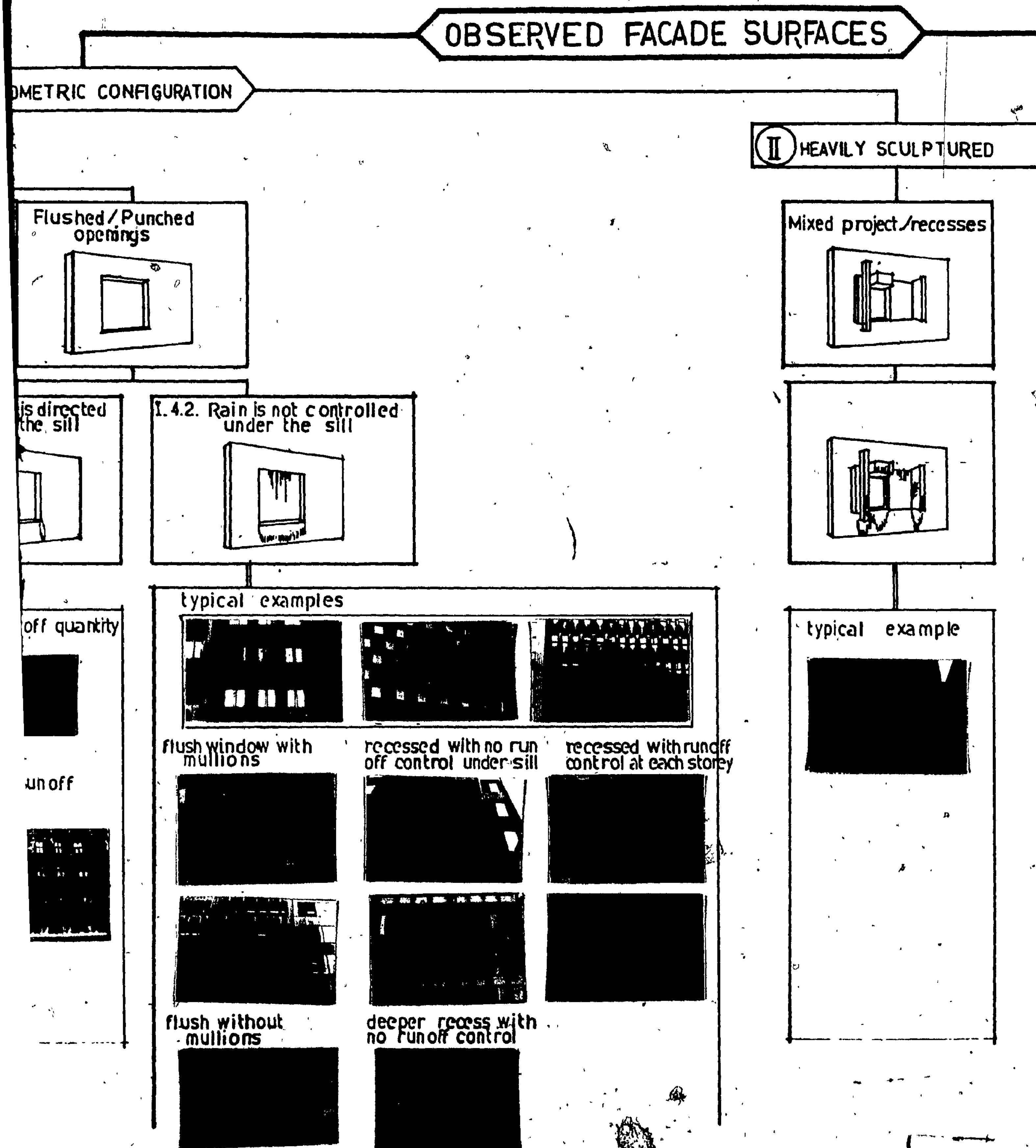
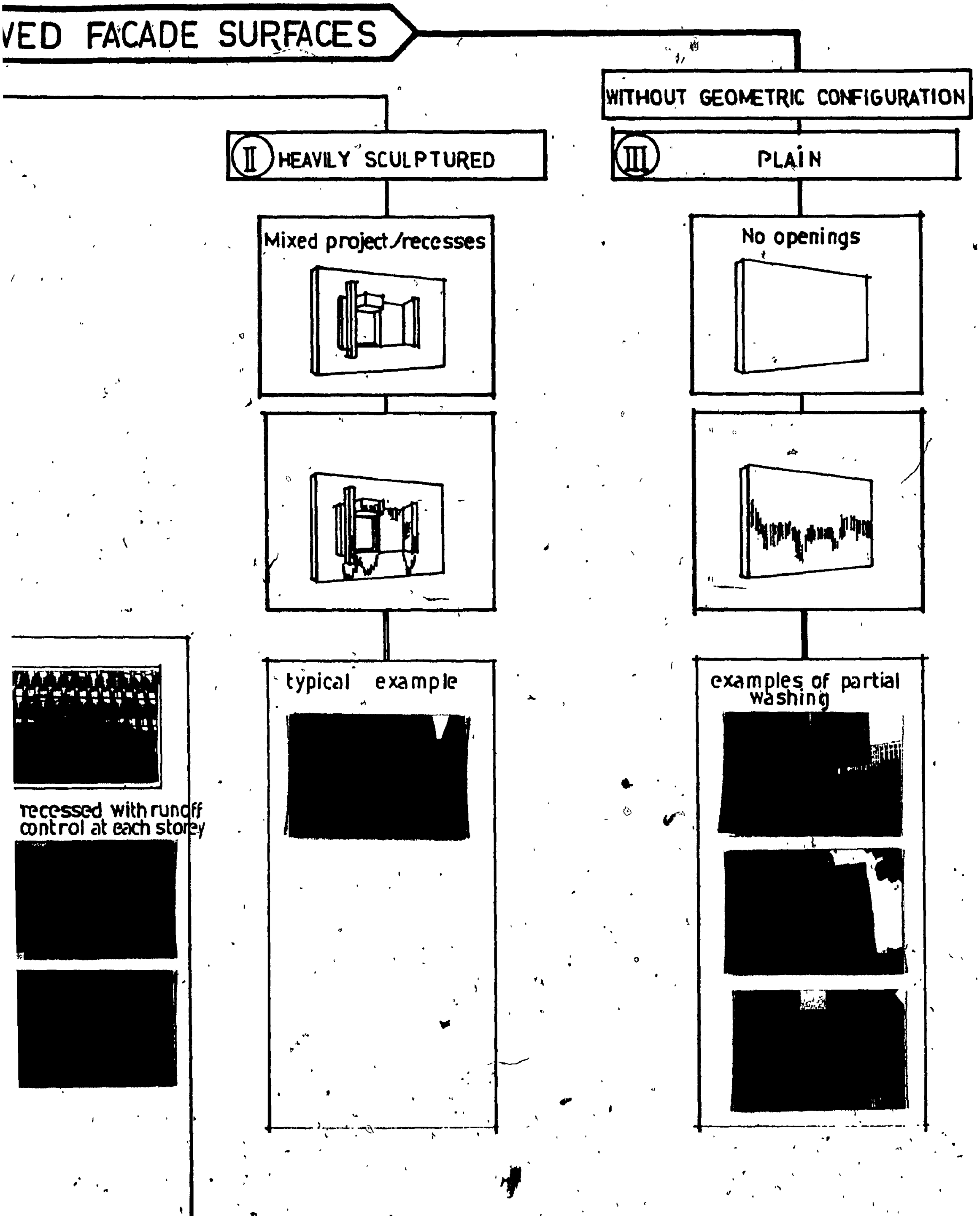


FIGURE 3.24 **Classification of facade elements with respect to staining patterns**

1 of


WITH GEOMETRIC CO
I MODERATELY SCULPTURED
projections
I.3 Vert./Horiz. project. (ie. projecting frames)
I.4 Flushed/
openi
I.2.2 Small scale
I.3.1 Separated frames
I.3.2 Attached frames
I.4.1. Rain is directed sideway the sill
belt-course, water directed sideways
belt course water uncontrolled
irregular flow over a spandrel
small t,v. X/V <1, Y/V = 1
bigger t,v. X/V, Y/V = 1
small t,v. X/V, Y/V > 1
ribs allow continuous downward flow
ribs interrupt water flow
small run off quantity
bigger run off
nents
tterns
Y
t
V


OBSERVED FACADE SURFACES
METRIC CONFIGURATION
II HEAVILY SCULPTURED
Flushed / Punched openings
Mixed project./recesses
is directed the sill
I.4.2. Rain is not controlled under the sill
typical examples
typical example
off quantity
unoff
flush window with mullions
recessed with no run off control under sill
recessed with runoff control at each storey
flush without mullions
deeper recess with no runoff control


VED FACADE SURFACES
WITHOUT GEOMETRIC CONFIGURATION
II HEAVILY SCULPTURED
III PLAIN
Mixed project./recesses
No openings
recessed with runoff control at each storey
typical example
examples of partial washing

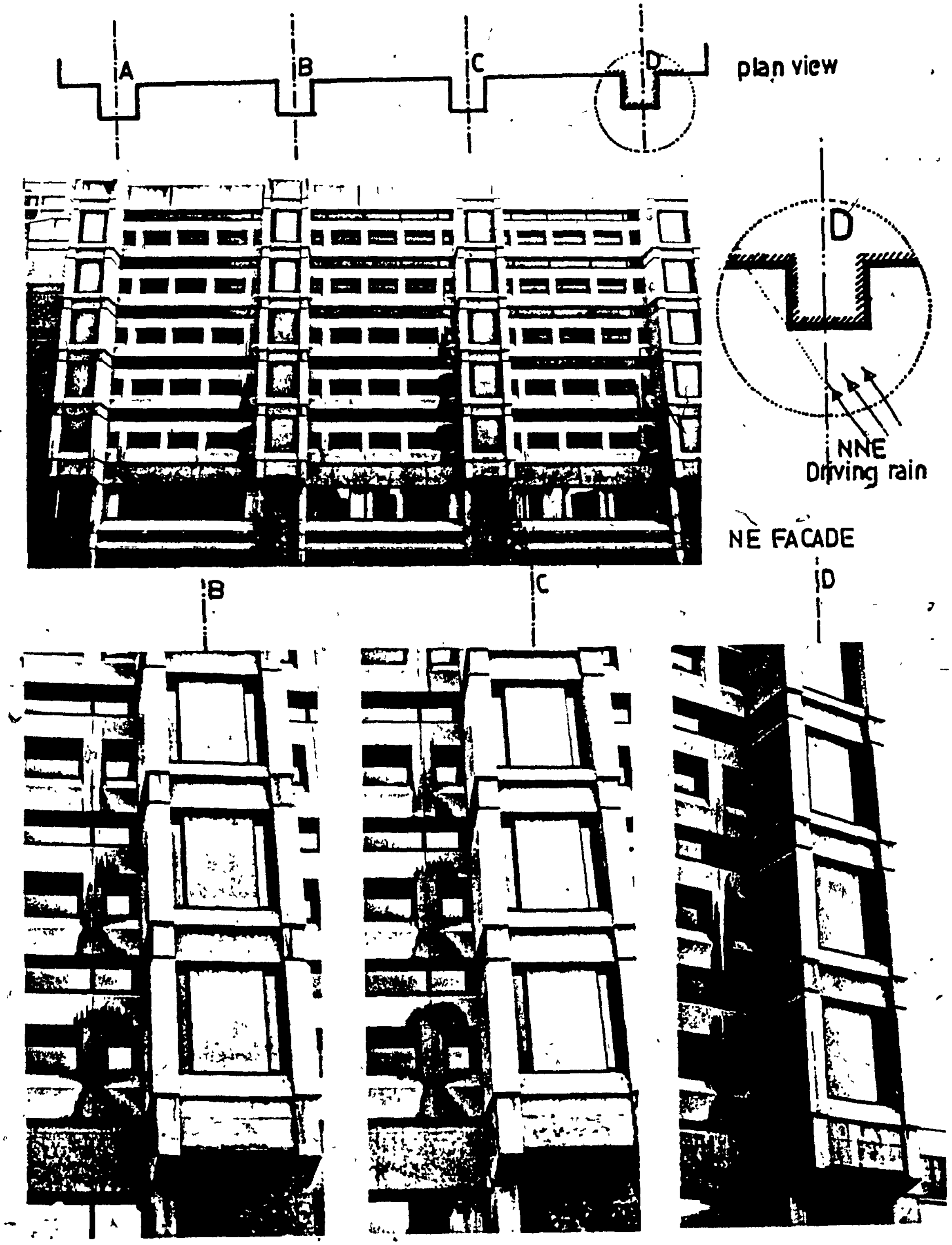


FIG. 3.25: Type 1.1.1, the vertically projecting masses minimize wetting at the inside corner and hence increase the risk of localized stain.

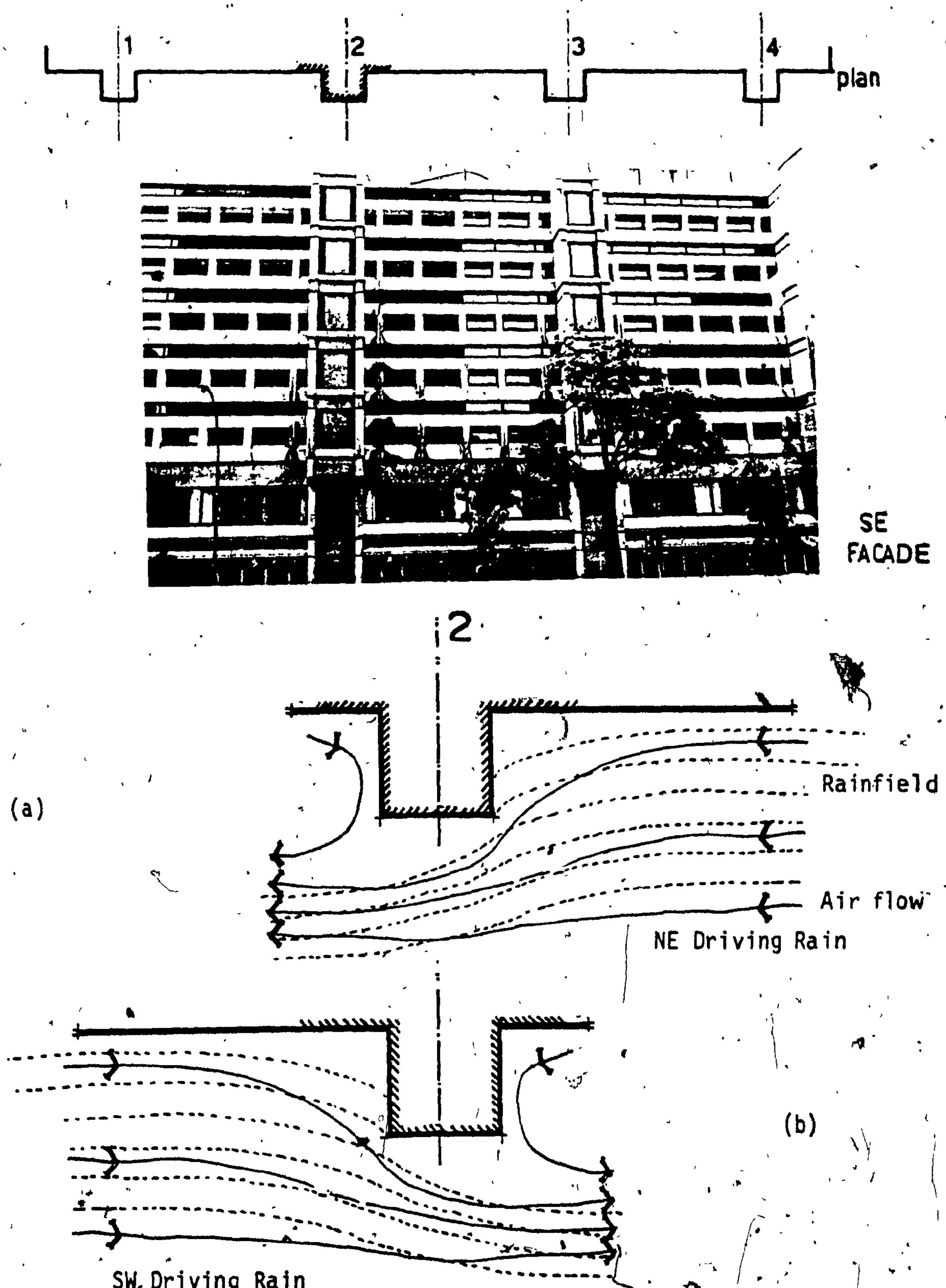
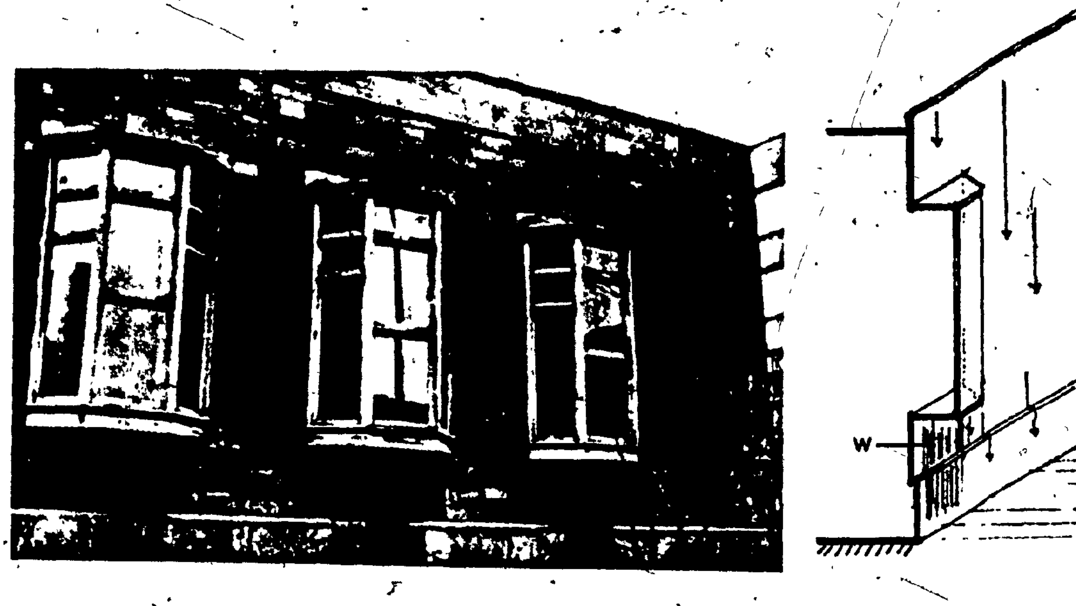


FIG. 3.26: Type 1.1.1, both inside corners of the vertically projecting masses display localized stains. The probable trajectories of raindrops around one of the projecting masses is illustrated in a and b. (Based on Couper [9]).

FIG. 3.27: Type 1.1.2, small scale vertical projections and the potential differential staining likely to occur.

NOTE: (In all figures the letter 'W' is used to point out the weathered surface).



(1)

(2)

FIG. 3.28: Type 1.2.1, horizontally projecting masses illustrating:

(1) staining of the surfaces under projections because of the protection from driving rain.

(2) Differential staining over the surface of the projecting mass due to water flow from the top of projecting surface downward.

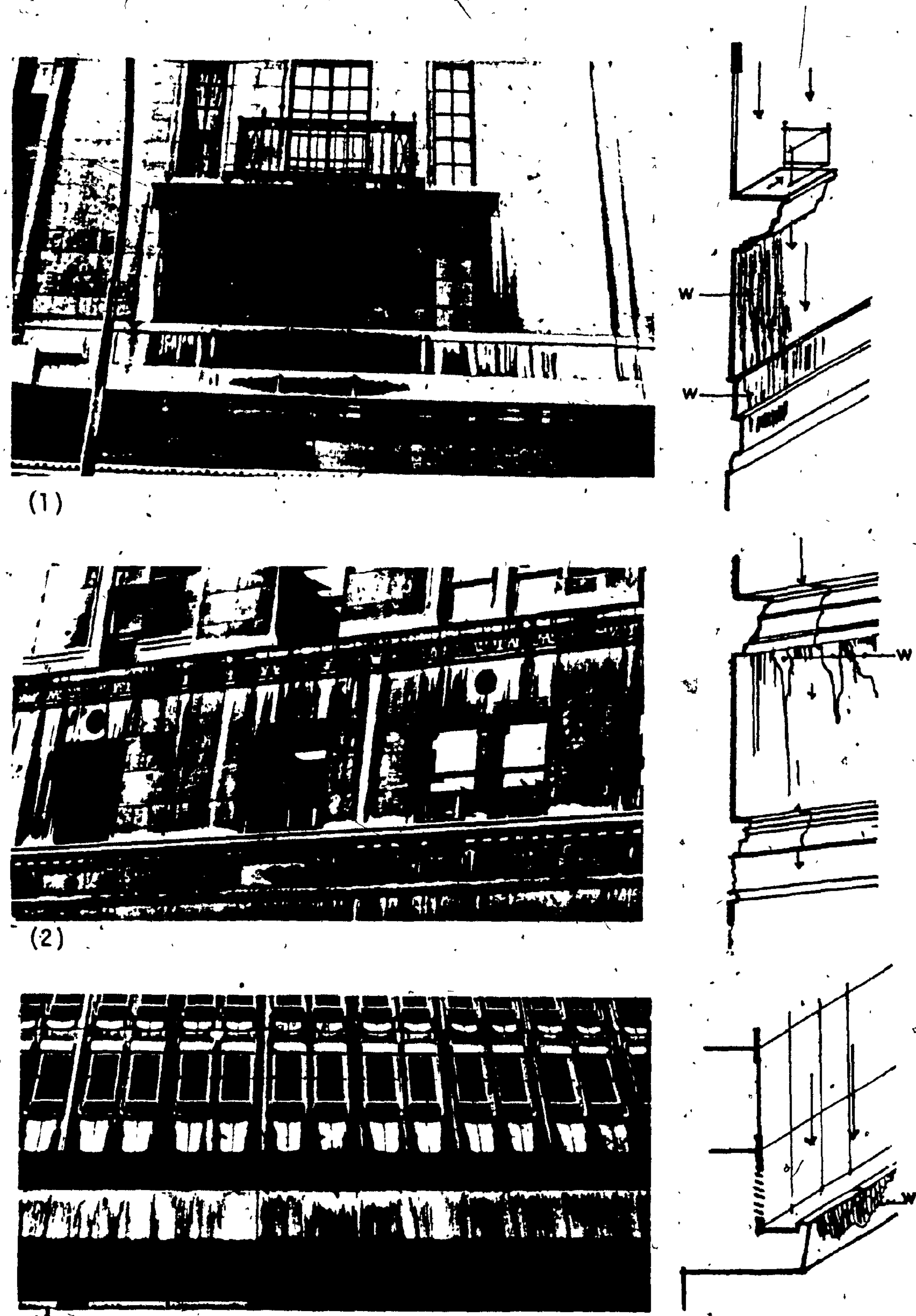


FIG. 3.29: Type 1.2.2, examples of possible weathering patterns resulting because of the lack of adequate detailing to control rainwater flow.

FIG. 3.30: Type 1.2.2, uncontrolled water movement causes redeposition of pollutants over the spandral surfaces.

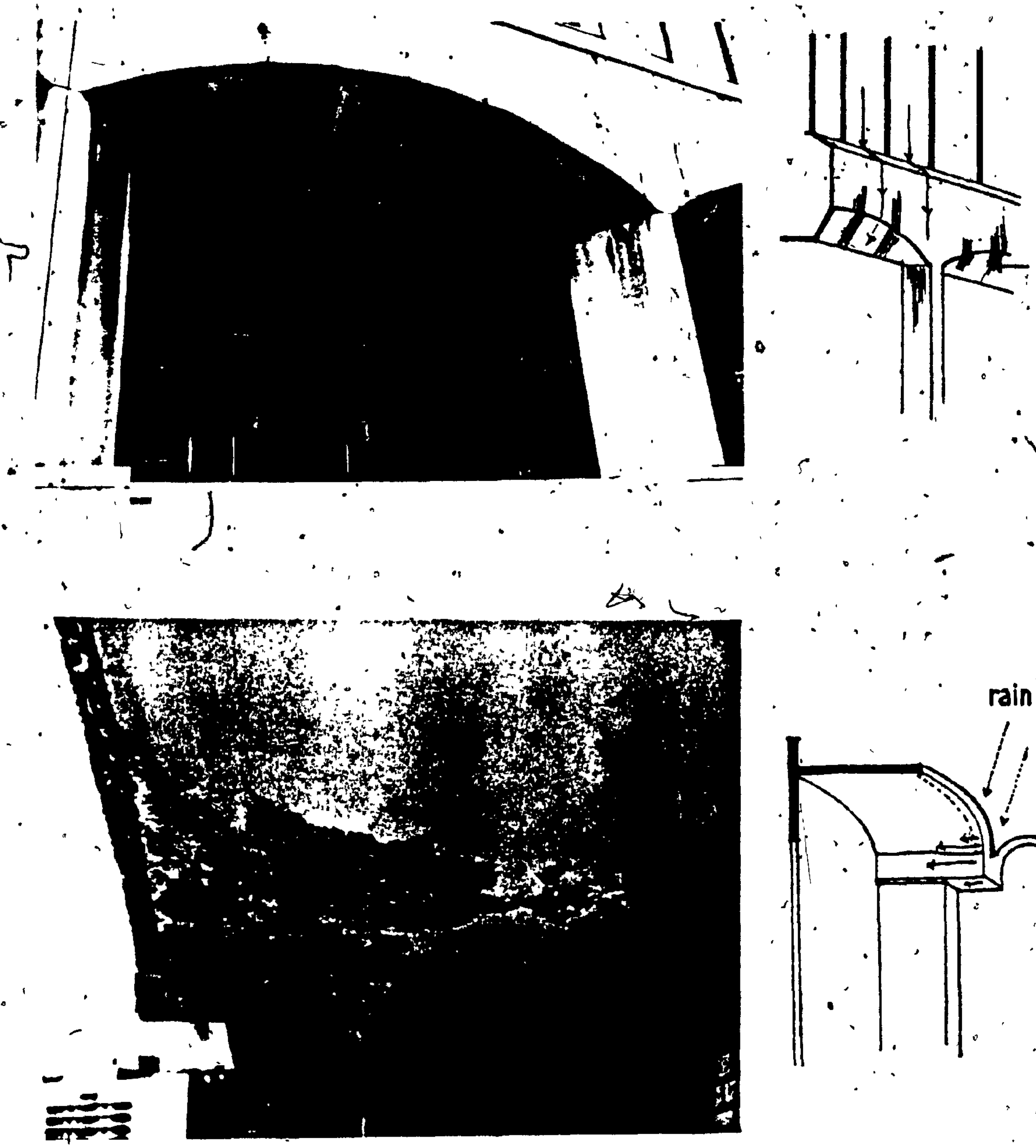
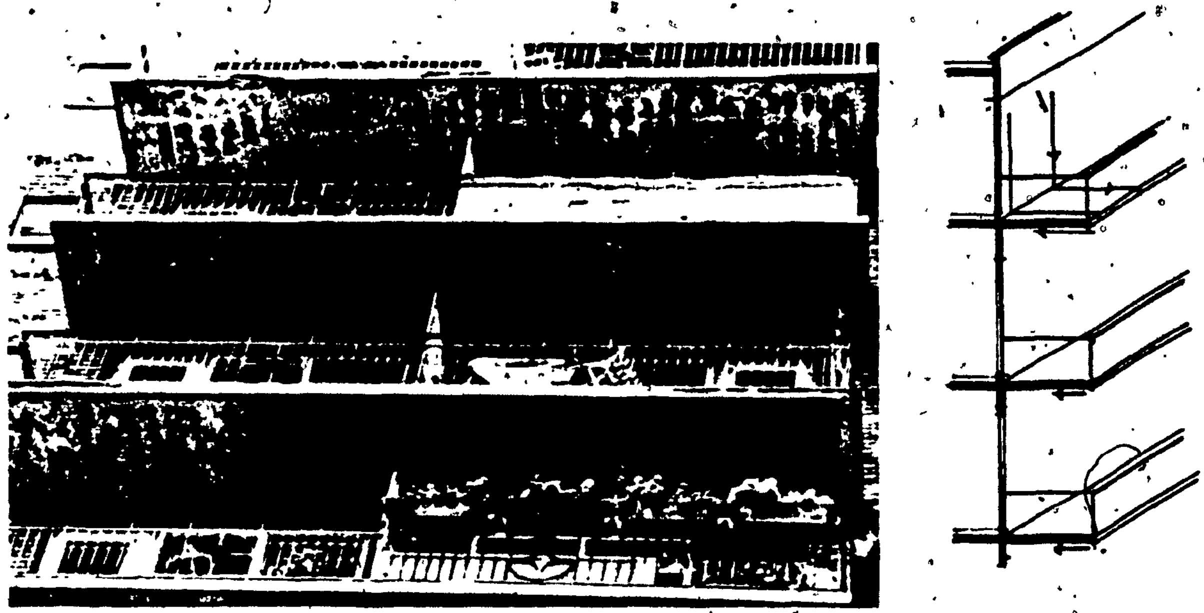
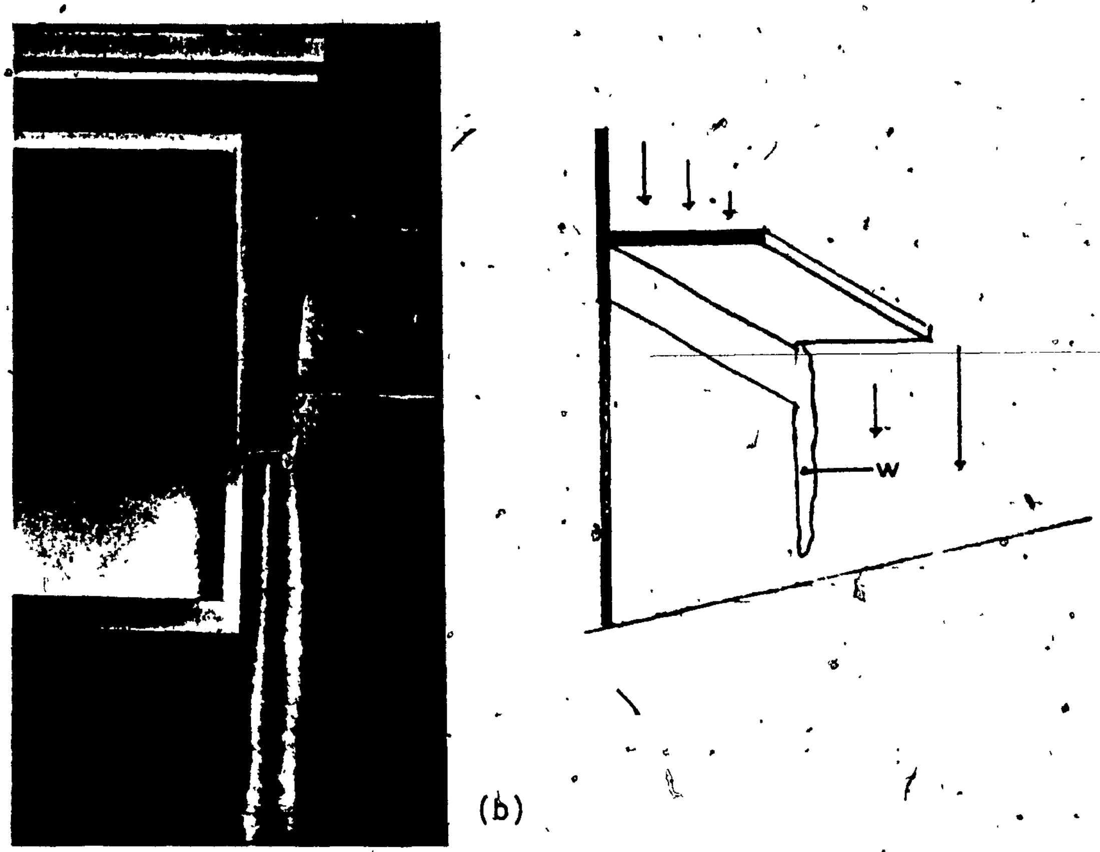


FIG. 3.31: Omission of drips or lack of proper dimension results in not only changes in appearance but also to deterioration of the soffit material.



(a)



(b)

FIG. 3.32: (a) excess wetting leads to serious decay repeated in all soffits of balconies.

(b) uncontrolled water flow causes streaks of the wall surface.

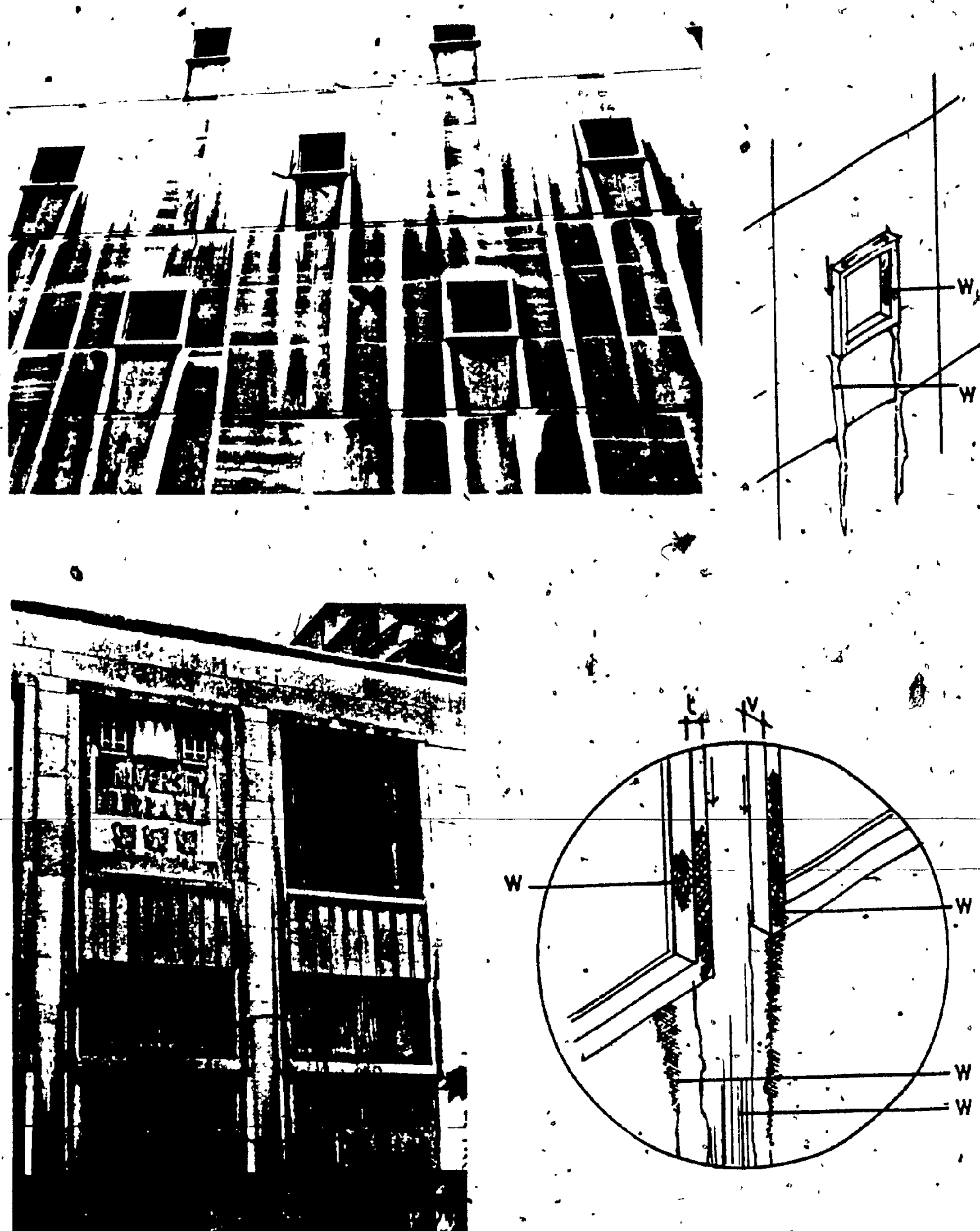


FIG. 3.33: Type 1.3, typical weathering pattern likely to occur around projecting frames.

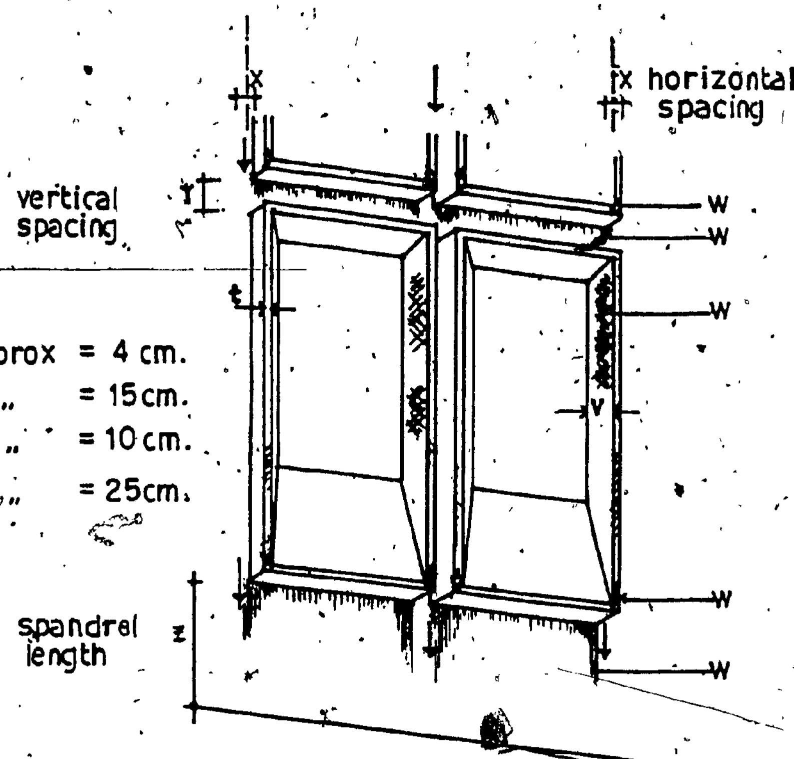
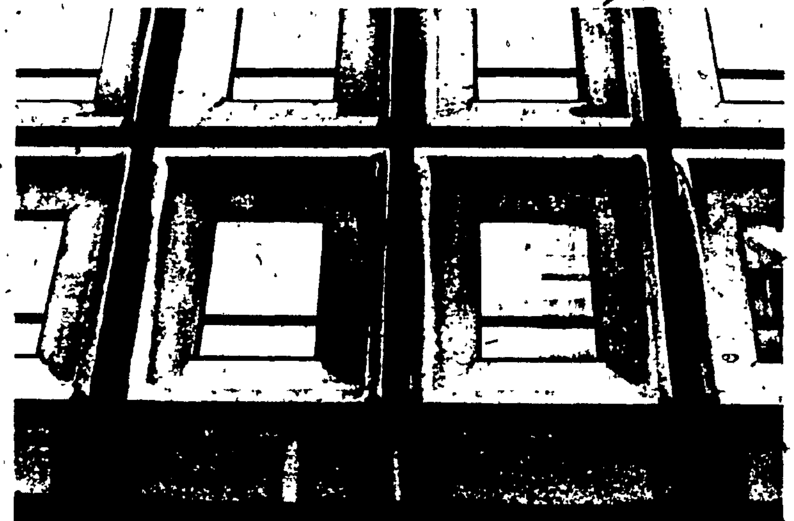


FIG. 3.34: Type 1.3.1, an example of a projecting frame panel demonstrating the basic dimentions t, v, x, Y, z that affect the resulting weathering.

- Minimizing t,v decreases the potential staining of frame surfaces
- Minimizing x,Y relative to v increases masking of stains between projections.



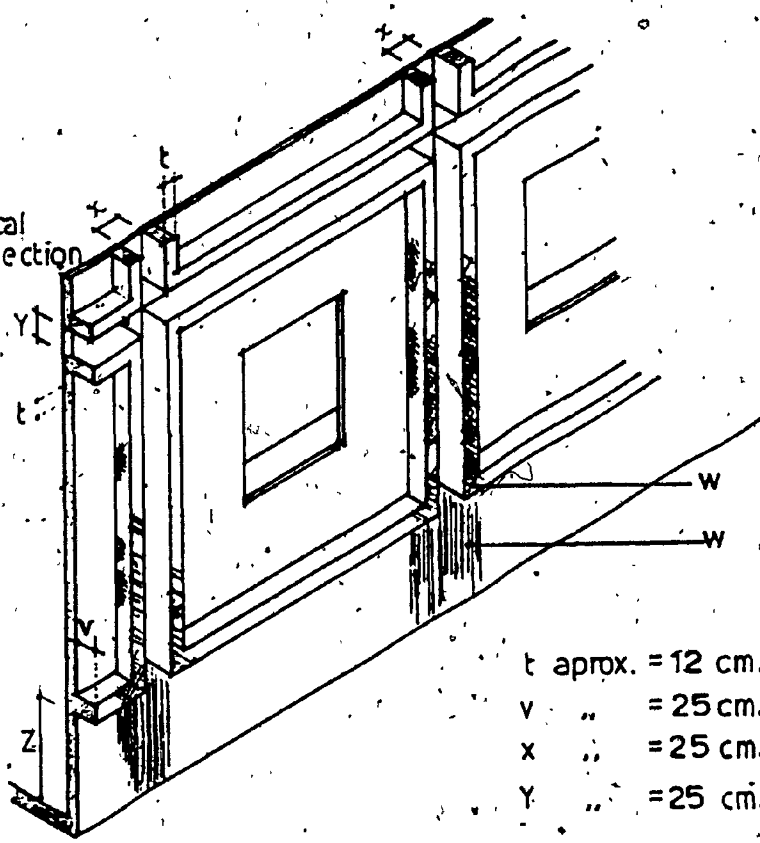
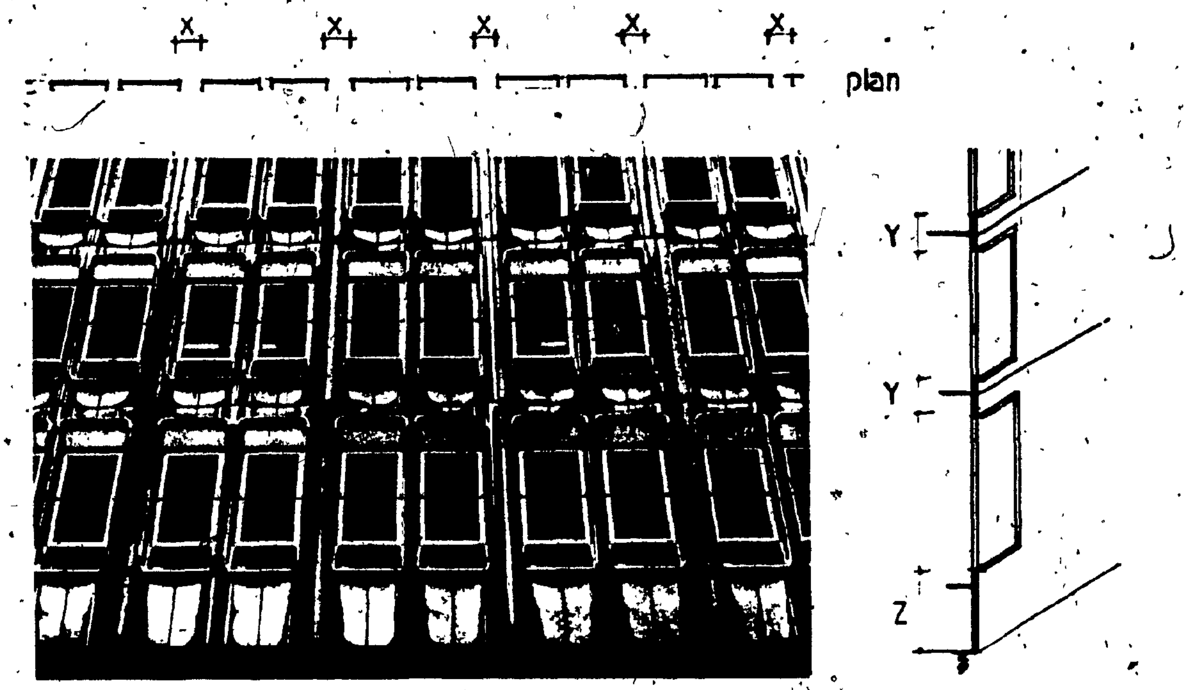
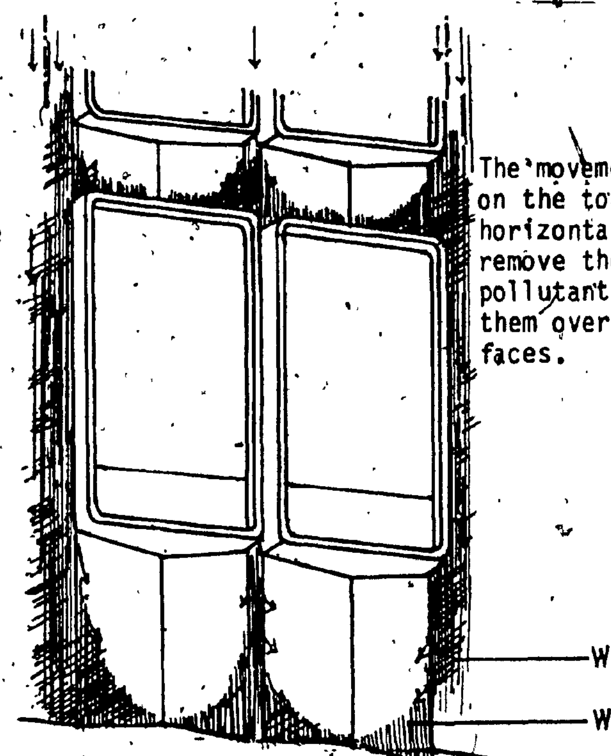


FIG. 3.35: Type 1.3.1, example of projecting frame panels showing that:

- Increasing 't','v' maximizes the framesurfaces subjected to weathering.
- Increasing x, Y, z minimizes masking the stains around projections.

FIG. 3.36: Type 1.3.1, two examples showing weathering of the surfaces of the projecting frames when water is allowed to move irregularly.





The spandral surface is splayed inwards and hence increases the interruption of the downward flow of water.

The movement of water on the top surfaces of horizontal projections remove the accumulation pollutants and redeposit them over the wall surfaces.

FIG. 3.37: Type 1.3.1, increasing the dimensions of x, Y, z relative to the projecting distance v, results in increasing the surfaces susceptible to localized dirt accumulation.

- Sharp-edged Corners:

  Line where water is allowed to move horizontally.

- Rounded Corners:

  Water flow attached to round corners interrupts the vertical channell decreasing washing action therein.

- Angled Corners:

  Similar to round corners above with pronounced stain depositions.

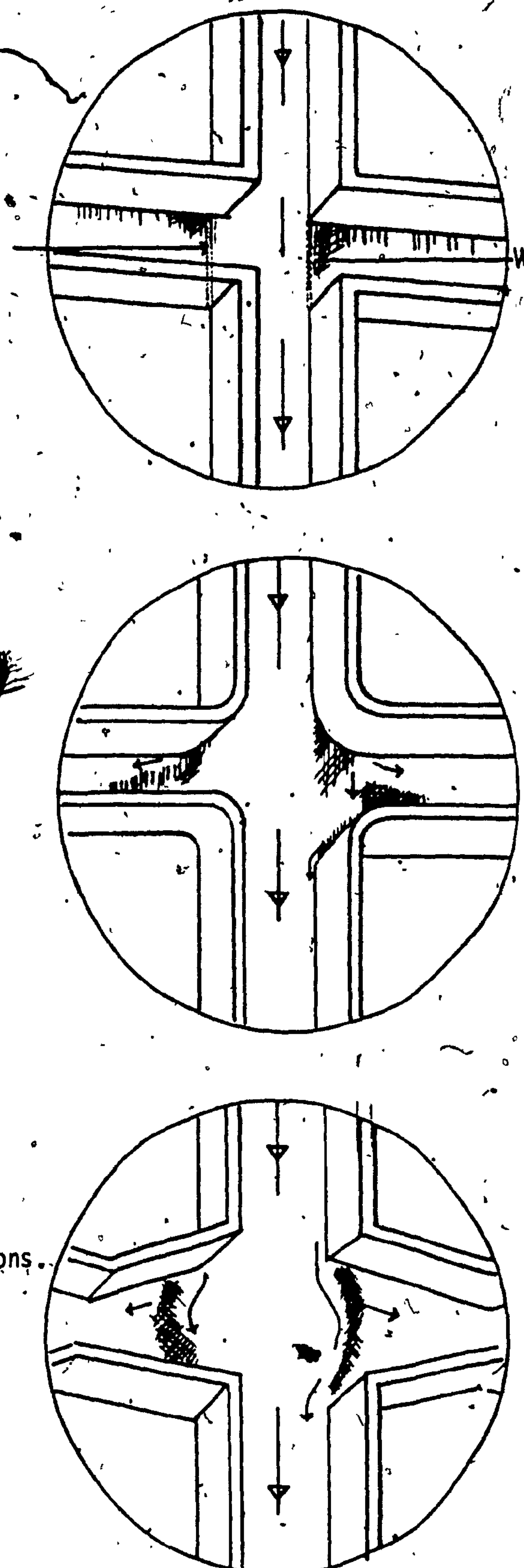


FIG. 3.38: A comparative example of different corner types of projecting frames.

FIG. 3.39: Lack of adequate control of vertically channeled rainwater leads to localized concentration of dirt over the spandrals below projections.

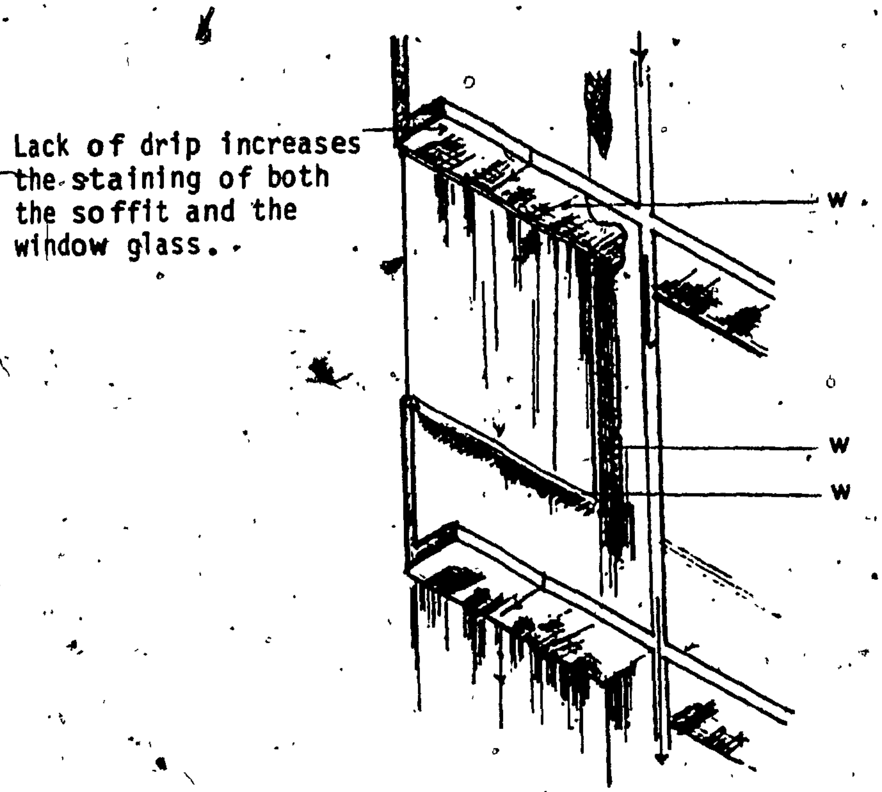


FIG. 3.40; Type 1.3.2, attached projecting frames, examples showing the weathering pattern likely to occur.

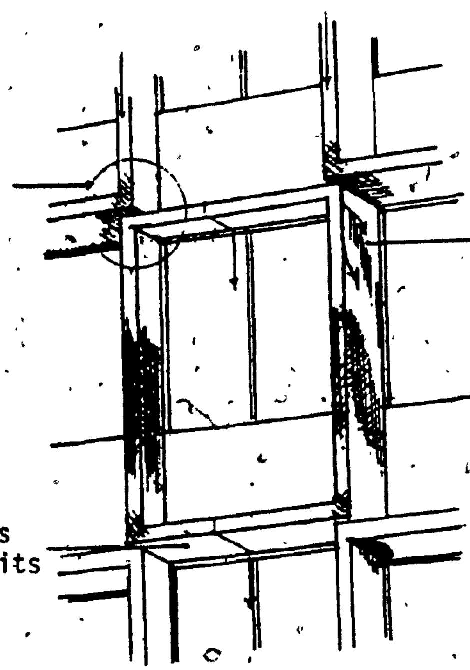


FIG. 3.41: Type 1.3.2, discontinuity of the vertically projecting members interrupts the flow of water and hence aggravates staining.

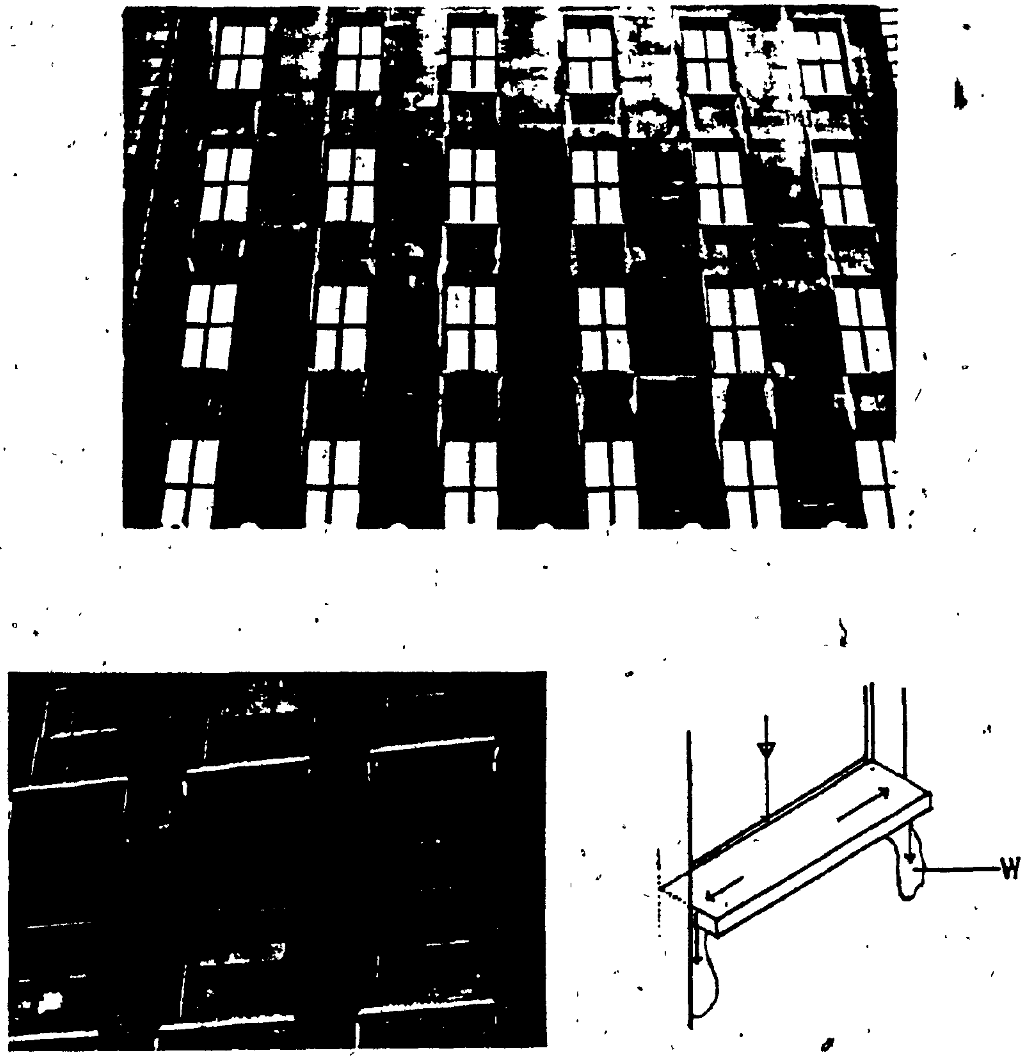


FIG. 3.42: Type 1.4.1, typical examples of recessed windows when rainwater is directed sideways of the window sill.

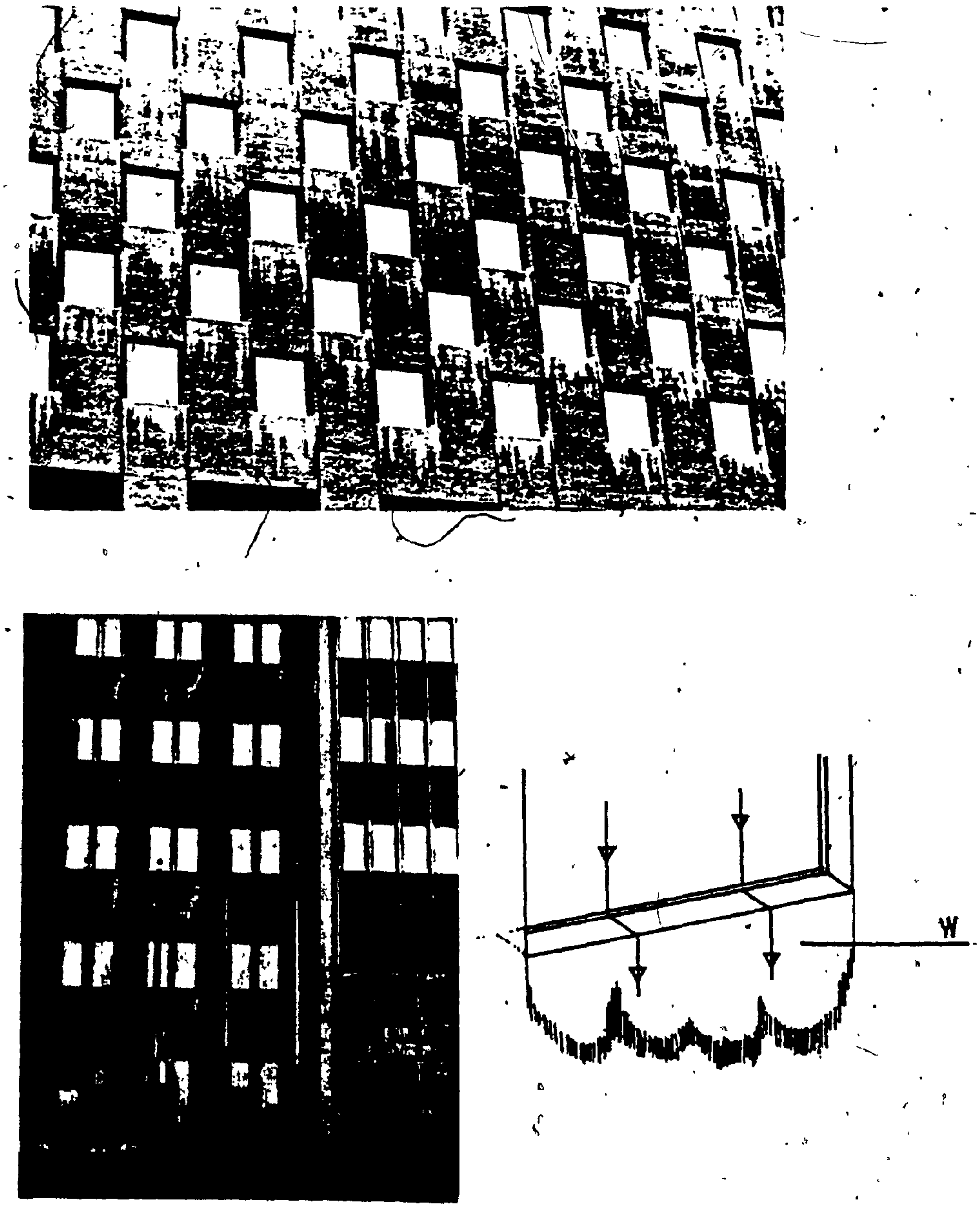


FIG. 3.43: Type 1.4.2, typical examples of punched recessed windows when water is allowed to move freely below sills.

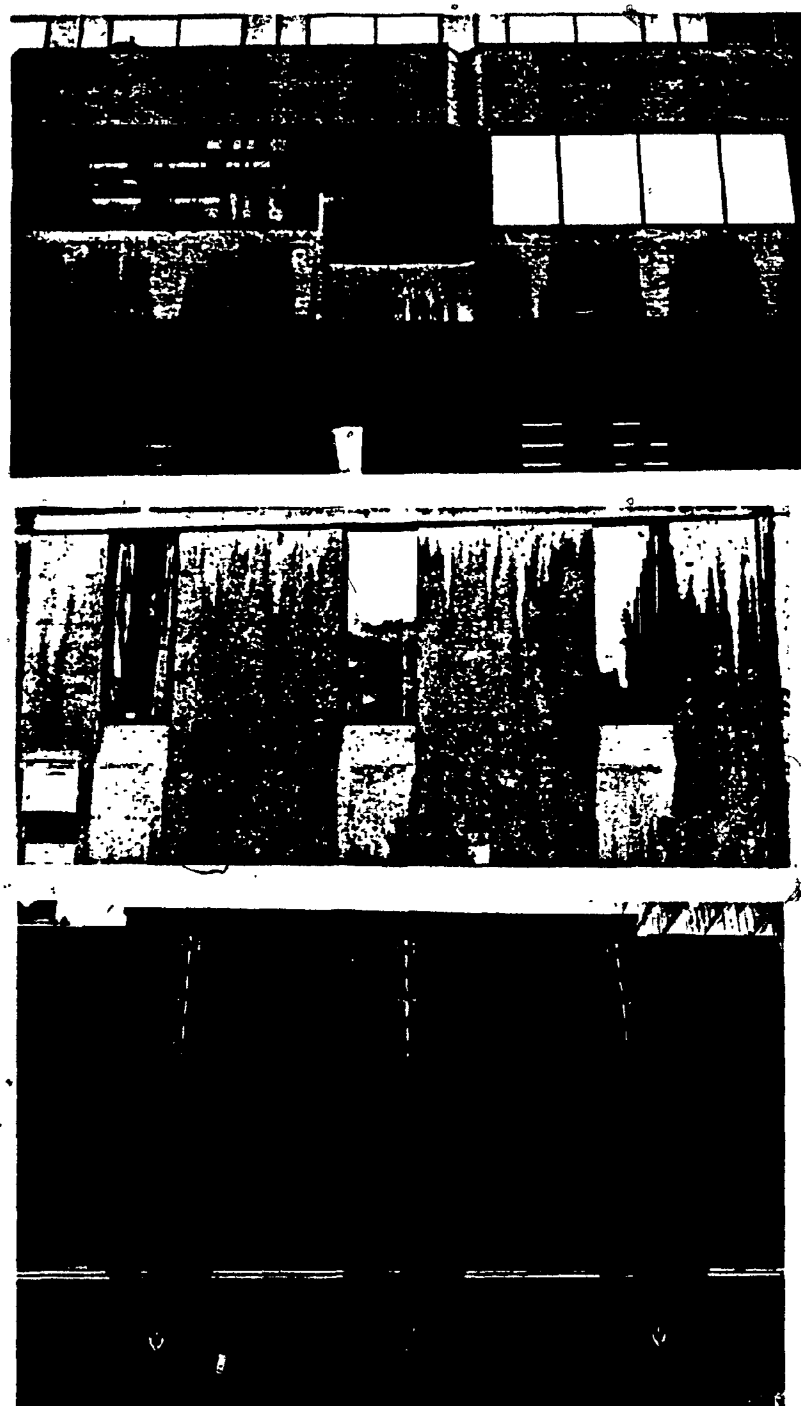
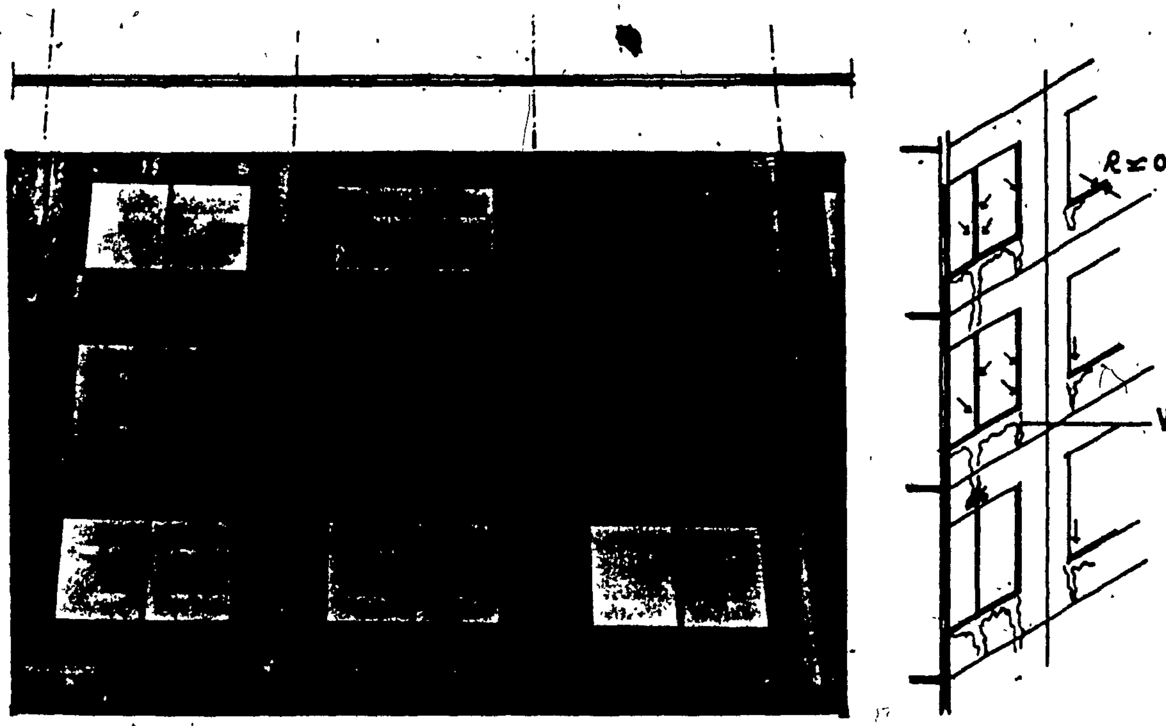
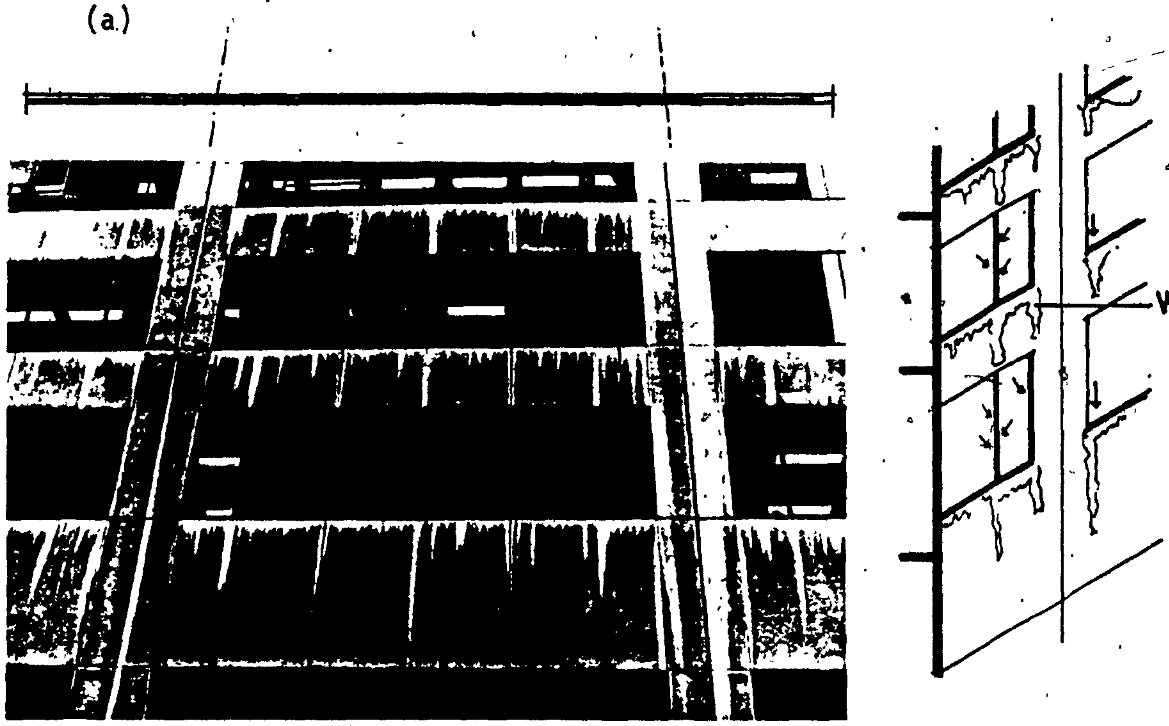


FIG. 3.44: Type 1.4.2, examples of the resulting differential staining under window sills due to lack of adequate control of rainwater flow.



(a)



(b)

FIG. 3.45: Type 1.4.2, two examples showing that below-sill weathering can still occur even with slightly recessed windows (R ≃ 0) as run-off is not controlled. Weathering is more pronounced in example (b) due to its smooth and light colour concrete surface.

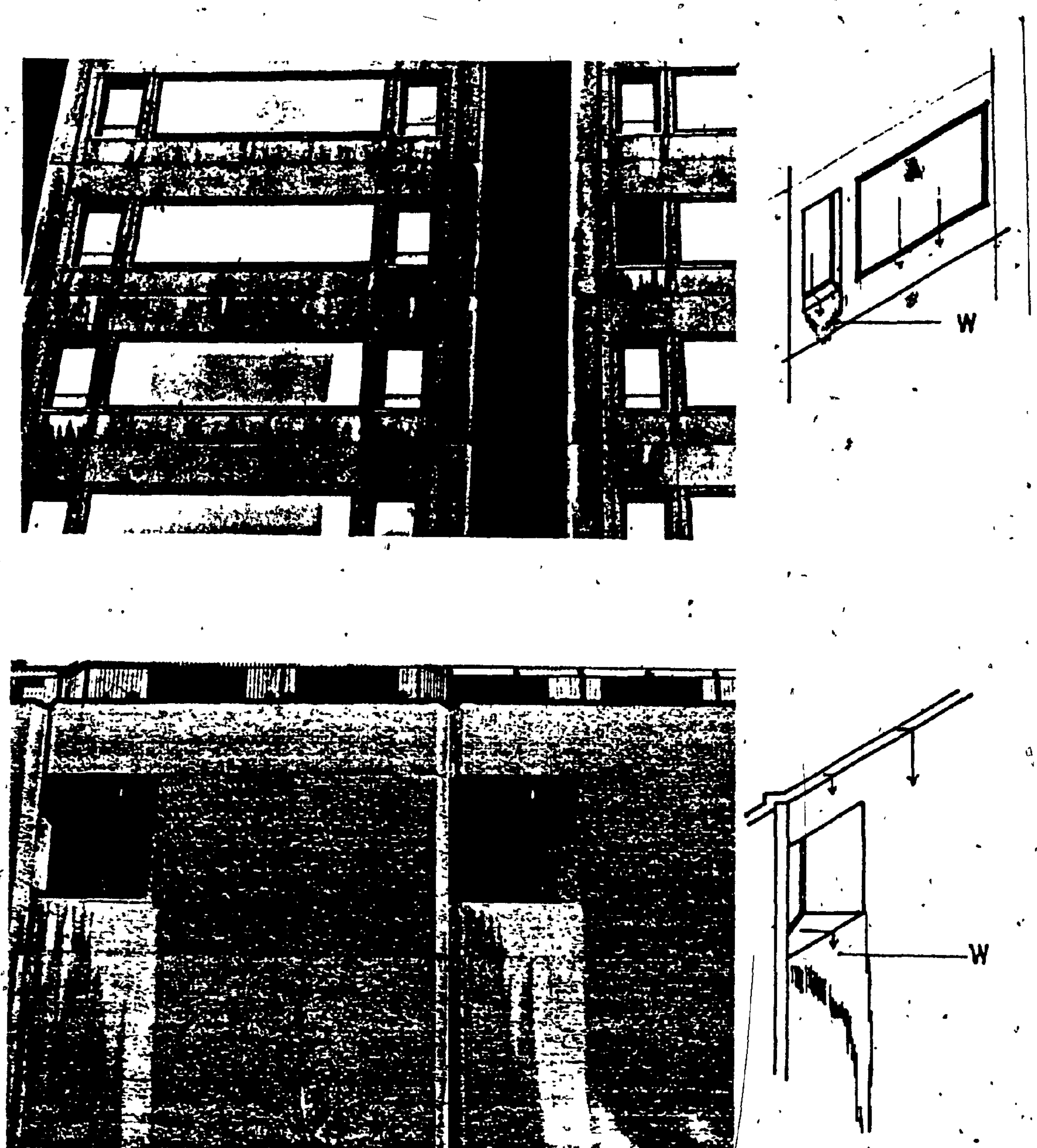
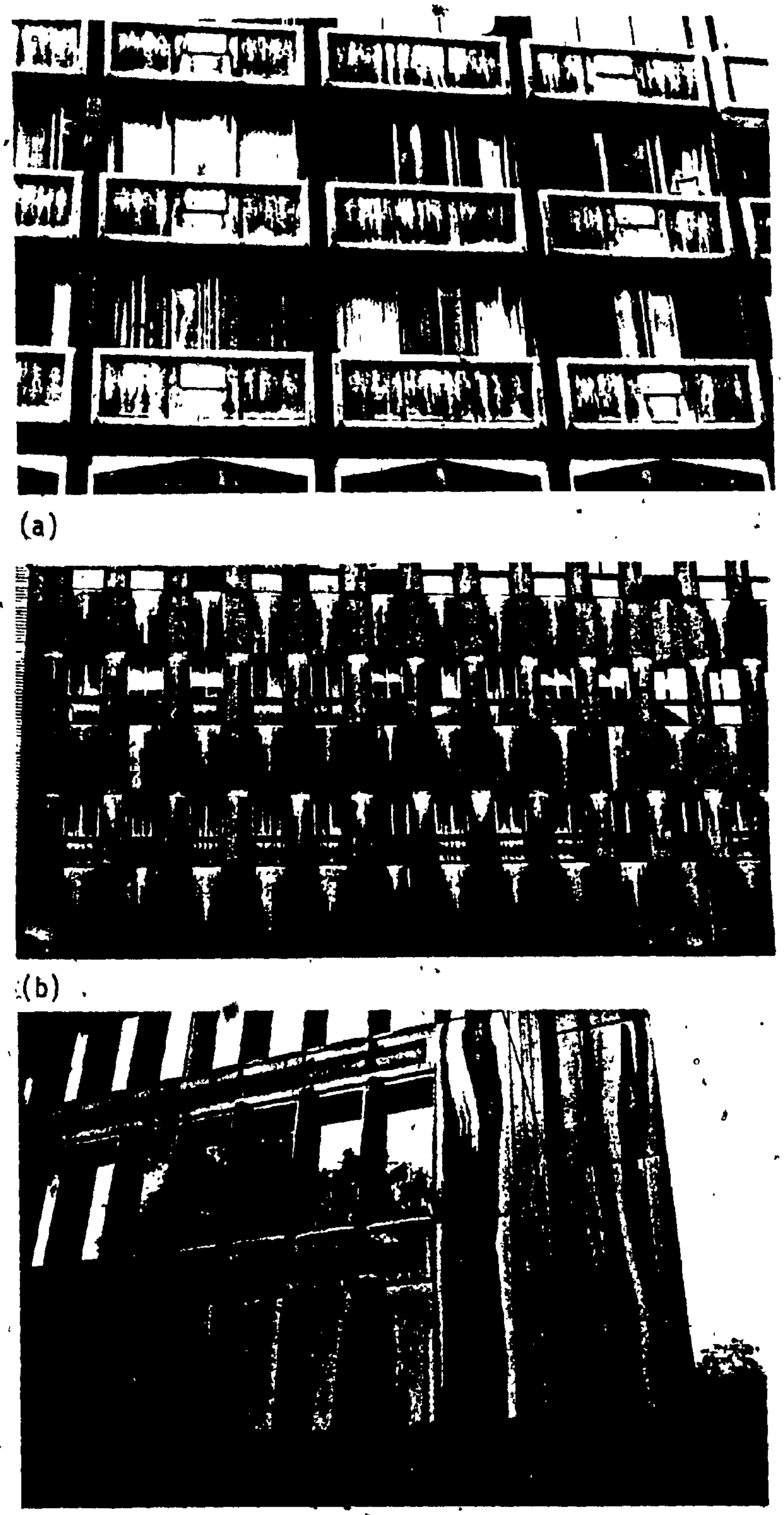


FIG. 3.46: Type 1.4.2, comparative examples of three window sills having different depths. The worst case occur with the deepest sill..

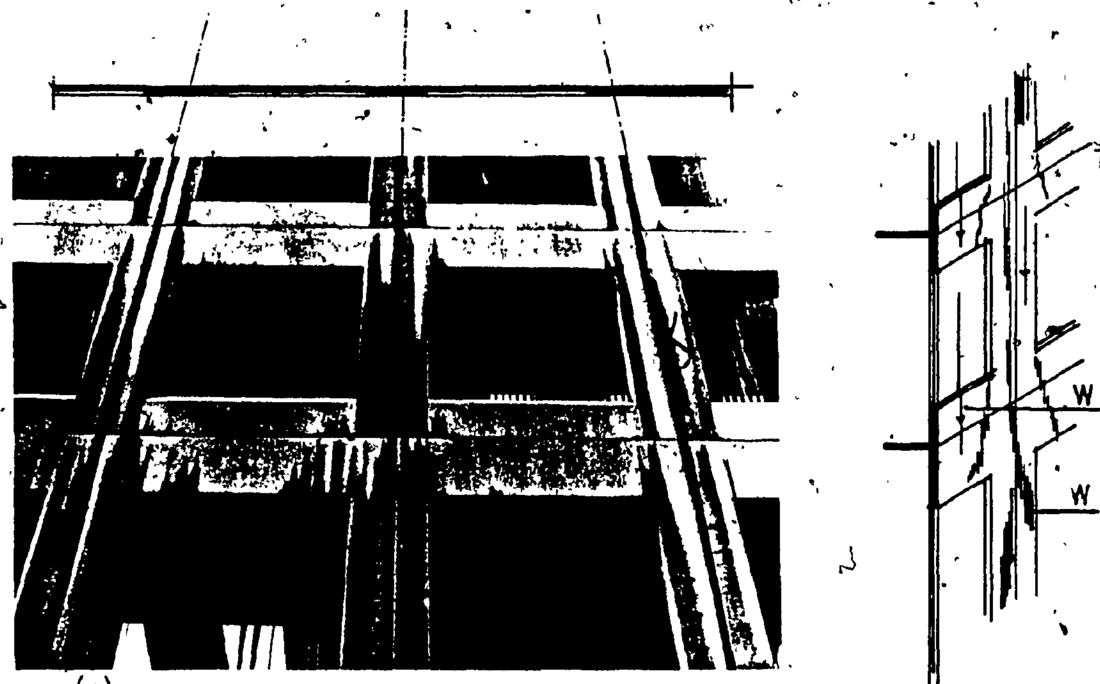


(a)

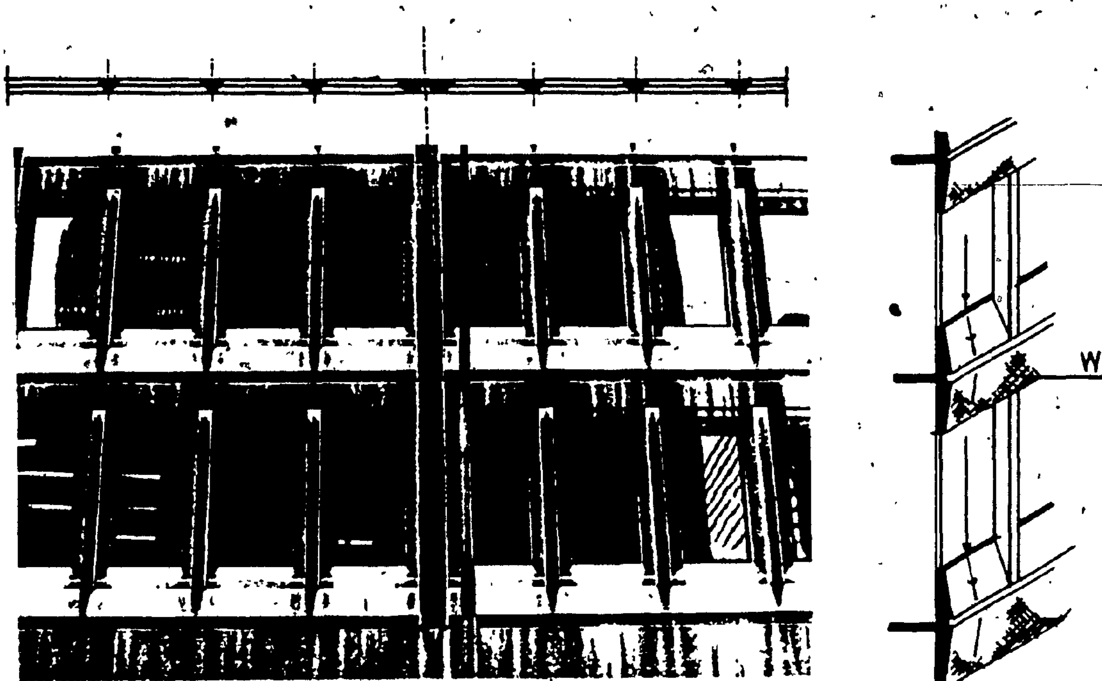
(b)

(c)

FIG. 3.47: Type 1.4.2, serious disfigurement echoed below window sills of all facade panels.



(a)



(b)

FIG. 3.48: Type 1.4.2, examples of vertical sectional profile that allow continuous water flow from one storey to the other below.

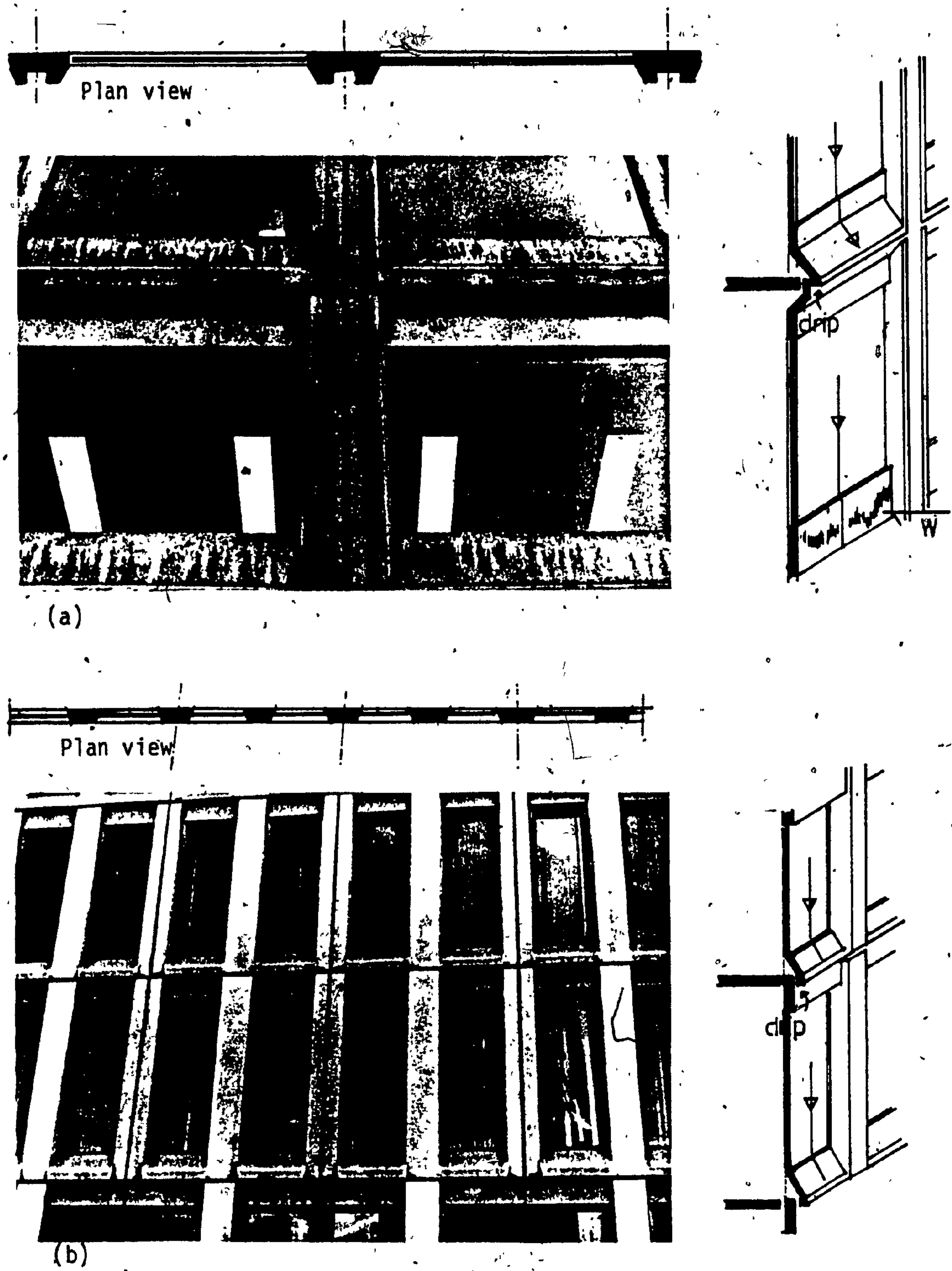


FIG. 3.49: Type 1.4.2, examples of vertical sectional profile that interrupt water flow from one storey to another.

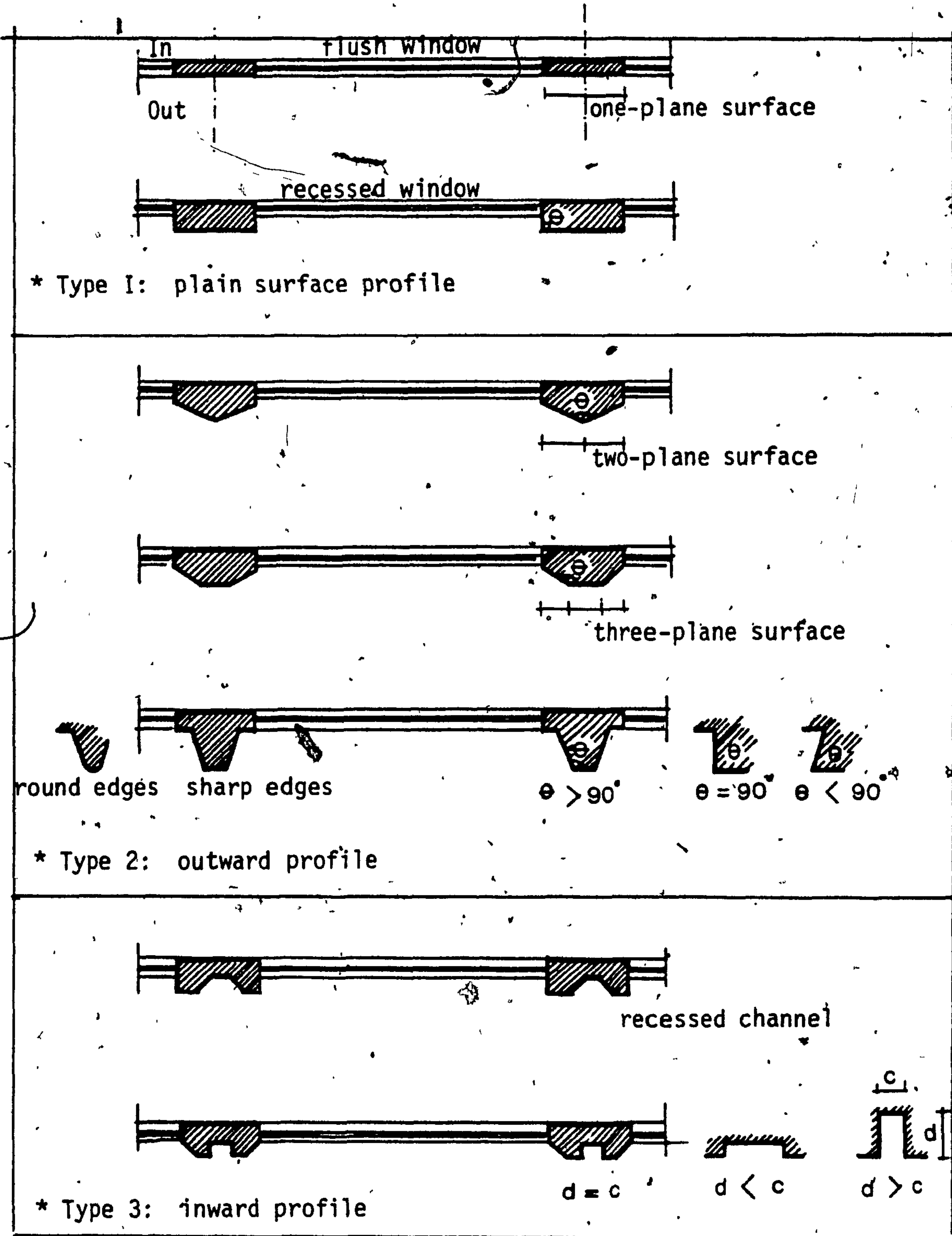


FIG. 3.50: A comparison of different horizontal sectional profiles of piers between flush and punched openings.

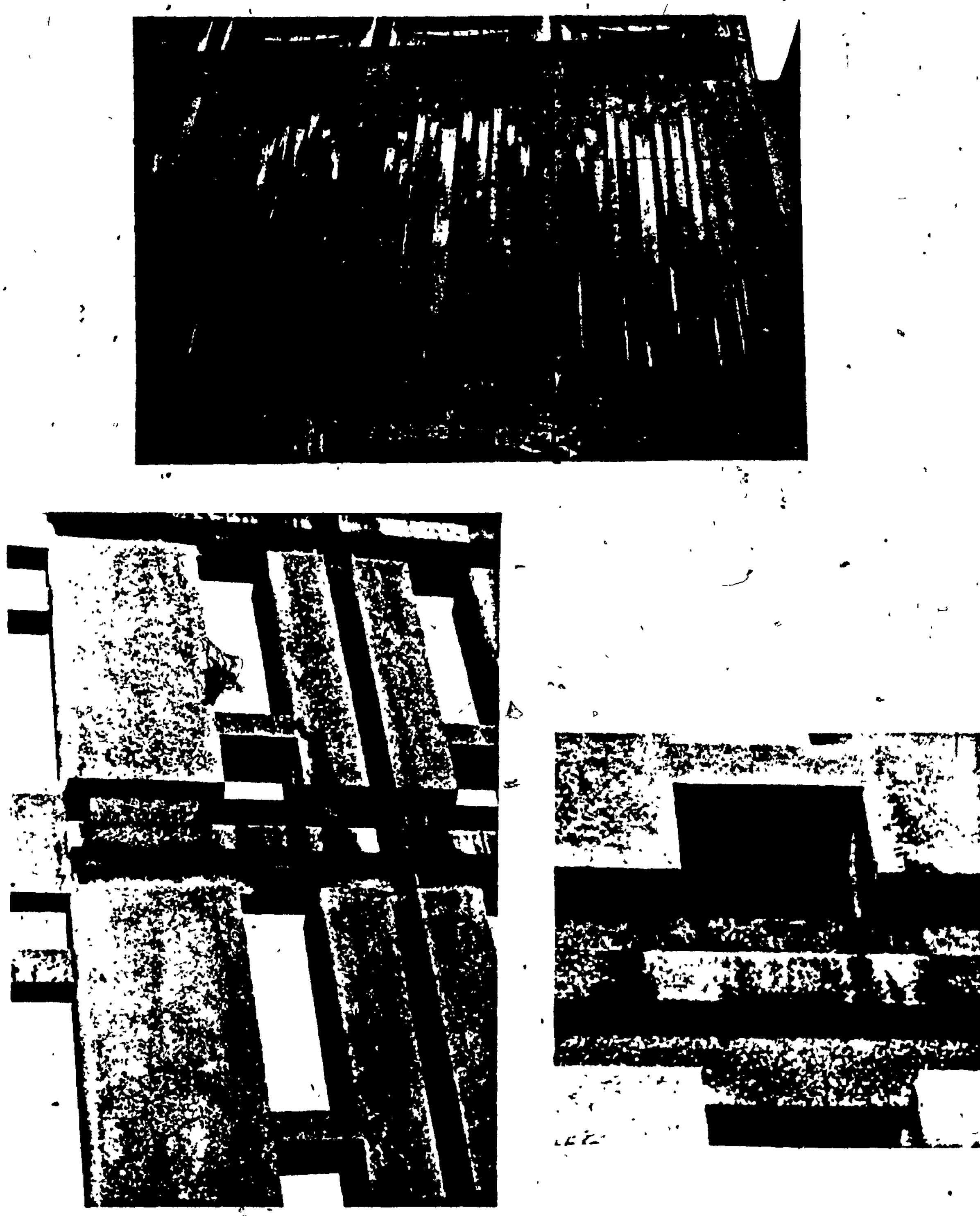
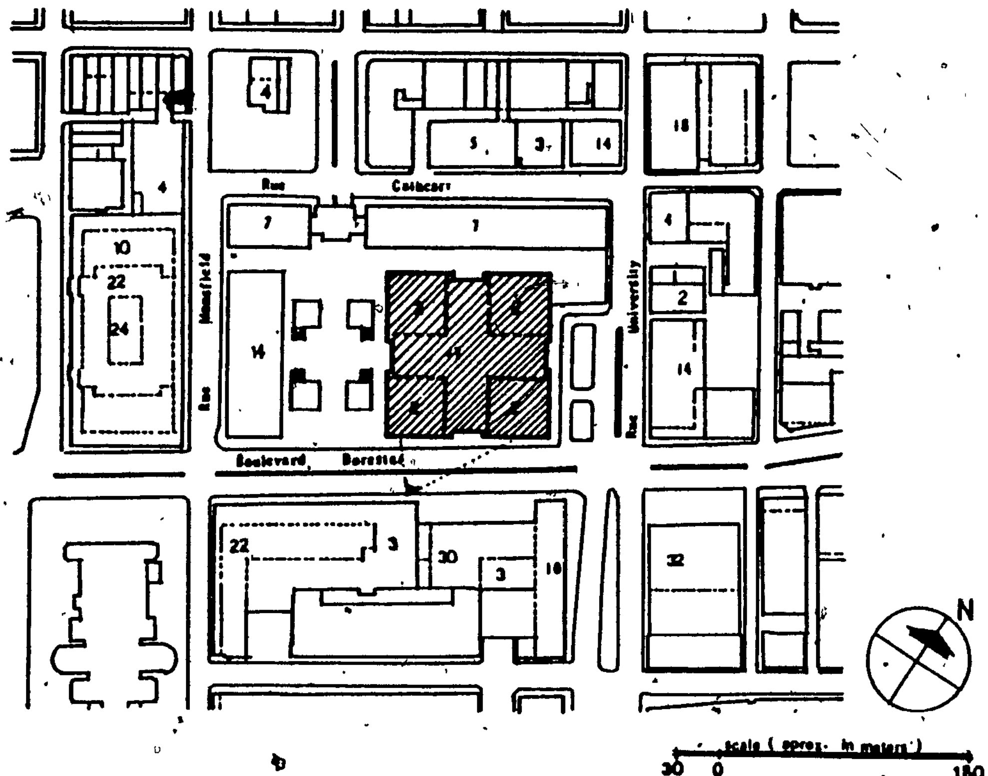


FIG. 3.51: Type II, two examples of the implications of increasing the panel sculptures on complicating the surface hydraulics and hence the resulting stain patterns.

Building name : Place Ville Marie
Age in years : 16
Facade material : Cut Sand-stone

o Residential
ø Commercial
o Others

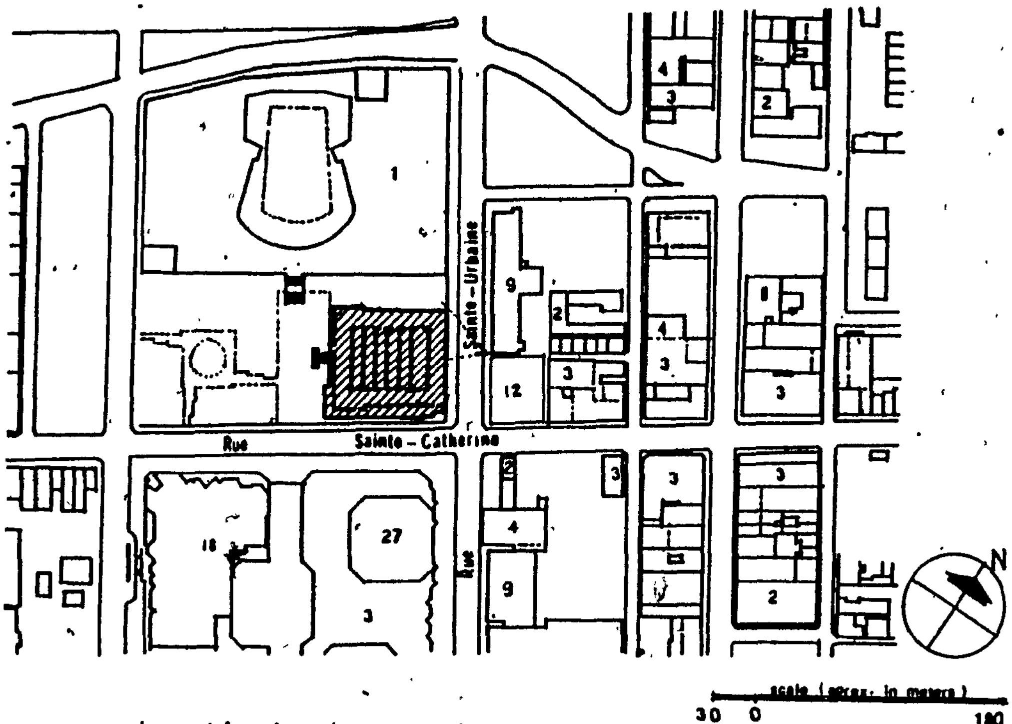


Location/nature of the surroundings

FIG. 3.52: Type III, an example of servere dirt accumulation over a plain facade surface due to partial washing induced by rainwater.

Building name : Place des Arts
Age in years : 16
Facade material : Precast concrete panels

- o Residential
- o Commercial
- ø Others



Location/nature of the surroundings.

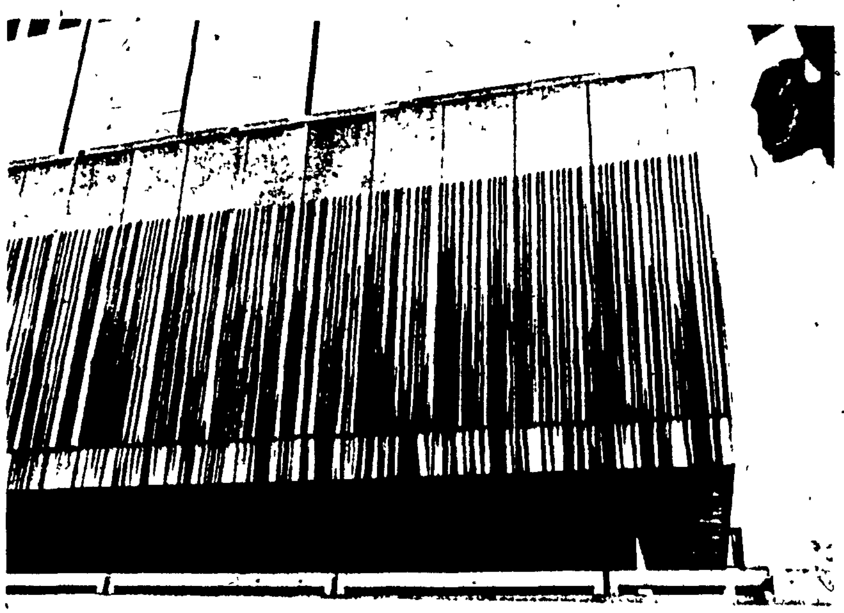


FIG. 3.53: Type III, weathering of a facade surface due to insufficient run-off that causes dirt redeposition and concentration at lower levels.

Building name : Complex Desjardins

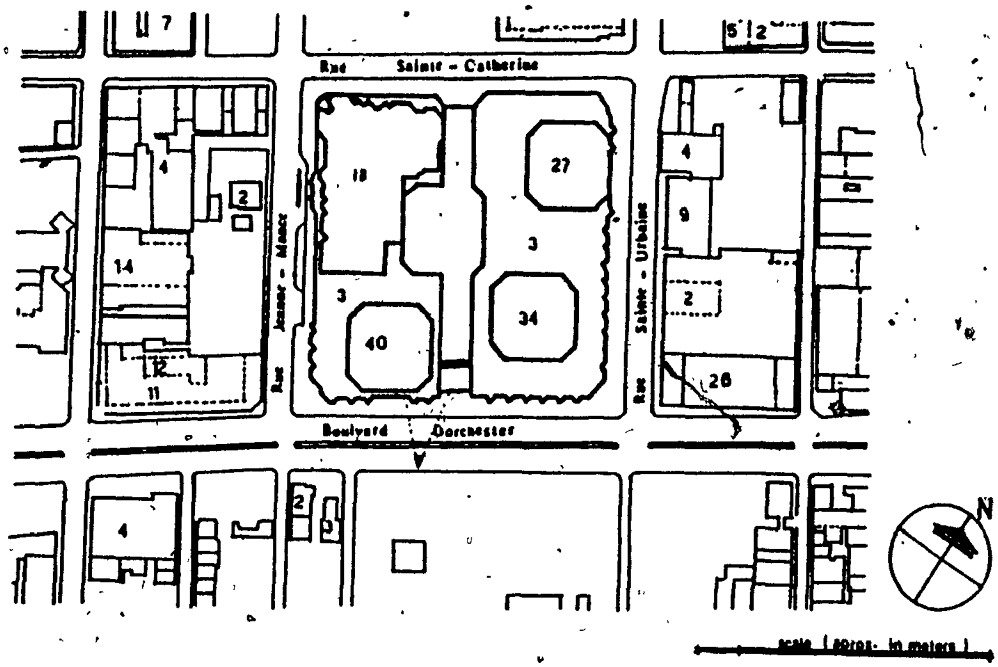
Age in years : 2

Facade material : Concrete bricks

o Residential

ø Commercial

o Others



Location/nature of the surroundings

FIG. 3.54: Type III, an example of weathering of a large plain surface because of the partial washing by rain.

CHAPTER IV

INVESTIGATION FOR A PRELIMINARY MODEL OF RAIN RUN-OFF OVER BUILDING FACADES

4.1 INTRODUCTION

Based on the discussions in Chapters II and III, it can be stated that the complexity of studying the 'surface hydraulics' and the rain run-off patterns over building facades is associated with the following principal factors:

1) driving rain;

2) material characteristics (particularly absorptivity);

3) geometry of facades.

In this chapter, the behaviour of rainwater over building facades having different material absorptivities is modeled. As a prerequisite exercise to assess the water behaviour over different geometric configurations, the present investigation will be concerned first with plain surfaces. In formulating the model, a facade of low-rise building, ie. 4-5 storey high, plane, and with no openings is used. Exposure to uniform driving rain field with varying rain intensities and wind speeds are considered. Assessing the complex run-off patterns over building surfaces is intended to aid researchers and designers towards a further understanding of the weathering problem of facades.

4.2 MODEL INVESTIGATIONS

4.2.1 ASSUMPTIONS

(1) the incident driving rain rate - ie., quantity per unit time, is assumed to be constant during the rain period.

(2) Wind is assumed to be steady, accordingly, the angle of the falling rain, θ, is considered constant. For different wind speeds, θ will have different values.

(3) The water drops in the rain field are considered to have the same diameter.

(4) The water drops hitting a wall surface will be either absorbed by the wall material, run-off its surface, or will be reflected away after the impact process. In this study, it is assumed that all reflected drops will re-enter the driving rain field and restrike the building facade. Accordingly, all driving rain quantities will be either absorbed or run-off down the wall.

(5) The facade materials considered are classified into three main categories:

			Absorption Coeff.
(a) Porous Material	- such as:	burnt brick	600 g/m^2 sec.$^{1/2}$
		lime mortar	250 g/m^2 sec.$^{1/2}$
(b) Semi Porous Material	- such as:	hard burnt brick	125 g/m^2 sec.$^{1/2}$
(c) Non-porous Materials	- such as:	glass and metals with almost zero absorptivity	

The above values, as reported by Beijer [5], were determined for dry materials. It was also noted that almost half those values are the practically applicable ones, since ambient humidity conditions reduce the absorptivity.

(6) Rate of absorption is assumed to follow a constant steady decrease with time until it reaches the value 'zero'. At this time full saturation of the material occurs, and hence, run-off starts. To compare the absorbed and run-off quantities for different materials, the time of zero absorption rate is assumed to be constant for the

materials considered in this investigation.

(7) The materials considered are assumed to have the same surface texture and are subjected to the same atmospheric conditions, eg., temperature and humidity.

4.2.2 DETERMINATION OF DRIVING-RAIN QUANTITIES

Estimating the quantity of driving-rain, I, impinging on a building facade is a prerequisite step in determining the quantity of rain run-off, RO, over the facade surface.

One way of calculating the quantity I is to use the driving-rain index* for the annual mean rainfall and wind-speed using 'open country' wind speed. The index also indicates the relative severity of conditions in different regions of the same country. To obtain accurate values applicable to a particular site, correction factors should be applied to allow for topography and for local terrain roughness. Though this concept has proved to be useful in countries such as England**, it is not recommended for use in a more continental climate (eg. Canada, U.S.A.) [16]. The reason is attributed to the greater proportion of driving-rain that occurs in intense storms (recall Tables 3.1 and 3.2); the mean *annual* index will be seriously underestimated. Achieving more accurate predictions of driving-rain quantities should then be based on *monthly* or *daily* data.

In another method, introduced by Lacy [17], the rate of driving rain striking a vertical surface can be determined for different rain intensities (measured on the horizontal surface) and the accompany-

* The driving-rain index is the product of the annual rainfall multiplied by the mean wind speed [25].

** Field measurements of driving-rain with gages set in the faces of buildings suggested that the produce of rainfall and mean wind speed could be used as an indication of the amount of rain which would be driven to a wall [17].

ing wind speeds in accordance with the following formula:

$$r_v = 0.222\ u.r_h^{0.88} \tag{4.1}$$

where r_v is the rate of driving rain on a vertical surface in litres/meter^{2}hr.

r_h is the depth of rain accumulated on a horizontal surface mm/hr as recorded in the weather data for any given site.

u is the mean wind speed during the rain m/s (wind is normal to the facade surface).

A plot of r_v versus r_h for different wind speeds is reproduced in Fig. 4.1.

Based on the analysis of climatic data of Montreal, presented in Fig. 3.6, r_h is equal to 0.2 inch/hr (5.0 mm/hr) and u is generally less than 8 m.p.h. - ie., less than 3.55 m/s - recall Table 3.3. It should be noted that, for the purpose of this investigation, and to cover a wider range of possible weather combinations, u will be considered between 2.5 and 5 m/s. In general, increasing the rain quantities or wind speed will result in more driving rain and wetting of facades, thus, in more washing action. Accordingly, emphasis should always be given to the potential consequences of a facade exposure to small amounts of driving rain that, in most cases, result in partial washing.

Based on the values determined above, the equivalent driving rain quantities extracted from Fig. 4.1 will lie in the vicinity of:

2 L/m^2 hr. for a winds speed of 2.5 m/s

4.5 L/m^2 hr. for a wind speed of 5 m/s

therefore, 1-5 L/m^2 hr. (0.2 - 1.4 gram/m^2 sec.) is the range of driving rain quantities to which the typical vertical wall under consideration will be subjected to. It should be emphasized that these values cannot be generalized for the Montreal area, and the appropriate estimates will still be strongly dependent on the locality of each site condition. However, for the comparison of the performance of different materials (concrete, stone and bricks), the above values (0.2 - 1.4 gram/m^2.sec.) are used.

4.2.3. PROCEDURE OF CALCULATING RUN-OFF QUANTITIES

As previously explained, when a porous material wall is subjected to driving rain, it will first absorb some quantities of water at a certain rate until saturation of the material occurs. All unabsorbed quantities will then run-off the surface in downward streams. To calculate this run-off quantity, the maximum absorbed water should first be determined for the unit area of the wall surface. According to an impirical formula developed by Beijer [5], the absorbed quantity G is a function of both the material absorptivity and time, and can be determined as:

$$G = C\sqrt{t} \qquad (4.2)$$

where C is the absorption coefficient of the material gram/m^2.sec.$^{1/2}$,

t is the time in seconds.

It can be noted from the above formula that the quantity G increases exponentially with time - as illustrated in Fig. 4.2 (exemplified for concrete), and its peak value upon material saturation cannot be determined. Accordingly, the rate of absorption $\frac{dG}{dt} = \frac{C}{2\sqrt{t}}$, never reached zero.

In order to determine the time at which zero absorption rate occurs (ie., upon material saturation), simulating a more realistic behaviour of the material, recall assumption (6) that can be presented mathematically by the equation

$$\frac{dG}{dt} = -at + b \qquad (4.3)$$

in which $\frac{dG}{dt}$ is the rate of absorption gram/m^2.sec.

t is the time in seconds

a,b are constants related to the material absorptivity C.

By integrating equation (4.3) with respect to time t, the absorbed quantity G at any given time up to saturation is then given as:

$$G = -\frac{a}{2} t^2 + bt \qquad (4.4)$$

The values of both constants a, b as functions of the material absorption coefficient C can be obtained by applying the least square method to minimize the difference between the curve of the empirical formula (4.2) and the one proposed in equation (4.4). This linear relation is found to be in the form

$$a = \alpha C \qquad (4.5)$$

$$b = \beta C \qquad (4.6)$$

A detailed derivation of the values a, b, α, β, can be found in Appendix II. The parameter α is found to have a value of 0.0188 sec$^{3/2}$, and β a value of 0.4157 sec$^{1/2}$. Equations (4.3) and (4.4) can then be rewritten as:

$$\frac{dG}{dt} = -0.0188\ ct + 0.4157\ C \qquad (4.3)$$

$$G = -0.0094\ ct^2 + 0.4157\ ct \qquad (4.4)$$

Having determined G, the run-off quantity RO at any driving rain intensity I(gram/m^2.sec.) and time (sec.) can then be determined as:

$$RO = It - G_{max} \qquad (4.7)$$

where G_{max} is the maximum absorbed quantity determined from equation (4.4) by satisfying the condition $\frac{dG}{dt} = 0$ in equation (4.3).

4.3 APPLICATION ON FACADE SURFACES WITH DIFFERENT ABSORPTION RATES

The behaviour of rain water over three surfaces, ie., concrete, stone and brick, having C values equal 10, 50, 300 gram/$m^2 s^{1/2}$, respectively, has been studied. For a concrete wall subjected to different driving rain intensities varying from 0.2 to 1.4 gram/m^2sec., the resulting behaviour of rain water over the surface is presented graphically in Fig. 4.3. In this figure, the absorption rate of wall material until saturation is illustrated by a curve representing Eq. (4.4). At the point of maximum absorbed quantity (G max.) a horizontal line is drawn to represent the ultimate potential absorption after which run-off will practically start. The driving rain rate I is illustrated by the radiant lines emanating from zero and steadily increasing with time. The intersection of these lines with the ultimate absorption line of the material identifies the time t_{RO} at which run-off starts. As illustrated in Fig. 4.3, t_{RO} for concrete lies between 0.54 and 3.83 minutes of the driving rain intensity varies from 0.2 - 1.4 gram/m^2 sec.

Once the maximum absorbed quantity G max and the time of run-off start t_{RO} are determined, the run-off quantity RO over the surface unit area after any time t_n can be graphically determined. For example, if the driving rain intensity is 0.6 gram/m^2 sec. the time t_{RO} will equal 1.27 minutes. As shown in Fig. 4.3, the run-off quantity after 2 minutes, from the rain start, will have the value 26 grams. The RO quantity can also be calculated using equation (4.7).

Comparisons between RO, I and Gmax. for the three materials under consideration during an hour of exposure to varying rain is illustrated in Fig. 4.4. It can be noted that t_{RO} for stone lies between 2.1 and 19.1 minutes for I varying from 1.4 - 0.2 gram/m^2.sec. For bricks, the value of t_{RO} lies between 16.3 and 114.6 minutes. Accordingly, run-off quantities at certain time t_n differ substantially from a material to another. For example, if the driving rain intensity is 10. gram/m^2sec., the run-off quantity after 30 minutes will be 1754, 1750 and 425 grams for concrete, stone and bricks, respectively.

4.4 DESIGN IMPLICATIONS

The above comparison has a direct implication on the selection of building materials exposed to different site conditions. In the downtown area where facade surfaces near the ground level do not receive enough wetting because of the surrounding buildings, using materials with comparatively high absorptivity will increase the risk of partial washing. The problem is further aggravated with large plain surfaces since run-off water can not perform a complete washing action (recall figures 3.52 ~~to~~ 3.54). Weathering is generally less evident on smaller plain surfaces particularly when their absorptivity is minimized to allow greater run-off quantities.

In essence, the panel material and its surface characteristics are important factors that can aggravate or minimize weathering problems of building facades. The foregoing investigation to estimate run-off quantities over the surfaces of different materials is a preliminary exercise in an area where considerable need exists.

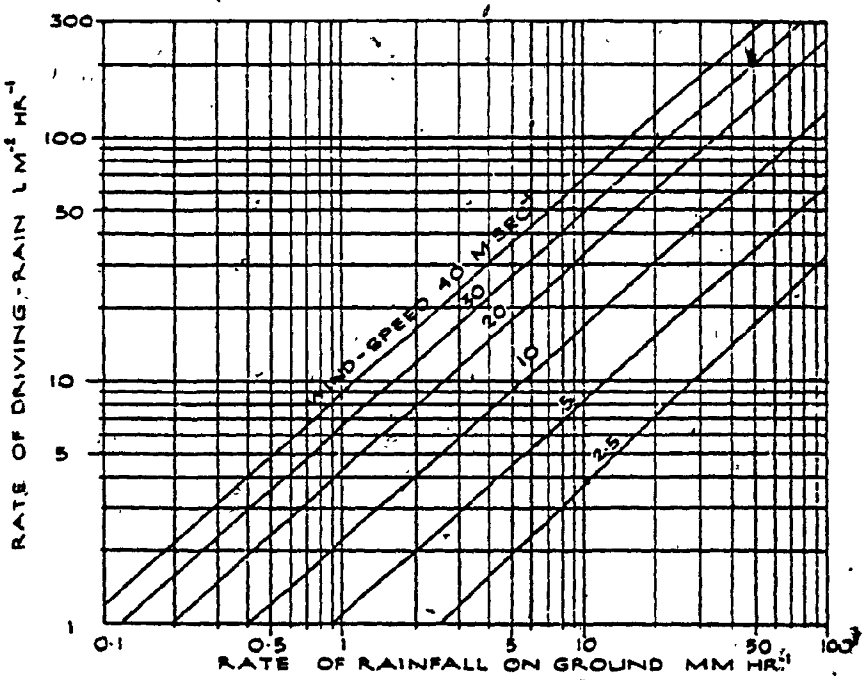


FIG. 4.1: The relation between rate of rainfall, wind-speed and computed rate of driving rain. (After Lacy [17]).

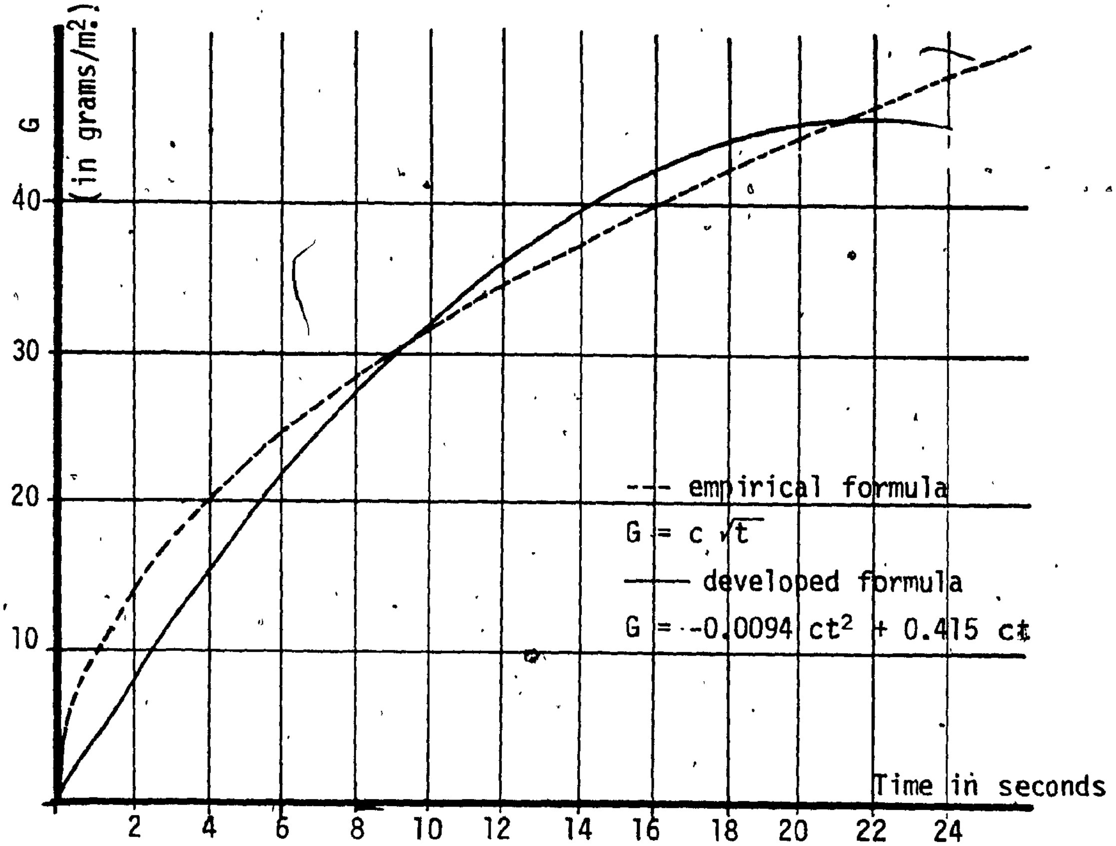


FIG. 4.2: Quantities of water absorbed (G) by a concrete surface having absorbed coefficient C = 10 grams/m^2.$sec.^{1/2}$

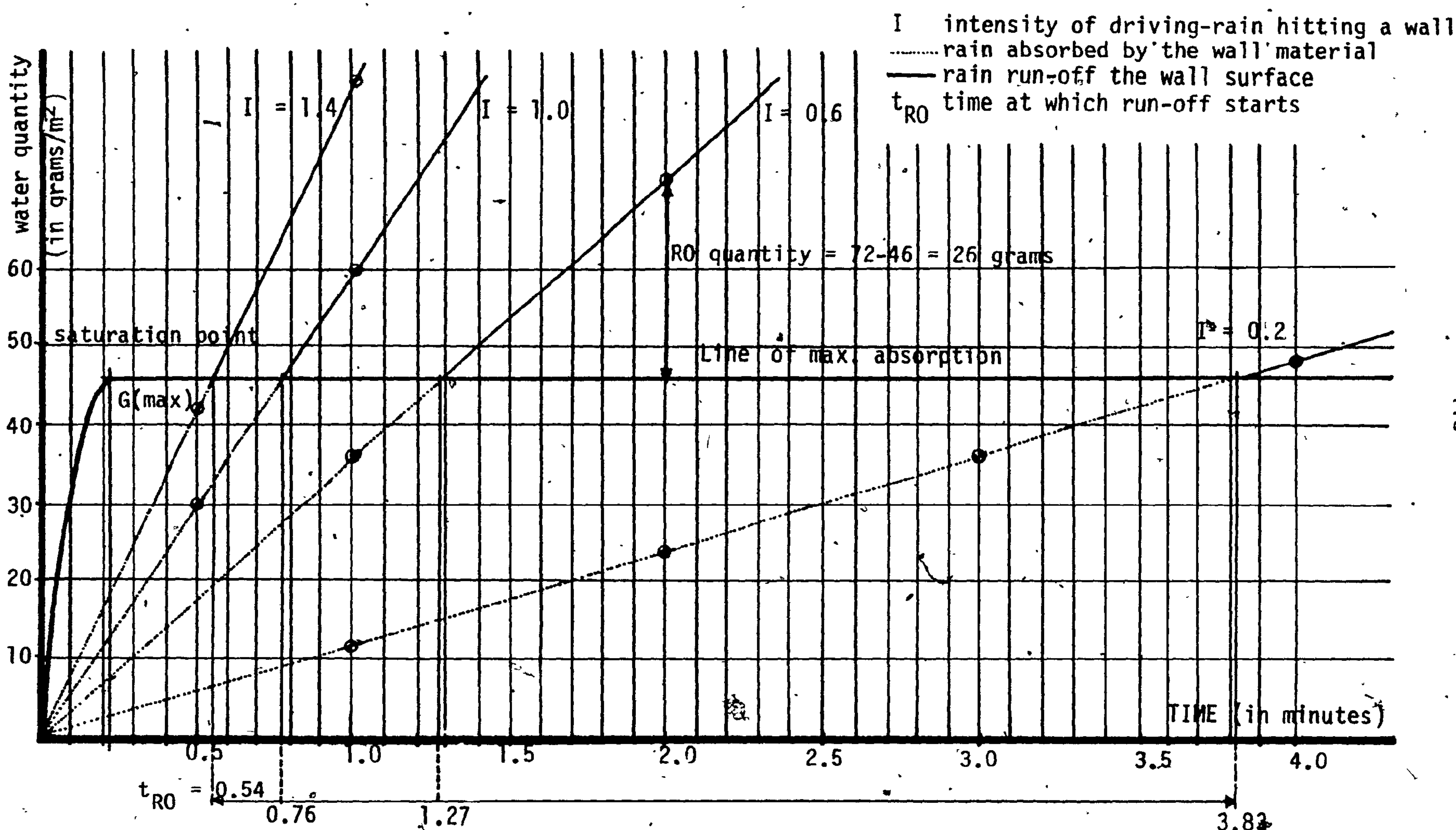


FIG. 4.3: Absorption/run-off curve for a concrete wall having C = 10.

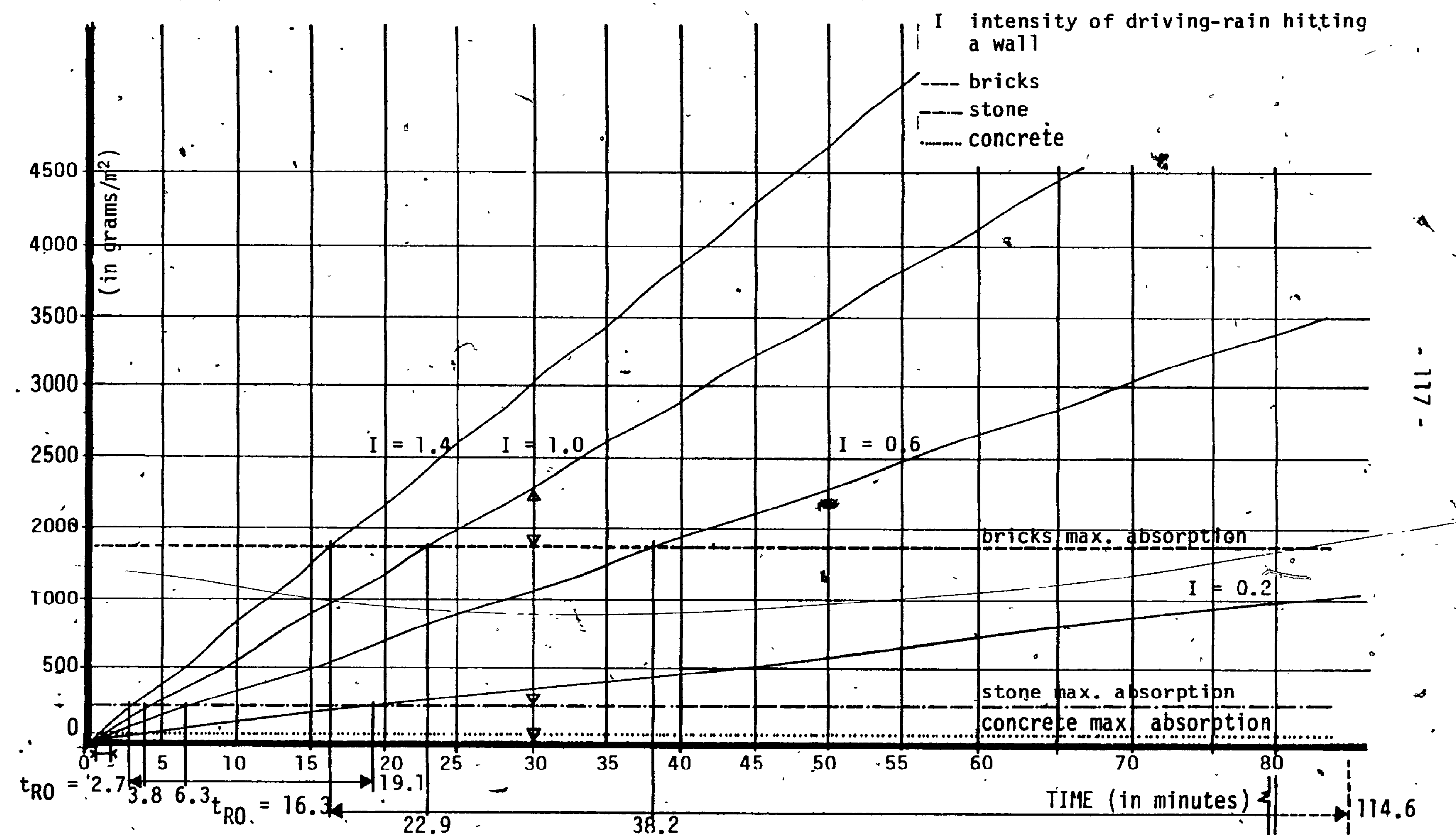


FIG. 4.4: Comparison of run-off time t_{RO} for bricks, stone and concrete when subjected to different rain intensities.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Through the foregoing study, it has been shown that assessing weathering problems of building facades involves complex interrelated factors pertaining to:

(i) Variety of exposure conditions to weather factors (ie., pollution, driving rain).

(ii) Different geometrical configuration of facade surfaces.

(iii) Materials' properties and surface characteristics.

Preceeding chapters in dealing with these factors have found the following conclusions:

5.1 ON THE MACRO-CLIMATE SCALE

(5.1.1) In Montreal and in most other large cities, building facades are subjected to driving-rain on all sides to various degrees at different times. The resulting wetting patterns superimposed on each other determine the final washed and unwashed pattern. Regardless of facade orientation, generally the top and side edges of facades are more subjected to wetting and hence are clearer than the remaining surfaces. The observed case studies have indicated that the overall staining pattern is usually a bell-shaped form (recall figures 3.14 to 3.20). The contrast between washed and stained surfaces is further aggravated if:

- The facade is more frequently exposed to direct driving-rain (recall figure 3.14).
- The surrounding buildings influence the periodic driving-rain to be limited to the upper storeys (recall figures

3.22 and 3.23).

- The wall material is more susceptible to retain dirt particles over its surface pores (recall figures 3.19 and 3.21).
- The local environment is highly polluted as the case with most sites in the downtown area.

ACCORDINGLY, IT IS RECOMMENDED TO:

1. Utilize the driving-rain rose to help estimate the potential exposure of each building facade to wetting*.
2. Account for the local climatic influences by using the wind-tunnel tests to assess the effect of wind-induced pressure and suction gradient on the accompanied rain field. This can help anticipate, at least to a certain extent, the areas of increased wetting compared to regions of minimum exposure to rain.
3. Use materials with minimum surface porosity to reduce the potential resulting weathering.
4. Assess the available records of atmospheric pollution levels in the locality, as well as, evaluate the performance of nearby buildings and the extent of weathering of their facade surfaces.

5.2 ON THE MICRO-CLIMATE SCALE

(5.2.1) The vertically projecting masses cause protection of the inside corners from driving rain at any angle other than the one perpendicular to the wall. Weathering is expected at these locations particularly near the street level. The width of the stained area is

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* For Montreal, the wind-driven rain rose developed during the course of this work (recall figure 3.12) has showed that there is not particular direction dominates and the building facades are almost subjected to the same frequent driving-rain.

approximately half the extent of projection (recall figure 3.25).

IT IS THEREFORE RECOMMENDED:

1. Minimize the extent of projection to reduce the width of the potential staining to acceptable limits.
2. Allow continuous downward flow of rainwater near the inside corners by channels.
3. Use materials with minimum surface porosity to maximize the run-off at locations likely to be stained (see page 107 for comparative porosities). Higher porosity materials with inherent dirt masking characteristics - eg., bricks - can also be used.

(5.2.2) The vertical projections such as ribs, louvers, mullions, etc. direct rainwater in downward streams increasing washing action at the inside corners. In contrast, deposits remain over the exterior flat and side surfaces of these projecting elements. If the concentrated downward flow is allowed to move over the wall surface under projections, more differential staining is expected. (recall figure 3.27)

IT IS THEREFORE RECOMMENDED TO:

1. Minimize the vertical and side surfaces of the projecting elements where deposition of dirt particles are inevitable.
2. Assure smooth finishes to allow for more continuous flow of water over such surfaces and hence increase the washing action.
3. Avoid the irregular flow over the wall surface under projections.

(5.2.3) The horizontally projecting masses give shelter from driving-rain to the surfaces below. Differential weathering is expected between the protected zones (ie., less or never washed) and the other nearby surfaces (ie., regularly washed) (recall figure 3.28).

Horizontal projections such as belt courses, spandrels, balconies, etc. allow increased quantities of dirt and pollution deposits. They are also likely to receive the greater rain quantities for all angles of rainfall varying from 0° to 45° to the vertical. When the flow of rainwater from such projections is not controlled, weathering of the wall surfaces is expected (recall figures 3.29 and 3.30). Furthermore, omission of drips in soffits of projections allow excess wetting that leads not only to weathering but also to deterioration of the soffit material (recall figures 3.31 and 3.32).

IT IS THEREFORE RECOMMENDED TO:

1. Select materials used in surfaces below projecting masses that allow minimum dirt deposition or at least mask it.
2. Provide positive channels for water movement across horizontal elements.
3. Provide continuous and positive drips in soffits of projections with minimum cross sectional dimensions 2 x 2 cm.

(5.2.4) Wall elements having vertical and horizontal projections (classified under projecting frame, type I.3) allow localized weathering patterns between and under projections as well as on the surfaces of the projecting frame itself (recall figures 3.33 to 3.37). Further staining of soffits and window glass panels takes place when drips are omitted (recall figures 3.40 and 3.41).

IT IS THEREFORE RECOMMENDED TO:

1. Minimize the thickness 't' of the projecting frame to reduce the potential dirt deposition on the exterior flat surface of the frames.
2. Design the horizontal and vertical spacing (ie., x, y) between frames in dimensions less or equal to the frame projection (v) to

minimize the surfaces likely to display stains.

3. Avoid horizontal sideway movement of rainwater between frames and assure continuous vertical flow in guided channels (see figure 5.1).
4. Minimize the length of the spandrels (z) and prevent run-off over their surfaces.
5. Incorporate drips in soffits of projections to eliminate the potential soffits and glass staining. Assure continuity of drips from horizontal to vertical surfaces (see figure 5.1).

(5.2.5) Wall elements without projections (classified under flush and punched openings, type I.4) are characterized by the lack of adequate control of rainwater under window sills that in many cases has extended from one storey to another below (recall figures 3.43 to 3.48). The irregular flow of water also causes streaking of the pier surfaces between openings.

IT IS THEREFORE RECOMMENDED TO:

1. Minimize the horizontal surface of the window sill to assure less deposition of pollutants and minimum rainwater to be received.
2. Attempt to control run-off water from windows whether to collect it then discharge it through designed scuppers or direct it sideways and drain it vertically as illustrated in figure 5.2.
3. Prevent run-off water from window sills of one storey to the wall surfaces of the storey below. This can be achieved by properly sloping the sill surface to overhang the wall below. Drip must be provided to assure discontinuity of flow at each floor (see figure 5.2).
4. Design window heads to minimize the irregular water flow down glass

surfaces and hence, avoid the potential resulting staining. This can be achieved by incorporating drip or providing a small projecting lip (see figure 5.2).

5. Design splays and piers profiles to guide water continuously in grooved paths or channels so that any potential weathering is masked into the recessed surfaces of the channels.

(5.2.6) Wall elements with heavy sculptures are highly susceptible to weathering because of their multi-planed surfaces that have different compositions of projections and recesses (recall figure 3.51).

IT IS THEREFORE RECOMMENDED TO:

1. Minimize using such panels in all but the cleanest of micro-climates.

(5.2.7) Plain surfaces of one or two storey height designed near the street level are also susceptible to weathering. The main reason is attributed to the movement of rainwater that cannot perform a complete washing action of the deposited pollutants over such surfaces. Increasing the area of plain wall in any facade, unless the surrounding buildings allow enough exposure to driving-rain, increases the chance for a potential partial washing. Weathering can also be enhanced if the wall material allows great quantities of atmospheric pollutants to deposit and adhere to the surface (recall figures 3.52 and 3.54).

IT IS THEREFORE RECOMMENDED TO:

1. Avoid large plain surfaces designed in the facade near the street level, particularly when high pollution levels are expected and when the facade is surrounded by taller buildings that are expected to reduce its regular wetting by driving-rain.

2. Avoid using porous materials that are highly susceptible to retain

and show pollution deposits over their surfaces. Correlate the properties of the selected material to be used with the ambient conditions in the locality in order to avoid any undesirable chemical interactions (see Appendix I).

(5.2.8) In general, textured surfaces allow more pollution accumulation. If rainwater is allowed to move freely over their surface contours, redeposition and concentration of dirt particles would be expected (recall figures 3.43, 3.46, 3.51, 3.52 and 3.54). Textured concrete surfaces with smooth exposed aggregates have better weathering characteristics particularly when the area of the background matrix is minimized. The smooth surface aggregates allow minimum dirt deposits and develop more run-off that increases the potential washing action. At the same time, the slightly recessed matrix help absorbing and masking the pollution deposition. Textured exposed aggregates, on the contrary, are more likely to alter their original appearance.

Smooth surfaces have generally less porosity and hence develop more rain run-off (recall section 4.3). Though they allow less pollution deposits, they are still susceptible to streaks by rain movement (recall figures 3.37 and 3.45 example B, 3.47 example C and 3.48).

Colour of the surface finishes, too, has a relation with weathering of facades. White or light toned surfaces are practically more likely to weather than darker colours (recall figures 3.36, 3.37, 3.41, 3.45 example B, and 3.47 example C).

IT IS THEREFORE RECOMMENDED TO:

1. Choose the aggregates of textured concrete panels with smooth surfaces, and specify minimum area of the cement/sand matrix.

2. Minimize using white or light toned surfaces except in clean environments.

5.3 RECOMMENDATIONS FOR FURTHER RESEARCH

On the basis of the present work, it is suggested that a number of problems should be further investigated. Each is formulated below in general terms:

(i) More systematic correlation between the weather facades (such as pollution, rain and wind) and the materials' properties (eg., absorptivity, surface texture and colour, solubility) still needs to be studied and presented in a practical format for designers to utilize. For example, studying the susceptibility of commonly used materials - having different porosities - to dirt accumulation in a variety of polluted atmospheres (consulting reference [6] is recommended). Moreover, assessing the ability of different combinations of rain and wind to cause erosion of the surface for these materials and to perform a certain washing action. The limits of the induced washing action and their relation with run-off quantities and the water film thickness develops and moves over the facade material is not a systematically explored area as yet.

(ii) Further utilization of the wind-tunnel tests now being done for many buildings at the planning/design stages, can be directed to predicting the influence of wind when it accompanies a rain field. The differential pressure/suction induced on a facade cladding has proved to have a relation with the wetting patterns induced in certain locations (recall sections 2.3.2 and 2.3.3). It is believed that more informed evaluation can be attained through a continuous correlation between assumptions of differential wetting of facades (established during wind-tunnel tests) and the actual weathering behaviour after a few years of exposure to wind-driven rain.

(iii) In assessing the performance of in-use buildings, a need for test-and-measuring techniques has been existed [19]. Therefore, developing methods of evaluating the degree of disfigurement of facade surfaces because of dirt accumulation is recommended for further investigations. Generally, evaluation of weathering problems - particularly appearance changes due to pollution deposits - is still being done on subjective basis. Only recently (1973), the American Society for Testing and Materials (ASTM) has reported a tentative method (D3274-73T) for evaluating the degree of disfigurement of paint films due to both fungal growth and dirt accumulation. The method provides a numerical basis for rating different degrees of disfigurement on a simple scale from 0 - 8. With photographic reference standards - using 100x magnification of observed specimens - the maximum and minimum disfigurement were assigned the values of 0 and 8 respectively, assuming no totally clean surface that could have been assigned 10.

Further investigations in this area is desirable in order to establish more practical scales of measurement of the performance of building facades.

(iv) Assessing the advantages and disadvantages of using surface coatings and other types of clear and thin finishes present another area where further investigations are required. Surface coatings can generally improve the weathering characteristics of all types of building facades and can substantially minimize the inevitable changes in the appearance of their surfaces. Coatings also facilitate the regular cleaning of surfaces and reduce maintenance cost. On the other hand, surface coatings cause moisture trapping inside the material and in some cases bring about discoloration of the wall surfaces.

The performance of the available types of coatings when applied to different materials and the possible improvements of their qualities still warrant more integrated field studies and laboratory tests.

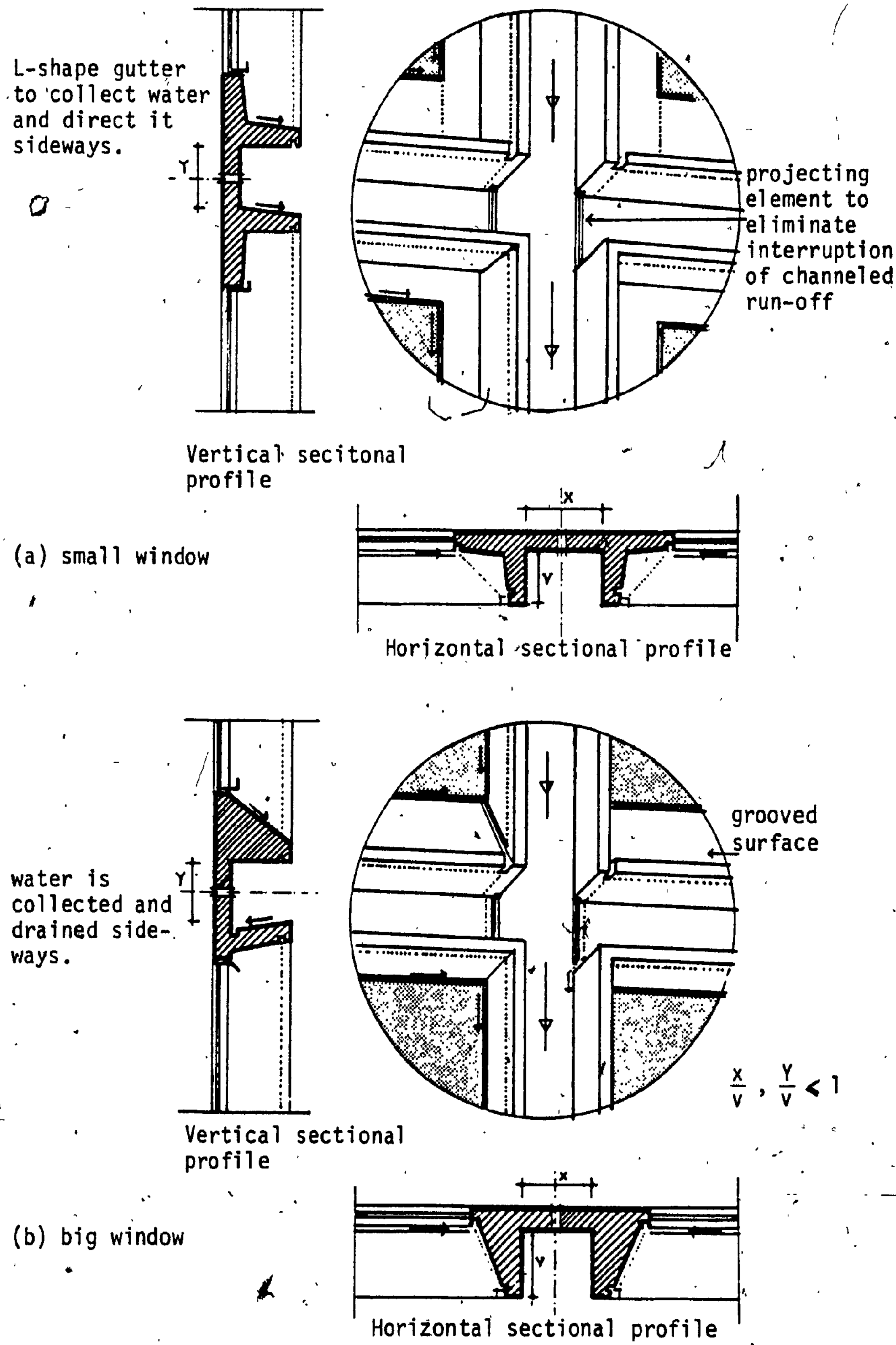

FIG. 5.1: Typical recommended profiles for type 1.3.

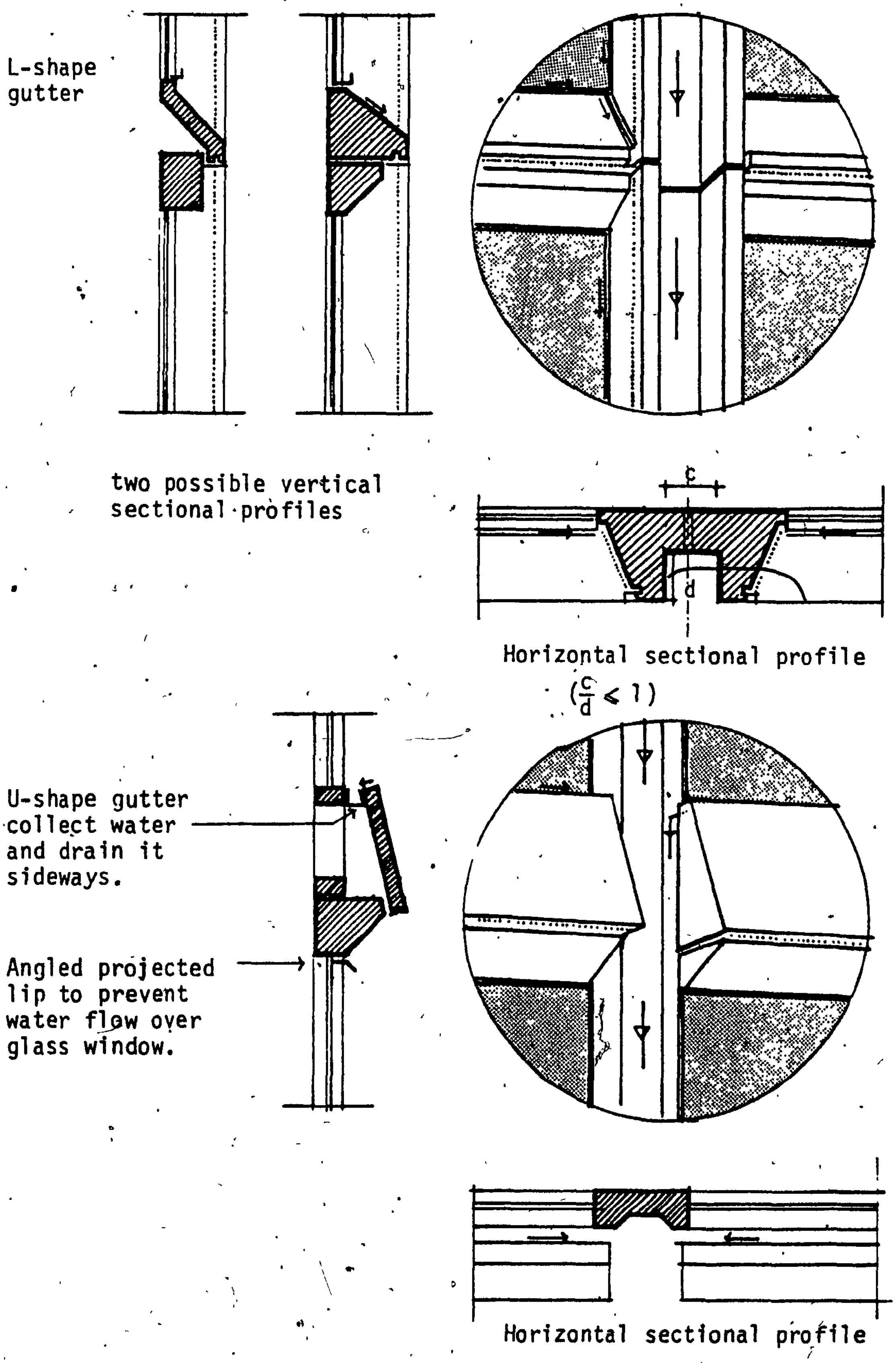

FIG. 5.2: Typical recommended profiles for type 1.4.

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APPENDIX I

DETERIORATION OF FACADE ATTRIBUTED TO CARBONATION AND SULPHER ATTACK

Many building materials react with their ambient environments. Some materials are unstable when exposed to damp or humid atmospheric conditions; lime - calcium oxide CaO - commonly used in plasters, mortars, clay bricks and concrete work is an example of this category of materials. Lime is alkali and is soluble in water especially if it contains acid forming gasses such as carbon dioxide CO_2 and sulpher dioxide SO_2. When lime reacts with this acidic water, a salt product such as calcium carbonate CA CO_3 or calcium sulphate Ca SO_4 is formed. These products have a tendency to adhere to any solid surface thus forming a layer of foreign deposit which will have very much different characteristics as compared to the underlying material. The amount of the deposited salts - Ca CO_3 or Ca SO_4 - can be substantially increased if other contributing sources such as pollutants from chimneys, street traffic, etc. are also present. This is due to the fact that dirt and soot also have the tendency to settle down on the surface of solids. The deposition of their particles is likely to alter the surface characteristics and the chemical salts because of their inert nature.

The degree of the resulting damage or deterioration of the surface material is dependant upon the frequency of periodic cleaning and washing by rainwater. If the solid surface is continuously washed, it would be kept clean and free from any accumulated deposition of foreign materials. On the contrary, sheltered areas that are less subjected to rainwater will usually display unwashed surfaces.

The chemical reactions discussed above can be grouped into two general areas, namely carbonation and sulphate attack.

1. CARBONATION:

The chemical combination between carbon dioxide CO_2 and hydrated lime $Ca(OH_2)$ is referred to as carbonation. It is often developed in cement-based products and over the lime stone surfaces. The carbonation process has been known for over forty years, however, only recently it has attracted close attention [24]. Its significance lies in the action that would increase the thickness of the carbonated surface layer with time and the potential detrimental effects on the materials of exterior surfaces [22]. Since the carbonation process depends on the presence of moisture conditions, the non-uniform wetting of building facades causes different effects on their surfaces (recall figures 3.14, 3.16, 3.19 and 3.22).

In general, the carbonation process can produce several significant effects such as the following:

(1) Formation of insoluble white deposits which are known to be calcium carbonate $Ca\ CO_2$. This formation of $Ca\ CO_3$ - sometimes referred to as lime bloom [27] - is different from the efflorescence effect as $Ca\ CO_3$ is not soluble in rainwater. In presence of dark pollutants, the $Ca\ CO_3$ deposits substantially change its colour.

(2) Alteration of the porous characteristics of the surface layers of the building materials. As a result, it influences the degree of water absorption and consequently affects the quantity of run-off water over facade surfaces.

(3) Increase the hardness of the surface layer of the material.

(4) Decrease the homogeneity of surface.

2. SULPHATE ATTACK:

Sulphate attack is often developed in cement-based products. It is a series of complex chemical reactions between sulphate ions in solution and one of the cement constituents such as hydrated lime $Ca(OH)_2$ and tricalcium aluminate 3 CaO. $Al_2 O_3$, usually referred to as C_3A. The degree and rate of sulphate are determined by the type and quantities of sulphate present, the amount of $Ca(OH)_2$ and C_3A present, the distribution of water quantities over the material surface, and the penetration of the soluble sulphates into the material.

Sulphate attack can cause a number of serious problems, these include the following:

(1) Formation of calcium sulphates - gypsum $CaSO_4 .2 H_2O$ of molecular volume 74.3 ml from calcium hydroxide $Ca(OH)_2$ of molecular volume 33.2 ml. This results in almost doubling the solid volume of the surface material that will cause blistering and disintegration.

(2) Formation of magnisium sulphates ($Mg SO_4$) which is highly soluble and more reactive with other components since it has greater effects on material decomposition. This type of attack is also characterized by forming a hard glassy skin that will decrease the porosity of the surface [2].

APPENDIX II

DERIVATION OF THE CONSTANTS 'a,b' AS A FUNCTION OF THE MATERIAL ABSORPTIVITY 'C'

In Chapter 4, the values of the constans a,b as a function of the material absorption coefficient C was stated in the form:

$$a = \alpha C$$

$$b = \beta C$$

In order to arrive at the values of α and β that minimize the difference between the curve of the empirical formula

$$G = C\sqrt{t} \qquad (1)$$

and the one proposed in equation 4.4

$$G = -\frac{a}{b}t^2 + bt \qquad (2)$$

the least square method is utilized and the solution steps are as follows:

Let $E = G_{empirical} - G_{proposed}$,

the objective is then to find the expression for a and b in terms of C that minimizes the sum of E^2 over all the time range of interest. This can be expressed mathematically as:

minimize: $\sum_{i=1}^{N} E_i^2$

$$\text{or minimize } \sum_{i=1}^{N} (G_{emp.} - G_{prop.})^2 \qquad (3)$$

the necessary conditions to satisfy equation 3 are:

$$\frac{\partial \sum_{i=1}^{N} E_i^2}{\partial a} = 0 \qquad (4)$$

and $$\frac{\partial \sum_{i=1}^{N} E_i^2}{\partial b} = 0 \qquad (5)$$

substituting 1 and 2 into 4 and carrying the differentiation, we have

$$2 \sum_{i=1}^{N} [C\sqrt{t_i} + \frac{a}{2} t_i^2 - bt_i] (\frac{t_i^2}{2}) = 0 \qquad (6)$$

and, 1 and 2 into 5 and carrying the differentiation, we have

$$2 \sum_{i=1}^{N} [C\sqrt{t_i} + \frac{a}{2} t_i^2 - bt_i] (-t_i) = 0 \qquad (7)$$

Solving 6 and 7 for a and b gives

$$a = \propto C$$

$$b = \beta C$$

where $$\propto = \frac{\sum_{i=1}^{N} t_i^3 \left[\frac{\Sigma t_i^{3/2} - \frac{\Sigma t_i^{5/2} \; \Sigma t_i^3}{\Sigma t_i^4}}{\Sigma t_i^2 - \frac{\Sigma t_i^2 \; \Sigma t_i^3}{\Sigma t_i^4}} \right] - \sum_{i=1}^{N} t_i^{5/2}}{\sum_{i=1}^{N} t_i^4/2}$$

$$\beta = \frac{\sum_{i=1}^{N} t_i^{3/2} - \frac{\Sigma t_i^{5/2}\, \Sigma t_i^3}{\Sigma t_i^4}}{\Sigma t_i^2 - \frac{\Sigma t_i^3\, \Sigma t_i^3}{\Sigma t_i^4}}$$

The value of N in the above expression can be obtained by trial procedures. Increasing the value of N gives a more accurate approxmation to the proposed curve. Therefore, different expressions of α and β do not change up to the forth decimal point. The value of N is found to be 25.