CERAMIC MATERIAL SYSTEMS

IN ARCHITECTURE AND INTERIOR DESIGN

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CONTENTS

8 CHAPTER 1
CERAMIC MATERIAL SYSTEMS

12 CHAPTER 2
FIRED CLAY – A MATERIAL LEGACY

12 From the Origins to the 19th Century
16 From the 20th Century to Today

18 CHAPTER 3
MATERIALS AND MATERIAL PROPERTIES

18 Clay
19 Clay Bodies
21 Shrinkage
22 Properties of Ceramic Parts
22 Glazes
25 Other Surface Treatments and Coatings

26 CHAPTER 4
PRODUCTION PROCESSES

28 Dry-pressing
29 Extrusion
31 Slump Forming/Slump Molding
32 Die-cutting
32 Plastic Pressing
33 Slip Casting
35 Wheel-throwing
35 Jiggering
35 Firing and Kilns
38 Glazing
38 Post-processing
39 Packaging and Distribution

40 CHAPTER 5
APPLICATIONS: INTERIORS

40 Adhered Tile Systems
43 Mechanically Connected Tiles
45 Sanitary Ware

46 CHAPTER 6
APPLICATIONS: EXTERIORS

46 Bonded Tile Facades
50 Ventilated Facades
52 Screen Surfaces
53 Acoustic Surfaces
54 Roofs
55 Other Outdoor Applications

56 CHAPTER 7
MATERIAL FLOWS: LIFE CYCLE ASPECTS

58 Extraction-to-Production Phase
59 Construction and Use Phase
60 End-of-Life Scenarios
62 Life Cycle Analysis (LCA) and Material Comparisons

64 CHAPTER 8
SURFACE EFFECTS

64 Introduction
66 Surface Reliefs
The Wallpaper Factory, Islington, North London, UK
68 Color Variation
Museum Brandhorst, Munich, Germany
70 Custom Glazes
The Holburne Museum Extension, Bath, Somerset, UK
72 Three-dimensional Surfaces
Museum der Kulturen Basel, Switzerland
74 Pearlescent Glazes
Algueña MUCA Music Hall and Auditorium, Alicante, Spain
78 Glaze Transfers
One Eagle Place, London, UK
80 High Performance Surfaces
West Beach Promenade, Benidorm, Spain
82 Inkjet Printing
La Mandarra de La Ramos, Pamplona, Spain
84 Nano-coatings
Pinnacle, Bologna, Italy

86 CHAPTER 9
PATTERNS AND AGGREGATIONS

86 Introduction
88 Complex Geometry
Pulsate, Primrose Hill, London, UK
90 Complex Assembly
Jewish Community Center, Mainz, Germany
94 Non-repeating Patterns
Zamet Center, Rijeka, Croatia
98 Figurative Urban Mosaics
Muhammad Ali Center, Louisville, Kentucky, USA
100 Curved Surface Urban Mosaics
Santa Caterina Market, Barcelona, Spain
104 Robotic Tiling
Iowa State Mural, Ames, Iowa, USA
106 Tessellated Surfaces
Urban Guerrilla, Valencia, Spain
108 Hanging Assemblies
Xinjin Zhi Museum, Chengdu, China
112 Three-dimensional Assemblies
3Dx1, Milan, Italy
114 Structural Assemblies
Casalgrande Ceramic Cloud (CCCLoud), Reggio Emilia, Italy

118 CHAPTER 10
THERMODYNAMIC SKINS

118 Introduction
120 Reclaimed Tile Tectonics
Warehouse 8B Administrative Offices, Madrid, Spain
124 Grão – Ceramic Pixels
Jardim Botânico Tropical, Travessa do Marta Pinto, Belém/Lisbon, Portugal
126 Masonic Louvers
Student Services Building, University of Texas at Dallas, Texas, USA
130 Modulating Light
Addition to the Israel Museum, Jerusalem, Israel
134 Perforated Slab
School Library, Gando, Burkina Faso
136 Cool Cavity
Patio 2.12, Andalucía Team, Solar Decathlon Europe 2012, 2nd Prize, Madrid, Spain
140 Breathing Columns
Spanish Pavilion at the International Exposition of Zaragoza, Spain
144 BIO SKIN
Sony Research and Development Office, Tokyo, Japan

148 CHAPTER 11
FORM CUSTOMIZATION STRATEGIES

148 Introduction
150 Computer-aided Slump Molding
Villa Nurbs, Empuriabrava, Spain
154 Volumetric Pixelization
Spanish Pavilion, Expo 2005, Aichi, Japan
158 High-relief Slip-cast Surfaces
Villa for an Industrialist, Shenzhen, China
162 Low-volume Custom Extrusion
Kosemo Brick, Archie Bray Foundation, Helena, Montana, USA
166 Systemic Variation
Ministry of Urban Development and Environment, Hamburg, Germany
170 Digital Reconstruction
Alberta Legislature Building Dome Reconstruction, Edmonton, Alberta, Canada
172 Angular Variation
Trumpf Industrial Campus Restaurant, Ditzingen, Germany
176 Delineated Parallax
La Riera de la Salut Remodel, Sant Feliu de Llobregat, Spain
180 Aggregate Production Processes
Oceanário Addition, Lisbon, Portugal
184 Compound Surface Discretization
Museum de Fundatie Extension, Zwolle, Overijssel, The Netherlands

188 CHAPTER 12

EMERGING SYSTEMS

188 Introduction
190 Robotic Tile Mosaics
Design Robotics Group at Harvard University Graduate School of Design
192 Integrated Environmental Design-to-Robotic Production
Design Robotics Group at Harvard University Graduate School of Design
194 Thermally Active Building Envelope
The Center for Architecture, Science and Ecology, Rensselaer Polytechnic Institute and Skidmore, Owings & Merrill (SOM)
196 Structural Ceramic Shell
Material Processes and Systems Group at Harvard University, Graz University of Technology
198 Photosensitive Blueware
Studio Glithero
200 Foamed Ceramics
European Ceramic Work Center, Joris Laarman Studio BV
202 Additive Ceramic Systems
204 Automated Material Manipulation

PRODUCTS AND TECHNOLOGIES

206 Introduction
207 Large-format Production Lines
207 Large-format Tiles: Neolith, Techlam, Maximum
208 High-strength Porcelain: SaphirKeramik Sink
208 Bioactive Ceramics: Bionictile
209 Slumped Tile: UP
209 Slumped Tile: STAR
210 Translucent Porcelain: SlimmKer-Light
210 Modular Ceramic Stove
211 Berlin Stove Tiles
211 Keramos Cabinets
211 Inkjet-printed Tiles: Emotile
212 Physical Vapor Deposition: Metallic Coatings
213 Laser Engraving
213 Recycled Tiles
213 Preassembled Systems: Flexbrick
214 Ceramic-Concrete Composition System: Terraclad
214 Ceramic Louver System: Shamal
215 Photovoltaic Roof Tiles: Panotron
215 Ceramic Wardrobe: Milky Star
216 Acoustic Ceramics: Acoustic Shingle
216 Industrial Tile: Acigres
216 Material Mimicry: Age Wood, Age Beton, Age Blend

APPENDIX

218 About the Authors
219 Index of Names
221 Subject Index
223 Sponsor’s Profile
224 Illustration Credits

CHAPTER 1

CERAMIC MATERIAL SYSTEMS

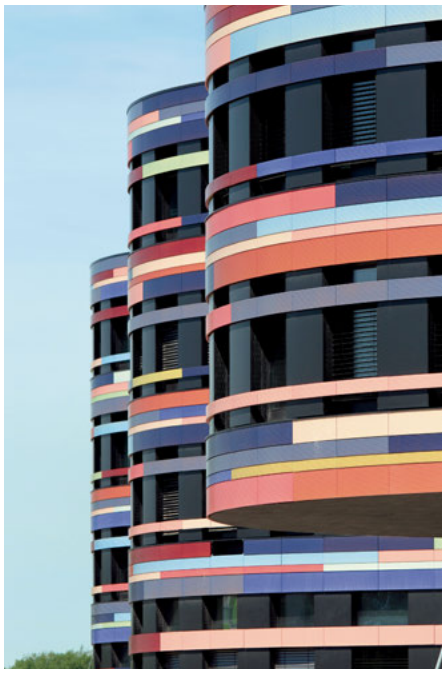
The past decades have been marked by the rediscovery of architectural ceramics—a material system that has long served merely as a practical surface treatment for buildings, but that is now coming into its own as a multi-functional, intensely aesthetic boundary layer for buildings, landscapes, and cities. This renaissance is enabled and catalyzed by recent advances in material science, fastening technology, industrial production methods, design computation, digital fabrication workflows, and design robotics. Today's highly controlled clay mixes, combined with computer-controlled kilns, can be customized to design specific material behaviors. Rigid industrial mass-production systems are being complemented by fabricators geared towards collaborating with architects in the development of custom solutions for buildings. Project-specific ceramic designs are increasingly supported by digital environments that address the entire material life cycle from production to robotic assembly approaches. Glaze technology has always been among the most forward-looking aspects of ceramic elements, and recent advances such as self-cleaning or pollution-reducing glazes continue this tradition. These developments now afford architects and other design professionals new opportunities for aesthetically committed, structurally and environmentally active ceramic systems that far transcend the ubiquitous tile as a solution for water-resistant, durable finishes.

Ceramic material systems comprise the ecosystem of material extraction and processing to the assembly of construction elements and their eventual reuse and recycling. They are moving from the margins to the forefront of contemporary construction and design culture (1). This book establishes the state of the art of this quickly emerging field, with a particular interest in presenting the knowledge needed for developing project-specific solutions that often involve custom ceramic elements. Doing so requires, on the one hand, a rigorous background of the materials and associated technologies, and on the other, inspiration from the very best built examples of ceramic systems today. The book not only addresses both of these related needs, but also presents the most promising emerging developments and research that will likely shape the future design of ceramic elements and processes.

For most laypeople—and indeed for many design professionals—the term "ceramic" is synonymous with surfaces covered by flat tiles, bonded with mortar or adhesives, and sealed with grout joints. Indeed, that description fits the vast majority of present and past ceramic applications, and it continues to serve us well. Glazed or unglazed ceramic surfaces are durable, moisture-resistant, and inflammable. The incredible wealth of tile patterns and glaze colors reflect our diverse cultural and societal heritage (2). But adhering tiles to rigid underlying surfaces is limiting.

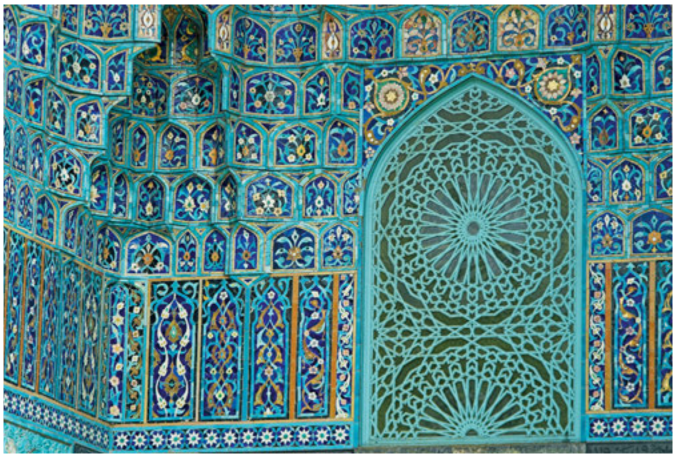
Multiple technical advances have brought about much larger, extremely slender, structurally more capable ceramic elements that, when used with mechanical fasteners, allow ceramic claddings to diverge from their slavish adherence to the geometry of supporting walls. These cladding systems feature ceramic elements in their own distinct layer, interacting in new performative ways with the environment. Ceramic elements now can control the transfer of moisture, heat, or sound. They construct deeply contoured surface layers that support new forms of architectural expression. They buffer and modulate daylight. In short, ceramic surfaces now enable multi-functional physical boundary layers that enrich and improve life in buildings and cities alike (3).

1



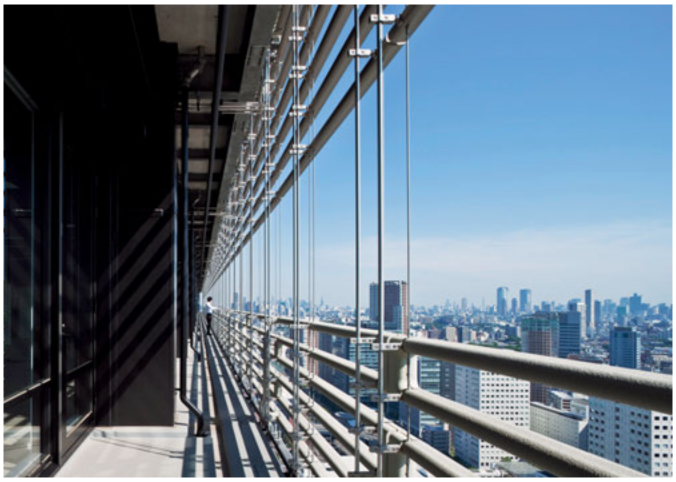
The Hamburg State Ministry for Urban Development and the Environment in Germany, designed by Sauerbruch Hutton, features a richly colored ventilated facade that includes planar and single-curved pieces.

2



Complex tile patterns in a mosque in Saint Petersburg, Russia.

3



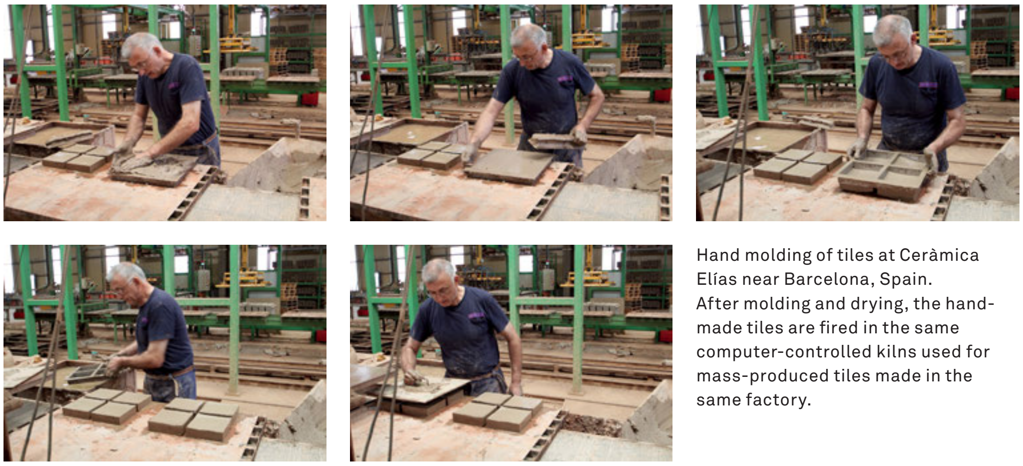
The ceramic facade for the Sony Building in Osaka, Japan, designed by Nikken Sekkei Ltd., uses evaporative cooling to improve the occupants' comfort and lower the microclimate around the building at the same time.

From a material science standpoint ceramics are oxides, with particular molecular bonding characteristics. They include, among others, cement-based materials, glass, clay-based materials, as well as so-called technical ceramics consisting of alumina, boron, graphite, silicon, and other substances. This book deals with glazed or unglazed clay-based ceramics that are, more specifically, relatively thin compared to their surface area, and fired at high temperatures to produce hard and durable products. Typical examples include multi- and single-layered ceramic panels used for claddings, shaped ceramic roof tiles, wall and floor tiles, as well as the many specialty elements for sunshades, screens, landscaping elements, and other applications. Bricks and brick products, despite being made from similar clays, are not included; instead, the reader is referred to the extensive existing literature.[1]

Ceramic elements, i.e., the fired-clay base shape, often bonded with a glaze or other finish, combine with adhesives or mechanical fasteners, grout and sealants, and other support elements into functionally complex construction systems. The material system view expands the scale of consideration further by including analysis of, and research on, relevant fabrication methods, understanding of the associated supply and distribution networks, and the life cycle study of resource flows.

Understanding the basic principles of contemporary production techniques for ceramic elements is important for designers who want to go beyond purchasing a standard product. Production techniques determine the characteristics of the end product to a high degree. Industrial mass-production settings are extremely unforgiving and inflexible, while craft-based manual techniques tend to be rather accommodating. Wall and floor tiles, for example, are produced in both settings. Hand-molded tiles feature subtle color and form variations that are appreciated by many end-users such that a small but sizeable market continues to exist (4). Such tiles contrast visibly with industrially made products that tend to be more uniform in color and size unless, of course, post-processing techniques have deliberately been used to create the "look and feel" of a hand-made tile. The highly automated production systems with their high set-up and tooling costs practically exclude the production of custom tiles (roof, wall, or floor products) for a specific project (5). But even companies that hand-mold tiles are rarely set up to communicate directly with designers who might wish to pursue a project-specific solution. Tiles are typically sold through resellers who receive their products from distributors, so that architects and designers are far removed from the actual places of production.

4



Hand molding of tiles at Ceràmica Elías near Barcelona, Spain.
After molding and drying, the hand-made tiles are fired in the same computer-controlled kilns used for mass-produced tiles made in the same factory.

5

Highly automated mass-production of dry-pressed floor tiles at Porcelanosa, Castellón, Spain. Industrial production settings such as these can output several thousand tiles per hour.

Producers who primarily focus on facade elements are organized in a slightly different way. Their products represent the largest, most structurally capable ceramic elements on the market. Industrial production methods dominate, but the need to customize solutions project by project has created an industry setup where medium-size producers are geared to collaborate with architects, engineers, and facade consultants in developing and producing custom ceramic systems for building envelopes. Appropriate fastening substructures are usually included in the scope of work, even though their production tends to be outsourced. This approach represents the middle ground between craft-based hand molding (low-volume but flexible production) and industrial mass-production (high-volume, inflexible), combining the best of both worlds. The relative ease with which even three-dimensional pieces with unique expressions and performance characteristics can be created differentiates ceramics from many other cladding and surface finish systems.

The costs of ventilated ceramic facades tend to be similar to equivalent stone facades, but with the added advantage of a vastly increased potential for design intervention in form and functional customization. Broadened design scope is one of the main reasons for today's rediscovery of ceramic material systems. It allows architects to engage a long material legacy while still pursuing forward-looking, conceptually and tectonically ambitious designs (6).

6

The extension of Antoni Gaudí's Teresianas School in Barcelona, Spain, designed by Picharchitects, features a facade composed of hollow ceramic extrusions. The so-called Flexbrick system features ceramic elements clipped onto a thin wire mesh to create a semi-transparent screen that filters light and views.

Following this introduction, Chapter 2 introduces an evolutionary perspective on ceramic material systems. The following chapters introduce the material properties and production processes (Chapters 3 and 4) used to create ceramic elements for applications in the built environment, followed by Chapters 5 and 6 that survey common applications, from interior adhered surface finishes to bonded facades, ventilated facades, sunscreens, acoustic claddings, and more. Chapter 7 on life cycle design outlines resource use and environmental issues from material extraction to end-of-life scenarios. Chapters 8 to 12 are dedicated to case studies of the most interesting, forward-looking, and inspiring uses of ceramic systems in buildings. The cases are grouped by themes that best represent the unique opportunities of ceramics: surface effects, patterns and aggregations, thermodynamic skins, customization strategies, and emerging technologies like 3D ceramic printing, ceramic-concrete composites, robotic construction, and others. Each section includes an introduction that addresses the general issues relating to each theme.

The last chapter on Products and Technologies presents a selection of current products from a range of producers. The intent is to provide a glimpse of product trends that complement architecturally ambitious design pursuits with ceramic material systems.

NOTE

1 For example Pfeifer, G. et al., *Masonry Construction Manual.* Basel, Boston, Berlin: Birkhäuser; Munich: Edition Detail, 2001.

CHAPTER 2

FIRED CLAY – A MATERIAL LEGACY

1

The Venus of Dolní Věstonice is among the earliest ceramic figurines found, dating back to 29000 to 25000 BC. It was discovered in 1925 in Moravia, Czechoslovakia. Fingerprints embossed into the surface even let scientists trace back the handling of the unfired object by a child between the age of seven and 14.

From the Origins to the 19th Century

The history of humanity, of civilizations dating back tens of thousands of years, is inextricably linked to firing clay and transforming it into a stone-like, durable material—ceramic. This hard, water-resistant material formed vessels, ovens, musical instruments, eventually tiles and sanitary ware, and much more. The word "ceramic" translates from the Greek *keramikos or keramos*, describing the product of the potter's art.[1] But long before humans produced ceramic tableware or cookware they made figurines and sculptures for ceremonial use.[2] The earliest fired clay figure found to date originates from a Stone Age settlement excavated in the 1920s in Czechoslovakia. Archeologists date this small female figurine to between 29,000 and 25,000 BC (1). Remnants of a purposefully constructed kiln were found on the same site—one of, or maybe the first ever, organized ceramic productions that ultimately led to today's fully automated production environments.[3]

Ceramic is considered the first human-designed material, as opposed to materials that were essentially used as extracted from nature and just shaped for specific purposes (e.g., wood, stone). Neolithic gatherers and hunters already employed fired clay items sporadically, but there is evidence that ceramics became more widespread once humans started to settle. Firing changed the material composition on the particle scale as clay, sand, and other materials were sintered and permanently bonded under the intense heat. Material properties changed substantially in the process, creating a harder, durable, and water-resistant substance. This man-made material—ceramic—had properties similar to stone, but was easier to shape and work while soft compared to the tremendous effort of chiseling and shaping stone. This ease of shaping ceramics remains attractive to the present day.

Early vessels for consumption and storage of food and liquids were initially hand-built using similar techniques employed by artists and hobbyists today. These manual techniques were supplemented and eventually replaced by one of the first machines ever invented—the potter's wheel. This simple yet effective device probably evolved around 3,500 BC in the Middle East and in China, and in principle has changed little to the present day. Its attraction lies in that it combines the regular and predictable rotational movement with direct hand-control—a clever method to lower the cost of repetitive as well as customized pottery production. Regular forms can be produced relatively easily and economically and without costly molds and templates. However, while the range of possible shapes is immense, the output is limited to axi-symmetrical shapes.

The desire to decorate ceramic ware and push designs beyond purely practical uses is almost as old as ceramic production itself. Early pottery often imitated textures from other production techniques such as weaving reed or wood. Color was likely first introduced through fire clouds, dark discolorations of the ceramic body from firing it in an oxidizing or a reducing atmosphere. When firing red earthenware, for example, the iron in the clay reacts with oxygen in the atmosphere and turns the ceramic bright red. Cutting off this oxygen supply turns the same ceramic black. Early Egyptian and Chinese cultures understood and deployed this discoloration, initially discovered by accident, to add value to some of the world's earliest ceramic vessels. The best-known use of this technique is arguably the black and red pottery of ancient Greece around 500 BC.

Beyond manipulation of the ceramic body itself, craftspeople have been using glazes, thin glass-based coatings. Such vitreous coatings consist of a glass former (silica), a flux to cause the silica to melt, and a refractory element to give it durability. Their first use dates back to ancient Egypt and Mesopotamia. In the stepped pyramid in Saqqara (2,667–2,648 BC) of pharaoh Djoser glazes with copper oxides were used to produce thousands of small bluish-green tiles resembling turquoise and lapis-lazuli to adorn the burial chamber (2). Another type of early glaze was the salt glaze: salt in the clay body migrates to the surface, where it reacts with the clay silica to form a vitreous coating. Later, powdered glass became a common glaze component and various metal oxides were used to create a range of colors. Since then glazes continue to evoke other, more noble materials. They also prolong the life of ceramic elements by keeping the often porous ceramic material dry.

2

Early blue-glazed ceramic tile used to decorate tomb interiors at the Djoser pyramid in Saqqara, Egypt. The tile measures 36 × 60 mm and is 13 mm thick. Approximately 36,000 tiles were molded for the project. They feature a projection on the back used to connect them to wet plaster substrates. The hole allowed a wire to mechanically secure the tile to the wall—much like mechanical connectors used in modern ceramic construction.

The centers of pottery production were usually in close proximity to where suitable clay could be readily extracted, thus avoiding costly and slow transport of heavy clay. Affordable fuel sources were needed as well, starting with wood or dung, and eventually switching to coal and natural gas as well as electricity. Many early production centers often started with small-scale pottery that gave way to more systematically organized manufacturing activities. Many of today's industrial producers remain in these original locations, still affecting local economies despite a now more widespread network of clay extraction and its associated trade. Landscapes in parts of the worlds have literally been shaped by clay extraction, but environmental problems are relatively minor compared to surface mining of coal or other minerals.

The earliest ceramic artifacts were fired in open fires that led to rough ceramic end products. Exposure to the elements allowed wind and rain to change firing temperatures suddenly—most certainly leading to much loss during ceramic production. Fuel consumption was high, controls were limited, and danger to the craftsperson and the surroundings was always imminent. The development of enclosed ovens, or kilns, satisfied the need for efficiency, and eventually allowed for the production of higher-quality, finer ceramics as a result of slower, more controlled firing sequences.

This also permitted the know-how and sophistication of glazes to evolve considerably. Along with material composition, firing sequences thus evolved as the second way through which potters—or should we call them the first material designers—created desirable material properties. Early pottery kilns served as catalysts of innovation far beyond ceramic production. Around 3,500 BC kilns had evolved whose temperatures were high enough for the reduction of the minerals azurite and malachite into copper. This discovery paved the way for blending tin and copper in the production of bronze, ushering in the Bronze Age.

Early kilns may have been (partially) dug into the ground or were self-supporting vertical, dome-shaped structures. Cross-draft kilns were an attempt to increase interior volume and better control the distribution of heat. But these kilns had to cool down for loading and unloading, disrupting production cycles and increasing fuel consumption. Fire temperatures were key, and with the emergence of industrial methods more continuous production cycles were highly desirable. The logic of continuous production is best represented in today's computer-controlled tunnel kilns, horizontal chambers with evenly distributed heat sources throughout, where green clay elements enter on one end, travel through a sequence of temperature zones, and warm ceramic products exit on the other.

The production techniques that had been developed for pottery transferred relatively easily to elements used in buildings. Sun-dried clay had long been used as plaster and brick in the Near East.[4] Fired ceramic tiles were first developed most likely in Ancient Egypt, as demonstrated by the tiles for the Djoser pyramid discussed earlier. Another early example of ceramic elements as building cladding are the tile-like cones used around 3,300 BC in the Sumerian city of Uruk. The ceramic cones were pressed like nails into an outer mud layer and served as a protective layer. They were painted and organized to form geometric patterns similar to the later tile mosaics.

The Assyrians and Babylonians are later cultures that used colorfully glazed tiles. Some of their best-known brick and tile work introduces three-dimensional reliefs as a design feature. The Ishtar gates in Babylon (~ 580 BC)[5] show a compelling glazed example, even though the format of the elements was more brick-like. Here careful planning must have taken place to assemble the 60 lion reliefs from many glazed pieces in regular vertical layers. It is assumed that the production involved molds used to prefabricate identical elements for the lions, thus constituting one of the earliest examples of prefabrication methods using indirect (i.e., mold-based) techniques (3).

Chinese culture contributed much to advances in ceramic technology and applications, from pottery to exuberant roof tiles and figurines. Around 2500 BC, Chinese potters invented porcelain, a particular kaolinite mix fired at higher temperatures to produce a vitrified material that is more durable, harder, and absorbs less water. The long-lasting Chinese leadership in developing ceramic technology is still reflected in the naming of one of the dominant raw materials as kaolinite; the name traces back to the Chinese city of Gao Ling, a mountainous area of ceramic discovery in early China.

Over the centuries the knowledge of clay bodies, firing techniques, and glazes grew. Wooden Greek temples were adorned with terra cotta friezes and column claddings to produce a more solid, stone-like impression. These were painted to blend with other materials. Ceramic roof tiles protected these and other buildings from the elements. Production techniques transitioned from manual methods to pre-industrial serial production techniques using animal or water power to mix clay bodies. Roman engineers set up efficient production centers for the making of roof, wall, and floor tiles (4). Ceramic roof tiles finally allowed for durable roof systems in the wet climates

3

The reconstructed Ishtar gate of Babylon at the Pergamon Museum in Berlin, Germany. Glazed relief tiles were likely molded in small lots to reproduce the lion reliefs.

4

Reconstructed Roman roof tiles in an archeological park in Xanten, Germany. Tiles were serially produced and held in place in heavy mortar beds. Similar cap and pan designs still exist in the present day.

5

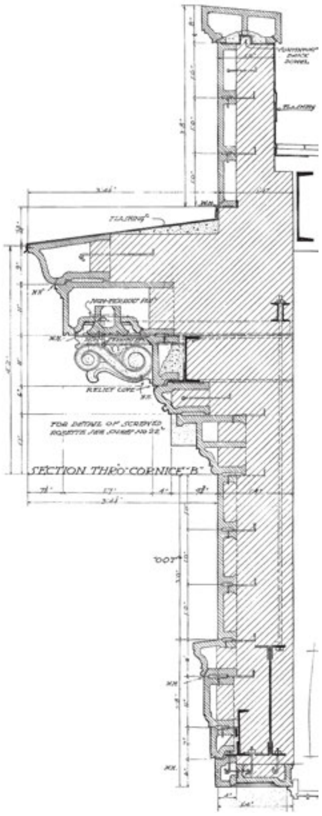
Highly decorated chien nien roof elements at the Mengjia Longshan temple in Taipei, Taiwan. Elaborate ornamentation was traditionally reserved for use on temples and palaces. The figures express authority and are to protect from evil spirits.

of Northern Europe. The Romans also embedded large hollow ceramic vessels in their concrete domes, saving material and lightening dead loads. Larger elements could now be produced in more substantial facilities, bringing down cost that in turn helped to spread their use. Much of this advancement was forgotten in Europe after the demise of the Roman Empire, and relatively little progress took place from the Middle Ages to the Industrial Revolution. Islamic architecture produced some of the most compelling ceramic mosaics in the period between 750 and 1,300 AD. Complex architectural forms, such as the doubly curved domes and *mihrabs* (semi-circular niches)—often embellished with hundreds of *muqarnas* (corbels)—were surfaced with glazed ceramic mosaics. Chinese architecture has used glazed decorated roof tiles for centuries. In the 17th century figures were introduced, a tradition very much alive today in the repeatedly reconstructed temples (5).

During the Renaissance ceramic ornaments and figures were used on buildings, but their true materiality was usually downplayed by reproducing the appearance of stone. Beginning around 1840, ceramic elements for building facades—known as *terra cotta*, Italian for "baked earth or clay"—again became an essential and economical choice when highly ornamental features were desired, yet carved stone was either unavailable or too expensive. Terra cotta was not only aesthetic and economical, it also protected 19th century iron and steel structures from fire. The survival of many terra cotta-clad buildings during the 1871 Chicago fire demonstrated the advantage of terra cotta in combination with metal building frames compared to brick facades and timber structures. Production methods were based on full-scale detail drawings, dimensioned to compensate for shrinkage. Sculptors produced positive plaster plugs from which plaster molds were subsequently cast. Moist clay was hand-pressed into these molds and removed for glazing and firing, once the originally wet clay had been sufficiently dried (e.g., green state). The resulting richly detailed, ornamental terra cotta elements were widely used. They became essential with the development of high-rise buildings in 19th century USA (6), and promoted the development of the modern curtain wall with their thin, lightweight claddings. The work of Louis Sullivan and the firm Adler & Sullivan became exemplary of this period and remains inspirational in its use of intricately detailed terra cotta elements. Ceramic was frequently

6

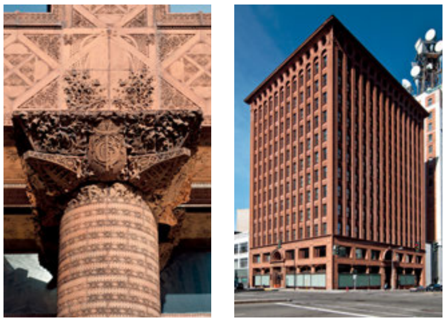
The USA-based National Terra Cotta Society, founded in 1911, issued standard details for terra cotta-clad buildings, both for steel frame structures as well as for steel/concrete buildings.



disguised behind layers of paint or glazes, often painstakingly executed to mimic other, more noble materials such as stone (7). The intrinsic materiality of fired clay was rarely appreciated as clients, as well as many architects, valued a more traditional appearance. During this period Rafael Guastavino patented and successfully commercialized his fireproof tile vaults in the USA, creating one of the first structural applications for ceramic tiles.

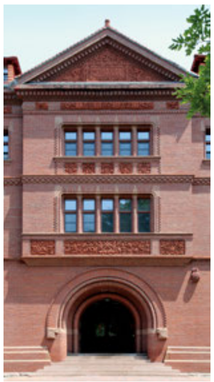
Combinations with brick such as in Harvard University's Sever Hall by H. H. Richardson were widely used in the second half of the 19th century (8). Richardson used ceramic systems as ornamentation, leaving the brick for the walls and arches, and cut stone for special pieces such as keystones. This tectonic language already points towards the emerging appreciation of ceramics as a pure cladding, without pretense of a tectonic role designated to steel and concrete.

7



Adler & Sullivan's Guaranty Building in Buffalo, NY, USA, was completed in 1896. Some of the highly ornamental, complex elements have been recently recreated and replaced using hand-pressed molding techniques almost identical to the methods employed when the building was first built.

8



Sever Hall, completed in 1880, is an example of using terra cotta to "embellish" brick buildings in the Northeastern United States. Ceramics are used for highly ornamental elements only, and in combination with cut stone.

From the 20th Century to Today

Architects such as Frank Lloyd Wright led a slow turnaround towards a new appreciation of ceramic as a material system with its own inherent expression. The Modern Movement continued this incremental change in attitude, but only relatively few architects had more than a cursory interest in the material. The Bauhaus maintained a ceramics studio with a pottery focus during the Weimar years, abandoning the study of this material in 1925, and never engaging with ceramic systems as an industrially producible material. Arne Jacobsen's Stelling House and Henry van de Velde's Tweebronnen School (1937–1940, now converted into a library) used glazed flat ceramics—albeit not always to the public's liking. Architects like Alvar Aalto introduced glazed tiles as a deliberate choice, indulging in their colorful surfaces as accents within modern interiors. Starting in 1954, Eladio Dieste expanded Guastavino's structural use of ceramics with his tile shells in Uruguay and Spain. Jørn Utzon's Sydney Opera House (1956–1973) features over 1,050,000 ceramic tiles pre-applied onto precast panels that make up the outer roof surfaces. The use of bonded tile facades became more widespread in many parts of the world, especially in Eastern Europe and the Soviet Union after World War II, and later in parts of Asia. Economic concerns, combined with the well-known practical advantages of durability and water resistance, drove much of this interest.

A major breakthrough occurred when larger ceramic elements were designed to be freely suspended outside the enclosed building envelope, serving as a rain screen and protecting other layers such as the insulation or the water barrier from the elements. Better control of clay bodies reduced the risk of fractures that occasionally plagued earlier terra cotta facade ornamentation. Engineering analysis advanced sufficiently to model the connections and design them safely. Production methods evolved with the refinement of machines such as extruders used initially for brick production,

9

Following Renzo Piano's earlier residential projects in Paris, France, the IRCAM studio was the architect's first implementation of a ceramic rain screen for a public building in a prominent location in the historic center of the city.

adding enough control to transform a production model still based on craftspeople handling relatively wet clay mixtures in molds to one that relied on high-volume manufacturing techniques such as extrusion and dry-pressing.

With these developments ceramic systems finally came into their own. In Germany, Thomas Herzog at the TU Munich developed a first ceramic ventilated facade jointly with fabricator Moeding. The first installation was executed on a project in Munich's Lohhof quarter in 1984. Renzo Piano continued the development of ventilated terra cotta facades on his projects in France. His office worked closely with manufacturers such as Giraud Frères in Southern France. The IRCAM studio, completed in 1990 near the Centre Georges Pompidou in Paris, was among his first projects (9). These collaborations between architects and producers created innovative construction solutions that are now widely applied, encouraging several manufacturers to focus on custom production and collaboration with architects as their core business model, a tradition that has enabled much of the most interesting and forward-looking work in architectural ceramics. Industrial tile manufacturers have continued to mass-produce tiles based on market research, and this segment represents the bulk of the production volume. Tile customization through inkjet printing is now entering even these industrial companies, linking them closer to the end-user than ever before.

The present manufacturing culture in the ceramics industry continues to be dominated by the duality of relatively few and small craft-based firms and the many highly industrialized tile companies. This book does not favor either, but raises awareness of different production cultures along with their specific abilities and constraints. A small number of companies specialize in producing facade elements and most are geared to working with architects, engineers, and facade consultants to design and ultimately manufacture custom elements. Some industrially produced varieties continue the tradition of disguise by displaying a myriad of surface effects, from photorealistic representations of wood or stone to actual images or text. The aesthetics of ceramics have become widely appreciated for building envelopes, allowing contemporary modes of expression even in a realm otherwise dominated by brick construction.

NOTES

1 Oldfather, W. "A Note of the Etymology of the word 'Ceramic'". *Journal of the American Ceramic Society*. Vol. 3, Issue 7, July 1920. pp. 537 – 542.

2 The durability of ceramics did not only serve its early users well, it also preserved these artifacts over thousands of years, helping today's historians to better understand ancient cultures.

3 Other early ceramic objects date back to around 7,000 BC in the Near East and the Middle East. Chinese pottery can be traced back to 6000 BC.

4 The earliest evidence of using unfired clay bricks is the use of adobe clay bricks in Jordan around the 9th century BC. It is interesting to note that the use of fired ceramic pottery was widespread long before that, but entered construction culture relatively late in Sumeria (in today's Iran) around the 4th century BC. Fuel was expensive, and might have included a mix of camel dung and plant materials, limiting the use of the fired clay bricks on the exterior wall surfaces where they provided a durable surface layer.

5 The gate has been reconstructed in the Pergamon Museum in Berlin, Germany.

CHAPTER 3

MATERIALS AND MATERIAL PROPERTIES

The properties of ceramic materials enable a variety of architectural applications. Hardness, density, durability, ability to take on a wide range of finish appearances, and other properties have facilitated the application of ceramics in buildings throughout the world for centuries. Brittleness and lack of tensile strength are disadvantages that need to be compensated for with appropriate part and system design strategies. Clay-based ceramics have unique regional material characteristics that vary based on the geological conditions in a given location over centuries (1). Modern architectural ceramics have highly tailored material properties that are determined by specific mixes of raw materials (clay bodies). Transformation from clay to ceramic occurs during the sintering or firing process, and in some cases the material is vitrified, resulting in a non-porous homogenous product. Material properties should be discussed as they change between unfired stages (clay), fired stages (ceramic), and finished stages (glazed, etc.). The following chapter details each of these phases leading to an in-depth look at forming processes in Chapter 4.

1

Raw clay materials at a Ugandan ceramic production facility.

Clay

“Clay” is a broad term describing a family of naturally occurring materials that have unique compositional and material properties and when fired become ceramic. Clay is abundantly available across the globe, primarily composed of alumina, silica, and water (Al_2O_3 +$2SiO_2$ +$2H_2O$), and formed naturally over geological time periods through the decomposition of igneous rocks, especially granite, into feldspar through weathering and chemical action. Combined with a chemical hydration process, the decomposition of feldspar into alumina and silica along with other minerals results in clay, both residual clay (primary clay) as well as sedimentary clay (secondary clay). Residual clay remains in the site of the original feldspar and is often the purer and more rare of the two types. The more common sedimentary clay is typically more plastic and forms the basis for the vast majority of current architectural ceramics production. Wind, water, and glacial forces can transport sedimentary clays from their origin. During this process clays often become contaminated with additional minerals and organic compounds, giving clays from different geologic regions unique characteristics (2).

Clay Bodies

Over time, first craftspeople and later chemists and material scientists developed highly specialized knowledge that today allows for the design of “clay bodies”—blends of different clays and additives—in response to project-specific needs. When combined with firing techniques that regulate temperature profiles over time, the resulting ceramic materials are highly customizable, with significant variations in density, porosity, strength, and thermal properties.

Today, the design and production of clay bodies is a specialized field combining chemistry with process engineering. Clay bodies are critical to the performance of the resulting ceramic elements, and their design requires deep knowledge of the materials as well as the production processes. Given the complexity of the issue, this part of the design process, while based on the performance specifications provided by the design team, is designated entirely to the producer. Many producers have material scientists, chemists, or ceramic engineers on staff that customize clay bodies and the related firing strategies and also coordinate the many glaze finishes.

Most clay bodies for architectural ceramics are earthenware and stoneware—both sedimentary clay types—as well as porcelain. These terms, used in common language to reference pottery, here designate technical expressions of the blends of clays and additives (3). Further distinctions are made based on the nuanced compositions within each type of clay. Earthenware, including terra cotta, is a common low-fire clay body well-known from flowerpots and often used for roof tiles, thick tiles, and bricks or larger facade elements. Particle size in the earthenware clay bodies tends to remain relatively large. Stoneware is commonly used for architectural tile applications as well as for facade elements. It consists of finer granules, exhibits better mechanical properties, and is less porous. Glazed water pipes for urban water systems are commonly produced in stoneware. Porcelain is a white kaolinite body, fired at the highest temperatures, and usually fully vitrified to make for very low water absorption even without a glaze finish. Any of these basic clay bodies can be prepared as near-liquid casting slip by adding deflocculants. These are typically sodium silicates used to dispel the electrical attraction between the clay particles, thereby keeping the clay in a liquid, low-viscosity state. Casting slips are used in the molding of geometrically complex, often hollow, parts. Toilets and sinks are typical products manufactured using slips (see Chapter 4 for process details).

2

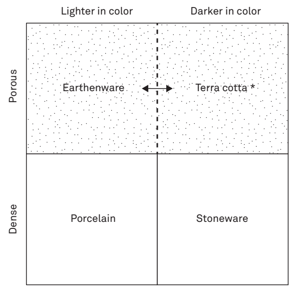


Diagram of common earthenware, stoneware, and porcelain clay body compositions.[1]

** Terra cotta is often considered an earthenware and the term is typically used to refer to all reddish and brown porous ceramics in architectural applications.*

3

Typical Earthenware compositions	Sample Clay body compositions (A–E)*				
	A	B	C	D	E
Common red clay	30	▨	25	▨	▨
Stoneware clay	25	▨	35	▨	▨
Red clay	▨	75	▨	▨	▨
Ball clay	25	15	20	20	20
Kaolin	▨	▨	▨	30	35
Fire clay	10	10	▨	▨	▨
Flint	10	▨	10	10	20
Nepheline syenite	▨	▨	10	30	10
Talc	▨	▨	▨	10	15

Typical Stoneware compositions	Sample Clay body compositions (A–E)*				
	A	B	C	D	E
Stoneware clay	80	75	40	30	▨
Sagger clay	▨	▨	20	▨	▨
Ball clay	10	15	20	30	30
Kaolin	▨	▨	▨	▨	40
Red clay	▨	▨	▨	10	5
Feldspar	10	10	10	▨	15
Flint	▨	▨	10	▨	10
Fire clay	▨	▨	▨	30	▨

Typical Porcelain compositions	Sample Clay body compositions (A–E)*				
	A	B	C	D	E
Georgia kaolin	35	25	25	5	30
Florida kaolin	10	15	▨	40	15
English ball clay	5	10	25	▨	15
Kentucky ball clay	▨	▨	▨	10	▨
Feldspar	30	30	25	▨	20
Nepheline syenite	▨	▨	▨	25	▨
Flint	20	20	25	20	20

**Parts per one hundred*

Chart summarizing common base clay compositions.[2]

4

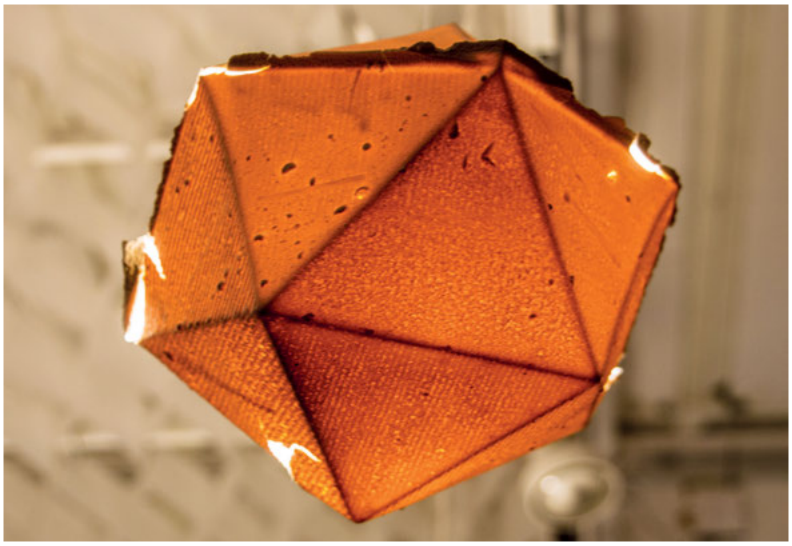
Automated clay body preparation in a high-volume production system.

The distinction between different clay bodies can be complicated, as the specific terminology differs to some degree according to the context in which the material is described. Material composition, part performance, density, plasticity, color, and firing range are all considered when distinguishing materials in their contexts. In the architectural discourse, particularly in historical contexts, the term terra cotta is often used to describe all architectural ceramics regardless of clay body, material performance, and other distinguishing characteristics. Often, color alone is mistakenly used to identify specific clay bodies, and it is common for all red or brown clay bodies to be considered terra cotta once fired, and all white clay bodies to be identified as porcelain. Color, however, is not a good indicator of clay type—white stoneware, for example, is quite common but should not be confused with porcelain. In the context of contemporary architectural ceramics the distinction is even more difficult, as additives and coatings can effectively disguise the appearance of the underlying part. Adding coloring agents can give the clay body almost any appearance, blurring any direct relationship to the base material (4).

Maybe the most useful parameter for discussing clay bodies is the density and related porosity of the fired component (see also introduction to Chapter 10). Earthenware is less dense than stoneware, which in turn is less dense than porcelain. Density relates to the amount of water that can be absorbed by a fired part and therefore determines the absorption range of the unglazed ceramic element—the less dense the body the higher the absorption rate and the greater the porosity. Most low-density clays, when fired to maturity, do not vitrify and therefore are always permeable by water whereas clays of higher density can become vitreous and resistant to water infiltration. Water absorption in turn determines the resistance to freeze-thaw cycles.

The ceramics industry today has a wide and growing set of additives at its disposal that can be incorporated into the clay body for a variety of reasons. This includes recycled ceramics, glass, or stone dust as discussed in Chapter 7. Many performance characteristics can be addressed by combining the appropriate clay body—typically a mix of clays, fluxes, and silica—with additives. Some additives improve material behavior during processing, particularly in craft and low-volume settings. The addition of nylon fibers, for example, increases the “green strength” of the dried clay before firing, thus facilitating the handling of delicate unfired elements. These fibers have little impact on the properties of the finished part because they burn away during firing. Other additives are specifically designed to affect the properties of the end product. Kyanite, for example, reduces thermal stress and increases mechanical strength in the finished product. Reinforcements such as basalt fibers or high-temperature steel fibers are being investigated, but have not yet reached commercial maturity.

5



The results of differential shrinkage and part geometry. Here, forces concentrated at the corners of the part lead to undesirable results.

Shrinkage

Once the clay body has been formed into an element, it dries to the “green state”—either naturally or through machine-based, more controlled drying processes. During drying and subsequent firing, shrinkage occurs as moisture is removed. From a design perspective, it is important to understand the relationship of clay body to shrinkage. Raw material properties such as particle size and moisture content impact shrinkage rates: the smaller the particle size and greater the moisture content the higher the shrinkage rate. All clay shrinks, but while this may be straightforward when considering flat parts where simple oversizing can compensate for dimensional change, formally complex parts can be problematic. A deeply curved part dried on a convex mold, for example, may be more susceptible to cracking, while drying the same part on a concave mold may result in a successful part (5).

Shrinkage rates vary between clay bodies from approximately 8–12%. Two stages of shrinkage can be distinguished. First, approximately half of the overall shrinkage occurs during drying when moisture evaporates from the surface, drying the clay from the outside in. Water moves from the center out through capillary action. This causes “differential shrinkage”, which can result in warping and even cracking as outer surfaces dry faster than the core material. Drying can be highly controlled, often using specialized equipment, and by ensuring that all sides of the part dry uniformly by supporting the parts in a way that avoids warping and sagging.

Additional shrinkage, typically 50% of the overall rate, occurs during firing when particles are sintered or bonded together and all remaining chemical moisture is released from the clay body. Shrinkage during firing impacts all clays and clay bodies but tends to be much less in dry-processed parts compared to plastic-processed parts, again due to initial moisture content and particle size. Deformation or warping is also possible during firing and is typically accounted for in part design (explored in the case studies later in this book), kiln positioning, and the use of removable support structures that hold cantilevering or unsupported areas (6).

6

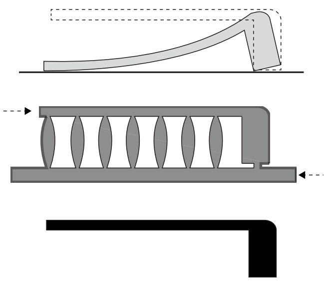


Diagram of geometric features of an extruded stair tread designed to minimize potential failures and deformation during production.

The most common method of addressing shrinkage is to scale up parts to match final desired dimensions. It is often possible to dimensionally rectify parts after firing (by grinding, cutting, etc.), but there are costs involved in this additional step. Today’s material and fabrication knowledge allows for fairly precise dimensions, yet tolerances remain and have to be considered in the detailed design for production phase when design teams need to work in close consultation with producers. Each production process inevitably comes with its own constraints and rules (see Chapter 4).

Properties of Ceramic Parts

Generally, ceramic parts are brittle, have a relatively high compressive strength, and behave poorly under tension. Bending strengths range between 7 MPa and 30 MPa for typical tiles to 120 MPa for high-end porcelain sinks. Typically, clay bodies fired at higher temperatures, up to 1,300°C, exhibit increased strength compared to those fired at temperatures as low as 1,000°C. Terra cotta, for example, does not exhibit the structural properties of porcelain. In most cases, the desired finished part properties drive the design of the clay body, but in others a clay body is chosen for its behavior during processing and part properties are manipulated during firing. Some producers might use a consistent stoneware clay body for their entire production but vary firing temperatures and firing sequence in order to control the strength or porosity of the ensuing product.

Brittleness and vulnerability to crack propagation should be considered in part design and assembly detailing. Designers should avoid creating areas of high stress concentration, which include drastic changes in wall thickness, sharp edges, openings, localized fasteners (particularly those requiring perforations), acute corners, and non-filleted intersections.

Vitrification becomes a critical consideration when determining finished part properties. A ceramic element that has been vitrified can resist moisture infiltration and therefore typically performs better in climates that undergo regular freeze-thaw cycles. When a part is not fully vitrified it remains porous, which can lead to spalling when internal moisture expands during freezing. Porosity, on the other hand, can be highly beneficial for applications that depend on moisture absorption, for example, when ceramic elements are used as evaporative cooling systems.

Glazes

Glaze is the primary material used to finish architectural ceramic elements, seal the surface to reduce wear, resist stains and dirt, and improve impact resistance. The design of glazes is a technical activity at all volumes of production (e.g., craft-based and industrial), usually balancing aesthetics and a variety of performance goals (7). Some artisans and chemists at industrial manufacturers develop proprietary glazes or glaze techniques beyond what glaze suppliers offer (8).

Glazes are glass finishes primarily composed of alumina, silica, and a mix of oxide fluxes such as soda, potassium, and lime/calcium that reduce the overall melting points of the silica and alumina. Alumina, derived from clay and feldspar, increases the viscosity of the glaze and thus keeps it from running off the part as it fuses to the ceramic element during firing. Silica, the glass-forming component in glazes, primarily comes from flint. Most glazes also contain additional oxide fluxes that are used to modify the melting temperature of the glaze and control the coefficient of expansion (COE) of the glaze composition. Different from glass, which is typically mixed and formed into pellets, rods, and other stock shapes for later use in the production of glass products, glaze is applied to the ceramic surface as a mixture of liquid raw materials, and fused in place during firing.

7

Industrially produced ceramic elements are commonly differentiated with unique, often manually applied, glaze decorations. This strategy increases the value of manufacturing tooling by increasing variety in a single element typology.

8

Coloring oxide combinations		Resulting color
IRON +	Cobalt	*grey-blue*
	Copper	*warm green, metallic green, black*
	Manganese	*brown*
	Vanadium	*ochre*
	Rutile	*ochre, brown*
	Nickel	*brown to grey*
	Chrome	*blackish green*
COPPER +	Cobalt	*blue-green*
	Manganese	*brown, black*
	Vanadium	*yellow-green*
	Rutile	*warm or textured green*
	Nickel	*grey-green*
	Chrome	*green*
MANGANESE +	Vanadium	*yellow-brown*
	Nickel	*grey or brown*
	Rutile	*brown*
	Cobalt	*blue-purple*
	Chrome	*brown*
NICKEL +	Vanadium	*grey, brown*
	Rutile	*brown*
	Cobalt	*blue-purple*
	Chrome	*brown*
COBALT +	Vanadium	*greyed yellow or mustard*
	Rutile	*textured warm blue or grey-blue*
	Chrome	*blue-green*
RUTILE +	Vanadium	*ochre, yellow*
	Chrome	*warm green*
CHROME +	Vanadium	*yellow-green*

Chart showing basic glaze compositions relative to color.[3]

Glaze compatibility becomes a critical factor for ensuring that the COE of the glaze and ceramic base part are compatible. To ensure a durable bond, both must behave in a similar manner during heating and cooling. This is particularly important for roof tiles that are subject to extreme temperature fluctuations.

Glazes have long been used to provide surface coloring. The complexity of glaze chemistry is exacerbated when color is considered. Color is typically created by the addition of oxides into the transparent glaze mixture. Multiple oxides are often mixed to create particular colors, and while only a limited number of oxides are used in glazing the range of colors is almost endless. Iron oxide is a common coloring agent, but is also regarded as an impurity in products where the desired outcome is white—sanitary ware for example. Environmental conditions (temperature, relative humidity, etc.) and process parameters (firing technique, kiln schedule, etc.), along with the composition of the clay body, have potentially dramatic effects on the color of the fired ceramic pieces (9).