PERFORMANCE OF THE STONE BUILDING ENVELOPE: CLADDING TO CURTAIN WALL

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BİLGE OĞAN MUSAAĞAOĞLU

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Director
Prof.Dr. Canan Özgen

I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy

Head of Department
Assoc. Prof. Dr. Selahattin Önür

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Doctor of Philosophy

Asst. Prof. Dr. Ercüment Erman
Supervisor

Prof. Dr. Emine Caner SALTIK	(METU, ARCH)	
Asst. Prof.Dr. Ercüment Erman	(METU, ARCH)	
Prof. Dr. Tanju GÜLTEKİN	(GU, ARCH)	
Assoc. Prof.Dr. Mualla Bayar Erkılıç	(METU, ARCH)	
Inst. Dr. Halis GUNEL	(METU, ARCH)	

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Bilge Oğan Musaağaoğlu

ABSTRACT

PERFORMANCE OF THE STONE BUILDING ENVELOPE: CLADDING TO CURTAIN WALL

Musaağaoğlu, Bilge
Ph.D, Department of Architecture, Building Science Program
Supervisor: Asst.Prof.Dr. Ercüment Erman

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The main objective of this thesis is to review the problems of stone facades according to the performance criteria determined with codes and standards and to propose solutions for proper application. In this process codes, standards, other documents, and the knowledge of the researcher all served to determine the inadequacies present in this field. The thesis also aims at clarifying the terminology confusion related to stone cladding and stone curtain wall.

On account of the problems encountered in stone facades, the components of stone facades and the stone façade obtaining process are evaluated and thoroughly reviewed. These are: 1. Stone, 2. Fixing,
3. Mortar, 4. Joint 5. Backing structure, 6. Workmanship, 7. Maintenance,
8. Service life span and durability. These components are the determining factors of the performance of the stone facades.

The common stone façade failures derived from literature and personnel observations are as follows:

1.Stone fall down, 2. Stone panel displacement, 3. Stone buckling, 4. Stone crumbling, detachment, 5. Stone crack, 6. Staining, 7. Discoloration, 8. Water penetration, 9.Condensation behind the wall, 10. Condensation within the wall, 11. Stone surface abrasion, 12. Thermal insulation material deterioration, 13.Deterioration of the joint fill material.

The classified problems and their reasons are checked and confirmed on some sample buildings from literature and Ankara and their relation with the European Union, USA and Turkish codes and standards are provided. The aim of this procedure is to determine the missing items of the existing standards.

The reasons underlying common problems concerning the stone façade can be grouped as:
A. Movement, B. Use of insufficient material, B.1 Stone, B.2 Other materials,
C. Weathering, D. Poor workmanship.

The thesis concludes by emphasizing the need for new codes to guide professionals, not only in existing standards for test methods determining the physical properties of stone, but also in detailing the whole stone façade system since the performance of the system depends on both the individual performance of the components separately and their performance as a whole.

Key Words: Performance of building envelope, Stone, Cladding, Curtain Wall, Standards, Codes

ÖZ

TAŞ BİNA KABUĞUNUN PERFORMANSI: KAPLAMADAN, GİYDİRME CEPHEYE

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Bu tezin ana amacı, taş kaplamaların problemlerini mevzuat ve standartlarda belirtilen performans ölçütlerine gore gözden geçirmek ve doğru uygulamalar için çözümler önermektir. Bu süreçte; ilgili standartlar, diğer dökümanlar, araştırmacının konu ile ilgili bilgi birikimi, eksikliklerin tespit edilmesine olanak sağlamıştır. Tez, aynı zamanda, kaynaklardaki taş kaplama ve taş giydirme terimlerinin karışıklığına da açıklık getirmektedir.

Taş cephe ve taş cephe elde etme sürecindeki bileşenler, problemlerin kaynağı olarak tek tek detaylı bir şekilde gözden geçirilmiştir. Problem kaynağı olabilecek etkenler şunlardır: 1. Taş, 2. Tespit elemanı, 3. Yapıştırma harcı, 4. Derz, 5. Arka duvar, 6. İşçilik, 7. Bakım, 8. Servis ömrü ve dayanıklılık. Bu bileşenler, taş cephelerin performansını etkileyen faktörlerdir.

Kişisel gözlem ve kaynak taraması ile ortaya konan ve yaygın olarak rastlanan taş cephelerin problemleri sıralanmıştır:1. Taş düşmesi, 2. Taşın yerinden oynaması, 3. Taşın eğilmesi, 4. Taşın kopması, ufalanması, 5. Taşın çatlaması, 6. Lekelenme, 7. Renk değişimi, 8. Su emme, 9. Duvar arkasında yoğuşma, 10. Duvar içerisinde yoğuşma, 11. Taş yüzeyinin aşınması, 12. Isı yalıtım malzemesinin bozulması, 13. Derz malzemesinin bozulması.

Gruplanan bu problemler kaynaklardaki ve Ankara'daki bazı bina örnekleri üzerinde gözlemlenmiş ve nedenleri doğrulanmış, bunların Avrupa Birliği, Amerikan ve Türk mevzuat ve standartlarındaki cözümleri ilişkilendirilmiştir. Burada amaç, mevzuat ve standartların eksiklik noktalarının tespit edilmesidir.

Yaygın taş cephe problemlerinin nedenleri aşağıdaki şekilde gruplanmıştır: A.Hareket, B. Yeterli olmayan malzeme kullanımı, B.1 Taş, B.2 Diğer malzemeler, C. Yıpranma, D. Kalitesiz işçilik.

Tez, sadece mevcut taşın fiziksel özelliklerini belirleyen test yöntemleri ile ilgili standartlara değil; aynı zamanda uzman kişilere rehberlik edecek, tüm cephe sistemini detaylandıran yeni mevzuatlara ihtiyaç olduğunu vurgulamaktadır. Tüm sistemin performansını, ayrı ayrı bileşenlerin performansı değil; hepsinin bir bütün olarak gösterdiği performans belirler.

Anahtar Kelimeler: Bina Kabuğu Performansı, Taş, Kaplama, Giydirme Cephe, Standartlar, Mevzuat,

To My Mother
Nevin Oğan

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CHAPTER I

INTRODUCTION

I.1 Definition of the Problem

Stone is one of the oldest and most popular materials used on the external wall because of its durability and abundance. However, although it is a highly durable material, there are many examples of stone facades which do not satisfy the external wall performance requirements. Naturally, the performance of the stone wall is a determined by the building obtaining process, which consists of design, construction and service life phases. Specifying the proper stone type and thickness as an external wall element i.e. specification and the correct detailing of the components at the design stage; installation by a qualified workmanship during the construction phase and the employment of right maintenance techniques during service life are important requirements of the expected performance of stone walls. If the requirements of each stage are not fulfilled, the result will be low performance of a high quality external wall cover material like stone. Stone may crack, fall down, detach, buckle; thus ending up with a low performance if the construction details are not prepared properly, built correctly and maintained (cleaned) accordingly. If the reasons underlaying these problems are to be overcome at each stage, it will be possible to obtain the expected high performance from stone facades.

Research in the area of stone facade also involves problems that during literature review and personal observations. They are as follows:

1. Lack of past knowledge and experience;
2. Misconception of terminologies;
3. Misconduct of codes and standards.

1. Lack of past knowledge and experience

Observations and analysis of existing buildings provide vital knowledge of failures in the stone wall obtaining process. The reasons of the low performance of the stone external wall are critical and should be determined for future applications of better facades. The experience gained from the historical and new buildings is very valuable in providing solutions. Thus their performance can be improved. It is critical for architects, engineers and other professionals to be aware of failures that may occur during manufacturing and construction process. This study determines and groups the problems that may emerge in stone cladding and the stone curtain wall and their reasons as mentioned in literature and observe and check them in case studies as a source for high performance applications.

2. Misconception of terminologies

Stone is used in different methods as an external wall covering element. It was the masonry element at the beginning of history, fixed directly to a backup wall with or without a ventilation space. Later it was used as an infill material of a curtain wall suspended in front of a back up wall with a ventilation space in the contemporary architecture. Terminology confusion arose when literature was reviewed for all these systems used in history. The same systems were named as stone cladding or as stone curtain wall in different literature. A clarification is needed to prevent this confusion.

3. Misconduct of codes and standards

There are some codes and standards related with stone and stone facades in Turkey, Europe and theUSA. In order to obtain a high performance in the stone external wall, one has to refer to codes and standards that are universally valid. Nevertheless, when the problems of stone external walls are reviewed and observed, it can be said that there is a need for some other standards and additional items to the existing standards.

I.2 Scope of the Research

The use of stone as an external wall cover material is the scope of this thesis and, it is limited with the practice and knowledge in Europe, the USA and Turkey. Yet, the use of stone as a load bearing element of the whole structure is not included in this thesis. Some additional information is taken from literature on western practices as well as historical buildings and experience in Anatolia. The case studies are selected from the Turkish Republican era, expanding from the1930's to recent times. The context of case study is Ankara, being the capital of the Republic. Example of low performance stone exterior walls from literature and case studies are extracted to show the importance of the problems. There are also some high performance stone external wall examples that are taken from the western literature to show the possibility of eliminating the reasons of failures. The Turkish, European and USA building standards and codes related with natural stone panels are within the context of this thesis as a source of remedy for failures.

I.3 Objectives, Methods and Materials

The objectives of this thesis are to review the reasons of problems that may arise in stone facades, provide solutions to the problems with the help of existing codes and standards on stone and stone facades. During this review, the terminology confusion is clarified; the missing items of the codes and standards are also indicated as well as the need for new codes and standards.

The method used in this research is review of literature to determine the terminology confusion in this subject and the problems emerging in stone facades and their reasons to group and define the problems and their reasons by examining the performance of stone façade components based on the general building envelope performance criteria. The solutions to the problems are proposed according to the existing standards, **observed** on buildings selected from Ankara and determined the missing parts of codes and standards with the help of this review and observation.

The materials reviewed in this thesis are composed of books, articles, internet sources, standards, specifications and codes of practices. The documents reviewed are mostly of western world, USA, British and Turkish origin, either written in English or Turkish or translated into English or Turkish.

I.4 Structure of the Thesis

The thesis consists of five chapters. Following the 'Introduction' in Chapter I, Chapter II dwells on 'The Historical and Technical Aspects of Stone Facades' covering the historical background of stone facades in the USA, Europe and Anatolia. Reviewing the historical development of stone facades is also beneficial in guiding the classification of stone façade systems. Furthermore, this classification has given the researcher the opportunity to clarify the terminology confusion in the existent literature for the terms of stone cladding and stone curtain wall. The focus of Chapter III is the performance of stone facades. The components of stone façade were identified in this Chapter as a source of factors affecting the performance of stone facades. The problems related with each component and their reasons are reviewed from literature, codes and standards and with personal knowledge. The Turkish (TS), European Union (CEN) and US (ASTM) standards and codes related with stone façade components are reviewed and their relations with the failures are sought in the first part of Chapter III. The failures of stone faces are grouped according to this evaluation and the reasons of the failures of each case are discussed in the thesis. Some of the determined failures and their reasons are observed and checked on the example buildings stated in literature and those in Ankara at the end of Chapter III. In Chapter IV 'Discussions and Conclusions', the problems and solution proposals are summarized. The active situation of standards and codes on stone facades in some European Countries, Turkey and the United States are also reviewed in the same Chapter. The thesis concludes with Chapter IV.4 in which the researcher proposes for further studies and presents her foresight on the subject.

I.5 Terms and Definitions

Some of the terms used in this research are defined in this section. An English-Turkish Glossary is introduced in Appendix A.

Building Code: (Tr:*Yapı Mevzuatı*) It is the collection of rules and regulations adopted by authorities having appropriate jurisdiction to control the design and construction of buildings alteration, repair, quality of materials use and occupancy

and related factors of buildings. It contains minimum architectural, structural and mechanical standards for sanitation, public health, welfare, safety and the provision of light and air (Harris, 2000:132).

Building Envelope: (Tr:*Bina Cidarı,Bina Zarfı*) Building envelope is the unity of building components separating inside and outside of it. It consists of roofs, external walls, doors, windows, foundation, basement walls (if exists).

Cladding (Siding): (Tr: *Duvar Kaplaması,* Hasol,1993) Smith (1999) defined 'Cladding' as the external covering of a building. The Academic Press Dictionary of Science and Technology (viewed in 2003) defined cladding use in engineering as any of various processes in which two materials are bonded together under high
pressure and heat. The cladding (siding) is defined as "the finish covering of an exterior wall of frame building; the siding may be cladding material such as wood, aluminum or asbestos cement (but not masonry) applied vertically or horizontally" in the Dictionary of Architecture and Construction by Harris (1993).

Carlson (1974) defined cladding as external covering of a skeleton frame, such as steel frame building with thin stone blocks.

Curtain Wall: (Tr: *Giydirme Cephe, Takma Cephe* Hasol, 1993) It is defined as an exterior wall covering which bears no structural load. In building engineering the curtain wall is defined as an exterior wall with no structural function in a frame building; therefore, it is not load bearing. Carlson (1974) defined curtain wall as a thin wall supported by the structural steel or concrete frame of the building,

independent of the wall below. Brooks (1976) mentioned curtain wall as any of several types of prefabricated finished wall panels attached to the exterior structural frame of a building to form a finished wall surface. The panels may or may not incorporate with windows. According to Harris (1993), curtain wall is a non load-bearing exterior building wall between piers or columns that is not supported by the beams or girders of a skeleton frame. Osterle *et al.* (2003) defined curtain wall as a storey height form of construction suspended between the floors of the building. The outer skin is continuous and it is point fixed to the structure only at the front edges of the floors. The facade is separated from the back-up wall.

The terms cladding and curtain wall are confusing in the technical literature. Even in technical dictionaries the terms cladding and curtain wall are defined with similar properties i.e. non- load bearing wall of a skeleton frame. Osterle *et.al.* (2003) made a distinction between solid and transparent facades. According to them, the non-transparent area of the façade will be thermally insulated and then rendered or finished with modern cladding systems. The cladding with a ventilated cavity to the rear is fixed with carcass structure. Stone is one of the cladding materials used for these non –transparent facades. According to the definition of curtain wall by Osterle *et.al.* (2003), the curtain wall is separated from the structure and its structure, suspended between the floors of the buildings and façade elements can be prefabricated. The type of infill material is not important in most of the definitions. Schaupp (1967:51) explained the development of stone facades with stone adhered to the back structure to ventilated walls and he named this ventilated stone wall as a curtain wall, but this should be called as stone cladding since there is a direct connection of the stone panels to the back-up wall.

Curtain wall can be defined as a non-load bearing wall suspended in front of a load bearing structure of the building with a ventilation layer filled with transparent or opaque semi opaque materials.

Code of Practice: (Tr: *Meslek Uygulama Kuralları*) It is a technical document setting forth the standards of good construction for various materials and trade (Harris, 2000:205).

Dimension Stone: (Tr: *Kesme Taş*) Dimension stone is defined as any rock that is cut and worked to a specific size or shape for use in building and that the stone

should be free from fractures, tough and devoid of minerals that can break down chemically or by weathering. The surfaces of the finished block may be dressed by one or more mechanical treatments
Dimension stone will shortly be called stone in this thesis.

Panel (stone panel) : (Tr: *Taş Panel*) Piece of stone that is cut at a certain thickness.

Panel Wall: (Tr: *Pano*) The thin wall used for separation and that is not load bearing (Hasol,1998:347).

Performance: (Tr: *Performans*) The parts (components, elements) which shape a building are affected from the natural and unnatural events. These parts with their particular properties can resist different effects. The behavior of these parts related with their usage is called performance.

Performance Criteria: (Tr: *Performans Kriterleri, Performans Ölçütleri*) Indication to measure the performance.

Performance Specification: (Tr: *Performans Şartnamesi*) It is a specification based on the performance required of a given assembly, component, device, equipment or material. It is often such a specification referring to relevant standards (Harris, 2000: 671).

Performance Requirement: (*Tr: Performans Gereksinimleri*) It is a requirement that a material, device, piece of equipment or a system must posses as a stated characteristic (Harris, 2000: 671).

Safety Factor: (Tr:*Emniyet Faktörü, güvenlik katsayısı,* Hasol, 1998:162,194) It is the ratio of the amount of load when one structural element has lost its structural property to the amount of load that it can carry safely. General tendency in building design is to get this factor to take 1.75. It can take up to 3 for foundations of the buildings.

Slab: (Tr: *Plaka)* Load bearing element, which has a very small dimension compared to the other dimensions (Hasol, 1998:360).

Specification: (Tr: *Şartname*) Documents that specify the requirements.

Stone Cladding: (Tr: *Taş Kaplama*) It is defined in this research as the natural stone covering where the back of stone panels are bonded to the brick or stone masonry or concrete back –up wall directly with a mechanical fixing and/or with a ventilation layer.

Stone Curtain Wall: (Tr: *Taş Giydirme Cephe*) It is defined as non-load bearing external wall suspended in front of the structural frame consisting of a rectangular grid of vertical and horizontal members framing openings filled with inserts of natural stone that transfer their own dead weight and wind loads to the structural frame through point anchors.

To prevent a terminology confusion in this thesis, it seems acceptable to define “stone cladding” as the structure where the stone adheres to the back structure with mortar and/or mechanical fixing with or without a ventilation layer’ and to define “stone curtain wall” as stone façade with ventilation between the back face of stone and the carcass and its filling material. Although there are important differences between the two, the term cladding is used as curtain wall in some literature. In this research, the cladding materials of the exterior wall is bonded to the back structure with its whole back surface or stone panels anchored directly to the back structure even if it is ventilated is called cladding. The curtain wall is defined as the external wall element of the building envelope which is non-load bearing wall and suspended in front of the structural frame.

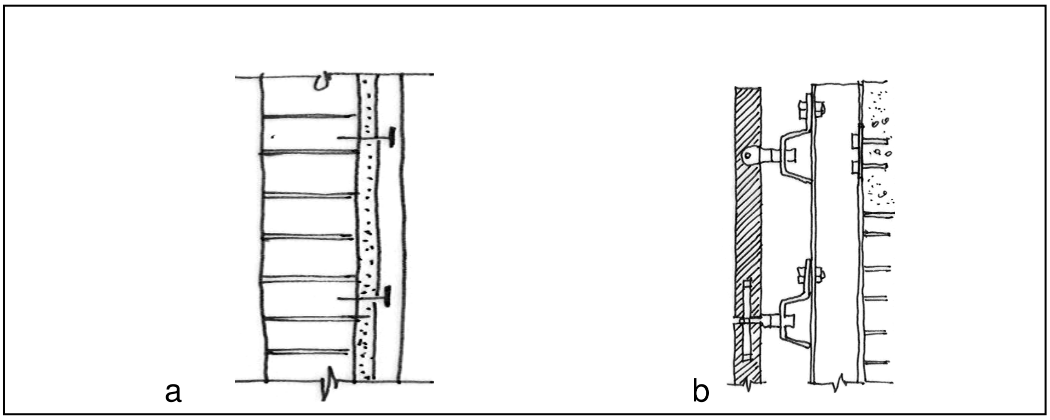

Figure I.1.a-b Stone cladding and stone curtain wall.

Stone Façade: (Tr: *Taş cephe*) The façade that has stone cladding or stone curtain wall.

Stone Veneer: Nashed (1995) defined stone veneer as composite thin stone systems created by bonding a thin stone veneer ranging in thickness from 4-7 mm to a steel mesh or an aluminum honeycomb backing to form exterior cladding panels.

Standard: (Tr: *Standart*) Turkish Standards Institute WEB page (viewed in October 2004) defined standard as unity in production, understanding, measurement and experiment. It can also be defined as the norm that has to be carried by a product or an outcome by an institute related with this matter or by international institutions (Hasol, 1998:416).

Thin Stone Cladding: (Tr*: İnce Taş Kaplama*) Nashed (1995) determined the thin stone cladding as 50 mm thick or less stone veneers.

Thermal Bridge: (Tr: *Isı Köprüsü*) An element that transfers heat that has higher thermal conductivity compared to near of it.

CHAPTER II

HISTORICAL AND TECHNICAL ASPECTS OF STONE FACADES

The use of stone as an exterior wall construction and cladding material has shown great development in increasing its performance. The historical development provides the clues to this effort. The historical and technical development of the stone façade systems in Europe, the USA and Anatolia is the subject of this Chapter. It is possible to make a classification of stone facades according to the determined criteria at the end of this historical development.

II.1 Historical Background of Stone Facades

The historical development of the stone façade systems in Europe, the USA and Anatolia are reviewed in this section.

II.1.1 Historical Background of Stone Façade Systems in Europe and the USA

The history of the external skin from the sheltering roof to the curtain wall is summarized by Schittich (2001:10-18) under the following headings:

1. The calling principle;
2. The increasing opening of the external wall;
3. Iron and glass-new materials as revolutionary the building skin;
4. The transparent façade;
5. The rise and fall of curtain wall.

Schittich (2001) further explains these subjects in detail.
Human beings build a house as shelter to protect themselves from the wind, rain,

cold and heat and also to create their own private spheres. Schittich (2001:9) uses the term ‘Building Skin’ instead of the term ‘Building Envelope’; which is different from today’s widely use. The building skin serves primarily as a roof to provide weather protection and then it becomes an enclosure to be protected from animals.

Schittich (2001) refers to Gottfried Semper's seminarian work 'The Style' in the mid 19th Century for the origin of the building. Semper divides architecture into load-bearing structure and cladding. This theory would have a far-reaching influence on Modernism (through Otto Wagner, among others) and this is pertinent today.

The more developed forms of construction in the Sumerian sense are tents of some nomadic tribes, such as Yurt among ancient Turkish or the Mongolian tribes. These have survived until today on the steppes of Central Asia. The lifestyle and the availability of the local materials determine the building types as load bearing or shell (Schittich 2001:10).

Nashed (1995:149) began his research with the historical background of the stone walls built by Egyptians. They constructed their burial chamber, pyramids and templates using stone in the third millennium B.C. Nashed (1995:146) states that the Egyptians were also followed by the Greeks and Romans. The importance of decoration in the history of building skin is emphasized by Schittich (2001). In time, people began to decorate the building skins as if they were their outfits. It may be a simple house or an elaborated frescoed Greek and Chinese temple or an Islamic palace or mosque. The European antiquity changed the façade to a showcase. The classical facades with their proportion, fenestration, division by architrave, columns and rusticated ashlar stones were important elements of the facades (Schittich,2001).

Schittich (2001:11-12) states the difficulty of puncturing the wall for large window openings in many European traditional construction styles using massive stones. In time, glass was used, but it was a source of energy loss so it was used in openings as small as possible. Architecture was freed from the constraints of load bearing wall and the progress in glass manufacture and technology made larger openings possible.

Religious gothic buildings were the first attempts to create large openings. A large section of the walls were freed from their load bearing function of ribs and vaults. Flying buttresses and pillars gave the opportunity for large windows. However, the windows in housing were still small. From the Middle Ages onwards, in Europe most of the windows were glazed but the glass was luxurious until the Industrial Age. Nashed (1995:147) states that stone reached its top potential for refinement in the Middle Ages. They introduced flying buttresses to resist the vaulted ceiling. The use of stone during this period was as load bearing wall. The molten lead was poured through channels carved in stone to connect the stone pieces.

During the first three quarters of the 19^{th} century in Europe, stone was used as facing material to a backing masonry of brick or stone wall. Schittich (2001:12) continued his research of building skin with the effects of the Industrial Revolution in architecture in the 19^{th} Century, when iron and glass become the dominant materials of architecture. To achieve a maximum amount of sunlight, architects tried to reduce the massive wall components to a minimum. There was no ornamentation in structures.

In the middle of the 19^{th} Century, the first tall buildings with steel skeleton structures were built in the USA. Skeleton construction was made possible to open up large windows in metal frames. With economic growth and increase in real estate values in the downtown area of the crowded metropolis, the high-rises were built with this technology. Traditional massive external walls were offered few opportunities for lighting. Some buildings with natural stone façade remind us of the Roman Antiquity (Figure II.1).

Figure II.1 Henry H Richardson's Natural Stone Façade-Marshall Field Store 1885-87 (Schittich, 2001:14).

The steel structure was hidden behind the natural stone façade in this example. Some architects like Sullivan, were convinced with the necessity of an ornamentation that was not superficial, but an integral component of the whole.

It is Brookes (1998:150) who states that the 'curtain walling' is a rectangular grid of vertical and horizontal frame introduced in America during the 1950's mainly for the use in high-rise office buildings. Schittich (2001:14) also marks the US as the starting point of curtain walling construction techniques. Since the external skin became independent of its structural function, it was separated from the load bearing structure and its requirements. This situation started in Chicago in the 19th Century. At first, examples of facades with claddings in industrial buildings were freed from the load bearing structures. This construction type was later named as the curtain wall. To achieve maximum light, external walls were glazed as much as possible. The building of the Margarethe Steiff factory in Giengen (Southern Germany) was one of the earliest examples of this kind in Europe. The external layer of the double-layered façade composed of translucent glass panels was suspended in front of the structure and stretched across three stories high and around the corners as a smooth skin. The overall internal skin lay between the supporting pillars. Walter Gropius in collaboration with Adolf Meyer (Fagus Works 1911-25) succeeded in suspending a curtain wall of an industrial hall as filigree, transparent skin that did not have a load bearing function. He demonstrated the principle of the 'curtain wall' by dispensing with corner piers, achieving a fully glazed corner across three floors.

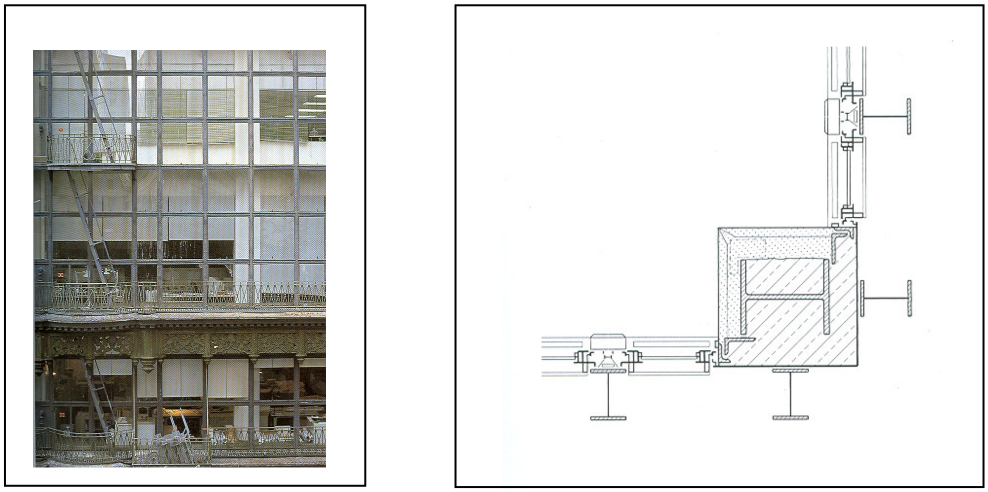

Figure II.2 The Halladie Building in San Francisco by Willis Jefferson Polk in 1918 was the first example of a suspended façade (Schittich, 2001:15).

In 1918, Willis Jefferson was the first to suspend a curtain wall in front of an urban office building in San Francisco (Figure II.2) while this building could not succeed in emphasizing the principle of the curtain wall as, Grophious was able to with the Fagus Works. Schittich (2001:15) continued his carrier in the building skin with Mies van der Rohe. His design for a high-rise in Berlin (1922) was the most daring execution of a glass façade in the same period. This building was not as transparent as his first high rise on Lake Shore Drive in Chicago. Mies van der Rohe re-interpreted the curtain wall in his American high-rise building facades. The volume of the building was not transparent nor light, and his buildings of the 1960's, like Seagram Building, in New York were almost opaque. He seemed to have abandoned the transparency he strove for in the 1920's.

Schittich (2001:16) explains the development of curtain wall from the USA. A few years earlier than Seagram Building, Skidmore, Owings and Merrill (SOM) had created the prototype for a light curtain wall on a high-rise at the Lever Building in New York. A polished stainless steel frame clothes the façade and it is completely detached from the load bearing structure and is only linked by discrete fixings to transfer the wind loads. The minimized glazing area is filled with semi-reflective glazing. The building is closed on all sides without any openable windows and fully reliant upon artificial ventilation and air conditioning. These two solutions contribute to the progress of the curtain wall. Until the early 1970's, glass curtain wall buildings spread rapidly all over the world under the influence of the International style. The number of office buildings and glass façade with its grid as their symbol increased to a great extend. From the mid sixties on-wards, the new method of fixing external glazing with load –bearing silicon emerged and other innovative fixing techniques contributed to these changes. Thus, it was possible to clad the entire building in the same smooth skin. Investors and clients' demand for unique, image building structures brought eclecticism, and this gave rise to criticisms. The energy crises of the 1970's increased these criticisms. For example, they have criticized to be encased in glass without openable window and depended on air conditioning consuming energy. The curtain wall reached to limitations with these attempts. Different architectural styles followed the International Style. Post- Modernism looked back to the examples in history and constructivism questioned traditional orders. The aura of the traditional building materials such as natural stone, brick and wood were applied into new contexts (Schittich:2001:16).

The chronology indicates that the technical development of stone facades from cladding to curtain wall was a result of its inefficiency as a building material. Schaupp (1967:51) explains this inadequacy referring to the physical properties of stone and also states that the technical development of the stone façade was a result of the efforts to remove this inadequacy. Stone has a high density and specific weight when compared to wood, and this property is combined with an unfavorable thermal conductivity and high heat storage capacity. In summer, it collects the heat during the day and generates it at night.

Natural stone is a good vapor barrier so damp can not evaporate and it condenses behind the stone panels. With the development of tools, it was possible to saw stone into thin slices which was used as a wall facing because of its qualities of weather resistance and watertightness. The facing units were bonded into the brick or lightweight backing. The whole satisfies the static requirements but the problem of the joints has arisen. The more detailed the façade, the more saturation occurs. Thermal insulation is better on the inside than on the outside while vapor tightness is better on the outside, which is reverse of what it should be from the point of heating. Stone has left its mark in architecture because of this reason in buildings that have come down to us from classical times (Schaup,1967:51).

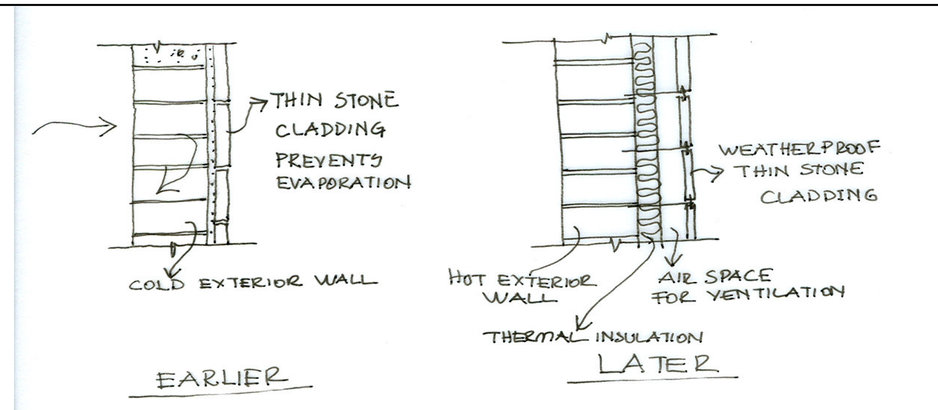

Figure II.3 The development of stone façade from the point of building physics.

Recent architecture has produced slender framed structures which require weatherproof form of cladding. In the 21st Century technology, it is possible to use stone like wood, but there are limits to these developments and this can be understood from the large numbers of claims of failures expressed in recent years.

Schaupp (1967:51) defines the development of the stone curtain wall as follows:

> "In the light of recent discoveries it seems advisable, if the advantages of stone cladding are to be fully exploited , i.e. if natural stone is to be used as a weatherproof cladding, to ventilate it from behind in order to facilitate the essential drying out of the building, to find room for some form of external insulation, and to assign the function of load-bearing solely to the framed structure. This amounts to a kind of curtain walling".

Schaupp (1967:52-53) combined the technical development of stone facades from stone cladding to stone curtain wall with the deficiencies of stone from the building physics point of view and the technical development of stone cutting techniques. Another reason for the use of stone as a curtain wall material as defined by Schittich (2001) was looking back to historical background of architecture and energy conservation policies.

The thicknesses of the exterior walls were decreased with the development of the steel skeleton system and thus there was no need for the large load bearing walls. One of the reasons for the intensive use and the development of the curtain wall was the value of land in metropolitan areas of the cities. The thickness of the walls was decreased with the development of the curtain wall for the tall buildings. Stone was one of the infill materials used with these systems to give a classical appearance to the buildings.

II.1.2 Historical Background in Anatolia

The development of stone facades in Anatolia was not different than in Europe and the US. Stone was initially used as a load bearing wall construction material. Later, it was used as cladding material to a brick or stone wall and it has been used as curtain wall infill material for the last 15 years.
Meriç (1994:179) summarizes the use of stone in buildings as follows:
13th Century BC: The little shaped stone block walls were used without mortar in the Myken Palaces.
13th Century BC: Blocks were shaped with gypsum or lime mortars in Egypt.
4th Century BC: Blocks were connected with lead anchors in aesthetic forms at Greek Temples.
3rd Century: Stone blocks were shaped in Roman baths to span with domes.
1-18th Century: Cut stone was used in all buildings. Seljuk and Ottoman buildings were decorated with stone elements.

Stone use in Anatolia
A similar chronology for the development of walls in Anatolia was prepared by Başgelen (1993). Stone was used in defensive walls in the period of 3000-2000 B.C. The size of the stones used in the walls became larger with the increasing power of the Hittite Empire during the second millennium. The biggest stone blocks were placed reaching a height of 1.80 m. and of varying width. The

transition period from rough stone to shaped stone took a long time. Regarding the technical development of stone walls, stones were lined up to form different rectangular shapes on the surface of the wall without horizontal seam. The next stage of horizontal seaming was the shaping of the stone wall. Clamps were used to connect stone blocks. Although it was used in limited number, copper clamps were used for this purpose by the Hittites (Başgelen,1993) .

Başgelen (1993: 31-53) states that the use of regularly cut stone over the ground level of the foundation at a height of 1.5 -2 m. protected the upper mudbrick wall from deterioration and was, thus, an important technical development which is called ‘the orthostat’. Besides its function, the orthostat was used as a decorative element and ornamented with relief. After the Hittites, the Phrygians in Western Anatolia and the Urartus (in the east) became the masters of the masonry. The cyclopic masonry was a remarkable development used by Urartians and this was used widely in the Hellenistic era. The large irregular polygonal stones were used without mortar in this technique. This technique was used by the Hittite but improved by the Urartians by using hard stones, such as basalt.

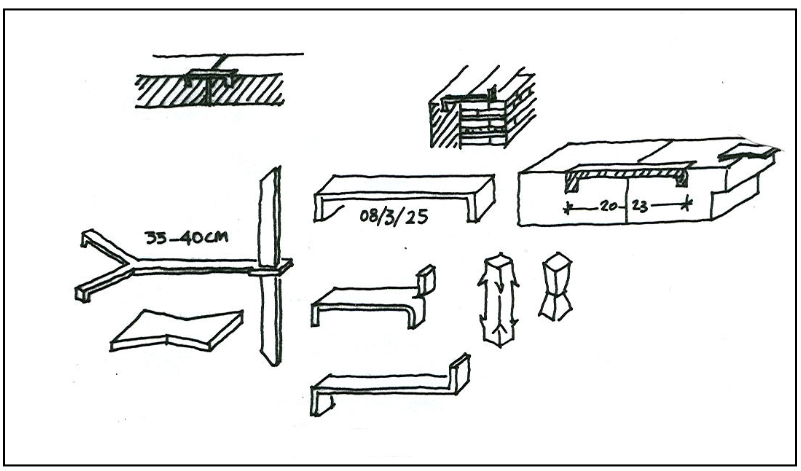

Figure II.4 Metal clamps used in Roman Architecture stone masonry wall (Adopted from Binan,1961:31).

The Greeks used different techniques of stone masonry such as Regular, Isodomus, Pseudo-Isodomus. They preferred copper or bronze clamps over iron ones because of its practical use and relative cheapness. The Roman Architecture was affected from the accumulation of cultures in Anatolia. The contribution of the Roman was the invention of the masonry techniques similar to the modern ones. Besides, the use of the old dressed stone technique with clamps by the Romans, the application of tendons and the double wall system were popular (Figure II.4). In the double wall system, the two layer walls were filled with a kind of concrete called ‘opus caementicum’. The usage of this technique by the Ottomans at a later period (Figure II.4.-II.5.) is mentioned by both Başgelen (1993:79) and Tanyeli, *et al*. (1990).

Başgelen (1993:60) emphasizes the Romans’ revolution in succeeding cutting marble into layers thinner than 1 cm. Bakırer (1990) and Başgelen (1993:73) state that stone was used for prestigious buildings in the Seljuk and Ottoman periods. When the Seljuk arrived in Anatolia in the 11th Century, they had planned to build many religious, educational, social and commercial and military buildings. Stone was used in the construction of these buildings. The local material of the Anatolian Peninsula had been mudbrick until that point. However,in time, stone became the primary material for both construction and ornament. In the late 12th and throughout the 13th Centuries, monumental buildings were constructed of stone masonry. Local materials like sandstones and limestone found near construction sites were used in order to decrease the transport cost. The use of colored and reused stone started in this period. From time to time, the reuse of antique stones is seen on buildings.

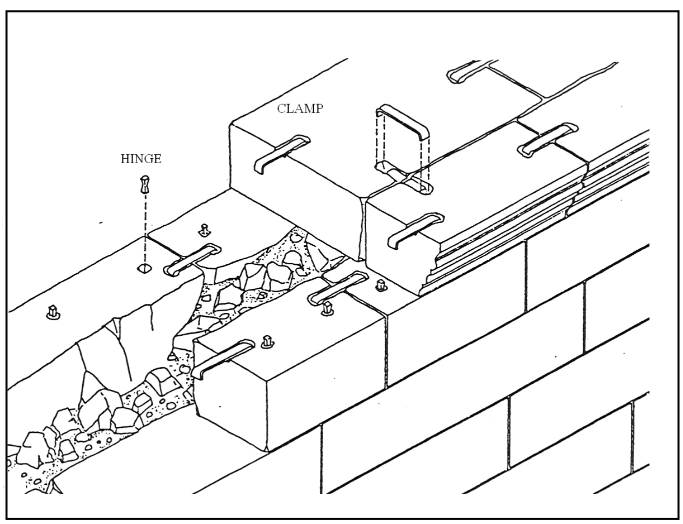

Figure II.5 The use of metal clamp and hinge of double wall in the Ottoman period (Tanyeli , *et. al* ,1990:117).

The Ottoman architect Sinan largely used *Küfeki* [1]stone (Eng: Limestone) in their buildings. Arıoğlu, *et al*. (1999) analyze the resistance of the Kufeki stone used in the Şehzade Mosque elevations. The tests made on the *Küfeki* stone in the Şehzade Mosque building indicate that the deterioration of stone in 450 years from outside to inside is a minimum of 1 mm to a maximum 15 mm/ 450 years (average 7, 5 mm) due to climatic conditions. On the other hand, deterioration of concrete is calculated to be 40mm within a period of 60 years. Arıoğlu, *et al.* (1999) conclude with this analysis that *Küfeki* stone has a very high performance regarding weathering resistance when compared to concrete, derivatives of concrete like artificial stone and even sandstone and granite.

Başgelen (1993:79) states that clamps had rarely been used before the Ottoman period. From the end of the15th Century, iron clamps became widespread in connecting stones strengthening the wall. Melted lead was used to fix the clamps. The clamps were different in size and shape. Another type of jointed masonry appeared in the second half of the 19th Century. In this technique the external wall material was marble and the internal wall material was coarse limestone. The thickness of the blocks was 20-30 cm. 'T' shaped clamps were used instead of 'U' ones. Marble was used as a construction material rather than a cladding material until the 19th Century. The used colored marbles became popular in the Ottoman Period especially during the Classical Ottoman Architecture. The use of colored marble was so excessive that it was defined as 'the Ottoman craze for marble' by Bakırer (1990).

Rise of the reinforced concrete

From 19th Century onwards, stone has lost its importance with the invention of reinforced concrete. It should be kept in mind that most of the buildings standing from the past centuries were constructed with load bearing masonry walls or finished with stone cladding. Stone cladding was widely used by Seljuks and Ottomans because of its superior property of durability. The important buildings in İstanbul and Edirne were built or clad with mostly limestone and they are still in good condition although their maintenance was neglected over years to an important degree. Stone was also widely used in the Turkish Architecture of the

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[1] Küfeki Stone: It is a kind of sedimentary stone that can be worked easily. It gets harder in time and it was widely used in Ottoman Architecture (Hasol,1998:247).

1930's as a cladding material. The latest popular use of stone in Turkey is travertine, generally granite in curtain walls. The use of granite curtain walls in Turkey extends back to the 1980's.

It can be said that with its durable character, stone has been a widely used construction material both in history and today and it is adapted to new construction techniques to overcome the disadvantages of the former stages in history.

All this information does not only shed light onto the historical development of the stone façade, but as also beneficial in classifying stone facades. Thus, the subsequent section in this chapter is devoted to the classification of stone facades from literature.

II.2 Classification of Stone Facade Systems

The use of stone as an exterior wall construction and cladding material showed progress in history and some types of methods were abandoned leaving their place to new ones that became popular. The construction methods of stone cladding and curtain walls in general and stone curtain wall constructions in detail in the Western (International) and Turkey context is presented in this section. With this classification the stone cladding and stone curtain wall are defined in detail.

Outer wall coverings according to their construction methods are itemized into three groups by Deniz (2003:83):

1. Type 1: Outer wall may consist of material that does not require additional wall covering- Masonry or reinforced concrete wall (Figure II.6.).
2. Type 2: Application of wall covering with the main body of the wall (Figure II.7).
3. Type 3: Application of the wall covering material on to the existing main body of the wall. (Figure II.8).

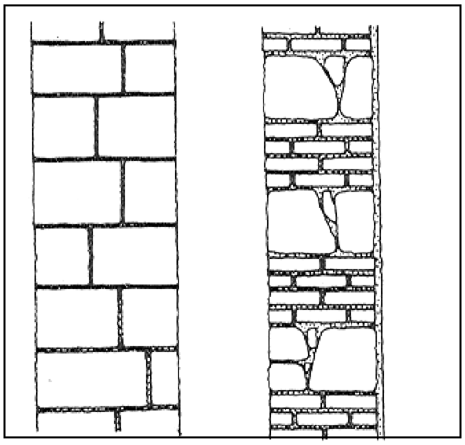


Figure II.6 Masonry Wall-Type1.

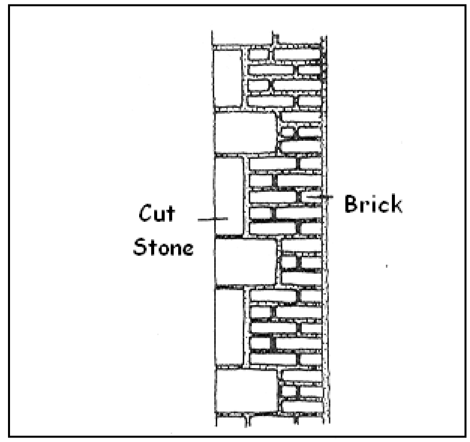


Figure II.7 Wall covering with the main body of the wall Type 2.

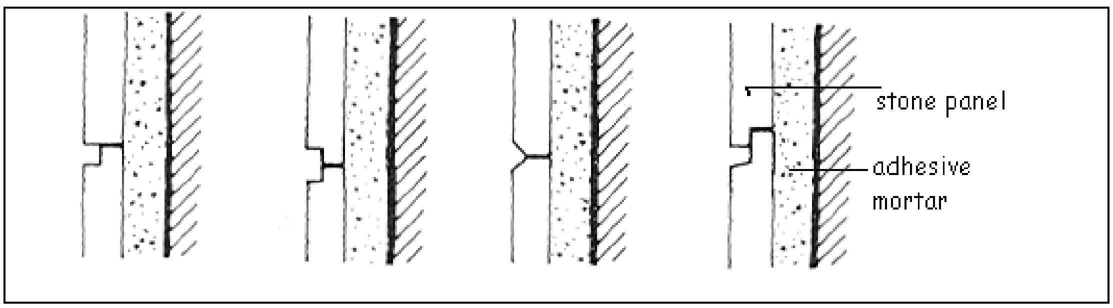


Figure II.8 Wall covering material on to the existing body of the wall Type-3 (Deniz, 2003:86).

The masonry wall and wall covering with the main body of the wall i.e. Type 1 and 2. are excluded from this research.

Type 3 presents more visual and aesthetic possibilities. The wall cladding is applied after the construction of main the body wall. Type 3 is classified into three groups according to the materials used and type of application by Deniz (2003:84-88)

3.1 Application of liquid or the type of paste material on the main body of the wall-plaster;
3.2 Application of wall cladding on the existing main body as half independent bonding;
3.3 Installation of the rigid wall cladding material to the main body of the wall with a spacing element.

The implementations have shown that the missing part of this classification is the curtain wall. Type 3.3 can be divided into two:
3.3.1 Wall cladding material installation to the main body of the wall with a fixing element providing a ventilation space between the back of the stone panel and the backing structural or non structural wall;
3.3.2 Wall cladding material installation to a frame carried by the load bearing structure of the building.

Type 3.2 and type 3.3.1 are called 'cladding' and type 3.3.2 is called curtain wall' in this thesis to prevent terminology confusion.

The use of stone in walls is listed as follows by Smith (1999:328-341) in a similar way:

A. Load bearing and self supporting masonry

B. Masonry facades to framed buildings

C. Claddings and linings

The detail of their constructions is as follows:

A. Load bearing and self supporting masonry

The performance of these types of stone walls is not included in this thesis since they are not used in the contemporary construction techniques.

B. Masonry facades to framed buildings

The required thicknesses of the exterior wall with masonry slowed down the construction time and increased the expenses of the buildings more than two storey high owing to regulations. This problem was overcome with the introduction of steel or concrete frames. In these cases, the floors and the walls were supported by the beams of the frame at one point in time. This meant that walls could resist the wind forces and bear their own one storey height weight.

This type of construction reduced the thickness of the wall. Smith (1999) explains different variations of this type of stone wall as follows:

B.1 Facing bonded and/or cramped to backing brick or blockwork, supported floor to floor on a steel frame

The thickness of the masonry was determined by requirements for fire resistance, thermal insulation, wind resistance and decorative features in this type of construction. The backing masonry of the floor structure was built and the stonework was 'wrapped round' the steel stanchions.

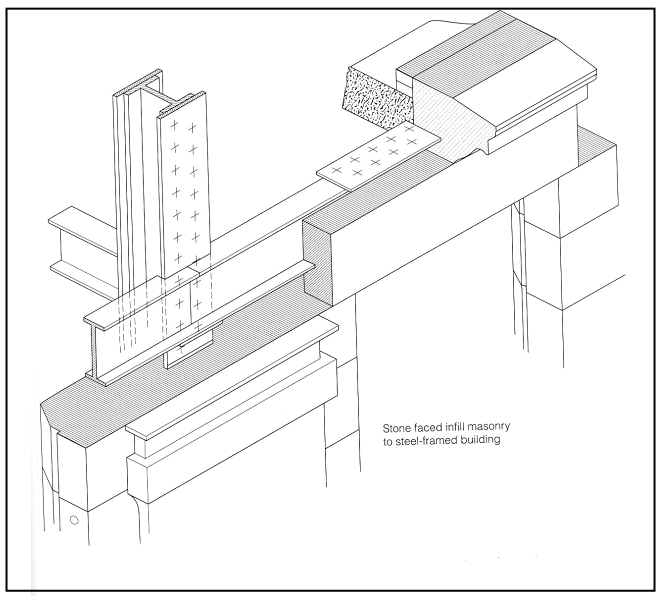


Figure II.9 Isometric view of a masonry wall supported by a steel frame (Smith,1999:335).

After the 1940's the steel frame was usually encased in concrete, but earlier practice did not provide corrosion protection and many buildings of this type suffered from the cracking stonework due to rust expansion of the steel members. With the developments in cladding techniques since mid 1960's, this type of construction superseded with sub-frame mounted stone facing, which is described in the following parts of this thesis.

B.2 Facing bonded and/or cramped to backing brick or block work, supported floor to floor on a concrete frame

This is almost identical to the cladding technique described in B.1. However, the nature of facing bonded and/or cramped to backing brick or blockwork, supported floor by floor on concrete frame. However, the concrete frame does leave more scope for connecting the masonry to the frame by metal ties and being generally of later date. Smith (1999) states that this form of construction was substituted with cladding.

C. Cladding and lining to framed buildings

Smith (1999:336) classifies the third use of stone as cladding and lining to framed buildings.

C.1 Individually fixed cladding and lining slabs

The use of granite, marble and other stones in the form of relatively thin slabs has been a popular method of covering complete facades. In this way the benefits of natural stone, its appearance, durability and weathering characteristics could be gained without the cost penalty of thick stone walls. In this case, the stones were held in place with metal fixings without bearing on the course of stone below. As a consequence, entirely different technologies had been developed for fixing, jointing and weatherproofing. Factory cut and finished stone slabs were held in place with mechanical fixings on site at the construction of external claddings. Although the developments in the cutting technology allows the designer to use a wider range of finishes, sections, thinner slabs than in the past, fixing slots to accommodate construction inaccuracies was usual, but in some cases it initiates fine cracks in the cladding slabs. The failures of stone facades are reviewed in detail in the following chapter. Smith(1999) explains the types of individually fixed cladding and linings slabs as follows:

C.2 Stone faced pre-cast concrete panels

Stone is fixed to concrete panels with close-spaced stainless steel dowels. These dowels are placed and glued into holes drilled in the back face of the finished stone slabs which are then laid in the moulds prior to pouring the concrete. The advantages of this system are that the stone fixings are simple and cheap and their installation does not require the skills of a mason on the other hand, the disadvantage of this technique is that it has a greater dead weight than many cladding systems and it is difficult to replace any damaged stone.

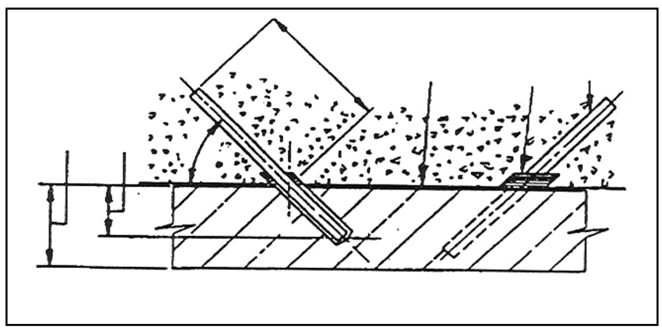


Figure II.10 The diagram of dowel fixing of a stone slab to a prefabricated concrete panel (Smith,1999:338 ; BSI 8298, 1994:25).

C.3 Sub-frame mounted stone facing

In this method, frames are used to support a number of individual stone slabs. The frames are made out of steel sections with welded joints and hot dip galvanized after fabrication. Frames are typically full storey height. This is called stick system 'curtain wall' by Blyth (1990:226) whereas Smith (1999) called it 'cladding'

Individually fixed curtain wall slabs and sub-frame mounted stone facing methods have been used in Turkey for about 10 years, especially in granite curtain walls. Some installation techniques of stone, especially granite, panels in Turkey have been used in recent times (Figure II.11 –II.12).

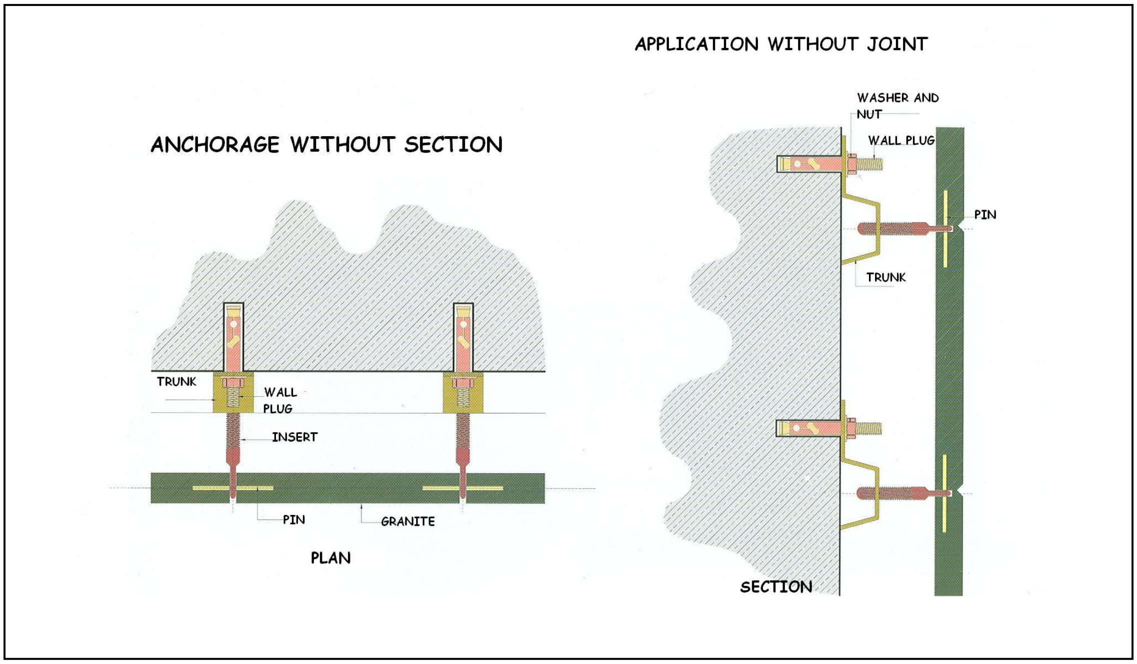


Figure II.11 Stone cladding details applied in Turkey in recent times especially in the granite facades (Mangan Granite Company Catalog Details).

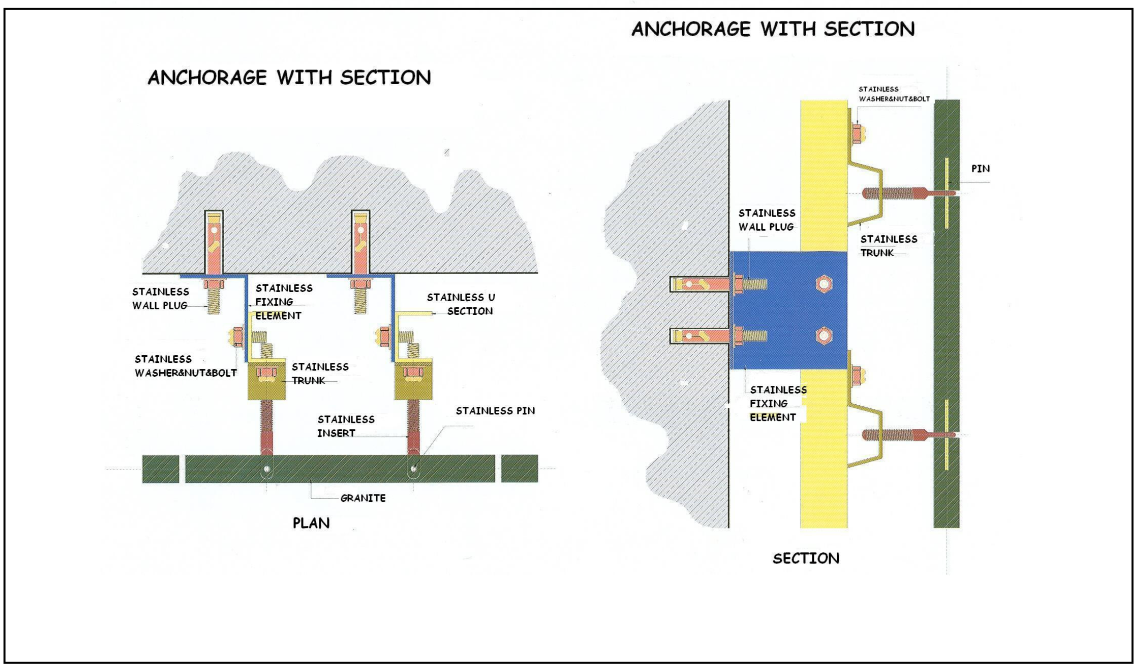


Figure II.12 Stone curtain wall details applied in Turkey in recent times especially in the granite facades (Mangan Granite Company Catalog Details).

C.4 Veneer panels

During the 1980's , light weight composite stone faced boards and reinforced stone panels have come to the market manufactured in Italy and the USA. The panels were manufactured by gluing honey comb core boards to each side of a slab of stone, typically 20 mm thick with a plastic resin (Smith,1999:340).

Nashed (1995:149) also mentions this type of veneer panels. The thickness of the stone varies from 4-7 mm. Nashed (1995) points out that the long term durability of this in exterior applications has not been established yet because of the fact that it has not been on the market long enough. It may be a good choice for earthquake zone applications with its reduced weight.

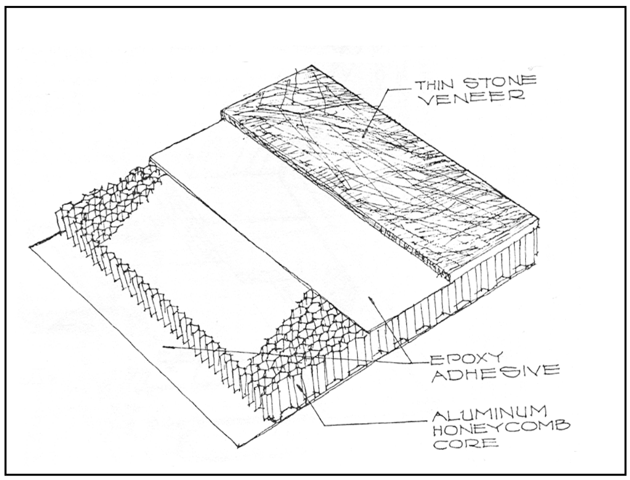
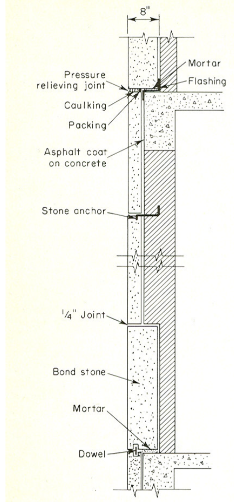


Figure II.13 Lightweight, composite panels (Nashed ,1995:149).

Smith (1966,325) classifies the use of stone as an exterior wall material in two groups:

1. Stone facing over a back-up wall,
2. Stone facing supported by a subframe of aluminum or steel.



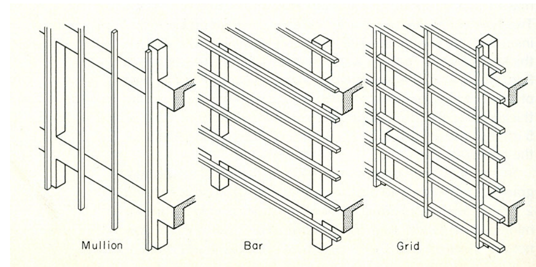


Figure II.14 Stone face over a back-up wall

Figure II.15 Stone face supported by a subframe of aluminum or steel (Smith, 1966:326-327).

There is a difference in terminology between the US and Europe while classifying the stone façade systems. There is also confusion in the European literature regarding the term ‘cladding’. The distinction between stone cladding and stone curtain wall structure is not clarified in most literature. The terms ‘hand-set’ and ‘panelized’ are not used in European literature. Some authors such as Smith (1966), Blyth (1990), O’neil(1965) use the term ‘cladding’ term both for stone cladding and stone curtain wall types whereas, it is differentiated by Vandenberg (1975:151) and Schaupp (1967:51). Nashed (1995:155) from US classifies the stone systems into two groups:

1. Hand-set Systems
2. Panelizes Systems

1. Hand-set Systems: Nashed (1995:155) has defined hand set systems as setting stone piece by piece. Stones may be light enough to be lifted by hand and laid in the wall in a manner similar to brick masonry.

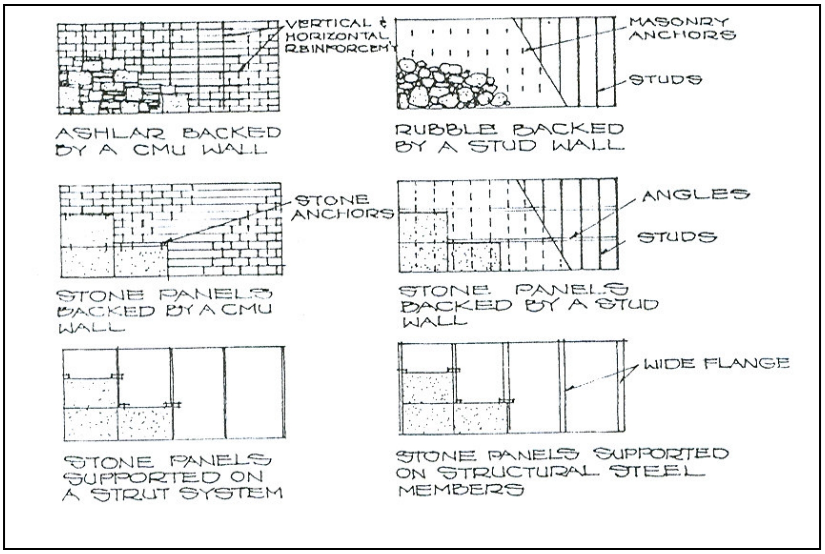


Figure II.16.Hand-set stone systems(Nashed,1995:152).

2. Panelized Systems: Nashed (1995:155) states that stone may be shop prefabricated and assembled into panels in this system. These panels may be all stone construction; a stone veneer backed with precast or a metal subframe composed of a steel truss or a stud assembly.

Nashed (1995) continues to state that in glass curtain walls, stone panels may be integrated into the mullion system to form spandrel panels.

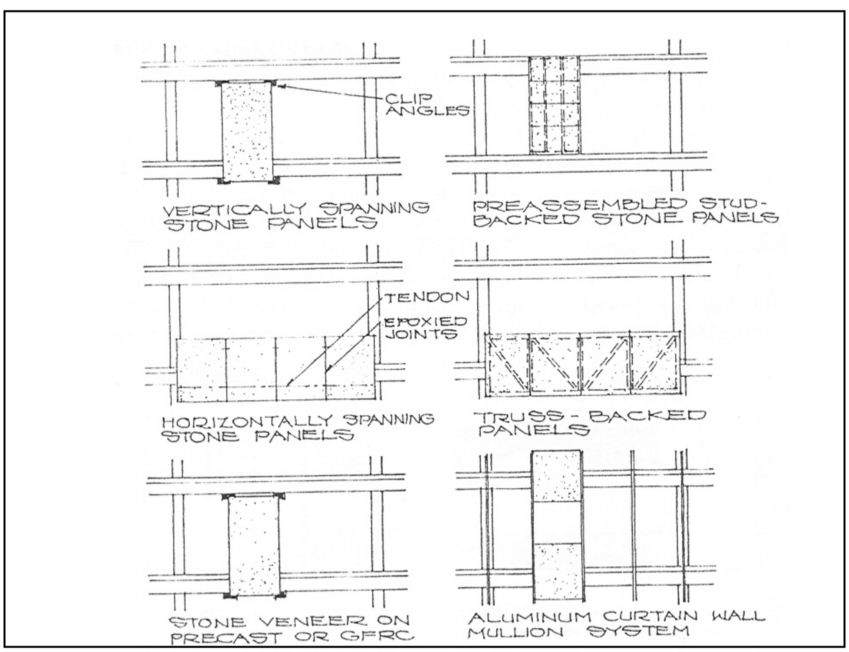


Figure II.17 Panelized stone systems (Nashed 1995:152).

These types of stone facades are called ‘stone curtain wall’ in this research. In Turkish practice stone curtain walls are similar to hand set systems in that stone panels are supported on a strut system, which is located infront of a load bearing structure.

Blyth (1990:225) defines curtain wall as the concept by which the interior of a building is enclosed by a cladding which supports no load apart from its own weight and the environmental forces which may act upon on it. According to this definition, curtain wall is a non-load bearing enclosure suspended from the main structure. Blyth (1990:225) defines the properties of curtain wall as a non-load bearing enclosure suspended from the primary structure, and the properties of curtain wall comprise one of the following:

1. A light bearing framework of site assembled aluminum alloy components supporting preassembled opaque and translucent infill materials,
2. Sections of prefabricated wall which are transported to the site in the form of large panels and hoisted into position on the buildings façade.

Blyth (1990:225) classifies the construction of a curtain wall as 1.Stick and 2.Unit systems. Stick construction comprises a grid of mullion and transom bars into which various types of infill panel can be fitted. Most of the assembly work is done on site (Figure II.18).

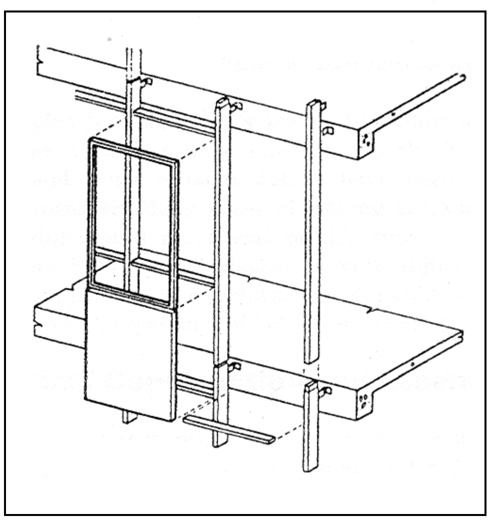


Figure II.18 Frames attached to the back surface to fix different façade material (Stick System). (Vandeberg,1975:152).

In the unit construction sections of wall are prefabricated and brought to site in complete modules ready for bolting to the structure (Figure II.19).

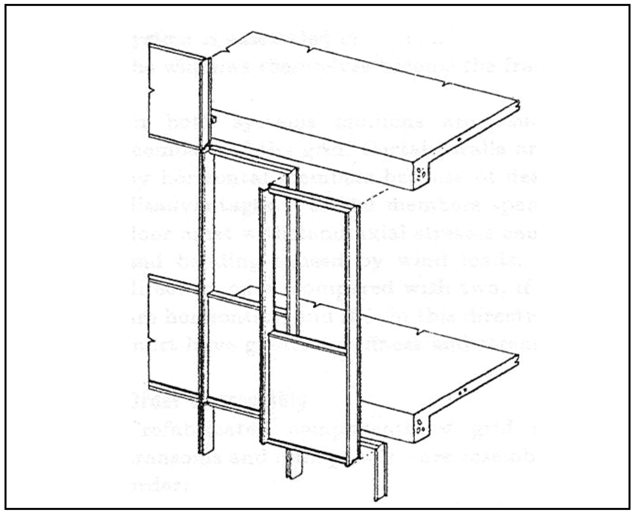


Figure II.19 Prefabricated panels bolted to the structure (Unit System) (Vandeberg ,1975:152).

Vandenberg (1975) does not identify these systems of the curtain walls as stick and unit but mentions the two types of curtain wall constructions similar to how they are expressed by Blyth (1990:225). (Figure II.18; II.19.)

a. The system assembled on site and offered to the frame
b. The windows themselves become the frame.

Blyth (1990:226) classifies the curtain wall systems into five recognized groups which are: **a**. stick, **b.** unit, **c**. unit and mullion, **d**.panel, **e.** column span.

a. In the **stick system** there is a visible grid of metal framing and installed bar by bar, usually commencing with the mullions, followed by the transoms and then the infill panels. The advantages of this system are the low cost and its ability to provide some dimensional adjustment to take account of site tolerances. The disadvantage is the necessity for site assembly, which makes its performance depend upon the quality of its site labor and the weather at the time of installation. This system covers a wide aesthetic range from exposed bars to invisible when viewed from the outside.

b. The **unit** system comprises factory assembled units, complete in all respects including glazing which are brought to site sequentially and bolted to the building's structure. The advantage of the system is its pre-assembly under controlled factory conditions. This reduces inaccuracy and facilitates rapid enclosure of the building with minimal site works. The main disadvantage is the bulkiness of the modules. This requires greater factory and storage space and cause transportation difficulties.

c. The **unit and mullion** system is the amalgam of the two former systems. The mullions are installed first and lined through, and the pre-assembled units are located between them. The system is used where mullions with a particularly large cross-sectional area make full unit impractical. The infill units can be of one storey height in size, or separated into spandrel and vision units. The advantages and disadvantages are similar to those of a fully united wall. The size of the units is smaller in this system.

d. The.**panel** system is similar to the unit system. The main difference is that the panels are formed as homogenous units usually from vacuum, press or brake formed sheet metal, casting or plastics.

e. The **column span** system comprises covers which clad the vertical structural elements, long spandrel panels which span between them and pre-assembled glazing unit infill.

Curtain walls consist of rectangular grid of vertical and horizontal members creating openings, and these openings are filled with planes of glass and panels of other materials. The grid is expressed in elevation and gives the curtain wall its characteristic appearance. Today, the curtain wall has broken the barriers imposed upon it by its supporting gridwork and presents a lot of alternative materials for façades.In general, the grid is not expressed in stone curtain walls. Stone covers the grid and it can not be seen from the outside of the building.

The use of granite, marble and other stones in relatively thin slabs has become a popular method of covering complete facades. In this way, the benefits of natural stone, its appearance, durability and weathering characteristics can be gained without cost increase in thick stone walls.

According to Vandenberg (ed. 1975) curtain wall has the following properties:

1. It is a non-load bearing external walls;
2. It is suspended in front of the structural frame;
3. The dead weights of the curtain wall and wind loads are transferred to the structural frame through point anchors.

The advantages of the curtain walls compared to the cladding are:
The lightweight slender curtain wall maximizes the available floor area within the building (Blyth,1990).

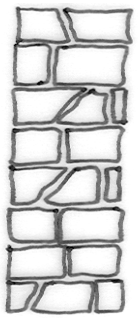
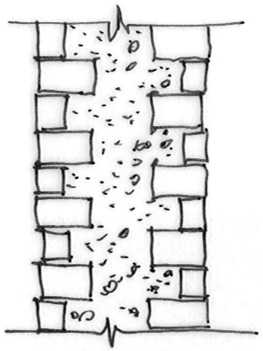
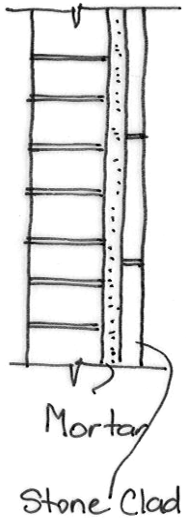
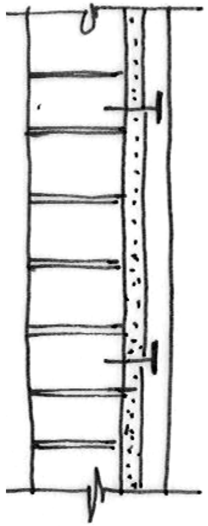
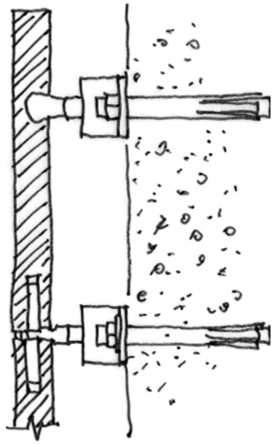
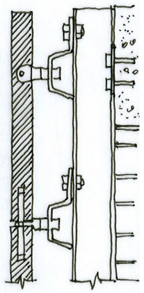
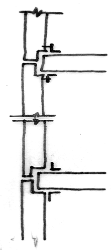
- Curtain wall minimizes the load imposed upon the structure and foundations,
- It protects the building against climatic conditions better than stone cladding,
- It is a more flexible system compared to stone cladding at expansion joints,
- Its design is compatible against earthquake.

After all these discussions the following classification is proposed by the researcher for stone façade systems (Table II.1).

1. Masonry stone wall;
2. Stone as an integral part of the wall;
3. Stone cladding on the main body of the wall;
    3.1. Stone cladding installed with mortar;
    3.2. Stone cladding installed with mortar and mechanical fixing;
4. Ventilated stone façade;
    4.1 Stone cladding with metal fixing anchored directly to the back-up load bearing or non-load bearing wall;
    4.2 Stone curtain wall with metal fixing anchored to the load bearing structure;
        4.2.1 The stick system;
        4.2.2 The unit system.

The classification is based on the transfer of dead and live loads of stone facade to the structure. In stone cladding systems, the loads of stone panels itself, wind, earthquake etc. in the stone façade system are transferred to the back up bearing or non-load bearing wall directly. In the stone curtain wall, the loads are transferred to the load bearing structure of the building through a sub frame.

TABLE II.1. Classification of stone facade systems .NOT TO SCALE

					1960's
1. MASONRY STONE WALL	**2. STONE AS AN INTEGRAL PART OF THE WALL**	**STONE CLADDING**			**STONE CURTAIN WALL**
		3. STONE CLADDING ON THE MAIN BODY OF THE WALL		**4. VENTILATED STONE FACADE**	
		3.1.INSTALLED WITH MORTAR	**3.2 INSTALLED WITH MORTAR & MECHANICAL FIXING**	**4.1. ANCHORED DIRECTLY TO THE BACK-UP WALL**	**4.2. ANCHORED TO LOAD BEARING STRUCTURE**
					**4.2.1 STICK SYSTEM**  **4.2.2 UNIT SYSTEM** 
SECTION	SECTION	SECTION	SECTION	SECTION	SECTION

The order in this classification also indicates the historical development of stone use in walls. For example, masonry stone wall is the oldest method of construction while the last item in the classification, curtain wall, is the recent and contemporary application.

The first and second type in the classification refer to the stone face masonry walls. In time it was used as an integral part of a brick or other types of walls since it is a construction material that is highly durable to weathering, but expensive and heavy. The second group, i.e. stone as an integral part of the wall, was abandoned due to the thickness of the wall. They were not the economical methods from the point of construction and land use. The inside of the wall was usually left exposed. This meant the uninsulated wall required too much energy for space heating especially during cold climates. Also, it was not possible to build the tall buildings with these systems. The exterior walls of the buildings became thinner with the invention of reinforced concrete frame construction system. After the invention of the concrete and steel framework, stone was used as a cladding material to the back-up wall due to its durability and low maintenance requirement especially in high rise buildings.

In the third type of the classification, stone was used as a cladding material installed with mortar in font of a back-up wall due to its durability and the possibility to cut thin slabs using technology. Since stone is a very dense material and does not permit evaporation of the humid air, it causes condensation within cold walls and this pushes the stone panels outwards. Thin stone panels were fixed with mechanical fixing to the back-up wall to provide strength of fixing so the 3.2 type stone facades appeared. To overcome the disadvantage of non ventilation of a dense material of an uninsulated wall, ventilated stone walls were developed. It was possible to provide insulation and ventilation of the humid air between the wall and dense stone cladding. Schaupp (1967:52-53) indicates that this building physics failure as a development of the ventilated stone cladding and named this as a stone curtain wall but the curtain wall had to carry some other properties. In group 4.1 the loads are transferred to the back up wall and not to the load bearing element of the building, although it is ventilated.

The term ventilated wall was used for the constructions where stone panels were fixed with spacing element between panel and wall.(Guillen, wieved in 2003). This space provides air let in the bottom and out at the top. In case the façade material gets wet, it gets dry with the help of ventilation. Ventilation also prevents the condensation within the wall.

Stone claddings to the main body of the wall and ventilated stone façade with metal fixing anchored directly to the back-up load bearing or non-load bearing walls are called cladding in this thesis. The ventilated stone façades with metal fixing anchored to the framework which is carried by the load bearing structure of the building is called stone curtain wall to clarify the terminology confusion. The stone curtain wall concept satisfies all the requirements of the curtain wall since it is a non-load bearing external envelope, which is suspended by its own metal frame of a building. The loads are transferred to the structural frame of the building through a rectangular grid or as large panels spanning from one load bearing element to another. Ventilated or unventilated stone cladding facades have some problems due to direct connection to the back-up wall. In order to reduce these problems, stone is used as a curtain wall infill material but stone curtain walls still have some failures and show low performance.

Carrying out a literature survey, classification of stone facades in the USA, Europe and Turkey is reviewed in this chapter, and a new classification system is proposed by the researcher, which is based on the accumulation of knowledge in this subject. The elements consisting of stone cladding and stone curtain wall i.e. stone, fixing, mortar, joints, back-up wall affect the performance of stone facades and the details of the failures related with the components of stone facades are discussed in the following chapter, Chapter III.

CHAPTER III

PERFORMANCE OF STONE FACADES

Each component of a building has a function and should resist effects. The behavior of these parts related with their function is called performance (CIB Master List:7). As an example, the performance of an external wall is mechanically resistant and stable, safe, comfortable. The satisfaction level of these requirements affects the performance of the exterior wall, which it is determined via the technical specifications, regulations and standards.

Criterion is defined as an indication to measure something (Hasol,1998:341). In the exterior wall example, it should prevent the intrusion of water, air from inside to outside and vice versa; should be resistant to chemicals, mould attacks etc; should be structurally stable and should have a long service life span; should be transparent or opaque. These are the criteria to satisfy the performance of exterior walls.

The performance requirements of construction products are listed as follows (CIB Master List,1993:9) :

A. Mechanical resistance and stability;
B. Safety in case of fire;
C. Hygiene, health and the environment;
D. Safety in use;
E. Protection against noise;
F. Energy economy and heat retention.

The performance criteria of the building envelope are listed in BS 8200 (1985) as : 1. Size and weight 2. Appearance 3. Strength 4. Strength: Impact 5. Strength: Fixing 6. Fire 7: Air Permeability 8. Permeability to Water Vapor 9. Moisture Content 10.Water Absorption 11.Water Penetration 12. Capillarity 13. Moisture movement 14. Effects of frost 15. Effects of weathering atmospheric pollution and chemical attack 16.Thermal Properties 17.Protection against Solar

Radiation 18. Effects of Change in Temperature 19. Effects of Sunlight 20.Sound transmission 21.Junction 22. Durability and design Life 23. Safety and Security.

The Interdepartmental Subcommittee for Component Coordination (1971:1-26) made a similar classification in the technical note for the performance criteria and requirements of the external walls. It is indicated in Table B.1 in Appendix B by the researcher. The details of performance criteria are listed in the CIB Master List (1993:9-12) and BS 8200 (1985:4-18) is also placed in Appendix C.

All these items extracted from the standards, codes and technical reports were used as a source to evaluate the performance criteria of stone facades. The external wall as a component of a building envelope is the most salient element of a structure. While the interior of a building is perceived only by its users, the exterior wall is evaluated by the users and also by the environment. As a result, the appearance, safety, comfort and long term performance of a building's external wall become important properties for both users and its environment.

The durability of stone itself is not enough to obtain high performance in the stone façade. The deficiencies of the stone facade obtaining process, such as poor design, low workmanship, wrong material specification, incompatibility of stone with other façade elements and environmental factors affect the performance of the stone façade. As Perreault (viewed in 2003) emphasizes the individual performance of building materials can be predictable but it may perform differently as a building component. The expected properties from a building façade determine its performance. The satisfaction of these properties provides high performance.

The properties of the stone façade components, their effects on the performance of the whole system and the failures and reasons behind theses failures of the components and the system are discussed in this chapter to indicate the problems. The standards are reliable sources in coping with failures. The European Union Standards (EN), the British Standards (BS), the American Standard Test Methods (ASTM) and the Turkish Standards (TS) related with each stone facade component and as a system have been reviewed after the determination of the failures related with the components and the system. The failures of each component and system of stone facades have been observed in the case studies of sample buildings chosen from literature and Ankara. The active status of standards and codes in some European Countries, the US and Turkey on stone, stone cladding and curtain wall have been reviewed at the end of this chapter.

III.1 Performance of the Stone Façade Components and Related Standards

The classification of stone facades made in the previous chapter guides to the components of stone cladding and stone curtain walls. The components of stone cladding walls are:

1. Stone,
2. Mortar (If exists),
3. Metal or wooden fixing elements,
4. Backing structure.

Stone curtain wall components are:

1. Stone,
2. Fixing-Metal Frame,
3. Joints,
4. Backing structure.

The components of stone cladding and curtain walls like mortar, metal or wooden fixing elements are introduced and discussed separately in the following sections. Besides the components of the stone façade system, workmanship, maintenance, service life span and climate also affect the performance of stone cladding and the stone curtain wall. The performance items that are reviewed for stone facades are: 1.Stone 2. Fixing 3. Mortar 4. Joints 5. Backing Structure 6.Workmanship 7.Maintanance 8. Service Life Span and Durability. These items affect the performance of stone facades as explained below.

III.1.1 Stone

One of the most important factors affecting the performance of stone cladding and curtain wall is the type of stone used. Stone is defined as rock shaped according to man's need and its basic material is the earth's crust (Winkler,1997:1). The physical and chemical properties of stone depend on the minerals of which it is composed and on the process by which the parent rock has been formed up to the time of extraction (Winkler,1997:1 and Smith,M.R.,1999:360).

III.1.1.1 Types of Stone

Based on the origin of formation, rocks can be grouped as follows:

A. Igneous;
B. Sedimentary;
C. Metamorphic rocks.

A. Igneous or magmatic rocks: They are crystallized from a fiery fluid silicate melt. They can take place either deep below the earth's surface or at the surface. Granite and basalt are most common of this group.

B. Sedimentary rocks or layered rocks: They are formed by the concentration of inorganic or organic debris of variable size and shape. They are deposited by mechanical or chemical precipitation. Some examples are conglomerate, sandstone, shale, limestone marble, dolomite, travertine and onyx-marble.

Some of sedimentary stones especially sandstone have a tendency to absorb water. If the thin stone is placed with its bedding plane parallel to the face of the stone, it absorbs more. The bedding plane is a horizontal plane where the layers of sediment are formed. Water inside the stone freezes and expands, layers spall and exfoliation occurs (Nashed,1995,161). This is the evidence of the reason underlaying the travertine stone façades' performance deficiency in Ankara as it is studied in the following part of this chapter. If moisture charges with salts and this penetrates to the stone, crystal growth can occur below the stone surface and this causes stress on the pores of the wall. The result is flaking (Nashed,1995,161-162; Fitzner et al. 1995; Richardson, 2001:107).

C. Metamorphic rocks: These are the recrystallized igneous or sedimentary rocks with the effect of temperature and pressure. Slate, crystalline marble, quartzite, green stone and serpentine are some examples of this group.

Chacon (1999:175-200) gives a guideline for the selection of granite, limestone, marble, metamorphic stones for the compatibility of different applications (Appendix D).

The problems related with stone according to Fitzner, *et al.* (1995:41-87) are listed as follows (Figure III.1):

a. **Loss of stone material:** This may be in the form of a)back weathering; b)relief; c)Break out.

b. **Discoloration/deposit:** Stone color modifies due to deposits on the surface or near surface. Deposits can show itself in the shape of a)discoloration; b)soiling; c) loose salt deposits; d) crust; e) biological colonization; e) discoloration of crust; e) soiling of crust; f) loose salt deposits of crust; f) biological colonization of crust

c. **Detachment:** This is described by Fitzner,et.al (1995:49)as the actual detachment of stone material. It may be in the form of a)granular disintegration; b)crumbling; c)splintering; d)flaking; e)contour scaling; f)detachment of stone elements on the stone structure; g)detachment of crusts from the stone material; h)granular disintegration of flaking; i)granular disintegration of crumbling; j)crumbling of splintering; k)crumbling of contour scaling; l)splintering of contour scaling.

d. **Fissures/Deformation**: Individual or intersecting fractures in the form of single fissures or systems of fissures due to natural or constructional causes (statistical stress, wedge work of rusting iron etc.) and deformation is the bending/buckling of mainly thin stone slabs due to plastic deformation, especially in marble slabs. The formation may be in the shape of a)fissures; b)fissures dependent on stone structure of splitting up: c)deformation.

The synonyms of these terms in Turkish are located in Glossary (Appendix A)

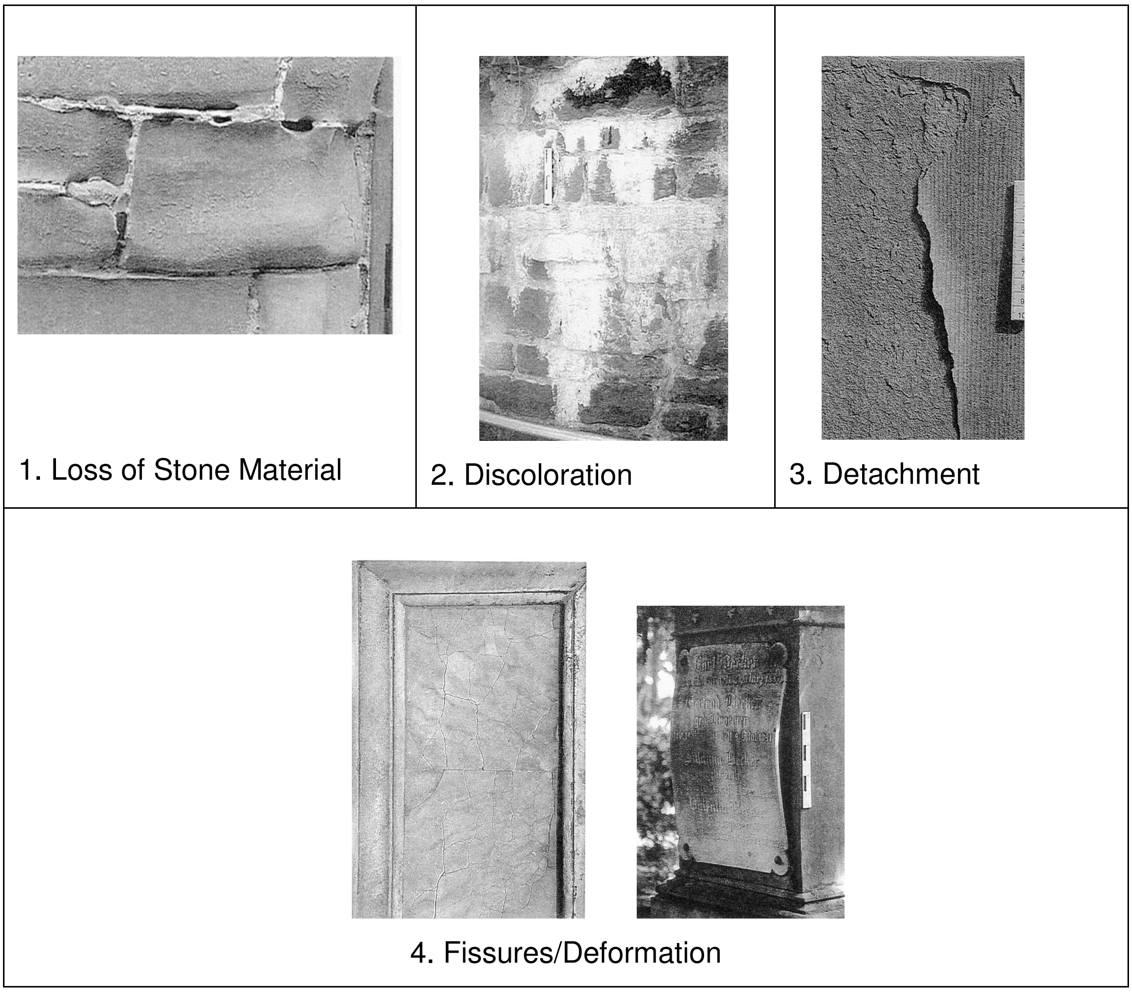


Figure III.1 Problems related with stone (Fitzner *et al.*1995:55,63,67,71).

The BS 8298(1994) Code of Practice for Design and Installation of Natural Stone Cladding and Lining groups the stones which are used for cladding into four:
a) Granites b)Marbles and hard limestones c) slates and quartzites d) limestones and sandstones.

III.1.1.2 Physical Properties of Stone

The information on the physical properties of stone helps us to evaluate the performance of stone cladding and curtain wall. Winkler (1997:32-61) lists the physical properties of stone as:

1. Rock Pores and Porosity;
2. Water absorption;
3. Bulk Specific Gravity;
4. Rock Hardness;
5. Compressive Strength;

6. Tensile Strength;
7. Modulus of Rupture;
8. Modulus of Elasticity;
9. Thermal Properties of Mineral Rocks;
10. Dry to Wet Strength;
11. Ultrasound travel in Stone;
12. Light Transmission.

If the stone were to be chosen as a cladding material, its weathering resistance and bending strength would be at top values. Smith (1999) lists the properties that have to be checked for stone usage for masonry, cladding and curtain wall material are as follows:

A. Compressive strength;
B. Bending strength;
C. Tensile strength;
D. Elastic Modulus;
E. Thermal and moisture movement;
F. Weathering resistance;
G. Precision workability and 'polishability';
H. Color variability and permanence;
İ. Abrasion resistance;

Abrasion resistance is not important for cladding and curtain wall.

The physical and mechanical properties of stone that can affect the performance of stone facades are :

a. Rock Pores, Porosity and Density **b.** Appearance and Dimension **c**. Petrographic Properties **d.** Compressive Strength **e**. Flexural Strength/Modulus of Rupture **f.** Thermal and Moisture Movement **g**. Wear and Weathering Resistance

a. Rock Pores, Porosity and Density: Porosity is the ratio of the volume of pore space to the total volume in percent. The formation of stone affects the porosity. Igneous stones have very little open pore space, sedimentary stones are subject to great variations, and metamorphic stones have minimum pore spaces (Winkler, 1997). The rate of open pores affects the water absorption of the stone panel.

BS 8298(1994) specifies the maximum dry weight of cladding stones between 2.500 kg/m3 for limestone to 2.750 kg/m3 for granite. For the general guidance purposes, 3.000 kg/m3 dry weight can be used to calculate the maximum load to be carried, which will also allow for cladding stones given in Table III.1. For the design of the fixings, the actual density and porosity of the particular stone should be ascertained and used.

Table III.I Maximum masses per square meter of cladding stones (BS 8298,1994:5).

Stone	20 mm thick kg/m	40 mm thick kg/m	50 mm thick kg/m	75 mm thick kg/m
Granites, marbles, hard limestone, slates and quartzite	60	120	a	a
Lime stones and sandstones	a	a	150	225
a These stones are not normally used as cladding at these thickness				

If the stone panels are heavier than the weight fixings and mortar can carry, it may fall down and not satisfy the safety requirement of the building envelope performance.

b. Appearance and Dimension: The stone panel surface finishes of different types of stone are listed as follows in BS 8298(1994:5):

1. Granite: polished, eggshell or honed,
2. Slate: riven, flame tectured, sawn or fine rubbed,
3.Quartizite: riven
4.Limestone and sandstone: fine rubbed, tooled, sawn or riven.

BS 8200 (1985:4) requires that an acceptable degree of variation should be established in agreement with the manufacturer from samples. The surface finishes should be homogenous to be acceptable from the point of performance criteria. Surface finish may affect the performance of stone facades. The textured finishes may collect dirt, or marble may lose its after some time.

The accuracy of the dimension of stone panels is very important for stone cladding. EN 13373 (2003) -Determination of geometric characteristics on units- describes how to measure the length, width and thickness of stone panels, and their required tolerances are determined in EN1469 (2004E:6-7) i.e Natural Stone Products – Slabs for cladding-Requirements.

Table III.2 Minimum Thickness of Stones (BS 8298,1994:11).
NA Not Applicable

Stone location	**Stone Types and Recommended Thickness (mm)**			
	Granite Homogenous Marble Slate Quartzite	Travertine Hard Limestone (e.g. Portland, Bath, Clipsham)	Brecciate Marble	Limestone Sandstone
Less than 3.7 m above ground or floor level and continuously supported (inc. fascias)	20	20	20	50
Fascias less than 3.7 m above ground or floor level (inc. fascias)	30	30	NA	50
More than 3.7 m above ground or floor level	40	40	NA	75
Soffits (including inclined soffits)	40	40	NA	75
Sills, copings and supported reveals	30	30	NA	50
Stone faced concrete units	30	30	NA	50

BS 8298 (1994:33) specifies that no stone should have a finished thickness less than 19 mm except in case of riven slate and quartzite.

The required thickness of the stone panels for different types of stone used in cladding is specified in Table III.2 (BS 8298,1999:11). The thin stone panels may not durable be against weathering and can not resist the loads transferred from fixing elements.

c. Petrographic Properties: Petrographic examinations determine the physical and chemical characteristics of the material. EN 1469 (2004) requires petrographic description according to EN 12407. The petrographic properties may be a guide to the long term performance of stone cladding. The results of this test have to be examined carefully at the design stage.

Although ASTM C 295 is a guide for the petrographic examination of aggregates for concrete, EN 12407 is especially for natural stone test methods – Petrographic examination.

d. Compressive Strength: Smith (1999:362) states that this property of stone is important for load bearing and self supporting masonry. The failure of masonry under vertical load is caused by the horizontal tensile strength of the stone, not the vertical compressive strength. Where stone was used as facing, bonded to backing brickwork, the lower strength of the backing would be the factor affecting the load-carrying capacity of the wall as a whole. Although Smith (1999:362) states that this is an important property of stone for the masonry stone wall, it is also important for stone cladding. Schaupp (1967:58) gives attention to the effects of structural movement on stone panels. According to Schaupp (1967:58), the main cause of the relative movement is the shrinkage and creep of the structural frame. When compared to the former days, stone is now applied at considerably higher permissible stresses and concrete and masonry strengths. The binding agents have become harden more rapidly. With the new structural possibilities, loadbearing structures become slender and reserves of stress ever smaller. The speed of construction and the cost of scaffolding have increased; therefore, the cladding works start at an early stage of construction. The shrinkage of the reinforced concrete is transmitted to the cladding. Since natural stone has been laid down over millions of years under pressure and at an intense heat, it no longer shrinks or expands. There can be no reliance on adjustments of the stresses involved on stone despite the structural movement. This situation creates an important problem by bearing compressive strength on stone panels.

Beasly (1998:80) points out that the thin stone cladding elements and narrow corner pieces of stone have weak compressive strength, and this causes failure due to thermal expansion and shrinkage of the concrete.

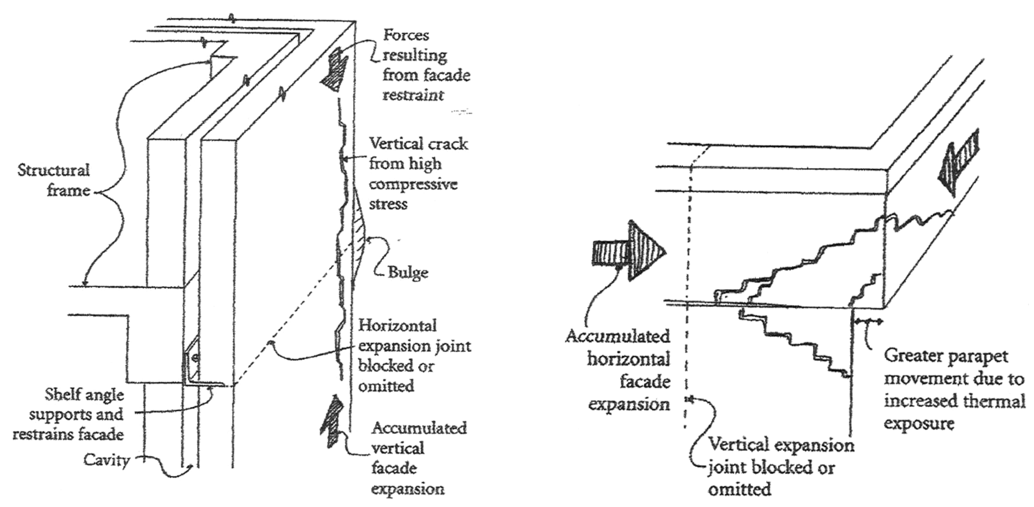


Figure III.2 Stone façade stress failure (Beasley,1998:80).

ASTM C170-90(1999) Standard Test Method for Compressive Strength of Dimension Stone defines the test method to determine the compressive strength of dimension stone (ASTM web page viewed in 2005). This standard is only related with the test method but National Building Granite Quarries Association recommends 19,000 psi or 131 MPa compressive strength for granite.

EN 1926 (1999) is the European Standard of the testing to determine the compressive strength of stone. Although there is an EN standard for the determination of compressive strength, this physical property of stone is not placed as a requirement in EN 1469 (November 2004)- Natural stone products-Slabs for cladding-Requirements.

e. Flexural Strength /Modulus of Rupture: Flexural strength indicates the strength in tension or in bending. The modulus of rupture shows the shear and diagonal strength of the stone and it is a valuable result in determining the strength of stone at the point of attachment with an anchoring device (Chacon,1999:176-177). Tensile strength is often replaced with the modulus of rupture, a combination of compression and tension (Winkler, 1997:45).

Stone elements that have to carry loads perpendicular to their largest dimension have to work in bending. At low levels of loading, bending causes stresses and it increases linearly from the middle plane of the member towards the faces. These stresses are compressive on the top surface and it becomes concave, so the original flat member bends and tensile on the back surface that becomes convex. As the loading increases, the neutral axis moves towards the concave (compressed) face, this force increases at a rate greater than linear, the tensile at a rate less than linear. As this leads to a greater part of the cross section under tension, the probability of a local weakness, such as a microcrack or grain boundary, triggers a tensile failure (Smith,1999:362).

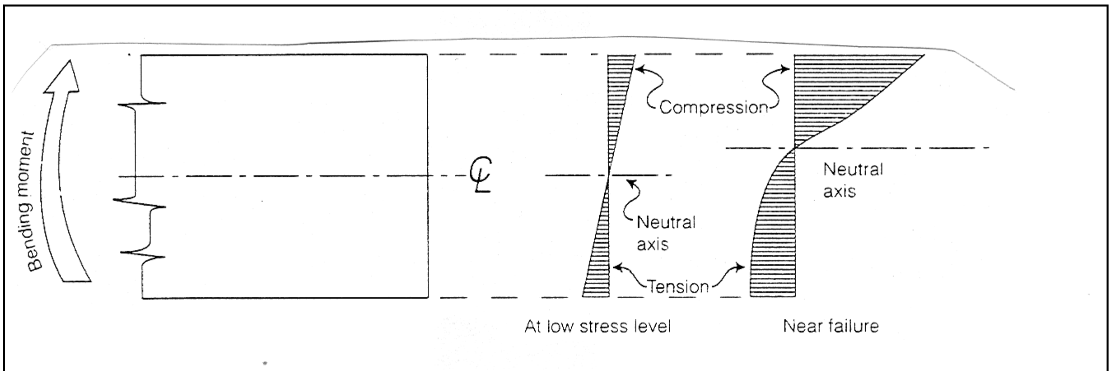


Figure III.3 Diagram of stress distribution under bending in a section (Smith ,1999:362).

The surface treatment of stone with bush hammering and thermal finishes decrease the thickness of the stone and this decreases the bending strength.

Although the curtain walls are non- load bearing walls, there is a horizontal wind load. The design for wind loading depends on

1. degree of exposure;
2. location of the building;
3. height above ground. (Vandenderg, 1975:152)

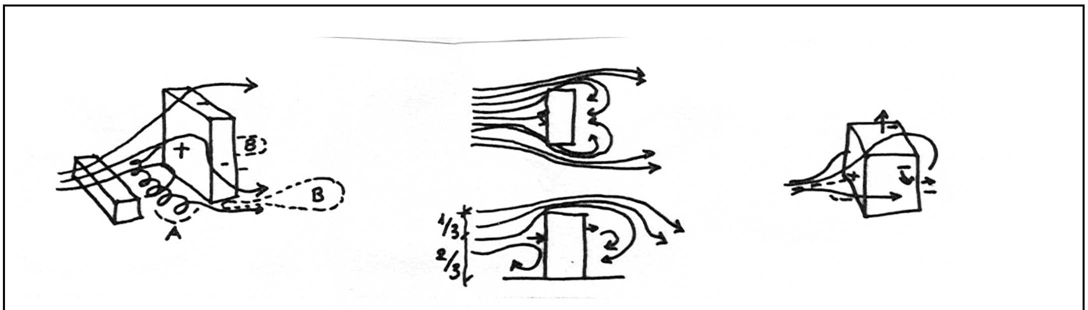


Figure III.4 Wind flow patterns around tall buildings (Modified from Blyth ,1990,225).

Wind produces negative and positive pressure on the curtain wall and these affect the design of anchors, fixings and glazing beads. Wind can cause deflection on curtain walling members. Deflection may be both ‘in’ and ‘out’, alternating at high frequency (Figure III.4).

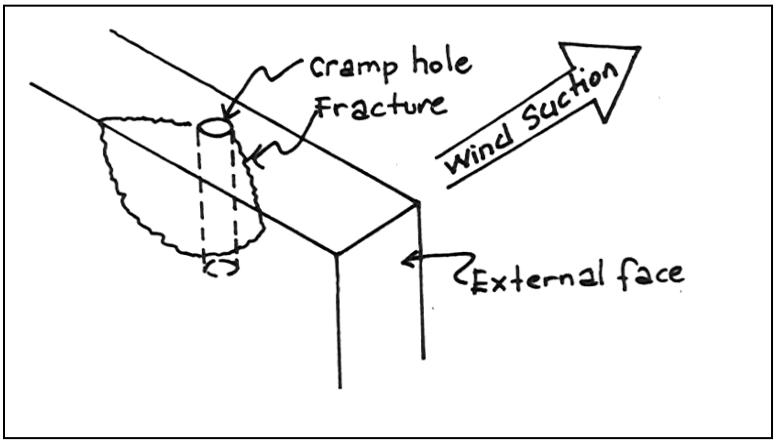


Figure III.5 Curtain wall stone element failure due to pull out of fixing cramp. (Modified from Smith, 1999:363).

Earthquake is another external factor which creates stress upon stone panels and fixing elements besides wind. Common cladding failures are due to poor location of panels during fixing and location of fixing holes. The thickness of stone panels affects this performance (Richardson;2001:137). Vandenberg (1975:153) emphasizes that complex junction details are used to allow movement between sections, but all elements should work together.

The thickness of stone affects the constructional performance of the façade. With improvement in technology in the mid 1970's, cutting marble and granite slabs to a thickness of 3 cm became possible ,and by the early 1980's thinner stones were used on buildings all over the US.

Today, granite of 2.5 to 3 cm thick, or even thinner panels are used as exterior cladding on high rise buildings around the world. The cladding experts spend most of their efforts to determine the optimum thickness by checking mid-span thicknesses against design wind loads. They compare design flexural stress with test results from small samples of the actual material to be used in order to verify a safety factor of 3.0 (Larkin 1998,65-67). The thickness is increased to prevent aging, loss of strength caused by exposure and the effects of weathering in some cases. Concentrating solely on flexural strength may cause potential problems at the stone's connection points. Larkin (1998) claims that if the flexural strength is the governing design factor, stone failure or breakage may occurring at mid span or between support points. The mid span failures are not common in thin stone cladding since projects have adequate safety factor or they have not been subjected to the design load event. The localized edge damage on stone façades is a common problem for stone cladding and curtain wall.

Larkin (1998, 65-67) has proposed engineers to focus on concentrated reactions at support points as free span analysis with the popular use of 2 and 3 cm thick stones. Other factors affecting localized edge damage are details, fabrication and quality control, shipping, handling and service life conditions.

There are two EN test standards to determine the flexural strength of natural stone these EN 12372 (1999) and EN 13161(2001) . The former determines the flexural strength under concentrated load and the latter is related with the flexural strength under constant moment. ASTM C 99 and C 880 are the standard test methods to determine the Modulus of Rupture and Flexural Strength of the natural stone. Although these standards are determined test methods NBGQA (viewed in 2005) determines minimum value of modulus of rupture for granite as1,500 psi (10,34 MPa) and flexural strength value as 1,200 psi (8,27 Mpa).

f. Thermal and Moisture Movements: Schaupp (1967:58) emphasizes that the heat of sun affects the surface of the cladding. The surface becomes warm while the backing maintains the old cold temperature. If there is a ventilated air gap and thermal insulation behind the slabs, thermal transmission from cladding to the backing is retarded. The cladding slab suffers from heat accumulation, i.e. the temperature increase proceeds too quickly and too forcibly so, which displacement in relation to the backing occurs. At night cladding cools quickly, this causes a reverse movement, i.e. joints may be subjected to tensile stresses and may open up. This event disturbs the bond and the water tightness of the joint. The absorption of the radiated heat depends on the color and surface. If different types of stones that have different color and texture are used in the same area of cladding, there will be great variations in temperature between the slabs and this may also cause displacement. The rise and fall of outside temperature cause movement too. The reason for this may be the shadows of the neighboring buildings. The fact that one part of the façade may be subjected to sun while another part remain in shade may lead to displacement. Nashed (1995:160-161) and Gerns (2000:42) used the term 'hysteresis' for permanent volume change due to temperature differences of stone panels.

Smith (1999:363) explains the effects of thermal and moisture change on stone in a similar way. When the temperature of an unrestrained body increases, it gets longer, and this elongation will be proportional to the original length to the temperature increase. This situation is different for different materials. The thermal expansion coefficient is the increase in length, per degree of temperature arises divided by the original length. When the moisture content of a body increases, it will get longer and this elongation will be proportional to the original length and the rise of moisture content. This event is the same for different materials. The moisture content is usually defined as the mass of water in a given volume of the stone, divided by the oven-dry mass of the same volume. Some sedimentary stones display drying shrinkage between extraction and in the finished work. The stresses caused by restraint of movements due to environmental fluctuations can be in the same order as those caused by gravity and/or wind loads. The external face, if exposed to the sun, may reach temperatures 40-50 ^{o}C above the mean during early afternoon, whereas at night, the face temperature may drop to about 10 ^{o}C below the mean. These expansions and contractions of the external face are restrained by the mass of the masonry that remains at the mean temperature. In time, this internal restrain causes stone to crumble.

Where stone is used as a facing to masonry, a temperature change that is the same for both materials can cause one to expand more than the other if their coefficients of thermal expansion are different. For curtain walls, the restraint of temperature movements due to the stiffness of the fixing devices can lead to high stresses at the holes and rebates in which the fixings hold the stone.

Temperature movements are usually fully reversible. But in some certain stones, such as some marbles, temperature expansions do not reverse completely on cooling. It leaves a residual permanent elongation and stone weakening is observed as a loss of flexural strength. There are examples where marble cladding panels have distorted and bowed as a result of thermal cycles and this has been attributed to differential expansion and creep induce by the weakening of the panels.

Thermal and moisture expansion coefficient is one of the most important properties of stone affecting the performance of stone cladding and stone curtain wall. Schaupp (1967:58) also explains the problems of stone facades due to thermal and moisture movement. Natural stone is very dense, and therefore good for protection from weather but it has some drawbacks as regards the drying out the building. Sometimes, the opinion that slabs should be given a coat of bitumen paint on the back before fixing is even expressed so, the moisture does not penetrate from the mortar bed, and no efflorescence or saturation from the building structure may give rise to staining. This idea also has a drawback. In most of the year the vapor pressure prevails from inside to outside. When this process is checked or delayed by denser materials or paints on the cold outer side, condensation may develop and, this causes sudden vapor pressure in strong sun shine or formation of ice at low external temperatures. In both cases, increase in volume and pressure from the facade to outwards occur. The solution of this is to ventilate behind the façade and not grout up with mortar.

BS 8298 (1994:29) emphasizes the importance of thermal movements, gives the coefficient of thermal expansion of building materials and an example of how to calculate thermal movement.

g. Weathering and Wear Resistance: Smith (1999:365) evaluates weathering in two groups which are: Chemical resistance and frost resistance.

g.1 Chemical Resistance: The chemical resistance of natural stone is important especially in polluted areas where acidic gases are present. Other chemical attacks may be spread from roads treated with de-icing salts and some cleaning agents particularly those used for stone cleaning. Limestone, calcareous sandstones and metamorphic slates containing significant amount of calcium carbonate are the types of stones that are particularly affected by acidic gasses. Weathered igneous rocks can also contain calcium carbonate and therefore be susceptible to chemical weathering. Chemical weathering can affect igneous rocks, for example granites, but the timescale over which weathering takes place is usually much longer than the expected life span of the building (Smith,1999:365).

BS 8298 (1994) proposes to check the effects of air pollution on the other buildings in the district as a design criterion.

g.2 Frost Resistance: Freeze-thaw resistance is important for stones used locations where temperatures drop below freezing for extended periods. The effects of freeze -thaw on a stone depend on:

The temperature the stone is exposed to,

The porosity and pore size distribution.

The amount of water present in stone at the time of freezing as it is the formation of ice crystals that leads to the distribution of the structure of the stone. Stones with low porosity, such as marble, or stones that are dry will have little water within their pore structure and therefore ice will not form when freezing occurs (Smith;1999:365; Richardson, 2001:107)

BS 8298 (1994) advises that stone should not be affected by frost and open joint is not recommended for some types of stones such as the softer limestone.

Abrasion and slip resistance of stone mentioned by Smith (1999, 365) are not important as much as the other properties of cladding and curtain wall use. They are mostly important when stone is used as pavement material.

Since stone is a natural material, it is very difficult to measure its properties as in manufactured materials. Each type of stone has different physical and performance characteristics because of its geological formation. Standard test methods have been created to measure the physical properties of stone to use it in a building system such as a curtain wall design or vertical application as a veneer on a building exterior.

III.1. 2 Fixing

The second component affecting the performance of stone cladding and the stone curtain wall is the fixing element of stone to the back structure or frame. Some types of stone swells up as they absorb water and distort when they dry out at different speeds. This creates great stresses on wall ties. Therefore, they have to be designed accordingly (Schaupp,1967:58).

The factors affecting the performance of the fixing are as follows:

A. Materials of fixing;

B. Types of fixing;

C. Fixing design;

D. Fixing Anchorages;

E. Layout and position of fixing (Smith,1999:357).

III.1. 2.A. Materials of Fixing: Smith (1999:357) defines the important properties of the materials used in stone fixings as:

- strength and stiffness,
- corrosion resistance,
- they should not cause staining or deterioration of the stone.

Apart from these, fixings should be installed easily and they should maintenance free. The materials used in the UK are various grades of stainless steel, copper and copper alloys. British Standards do not recommend the use of any other metals or alloys. In Turkey, most of the time because of economic reasons, some fixings are stainless steel and some are galvanized. There is not any specification for the use of galvanized fixing elements in BS 8298(1994:14). ASTM C 1242-04a emphasizes that metal in contact with stone should be 300 series stainless steel. If the fixing is open to the exterior climatic conditions and it is not in direct contact with stone but exposed to weather, it should be stainless steel, galvanized steel, zinc-rich painted or epoxy-coated steel, or aluminum. Corrosion of the fixing element decreases its strength.

The use of galvanized steel as a fixing element in direct contact with stone should be reviewed in Turkey.

III.1.2. B. Types of Fixing: The cladding Part in Albion Stone WEB page (viewed in 2004) makes the following classification according to the function of the fixing of cladding:

a. Load bearing fixings,
b. Restraint fixings,
c. Combined fixings.

Smith (1999) also makes a similar classification for the fixings as follows:

a. Load bearing fixings,
b. Restraint fixings which provide resistance to wind and other lateral forces,
c. Combined load bearing and restraint fixings,
d. Face fixings,
e. Soffit fixings.

This Smith's (1999:357-358) classification has similarities with that in BS 8298 (1994:13-14) .

2.B.a Load Bearing Fixings: These fixings bear the dead weight of the cladding and they are made out of relatively heavy metal sections.

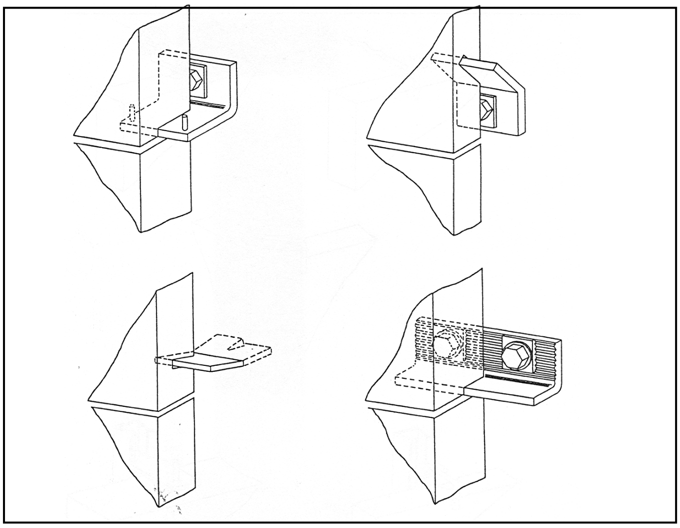


Figure III. 6 Illustration of typical load bearing fixings
(British Standards Institute, BS:8298, 1994:13).

2.B.b Restraint Fixings: These fixings restrain the cladding against applied loads and they are manufactured from relatively light metal sections.

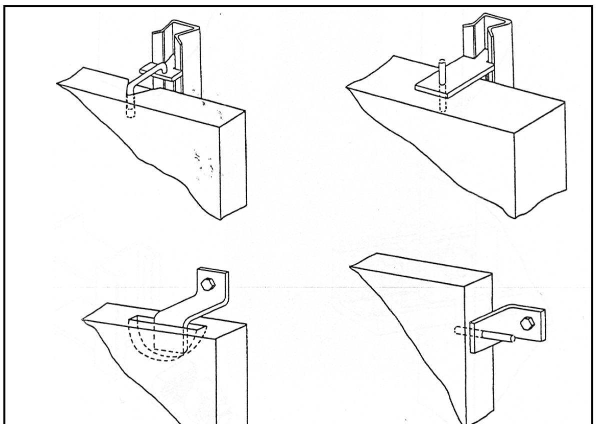


Figure III.7 Illustration of typical restraint fixings
(British Standards Institute, BS:8298, 1994:14).

2.B.c Combined Fixings: In some cases, particularly for large stone on precast units, a fixing may combine the functions of load bearing and restraint. The British Standards Institute BS 8298 (1994) states that these types of fixings should be designed to resist the positive and negative pressures and the load of the stone (Figure III.8).

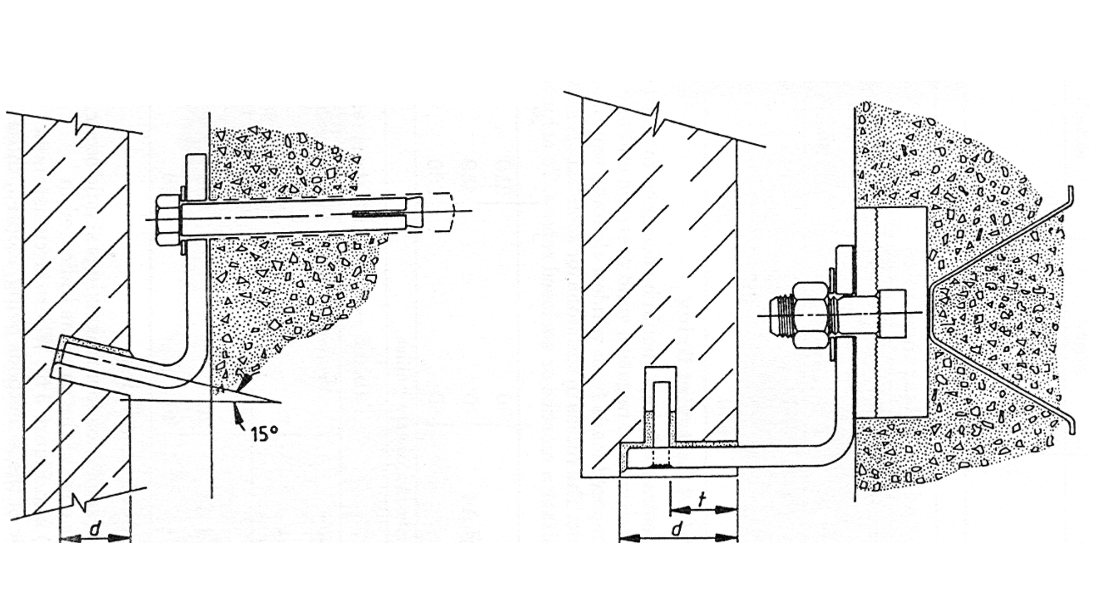


Figure III.8 Illustration of typical combined fixings
(British Standards Institute, BS:8298,1994:18).

2.B.d Face fixing: The British Standards Institute BS 8298 (1994:21) states that these types of fixings are used with marble and granite. Smith (1999:357) emphasizes that these types of fixings are used for the situations where hidden fixings are undesirable or impractical. The type of stone, however is not determined by Smith (1999:357).

2.B.e Soffit Fixing : The British Standards Institute BS 8298 (1994:21) states that soffit units are suspended from bolts or hangers which slide into anchorages cast into the structure.

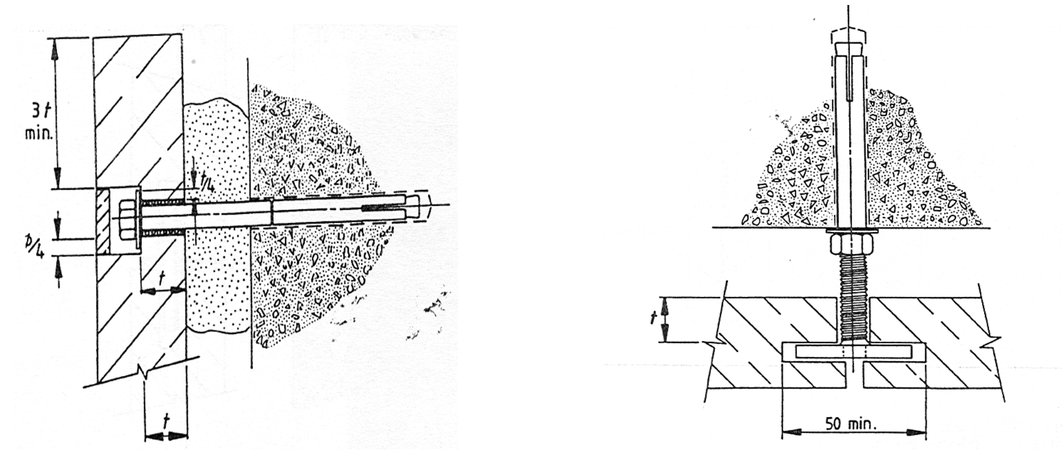


Figure III.9 Illustration of typical face and soffit fixings
(British Standards Institute, BS:8298,1994:20,21).

All the fixing elements specified in BS 8298 (1994) is for the fixing of stone directly to the back-up structure. Fixing of stone panels to frame is not specified in this standard. In ASTM 1242-04a (2005), these types of fixings are also indicated as:

a. Anchoring of stone panels directly to the building structure for support,
b. The anchoring of stone panels to subframes or to curtain wall components after these support systems are attached to the building structure,
c. The anchoring of stone panels to subframes or to curtain wall components with stone cladding preassembled before these support systems are attached to the building structure,
d. The supervision and inspection of fabrication and installation of the above.

Deniz (2003:83-93) defines the fixing points of stone panel as wall with four pins, two of which are face each other. If the pins are fixed at the horizontal edges (fixing system from horizontal edges) each stone element will have to carry pins at bottom and two holding pins at top. The lower carrying pins carry the stone elements and also prevent the lower stone element from torching and falling down. The upper holding pins prevent the stone from torching and falling down and also carry the upper stone element. If the pins are fixed to vertical edges (fixing system from vertical edges), each stone element carried with only one pin and the others hold the stone elements against torching and falling down (Figure III.10).

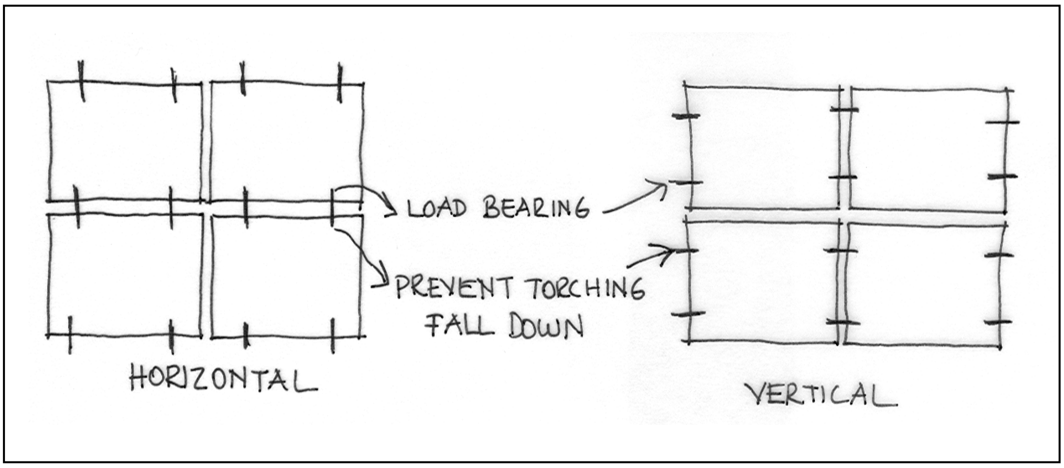


Figure III.10 The function of horizontal and vertical location of stone fixing elements.

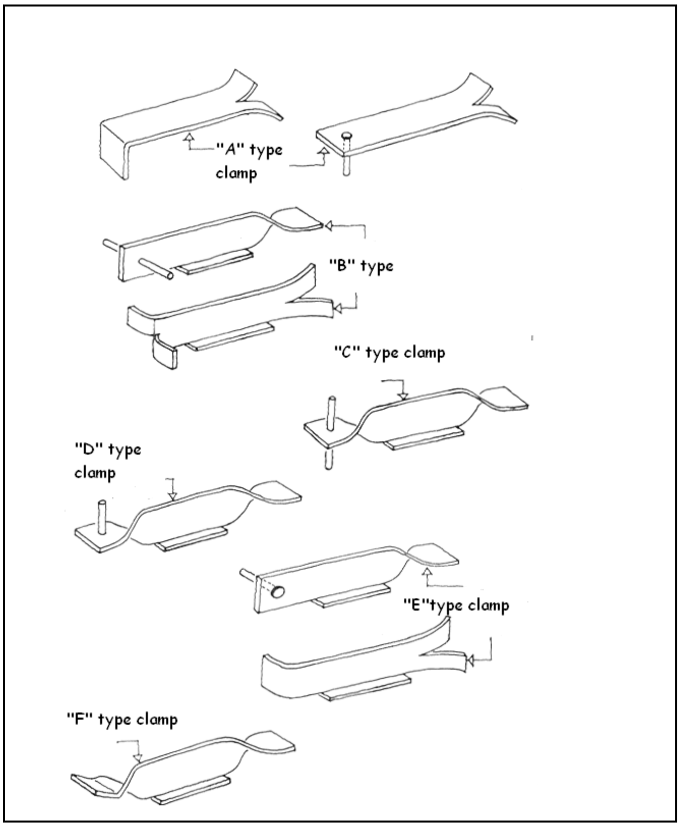


Figure III. 11 Mortar type of fixing elements for stone fixing to brick, cement or light concrete blocks (Translated to English from Deniz, 2003:88).

The function of the metal clamps shown in (Figure III.11 and III.12).

Metal Clamp A: Holding the top element

Metal Clamp B: Carrying and holding function at vertical edges of the stone elements

Metal Clamp C: Carrying and holding function at horizontal edges

Metal Clamp D: Carrying function of the bottom starting stone element

Metal Clamp E: Carrying and holding function of one of adjacent stone elements at vertical edge.

Metal Clamp F: In case of impossibility of fixing the stone element from bottom horizontal edge, the clamp is inserted to the stone element close to the bottom edge with 30mm and carries the stone element.

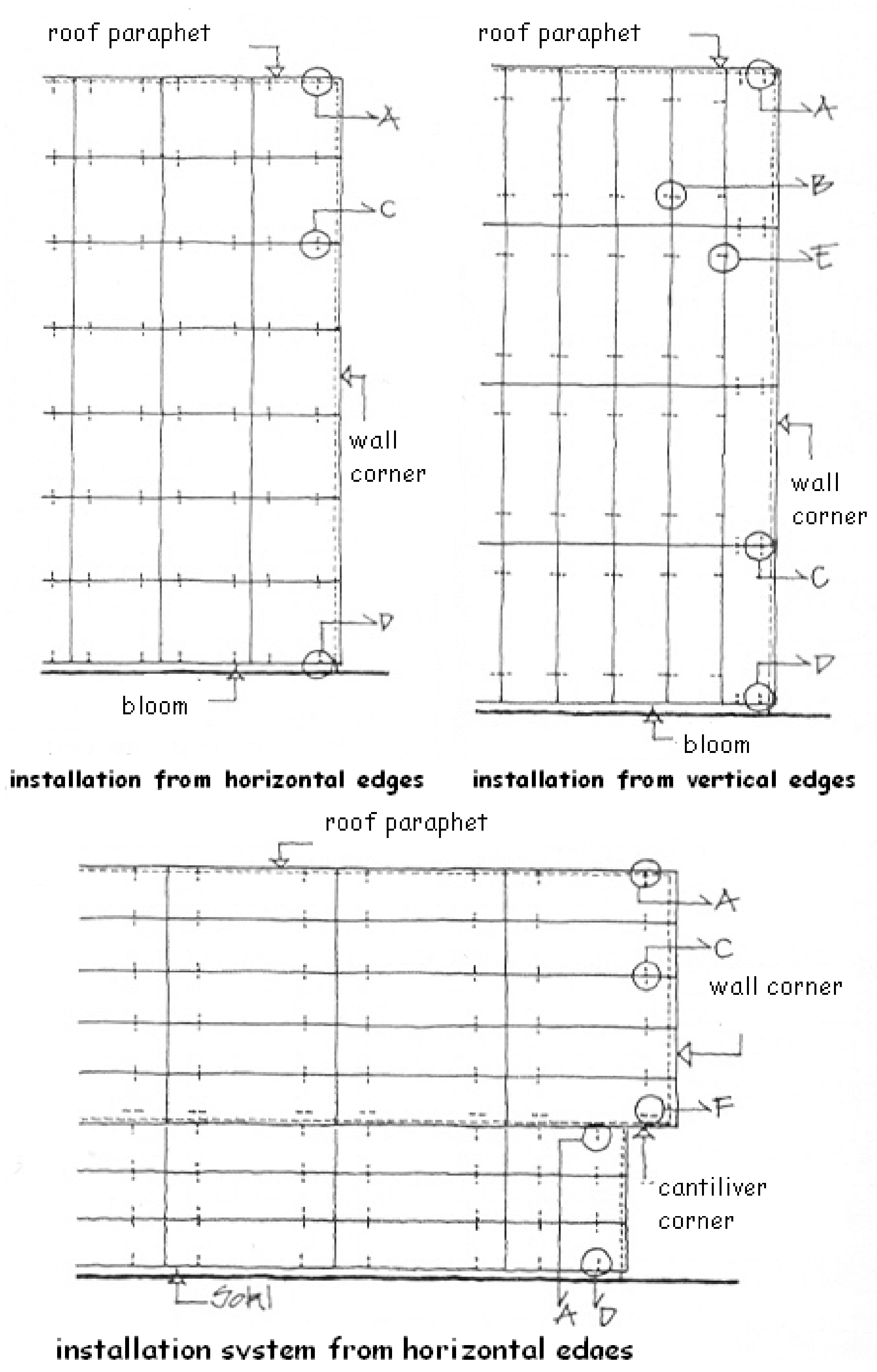


Figure III.12 Fixing elements locations on the stone curtain wall
(Modified from Deniz,2003:88)

Deniz(2003) and BS 8298(1994) classifications do no cover the fixings of the stone curtain wall that is defined in this research. These are fixing elements where stone is fixed directly to the back structure. Stone curtain walls have another section fixing element which transfer load to the load bearing structure of the building. These are generally U, L sections.

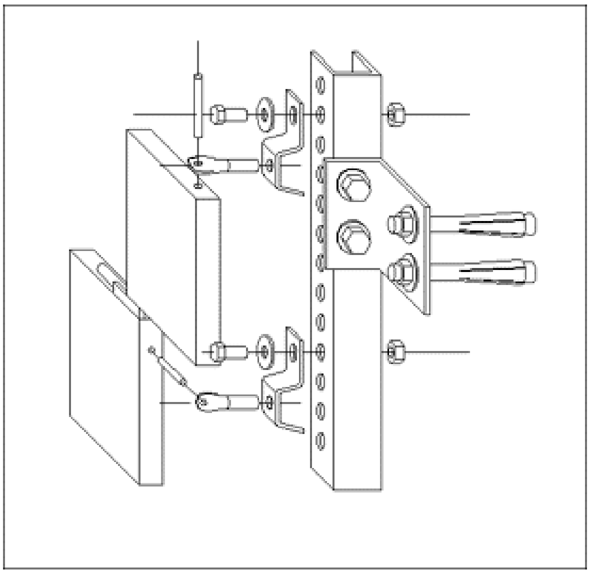


Figure III. 13 Some types of sections used for the frame of stone curtain wall (Orion Company web page-viewed in September 2005)

III.1.2.C Fixing Design: If the design of the fixing element is not realized properly, the stone falls down and detachment and cracks are inevitable for stone cladding and curtain walls.

Fixings should be designed according to the following criteria:

a. They should be strong enough to resist loads imposed by panel weight, wind, and earthquake (where applicable) and other imposed loads.

b. They should be able to accommodate movement which is predicted in the curtain wall and substructure as a result of thermal effects and structural deflection.

c. They should facilitate for adjustment which may be required to accommodate the construction tolerances.

d. They should have practicality in installation in a particular system and a particular panel fixing sequence (Smith,1999:357).

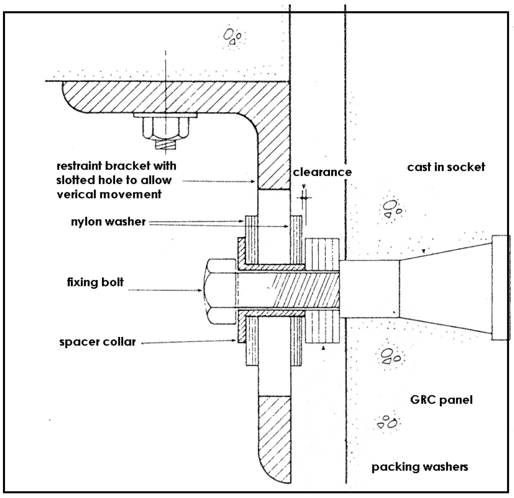


Figure III.14 Restraint fixing with allowance for vertical movement (Blyth, 1990:224).

Schaupp (1967:63) has some suggestions to increase the fixing performance for natural stone cladding facades based on experience gained from cases of damage over the last few years. These are as follows:

1. Each cladding slab must be individually and immovably fixed,
2. The method of fixing the stone slabs should be derived from a stone cutting diagram and cramping scheme, to be submitted by the mason. This should be examined by the architect and approved,
3. A structural calculation should be submitted in support of the loadbearing capacity and rigidity of the cramps,
4. Stainless steel cramps should be used,
5. When slabs are fixed to the stays by means of pins, they must be sufficiently thick to leave enough load bearing stone on both sides of the pin hole. This is generally the case for a slab thickness of 30 mm. It is not economical but safer for fixing,
6. The mastic joints create less stress on the façade. According to an individual design, every storey should have a soft horizontal joint, above which further slabs should be supported by immovable cramps. In the horizontal direction too there should be soft joints varying between 6-10 m to relieve stress. The shrinkage of the main body and expansion due to changes in temperature might cause pushing of infill panels,
7. When using cladding slabs, additional soft joints should be provided to overcome the different absorption rates,

8. If there is too much articulation of the façade, it means that a multitude of dowels becomes necessary and this weakens the reinforced concrete structure in the section,
9. On no account must plaster be used for fixing cramps; it is not waterproof and might make the metal rust,
10. Careful fitting of façade features such as windows, cornices, projecting roofs etc. has great importance where this is not a part of stonemason's responsibility.

III.1.2.D Fixing Anchorages: Smith (1999:357) states that there are different types of anchorage for fixing elements to the back construction. These include:

1. by mortar fixing of ties into pockets in the structure,
2. cast-in slots,
3. expanding and resin bolts.

The size of stone panels affect the type of fixing. If stone panels are small in size, mortar can be used but if the stone panels are large, a metal fixing should be used. According to Deniz (2003), a large size natural or artificial stone cladding (25-50 mm thick, bigger than 0,10 m^2 surface area) elements with different color and texture (granite, basalt, marble, sandstone, dense calcareous, travertine, etc.) can not be directly adhered to the main body of the wall because of their weight. For this reason, these should be fixed to the main body of the wall with galvanized or stainless steel fixing elements. To prevent the penetration of water coming from the joints to the main body of the wall and also to prevent the condensation due to lack of vapor diffusion of stone cladding, enough space (minimum 20 mm) should be left between cladding and the main body of the wall. This layer should be organized so as to be ventilated from the bottom and top. A thermal insulation layer can be placed on top of the main body of the wall. Stone cladding elements are fixed to the main body of the wall with insert or mortar type metal clamps. If mortar type metal clamp is to be used on brick or light weight concrete type massive non load bearing walls, a hole (with 40-45 mm diameter and 120-150 mm deep) perpendicular to the surface of the wall is drilled, cleaned and wetted. A metal clamp is put in this hole and cement mortar is poured into it. The entering edge of the metal clamp is twisted to increase adhering surface and a metal plate is fixed at the bottom to distribute the load. Curing of the mortar is done after the application continues.

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If metal insert type clamps (for reinforced concrete walls) are used, the fixing places are marked, and a hole according to the size of the insert (10-12 mm diameter and 100-120mm deep)is opened and the metal clamp screw with bolt is inserted and squeezed. After fixing the metal clamps, it is fixed to the holes opened horizontally and the vertical edges of the stone with fine mortar. The holes on stone should be 3-5 mm thick and 5 mm deeper than the metal clamp pin. Therefore the holes on the holes on the stone may therefore ought to be a minimum of 9 mm away from the surface of the stone whereas Deniz (2003:89) does not take into consideration the thickness of the stone panels, BS 8298 (1994:11,12) gives a table of thickness of the stone and the depth of the slot for corbel plate according to the type of stone and building height.

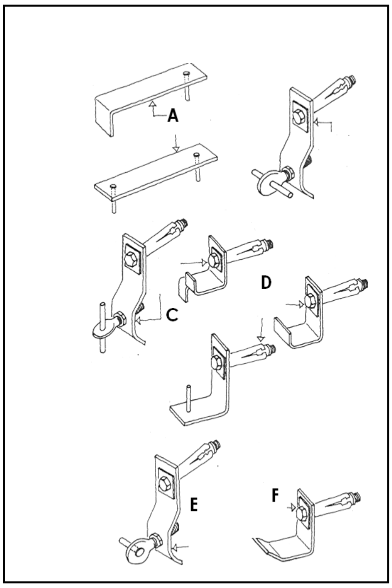


Figure III.15 Type of fixing for reinforced concrete.
The location of each type is in Figure III.12 (Deniz, 2003:89).

III.1. 3 Mortar

One of the important components of stone cladding is mortar. Its performance directly affects the performance of the facade. The purpose of using mortar is not to glue stones together but to keep them apart and seal the joints to provide weather tightness. These items are the advantages of the mortar joints but it also has disadvantages. Stowe (viewed in September 2005) lists the properties need for stone mortar used in cladding as: 1. Workability 2. Water retention 3. bond strength. Sawicki (viewed in September 2005) also mentions that the stone should be installed to the back-up structure in a manner resistant to thermal movements, shock and vibration and freeze/thaw.

The wall ties and mortar joints between stone and carcass must be firm and ensure lasting adherence (Schaupp, 1967:63). External cladding should be fixed securely to the cracking masonry by grouting with mortar behind each cladding unit in addition to cramping. In special cases, it may be appropriate to form this connection by strips or dabs of mortar.
The slab is set on a cramp in such a way that a 2-3 cm or smaller cavities remain behind it according to the permissible limits of the building than this cavity is filled with mortar.

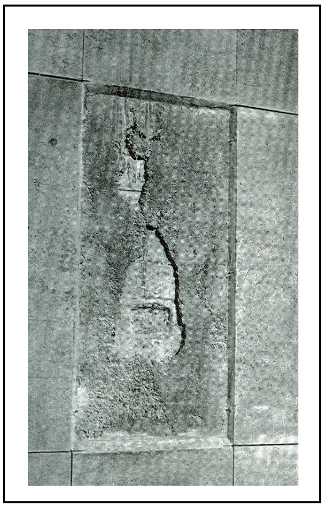


Figure III.16 Backing behind the stone cladding slabs have large cavities which produce a risk of frost damage (Schaupp,1967:61).

Large cavity increases the risk of frost damage. Water formation into ice creates pressure and this leads to displacement. Furthermore, humid air collected in this area leads to condensation and, as a result, vapor pressure creates stresses outward from the façade when the sun heats the cladding.

Schaupp (1967: 62) emphasizes that the grouting prevents the ventilation of the cladding during the building's drying out period and draining off any rainwater that may penetrate inside the wall. It also decreases the thermal insulation performance of the structure.
The properties of mortar mixes are defined in BS 8298 (1994:25-26). It states that the jointing and pointing type of mortar depends on type, size and the surface finish

of the stone cladding. Pointing mortar should be frost resistant when set on a similar strength to the jointing mortar; neither should be stronger than the stone.

Figure III.17 Efflorescence due to soluble salts in grouting (Schaupp, 1967:62).

Despite the grouting of large size cavities, the remaining cavities could be filled with water that exuded from the façade. This leads to efflorescence as the water carries soluble salts with it from grouting which crystallizes when water evaporates on the surface and the stains of efflorescence are left (Schaupp,1967:62).

It can be said that the choice and design of ventilated stone facades are the result of failures in stone cladding with mortar.

Deniz (2003:89) describes the use of mortar for stone cladding. Before the application, the surface is wetted and a thin layer of mortar in watery form is applied by striking on the surface. First, the bottom edge of the stone is adhered to the stroked layer with a cement mortar of 15-25 mm thickness. After this process, a watery cement mortar is poured to close all the voids. If there are joints between stones, they are filled with gypsum mortar first in order to prevent the flow of mortar to the surface. After the curing of the bottom layer, the upper layers are adhered with the same method, and all the cladding materials are adhered to the surface. If joint (3-5 mm) is applied between stones, it is cleaned first and filled with fine sanded cement mortar (portland, white or colored) tightly and shaped, and the residue is cleaned before curing; then all the surfaces are cleaned.

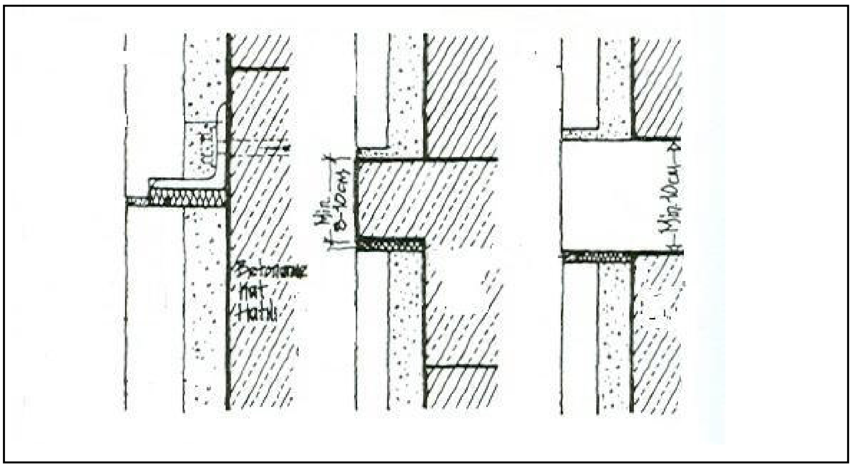


Figure III.18 Stone cladding with small panels are carried with storey cut profiles and arrangement of expansion joints (Modified from Deniz: 2003:86).

When cladding materials are fixed to a non-load bearing wall, it has to be placed on a load bearing element at each floor. Besides, to prevent the deterioration of the stone due to surface expansion stresses, elastic expansion joints (6-10 mm) should be formed at each floor vertically and at each 6 m horizontally (Schaupp, 1967).

Schaupp (1967, 62) has a recommendation for the adhesion of the stone to the backing structure to prevent the staining of the face due to wrong implementation. According to him, complete grouting has structural disadvantages. The weight of the cladding is increased unnecessarily and more stress is placed on the cramps. Dabs of mortar in the region of the cramps are generally sufficient. The dabs of mortar should not be horizontal in order to let the water drain. It is a better solution to ventilate the cladding. In this case fitting incoming air vents are located at the bottom and outgoing air vents are at the top.
The British Standards Institute, BS 8298 (1994:8), describes the materials of mortar in detail.

III.1.4 Joints

The joints are the other components of stone facades. The types of joints are listed as follows by (Smith,1999:358):

III.1.4.a Panel Joints;
III.1.4.b Movement Joints;
III.1.4.c Junctions with other elements.

III.1.4.a Panel Joints: Traditionally panel joints were filled with cement sand or cement lime sand mortar. But now elastomeric sealant particularly for marble and granite is increased. These joints are for the thermal and frost expansion and contraction of the panels.

III.1.4.b Movement Joints: These joints are used for the following cases:

- to prevent transfer of vertical loads from one lift of cladding to the next,
- to prevent transfer of loads from the structure to the cladding,
- to prevent stresses which would arise from thermal and other movements,
- to provide a continuous weather seal, while allowing movement. The width of these joints depends upon the movement expected, their spacing and the elasticity of the sealant used.

Smith (1999) has used the term stone cladding in this explanation but it is also relevant to the stone curtain wall.

III.1.4.c Junction with other elements: The former joints are in one direction. It is in the plane of the stone and perpendicular to the joint. Movement in junction with other building elements are two or three dimensional if the coefficients of the thermal expansion or the thermal mass of the adjoining elements are different from those of the stone. Sealant should not overstress in these joints (Smith,1999: 358).

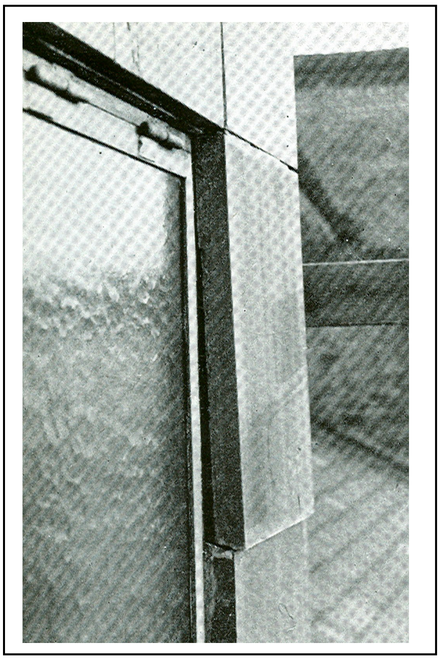


Figure III. 19 The loosing of individual slabs from the façade (Schaupp, 1967:56).

One of the reasons for the displacement of the stone may be the change in the temperature of the façade, or mechanical vibrations when the windows are opened and closed (Figure III.19). The backing is not rendered and the joints are open. Steel and wood window and door frames should not be attached to stone claddings. The movement of the metal and the distortion of timber due to swelling and shrinking cause stresses on the stone. Window frames must be attached to the masonry backing with metal ties. It is good practice to leave 3-5 mm air space between frame and stone cladding and to fill this cavity with mastic (Schaupp,1967:59).

Schaupp (1967:63) also concentrates on a similar point such as the connection between the stone façade and the window casement. One of the problems of the natural stone façade cladding is the saturation in the area of the window jambs after precipitation. Natural stone cladding can not be resistant to water pressure. Thus, rain water, humidity from inside and condensation may be collected behind the slab cladding. Window frames are set next to the stone slabs and sealed off with mastic so that water can not get out but trapped and be absorbed by the plaster on the jambs.

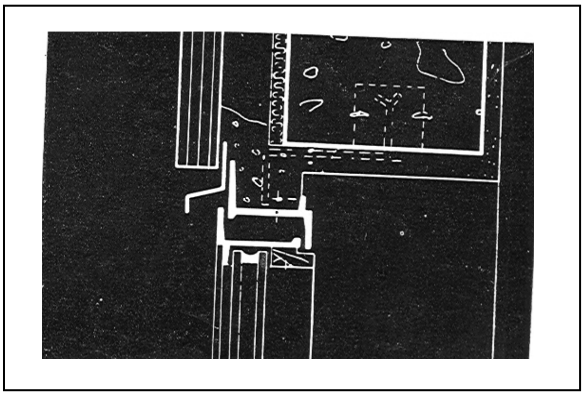


Figure III.20 Faulty detail of a window junction (Schaupp,1967:62).

Window frames must be fitted to the main structure in a way that is wind and waterproof. The space between the cladding and the backing or the internal thermal insulation layer must be drained towards the outside (FigureIII.20).

The decision of filling the joints or letting them be open should be decided at the design stage of the cladding or curtain wall system. Filling is acceptable and/or desirable if the curtain wall is designed as a sealed system, a rain screen. Otherwise, how else would the curtain wall function and what level of rain penetration and air movement through the joints would be desired.

Anderson (1988) states that a rainscreen with an airspace which can be drained, back ventilated and if required pressure equalized prevents the effects of rain and serves as a cosmetic element. Stone cladding and the stone curtain wall behave as if a rainscreen, if it is detailed correctly. BS 8298 (1994:26) states the width joints according to the type of stone and joint material i.e mortar or sealant.

There could be some improvements in the performance of the joints (Schaupp,1967:63). The mastic joints create less stress on the façade. According to individual design, every storey should have a horizontal joint, above which further slabs should be supported by immovable cramps. In the horizontal direction too, there should be joints that vary between 6-10 m to relieve stress. The shrinkage of the main body and expansion due to changes in temperature might cause the pushing of infill panels. When using cladding slabs, additional soft joints should be provided to overcome the different thermal absorption rates.

The performance expectations of the sealant with reference to BS 6213 are as follows: (Smith, 1999:358)

a. Life expectancy. Life expectancy of a sealant is lower than that of stone or of the whole stone installation. The manufacturers of sealant do not claim a service life of more than 20 years for the most widely specified sealant: silicones and polysulphide. They should be replaced several times during the service life of the building. The architect or designer should be aware of this situation and ensure that the joints are reasonably accessible to enable future inspection and replacement.

b. Compatibility**:** There are a number of instances for the use of sealant resulting stone stain. This event is seen almost on every granite curtain wall, which is very popular in Turkey in the last years. The sealant should be compatible with the stone. Other compatibility problems arise from contact between silicone sealant and damp-proofing membrane components which contain pitch or bitumen as a result sealant and stone stains.

Nakayma and Sasaki (1999:593-602) have done research on the long term penetration of silicone into stone and its prevention. The stone veneer finished curtain wall was developed so that stone was adhered and fixed to a steel curtain wall frame using silicone adhesive and metal fasteners. According to Nakayma and Sasaki (1999: 593-602), silicone migrates from the back of the stone to the front fascia. There is a risk of staining due to the penetration of silicone. It is a possible to prevent this. A chemical analysis is realized and with the results of this analysis a numerical analysis of the silicone migration is completed to predict the migration depth of silicone components in stone. Marbles are used as test samples since it is solely composed of calcite and contains no silicone based minerals. Different types of primers are used to control the migration of the silicone into the stone. The silicone component in the adhesive begins to migrate into marble at uncured state immediately after construction, but the migration may soon be terminated with the progress of the polymerization of the adhesive which bind the silicone components. The shielding primers can restrain the emission of the silicone component and prevent stains resulting from the migration of the silicone component into stone.

There are a lot of buildings in Turkey that has granite curtain walls whose joints are stained with silicone sealant.

III.1.5. Backing Structure

The type of backing structure of the stone cladding and stone curtain wall may affect the long term performance of the system. The infill of the backing structure may be concrete, brick or lightweight concrete. Different types of fixings should be used with different types of backing structure.

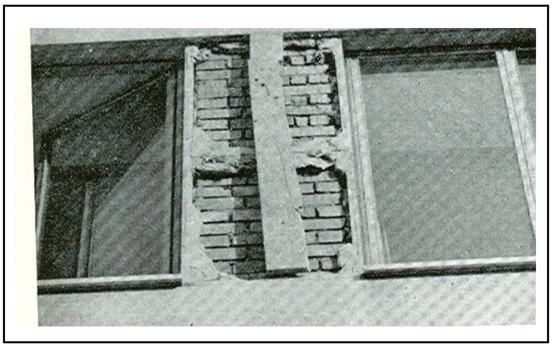


Figure III. 21 Façade slab displaced by compressive stress of the backing masonry (Schaupp,1967:56).

Schaupp (1967:56) gives an example of the effects of the backing structure on the stone cladding. The reason of the stone fall in some cases is the shrinkage of the masonry, i.e. the stone cladding should not be built too soon onto the backing masonry (Figure III.21).

Concrete structures are subject to drying shrinkage and creep (Smith,1999:356; Beasly,1998:80). The shortening in length creates stress on stone panels. The origins of movement in various types of structures are indicated by BS 8298 (Table III. 3).

Table III. 3 Origin of the movements in structures. BS 8298 (1994:28)

TYPE OF STRUCTURE	**SOURCE OF MOVEMENT**						
	Elastic Deformation	Thermal Movement	Differential Settlement	Drying Shrinkage	Moisture Movement	Creep	Long Term Expansion
Steel Frame	√	√	√				
Concrete Frame	√	√	√	√	√	√	

III.1.6. Workmanship

The building obtaining process continues with the construction after the design phase and workmanship is an important input in the construction stage. Workmanship is a general factor that affects the performance of the whole system. It is a very dominant factor in the construction of the buildings affecting the performance and is particularly same for stonework because stones' integrity and durability can be affected by defects which can not be seen by naked eye after the completion of the construction.

The reasons for the cracks in the stone due workmanship is as follows (Smith,1999:358-360):

- Stone extracted by blasting or by wedging from a face fissured from previous blasting,
- Unsuitable techniques employed in for cutting corbel slots and cramp holes.

To avoid these problems, it is necessary to ensure the standards of workmanship. To be able to increase the quality of the workmanship, the following items should be followed (Smith,1999:358-360):

1. **Specifications:** Standards should be followed for slating work.

BS 8298 (1994:33-36) specifies the workmanship in production, on site and in cleaning.

2. **Skill :** The fixers of stone cladding and curtain wall should have an adequate level of skill and expertise.
3. **Inspection:** A regular inspection should be carried out during the construction to assure that the work is adhering to the established standard.

III.1.7. Maintenance: Cleaning and surface repair techniques are recommended in BS 6270-1 for different types of stone (BS8298, 1994:37). The replacement method of detached or deteriorated stone panels is not mentioned. The changing of the deteriorated stone is an important problem during the maintenance phase. The design of the façade system should lend itself to an easy replacement method.

The improper cleaning techniques may cause the failure of stone irreversibly. The stone crack may occur and as a result the panels may absorb water.

III.1.8. Service Life Span and Durability: Stone has a very long service life span when compared to the other components of stone façade such as fixing elements and joint seal materials. The location and orientation of the building affects the performance of the stone façade. This has to be taken into consideration during the stone façade design.

Smith (1999:350) refers to BS 7543: Guide to Durability of Buildings, Building Elements, Components and Products- for a life span of granites, metamorphic slates, many marbles and some limestone which have at least 120 years. The service life span of the stone is subject to a correctly detailed design and installation.

The performance of stone façade components and their influence on the performance of the whole system is reviewed in detail at the beginning of this chapter. Distortions from standards at the design phase may cause a low performance of the system during its service life. It is difficult to determine the reasons of the failures since some of the failures have more than one reason. Subsequent to a literature review, the failures of stone facades related with the subject are grouped as follows:

1. Stone panel fall,
2. Stone panel displacement,
3. Stone buckling,
4. Stone crumbling, detachment,
5. Stone crack,
6. Staining,
7. Discoloration,
8. Water penetration,
9. Condensation inside the wall
10. Condensation within the wall
11. Stone surface abrasion,
12 Thermal insulation material deterioration,
13. Deterioration of the joint fills material.

The explanation of all these failures, their effects on the building envelope performance and their possible reasons are indicated by the researcher upon reviewing important sources and authors related with the subject :

1. Stone Panel Fall Down: Thin stone panels used for cladding or curtain wall may fall down completely from the back-up wall or metal frame. The stone panel fall down is one of the most important failures of stone facades since it is directly related with the safety criterion of the building envelope performance. Large stone panels that fall down from a certain height may create a disaster.

Figure III. 22 Stone fall down. Atatürk Cultural Center (May 2004)

The reasons behind stone panel fall down show variations for stone cladding and stone curtain wall. It can be summarized as follows:

- 1.A Improper type of stone selection as facade material (Chacon,1999:175-200; Smith,1999:352-354; BS 8298:1994:9-10);
- 1.B Inadequate stone thickness for anchorage in mechanically fixed stone cladding and curtain systems weakens the whole system. The thickness of stone panels decrease at fixing points and this reduces the strength of the whole facade.
  (Larkin,1998:65-67;BS8298:1994; Smith, 1999:363);
- 1.C Using stone panels which have different thermal expansion coefficients side by side (Schaupp;1967:58);
- 1.D The use of different color and texture stone on façade side by side, which creates surface temperature variations on the façade,(Scahaup,1967:58);
- 1.E Different shading resulting in different dimensional movement due to heat (Schaup, 1967);
- 1.F The increase of temperature on the surface of the stone and low

temperature at the back of the stone causing hysteresis (permanent volume change) and as a result stone bow (Gerns,2000:37,42; Nashed,1995:160-161);

1.G Condensation within the wall (Schaupp, 1967:58);

1.H Some types of stones swell up when they absorb water and distort when they dry out creating stress on the wall ties i.e. on mortar and mechanical anchorages (Schaupp,1967:58);

1.I Water absorption of some types of stones due to the installation of the bedding plane of stone parallel to the back-up surface (Nashed, 1995:161);

1.J Some types of stones swell up when they absorb water. The pores get larger when water freezes and stone suffers or falls down (Richardson,2001:107);

1.K Some types of stone surface treatment methods decrease the thickness of stone. This causes the loss in bending strength and increase the elastic deformation (Nashed,1995:162);

1.L Corrosion of the fixing elements due to improper material use (Smith,1999:357; Gerns,2000:42);

1.M Improper fixing design against loads like wind, earthquake;

1.N Poor location of dowel pin during fixing (Richardson,2001:137);

1.O Poor location of panels during fixing (Richardson,2001:137, Larkin,1998);

1.P Poor design of window and door frame connections with stone façade (Scahaup,1967);

1.Q Chemical reaction of the mortar with stone

1.R Since stone is a dense material, evaporation of water in mortar takes time, which creates stress on wall ties (Schaup,1967:58);

1.S Different movement of the back-up wall and stone panels;

1.T Stone panel crack due to poor workmanship (Larkin 1998:67);

1.U Shrinkage of the reinforced concrete structure at the back of the stone cladding.

1.X Unsuitable techniques for cutting corbel slots and cramp holes (Smith,1999:358-360);

1. W Wrong stone cleaning technique and materials.

2. Stone Panel Displacement: In some cases stone panels do not fall down but displace from the back-up wall or metal frame (Figure III.23).

Figure III. 23 Stone displacement. Ankara Kurtulus Park Wedding Ceremony Hall Parapet Wall. (2002)

Most of the reasons of stone panel fall down are the same for stone panel displacement. This is related with the 'strength' of the building envelope performance criteria. As a result of stone displacement, water absorption of the façade is reversible.

4. Stone Panel Buckling: Stone panels curves inward or outward from the vertical plane of the wall.

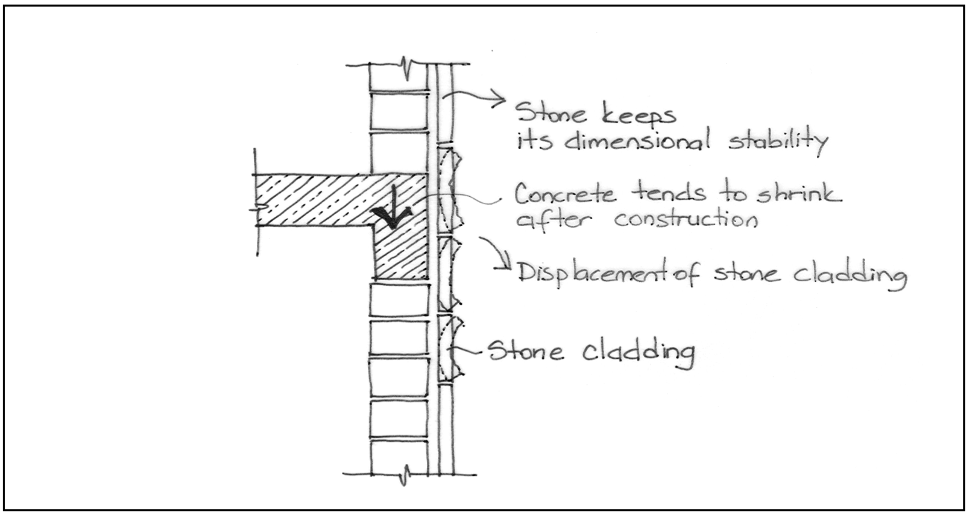


Figure III.24 Stone buckling.

Possible reasons of stone buckling are:

3.A. Improper type of stone selection as facade material, (Chacon,1999:175-200, Smith,1999:352-354, BS 8298:1994:9-10);

3.B. Using stone panels which have different thermal expansion coefficients side by side (Scahaup;1967:58);

3.C. The use of different color and texture stone on façade side by side, which creates surface temperature variations on the façade (Scahaup,1967:58);

3.D. Different shading on the façade (Schaup,1967);

3.E. The increase of temperature on the surface of the stone and low temperature at the back of the stone causing hysteresis (permanent volume change) cause stone bow (Gerns,2000:37,42; Nashed,1995:160-161);

3.F Condensation within the wall;

3.G Some types of stone surface treatment methods decrease the thickness of stone. This method decreases the bending strength and increases elastic deformation (Nashed,1995:162).

Stone panel buckling is directly related with the effects of change in temperature, thermal and moisture movement and the safety performance criteria of the building envelope.

4. Stone Crumbling, Detachment: A piece of stone detached from the rest of the stone panel results in the exposure of the fixing element to water absorption.

Figure III. 25 Stone crumbling. Ankara Kurtulus Park Wedding Ceremony Hall Parapet Wall. (2002)

5. Stone Crack: Individual or intersecting cracks on stone due to constructional causes.

Figure III.26 Stone crack. METU Cultural & Conventional Center wall by the staircase. (2002)

The reasons of stone cracks are:

5.A. Improper type of stone selection as façade material (Chacon,1999:175-200; Smith,1999:352-354, BS 8298,1994:9-10);

5.B. Surface abrasion of stone due to weathering (Richardson,2001:107;Nashed, 1995:161; Fitzner,1995);

5.C Using stone panels which have different thermal expansion coefficients side by side (Scahaup;1967:58);

5.D The use of different color and texture stone on façade side by side, which creates surface temperature variations on the façade (Scahaup,1967:58);

5.E Different shading on the facade (Schaup, 1967);

5.F The increase of temperature on the surface of the stone and low temperature at the back of the stone cause hysteresis (permanent volume change) which in turn, cause stone bow (Gerns,2000:37,42; Nashed,1995:160-161);

5.G Condensation within the wall;

5. H. Some types of stones swell up after absorbing water and distort when dried out this creating stress on wall ties i.e. on mortar and mechanical anchorages (Schaup,1967:58);

5.I. Water absorption of some types of stones due to installation of the bedding plane of stone parallel to the back-up surface (Nashed, 1995:161);

5.J. Some types of stone surface treatment methods decreases the thickness of stone. This decreases the bending strength and increases elastic deformation (Nashed,1995:162);

5.K. Corrosion of the fixing elements due to the use of improper material (Smith,1999:357, Gerns,2000:42);

5.L. Improper fixing design against loads like wind, earthquake;

5.M. Poor location of panels during fixing, (Richardson,2001:137; Larkin,1998);

5.N. Different movement of the back-up wall and stone;

5.O. Shrinkage of the reinforced concrete structure at the back of the stone cladding;

5.P. Stone panel cracks due to workmanship (Larkin, 1998:67);

5.Q. Unsuitable techniques for cutting corbel slots and cramp holes (Smtih,1999:358-360);

5.R. Wrong stone cleaning techniques and materials.

There is a serious of possible reasons of stone cracks. These have to be taken into consideration during design, construction and service life of the building.
The cracks affect the strength, durability, and the service life span and it may cause water absorption.

6.Staining: Efflorescence caused by different reasons on stone may cause stone staining. Water dissolves the salt aggregates in mortar, at the back up wall behind the stone and this causes staining.

Figure III.27 Staining of the travertine stone. The METU Cultural & Conventional Center wall by the staircase.(2002)

The reasons behind staining can be listed as follows:

6.A. Improper type of stone selection as facade material (Chacon,1999:175-200, Smith,1999:352-354, BS 8298:1994:9-10);

6.B. The capillarity of the stone at subbasement;

6.C. The corrosion of the fixing elements due to the use of improper material (Smith,1999:357, Gerns,2000:42);

6.D. Chemical reaction of mortar with stone;

6.E. Water absorption at joints causing staining on the stone (Nashed,1995:161);

6.F. Water dissolves the salt aggregates in mortar and the back up wall behind the stone, which causes efflorescence (Nashed, 1995:161).

The staining affects the appearance and durability of stone facades.

7. Discoloration: Alteration of the original stone color is one of the common failures of granite curtain wall facades especially in Turkey. The color of granite panels especially at the areas close to the joints turn into grayish color.

Figure III. 28 The color of the granite panels discolor at joints.
Ankara Bayındır Hospital Granite Façade (2002)

The reasons for discoloration of stone panels may be:

7.A. Improper joint material causing staining on the stone (Nakayma, Sasaki, 1999:593-6029);

7.B. Atmospheric deposits on the stone;

7.C. Water absorption at joints causing discoloration on stone the (Nashed,1995:161).

Discoloration of stone panels affects the appearance of the building.

8. Water Penetration: Water penetrates through joints and passes into the stone panels or the back-up wall.

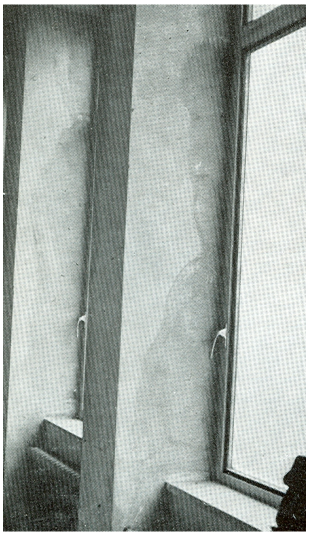


Figure III. 29 Water penetration at window jambs. (Schaup,1967:62)

The reasons of water absorption are:

8.A. Surface abrasion of stone due to weathering (Richardson,2001:107; Nashed,1995,161; Fitzner, *et.al.* ,1995);

8.B. The capillarity of stone at subbasement;

8.C. Improper joint design causing water penetration inside the wall (Smith,1999; Nashed,195:161);

8.D. Improper joint material use.

9. Condensation Behind the Wall: Mechanical fixing elements on stone cause cold bridges on walls (Figure III.30). The humid internal air may condense and cause condensation at the internal surface of the wall.

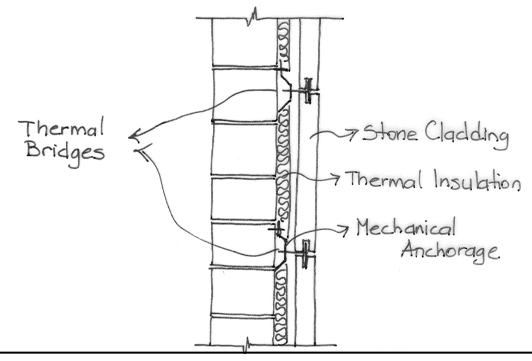


Figure III. 30 Condensation behind the wall caused by thermal bridges.

The reason of the condensation inside the wall is mostly related with the thermal bridges due to anchorages that pass through the thermal insulation layer. Condensation within the wall affects the thermal and moisture performance of the wall,

10.Condensation Within the Wall: Stone is a dense material due to the trapped humid air in the cold zone of the construction. Condensation occurs within the wall especially on the stone surface (Figure III.31) .

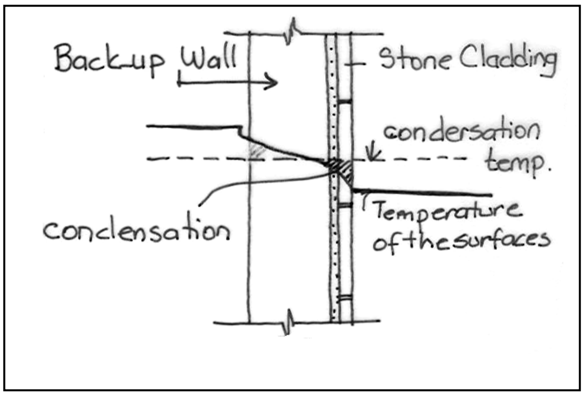


Figure III. 31 Condensation within the wall.

The reason behind the condensation within the wall is:
10.A. Lack of thermal insulation material, deficiency of its thickness or lack of vapor barrier material.

11.Stone Surface Abrasion: Loss of stone surface material due to weathering, the chemical composition of stone or cleaning techniques (Nashed,1995:161; Richardson,2001:107; Fitzner, *et al.*, 1995:54-58).

Figure III.32 Stone surface abrasion, Ankara- Ministry of Finance(2003).

The reasons behind the stone surface abrasion are:

11.A. Improper type of stone selection (Chacon,1999:175-200; Smith,1999:352-354; BS 8298:1994:9-10);

11.B. Surface abrasion of stone due to weathering (Richardson,2001:107; Nashed,1995:161; Fitzner, *et.al*,1995);

11.C. .Wrong stone cleaning techniques and materials.

Stone surface abrasion affects the durability of stone and its appearance.

12. Thermal Insulation Material Deterioration: If thermal insulation material has an open cell character, when condensation occurs within it, it gets wet; therefore, it can not perform its thermal insulation service properly. The mineral wool and expanded polystyrene as well as glass wool are some of the open cell thermal insulation material. Extruded polystyrene foams are the closed cell thermal insulation materials which does not absorb water and water vapor, can therefore, perform during the life time of the building safely. Other open cell thermal insulation materials should be protected with a water vapor barrier on the warmer side of the wall and a humidity barrier on the outside. The fire performance of the thermal insulation materials is important especially in high rise buildings. Thermal insulation materials should be evaluated carefully . The reasons of the thermal insulation material deterioration are:

12.A. Improper joint design causing water penetration inside the wall (Smith,1999; Nashed,195:161);

12.B. Water absorption at joints;

12.C. Improper thermal insulation material selection;

13. Deterioration of the Joint Fill Material: The joint fill material may change color or chemical composition.

The reason for the deterioration of the joint material is mostly related with the incompatibility of the joint fill material with the other stone façade components and with the stone from the aspect of service life.

The deterioration of the joint material is related with the water penetration, appearance, and the durability of the building envelope performance criteria.

Conclusion:

The way to cope with all these indicated problems is to apply the codes and standards during the building obtaining process phase, which consists of:

1. Design
   1.a Detailing
   1.b Specification
2. Construction
   2.a Material Supply
   2.b Workmanship
   2.c Inspection
3. Service Life
   3.a. Maintenance

The failures of stone facades, their reasons and the components of the stone facade or the properties of stone related with these failures and prevention and the building obtaining process stage are all indicated by the researcher in Table III.4. The standard and codes related with these components that should be followed are also listed in Table III.5.

TABLE III.4 The failure check Table. The reasons of stone façade failures, failures and the building obtaining phase and standards. Failures are : **1.**Stone fall down **2**. Stone panel displacement, **3.**Stone buckling, **4.**Stone crumbling, **5.**Stone crack, detachment **6.**Staining, **7**. Discoloaration, **8.**Water Penetration, **9.**Condensation behind the wall, **10.**Condensation within the wall, **11.**Stone surface abrassion, **12**. Thermal Insulation material deterioration, **13.** Deteroration of the joint material

	REASONS OF FAILURE	**FAILURE**	**BUILDING OBTAINING PHASE**	**COMPONENT & PROPERTIES**
1	Improper type of stone selection (Chacon,1999:175-200, Smith,1999:352-354, BS 8298:1994:9-10)	1,2,3,4,5,6,11	Design • Specification	1. Types of Stone-Stone Selection 1.2 Physical Properties of Stone 8. Service life and Durability
2	Surface abrasion of stone due to weathering (Richardson,2001:107;Nashed, 1995:161; Fitzner *et. al* ,1995)	4,5,8,11	Service Life	1.2.a Rock Pores and Porosity 1.2.g Weathering Resistance 8. Service Life and Durability
3	Inadequate stone thickness for anchorage (Larkin,1998:65-67, BS8298:1994, Smith, 1999:363)	1,2	Design • Detailing • Specification	1.1 Types of Stone-Stone selection 1.2.b Dimension 1.2.c Petrographic Properties 1.2.e. Flexural Strength / Modulus of Rupture
4	Using stone panels which have different thermal expansion coefficients side by side (Schaupp;1967:58)	1,2,3,4,5	Design • Detailing • Specification	1.1 Types of Stone-Stone Selection 1.2.a Rock Pores and Porosity 1.2.c Petrographic Properties 1.2.f. Thermal and Moisture Movement 1.2.g.2 Frost Resistance 4.b Movement Joints

TABLE III.4 (cont'd) The failure check Table. The reasons of stone façade failures, failures and the building obtaining phase and standards. Failures are : **1.**Stone fall down **2**. Stone panel displacement, **3**.Stone buckling, **4.**Stone crumbling, detachment **5**.Stone crack, **6**.Staining, **7**. Discoloaration, **8**.Water Penetration, **9**.Condensation behind the wall, **10**.Condensation within the wall, **11**.Stone surface abrassion, **12**. Thermal Insulation material deterioration, **13.** Deteroration of the joint material

	REASONS OF FAILURE	**FAILURE**	**BUILDING OBTAINING PHASE**	**COMPONENT & PROPERTIES**
5	The use of different colors and textures of stone on the façade side by side create surface temperature variations (Schaupp,1967:58)	1,2,3,4,5	Design • Detailing • Specification	1.1 Types of Stone- Stone Selection 1.2.c Petrographic Properties 1.2.f. Thermal and Moisture Movement 1.2.g.2 Frost Resistance 4.b Movement Joints
6	Different shadings on the façade (Schaupp, 1967)	1,2,3,4,5	Design • Detailing	1.1 Types of Stone-Stone Selection 1.2.c Petrographic Properties 1.2.f. Thermal and Moisture Movement 4.b Movement Joints
7	The increase of temperature on the surface of the stone and low temperature at the back of the stone cause hysteresis (permanent volume change) causing stone bow (Gerns,2000:37:42, Nashed,1995:160-161)	1,2,3,4,5	Design • Detailing	1.2.f. Thermal and Moisture Movement 2.c. Fixing Design 3.Mortar 4.b Movement Joints 5 Backing Structure
8	The capillarity of stone at subbasement	6,8	Design • Detailing	1.1 Types of Stone-Stone Selection

TABLE III.4 (cont'd) The failure check Table. The reasons of stone façade failures, failures and the building obtaining phase and standards. Failures are : **1.**Stone fall down **2**. Stone panel displacement, **3**.Stone buckling, **4.**Stone crumbling, detachment **5.**Stone crack, **6**.Staining, **7**. Discoloaration, **8.**Water Penetration, **9.**Condensation behind the wall, **10.**Condensation within the wall, **11.**Stone surface abrassion, **12**. Thermal Insulation material deterioration, **13.** Deteroration of the joint material

	REASONS BEYOND FAILURE	**FAILURE**	**RELATED BUILDING OBTAINING PHASE**	**RELATED COMPONENT & PROPERTIES**
9	Condensation within the wall	1,2,3,5,10	Design • Detailing	1.1 Types of Stone-Stone Selection 1.2.A Rock Pores and Porosity 1.2.C Petrographic Properties 1.2.F Moisture Movement
10	Some types of stones swell up when they absorb water and distort when they dry out, this creating stress on wall the ties i.e. on mortar and mechanical anchorages (Schaupp,1967:58)	1,2,3,5	Design • Detailing • Specification	1.1 Types of Stone-Stone Selection 1.2.A Rock Pores and Porosity 1.2.C Petrographic Properties 1.2.F Moisture Movement 2. Fixing 3.Mortar
11	Water absorption of some types of stones due to installation of the bedding plane of the stone parallel to the back-up surface (Nashed, 1995:161)	1,2,4,5	Construction	1.1 Types of Stone-Stone Selection 1.2.B Dimension 1.2.C Petrographic Properties 1.2.D Compressive Strength 1.2.E Flexural Strength /Modulus of Rupture 2. Fixing 8. Service Life and Durability

TABLE III.4 (cont'd) The failure check Table. The reasons of stone façade failures, failures and the building obtaining phase and standards. Failures are : **1.**Stone fall down **2**. Stone panel displacement, **3**.Stone buckling, **4.**Stone crumbling, detachment **5**.Stone crack, **6**.Staining, **7**. Discoloaration, **8**.Water Penetration, **9**.Condensation behind the wall, **10**.Condensation within the wall, **11**.Stone surface abrassion, **12**. Thermal Insulation material deterioration, **13.** Deteroration of the joint material

	REASONS OF FAILURE	**FAILURE**	**BUILDING OBTAINING PHASE**	**COMPONENT & PROPERTIES**
12	Some types of stones swell up when they absorb water. The pores get larger when the water freezes and the stone suffers (Richardson,2001:107)	2,3	Design • Specification	1.1 Types of Stone-Stone Selection 1.2.A Rock Pores and Porosity 1.2.C Petrographic Properties 1.2.F Moisture Movement 1.2.G.2 Frost Resistance 7.Maintanace
13	Atmospheric deposits on the stone	4,7	Service Life	1.2.A Rock Pores and Porosity 1.2.B Appearance 1.2.G.2 Chemical Resistance 7.Maintanace
14	Some types of stone surface treatment methods decrease the thickness of the stone. This causes the bending strength loss and increase elastic deformation (Nashed,1995:162)	1,3,4,5	Construction	1.2.E Flexural Strength /Modulus Of Rupture 2.C. Fixing Anchorages 8. Service Life and Durability
15	The corrosion of the fixing elements due to improper material; (Smith,1999:357, Gerns,2000:42)	1,2,3,4,5,6	Design • Specification	2.A Fixing Materials 8. Service Life and Durability

TABLE III.4 (cont'd) The failure check Table. The reasons of stone façade failures, failures and the building obtaining phase and standards. Failures are : **1.**Stone fall down **2**. Stone panel displacement, **3**.Stone buckling, **4.**Stone crumbling, detachment **5**.Stone crack, **6**.Staining, **7**. Discoloaration, **8**.Water Penetration, **9**.Condensation behind the wall, **10**.Condensation within the wall, **11**.Stone surface abrassion, **12**. Thermal Insulation material deterioration, **13.** Deteroration of the joint material

	REASONS OF FAILURE	**FAILURE**	**BUILDING OBTAINING PHASE**	**COMPONENT & PROPERTIES**
16	Improper fixing design against loads like wind and earthquake	1,2,5	Design • Detailing	2.B. Types of Fixing 2.C. Fixing Design 2.D. Fixing Anchorages 6. Backing Structure
17	Thermal bridges due to anchorages	9,10	Design • Detailing	2.C. Fixing Design 5. Backing Structure
18	The poor location of the dowel pin during fixing (Richardson,2001:137)	1,2,5	Design • Detailing Construction	1.2.B Dimension of Stone 2.C. Fixing Design 2.D Fixing Anchorages
19	The poor location of panels during fixing, (Richardson,2001:137, Larkin,1998)	1,2	Design • Detailing Construction	2.D Fixing Anchorages 6. Workmanship
20	The poor design of the window and door frame connections to the stone façade (Schaupp,1967)	1,2,5	Detailing Construction	4.C. Junction with other Elements 8. Service Life and Durability

TABLE III.4 (cont'd) The failure check Table. The reasons of stone façade failures, failures and the building obtaining phase and standards. Failures are : **1.**Stone fall down **2**. Stone panel displacement, **3**.Stone buckling, **4.**Stone crumbling, detachment **5**.Stone crack, **6**.Staining, **7**. Discoloaration, **8**.Water Penetration, **9**.Condensation behind the wall, **10**.Condensation within the wall, **11**.Stone surface abrassion, **12**. Thermal Insulation material deterioration, **13.** Deteroration of the joint material

	REASONS OF FAILURE	**FAILURE**	**BUILDING OBTAINING PHASE**	**COMPONENT & PROPERTIES**
21	The chemical reaction of the mortar with stone	1,2,6	Design • Specification	3. Mortar
22	Since stone is a dense material, the drying up of water in the mortar takes time, creating stress on wall ties (Schaupp,1967:58)	1,2,4	Construction	3. Mortar
23	Improper joint design cause water penetration inside the wall (Smith,1999; Nashed,195:161)	8,12	Design • Detailing	4. Joints
24	Improper joint material selection and use (Nakayma, Sasaki, 1999:593-6029)	7,8	Design • Specification	4. Joints
25	Water absorption at joints causing staining on the stone (Nashed,1995:161)	6,8,12	Construction Service Life	4. Joints 7. Maintenance
27	Different movements of the back-up wall and stone	1,2,4,5	Design • Detailing	4.b. Movement Joints 5. Backing Structure

TABLE III.4 (cont'd) The failure check Table. The reasons of stone façade failures, failures and the building obtaining phase and standards. Failures are : **1.**Stone fall down **2**. Stone panel displacement, **3**.Stone buckling, **4.**Stone crumbling, detachment **5**.Stone crack, **6**.Staining, **7**. Discoloaration, **8**.Water Penetration, **9**.Condensation behind the wall, **10**.Condensation within the wall, **11**.Stone surface abrassion, **12**. Thermal Insulation material deterioration, **13.** Deteroration of the joint material

	REASONS OF FAILURE	**FAILURE**	**BUILDING OBTAINING PHASE**	**COMPONENT & PROPERTIES**
28	Shrinkage of the reinforced concrete structure at the back of the stone cladding	1,2,4,5	Design • Detailing	4.B. Movement Joints 5. Backing Structure
29	Stone panel cracks due to poor workmanship (Larkin, 1998:67)	1,2,4,5	Workmanship	6. Workmanship
30	Unsuitable techniques for cutting corbel slots and cramp holes (Smtih,1999:358-360)	1,2,4,5	Workmanship	6. Workmanship
31	Wrong stone cleaning techniques and materials	11	Maintenance	7.Maintenance 8. Service Life and Durability
32	Incompatibility of other stone façade components with stone from the aspect of service life.	7	Service Life	8. Service Life and Durability
33	Water dissolves the salt aggregates in the mortar and back up wall behind the stone and this causing efflorescence. (Nashed, 1995:161)	6	Construction	3. Mortar 4.Backing Structure
34	Improper thermal insulation material	12	Design	1.2.F Thermal and Moisture Movement

Table III.5 Standards and codes related with the performance of the stone façade components and properties. The European Union Norms (EN), American Standards (ASTM), Turkish Standards (TS), British Standards (BS), the National Building Granite Quarries Association (NBGQA) .

NO	**STONE FAÇADE COMPONENT & PROPERTIES**	**STANDARDS /CODES**			
		EN	**ASTM**	**TS**	**OTHER CODES/ STANDARDS**
1	**STONE**				
1.1	Types of Stone- Stone Selection	1469 (2004)	C503-5 C568-03 C615-03 C616-03 C629-03 C1526-03 C1527-03 C1528-02	TS 11143 TS 10449 TS 6234	BS 8298 (1994:5,9)
1.2	Physical Properties of Stone	1469 (Nov.2004)			
a	Rock Pores and Porosity	1936(1999)	C97-02		
b	Appearance and Dimension	13373 (2003)		TS EN 13373 (2004)	
c	Petrographic Properties	12407(2000)			
d	Compressive Strength	1926 (1999) (should be mentioned in 1469 but not)	C170-90 (1999)	TS EN 1926 (2000)	BS 8298(1994:28) NBGQA Advice

Table III.5 (con'd) Standards and codes related with the performance of the stone façade components and properties. European Union Norms (EN), American Standards (ASTM), Turkish Standards (TS), British Standards (BS), the National Building Granite Quarries Association (NBGQA).

NO	STONE FAÇADE COMPONENT & PROPERTIES	STANDARDS /CODES			
		EN	ASTM	TS	OTHER CODES/ STANDARDS
e	Flexural Strength / Modulus of Rapture	13364(2001) 1469(Nov2004) 12371(2001) 12372(1999) 13161(2001) 14146(2004) 14158(2004) 14580(2005)	C99-87 (200) C120-05 C880-98 C1201-91(2003) C1354-96 (2004) C1242-04a C1352-96(2002)	TS EN 13364 (2003) TS EN 12372 (2001) TS EN 13161 (2003)	BS 8298(1994:11-12) NBGQA Advice
f	Thermal and Moisture Movement	1925 (1999) 13755 (2001) 14066 (2003) 14581(2004)	C97-02 C121-90(1999)	TS EN 1925 (2000) TS EN 13755 (2003) TS EN 14066 (2004)	BS 8298 (1994:29-30)
g	Weathering Resistance	12370 (1999) 12371 (2001)	C217-94(2004)	TS EN 12370 (2001) TS EN 12 371 (2003)	
g.1	Chemical Resistance	13919 (2002) 14147 (2003)		TS EN 13919 (2004) TS EN 14147 (2004)	
g.2	Frost Resistance	12371 (2001)		TS EN 12371(2003)	

Table III.5 (con'd) Standards and codes related with the performance of the stone façade components and properties. European Union Norms (EN), American Standards (ASTM), Turkish Standards (TS), British Standards (BS), the National Building Granite Quarries Association (NBGQA).

		EN	ASTM	TS	OTHER CODES/ STANDARDS
2	**FIXING**	13364 (2001)		TS EN 13364 (2003)	
	A. Materials				BS 8298 (1994)
	B. Types of Fixing				
	C. Fixing Design				
	D. Fixing Anchorages		C1242-4a C1354-96 (2004)		
3	**MORTAR**	13919 (2002)		TS EN 13919 (2004)	BS 8298 (1994:6)
4	**JOINTS**				BS 8298 (1994:24)
a	Panel Joints				
b	Movement Joints				
c	Junction with other Elements		C1354-96 (2004)		
5	**BACKING STRUCTURE**				
6	**WORKMANSHIP**				BS 8298 (1994:34)
7	**MAINTANANCE**	1469 (Nov:2004)	C1515-01 C1496-01		BS 8298 (1994:37)
8	**SERVICE LIFE AND DURABILITY**				

The titles of these standards are in Appendix E.

III.2 Performance of Stone Facades in Case Studies

The possible failures and facts that govern the failures are reviewed, analyzed and discussed in the previous part of this chapter. The review also includes the criticisms of standards and their missing items. In the following sections, stone facade failures are analyzed in case studies. In this analysis, the failure check list indicated in Table III.4 is the primary guide. Table III.5 is used to refer to the codes and and the standards related with the failures. Case studies have been included in two main aspects. The first group of case studies is selected from western literature and studies as examples of low and high performance stone facades and the second group of case studies are the domestic building examples from Ankara.

III.2.1 Case Study: Low and High Performance of Stone facades from Literature Review

The failures of stone facades, the reasons of the failures and the standards related with these failures have been reviewed literature.

Some of high performance buildings have also been reviewed to show the importance of detailing and its precision level in the design of stone façades.

1986-1988	**75 STREET OFFICE TOWER, Boston, Massachusetts USA**	**1**

Figure III.33 75 State Street - Stone Curtain Wall Façade Rendering (Hagen ,1989:Attachment 2)

Type of Construction	:	Steel Truss System
Type of Stone	:	5 types of granite in multiple finish
Type of Stone Facade	:	Stone curtain wall.

DIAGNOSIS OF STONE CURTAIN WALL FAILURE

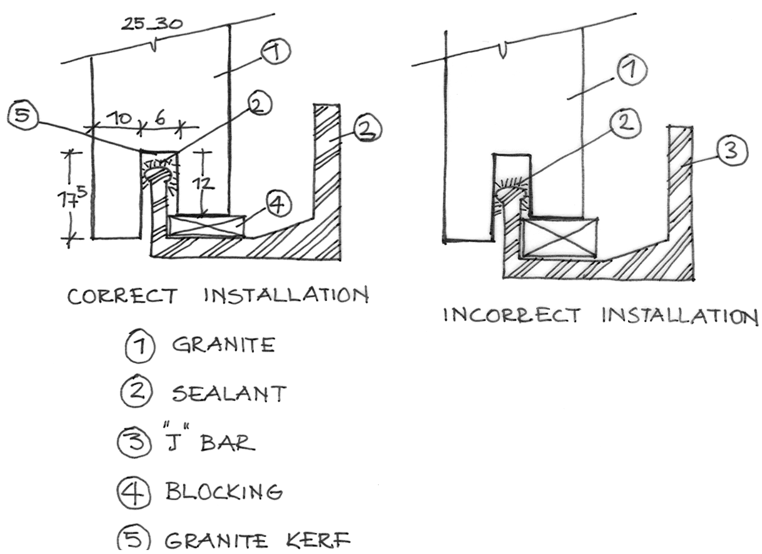


Figure III.34 J Bar engagement. Modified from Hagen (1989:Attachment II)

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) 75 Street Office Tower, Boston

Standards Related With	**2**. Fixing **4.** Joints **6.** Workmanship
Failure	**1**. Stone panel fall down **2.** Stone displacement **4**. Stone crumbling, detachment **5** stone crack
Possible Reason of the Failures	**18**. Poor location of the dowel pin during fixing **19**. Poor location of panels during fixing **29**. Stone panel cracks due to workmanship **30**. Unsuitable techniques for cutting corbel slots and cramp holes
Proposal	
Notes (Hagen ,1989: Attachment 2)	• During the fabrication process at Hingham and the installation of the trusses on the building stone, the contractor personnel damaged hundreds of granite panels. The majority of the breakage occurred at the bottom kerfs and varied from slight corner chips to broken pieces 30" in length. • SOM developed criteria for the acceptance of broken stone considering both the structural and aesthetics implications. The stone was repaired with polyester resin upon the suggestion of stone contractor. Several of the stones were repaired by the stone contractor in 1987 and have recently recracked and repaired a second time. The owner accepted the stone repairs which exceed the SOM criteria, but agreed to develop an ongoing inspection program for the building. • The stone contractor design included self-tapping/ self drilling stainless steel fasteners located in critical structural connections on the truss. The screws were 400 series stainless steel with a cadmium coat produced by several manufacturers. During the fabrication process at Hingham, when torques were checked, the failures occurred at these fasteners. It was suspected that hydrogen embrittlement had caused these failures. BGC developed a repair process by using carbon steel fasteners. • The joints between many granite panels were less than 1 /4 ". The space was not sufficient to fill sealant. The stone contractor was required to do remedial work after the trusses were installed. The repair work consisted of repositioning the granite, grinding their joints, and cutting the joints. (Hagen, 1989:Attachment II)

1991	RITZ CARLTON HOTEL HONG KONG	2

Figure III. 35 The Ritz Carlton Hotel Hong Kong (http://www.ritzcarlton.com/hotels/hong_kong/photo_tour/hotel/hotel.asp-viewed in September 2005)

Type of Stone	:	Travertine
Type of Stone Facade	:	Stone curtain wall.

DIAGNOSIS OF STONE CURTAIN WALL FAILURE

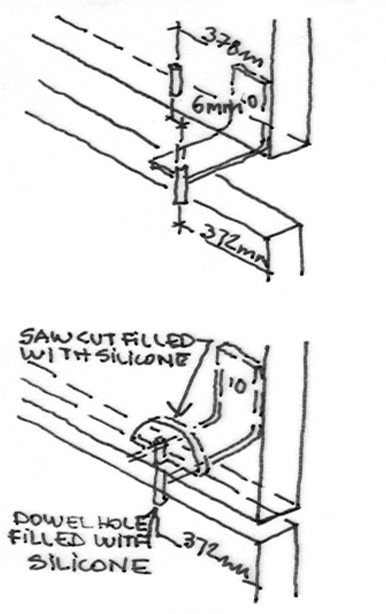


Figure III.36 Misalignment of the common dowel pin holes may be the cause of the stone spalling. (Modified from Larkin,1998:66)

Standards Related with	**1.2.d** Compressive Strength **1.2.e** Flexural strength /Modulus of Rupture
Failure	**1.** Stone fall down **4.** Stone crumbling

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd Ritz Carlton Hotel)

Possible Reason of the Failure	**18**. Poor location of the dowel pin during fixing **19**. Poor location of panels during fixing **28.** Shrinkage of the reinforced concrete structure at the back of the stone cladding (Larkin, 1998:66)
Proposal	
Notes (Larkin,1988:67)	25-story Ritz Carlton Hotel Hong Kong was completed in December 1991. The contractor had a lot of misalignment problems during the early stage of stone installation. They shifted 8 mm diameter holes into edge of 25 mm thick granite at field. They lost their ability to control the quality of drilling. Even a small amount of tolerance in the hole location and alignment relative to the face of the stone were significant in a 25 mm stone. Slightly skewed holes exerted force on the thin stone edges and they were pried into the place, and more than 300 of the building's 300,000 stones were broken. One of the reasons underlying the breaking of the stone is the plaster that was used to fill the edge anchor holes. Plaster expands when wet breaking the stone on a North Caroline high-rise. Elastomeric sealant is recommended instead of plaster in this case by Larkin (1998). To prevent a misalignment problem, groove or saw-cut modification to the common dowel pin design may be a solution. Without groove or saw-cut flexibility in the upper stone, stone setters sometimes use pry bars to bend pins and force the two stones together, and this causes edges to break. Stone anchors should be prefabricated at a factory instead of drilled at field by hand since the stones are very thin (Larkin,1988:67).

1973-4	AMOCO BUILDING CHICHAGO	3

Figure III.37 346 m high Amoco Building

(www.skyscraper.org/EXHIBITIONS/BIG_BUILDINGS/CONTENT/jumbos/j_11.htm viewed in September 2005)

Type of Construction	:	Steel Truss System
Type of Stone	:	Carrara Marble Changed with Mt Airy Granite
Type of Stone Facade	:	Stone curtain wall.

DIAGNOSIS OF STONE CURTAIN WALL FAILURE

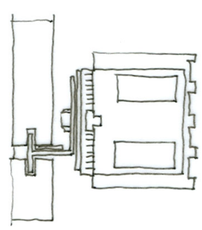


Figure III.38 80-Storey Amoco Building Granite Panel Assembly System (Modified from Harriman, 1999:78)

Standards Related With	**1.1** Types of stone –Stone selection **1.2.e** Flexural Strength **2.** Fixing
Failure	**1.** Stone fall down **3.** Stone buckling
Possible Reason of the Failure	**1.** Improper type of stone selection as facade material **3.** Inadequate stone thickness for anchorage **7.** The increase of temperature on the surface of the stone and low temperature at the back of stone causing hysteresis (permanent volume change) and thus stone bow **10.** Some types of stones swell up after absorb water and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) Amaco Building

Notes	In Chicago, on the Amoco Building's façade (346 meters) Mt. Airy granite anchored to its steel frame, but it was not its original façade. (ASTM, Standardization News, viewed in 2005), (Harriman, 1999:78), (Nashed, 1995:161) It was faced with 1 ¼ inch (3,2 cm) thick Carrara marble cladding of 50 by 45 inch (127x114.3 cm) stone panels. Stone panels have been bowed, wrapped, turned into dish shape after the completion of the construction in 1973-1974. This type of marble stress , termed "hysterisis", is caused by an uneven expansion of the exposed surface in relation to its rear face. (Harriman, 1999: 78; Gerns,2000:42; Nashed, 1995:161) All 43.000 panels are currently being replaced with Mt . Airy Granite of 2 inches (5 cm) thickness. The existing anchoring system (a clip angle set into panel kerfs, which is a common attachment method) is also improved. Continuous extruded, stainless steel self angles for supporting the top and bottom of the new panels (Figure III.44) replace the original 3- to 4 inch (7,6-10,1cm) bent steel angles that are intermittently at the base of the marble panels. A compressible foam pad under each shelf provides a pressure relieving joint, accommodating vertical movement by allowing each stone panel to expand and prevent stress crack and spalling. (Harriman, 1999: 78)

These are the buildings which show low performance when compared with the satisfaction level of the external wall performance criteria. In addition to the all listed low performance stone facades, there are some stone façade buildings that show high performance.

1. The Charlotte-Mecklenburg Government Center

As a high performance example of stone façade, the Charlotte-Mecklenburg Government Center building is the winner of a 1990 Tucker Award for stone application from the building Stone Institute.(Harriman, 1999:80). Rose colored granite stone panels of only ¾ inch (7,6cm) thickness are mounted on steel trusses. The 14 storey building is scaled and detailed with alternating bands of polished and flamed textured stone. The dimensions of the pattern are based on the golden mean. Three quarters of an inch and 11/4 inc (3,2 cm) thick Granite spandrel panels of ¾ inch and 11/4 inch (3,2cm) thickness and 31/2 feet (42,60 cm) and 5 feet (152,4 cm) in width are mounted on load bearing steel trusses.

The depth of the truss system provides better support compared to the standard curtain wall framing. The system is preassembled to provide better quality control for hand setting. The architects' decision to keep the glass and stone cladding flush with one another also increase the technical success of the curtain wall. A silicone compatible with stone, glass and metal was specified. Dividing the veneer into many individual pieces provides more structural movement.   In this way the expansion joints are integrated with the overall façade pattern. The building has not suffered from Hurricane-Hugo in 1990. (Harriman, 1999:79-80)

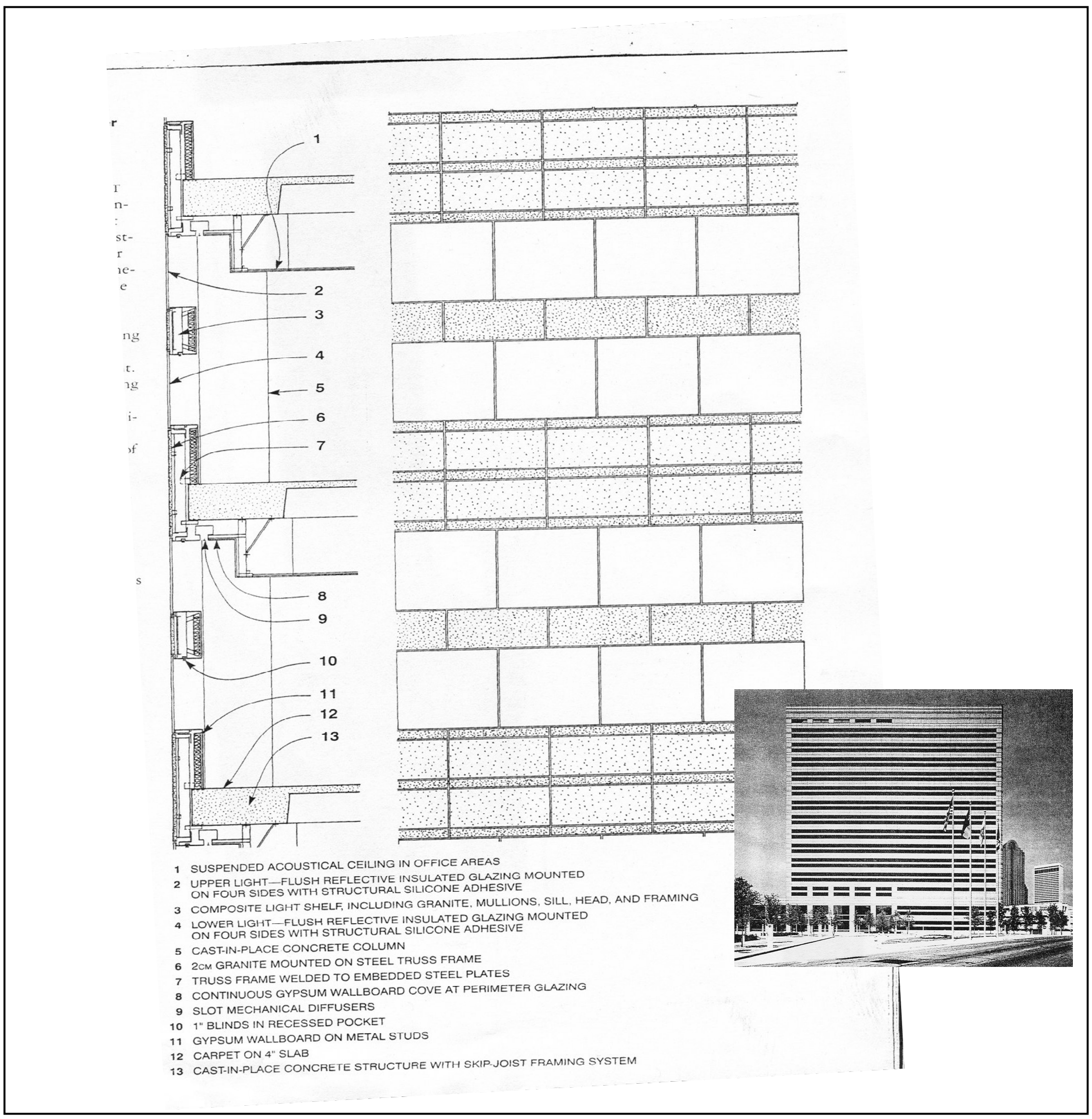


Figure III.39 The Charlotte-Mecklenburg Government Center Façade detail (Harriman,1999:79-80)

2. 712 Fifth Avenue New York

712 Fifth Avenue (50 stories) is clad with a stone veneer that combines limestone, granite and marble panels of varying thicknesses. The thickness of the stone panels are adjusted according to each stone's flexural tolerances and resistance to weathering. There are three types of stone with five separate surface finishes used to form a cohesive façade throughout the building. Limestone, the weakest of the building stones, is maintained at four inches (10.16 cm) and is anchored with steel angles to a solid, continuous masonry and concrete wall backing. Slimmer Vermont marble panels were specified for the inset skin. Originally designed to span the height of two windows, the panels of 2 inch (5.08cm) thick were reduced to half their original height when the stone proved to be too difficult to cut at the quarry and handle without risk of cracking. The granite panels correspond to the respective thickness of the adjacent limestone and marble veneers. Granite panels are connected to one another with dowels (Harriman,1999:79-81).

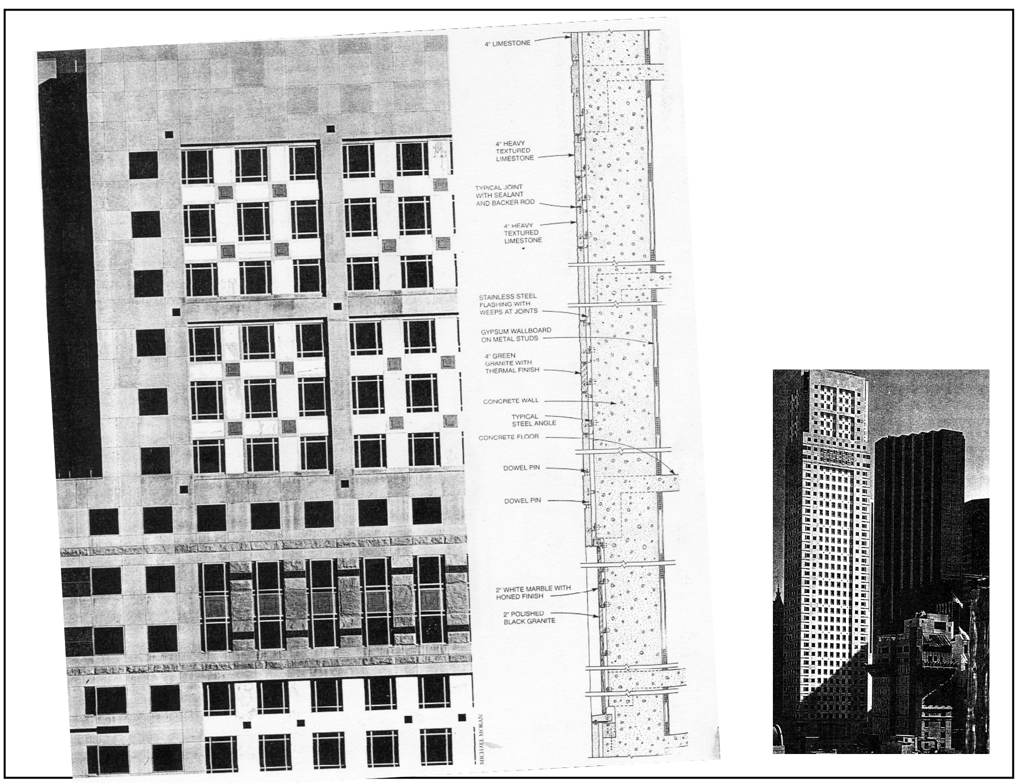


Figure III.40 712 Fifth Avenue New York Stone façade detail (Harriman,1999:79-82).

3. The Humana Building

Located in Louisville, Kentucky it was designed by Michael Graves , in 1982.
The architects had two choices for the use of stone as a cladding material in modern buildings: to use stone in what appears to be the traditional way by a serious clever deception, or to try to revise the traditional elements in a way that reveals the nature of the modern stone. Most architects, including Michael Graves would argue that they are doing the latter, but Humana seems to adopt both approaches (Ford,1998:363).

There is a contrast in the dimension of modern stone compared to the traditional one. Modern stone is larger in area and thinner in depth compared to the traditional stone. The typical panel of the Humana Building is 2 inches (5 cm) deep. False joints are used to give the appearance of traditional stone. In order to hide the real joints, the surface of the stone has to have a homogenous texture and color.

Figure III.41 Front view and wall section of the Humana Building.
Architect Michael Graves (Ford ,1998:360).

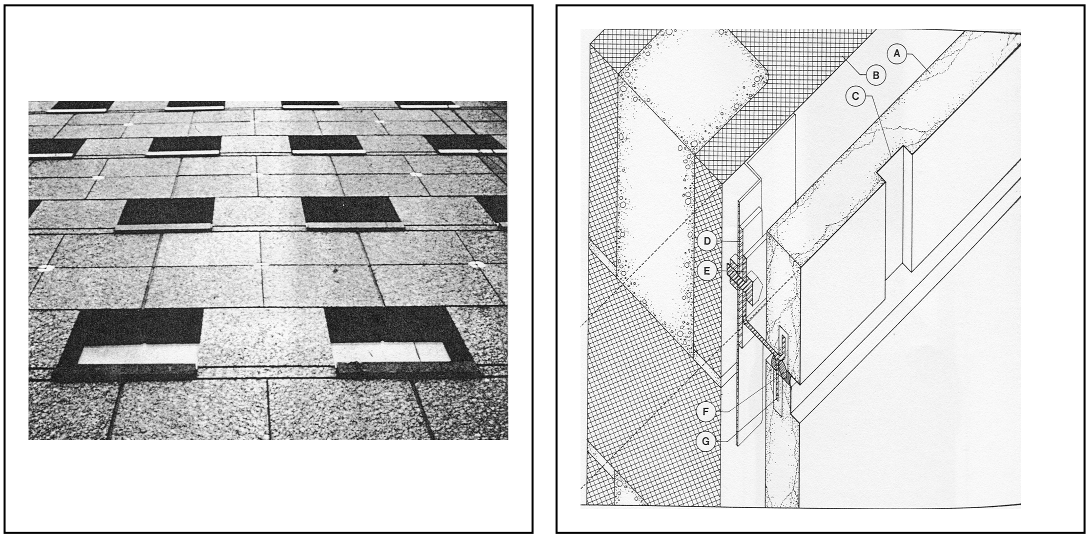


Figure III.42 a - b Wall and stone detail of the Humana Building (Ford,1998:362).
A. 2" granite panel **B.** Concrete Masonry with voids filled with concrete anchors **C.**Notch in Granite to create false joint **D**. Adjustable anchor support **E.** Stainless steel support angle and galvanized shim with plastic separator **F.** Seal and bond breaker (Note that the joint is artificially enlarged) **G** Anchor

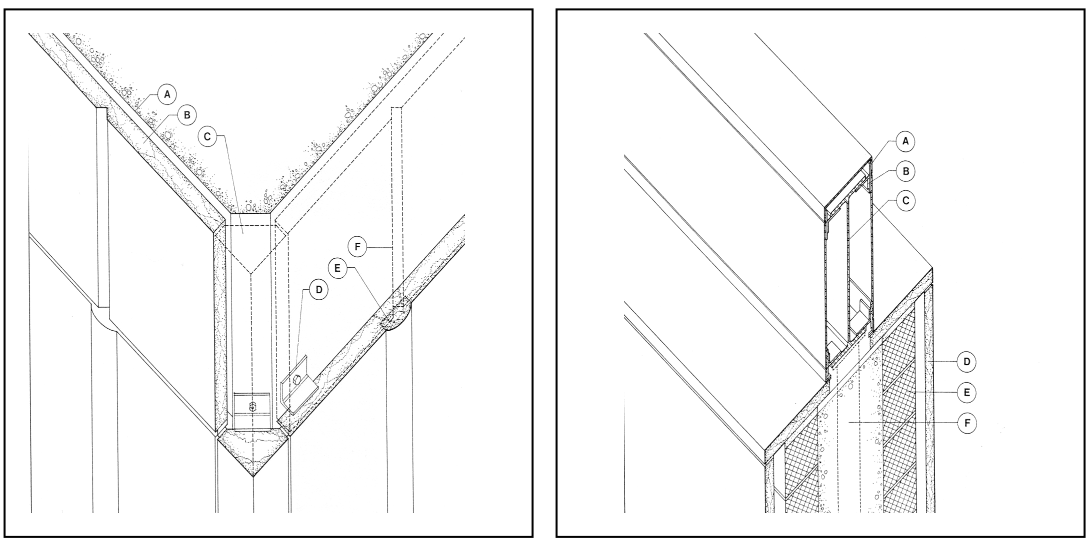


Figure III.43 Stone detail at corner and stone faced concrete columns at the base of the Humana Building (Ford,1998:364).

Having reviewed some examples of low and high performance stone facades according to the determined failures and their reasons in this chapter of the thesis, it can be said that the high performance of stone facades depend on the application of standards and codes at all stages of the building obtaining process.

III.2.2 Case Study: Low Performance Examples from Ankara

At this phase of the research, buildings in Ankara with stone cladding from the early period of the Turkish Republic up to 2004 are analyzed and evaluated with respect to their façade performance. The failures are listed by the researcher and their possible reasons and proposals of solutions to these problems are also included. Standards, codes and the observations of the researcher are indicated in the case studies. During these case studies, besides the researcher's observations, contacts were made with the users and contractors, and their comments and opinions have also been included. In the evaluation of the buildings, articles, technical notes and internet web pages have also played a major role.

The construction periods of the field study buildings have been grouped as follows:

1. 1923-1938 – The Early Republican Period Architecture.
2. 1938-1958
3. 1958-1978
4. 1978-200

Some of the visited and observed buildings have been listed in Table III.6. When the buildings are grouped according to their construction dates, it can be said that travertine was the most popular stone after the early Republican Period, i.e. from 1938 to 1978, and granite has been the most preferred stone during the last 10 years in the study field.

The failures defined and grouped in the previous part of this chapter, their possible reasons and related standards have been put on a table while diagnosing the buildings and some proposals have been made by the researcher with the help of standards, codes and professional experience for the observed case studies. In the following case study sheets, the failure was cited with the same numerals in Table III.4 and 5. for the readers' convenience.

Table III.6 The case Study Building list 1923-1938.

	Construction Date	Name of the Building	Name of the Building in Turkish (Tr)	Today's Function	Type of Construction	Type of stone
1	1925	The Ministry of Finance	Maliye Vekaleti Binası	Customs Seperintendency		
2	1927	The Ministry of Foreign Affairs	Hariciye Vekaleti Binası	Ministry of Culture		Marble
3	1933-1934	Emlak Bank	Emlak ve Eytam Bankası	Emlak Bank Ankara Branch Office	R.C frame	Marble and andezite

Table III.6 (cont'd) The case Study Building list 1938-1958

	Construction Date	Name of the Building	Name of the Building in Turkish (Tr)	Today's Function	Type of Construction	Type of stone
4	1937-1939	The Faculty of Literature, History and Geopgraphy	Dil Tarih ve Coğrafya Fakültesi	The Faculty of Literature, History and Geography		Andezite
5	1938-1941	The Turkish Railway and Harbour 2nd. Zone Directory	Devlet Demiryolları 2. Bölge Müdürlüğü	The Turkish Railway and Harbour Head Office	R.C frame	Andezite

Table III.6 (cont'd) The case Study Building list 1958-1978

	Construction Date	Name of the Building	Name of the Building in Turkish (Tr)	Today's Function	Type of Construction	Type of stone
6	1958	Hacettepe University Hospital	Hacettepe Üniversitesi Hatanesi	Hacettepe University Hospital	R.C frame	Travertine
7	1967	A.U The Faculty of Medicine Morphology Building	A.Ü Tıp Fakültesi Morfoloji Binası	A.U The Faculty of Medicine Morphology Building	R.C frame	Travertine
8	1969	Apartment Building Gazi Mustafa Kemal Street No:17	GMK Bulvarı No:17 Apartman	Apartment Building	R.C frame	Travertine
9	1960's	Apartment Building Gazi Mustafa Kemal Street No:37	GMK Bulvarı No:37 Apartman	Apartment Building	R.C frame	Travertine
10	1958	METU The Faculty of Economics and Administrative Sciences	ODTU İktisadi ve Idari Bilimler Fakültesi	METU The Faculty of Economics and Administrative Sciences	R.C frame	Travertine
11	1967-1968	Apartment Building Necatibey Street No:93	Necatibey Caddesi Apartman No:93	Apartment Building	R.C frame	Travertine

Table III.6 (cont'd) The case Study Building list 1978-2004

	Construction Date	Original Name of the Building	Name of the Building in Turkish (Tr)	Today's Function	Type of Construction	Type of stone
12	1985	İbni Sina Hospital	İbni Sina Hastanesi	İbni Sina Hospital	R.C frame	Travertine
13	1987	The Atatürk Cultural Center	Atatürk Kültür Merkezi	The Atatürk Cultural Center	R.C frame	Afyon Marble
14	1991	The Vakıfbank Education Management Building	Vakıfbank Eğitim Yönetmenliği Binası	The Vakıfbank Education Management Building	R.C frame	Marble

Table III.6 (cont'd) The case Study Building list 1978-2004

	Construction Date	Name of the Building	Name of the Building in Turkish (Tr)	Today's Function	Type of Construction	Type of stone
15	1993	Bayındır Hospital	Bayındır Hastanesi	Bayındır Hospital	R.C frame	Granite
16	1994	The Kurtuluş Park Wedding Ceramony Building	Kurtuluş Parkı Nikah Salonu	The Kurtuluş Park Wedding Ceramony Building	R.C frame	Granite
17	1997	METU Cultural and Convention Center	ODTU Kültür ve Kongre Merkezi	METU Cultural and Convention Center	R.C frame	Travertine
18	Last 10 years	OYAKBANK Head Office Atatürk Street No:70	Oyakbank Genel Müdürlüğü	OYAKBANK Head Office Atatürk Street No:70	R.C frame	Marble
19	Last 10 years	Ankara Chamber Of Commerce Building	Ankara Ticaret Odası	Ankara Chamber Of Commerce Building	R.C frame	Granite
20	2003	Armada Shopping Center	Armada Alışveriş Merkezi	Armada Shopping Center	R.C frame	Granite

1925	MINISTRY OF FINANCE (Tr: Gümrük Müsteşarlığı-Ulus)	1

Figure III.44 Ministry of Finance (2002)

Type of Construction	:	
Type of Stone	:	Yellow travertine
Type of Stone Facade	:	Stone cladding installed with mortar

DIAGNOSIS OF STONE CLADDING FAILURES

Figure III.45 Stone failure at window sill (2003).

Failure (Table III.4)	**4.**Stone crumbling, detachment **5.**Stone crack
Possible Reason of the Failure (TableIII.4)	**1.**İmproper type of stone selection, **2.**Surface abrasion due to weathering, **12.** Some types of stones swell up after absorbing water The pores get larger and stone suffers.
Standards Related With (TableIII.5)	**1.1** Types of stone-Stone selection **1.2.c** Petrographic properties **1.2.f** Thermal and moisture movement **1.2.g** Weathering resistance
Proposal	The type of stone used for sill must be resistant to weathering.

DIAGNOSIS OF STONE CLADDING FAILURES (cont'd) Ministry of Finance

Figure III.46 Failure of stone elements under balcony (2003).

Failure (Table III.4)	**4**.Stone crumbling, detachment, **5**.Stone crack **6**. Staining
Possible Reason of the Failure (TableIII.4)	**1**.İmproper type of stone selection, **2**.Surface abrasion due to weathering, **12**. Some types of stones swell up after absorbing water when it freezes the pores get larger and stone suffers. **33**. Water dissolves the salt aggregates in the mortar and the back up wall behind the stone causing efflorescence.
Standards Related With (TableIII.5)	**1.1** Types of Stone-Stone selection **1.2.a** Rock pores and porosity **1.2.c** Petrographic Properties **1.2.f** Thermal and moisture movement **1.2.g** Weathering resistance
Proposal	A waterproofing to the horizontal layer should be applied.

1925	**MINISTRY OF CULTURE** *(Tr: Kültür Bakanlığı)*	**2**

Figure III.47 Ministry of Culture (2002)

Type of Construction	:	
Type of Stone	:	Travertine and Marble
Type of Stone Cladding	:	Stone cladding installed with mortar

DIAGNOSIS OF STONE CLADDING FAILURES

Figure III. 48 The brownish color of the travertine stone (2002).

Failure (TableIII.4)	**6.** Staining
Possible Reason of the Failure (Table III.4)	**15.** Corrosion of the fixing element due to improper material
Standards Related With (Table III.5)	**2.a** Materials of Fixing **2.b** Types of fixing
Proposal	Gerns (viewed in September 2005) mentioned for these types of failure due to the corrosion of the fixing element. The fixing element should be stainless steel or galvanized steel.

DIAGNOSIS OF STONE CLADDING FAILURES (cont'd) Ministry of Culture

Figure III .49 Unevenness of the stone surface (2002).

Failure (TableIII.4)	**5**. Stone crack **11.** Stone surface abrasion
Possible Reason of the Failure (Table III.4)	**31**.Wrong stone cleaning techniques and materials
Standards Related With (Table III.5)	**7**. Maintenance

1933-1934	**EMLAKBANK-Ankara-Ulus** *(Tr :Emlak ve Eytam Bankası)*	**3**

Figure III.50 Emlakbank (2002)

Architect	:	Clemens Holzmeister
Type of Construction	:	R.C. frame
Ttpe of stone		White Marmara Marble and Andezite
Type of Stone Cladding		Stone cladding installed with mortar

DIAGNOSIS OF STONE CLADDING FAILURES

Figure III.51 White marble on the front surface is in a very good condition. Discoloration of the lower part due to the lack of waterproofing of the terrace (2002).

Failure (TableIII.4)	**6.** Staining
Possible Reason of the Failure (Table III.4)	**21.** Chemical reaction of the mortar with stone **33.** Water dissolves the salt aggregates in the mortar and the back up wall behind the stone, causing efflorescence
Standards Related With (Table III.5)	**1.f** Thermal and Moisture Movement **1.g.** Weathering Resistance **3.**Mortar
Proposal	The waterproofing material of the terrace should be renewed. The stone cladding at the lower part should be cleaned with a proper stone cleaning technique.

1937-1939	**FACULTY OF LITERATURE, HISTORY AND GEOGRAPHY** *(Tr: Dil tarih ve Coğrafya Fakültesi)*	**4**

Figure II.52 The Faculty of Literature, History and Geography (2002)

Type of Construction	:	R.C frame
Type of Stone	:	Ankara stone-Andezite
Type of Stone Cladding	:	Stone cladding installed with mortar

DIAGNOSIS OF STONE CLADDING FAILURES

a

b

Figure III.53 a-b Deterioration of the window sill stone and discoloration of the whole stone façade caused by air pollutants (2002)

Failure (TableIII.4)	**4**.Stone crumbling, detachment, **5**.Stone crack **7.** Discoloration
Possible Reason of the Failure (Table III.4)	**1**. Improper type of stone selection **2**. Surface abrasion of stone due to weathering **12**. Some types of stones swell up after absorbing water. The pores get larger when the water freezes causing the stone to suffer **13.** Atmospheric deposits on the stone
Standards Related With (Table III.5)	**1.1** Types of stone-Stone selection **1.2.c** Petrographic properties **1.2.f** Thermal and moisture movement **1.2.g** Weathering resistance

DIAGNOSIS OF STONE CLADDING FAILURES (cont'd) The Faculty of Literature, History and Geography)

Proposal	Window sills should be replaced with a durable stone profile with a proper slopping and dripping. The whole façade should be cleaned with a proper stone cleaning technique.

1938-1941	**THE TURKISH RAILWAY 2 nd. ZONE DIRECTORY** *(Tr: DDY 2. Bölge Müdürlüğü)*	**5**

Figure III.54 Turkish Railway 2. Zone Management (2002)

Architect	:	Vedat Tek
Type of Construction	:	R.C frame–Stone masonry
Type of Stone	:	
Type of Stone Facade	:	Stone cladding installed with mortar

DIAGNOSIS OF STONE CLADDING FAILURES

a

b

Figure III.55 a-b The arrow piece of stone panels had fallen down and replaced with a new one during restoration (2002) (2004)

Failure (TableIII.4)	**1.** Stone panel fall down
Possible Reason of the Failure (Table III.4)	**3.** Inadequate stone thickness for anchorage
Standards Related With (Table III.5)	**1.2.b** Stone appearance and dimension **1.2.e** Flexural Strength/Modulus of Rupture **2.b**Types of fixing **2.c** Fixing design
Proposal	A special detail has to be developed for the fixing of the narrow pieces of stone to the back-up wall.
Notes	Schaupp (1967:56-57) was given a similar example of long narrow stone panels falling down due to vibration or wrong fixing techniques.

DIAGNOSIS OF STONE CLADDING FAILURES
(Cont'd) The Turkish Railway 2nd. Zone Directory

a b

Figure III .56 a-b The surface of the decorative elements were deteriorated due to weathering and changed with the new ones during restoration. a. (2002) b.(2004)

Failure (TableIII.4)	**11**. Stone surface abrasion
Possible Reason of the Failure (Table III.4)	**1.**Improper type of stone selection **2.** Surface abrasion of stone due to weathering **12.** Some type of stones swell up after absorbing water. The pores get larger when the water freezes making the stone suffers
Standards Related With (Table III.5)	**1.1** Types of stone-Stone selection **1.2.a** Rock pores and porosity **1.2.c** Petrographic properties **1.2.f** Thermal and moisture movement **1.2.g** Weathering resistance
Proposal	Proper type of stone that is resistant to weathering had to be chosen as a decorative element. There is need for further standards determining the weathering resistance of stone other than the test for salt crystallization and the frost resistance.

1958	**HACETTEPE UNIVERSITY HOSPITAL** *(Tr: Hacettepe Universitesi Hastanesi)*	6

Figure III.57 Hacettepe University Hospital (2004)

Type of Construction	:	R.C frame
Type of Stone	:	White travertine
Type of Stone Facade	:	Stone cladding set on to the main body of the wall

DIAGNOSIS OF STONE CLADDING FAILURES

Figure III.58. The white travertine has been cleaned and some of stone panels close to the corner and the vertical expansion joints had fallen down and replaced with the ones that are different in color. (2004)

Failure (TableIII.4)	**1.** Stone panel fall down
Possible Reason of the Failure (Table III.4)	**27**. Different movement of the back-up wall and stone
Standards Related With (Table III.5)	**1.2.d.** Compressive strength **2.b** Fixing design **2.c.** Types of fixing **3.** Mortar **4.b** Movement joints
Proposal	The mortar is not enough to fix the stone on the back up wall. There is need for mechanical fixing especially at the corners. Movement joints should be provided. (BS 8298,1994:26).

1967	**ANKARA UNIVERSITY** **THE FACULTY OF MEDICINE** (*Tr: Ankara Üniversitesi Tıp Fakültesi*)	**7**

Figure III.59 Ankara University Faculty of Medicine (2004)

Type of Construction	:	R.C frame
Type of Stone	:	Yellow Travertine
Type of Stone Facade	:	Stone Cladding set on the main body of the wall with mortar

DIAGNOSIS OF STONE CLADDING FAILURES

Figure III.60 Discoloration of stone cladding due to heavy traffic near the building.(2004)

Failure (TableIII.4)	**7.** Discoloration
Possible Reason of the Failure (Table III.4)	**13.** Atmospheric deposits on the stone
Standards Related With (Table III.5)	**1.2.g** Weathering resistance
Proposal	A proper stone cleaning technique has to be used to clean the façade.

DIAGNOSIS OF STONE CLADDING FAILURES (Cont'd) Ankara University The Faculty of Medicine

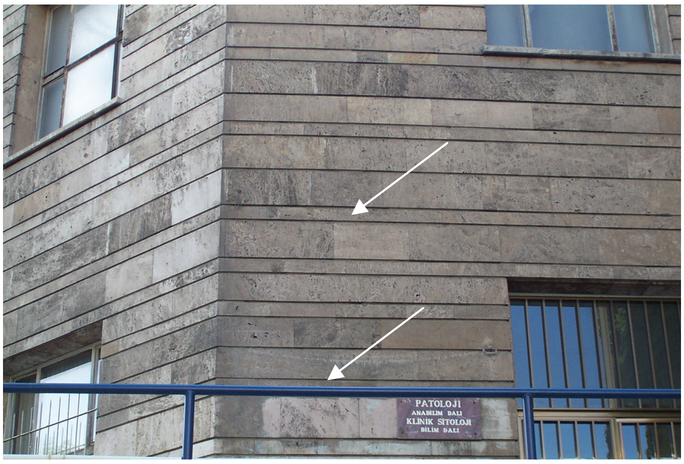
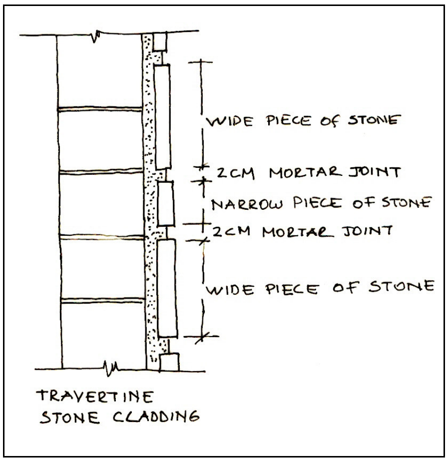


Figure III.61 The panels which have a different width fixed on to the back structure with large joints (2 cm) compared the width of the stone.

Failure (TableIII.4)	No failure from the point of the detachment of the stone to the back-up wall
Possible Reason of the Failure (Table III.4)	
Standards Related With (Table III.5)	**1.1.e** Compressive strength **1.2.e** Flexural strength/Modulus of Rupture **3.** Mortar **4.a** Panel joints
Proposal	The stone façade had a good performance generally from the aspect of stone facades' performance criteria determined in this research, excluding discoloration. Many of the travertine facades belonging to this building construction period had the problem of stone fall and displacement. The fixing technique may be advantageous in preventing stone fall. There may be a need for stone cleaning with a proper technique.  **Figure III.62** Section of stone cladding application

1969	PRIVATE APARTMENT AT GMK STREET NO:17 *(Tr: GMK Bulvarı No:17 Apartman)*	8

Figure III.63 Private Apartmant At GMK Street No: 17 (2003)

Type of Construction	:	R.C. frame
Type of Stone	:	Denizli Travertine
Type of Stone Facade	:	Stone cladding set on to the main body of the wall

DIAGNOSIS OF STONE CLADDING FAILURES

Figure III.64 Stone panels have fallen down and the whole façade stone panels have been screwed, Discoloration of the whole façade due to air pollution and wrong window sill detail. (2003)

Failure (Table III.4)	**1.**Stone panel fall down **7.** Discoloration

DIAGNOSIS OF STONE CLADDING FAILURES (cont'd) Private Apartment at GMK Street No.17

Possible Reason of the Failure (Table III.4)	**1**. Improper type of stone selection **7**. The increase of temperature on the surface of the stone and low temperature at the back of the stone causing hysteresis (permanent volume change) and thus stone bow **10**. Some types of stones swell up after absorb water and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **13.** Atmospheric deposits on stone **27**. Different movements of the back-up wall and stone **28.** Shrinkage of the reinforced concrete structure at the back of the stone cladding
Standards Related With **(**Table III.5)	**1.1.** Types of stone-Stone selection **1.2.a** Rock pores and porosity **1.2.c**. Petrographic properties **1.2.d** Compressive strength **1.2.e** Flexural strength / Modulus of Rupture1.2.f Thermal and moisture movement **1.2 g** Weathering resistance **4.b**. Movement Joints
Proposal	Some movement joints should be given for such a high building. There should be a mechanical fixing beside the mortar for the installation of the stone to the back up wall. A continuous window sill with a dripping profile may prevent the accumulation of dirt under window sill edges.
Notes	This stone is preferred due to its thermal insulation property with its porous structure. The stone was screwed 10 years ago after one of the stone panels had fallen down. (Reference: The contractor of the building was Nurettin Daş) The possible reasons may be the structural movement and the lack of expansion joint.

1960's	**PRIVATE APARTMENT AT GMK STREET NO:37** *(Tr: GMK Bulvarı No:37 Apartman)*	9

Figure III.65 Private Apartment at GMK Street No: 37 (2003)

Type of Construction	:	R.C frame
Type of Stone	:	Denizli Travertine
Type of Stone Facade	:	Stone cladding set on to the main body of the wall

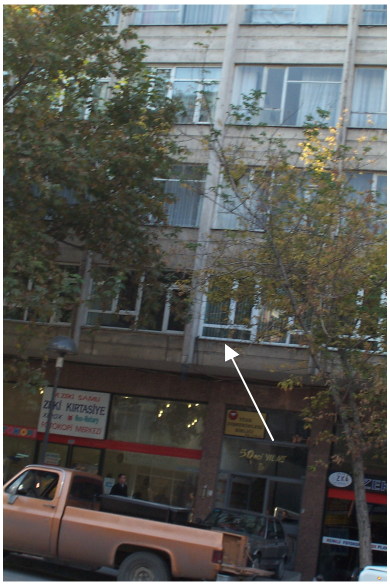


Figure III.66 All the stone panels have been screwed. The whole façade is discolored due to air pollution and water penetration under the window sill. (2003)

DIAGNOSIS OF STONE CLADDING FAILURES (cont'd) Private Apartment at GMK Street No:37

Failure (TableIII.4)	**1.**Stone panel fall down **7** Discoloration
Possible Reason of the Failure (Table III.4)	**1**. Improper type of stone selection **7**. The increase of temperature on the surface of the stone and low temperature at the back of the stone causing hysteresis (permanent volume change) and thus stone bow **10**. Some type of stones swell up after absorbing water and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **13.** Atmospheric deposits on stone **27**. Different movements of the back-up wall and stone **28.** Shrinkage of the reinforced concrete structure at the back of the stone cladding
Standards Related With (Table III.5)	**1.1**. Types of stone-Stone selection **1.2.a** Rock pores and porosity **1.2.c**. Petrographic properties **1.2.d** Compressive strength **1.2.e** Flexural strength / Modulus of Rupture1.2.f Thermal and moisture movement **1.2 g** weathering resistance **4.b**. Movement Joints
Proposal	Some movement joints should be provided for such a high building. There should be a mechanical fixing beside the mortar for the installation of the stone to the back up wall. A continuous window sill may prevent the accumulation of dirt under window sill edges.
Notes	The stone problems of this building is very similar to the building in GMK Street No:17. The type of stone is the same i.e travertine. All stone panels were screwed. There is accumulation of air pollutants on the stone surface and water penetrating near the window sill created discoloration on the façade. There are some examples of these types of facades in that area. The problems are almost the same.

1958	METU FACULTY OF ECONOMICS AND ADMINISTRATIVE SCIENCES *(Tr: ODTÜ İktisadi ve İdari Bilimler Fakültesi)*	10

Figure III.67 METU Faculty of Economics and Administrative sciences (2003)

Architect	:	Behruz Çinici
Type of Construction	:	R.C frame
Type of Stone	:	White Travertine
Type of Stone Facade	:	Stone cladding on to the main body of the wall with mortar.

DIAGNOSIS OF STONE CLADDING FAILURES

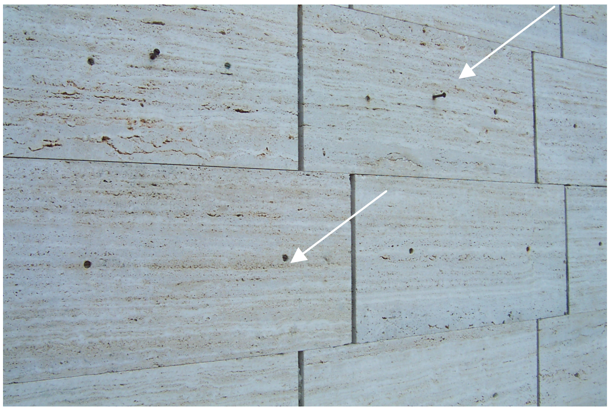


Figure III.68 Each stone panel was screwed to provide safety.

Failure (TableIII.4)	**1.** Stone fall down

DIAGNOSIS OF STONE CLADDING FAILURES (cont'd) METU Faculty of Economics and Administrative Sciences

Possible Reason of the Failure (Table III.4)	**1**.Improper type of stone selection **7**. The increase of temperature on the surface of the stone and low temperature at the back of the stone causing hysteresis (permanent volume change) and thus stone bow **10.** Some types of stones swell up after absorbing water and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **13**. Atmospheric deposits on stone **27**. Different movements of the back-up wall and stone **28**. Shrinkage of the reinforced concrete structure at the back of the stone cladding
Standards Related With (Table III.5)	**1.1** Types of stone –stone selection **1.2.a** Rock porosity and density 1.2 d. Compressive strength **1.2.e** Flexural strength /Modulus of Rupture **1.2.f** Thermal and moisture movement **3.** Mortar **4.b** Movement joints
Proposal	There should be a mechanical fixing beside the mortar for the installation of the stone to the back up wall.
Notes	There was no joint mortar between stone panels. This may cause water penetration under stone panels. Travertine is a sedimentary rock and water absorbent. Moisture at the back up stone may freeze and cause problems.

Figure III.69 Stone fall down at corner shows an irregular back structure and inadequate fill of mortar under stone panels. (2003)

DIAGNOSIS OF STONE CLADDING FAILURES (cont'd) METU Faculty of Economics and Administrative Sciences

Failure (TableIII.4)	**1**. Stone panel fall down
Possible Reason of the Failure (Table III.4)	**10.** Some type of stones swell up after absorbing water and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **21.** Chemical reaction of the mortar with stone **34**. Unqualified workmanship while installing with mortar. (This is added to Table III.4)
Standards Related With (Table III.5)	**3**. Mortar **5**. Backing Structure
Proposal	The mortar should be applied as to provide ventilation and should not create a closed air gap between the back of stone panel and the back-up wall.
Notes	The wall at the entrance of the Faculty of Economics and Administrative Sciences is similar to many other travertine claddings with mortar type walls. The mortar should be wholly filled to the back up of the stone panel or it is better to use the stone cladding on the main body of the wall with mortar and mechanical fixing. Schaupp (1967:61) mentions a similar problem of stone facades observed on this building.

1967-68	**PRIVATE APARTMENT BUILDING** *(Tr: Necatibey Street No:93 Ankara)*	**11**

Figure III.70 Private Apartment Building

Type of Construction	:	R.C frame
Type of Stone	:	Travertine
Type of Stone Cladding	:	Stone cladding on to the main body of the wall with mortar

DIAGNOSIS OF STONE CLADDING FAILURE

Figure III.71 All the stone panels were screwed after one of the panels had fallen down (2002)

Failure (TableIII.4)	**1.** Stone panels fall down **7.** Discoloration

DIAGNOSIS OF STONE CLADDING FAILURE
(Cont'd) Private Apartment Building

Possible Reason of the Failure (Table III.4)	**1**.Improper type of stone selection as facade material **7**. The increase of temperature on the surface of the stone and low temperature at the back of the stone cause hysteresis (permanent volume change) and thus stone bow **10.** Some type of stones swell up after absorbing water and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **13**. Atmospheric deposits on stone **27**. Different movements of the back-up wall and stone **28.** Shrinkage of the reinforced concrete structure at the back of the stone cladding **35**. Discoloration of stone due to wrong window sill and coping details
Standards Related With (Table III.5)	**1.1** Types of stone –stone selection **1.2.a** Rock porosity and density 1.2 d. Compressive strength **1.2.e** Flexural strength /Modulus of Rupture **1.2.f** Thermal and moisture movement **3.** Mortar **4.b** Movement joints
Proposal	The correct detailing of window sill should drip the water without flowing on the surface of the stone.

Figure III.72 Discoloration of stone under window sill and parapet wall copings (2002)

Failure (TableIII.4)	**1**. Stone panel fall down **7**. Discoloration
Possible Reason of the Failure (Table III.4)	Same as Figure III.59.F

DIAGNOSIS OF STONE CLADDING FAILURE (Cont'd) Private Apartment Building

Standards Related With (Table III.5)	**1.1** Types of stone –stone selection **1.2.a** Rock porosity and density 1.2 d. Compressive strength **1.2.e** Flexural strength /Modulus of Rupture **1.2.f** Thermal and moisture movement **1.2.g** Weathering resistance **3.** Mortar **4.b** Movement joints
Notes	The problems are very similar to other travertine clad facades in Ankara. The type of stone used for façade has to satisfy some of the criteria. (Chacon,1999:175-200-Appendix C.III.D) Travertine may not be a suitable stone for Ankara's climate. The reason of discoloration of the stone under the window sill and the parapet wall copings seems to be incorrect water drip detail. The stone stayed wet and collected the pollutants of the air more than it has done other areas. This reason should be added to the reasons of the failures mentioned in the previous part of this chapter as item an **35**. The discoloration of stone due to wrong window sill and coping details. This is a failure which is not reviewed from literature.

1985	ANKARA UNIVERSITY IBNI SINA HOSPITAL *(Tr: Ankara Universitesi Ibni Sina Hastanesi)*	12

Figure III.73 Ankara Ibni Sina Hospital (2004)

Type of Construction	:	R.C frame
Type of Stone	:	White Travertine
Type of Stone Cladding	:	Stone cladding to the main body of the wall with mortar

DIAGNOSIS OF STONE CLADDING FAILURE

Figure III .74 Stone fall down at the corner due to a void at mortar behind the stone panel (2004).

Failure (TableIII.4)	**1.** Stone panel fall down
Possible Reason of the Failure (Table III.4)	**10.** Some types of stones swell up when absorb water after absorbing and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **21.** Chemical reaction of the mortar with stone **34**. Unqualified workmanship while installing with mortar. (this is added to the list prepared before)
Standards Related With (Table III.5)	**3**. Mortar **5**. Backing Structure
Proposal	The mortar should be applied as to provide ventilation and should not create a closed air gap between the back of the stone panel and the back-up wall.

DIAGNOSIS OF STONE CLADDING FAILURE (Cont'd) IBNI SINA Hospital

Figure III.75 Stone discoloration at storey cut profiles.
Stone panels have been screwed against fall down. (2004)

Failure (TableIII.4)	**1.**Stone panel fall down **7.**Discoloration
Possible Reason of the Failure (Table III.4)	**10.** Some types of stones swell up when absorb water after absorbing and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **13.** Atmospheric deposits on stone **27.**Different movement of the back-up wall and stone **28.** Shrinkage of the reinforced concrete structure at the back of the stone cladding
Standards Related With (Table III.5)	**1.1** Types of stone , stone selection **1.2.a** Rock pores and porosity **1.2.e** Flexural strength –Modulus of Rupture **1.2.f** Thermal and moisture movement
Proposal	The floor cut profile details have caused the accumulation of air pollution. It has to be detailed carefully. Although this problem is observed widely, there is not any recommendation on codes about the detailing of these types of profiles, window sills.
Notes	The reason may be water penetration and it freezing of it under the stone panel. Other reason may be the absence of an expansion joint for a long piece of stone cladding. (Beasly, viewed in September 2005) The expansion of stone panels was not compensated with panel joints. There should be additional expansion joints.

DIAGNOSIS OF STONE CLADDING FAILURE (Cont'd) IBNI SINA Hospital

Figure III.76 Displacement of parapet wall coping (2004).

Failure (TableIII.4)	**2**. Stone displacement **3**.stone buckling
Possible Reason of the Failure (Table III.4)	**7.** The increase of temperature on the surface of the stone and low temperature at the back of the stone causing hysteresis (permanent volume change) and thus stone bow **10.** Some types of stones swell up when absorb water after absorbing and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages
Standards Related With (Table III.5)	**1.2.f** Thermal and Moisture Movement
Proposal	Movement joints should be placed within stone panels

Figure III.77 Stone breakage and fall down due to the water penetration of the wall from the window sill. Some of the stone panels have been fixed by screws to the back-up wall. (2004).

DIAGNOSIS OF STONE CLADDING FAILURE (Cont'd) IBNI SİNA Hospital

Failure (TableIII.4)	**4.** Stone crumbling
Possible Reason of the Failure (Table III.4)	**10.** Some types of stones swell up when absorb water after absorbing and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **12.** Some type of stones swell up when absorb water. The pores get larger when the water freezes making the stone suffer.
Standards Related With (Table III.5)	**1.**Types of stone-stone selection **1.2.a** Rock pores and Posrosity**1.2.c** Petrographic properties **1.2.f** Thermal and Moisture Movement
Proposal	
Notes	Most travertine claddings have the problems of falling down. It might be better to think about different type of fixings i.e. like the one that been applied in Ankara University The Faculty of Medicine Building.

Figure III.78 Cement bags were filled into the back of the stone cladding wall during construction instead of mortar during the construction of the additional part of the building.

Possible Failure (TableIII.4)	**29.** Stone panel cracks due to workmanship
Possible Reason of the Failure (Table III.4)	**3.** Stone buckling
Standards Related With (Table III.5)	**6.** Workmanship
Proposal	The gaps behind the stone panels should be filled with a proper kind of repair mortar.
Notes	Richardson (2001:137) was given an example of a failure similar to this kind of insufficient workmanship.

1987	**ANKARA** **ATATÜRK CULTURAL CENTER** *(Tr: Ankara-Atatürk Kültür Merkezi)*	13

Figure III.79 Ankara Atatürk Cultural Center (2004)

Architect	:	Filiz- Çoşkun Erkal
Type of Construction	:	R:C. frame
Type of Stone	:	Afyon White Marble.
Type of Stone Facade	:	Stone cladding on sloped wall with mortar.

DIAGNOSIS OF STONE CLADDING FAILURE

a **b**

Figure III.80 a.b. Stone fall down, stone displacement especially at construction joints due to the movement of the structure (2004)

Failure (TableIII.4)	**1.** Stone fall down **2**. Stone displacement **3**. Stone buckling **4**. Stone crumbling **5**.Stone crack
Possible Reason of the Failure (Table III.4)	**1.** Improper type of stone selection as facade material **7**. The increase of temperature on the surface of the stone and low temperature at the back of the stone causing hysteresis (permanent volume change) and thus stone bow **10.** Some types of stones swell up when absorb water after absorbing and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **21**. Chemical reaction of the mortar with stone **27**. Different movements of the back-up wall and stone **28**. Shrinkage of the reinforced concrete structure at the back of the stone cladding

DIAGNOSIS OF STONE CLADDING FAILURE (cont'd) Ankara Atatürk Cultural Center

Standards Related With (Table III.5)	**1.1** Types of stone-Stone selection**1.2.e** Flexural Strength **1.2.f** Thermal and moisture movement **3.** Mortar **4.b** Movement Joints
Proposal	There is a large wall – roof reinforced concrete slab under the stone cladding. The thermal movement, reinforced concrete shrinkage as Schaup(1967:58)and Smith (1999:356) mentions and this movement may have exceeded the calculated values.

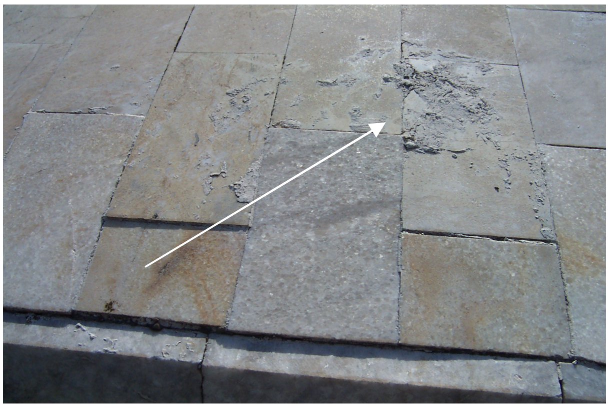


Figure III.81 Mortar dabs on top of the stone panels and irregular laying of stone panels due to unqualified workmanship (2004)

Failure (TableIII.4)	Although it is not mentioned in Table III.4, the appearance does not satisfy the performance criteria mentioned in BS 8200 (1985:4) related with appearance i.e. the acceptable degree of variation should be established.
Possible Reason of the Failure (Table III.4)	**29**. Stone panel cracks due to poor workmanship (In this case the poor workmanship causes an unacceptable appearance)
Standards Related With (Table III.5)	**6**. Workmanship
Proposal	A careful inspection of the workmanship is needed during construction.

DIAGNOSIS OF STONE CLADDING FAILURE (cont'd) Ankara Atatürk Cultural Center

Figure III.82 Deterioration of the joint material (2004)

Failure (TableIII.4)	**13**. Deterioration of the joint material
Possible Reason of the Failure (Table III.4)	**24.** Improper joint material selection and use
Standards Related With (Table III.5)	**4**. Joints
Notes	The failure of the joint material causes water penetration under the stone panels.

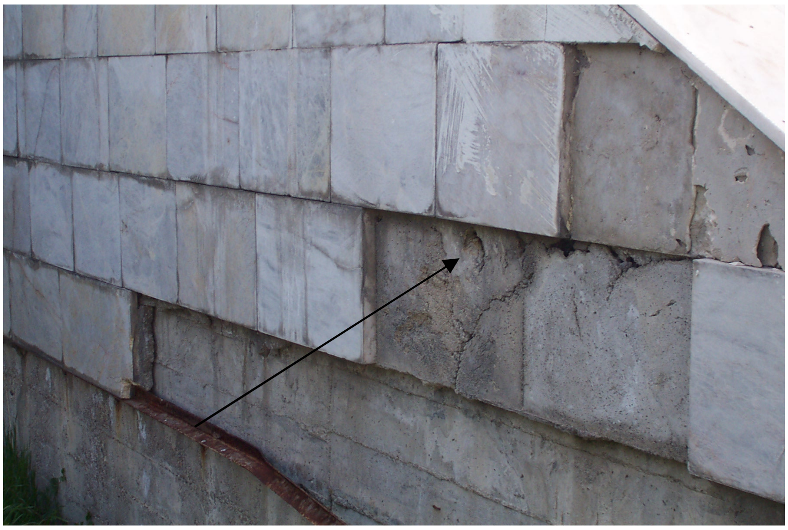


Figure III.83 Stone fall down due to irregular back structure and water penetration to the back of stone panels and corrosion of the fixing elements (2004)

DIAGNOSIS OF STONE CLADDING FAILURE (cont'd) Ankara Atatürk Cultural Center

Figure III.84 Stone fall down at the construction joint of the retaining wall and the top of the wall due to water penetration under stone panels (2004)

Failure (TableIII.4)	**1**. Stone panel fall down
Possible Reason of the Failure (Table III.4)	**10**. Some types of stones swell up after absorbing water and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **27**. Different movements of the back-up wall and stone
Standards Related With (Table III.5)	**1.2.d** Compressive strength **1.2.f** Thermal and moisture movement **3**. Mortar

Figure III.85 Grass has grown through the joints (2004)

Failure (TableIII.4)	**13**. Deterioration of the joint material
Possible Reason of the Failure (Table III.4)	**23.** Improper joint design causes water penetration inside the wall **24**. Improper joint material selection and use **32**. Incompatibility of other stone façade components with stone from the aspects of service life

DIAGNOSIS OF STONE CLADDING FAILURE (cont'd) Ankara Atatürk Cultural Center

Standards Related With (Table III.5)	**4.** Joints
Proposal	Proper joint material should be used to prevent water penetration at joints.
Notes	Fitzner *et.al* (1995:65) defines this failure as biological colonization. The reason is the continuous presence of water under stone panels.

Figure III.86 Stone detachment due to water penetration and differential settlement of sloping and vertical surface (2004)

Failure (TableIII.4)	**2.** Stone displacement **4**. Stone crumbling
Possible Reason of the Failure (Table III.4)	**10**. Some type of stones swell up after absorbing water and distort when dried out, this creating stress on wall ties i.e. on mortar and mechanical anchorages **12**. Some types of stones swell up when they absorb water. The pores get larger when the water freezes and the stone suffer **33.** Water dissolves the salt aggregates in the mortar and the back up wall behind the stone, which causes efflorescence and stone deterioration.
Standards Related With (Table III.5)	**1.1** Types of stone-Stone selection **1.2.f** Thermal and moisture movement

DIAGNOSIS OF STONE CLADDING FAILURE (cont'd) Ankara Atatürk Cultural Center

Figure III.87 Stone fall down due to improper water proofing of the horizontal surface (2004)

Failure (TableIII.4)	**1**. Stone fall down
Possible Reason of the Failure (Table III.4)	**10**. Some types of stones swell up after absorbing water and distort when dried out, creating stress on wall ties i.e. on mortar and mechanical anchorages **21**. Chemical reaction of the mortar with stone **27**. Different movements of the back-up wall and stone **28.** Shrinkage of the reinforced concrete structure at the back of the stone cladding
Standards Related With (Table III.5)	**1.2.f.** Thermal and moisture movement **3**. Mortar
Proposal	Waterproofing of the terrace should be done sufficiently and the water penetration between the mortar and stone should be prevented.
Notes	The marble is a metamorphic stone. The contact with rain due to the structure of the roof-wall may create acid attack results in the chemical deterioration of stone and mortar. (Richardson, 2001:107) One of the reasons of the failures of stone cladding of this building is this chemical reaction besides structural and thermal movement. It seems that stone façade cladding with mortar was not suitable for this type of a huge reinforced concrete slab. It should be a stone curtain wall that allows stone and back structure movement separately.

1991	VAKIFBANK TRAINING MANAGEMENT BUILDING *(Tr. Vakıfbank Eğitim Yönetmeliği Binası)*	14

Figure III.88 Vakıfbank Training Management Building (2004)

Type of Construction	:	R.C frame
Type of Stone	:	White Marble
Type of Stone Cladding	:	Stone cladding installed with mortar

DIAGNOSIS OF STONE CLADDING FAILURE

Figure III.89 The accumulation of dirt at marble joints up to at certain level of the building. It does not continue on to the parapet wall (2004).

DIAGNOSIS OF STONE CLADDING FAILURE (cont'd) Vakıfbank Training Management Building

Failure (TableIII.4)	**7**. Discoloration 13.Deterioration of the joint material
Possible Reason of the Failure (Table III.4)	**9.** Condensation within the wall **13.** Atmospheric deposits on stone **23**. Improper joint design causing water penetration inside the wall **24.** Improper joint material selection and use **25.** Water absorption at joints causing staining on the stone
Standards Related With (Table III.5)	**1.2.f** Thermal and moisture movement **4**.Joints
Proposal	
Notes	The reason of the failure may be the condensation within the wall, which may have made the stone and joints wet causing the discoloration of the stone and joint material. The reason of the condensation within the wall may be the lack or insufficient thickness of the thermal insulation material. Thermal insulation calculations should be checked before cleaning the stone surface. This may also lead to a stone fall at a further stage.

1993	**BAYINDIR HOSPITAL- Ankara** *(Tr.Bayındır Hastanesii)*	15

Figure III.90 Bayındır Hospital (2004)

viewdType of Construction	:	R.C frame
Type of Stone	:	Granite
Type of Stone Facade	:	Stone curtain wall. Ventilated stone façade anchored to the load bearing metal frame with stick system

DIAGNOSIS OF STONE CURTAIN WALL FAILURE

Figure III.91 Discoloration of the stone panel joints at the whole façade (2004)

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) Bayındır Hospital

Failure (TableIII.4)	**7**. Discoloration
Possible Reason of the Failure (Table III.4)	**23**. Improper joint design causing water penetration inside the wall **24.**Improper joint material selection and use **25**. Water absorption at joints causing staining on the stone **32.** Incompatibility of other stone façade components with stone from the aspects of service life.
Standards Related With (Table III.5)	4. Joints
Proposal	The joint material reaction with stone had to be tested before the application.
Notes	The reason of the accumulation of the pollutant may be the ingress of joint material to the granite. Proper primer had to be used. The profile of the joint may accumulate the water during rain and cause the penetration of water into the granite and this wet stone may collect the air pollutants as Nashed(1995:161) and Smith (1999:358) emphasize.

1994	KURTULUŞ PARK WEDDING CEREMONY BUILDING *(Tr:Kurtuluş Parkı Nikah Salonu)*	16

Figure III.92 Kurtuluş Park Wedding Ceremony Building (2003)

Architect	:	Haluk Pamir
Type of Construction	:	R.C frame
Type of Stone	:	Granite
Type of Stone Facade	:	Ventilated stone façade anchored directly to the back-up wall

DIAGNOSIS OF STONE CLADDING FAILURE

Figure III.93 Differential settlement has caused the detachment of stone panels from the fixing element and crumbling of the stone panels (2003).

DIAGNOSIS OF STONE CLADDING FAILURE
(cont'd) Kurtulus Park Wedding Ceremony Hall

Failure (TableIII.4)	**2.**Stone panel displacement
Possible Reason of the Failure (Table III.4)	**3.** Inadequate stone thickness for anchorage **16.** Improper fixing design against loads like wind and earthquake **18.** Poor location of dowel pin during fixing **27**. Different movements of the back-up wall and stone **28**. Shrinkage of the reinforced concrete structure at the back of the stone cladding **30**. Unsuitable techniques for cutting corbel slots and cramp holes
Standards Related With (Table III.5)	**1.2.d** Compressive strength **1.2.e** Flexural strength/Modulus of Rupture **2.**Fixing design
Proposal	

Figure III.94 The thickness of stone (2 cm) was not enough to compensate for the stress created by the dowel pin on the stone so it has broken and the adjacent stone panel displaced (2003)

Failure (TableIII.4)	**2.**Stone displacement
Possible Reason of the Failure (Table III.4)	**3.** Inadequate stone thickness for anchorage **16.** Improper fixing design against loads like wind and earthquake **18.** Poor location of dowel pin during fixing **27**. Different movements of the back-up wall and stone **28**. Shrinkage of the reinforced concrete structure at the back of the stone cladding **30**. Unsuitable techniques for cutting corbel slots and cramp holes
Standards Related With (Table III.5)	**1.2.d** Compressive strength **1.2.e** Flexural strength Modulus of Rupture **2.**Fixing design

DIAGNOSIS OF STONE CLADDING FAILURE (cont'd) Kurtuluş Park Wedding Ceremony Hall

Proposal	The thickness of the stone has to be a minimum of 3 cm at sills, copings and supported reveals according to BS 8298 (1999)
Notes	

Figure III.95 The corroded metal element could cause stone crumbling. The back of the stone is empty, so the compression stone may cause breakage (2002)

Failure (TableIII.4)	**4.** Stone crumbling
Possible Reason of the Failure (Table III.4)	**15.** Corrosion of the fixing elements due to the use of improper material
Standards Related With (Table III.5)	**1.2.d** Compressive strength **1.2.e** Flexural Strength/Modulus of Rupture **2.a** Fixing material
Proposal	BS 8298:1994:14 advises the movement of restrained fixings.
Notes	The settlement of some parts caused stone displacement in this building. The settlement should be minimized with additional precautions and the fixing element should give possibility for more settlement.

1997	METU CULTURAL AND CONVENTION CENTER *(Tr: ODTU Kongre ve Kültür Merkezi)*	17

Figure III. 96 METU Cultural and Convention Center (2004)

Architect	:	Haluk Pamir
Type of Construction	:	R.C frame
Type of Stone	:	Travertine at the building, Andezite retaining walls
Type of Stone Facade	:	Ventilated stone façade anchored directly to the back up wall.

DIAGNOSIS OF STONE CLADDING FAILURE

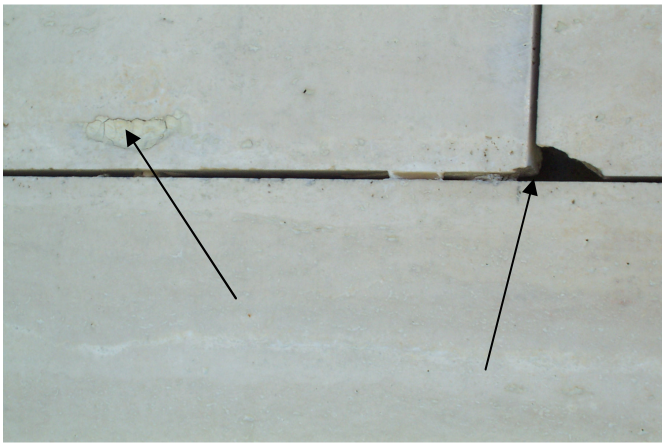


Figure III.97 Stone crumbling at the edge of the stone due to poor workmanship and big pores on the stone filled with a kind of plaster (2004)

Failure (TableIII.4)	**4.** Stone crumbling
Possible Reason of the Failure (Table III.4)	**1.** Improper type of stone selection as facade material **30.** Unsuitable techniques for cutting corbel slots and cramp holes **32**. Incompatibility of other stone façade components with stone from the aspect of service life
Standards Related With (Table III.5)	**1.1**. Types of stone-stone selection **1.2a.** Rock pores and porosity **1.2.c** Petrographic Properties **6.** Workmanship
Proposal	
Notes	The adhesion strength of the plaster applied on the stone surface to close the pores was not known.

DIAGNOSIS OF STONE CLADDING FAILURE (cont'd) METU Cultural and Convention Center

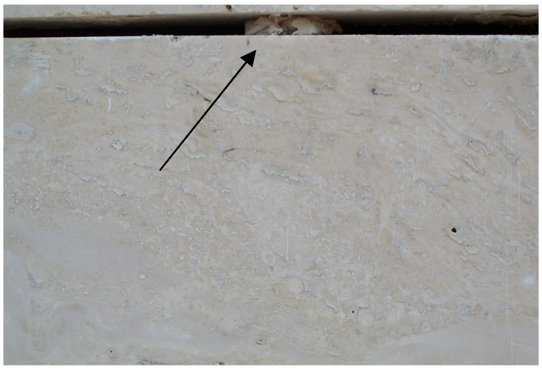


Figure III.98 Restraint fixing elements have been adhered to the stone with mortar but panels should have been free to move at these points. (2004)

Possible Failure (TableIII.4)	**5**. Stone crack
Possible Reason of the Failure (Table III.4)	**27**. Different movements of the back up wall and stone **29**. Stone panel cracks due to workmanship
Standards Related With (Table III.5)	**2.** Fixing
Notes	BS 8298:1994:14 advises the movement of restrained fixings. The mortar at fixing prevents movement. Appearance of the mortar from the façade is not homogenous.

Figure III.99 The Ankara stone on the retaining wall has got wet and soluble salt in the mortar and stone has caused staining of the stone (2004)

Failure (TableIII.4)	**6**. Staining
Possible Reason of the Failure (Table III.4)	**33.** Water dissolves the salt aggregates in mortar and back up wall behind the stone, which causes efflorescence.
Standards Related With (Table III.5)	**1.2.f.** Thermal and moisture movement **1.2.g** Weathering resistance **3.** Mortar 5. Backing structure
Proposal	The water has to be drained with a slopping coping and the water absorption of the wall has to be prevented.

DIAGNOSIS OF STONE CLADDING FAILURE (cont'd) METU Cultural and Convention Center

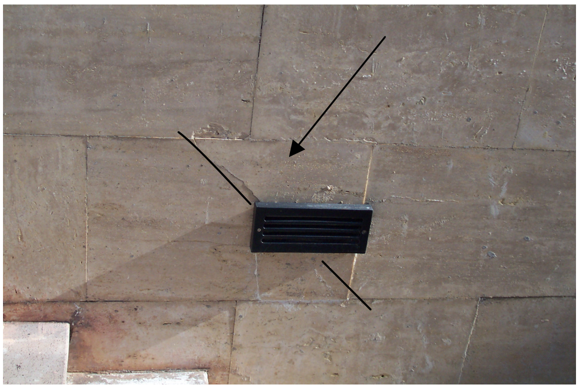


Figure III.100 A stone crack near the electrical grill due to stress created during installation (2004)

Failure (TableIII.4)	**5.** Stone crack
Possible Reason of the Failure (Table III.4)	**20.** Poor design of the window (electrical appliance) connection with stone façade **29**. Stone panel cracks due to workmanship
Standards Related With (Table III.5)	**1.2.e** Flexural strength **6**. Workmanship
Proposal	
Notes	The problems were due to unqualified workmanship and the use of stone which is not good for exterior use. This has affected the performance of the stone facade.

Last 10 Years	**OYAKBANK BUILDING** Atatürk Avenue No:90 Kızılay /Ankara *(Tr: Oyakbank Binası Atatürk Bulvarı No:90 Kızılay/Ankara)*	**18**

Figure III.101 Oyakbank Building (2004)

Type of Construction	:	R.C frame.
Type of Stone	:	White Marbe
Type of Stone Cladding	:	Stone cladding on to the main body of the wall with mortar

DIAGNOSIS OF STONE CLADDING FAILURE

Figure III.102 Stone panels have been fixed with screws to the back up wall to prevent falling down (2004).

DIAGNOSIS OF STONE CLADDING FAILURE
(Cont'd) Oyakbank Building

Failure (TableIII.4)	**1.** Stone fall down **7**. Discoloration **13**.Deterioration of the joint material
Possible Reason of the Failure (Table III.4)	**9.** Condensation within the wall **13.** Atmospheric deposits on stone **23**. Improper joint design causing water penetration inside the wall **24.** Improper joint material selection and use **25.** Water absorption at joints causing staining on the stone
Standards Related With (Table III.5)	**1.2.f** Thermal and moisture movement **4**.Joints
Proposal	
Notes	The building façade is similar to that of the building of Vakıfbank Training Management Building. Due to the possibility of falling down, stone panels were screwed.. There is not any expansion joint on the façade. The shrinkage of the reinforced concrete structure may cause stress on stone panels as Schaupp (1967:58) emphasizes or the problem of mortar mixture may exist.

1995	ANKARA CHAMBER OF COMMERCE *(Tr: Ankara Ticaret Odası)*	19

Figure III. 103 The Ankara Chamber of Commerce (2004)

Architect	:	Haluk Pamir
Type of Construction	:	R.C frame
Type of Stone	:	Granite
Type of Stone Facade	:	Stone curtain wall. Ventilated sloped stone façade anchored to the load bearing metal frame of the structure with stick system

DIAGNOSIS OF STONE CURTAIN WALL FAILURE

Figure III.104 Some parts of the sloped curtain wall are discolored but some are not (2004)**.**

Failure (TableIII.4)	**7.** Discoloration of stone
Possible Reason of the Failure (Table III.4)	**13.** Atmospheric deposits on stone **23.**Improper joint design causing water penetration inside the wall **25.** Water absorption at joints causing staining on stone
Standards Related With (Table III.5)	**1.2.f.** Thermal and moisture movement **1.2.g** Weathering resistance **2.** Fixing design **5.** Backing structure
Proposal	

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) Ankara Chamber of Commerce Building

a

b

Figure III.105 Discoloration of stone panel joints (2004)

Failure (TableIII.4)	**7.** Discoloration of stone
Possible Reason of the Failure (Table III.4)	**13.** Atmospheric deposits on stone **23.**Improper joint design cause water penetration inside the wall **25.** Water absorption at joints cause staining on stone **32.** Incompatibility of other stone façade components with stone from the aspect of service life.
Standards Related With (Table III.5)	**1.2.f.** Thermal and moisture movement **1.2.g** Weathering resistance **2.** Fixing design **5.** Backing structure **4.** Joints
Proposal	
Notes	

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) Ankara Chamber of Commerce Building

Figure III .106 Thermal insulation material does not continue under the fixing profiles of the curtain wall (2004).

Failure (TableIII.4)	**9**. Condensation inside the wall **10**. Condensation within the wall
Possible Reason of the Failure (Table III.4)	**17.** Thermal bridges due to anchorages
Standards Related With (Table III.5)	Standards do not mention the thermal insulation use and application under stone panels.
Proposal	The whole façade has to be finished with thermal insulation material first, and then the fixing elements should be applied on it.
Notes	

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) Ankara Chamber of Commerce Building

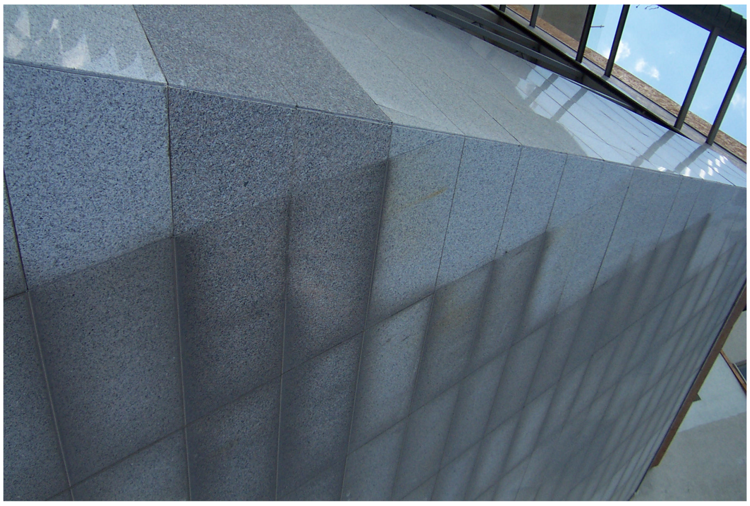


Figure III.107 Some parts of the stone panels are discolored and some are not in font of the Sport Center Pool.

Failure (TableIII.4)	**7.** Discoloration of stone
Possible Reason of the Failure (Table III.4)	**13.** Atmospheric deposits on stone **23**.Improper joint design causing water penetration inside the wall **25**. Water absorption at joints causing staining on the stone
Standards Related With (Table III.5)	**1.2.f.** Thermal and moisture movement **1.2.g** Weathering resistance **2**. Fixing design **5**. Backing structure
Proposal	
Notes	There was a possibility of condensation within the wall. The thickness of the thermal insulation material may be changed at the back of the stone panels due to the irregularities in the back structure.

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) Ankara Chamber of Commerce Building

Figure III.108 The terrace on top of a sloped stone curtain wall. The vegetation is the evidence of continuously existing water under terrace tiles that can penetrate through the wall.(2004)

Failure (TableIII.4)	**7.** Discoloration of stone
Possible Reason of the Failure (Table III.4)	**25**. Water absorption at joints cause staining on stone
Standards Related With (Table III.5)	**1.2.g** Thermal and moisture movement **4.** Joints
Proposal	
Notes	

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) Ankara Chamber of Commerce Building

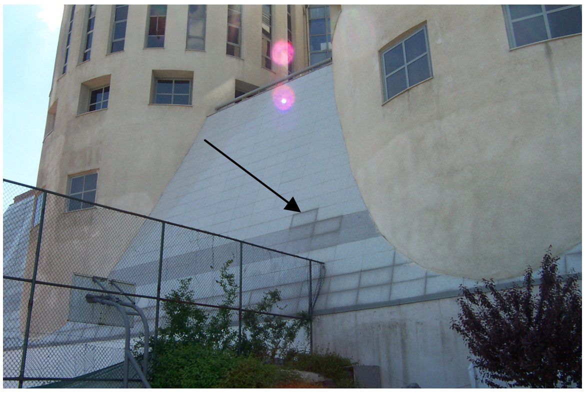


Figure III.109 Bottom parts of the stone façade has discoloration but the upper parts do not (2004).

Failure (TableIII.4)	**7.** Discoloration of stone
Possible Reason of the Failure (Table III.4)	**25**. Water absorption at joints causing staining on the stone
Standards Related With (Table III.5)	**1.2.g** Thermal and moisture movement **4.** Joints
Proposal	
Notes	The penetrated water may accumulate at the bottom part of the façade and this may cause discoloration due to the water absorption of the stone panels and joints.

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) Ankara Chamber of Commerce Building

Figure III.110 Looking down from the terrace the slope stone curtain wall. The joint material has deteriorated and the cutting of the stone panels are not accurate .

Failure (TableIII.4)	**13**. Deterioration of the joint material
Possible Reason of the Failure (Table III.4)	**29**. Unqualified workmanship
Standards Related With (Table III.5)	**4.a** Panel Joints **6**. Workmanship
Proposal	
Notes	The stone subcontractor (Orion Company Ltd) stated that there were big irregularities on the concrete sloping surface so they used steel sections to ensure the flatness of the surface. This may have caused the thermal insulation material deficiency and condensation had occurred within the wall. The waterproofing of the terrace upon the sloping wall was not effective. Water penetrates between stone panels and back structure, so stone panel joints get wet and accumulate the dust.

2003	**ARMADA SHOPPING CENTER -Ankara** *(Tr: ARMADA Alışveriş Merkezi)*	20

Figure III.111 Armada Shopping Center (2003)

Architect	:	Ali Osman Öztürk
Type of Construction	:	R.C frame
Type of Stone	:	Granite
Type of Stone Facade	:	Stone curtain wall. Ventilated stone façade anchored to the load bearing metal frame of the structure with stick system

DIAGNOSIS OF STONE CURTAIN WALL FAILURE

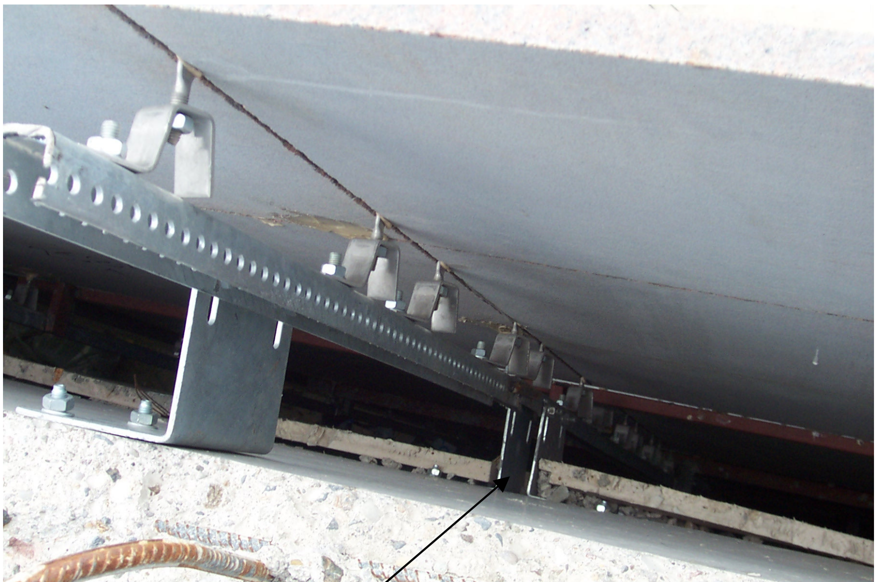


Figure III.112 Thermal Insulation material does not continue at the anchorage points of the stick system curtain wall, and this causes thermal bridges on the back up wall (2003)

DIAGNOSIS OF STONE CURTAIN WALL FAILURE (cont'd) Armada Shopping Center

Possible Failure (TableIII.4)	**9**. Condensation inside the wall **10**. Condensation within the wall
Possible Reason of the Failure (Table III.4)	**17.** Thermal bridges due to anchorages
Standards Related With (Table III.5)	Standards do not mention the thermal insulation use and application under stone panels.
Proposal	The hole façade has to be finished with thermal insulation material first and then the fixing elements should be applied on it.
Notes	Thermal insulation material should cover all the façade, and the curtain wall structure should be applied on it.

Figure III.113 There is not any thermal insulation material on the concrete wall. This may cause energy loss and condensation in time (2003)

Possible Failure (TableIII.4)	**9**. Condensation inside the wall **10**. Condensation within the wall
Possible Reason of the Failure (Table III.4)	
Standards Related With (Table III.5)	Standards do not mention the thermal insulation use and application under stone panels.
Proposal	
Notes	

Most of the buildings in Ankara were clad with travertine especially between 1958-1978. Stone cladding was set on the main body of the wall and had the problem of stone fall. The reason may be the physical and mechanical properties of travertine and also the movement of the structure.

Most travertine types are porous and have higher water absorption value compared to that of marble and granite. For example: Karabük Yellow travertine has a porosity of 6% and water absorption under atmospheric pressure of 6,7 % in volume, whereas Afyon White Marble's porosity is 0.2 % and water absorption under atmospheric pressure is 0.2 % in volume (Stone,2003). The source of the problem could derive from the physical property of the stone. Stone may absorb water and when it freezes and expands in volume the result is stone fall. Another possible reason of failure could be that the bedding plane of travertine should not be parallel to the wall surface in order not to increase the water absorption (Nashed;1995:161, Chacon,1999175-200).

The granite cladding and curtain wall applications in Ankara generally have the problem of staining at joints. The reason for this may be the use of improper joint material (Nakayma,1999:593-602), or the water accumulation in the cavity may be causing the discoloration of granite (Nashed,1995:161).

The discoloration of the travertine facades due to the air pollution and wrong window sill and façade profile details are also common failure of stone cladding facades in Ankara.

The next chapter dwells on the discussions and conclusions of these findings derived from a literature review and case studies.

CHAPTER IV

DISCUSSIONS AND CONCLUSIONS

IV.1 Confusion in Terminology

During this research, it is understood that there is an ambiguity in the terminology of stone façade in literature. Different terms are used for the same type of cladding. The same systems were named with different terms. For instance, the terms stone cladding and stone curtain wall were used for the same method in different sources. There is also a difference in the terminology used in Europe and the USA for stone facades. The terms 'Hand-set' and 'panelized' are not used in the technical documents of Europe. This ambiguity has been eliminated in this study by defining terms. The researcher of this study defines curtain wall as an external cladding where loads are transferred to the structural frame of the building and not to the back up wall. In stone cladding, the stone panels are beard by the back up wall. The most important aspect of the curtain wall is the non-connection of the back up wall and the availability of a ventilation cavity. The researcher also classifies stone facades according to the load carry and their load transfer characteristics (Chapter II.2).

IV.2 Stone Façade Problems and Reasons

The components of stone facades can be identified as follows:
1. Stone; 2. Fixing; 3. Mortar; 4.Joints; 5. Backing structure .

The performance of these components affects the performance of stone facades. The design stage consisting of detailing and specification; and the construction stage consisting of workmanship and the quality of the material also influence the performance of each component. For this reason, in addition to the design and construction phases, maintenance, service life span and durability should be added to these items.

The following items of the stone facade obtaining process are reviewed in detail from the aspect of performance criteria, and the reasons of failures are described. 1.Stone, 1.a Types of stone, 1.b Properties of stone, 2. Fixing, 3.Mortar, 4. Joints, 5.Backing structure, 6.Workmanship, 7.Maintenace, 8.Service life span and durability. The possible reasons of the failures of each item and process, the issues that affect the performance have also been reviewed in Chapter III.1, and the failures of stone facades have been classified as follows:

1. Stone fall down;
2. Stone panel displacement;
3. Stone buckling;
4. Stone crumbling, detachment;
5. Stone crack, fissures;
6. Staining;
7. Discoloration;
8. Water penetration;
9. Condensation behind the wall;
10. Condensation within the wall;
11. Stone surface abrasion;
12. Thermal insulation material deterioration;
13. Deterioration of the joint fills material.

The problems of condensation inside the wall (item 9); condensation within the wall (item 10), and thermal insulation material deterioration (item 12) have been added to the list by the researcher. If the thermal insulation material thickness is not calculated correctly or if there is a not a vapor barrier layer, condensation will possibly occur within the wall. Condensation causes corrosion of metals as in the reinforcement of concrete and stone failure due to the freezing of water. Condensation also deteriorates thermal insulation material. Open cell thermal insulation materials lose their thermal insulation performance when they absorb water or moisture into their cells.

The possible reasons of these failures, the stone facade obtaining process and the related components of the stone façade are indicated in Table III.4 by the researcher. It can be claimed that the common failures of stone facades are

stone fall down, stone displacement, stone crumbling and **stone crack.** There could be different kinds of reasons underlying these failures as listed. The failures affect the safety and durability of stone facades, and lower their performance. Therefore, the reasons of these failures have to be taken into consideration at every stage of the stone façade obtaining process, i.e design, construction, maintenance and service life phases.

The observations carried out of the buildings in Ankara and the literature reviews have produced similar results concerning failures and the reasons behind them. The common failures of travertine stones in Ankara are mostly due to the movement of the structure and the open pores of the travertine which absorbs water.

IV.3. Proposals for the Solution of the Problems

High performance examples from literature show the importance of a correct detailing of stone facades according to codes and standards. The types of stones and their thicknesses are chosen according to the physical properties of stone. As a result of this thesis, the proposals of the researcher with the documents extracted from the standards and personal knowledge are indicated in Table IV.1.

Table IV.1 Proposals to stone façade failures regarding standards.

	REASONS OF FAILURE	PROPOSAL	Standard /Code
1	Improper type of stone selection (Chacon,1999:175-200; Smith,1999:352-354; BS 8298:1994:9-10).	The physical properties of stone have to be tested according to standards to achieve the expected design performance.	Table III.5 Standards related with stone selection, petrographic properties.
2	Surface abrasion of stone due to weathering (Richardson,2001:107;Nashed, 1995:161; Fitzner,1995).	Proper type of stone has to be chosen. New accelerated weathering test methods have to be standardized to determine the aging of stone.	Table III.5 Standards related with weathering resistance
3	Inadequate stone thickness for anchorage (Larkin,1998:65-67;BS8298:1994;Smith, 1999:363).	The thickness of stone should be as given in Table III.2 which is based on satisfactory experience according to BS 8298 (1994: 11) Minimum thickness of stone behind a cramp mortise and minimum depth for a corbel plate according to the stone types listed in BS 8298 (1994:11-12) The position of the cramp mortise or slot should be on the center line of the stone .The minimum thickness of stone in front of a slot or mortise should be 20 mm for limestone and sandstone and 7mm for all other types of stone.	Table III.5 Standards related with dimension, compressive strength, flexural strength, fixing.
4	Using stone panels which have different thermal expansion coefficients side by side (Schaupp;1967:58).	Expansion joints have to be provided where necessary.	Table III.5 Standards related with thermal and moisture movement, joints.

Table IV.1 (cont'd**)** Proposals to stone façade failures regarding standards.

	REASONS OF FAILURE	PROPOSAL	Standard /Code
5	The use of different colors and textures of stone on the façade side by side creating surface temperature variations on façade (Schaupp,1967:58).	Expansion joints have to be provided where necessary. The fixing elements should be flexible enough to get this thermal movement.	Table III.5 Standards related with thermal and moisture movement, joints.
6	Different shadings on the façade (Schaupp,1967).	Expansion joints have to be provided where necessary. The fixing elements should be flexible enough to get this thermal movement. EN 1469(2004:15) requires thermal shock resistance test according to EN 14066.	Table III.5 Standards related with thermal and moisture movement, joints
7	The increase of temperature on the surface of the stone and low temperature at the back of the stone causing hysteresis (permanent volume change) and thus stone bow (Gerns,2000:37,42; Nashed,1995:160-161).	A ventilation layer between the stone and back up wall has to be given. The fixing elements and the thickness of the stone should resist to the volume change due to thermal expansion or the type of stone has to be chosen carefully in case of risk of hysteresis. EN 1469(2004:15) requires thermal shock resistance test according to EN 14066.	Table III.5 Standards related with petrographic properties thermal and moisture movement, fixing, joints.

Table IV.1 (cont'd**)** Proposals to stone façade failures regarding standards.

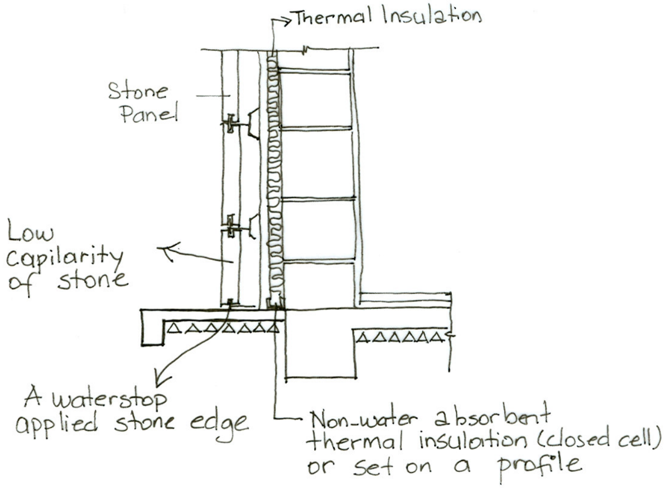
	REASONS OF FAILURE	PROPOSAL	Standard /Code
8	Capillarity of stone at subbasement.	The type of stone to be used at subbasement should be less porous. Primer or waterproofing sheet has to be applied at the bottom edge of the stone panel. The type of stone which has low capillarity should be preferred at the subbasement of the buildings.  **Figure III.113** The subbasement detail of a stone curtain wall facade	No codes related with this failure are available. The capillarity of the stone test result may be used i.e. EN 1925 (1999)

Table IV.1 (cont'd**)** Proposals to stone façade failures regarding standards.

	REASONS OF FAILURE	**PROPOSAL**	**Standard /Code**
9	Condensation within the wall.	Thermal insulation of appropriate thickness should be provided where necessary behind the cladding. Thermal insulation material should be : 1.non-combustible or of limited combustibility 2.non-absorbent 3.root and vermin proof The insulation should be fixed in such a manner as to maintain a clear cavity behind cavity wall (BS 8298,1994:8) There may also be a need for a vapor barrier.	Table III.5 Standards related with thermal and moisture movement.
10	Some type of stones swell up after absorbing water and distort when dried, creating stress on wall ties i.e. on mortar and mechanical anchorages (Schaupp,1967:58).	Stone that is porous or having high water absorption should not be used as façade cladding material. The test results determined with the determination of the porosity of the stone and water absorption should be evaluated.	Table III.5 Standards related with types of stone, fixing, moisture movement
11	Water absorption of some types of stones due to the installation of the bedding plane of stone parallel to the back-up surface (Nashed,1995:161).	The cutting of stone at the workshop should be inspected carefully.	Table III.5 Standards related with the workmanship
12	Some types of stones swell up after absorbing water. The pores get larger when the water freezes and the stone suffers (Richardson,2001:107).	Frost resistance test should be applied i.e. EN 12371. This is also a requirement of EN 1469 (2004)	Table III.5 Standards related with weathering

Table IV.1 (cont'd**)** Proposals to stone façade failures regarding standards.

	REASONS OF FAILURE	**PROPOSAL**	**Standard /Code**
13	Atmospheric deposits on stone.	A periodical cleaning method according to the type of stone and dirt has to be applied. Stone should be resistant to chemicals and should not suffer from the accumulation of dirt on it.	Table II.5 Standards related with weathering
14	Some types of stone surface treatment methods decrease the thickness of stone. This decreases the bending strength and increases elastic deformation (Nashed,1995:162).	The cleaning method has to be chosen carefully.	Table II.5 Standards related with maintenance
15	Corrosion of the fixing elements due to the use of improper material; (Smith,1999:357; Gerns,2000:42)	The mechanical fixing elements should be made from stainless steel, copper or copper based alloys. Welding can cause scale formation and discoloration so should be done by experts followed by an inspection.	Table III.5 Standards related with fixing.
16	Improper fixing design against loads like wind and earthquake	Proper type of fixing has to chosen according to the type of stone, loads, location of the building, and building type.	Table III.5 Standards related with fixing.
17	Thermal bridges due to anchorages	Thermal insulation materials continuity has to be provided on the back-up wall.	Not mentioned in codes and standards
18	Poor location of the dowel pin during fixing (Richardson,2001:137)	Qualified workmanship and a continuous inspection has to be applied.	Table III.5 Standards related with workmanship
19	Poor location of panels during fixing (Richardson,20001; Larkin, 1998)	Qualified workmanship and a continuous inspection has to be applied.	Table III.5 Standards related with workmanship

Table IV.1 (cont'd**)** Proposals to stone façade failures regarding standards.

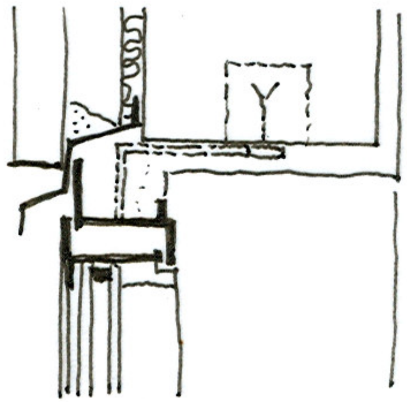
	REASONS OF FAILURE	**PROPOSAL**	**Standard /Code**
20	Poor design of the window connection with the stone façade, (Schaupp,1967)	 **Figure IV.1** A window frame fit to the main structure in a way that is wind and weatherproof (Modified from Schaupp,1967:62).	Table III.5 Standards related with fixing
21	Chemical reaction of the mortar with stone	Cement, sand , water and admixtures should satisfy the related standards.	Table III.5 Standards related with mortar These standards need to be improved.

Table IV.1 (cont'd**)** Proposals to stone façade failures regarding standards.

	REASONS OF FAILURE	PROPOSAL	Standard /Code
22	Since stone is a dense material, the drying up of water in mortar takes time. And this creates stress on the wall ties i.e. on the mortar (Schaupp,1967:58)	A ventilation layer has to be provided under stone panels. The construction of the structure should dry up before the application of the stone cladding. Water vapor permeability i.e. EN 12524 is a requirement for EN 1469 (2004).	Table III.5 Standards related with moisture movement
23	Improper joint design causes water penetration into the wall (Smith,1999; Nashed,195:161)	Stone cladding and curtain wall may behave as a rainscreen if it detailed correctly.	Table III.5 Standards related with joint
24	Improper joint material selection and use (Nakayma, Sasaki, 1999:593-6029).	Joint material should not cause the deterioration of the stone so it has to be selected according to the standards.	Table III.5 Standards related with joint
25	Water absorption at joints cause staining on the stone (Nashed,1996:161)	There may be need for the use of a compatible joint fill material with stone to prevent the ingress of water at joint according to the joint design.	Table III.5 Standards related with joint
27	Different movement of the back-up wall and stone	Joints between the units should be designed carefully. The design of fixing should allow freedom for vertical and lateral movements between the structure and unit. Although the differential settlement is insignificant for claddings the structural engineer should be consulted.	Table III.5 Standards related with compressive strength, Flexural strength, back up wall, fixing

Table IV.1 (cont'd**)** Proposals to stone façade failures regarding standards.

	REASONS OF FAILURE	**PROPOSAL**	**Standard /Code**
28	Shrinkage of the reinforced concrete structure at the back of the stone cladding	The stone cladding applied on to the concrete structure should be delayed as long as possible after the striking of the formwork. (BS 8298, 1994:31)	Table III.5 Standards related with back up wall.
29	Stone panel cracks due to workmanship (Larkin, 1998:67)	Damage of the units during handling of stone, in the factory, during transport, installation or on site has to be prevented via continuous supervision.	Table III.5 Standards related with workmanship
30	Unsuitable techniques for cutting corbel slots and cramp holes (Smtih,1999:358-360)	Qualified workmanship and a continuous inspection have to be applied.	Table III.5 Standards related with workmanship
31	Wrong stone cleaning techniques	Small surface areas should be treated as a sample of cleaning technique. Most granite with a polish surface can be cleaned with clean water. Honed finished marble can be washed with clean water. A mild detergent can be added if necessary. Polished finished marble will need to be cleaned with clean water and detergent if necessary at least twice a year and a silicone clear wax polish applied with a buffer. Slate and quartzite does no need any other maintenance than washing. For limestone and sandstone cleaning, every 5 to 10 years, according to the amount of discoloration of the facing , washing with clean water and scrubbing with bristle brushes will maintain the appearance of stone work (BS 8298:36)	Table III.5 Standards related with maintenance

Table IV.1 (cont'd**)** Proposals to stone façade failures regarding standards.

	REASONS OF FAILURE	**PROPOSAL**	**Standard /Code**
32	Incompatibility of other stone façade components with stone from the aspect of service life.	Short service life span of the other façade materials such as fixing and joint compared to stone should be taken into consideration at the design stage.	Table III.5 Standards related with joint, fixing, maintenance
33	Water dissolves the salt aggregates in the mortar and back up wall behind the stone, causing efflorescence. (Nashed,1995:161)	Proper waterproofing has to be provided especially at horizontal surfaces. The mortar mixture should satisfy the standards.	Table III.5 Standards related with moisture movement

IV.4 Lack of Codes and Standards

The standards are the most effective documents that can prevent the emergence of problems. The existing European Union Standards, the United States, Turkish and British Standards and Codes and the National Building Granite Quarries Association manuals are reviewed in this research.

The ASTM Web sites Tech News (viewed in 2005) emphasizes the importance of standardization and the development of stone in the US. The Web site contains detailed information on stone standards in the US and those in Europe.

The ASTM standards of dimension stone developed by the subcommittee C18 consists of technical committees. The committees developing 1. Test methods 2. Material specifications 3. Anchorage components and systems 4. Environmental properties, behavior and cleaning (ASTM web page, viewed in 2005). There are ASTM standards developed on the specification of stones such as marble, limestone, granite and slate in the USA, whereas there are not such specifications in the European Union standards (CEN). The reason for this may be that the development of stone curtain wall occurred in the USA, and it has a long term experience on the use of stone as a curtain wall element than Europe. In time, European Countries will most probably be in need of such specifications. These ASTM standards specify the material characteristics, physical requirements and sampling for the selection of marble for general (exterior) building and structural purposes (Appendix E). Some of the physical properties determined in these ASTM standards are:
Absorption weight -max %, Density-min lb ft3 (kg/m3), Compressive strength-min, psi (MPa), Modulus of rapture-min psi (MPa), Absorption resistance -min hardness and Flexural Strength, min psi (MPa) (NGBQA web page, viewed in 2005)

ASTM C 1242-4a 'Guide Specification for the design, selection and Installation of Exterior Dimension Stone Anchors and Anchorage System' is a detailed guide for the anchorage system of stone facades. It is prepared by the ASTM Committee C18 and published in 1993. Standard C 1242-4a is referenced on the Web site of the National Building Granite Quarries of Association, whose member companies produce most of the USA's architectural granite. It is one of the most detailed standards of the world on stone facades.

The National Building Granite Quarries Association (NBGQA web page, viewed in 2005) emphasizes the necessity of tests on durability or the performance of life the cycle of natural stone. The failures observed in case studies and reviewed from literature also show the necessity of this requirement. In case studies from Ankara (no 3), the stone used at the window sill (andezit) of the Faculty of Literature, History, and Geography is deteriorated due to weathering. If this experience is shared in the form of standards, it may prevent another improper detailing.

The test methods to determine these physical properties are also becoming standard applications in the USA. The CEN standards of the test methods in the determination of physical properties of stone are also very detailed (Appendix E).

The creation of EU (European Union) increased the importance of the standards due to the need of providing technical assistance. When CEN (Centre Europeene de Normalisation) was established in the early 1960's, the aim was to unify or harmonize national norms with the "European". EU Standard studies on stone started in the early '90's. Working groups were established. These groups are part of these Committees. The dimension Stone is dealt with by CEN 246 (Shadmon, viewed in 2005). The member countries harmonize their national standards with EN at this stage.

Italy has more standards on stone cladding, which is not harmonized with CEN yet, when compared with the other countries. The reason why Italy has a lot of national standards on stone and stone cleaning compared to other countries is most probably that they have the most famous marble quarries of the world (Appendix F).

The EN standards do not cover the cladding systems yet (Appendix E). The standards are on terminology, test methods and products and not on the construction methods.

The British Standards, BS 8298, is the most detailed Code of Practice for natural stone cladding and lining but it does not contain information on the stone curtain wall. Besides DIN 18516-3 Cladding for exterior walls ventilated at rear, DIN 482-Natural stone kerfs, DIN 52104-Testing of Natural stone freeze-thaw cycle, UNI 11018 Cladding and anchoring systems for back ventilated external enclosures of buildings, ONORM 3123-1:1990 Testing of Natural stone ; resistance to weathering principles for assessment are some of the standards that can substitute for the CEN standard when the stone façade failures are taken into consideration. These are some of the proposals of the researchers review on western standards.

The major invention in the CEN standards compared to the traditional BS, DIN and other national standards is that they are geared to the evaluation of conformity and factory production control (Shadmon; viewed in 2005).

Some of the test methods on stone in the Turkish Standards are also harmonized with EN. The National Standards on stone are basically on the properties of stones such as marble, conglomerate, limestone, andesite, dolamit and travertine (Appendix E). There is no system code of applications for stone facades although Turkey has a lot of experience in this field.

IV.5 Conclusions

This thesis has evaluated the historical and technical development of stone façade systems from the point of building envelope performance criteria and has determined and classified the failures, reviewed the standards and provided proposals to the construction problems to some extent. There is literature available discussing the failures of stone facades separately but this thesis has collected this information by adding personal observations as a starting point for further studies on guiding professionals for high performance stone facades.

Reasons of the problems, proposals

The reasons of the common failures of stone facades can be listed as:

A. Movement B. Insufficient material C. Weathering D. Poor workmanship

A. Movement

Movement is one the determining factors affecting the performance of stone facades. The origin of the movements in structures is indicated in BS 8298 (1994:28) (Table III.3). The researcher's observations have shown that the stone cladding fixed to the back up wall other than mechanical fixing devices, like mortar, is subject to stone fall especially during earthquakes. These kinds of failures, which are very critical from the point of public safety, have also been observed in the1999 earthquakes in Gebze and İstanbul. The mechanical installation of stones limits this problem by careful detailing. Free movement of the curtain wall from the building structure should be provided. The façade detailing should be appropriate to prevent the problems which are caused by the movement of the structure.

B. Use of insufficient material

B.1 Stone

The thickness of stone and its physical properties affect the performance of the stone facades. The recommended thickness for different kinds of stone used in cladding is specified in BS 8298 (1994:11). The minimum physical property requirement of stone is determined in the ASTM standards. European standards do not indicate values but only describe the test methods to measure the physical and mechanical properties of stone.

B.2 Other materials

The detailing and materials specification should be done according to the existing standards. The compatibility of other materials like mortar, joint fill, anchorage with stone should be checked and become a standard or code for proper applications.

C. Weathering

The physical properties of stone affects its durability. Weathering is a natural result but proper testing has to be realized on stone façade systems to predict their long term performance. The related tests determining these properties give an idea about its long term performance. Standards determining the aging of stone have to be developed because it is obvious that in the future, stone will be a widely used façade material with its long service life span and low maintenance requirement all around the world.

D. Poor workmanship

The dimensioning of stone at the quarry, transportation, handling and workmanship during installation are all very important items that should be inspected.

When the problems of stone facades are reviewed from literature and case studies, it is concluded that there is a need for code of practices guiding professionals to make use of not only the behavior of the components of stone façade, but also its behavior as a whole. This requires an interdisciplinary study between architects, restorators, civil engineers and material engineers.

Turkey, a very rich country from the point of stone quarries, has much experience in stone façade buildings. However, there is a need for further studies on the performance of stone facades using these experiences to develop new codes and standards.

Future Foresight

The future use of stone cladding will be towards ventilated stone facades due to the problems of unventilated claddings. Although ventilated stone cladding walls decrease problems, stone curtain walls also avoid problems caused by connection with the back up wall. Nevertheless, the stone curtain wall still has failures due to stone panels, which are getting thinner with the developing cutting technology.

During case studies, it is observed that lately the popular use of stone in Turkey is mostly in the form of granite panels, mechanically fixed to the back up wall or to a frame suspended on a steel structure. The sizes of slabs are limited in these examples and large panels are not used in Turkey yet. The increase of high rise steel construction will force large size stone use due to its durability and low maintenance requirement.

The developments in the construction industry made the production of artificial stone possible. It can be claimed that the artificial stone may be an alternative for natural stone and could have a large application area in the future. Economic reasons and the deterioration of natural stone due to its non homogenous structure will also force the use of the artificial stone. In time, natural stone may get thinner as a veneer material in front of another industry product, the façade panel to provide higher performance. The light and artificial stone panels can provide good performance during earthquakes too. They may be used as in ventilated wall cladding or curtain wall methods to overcome problems of unventilated stone façades. Further research and test methods have to be established and performed to provide progress in the performance of natural and artificial stone facades.

Although natural stone is a very durable material, it may decay because of faulty design, mistakes during construction and service life, such as insufficient maintenance, modified use of the building, or inappropriate conservation. The development of technology may give opportunity to the production of stainless steel anchorage and fixing elements, better performance of mortar additives providing economy and durability. The complex nature of stone has to be studied and researched accurately; appropriate methods of construction and detailing should be used in the building obtaining process to reach the high performance expected from it.

APPENDIX A

GLOSSARY OF STONE EXPRESSIONS

ENGLISH	TURKISH
Absorption	Emme/Soğurma
Anchorage	Ankraj
Anchorage Hole	Ankraj Deliği
Bending	Eğilme
Building Code	Yapı Mevzuatı / Yapım Kuralı
Building Envelope	Bina Cidarı Bina Zarfı
Cladding (Siding)	Duvar Kaplaması
Code of Practice	Meslek Uygulama Kuralları
Compressive Strength	Basınç Dayanımı
Coping	Harpuşta
Covering	Kaplama
Crack	Çatlak
Crumbling	Parçalanma, Ufalanma
Curtain Wall	Giydirme Cephe
Detachment	Kopma
Dimension Stone	Kesme Taş
Discoloration	Kirlenme, renk değişikliği
Expansion Joint	Genleşme Derzi
Fissure	Kılcal Çatlak/ Yüzey Çatlağı
Fixing Element	Tespit Elemanı
Flexural Strength	Eğilme Dayanımı
Igneous	Püskürük
Panel	Plaka
Joint	Derz
Installation	Montaj
Metamorphic	Başkalaşmış
Modulus of Rupture	Kopma Modulüsü
Mortar	Harç
Mullion	Düşey Kayıt –Dikey Eleman
Panel Wall	Pano
Performance	Performans
Performance Criteria	Performans Ölçütleri
Performance Specification	Performans Şartnamesi
Performance Requirement	Performans Gereksinimleri
Porosity	Gözeneklilik
Quarry	Taş ocağı

Resistance to Chemicals	Kimyasallara Dayanım
Safety Factor	Emniyet Faktörü
Sealant	Mastik
Sedimentary	Tortul
Slab	Plaka
Specification	Şartname
Staining	Lekelenmek
Stainless steel	Paslanmaz Çelik
Stone Cladding	Taş Kaplama
Stone Curtain Wall	Taş Giydirme Cephe
Stone Facade	Taş Cephe
Stone Veneer	Kompozit Taş Levha
Standard	Standart
Structural Joint	Çalışma Derzi
Stick	Dikme
Thin Stone Cladding	İnce Taş Kaplama
Thermal Bridge	Isı Köprüsü
Unit	Hazır Panel
Window Sill	Denizlik
Weathering	Havadan Bozulma, Yaşlanma

APPENDIX B

EXTERNAL WALL BUILDING ENVELOPE PERFORMANCE CRITERIA, REQUIREMENTS, RECOMMENDED VALUES AND TESTS RELATED WITH THE CRITERIA

The external Wall Building Envelope Performance Criteria, requirements and recommended values and tests related with the Criteria of ISCC (1971; 3-26) Performance Requirements for Exterior Walls in England-.are placed in Table B.1 by the researcher. This information helps to evaluate the performance of the buildings external wall chosen from the literature and the buildings from Ankara as case study.

TABLE B.1. The external Wall Building Envelope Performance Criteria, requirements and recommended values and tests related with these Criteria. These data have been placed in a table by the researcher, and figures are taken from the ISCC (1971:3-4) list for the Performance Requirements for Exterior Walls in England.

	CRITERIA	REQUIREMENTS	RECOMMENDED VALUES		COMMENTS	TESTING AND ASSESEMENT
A	Air Penetration	Air penetration through external envelope shall not cause an unacceptably high rate of air change within the enclosed space. Air penetration shall not produce draughts which may be uncomfortable for the occupiers. Air filtration into external wall shall not cause significant deterioration of its thermal performance	Design wind speed	Pressure Difference		BS 4315
			10.3 m/s	10 mm water gauge		
			12.7 m/s	15 mm water gauge		
			18.7 m/s	30 mm water gauge		
B	Water Absorption	An external wall shall be capable of preventing rainwater from reaching its internal face	600 N/m2	60 mm water gauge	The effect of water penetration into the fabric of an external wall will depend on its construction and its material characteristics	1. an inspection of the design 2. Testing similar to BS 4315 part 2.
C	Water Penetration	An external wall shall be constructed so that any rainwater entering its fabric will not cause permanent or significant temporary deterioration of its performance	1 000 N/m2	100 mm water gauge		

TABLE B.1. (cont'd) The external Wall Building Envelope Performance Criteria, requirements and recommended values and tests related with these Criteria. These data have been placed in a table by the researcher, and figures are taken from the ISCC (1971:6-12) list for the Performance Requirements for Exterior Walls in England

	CRITERIA	REQUIREMENTS	RECOMMENDED VALUES		COMMENTS	TESTING AND ASSESMENT
D E	Water Absorption Water Penetration	An external wall shall be capable of preventing rainwater from reaching its internal face An external wall shall be constructed so that any rainwater entering its fabric will not cause permanent or significant temporary deterioration of its performance	600 N/m2	60 mm water gauge		
F G	Moisture movement Thermal movement	Changes in dimensions and shape of any part of an external wall, due to the effect of rainwater or changes in humidity and temperature conditions, shall not cause deterioration of its performance.	Relative humidity extreme limits 60 % - 95 % (outside) and 30 %-90% (inside) air temperatures within extreme limits of – 20 C and +45 C the temperature of a surface of an external wall exposed to direct sunlight will not exceed 80 C		Temperature and humidity appropriate to the conditions of use should be selected. The surface temperature occur in a external wall depend on its surface color and its material characteristics and construction.	

TABLE B.1. (cont'd) The external Wall Building Envelope Performance Criteria, requirements and recommended values and tests related with these Criteria. These data have been placed in a table by the researcher, and figures are taken from the ISCC (1971:23-16) list for the Performance Requirements for Exterior Walls in England

	CRITERIA	REQUIREMENTS	RECOMMENDED VALUES	COMMENTS	TESTING AND ASSESMENT
H I J	Effect of High and Low temperatures Thermal shock Effect of freezing conditions	An external wall shall not suffer any mechanical or chemical breakdown which may effect its performance, when subjected to the thermal changes. No damage shall occur as a result of rapid changes between extreme temperatures and effects of repeated freezing and thawing of water in contact with the external face of the wall.			
K	Strength-Bending	1. An external wall shall be capable of sustaining and transmitting to its point of support all loadings of its dead weight, wind loads, and operational bending forces without fracture or permanent deterioration of its performance. The deformation shall not be irreversible. 2. An external wall should support any temporary or permanent loads. Strength – ability to receive and hold fixings, without excessive deflection or permanent deterioration of its performance.	Experience in practice has shown that for most conditions of normal use the deflection of the inside face of a wall should not exceed 1/ 500 of its height, measured between its point of supports or 5mm whichever is less	The amount of deflection of an external wall which is acceptable will depend on the manner in which such deflection affects other properties of the wall e.g. its general appearance, its finishes, jointing conditions, objects in contact with its faces.	

TABLE B.1. (cont'd) The external Wall Building Envelope Performance Criteria, requirements and recommended values and tests related with these Criteria. These data have been placed in a table by the researcher, and figures are taken from the ISCC (1971:17-20) list for the Performance Requirements for Exterior Walls in England

	CRITERIA	REQUIREMENTS	RECOMMENDED VALUES	COMMENTS	TESTING AND ASSESMENT
L	Strength- Impact	1. An external wall shall be capable of withstanding impacts which are applied or transferred to its face without suffering damage which is not easily repairable and without deterioration 2. Any fracture resulting from impacts shall not produce falling debris which may be a safety hazard to the occupants or to the outside the building			
M	Strength- Ability to receive and hold fixings	An external wall will expected to carry fixings for lightweight fixtures. An external wall that is supporting heavy fixtures shall be capable of withstanding permanent and temporary loads without loosing or failure of the fixings and without showing deflections.	For the external face of the wall, the specifying authority should decide weather the fixture should be fixed to non load bearing or structural part of the external wall.	Typical bending loads on external walls are extracted fans, street signs, external Venetian blinds, canopies, awnings etc. It has to be decided weather these elements will be fixed to the non-load bearing or structural parts of the external wall.	

TABLE B.1. (cont'd) The external Wall Building Envelope Performance Criteria, requirements and recommended values and tests related with these Criteria. These data have been placed in a table by the researcher, and figures are taken from the ISCC (1971:21-24) list for the Performance Requirements for Exterior Walls in England

	CRITERIA	REQUIREMENTS	RECOMMENDED VALUES	COMMENTS	TESTING AND ASSESMENT
N	Sound transmission	An external wall requirements will be specified in terms of a minimum average sound reduction index against airborne sound , measured in DB		The required level of sound reduction for an external wall depend on external noise level (traffic noise, aircraft noise, ind. noise)	BS 2750
O	Effect of sunlight	No part of an external wall shall suffer from direct sunlight during use as a result of such exposure any chemical or mechanical breakdown or other damage, which may cause deterioration of its performance.			BS 2782 BS 1006
P	Effect of fire	1. External wall shall not contain a substance which will emit abnormally toxic fumes as a result of overheating or combustion. 2. Requirements for external walls may be specified for each of the following properties: Combustibility, Fire resistance, Surface spread of the flame			

TABLE B.1. (cont'd) The external Wall Building Envelope Performance Criteria, requirements and recommended values and tests related with these Criteria. These data have been placed in a table by the researcher, and figures are taken from the ISCC (1971:24-26) list for the Performance Requirements for Exterior Walls in England

	CRITERIA	REQUIREMENTS	RECOMMENDED VALUES	COMMENTS	TESTING AND ASSESMENT
Q	Effect of chemicals	An external wall shall be capable of withstanding the weathering and atmospheric pollution conditions. It collapse or become dislodged because of chemical corrosion. This may cause safety hazards during the projected life of the building.			
R	Liability to vermin infestation etc.	An external wall shall be resistant to infestation by fungus, insects, rodents, etc and shall not allow the ingress of vermin in to the building.			BS CP 3 Chapter
S	Liability to become dirty: ease of cleaning	The texture and other surface characteristics of an external wall shall be such that the weathering and atmospheric pollution conditions or vandalism to which the component will be exposed during use will not cause objectionable discoloration or disfiguration, which can not be removed by a cleaning process using commonly available materials and normal skills.			

TABLE B.1. (cont'd) The external Wall Building Envelope Performance Criteria, requirements and recommended values and tests related with these Criteria. These data have been placed in a table by the researcher, and figures are taken from the ISCC (1971:3-4) list for the Performance Requirements for Exterior Walls in England

	CRITERIA	REQUIREMENTS	RECOMMENDED VALUES	COMMENTS	TESTING AND ASSESMENT
T	Security	An external wall shall not be vulnerable to malicious damage or to unlawful entry by dismantling its fixing devices or joints.		Detailed requirements can be specified according to identified products, types of construction and conditions of use.	
U	Durability of the component or assembly	There shall be a maintenance-free life of the external wall and parts of which it is composed. Within this period the external wall shall perform levels specified at this list.		The term maintenance include cleaning necessary for maintenance	

APPENDIX C

DETAILS OF PERFORMANCE CRITERIA

The performance requirements of construction products are listed as follows: (CIB Master List,1993:9)

1. Mechanical resistance and stability;
2. Safety in case of fire;
3. Hygiene, health and the environment;
4. Safety in use;
5. Protection against noise;
6. Energy economy and heat retention.

The details of performance criteria that are essential for these six requirements are as follows : (CIB Master List ,1999:10-12):

1. Active: capacity, output, consumption,

2. Structural, mechanical: This information relevant for the requirement of mechanical resistance and stability. It includes resistance to effects of external forces causing collapse, deformation, bursting, tearing, peeling, cracking, shattering, indentation, scratching, mechanical wear, fatigue, creep, soft or hard body impact.
It may be measure in terms of compressive strength, shear strength, tensile strength, bending strength, long term deflection, modulus of elasticity, dynamic, and static stiffness, coefficient of friction, slipperiness, skid resistance, resistance to shock (CIB Master List, 1993:10).

3. Fire: This information is related to the requirement safety in case of fire.
Safety in case of fire should be in reference with national and international fire standards. It may be described in terms of burning behavior, reaction to fire, non-combustibility, ignitability, flammability, resistance to surface spread of flame, heat smoke and gas release, penetration of flame, smoke, gas, heat, fire resistance of components and structural elements-stability, integrity, insulation (time, class),

flashpoint of liquid, heat emission from building materials, contribution to fire load, resistance to exposure from heat radiation, smoke and flame stopping, containment of effects of explosions (CIB Master List, 1993:10).

4. Gaseous, liquid, solid: This information is related with the performance requirements of hygiene, health, the environment and safety in use. These are air tightness of joints, effectiveness of sealing air gaps, control of air leakage of ductwork etc. after installation, permeability to gases and water, frost resistance, release of volatile organic compounds, odors and other pollutants, effectiveness of control by coatings etc, effectiveness of water vapor combustion products, tobacco, smoke and other harmful gasses and airborne substances, supply of air of satisfactory quality, liquid water absorption, imperviousness to water, resistance to penetration of driving rain and snow, resistance to rising damp, vapor permeability, control of interstitial and surface condensation, moisture absorption, hygroscopic humidity content, hygrometric expansion coefficient, effect of relative humidity change, precautions against hazard of Leionnaires' disease, resistance to corrosion, resistance to abrasion, permeability to pollutants, effectiveness in disposal of liquid waste, non-release of foul air, ease of cleaning, effectiveness of self-cleaning (CIB Master List, 1993:11).

5. Biological

Living organisms affect the performance of products and services. These are related with the requirements of hygiene, health, the environment and safety in use.

The criteria related with this are susceptibility to harmful microorganisms, growth of fungi, insect attack, effectiveness of fungicides for surface treatment, for pressure treatment (CIB Master List, 1993:11).

6. Thermal

It is related with the requirements of energy economy and heat retention.. Energy economy and heat retention for elements of construction are related with thermal transmittance (U value), thermal capacity, thermal inertia and heat loss characteristics.

Solar protection factors are transmissivity and absorptive of solar radiation, shading, effectiveness in reducing solar radiation (CIB Master List, 1993:11).

7. Optical

It may be relevant to essential requirements of safety in use and energy economy and heat retention. The criteria related with this are daylight transmission, spectral transmission characteristics, retro reflection, transparency (CIB Master List, 1993:12).

8. Acoustic

It is essential for the requirement protection against noise. The related criteria is protection against airborne noise from outside, from another internal space, protection against structure-borne and impact noise, direct and flanking airborne, sound reduction, protection against equipment noise, against reverberant noise, absorption coefficient, damping, dynamic stiffness, noise frequency weighting, single number noise rating, sound power level, sound pressure level, sound radiation, sound scattering, speech intelligibility rating (objective), vibration effects, intensity, frequency (CIB Master List, 1993:12).

9. Electric, magnetic, electromagnetic radiation

It is related with the requirements of hygiene, health, the environment , safety in use, energy economy, and heat retention.

The factors related with this criteria are the effects of energy in electrical and electromagnetic forms, electric field strength, potential, resistance, capacitance, reaction to radio-active emissions, radon, ionization, electromagnetic disturbance, compatibility, static electricity, avoidance of shocks, lighting protection.

10. Resistance to attack

The factors affecting these criteria is information on resistance to argon, vandalism, forced entry, protection against threatening behavior (CIB Master List, 1993:12).

11. Service Life, durability, reliability

Factors determining service life, durability and reliability are effects of biological, chemical and physical agents, conditions of use, durability rating, vulnerability to decay, resistance to abrasion, corrosion acid or sulphade attack, carbonation, alkali, silica reaction, aging, loss of solvents and plasticizers, blistering, creep, loss of flexibility, chemical and mechanical effects of cleaning substances, light fastness, loss of serviceability, deterioration of fail-safe mechanism (CIB Master List, 1993:12).

The performance criteria of the building envelope are determined at BS 8200 (1985:4-18) as follows :

1. **Size and weight:** It was advised that the components of the exterior wall could be maneuvered by two men, i.e. 55 kg (BS 8200,1985:4);

2. **Appearance:** The acceptable degree of variation should be established in agreement with the manufacturer e.g. from samples (BS8200,1985:4);

3. **Strength:** Structural strength and stability;

4. **Strength: Impact:** The visible surfaces of vertical enclosures should be capable of withstanding applied or transferred impacts that occur during normal use without a sustaining damage which is not easily repairable and without deterioration of its performance (BS8200,1985:4);

5. **Strength: Fixings**: The permanent fixing of any component should be capable of withstanding the combined dead load and maximum load arising from that component with an appropriate factor of safety (BS8200,1985:5),

6. **Fire:** Fixings, insulation materials should have sufficiently high melting points to satisfy the period of the fire resistance (BS8200,1985:8);

7. **Air permeability:** Air penetration through the enclosure structure should not cause an unacceptably high rate of air change and energy loss within the enclosed space or uncomfortable for the occupiers (BS8200,1985:10);

8. **Permeability to water vapor:** The wall performance of the wall should not be adversely affected by water vapor which is allowed to penetrate to the interior of the wall or by condensation resulting from the presence of the vapor (BS8200,1985:10);

9. **Moisture content:** The overall performance of the enclosure should not be adversely affected by any changes in moisture content resulting from changes in the humidity of the air, either external or internal (BS8200,1985:10);

10. **Water absorption:** The overall performance of the enclosure should not be adversely affected by water to be absorbed by either surface (BS8200,1985:11);

11. **Water penetration:** An external enclosure should be so constructed as
    a. to prevent rainwater from reaching its indoor surface
    b. to prevent any rainwater entering its external surface from causing permanent or significant temporary deterioration on its performance (BS8200,1985:15);

12. **Capillarity:** All components and joints between components should be designed to prevent ingress of water by capillarity (BS8200,1985:11);

13. **Moisture movement:** Changes in dimensions and shape of any component due to the effect of water or moisture should not adversely affect the performance of the enclosure (BS8200,1985:11);

14. **Effects of frost:** Water taken in by a porous material or trapped in joints or gaps in the enclosure and subsequently frozen should not cause spalling that would adversely affect the overall performance of materials or permanent distortion of any part of the enclosure by its expansion (BS8200,1985:11);

15. **Effects of weathering atmospheric pollution and chemical attack;**

16. **Thermal properties;**

17. **Protection against solar radiation;**

18. **Effects of changes in temperature:** Change in dimensions and shape of any component resulting from changes in air or surface temperature should not adversely affect the the performance of the enclosure (BS8200,1985:14),

19. **Effect of sunlight:** Direct sunlight should not cause chemical, mechanical or optical changes (BS8200,1985:15);

20. **Sound transmission:** The opaque part of the walling should never have a sound insulation less than windows and other openings (BS8200,1985:15);

21. **Junction:** No joint should reduce the performance of the enclosure Junction design is related with elements of junction, junctions with ceiling, partitions and floors and internal columns (BS8200,1985:17);

22. **Durability and design life:** The durability and design life of external face of the enclosure and its components should be relative to , but not necessarily the same as , the design life of the completed building (BS8200,1985:18);

23. **Safety and security:** Related with opening and opening parts (BS8200,1985:18).

APPENDIX D

GUIDELINES FOR THE SELECTION OF STONE

Chacon (1999:175-200) has provided a guidline for the selection of stone for prcatical considerations.
Stone is a natural material so it is difficult to measure its propertires like manufactured materials. Each type of stone has different physical and performance characteristics because of its geological formation. Tests have been created to measure the physical properties of stone to use in a building system such as a curtain wall design or vertical application as a veneer on a building exterior.

Is the stone suitable for the intended application ?
There are specific guidelines that have been been developed, such as for the use of stone in curtain wall systems , their anchors, and attachments, and for the use of stone as veneer. Asking the following questions and using these questions as guidelines in pursuing the information required to make a responsible decision is necessary.

- Is stone suitable for the intended application ?
- What are the characteristics of the stone ?
- Has the stone been tested ? What do the test results tell us ?
- Where hasthe stone been used before?

What are the characteristics of the stone ?
Geological formation is important for the eveluation of the stone. It affects the characteristics, mineral composition and performance of the stone. The two basic minereal types present in all stones are calcium and silica.
There are three main groups of geological formation:
A.Igneous
B.Sedimentary
C.Metamorphic

Granite is an igneous stone. Because of its molten beginning it has a uiform appearance. Many granites are suprisingly porous, some with high rates of absorbtion. This is common for large grain structure. Granites are extremely hard and resistant to acids and abrasion. This is due to feldspar and quartz particles that were formed during the molten stage of development. Its hard polished surface repels the water and airborne acids, and it is a highly reflective surface compared to other types of stone. Because of its uniform structure, it gives similar test results from different samples for a single deposit.

Characterisitics to look for when selecting Granites

- If the granite has a large pore structure, it has higher water absorbtion. For the exterior use, the water absorbtion should be low; less than 0.5 % to withstand the effects of freeze-thaw cycles.
- The presence of mineral pyrite within a stone that is exposed to moisture may result in rust staining of the stone surface.
- Light colors are softer than dark color granites with the exceptions of granites which are from the gabbro igneous subgrop.

Limestone is a sedimentary stone created by the accumulation of finely eroded particles of rock and other fine materials carried by wind or water. The layers of sediment contain organic material that is cemented with other materials that are sometimes inorganic in origin. Since infinite types of materials are accumulated, it results in a variety of characteristics. High density materials with low absorption and soft materials with high rates of absorption can be formed. It is not possible to stereotype limestones.

Characteristics to Look for when Selecting Limestone

- The cuting of the lime stone according to the bedding plane affects its compressive strength. The faces of limestones that are fleuri cut (parallel to the bedding plane) have a greater compressive strength than the same stone vein cut (perpendecilar to the bedding plane). The stone that is fleuri cut yields wilder variation in color and character than the more predictable color and variation of a vein cut stone.
- There may be fissures because of the layering process. This is particularly true for fleuri cut limestone. Few limestone producers fill the open areas and fissures with any material.,it is seldom a hard resin based fill. In a short time, abrassion takes infill out. The open fissures collect dirt. Rarely is this a detriment to the

integrity of a stone's strength or its performance; however, once the fissure is fully compacted with dirt, it appears as a crack.

- Many of less dense limestone has a face looking like a sponge. When it is filled with a material, it is difficult to see the degree of openness of the surface. To determine the characterisitics of the stone, it is necessary to look at its back side. If it looks like a sponge, it means it can absorb water at high rate. These stone types will show staining more easily and stain will not be removed easily once it has been absorbed.

Marbles are metamorphic stones. They begin as limestone from a sedimentary deposit, then experience one or more metamorphoses that includes dramatic movement and extreme heat. The dynamic forces acting on the deposit cause new minerals, not present in the original deposit, to recrystallize to form marble. It is amore colorful stone. The accumulation of varying characteristics may create weakness in marble or an unpredictable performance of the same material quarried at different times. The metamorphic process can create a material that is stronger in the overall composition.

Characterisitics to Look for When Selecting Marble

- Marble is harder and more durable than the original limestone as a methamormophosed stone. The calcium carbonate of limestone becomes calcite when methamorphosed to marble. The color, texture and structural characteristics change a lot, so it is difficult to distinguish the test data between marbles and stones from the same deposit.
- The calcit material that composes marble, similar to the calcium carbonate of limestone, makes it weak against acid, and it should be located in areas where they will not be exposed to weather.
- The structure of the marble should be examined carrefully. The bond between the surrounding material and the vein or inclusion should be without interruption or separation. The separation of the vein may cause a crack and break under pressure. If there is no separation, it will be very strong like a metal welded together.
- The soundness and compactness of the large white colored quartz spots should be examined. If there is a great difference between the hardness of the quartz

inclusion and hardness of the surrouding marble, the two materials can be separated easily. It is a negative reaction of the dry vein.

- Large variations in color and character of the marble should be anticipated because of the dynamic forces that combine to create it.

Slate is a metamorphic stone. The origins of slate are the sedimentary deposits of finely sorted silt that are compressed to form clay and shale. Quartz and mica are primary mineral components of slate. The density of the slate type is determined by the degree of metamorphic action that occurrs during its formation. Many shales are extremenly dense and many are loose in compaction.

Characterisitics to look for when selecting slate

- The density of the slate type can vary dramatically. It should be chosen according to the use of intention.
- Many types of slate that are loosely cleaved have a more rustic appearance. This increases the variation in its thickness. This makes it difficult to place the stones next to each other.
- In designing with slate and other rustic types of stone, it is important to be aware of the limitations of the material and to avoid application where precision is required. Wider grout joints between moduls, thicker setting beds, and the use of smaller stone modules should be considered, so as to avoid disapointment when using rustic stones.

APPENDIX E

STANDARDS ON STONE AND STONE FACADES

E.1 PUBLISHED CEN STANDARDS BY TECHNICAL COMMITTEE CEN / TC 246 NATURAL STONE

(http://www.cenorm.be/CENORM/BusinessDomains/TechnicalCommitteesWorkshops/CENTechnicalCommittees/CENTechnicalCommittees.asp?param=6227&title=CEN%2FTC+246) –viewed in June 2005)

Table E.1 The European CEN Standards related with stone and stone facades.

STANDARD REFERENCE	TITLE
EN 12057:2004	Natural stone products - Modular tiles - Requirements
EN 12058:2004	Natural stone products - Slabs for floors and stairs - Requirements
EN 12370:1999	Natural stone test methods - Determination of resistance to salt crystallisation
EN 12371:2001	Natural stone test methods - Determination of frost resistance
EN 12372:1999	Natural stone test methods - Determination of flexural strength under concentrated load
EN 12372:1999/AC:2002	Natural stone test methods - Determination of flexural strength under concentrated load
EN 12407:2000	Natural stone test methods - Petrographic examination
EN 12440:2000	Natural stone - Denomination criteria
EN 12670:2001	Natural stone - Terminology
EN 13161:2001	Natural stone test methods - Determination of flexural strength under constant moment
EN 13161:2001/AC:2002	Natural stone test methods - Determination of flexural strength under constant moment
EN 13364:2001	Natural stone test methods - Determination of the breaking load at dowel hole
EN 13373:2003	Natural stone test methods - Determination of geometric characteristics on units
EN 13755:2001	Natural stone test methods - Determination of water absorption at atmospheric pressure
EN 13755:2001/AC:2003	Natural stone test methods - Determination of water absorption at atmospheric pressure
EN 13919:2002	Natural stone test methods - Determination of resistance to ageing by SO2 action in the presence of humidity
EN 14066:2003	Natural stone test methods - Determination of resistance to ageing by thermal shock
EN 14146:2004	Natural stone test methods - Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency)
EN 14147:2003	Natural stone test methods - Determination of resistance to ageing by salt mist
EN 14158:2004	Natural stone test methods - Determination of rupture energy

Table E.1 (cont'd) The European CEN Standards related with stone and stone facades.

STANDARD REFERENCE	TITLE
EN 14205:2003	Natural stone test methods - Determination of Knoop hardness
EN 14231:2003	Natural stone test methods - Determination of the slip resistance by means of the pendulum tester
EN 14579:2004	Natural stone test methods - Determination of sound speed propagation
EN 14580:2005	Natural stone test methods - Determination of static elastic modulus
EN 14581:2004	Natural stone test methods - Determination of linear thermal expansion coefficient
EN 14617-9:2005	Agglomerated stone - Test methods - Part 9: Determination of impact resistance
EN 14618:2005	Agglomerated stone - Terminology and classification
EN 1467:2003	Natural stone - Rough blocks - Requirements
EN 1468:2003	Natural stone - Rough slabs - Requirements
EN 1469:2004	Natural stone products - Slabs for cladding - Requirements
EN 1925:1999	Natural stone test methods - Determination of water absorption coefficient by capillarity
EN 1926:1999	Natural stone test methods - Determination of compressive strength
EN 1936:1999	Natural stone test method - Determination of real density and apparent density, and of total and open porosity

Agglomereted stone standards were not reviewed in the context of this thesis.

The standards under development are as follows:

Table E.2 The European CEN Standards under development.

STANDARD REFERENCE	TITLE
prEN 1926 rev	Natural stone test methods - Determination of compressive strength
prEN 1936 rev	Natural stone test method - Determination of real density and apparent density, and of total and open porosity
prEN 12372 rev	Natural stone test methods - Determination of flexural strength under concentrated load

E.2 ASTM STANDARDS OF DIMENSION STONE DEVELOPED BY SUBCOMITTEE C18

(www.astm.org-viewed in july 2005)

Each main committee in ASTM International is composed of subcommittees that address specific segments within the general subject area covered by the technical committee. The subcommittees are :

C18.01 Test Methods
C18.03 Material Specifications
C18.06 Anchorage Components and Systems
C18.07 Environmental Properties, Behavior, and Cleaning
C18.08 Selection of Exterior Dimension Stone
C18.90 Executive
C18.91 Nomenclature and Definition

E.2.1 (C18.01) Test Methods

C97-02 Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone

C99-87(2000) Standard Test Method for Modulus of Rupture of Dimension Stone

C120-05e1 Standard Test Methods of Flexure Testing of Slate (Breaking Load, Modulus of Rupture, Modulus of Elasticity)

C121-90(1999) Standard Test Method for Water Absorption of Slate

C170-90(1999) Standard Test Method for Compressive Strength of Dimension Stone

C217-94(2004) Standard Test Method for Weather Resistance of Slate

C880-98 Standard Test Method for Flexural Strength of Dimension Stone

C1201-91(2003) Standard Test Method for Structural Performance of Exterior Dimension Stone Cladding Systems by Uniform Static Air Pressure Difference

C1352-96(2002) Standard Test Method for Flexural Modulus of Elasticity of Dimension Stone

C1354-96(2004) Standard Test Method for Strength of Individual Stone Anchorages in Dimension Stone

E.2.2 (C18.03) Material Specifications

Most of these standards are under revision.

C503-05 Standard Specification for Marble Dimension Stone

C568-03 Standard Specification for Limestone Dimension Stone

C615-03 Standard Specification for Granite Dimension Stone

C616-03 Standard Specification for Quartz-Based Dimension Stone

C629-03 Standard Specification for Slate Dimension Stone

C1526-03 Standard Specification for Serpentine Dimension Stone

C1527-03 Standard Specification for Travertine Dimension Stone

E.2.3 (C18.06) Anchorage Components and Systems

C1242-04a Standard Guide for Selection, Design, and Installation of Dimension Stone Anchoring Systems

E.2.4 (C18.07) Environmental Properties, Behavior, and Cleaning

C1496-01 Standard Guide for Assessment and Maintenance of Exterior Dimension Stone Masonry Walls and Facades

C1515-01 Standard Guide for Cleaning of Exterior Dimension Stone, Vertical And Horizontal Surfaces, New or Existing

E.2.5. (C18.08) Selection of Exterior Dimension Stone

C1528-02 Standard Guide for Selection of Dimension Stone for Exterior Use

E.2.6 (C18.90) Executive

No standards available developed by this subcommittee.

E.2.7 (C18.91) Nomenclature and Definitions

C119-05 Standard Termninology Relating to Dimension Stone

E.3 THE TURKISH STANDARDS

E.3.1 Harmonized Standards

The Turkish Standards harmonized with the CEN standards are highlighted on the list of CEN standards (Table E.1) as follows to help for finding the non existent standards (TSE web page; viewed in August 2005):

Table E.3 The Turkish Standards (highlighted) harmonized with the CEN standards related with stone and stone façade.

STANDARD REFERENCE	TITLE
TS EN 12370	Natural stone test methods - Determination of resistance to salt crystallisation
TS EN 12371	Natural stone test methods - Determination of frost resistance
TS EN 12372	Natural stone test methods - Determination of flexural strength under concentrated load
EN 12372:1999/AC:2002	Natural stone test methods - Determination of flexural strength under concentrated load
TS EN 12407	Natural stone test methods - Petrographic examination
EN 12440:2000	Natural stone - Denomination criteria
EN 12670:2001	Natural stone - Terminology
TS EN 13161	Natural stone test methods - Determination of flexural strength under constant moment
EN 13161:2001/AC:2002	Natural stone test methods - Determination of flexural strength under constant moment
TS EN 13364	Natural stone test methods - Determination of the breaking load at dowel hole
TS EN 13373	Natural stone test methods - Determination of geometric characteristics on units
TS EN 13755	Natural stone test methods - Determination of water absorption at atmospheric pressure
EN 13755:2001/AC:2003	Natural stone test methods - Determination of water absorption at atmospheric pressure
TS EN 13919	Natural stone test methods - Determination of resistance to ageing by SO2 action in the presence of humidity
TS EN 14066	Natural stone test methods - Determination of resistance to ageing by thermal shock
EN 14146:2004	Natural stone test methods - Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency)
TS EN 14147	Natural stone test methods - Determination of resistance to ageing by salt mist
EN 14158:2004	Natural stone test methods - Determination of rupture energy
EN 14205:2003	Natural stone test methods - Determination of Knoop hardness
EN 14231:2003	Natural stone test methods - Determination of the slip resistance by means of the pendulum tester
EN 14579:2004	Natural stone test methods - Determination of sound speed propagation
EN 14580:2005	Natural stone test methods - Determination of static elastic modulus
EN 14581:2004	Natural stone test methods - Determination of linear thermal expansion coefficient

Table E.3 (cont'd) The Turkish Standards (highlighted) harmonized with the CEN standards related with stone and stone façade

EN 14617-9:2005	Agglomerated stone - Test methods - Part 9: Determination of impact resistance
EN 14618:2005	Agglomerated stone - Terminology and classification
EN 1467:2003	Natural stone - Rough blocks - Requirements
EN 1468:2003	Natural stone - Rough slabs - Requirements
EN 1469:2004	Natural stone products - Slabs for cladding - Requirements
TS EN 1925	Natural stone test methods - Determination of water absorption coefficient by capillarity
TS EN 1926	Natural stone test methods - Determination of compressive strength
EN 1936:1999	Natural stone test method - Determination of real density and apparent density, and of total and open porosity

E.3.2 Other Turkish Standards

1 TS 5695 05.04.1988
Yapı ve Kaplama Taşları - Tabii - Sınıflandırma

2 TS 5762 22.04.1988
Diyabaz-Yapı ve Kaplama Taşı Olarak Kullanılan

3 TS 5961 06.09.1988
Serpantin-Yapı ve Kaplama Taşı Olarak Kullanılan

4 TS 6234 20.12.1988
Granit-Yapı ve Kaplama Taşı olarak Kullanılan

5 TS 10449 10.11.1992
Mermer-Kalsiyum Karbonat Esaslı-Yapı ve Kaplama Taşı Olarak Kullanılan

6 TS 10834 13.04.1993
Gabro-Yapı ve Kaplama Taşı Olarak Kullanılan

7 TS 10835 13.04.1993
Andezit-Yapı ve Kaplama Taşı Olarak Kullanılan

8 TS 11135 16.11.1993
Trakit - Yapı ve Kaplama Taşı Olarak Kullanılan

9 TS 11137 16.11.1993
Kireçtaşı (Kalker)- Yapı ve Kaplama Taşı Olarak Kullanılan

10 TS 11143 07.12.1993
Traverten-Yapı ve Kaplama Taşı Olarak Kullanılan

11 TS 11145 07.12.1993
Konglomera - Yapı ve Kaplama Taşı Olarak Kullanılan

12 TS 11443 08.11.1994
Oniks Mermeri- Kalsiyum Karbonat Esaslı- Yapı ve Kaplama Taşı Olarak Kullanılan

13 TS 11444 08.11.1994
Dolomit-Yapı ve Kaplama Taşı Olarak Kullanılan

14 TS 11553 07.02.1995
Siyenit-Yapı ve Kaplama Taşı Olarak Kullanılan

15 TS 5762/T1 02.03.2004
Diyabaz-Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

16 TS 5961/T1 02.03.2004
Serpantin-Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

17 TS 6234/T1 02.03.2004
Granit-Yapı ve Kaplama Taşı olarak Kullanılan Tadil 1

18 TS 10449/T1 02.03.2004
Mermer-Kalsiyum Karbonat Esaslı-Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

19 TS 10834/T1 02.03.2004
Gabro-Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

20 TS 11135/T1 02.03.2004
Trakit - Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

21 TS 11137/T1 02.03.2004
Kireçtaşı (Kalker)- Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

22 TS 11143/T1 02.03.2004
Traverten-Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

23 TS 11145/T1 02.03.2004
Konglomera - Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

24 TS 11443/T1 02.03.2004
Oniks Mermeri- Kalsiyum Karbonat Esaslı- Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

25 TS 11444/T1 02.03.2004
Dolomit-Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

26 TS 11553/T1 02.03.2004
Siyenit-Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

27 TS 10835/T1 02.03.2004
Andezit - Yapı ve Kaplama Taşı Olarak Kullanılan Tadil 1

E.4 Italian National Standards on Stone

There are many national standards in Italy, regarding stone, stone cleaning etc. besides from standards harmonized with the European CEN standards. Table E.4 is the list of natioal Italian standards related with stone.

Table E.4 List of National Italian Standards on Stone
(http://webstore.uni.com/unistore/public/searchproducts?usecache=true&action=search&startIndex=41-viewed in September 2004)

STANDARD REFERENCE	**TITLE**
UNI 9724-4:1990	Natural stones. Preparation of thin and polished sections
UNI 9725:1990	Natural stones. Acceptance criteria.
UNI 9726:1990	Natural stones (raw and worked products). Criteria for techical information.
UNI 9728:1990	Coating products for stones and rendering mortars. Criteria for technical information
UNI 10813:1999	Cultural heritage - Natural and artificial stones - Check the presence of photoautotrophic micro-organisms on stone materials by UV/Vis spectrophotometric determination of chlorophyll a, b e c
UNI 10859.2000	Cultural heritage - Natural and artificial stones - Determination of water absorption by capillarity
UNI 10921-2001	Cultural heritage - Natural and artificial stones - Water repellents - Application on samples and determination of their properties in laboratory
UNI 10922-2001	Cultural heritage - Natural and artificial stones - Preparation of thin and polished sections of stone colonized by biodeteriogens
UNI 10923-2001	Cultural heritage - Natural and artificial stones - Preparation of biological specimens for the observation by light microscopy
UNI 10925-2001	Cultural heritage - Natural and artificial stones - Method for artificial solar light test
UNI 11018-2003	Cladding and anchoring systems for back ventilated external enclosures of buildings - Instructions for the design, installation and maintenance - Ceramic and stone cladding
UNI 11085-2003	Cultural heritage - Natural and artificial stones - Moisture content determination: Gravimetric method
UNI 11086-2003	Cultural heritage - Natural and artificial stones - Determination of equilibrium moisture content

BIBLIOGRAPHY

ACI-ASCE (1989) *Building Code Requirements for Masonry Structures (ACI 530-88/ ASCE 5-88) and Specifications for Masonry Strutures (ACI 530.1-88/ASCE 6-88),*

ADDLESSON, L., RICE, COLIN, (1991), *Performance of Materials in Buildings*, Butterworth – Heinemann Ltd., Oxford.

ADDLESSON, L. (1989) *Buildings Failures A Guide to Diagnosis Remedy and Prevention*, Butterworth Architecture, London 66-77

ALLEN, W. (1997) *Envelope Design for Buildings*, Architectural Press, Oxford.

AMERICAN CONCRETE INSTITUTE (1999) *Building Code Requirements for Masonary Structures,* American Concrete Institute.

AMARASO, G. G.; FASSINA, V. (1983,1943) *Stone Decay and Conservation: Atmospheric Pollution, Cleaning, Consolidation, and Protection*, Elsevier, New York.

ANDERSON, J.; M.GILL, J.R. (1988) *Rainscreen Cladding A Guide Design to Principles and Practice,* CIRIA Building and Structural Report: Walls, Butterwoth, London.

ANDREW, C.,YOUNG, A., YOUNG, M. (1994) *Stone Cleaning : A Guide for Practitioners*, Historic Scotland & The Robert Gordon University, Scotland.

ARIOĞLU, N. *et al* (Ekim 1999) *Küfeki Taşının Dayanıklılık Analizi-Şehzade Camii Örneği-2*,(*Resistance Analysis of Kufeki Stone- Sehzade Mosque Case Study)*, Yapı Dergisi, No.215, YEM Publication, İstanbul.

ASHURST, J.; DIMES F.G. (1977) *Stone in Building-Its Use and Potential Today*, W&J Mackay Limited, Chatham

ASHURST, J.; DIMES F. G. eds. (1990) *Conservation of Building and Decorative Stone*, Butterworth-Heinemann, London.

ASLANOĞLU, İ. (2001) *Erken Cumhuriyet Dönemi Mimarlığı* (*Early Turkish Republic Era Architecture*), METU Faculty of Architecture Press, Ankara.

ASTM 1242-4a *Guide Specification for the Design, Selection and Installation of Exterior Dimension Stone Anchors and Anchorage System*

BAKIRER, Ö. (1990) *Materials of Construction in Ottoman Architecture, The Use of Colored Marbles*, Seventh International Congress of Turkish Arts, University of Warsaw, Akten (ed. T.Majda), Polish Scientific Publishers, Warsaw.

BAŞGELEN, N. (1993) *The Wall in Anatolia, trans*, B.Atlamaz, Grasbas Matbaacılık A.Ş, İstanbul.

BROOKS, H. (1976) *Illustrated Encyclopedia Dictionary of Building and Construction Terminology*, Prentice-Hall Inc., N.J.

BİNAN, M. (1961) *Tabii Taş Duvar-Block Taş Duvarlar- Blok ve Kaplama Duvarlar* (*Natural Stone Walls-Cut Stone Walls- Stone Claddings*), ITÜ Press, İstanbul.

BINDA, L., GARAVAGLIA, E., MOLINA, C. (1999) *Physical and Mathematical Modeling of Masonry Deterioration Due to Salt Crystallization*, Durability of Building Materials and Components 8, Proceedings of the Eighth International Conference on Durability of Building Materials and Components, 8 dbmc, (May 30-June 3 19999), eds.M. A. Lacasse, D.J.Vanier, NRC Research Press, Ottawa.

BLANC, A. (1994) *International Components*, Longman Scientific & Technical, Singapore.

BLYTH, A. (1990) *Specification Technical 90*, MBC Architectural Press & Building Publications, London.

BRITISH STANDARDS (1994) *Code of Practice for Design and Installation of Natural Stone Cladding and Lining*, BS 8298, Arrowsmith. Ltd.

BRITISH STANDARDS (1985) *Code of Practice of Non loadbearing External vertical Enclosures of Buildings*, BS 8200, Arrowsmith Ltd.

BRITISH STANDARDS (1993) *Code of Practice for Design of Joints and Jointing in Building Construction*, BS 6093, Arrowsmith Ltd.

BROOKES, A..J. (1997) *Concepts in Cladding-Case Studies of Jointing for Architects and Engineers,* Longman Inc., New York.

BROOKS, A. (1985) *Concepts in Cladding*, Construction Press, Newyork.

BROOKES, A.J., GRECH, C. (1997) *The Building Envelope + Connections*, Architectural Press, Oxford.

BROOKES, A.J. (1998) *Cladding of Buildings*, E& FN Spon, Oxford.

BURN, K.N. (1984) *Performance of Stone Facades, Performance of Materials in US Seminer Notes, Building Science Insight'84* (viewed in May 2004) file:// A\BSI'84-Performance Of Stone Facades.htm

CIB Master List (1993) *CIB Master List*, CIB Publication 18.

CARLSON, G.E. (1974) *Architectural and Building Trades Dictionary*, American Technical Society, Chicago.

CHACON, M.A (1999) *Architectural Stone: Fabrication, Installation and Selection*, John Willey & Sons, New York.

COVAN, H.J., SMITH P. (1986) Dictionary of Architectural and Building Technology, Elsevier Applied Science Publisher, London.

DENİZ, Ş. Ö. (2003) *Masif Duvarlarda Dış Kaplama Uygulamaları (Exterior Wall Cladding Applications at Massive Walls*), Dizayn & Konstrüksiyon (206:1) Cemre Basın Yayın Ltd. Şti, İstanbul , 83-93

FITZNER, B.; HEINRICHS, K.; KOWNATZKI, R. (1995) *Weathering Forms-Classification and Mapping*, Verlag Ernst & Sohn GmbH, Berlin.

FUKES, J. (2000) *Sky-high Security, Occupational Health & Safety*, (69:3) 45 (viewed in May 2004) http://proquest.umi.com

FOSTER, J.S., HARINGTON, R. (1985) *Structure and Fabric Part 2*, Batsford Academic and Educational Ltd., London.

FORD, E. (1998) *The Details of Modern Architecture*, V.2 (1928-1988), The MIT Press, Massachusetts.

GANGULI, U. (1989) *Wind and Air Pressures on the Building Envelope*, An Air Barrier for the Building Envelope Proceedings of Building Science Insight'86, Natural Research Council Canada, Ottawa.

GRUNDY, J.T. (1989) *Construction Technology-Volume 1*.

HAGEN, Michael L. (16-17 June 1989) *75 STATE STREET –Stone Cladding, SOM National Interdisciplinary Technical Meeting*, Chicago.

HARRIS, C.M. (1993) *Dictionary of Architecture and Construction,* McGraw Hill Inc., New York.

HARRIS, C.M. (2000) *Dictionary of Architecture and Construction,* McGraw Hill Inc., New York.

HARRİMAN, M. (1991) *Set in Stone*, Architecture, February 1991,p :78-32

HASOL, D. (1998) *Ansiklopedik Mimarlık Sözlüğü* (*Encyclopedic Dictionary of Architecture*), YEM Publications, İstanbul.

HASOL, D. (1993) *Dictionary Architecture + Building,* YEM Publications, İstanbul.

HEYMAN, J. (1995) *The Stone Skeleton : Structural Engineering of Masonry Architecture*, Cambridge University Press, Cambridge.

INTERDEPARTMENTAL SUB-COMMITTEE FOR COMPONENT COORDINATION (1971) *Performance Requirements for External Walls,* Technical Note No:4, Department of Environment, London.

KUBAL, M.T (1993) *Waterproofing the Building Envelope*, Mc. Raw-Hill Inc, New York,1-7

LARKIN, J.H. (1998) *Securing The Stone*, Civil Engineering ASCE (68:1) 65-67.

LEWIS, M.D. (1995) *Modern Stone Cladding- Design and Installation of Exterior Dimension Stone Systems*, ASTM Manual Series MNL 21, Philadelphia.

LUX, M. E.; BROWN, W.C. (1989) *Air Leakage Control*, An Air Barrier for the Building Envelope Proceedings of Building Science Insight'86, Natural Research Council Canada, Ottawa.

MARSH, P. (1977) *Air and Rain Penetration of Buildings*, Longman Inc., NewYork.

MARTIN, B. (1971) *Standards and Building*, Riba Publications Ltd., London.

MUMYAKMAZ, E. (1999) *Doğal Granit Cephe Sistemleri* (*Natural Granite Façade Systems),* Cephe Sistemleri ve Cephe Kaplamaları Sempozyum Bildirileri (Façade Systems and Façade Claddings Symposium Proceedings 11Kasım 1999, Yapı Endüstri Merkezi, İstanbul.

MURPHY, S., HARRINGTON, W. (1966) *Stone Mad with Illustrations*, Routledge & K. Paul, London.

NAKAYMA, M, SASAKİ, M. (ed. 1999) Long Term Migration of Silicone into Stone and Its Prevention, Durability of Building Materials and Components and 8 – *Proceedings of the 8th International Conference on Durability of Building Materials and Components May 30-June 3 1999,* Volume 1, eds Lacasse, M. A. and Vanier, D. J, NRC Research Press, Ottawa, 593-602

NASHED, F. (1995) *Time Saver Standards for Exterior Wall Design,* McGrawHill, NewYork.

NATIONAL RESEARCH COUNCIL (1989) *Proceedings Of Building Science Insight '86*, *An Air Barrier for the Building Envelope*, National Research Council Press, Ottawa.

MERİÇ, M. (1994) *Yapı Fiziği ve Malzemesi,(Building Physics and Materials)* Literatür Yayınları, İstanbul.

O'NEILL, H. (1965) *Stone for Building*, Heinemann, London.

OESTERLE; et al. (2003),*Double Skin Facades*, Prestel, London

QUIROUETTE, R.L. (1989) *The Air Barrier Defined*, An Air Barrier for the Building Envelope Proceedings of Building Science Insight'86, Natural Research Council Canada, Ottawa, (1-5).

PERREAULT, J.C. (1989) *Air Barrier Systems: Construction Applications*, An Air Barrier for the Building Envelope Proceedings of Building Science Insight'86, Natural Research Council Canada, Ottawa.

PERREAULT, J.C. (2001) *Service Life Of the Building,* National Research Council (viewed in May 2004) http//www.ptcbs.org/irc/bsi/84-1_E.html

PFEIFER, G. et.al. (2001) *Masonry Construction Manual*, BirkHauser, Berlin

PRICE, C.A. (1996) *Stone Conservation: An Overview of Current Research*, Getty Conservation Institute, Santa Monica.

RICHARDSON, B.A. (2001) *Defects and Deterioration in Buildings*, Spon Pres, New York.

RIEDERER, J. ed. (1996) *Proceedings of the 8th International Congress on Deterioration and Conservation of Stone Berlin, 30. Sept. - 4. Oct. 1996*, Möller Druck und Verlag, Berlin.

RUPP, W., FREIDMAN, A. (1989*) Construction Materials for Interior Design-Principles of Structure and Properties of Materials*, Watson Guptill Publications, New York.

RUSKIN, J., ARNOLD W. ed. (1976) *Ruskin's Venice*, Whitney Library of Design, New York.

SCHAUPP, W. (1967) *External Walls- Cladding, Thermal Insulation, Damp Proofing*, Transatlantic Arts, New York.

SCHITTICH, C. eds. (2001) *In Detail Building Skins*, Kosel GmbH & Co. KG, Kemptenhel.

SEZER, Ş.F. (2003) *Giydirme Cephe Sistemlerinin Sınıflandırılması*- (*Classification of Curtain Wall Systems)*, *Yalıtım* (7:40), 40-43.

SEZER, Ş.F. (2003) *Giydirme Cephe Sistemlerinde Standartlar ve Deneysel Test Kontrol Yöntemleri* (*Standardts and Experimental Test Kontrol Methods for Curtain Wall Façade Systems)*, Dizayn & Konstrüksiyon, (206:12) Cemre Basın Yayın Ltd. Şti, İstanbul , 80-82.

SHOHET, I..M.; LAUFER A. (1996) *Exterior Cladding Methods: A Technoeconomic Analysis*, Journal of Construction Engineering and Management, (122:1), ASCE Publication, New York, 242-247.

SMITH, M.R.ed. (1999) *Stone : Building Stone, Rock Fill and Armourstone in Construction*, Geological Society, London.

SMITH, R.C. (1966) *Materials of Construction*, McGraw-Hill Book Company, New York.

TANYELİ, G.; GEÇKİNLİ, E.A.; ATA, A., (1990) *VI. Arkeometri Toplantısı Sonuçları* 28 Mayıs-1 Haziran 1990*, Osmanlı Mimarisinde Kullanılan Demir Ögelerin Üretim Teknolojisi* (*Proceedings of Archiometry Meeting, The manufacturing Technology of iron elements in Ottoman Architecture*) T.C. Kültür Bakanlığı-Anıtlar ve Müzeler Genel Müdürlüğü, Ankara.

TURKISH STANDARDS INSTITUTE (1977) *Natural Facing Stones TS 1910*, Turkish Standards Institute Publication, Ankara.

TURKISH STANDARDS INSTITUTE (1988) *Natural Building and Facing Stones Terms TS 5694*, Turkish Standards Institute Press, Ankara.

UNITED NATIONS (1985) *Building Regulations in ECE Countries-Second Report,* United Nations, New York.

VANDENBERG, M. ed. (1975) *Handbook of Building Enclosure,* The Architectural Press, London.

WEBSTERR, R.G.M. (1992) *Stone Cleaning ; and the Nature, Soiling and Decay Mechanisms of Stone: Proceedings of the International Conference held in Edinburgh, UK,* 14-16 April 1992, Historic Scotland and the Robert Gordon Institute, London.

WINKLER, E. M. (1997) *Stone in Architecture- Properties-Durability*, Springer-Verlag, New York, Berlin.

WEB REFERENCES

GERNS, E. (February 2000) *Lessons Learned from Thin Stone Cladding, Masonary Construction,* (viewed in September 22005) www.wje.com

GULIEN, J.M. (2001) *Fixing of Natural Stone Pieces on Ventilated Walls- The Point to Point Systems* (viewed in September 2005) http://www.litosonline.com/articles/43/art4301.shtml

KUECKS, B. (1999) *Building Envelope Design* (viewed in September 2005) http://depts.washington.edu/fseweb/fdi99/envelope/html

PETER, H. (2004) *Stone Cladding-Technical Advice* (viewed in September 2005) http://www.szerelmey.com

SAWICKI, M.W. (2004) Stone Cladding by the Direct Adhered Method (viewed in May 2004) http://stoneworld.com/CDA/ArticleInfor.../0,4046,76956,00.htm

THE NATIONAL TRAINING CENTER FOR STONE AND MASONRY TRADES (2004) *Tech Center* (viewed in 2005) http://www.stoneinfo.com/tech/html

TODT, G. (2004) *Fixing Systems the Safer The Better* (viewed in September 2005) http://www.litosonline.com/articles/52/art5202e.shtml

VANIER, D.J, LACASSE, M.A. (2004) *Belcam Project: Service Life, Durability and Asset Management Research*,(viewed in September 2005) http://www.nrc.ca/irc/belcam/7DBMCDV.html

WYMOND, B. (2004) *Sealing The Building Envelope- Curtain Wall and Cladding in Hong Kong* (viewed in May 2004) http://www.building.com/hk/supplement/curtain/curtaincon.htm

CEN Standards (viewed in Setember 2005) http://www.cenorm.be/CENORM/BusinessDomains/TechnicalCommitteesWorkshops/CENTechnicalCommittees/Standards.asp?param=6227&title=CEN%2FTC+246

TURKISH STANDARDS (viewed in September 2005), www.tse.org.tr

CIRRICULUM VITAE

Bilge Oğan Musaağaoğlu was born in 1965, Tarsus. She graduated from METU the Faculty of Architecture in 1987. She received her M.S. degree in Architecture from ITÜ the Faculty of Architecture in 1989. She has worked as an assistant architect at the Kemer County Project Office in İstanbul from 1988 to 1992.

She has been working for Canpa İzolasyon Inc., which specializes in thermal insulation and waterproofing in Ankara, as a Technical Manager since 1992. She is married and has one daughter.