(Pre)casting Architectural Concrete: Search for a Design Guide for Techniques, Resources, and Advancements of Architectural Precast Concrete

Dana K. Gulling[1][000-0001-5554-4505], **Gregory Lucier**[1][0000-0002-6648-9596]

[1]North Carolina State University, Raleigh, United States

ABSTRACT: The integration of computer-aided design (CAD) and computer-aided manufacturing (CAM) has revolutionized the fabrication of custom architectural components, particularly in the realm of custom architectural precast concrete. This paper delves into the multifaceted world of architectural precast concrete, by doing three things. First, it identifies the manufacturing variables for architectural precast. These include but are not limited to mix design, manufacturing processes, shipping and erection considerations, mold materials and configurations, and the role of CNC equipment in mold making. Second, it lists case studies of prominent architecture projects that make notable use of architectural precast concrete. The case studies include the Perot Museum of Nature and Science, Museum of Civilizations of Europe and the Mediterranean (MuCEM), and The Broad. Third, this paper provides a narrative-style literature review of book publications that feature architectural precast. The goal of this paper is to create the framework for a published guide for architects that demonstrates what is possible when designing with architectural precast. With over 175 examples gathered from various sources spanning the last two decades, this paper offers a comprehensive overview of the design and fabrication of custom architectural precast concrete elements.

KEYWORDS: architectural precast, concrete, custom

INTRODUCTION

The processes of computer-aided design (CAD) and computer-aided manufacturing (CAM) have allowed for the design and fabrication of complex surface articulations for buildings. The combination of computer numeric controlled (CNC) equipment's capabilities and architects' desire to design unique buildings, has led to contemporary projects with bespoke cladding elements, which requires architects to collaborate with industry leaders for the design and fabrication of custom components. The precast concrete industry, particularly those that produce architectural precast, have responded to this challenge by developing processes to produce custom precast elements.

Precast concrete is manufactured at off-site facilities and delivered, typically by truck, to the building site. Precast elements are structural, architectural, or a combination of both. Structural precast elements—such as double tees, beams, and columns—are primarily used for the building's vertical or lateral loads. Since these members are principally designed to fulfill a structural role, their surfaces may not be pristine and may be pitted by small air pockets or bug holes. In contrast, architectural precast's primary role is as the cladding or enclosure system for a building, and its surface quality is significantly better than that of structural precast. When forming architectural precast, manufacturers minimize bug holes and architects often specify concrete surfaces with specialty aggregates, integral color, and post-production finishing (e.g. sand blasting, acid washing, or polishing). Sometimes precast elements may be both structural and architectural, supporting the building loads while having the surface quality required for architectural precast.

Architectural precast manufacturers can accommodate different types of concrete (e.g. traditional, Portland cement-based concrete versus ultra-high performance concrete (UHPC)) with custom molds, specifically built by the precast manufacturer for a particular project. For architectural precast elements, the design and fabrication team consider the manufacturing process, transportation limitations, joints between panels, mold materials (e.g. wood, steel, rubber) and fabrication (e.g. CNC-milled versus hand-built), mold durability and costs, mold configuration (e.g. tessellated modules versus interchangeable plugs), and erection costs and methods.

This paper seeks to do three things. First, it establishes and provides an overview of the variables associated with precast concrete. Second, it provides a list of notable architectural projects that have prominent use of custom architectural precast to serve as case studies. Our examples are limited to those that have been completed in the last twenty years and includes the Perot Museum of Nature and Science by Morphosis, Museum of Civilizations of Europe and the Mediterranean (MuCEM) by Rudy Ricciotti, and The Broad by Diller Scofidio and Renfro. See Figure 1. Third, we provide a narrative-style literature review of existing book publications on precast concrete, particularly focusing on books that appeal to architects and building designers.

Figure 1: Selected precast projects. From left to right, Perot Museum of Nature and Science, with traditional architectural precast concrete; Museum of Civilizations of Europe and the Mediterranean (MuCEM), with ultra-high performance concrete (UHPC); The Broad, with glass-fiber reinforced concrete. Sources (from left to right): (Cutrer 2017, Harald 2013, Author 2016)

1.0 PRECAST VARIABLES

1.1 Materials

A typical precast concrete mix includes cement, large and small aggregates, water, and relatively small amounts of additives, admixtures, and air. Within a typical architectural precast mix, the designer can specify grey or white Portland cement, specific aggregates to meet performance or aesthetic standards, and additives and admixtures to decrease required water or cement, alter color, or improve durability and performance. Engineers will require that the precast concrete be reinforced; typically, this includes reinforcing steel and welded wire reinforcement (WWR) but can also include prestressing strands—either pre- or post-tensioned. Other specialized concrete mixes include fiber reinforced concrete (FRC), typically with alkali-resistant glass fibers; UHPC, which uses fine aggregates and steel or glass fiber reinforcing; and polymer concrete, which uses thermoset plastic as the binder rather than Portland cement.

Architectural precast can be made into composite panels that may use two different concrete mixes or may have other materials (e.g. brick, ceramic tile) in the finish surface. If the composite has two concrete mixes, often the more expensive white cement-based concrete will be used for the panel's exterior with a less expensive grey cement-based concrete as the backing material. The two concrete wythes may be bonded to one another through chemical and mechanical bonding, or they may be separated by solid insulation that provides a thermal break between the concrete wythes. If the panels have a thin facing brick, then the bricks are set into a form liner that holds the bricks during casting and provides a profiled shape to the concrete between the bricks that mimics tooled mortar.

1.2 Manufacturing processes

Typically, architectural precast is manufactured by placing a wet concrete mixture into a mold and using gravity and vibration so that the concrete fully fills the mold cavity. Other types of precast manufacturing include centrifugal or spin casting, which spins a hollow, cylindrical-shaped mold filled with concrete at high speeds, using centrifugal force to compact the concrete against the mold; and contact molding, which applies layers of FRC against a mold to create a shell-like component. Generally, a given architectural precast producer does not have the capacity to use all three manufacturing processes.

1.3 Shipping and erection

In nearly all cases, practical limitations related to shipping and erection constrain the physical sizes and maximum weights of precast concrete elements, especially if elements must be transported by truck. Exact limits on size and weight for shipping vary by locality, route, available equipment, and jobsite. Elements measuring up to 12 ft by 40 ft and weighing 20 tons or more are relatively common, with larger and heavier elements possible. Smaller elements can be common, particularly on jobsites that are congested or must be serviced with lower capacity handling equipment such as tower cranes. During the initial phases of architectural design, the precaster, engineer, and contractor can help optimize designs for shipping and installation.

1.4 Mold materials

Architectural precast molds can be made of a range of materials, each affecting its cost, durability, life span, tolerances, panel design, desired finish, and fabrication methods. Generally, as a mold material's cost increases so does its durability and its life span. Architectural precast may be formed on foam, thermoplastic, wood (including plywood, medium-density fiberboard (MDF), etc.), glass fiber reinforced plastic (GFRP), cast elastomeric or rubber, carbon fiber reinforced plastic (CFRP), aluminum, or steel. Foam is the least durable mold material and lasts for only 1-3 castings, or pulls, while steel is the most durable, lasting for 200 pulls or more. Plastic and wood molds tend to warp over multiple castings due to the concrete's moisture and heat of hydration, and they are dimensionally unstable with long-term temperature and humidity changes, thus impacting how long the mold can be stored. The panel design is impacted by the mold material. For example, foam requires large draft angles to demold the concrete without damaging the foam surface, while rubber is flexible and can accommodate steep or even negative drafts. If the precast is left as-cast, meaning no post-production finishing is done, then the mold material impacts the concrete's surface. Wood can leave its grain on the concrete surface, while epoxy-coated wood and foam leave a matt finish. Rubber can leave an egg-shell finish on the concrete surface, while polished steel and gel-coated GFRP molds can leave a satin or semi-gloss finish on the concrete surface. Some mold materials like foam can be fabricated by CNC equipment; while thermoformed plastic, GFRP, and rubber are a two-step process that requires the mold to be formed on a master mold.

1.5 Mold configurations

Typical architectural precast molds are open, horizontally oriented, and the precast's best face is cast finish-side-down against the mold. Alternatively, molds can be semi-closed or closed with only a small opening to pour the concrete. Closed precast molds may be cast in horizontal, vertical, or inclined orientations, and the orientation will affect the component's finished surface. For wet casting, molds need to be caulked at all joints to keep the cement paste out of the joint, which damages the mold or casting when demolding. Precast molds are either envelope molds, which are five-sided molds in which the mold sides are left intact during demolding, or they are built-up molds, in which one or more mold sides are removed for demolding. Built-up molds require caulking at the mold edges, thus increasing mold set-up times; however, envelope molds require draft angles at the edges and cause additional wear on mold surfaces.

Molds can represent a large cost in the production of architectural precast (*Architectural Precast Concrete*, 2007). To reduce costs, producers want to reuse molds as many times as possible so that mold costs are amortized over the number of units produced. Often this is at odds with an architects' desire to minimize repeated elements. Architectural precast molds are sophisticatedly configured to address this balance. Molds may have tessellated or modular components, or be made with elements, inserts, or plugs that can be moved, eliminated, or flipped between pours to create individual panel designs. Examples include the rubber modular mold components for the Perot Museum that were reorganized and the window forms for One South First's window forms that were rearranged and flipped 180º between castings. For some projects, such as the MuCEM, the screen UHPC panels were cast vertically in closed, two-sided mold that allowed the panels to be placed on the building in four different orientations—original, turned upside down, flipped backwards, or flipped backwards and turned upside down. See Figure 2.

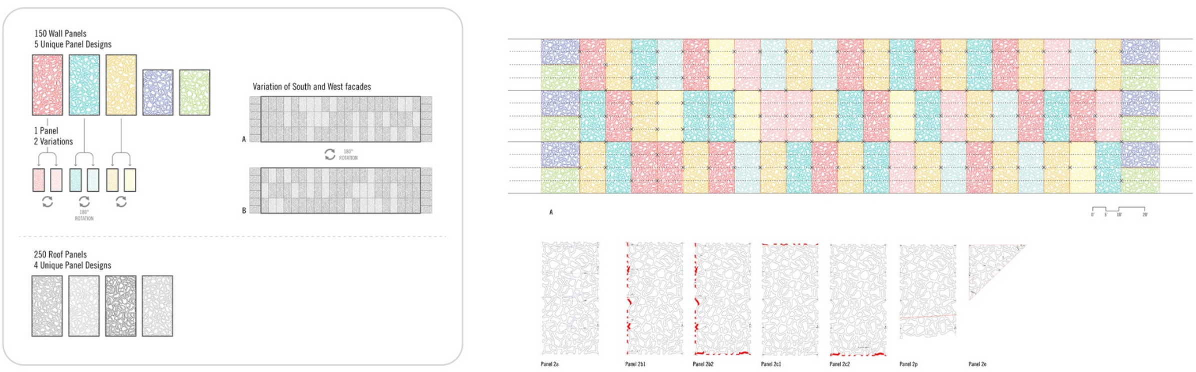

Figure 2: How the two-sided, UHPC screen panels are distributed, flipped, and rotated on the MuCEM. Source: (Lawing and Layman 2020)

1.6 CNC equipment

Precasters use CNC equipment to fabricate architectural precast molds. Directly, CNC millers and hot wire foam cutters can fabricate foam molds. Collaborative research between Oak Ridge National Laboratories (ORNL) and PCI investigated using the potential to use large-scaled 3D printing to fabricate molds. For One South First, Gate Precast used 3D printed CFRP molds; after printing, the molds were milled smooth by a five-axis CNC-miller, and the concrete was cast directly on the molds' surface to form window openings. Indirectly, CNC equipment may fabricate master molds from foam, MDF, or plaster and then the masters are used to fabricate precast molds from contact-molded GFRP, thermoformed plastic, or cast rubber.

2.0 CASE STUDIES

2.1. Overview

Through on-going research, we have gathered over 175 examples of notable custom architectural precast projects that have been completed in the last twenty years (2004-2024). See Table 1. We have identified our case studies through architectural print magazines (e.g. *Architect*, *Architectural Record*), architecture books (e.g. *Detail in Contemporary Concrete Architecture*, *Modern Concrete Construction Manual*), architecture and design-based websites (e.g. *ArchDaily*, *Dezeen*), industry organization design awards (e.g. PCI Design Awards), producer websites (e.g. Gate Precast, Lafarge), and architecture firm websites. To qualify, the building must be notable in its design, have custom architectural precast elements, and its custom molds must have been used for more than one casting.[1]

Table 1 is an excerpted list of our collected case studies, organized in alphabetical order by architecture firm and includes any known, notable precast variables, such as concrete mix design, manufacturing processes, and mold configurations.

Table 1: Case study list of architectural precast examples. Source: (Authors 2024)

Architect Firm	Building Name	Year	Notable Precast Variables
ACME	*Sächsische AufbauBank (SAB)*	2021	Centrifugal Casting. Steel mold.
ACME	*Victoria Gate Arcades*	2016	Concrete and brick composite panel
Adjaye Associates	*Sugar Hill Development Broadway Housing Communities*	2014	Rubber, photo engrained form liner. Window molds moved between casting to increase panel variety.
ALA Architects	*Kuopio City Theater*	2014	GFRC. Spray applied.
Alloy LLC	*Dumbo Townhouses*	2015	UHPC
AND	*Melting House*	2022	UHPC
Antistatics Architecture	*Wenzhou Ou-river Cystal Boxes Restaurant*	2020	UHPC. Cast in closed, rubber mold.
Architecture Studio	*Al Nahr*	2021	UHPC
AREP	*Lorient-Bretagne Sud Railway Station*	2017	UHPC
Arquitectura Nacional	*Casa Ventura*	2020	GFRC. Spray applied.
AUM architecture	*Cepovett Headquarters*	2018	UHPC
AUM architecture	*House under the Cliff*	2019	UHPC
Baier Bischofberger Architects	*Galerie Bruno Bischofberger: Pappardellehalle*	2013	Stainless steel reinforcing steel used when concrete coverage was not adequate to protect from corrosion. Closed, steel mold.
Baier Bischofberger Architects	*Galerie Bruno Bischofberger: Wellenhalle*	2013	Steel mold.
Belzberg Architects Group	*Apertures*	2022	Polymer-based concrete. Cast in a closed, steel mold.
BLACKhome	*YUE Art Gallery*	2018	UHPC
BNIM	*Tenth and Wyandotte Parking Garage*	2015	Steel mold with two-part rubber inserts. Inserts would be rearranged between pours to increase panel variety.
C.F. Moller Architects	*Danish Meat Research Institute*	2014	Concrete and brick composite panel
C.F. Moller Architects	*Technical Faculty University Southern Denmark*	2015	UHPC
Claudio Vilarinho	*Institute of Science and Innovation for Bio-Sustainability*	2015	GFRC. Spray applied.
COOKFOX Architects	*One South First*	2018	3D-printed, CFRP molds and built-up plywood molds to form window profiles. Window molds moved and flipped between casting to increase panel variety.
Dick van Gameren Architecten	*Block A Noordstrook*	2009	Concrete and brick composite panel
Diller Scofidio + Renfro	*The Broad*	2015	GFRC. Spray applied. Three different molds used (foam, gel-coated foam, GFRC), depending on durability needs.
Durisch + Nolli Architetti	*Federal Criminal Court*	2013	GFRC. Spray applied.
ECDM	*Day Nursery Rue Pierre Budin*	2012	UHPC
Ecker Architeckten	*Forum Eckenberg Academy*	2013	Centrifugal Casting.
Elenberg Fraser	*33 Mackenzie Street*	2013	Cast in a steel mold. Painted for final finish.
EM2N	*Extension Herdern Railway Service Facility*	2013	GFRC. Spray applied.

Empresa de Desarrollo Urbano	*EDU Headquarters*	2017	Wet cast GFRC
Estudio Arqtipo	*GU 2787*	2016	Lightweight concrete mix design
Estudio Arqtipo	*MA 3706*	2016	Lightweight concrete mix design
FCJZ atelier	*Concrete Vessel*	2018	GFRC
Foster + Partners	*Masdar Institute*	2010	GFRC
Franz&Sue	*Collections and Research Center of the Tyrolean State Museum*	2017	GFRC. Spray applied.
Gustau Gili Galfetti	*School Rossend Montane*	2011	Polymer-based concrete
Heatherwick Studio	*Little Island Park*	2021	Foam mold
Hild und K Architekten	*Hotel Werk*	2020	Concrete and brick composite panel.
Hild und K Architekten	*S40 Schwabinger Tor*	2017	Concrete and brick composite panel. Strips of rubber mold formliners to hold bricks and laid on plywood mold.
Hiroshi Nakamura & NAP Co, Ltd.	*Radiator House*	2016	Wet cast GFRC. Cast on rubber mold. Rubber mold cast against CNC-milled plaster master mold. Precaster applied non-stick, fluorocarbon polymer coating to repel water and dirt stains.
Huttunen-Lipasti-Pakkanen Arkkitehdit	*Lansisatamankatu 23*	2014	Wet cast GFRC
ikon.5	*Health and Wellness Center for Suffolk County Community College*	2019	Plywood mold with wood and plastic to form reveals. Mold sides are adjustable to produce different widths for variety.
Inrestudio	Kaleidoscope Office and Residence	2022	GFRC. Spray applied.
Johnston Davidson Architecture	*Lewis Estates Fire Hall*	2015	UHPC
K2S Architects	*Fazer Headquarters*	2016	Polymer-based concrete
Kapadia Associates	*BAPS Swaminarayan Girls Residence School*	2016	GFRC. Spray applied.
Kengo Kuma & Associates	*V+A Dundee*	2018	Steel molds that are angled between pours to create cross-sectional variety. Mold ends are dammed to create different lengths. Concrete retarder used to expose aggregate.
Kevin Daly Architects	*UCLA Ostin Basketball Center*	2017	GFRC. Spray applied.
Key Operation Inc/ Architects	*Kannai Blade Residence*	2021	UHPC
Kirsi Korhonen and Mika Penttinen Architects	*Lontoonkatu 9*	2013	GFRC. Spray applied.
KSP Jergen Engle Architeken	*Great Mosque*	2017	Centrifugal Cast with custom rubber formliner for decorative base.
Lake | Flato	*Confluence Park Pavillion*	2018	GFRP molds.
LMN Architects	*Global Center for Health Innovation*	2013	Foam master mold, dammed to form different rubber molds. Rubber molds ganged for larger panels.
Louis Paillard Architecte & Urbaniste	*229 Logements*	2017	Rubber molds.
Maki and Associates	*Aga Kahn Centre*	2018	UHPC
Manuelle Gautrand Architecture	*Lille Modern Art Museum*	2010	UHPC
Marc Mimram	*Gare TGV*	2017	UHPC
mecanoo	*Palace of Justice*	2017	GFRC. Spray applied.
Morphosis	*Perot Museum of Nature and Science*	2012	Rubber mold modules that can be rearranged to increase panel variety.
NBBJ Architects	*James F Battin Courthouse*	2012	Rubber molds.
NBBJ Architects	*Leonard J. Samia Academic Center*	2015	Wood molds.
Nemesi	*2015 Milan Exposition Italy Pavilion*	2015	Polystyrene molds.

Neri & Hu	*Aranya Art Center*	2019	GFRC.
Niall McLaughlin Architects	*Stratford Athletes' Village*	2012	Rubber molds with undercuts. Wood dams used to form smaller panels.
Nieto Sobejano Arquitectos	*Contemporary Art Center*	2013	GFRC with integrated foam core.
NOAHH	*Amare Home of the Performance Arts*	2021	Steel closed molds. Elements cast on incline angle to reduce bug holes.
OMA	*Lab City CentraleSupelec*	2017	Integrated color pigment.
Perkins+Will	*Florida International University Science Classroom Complex*	2013	Wood mold.
PROMONTORIO	*Embassy of Egypt*	2017	GFRC. Spray applied. Rubber mold.
ra15 a.s.	*Hotel Urban Crème Prague*	2019	GFRC. Spray applied.
Rafael Vinoly Architects	*277 Fifth Avenue*	2019	Integrated custom color pigment
Rivka Night	*The Gold Line Bridge*	2012	Composite concrete panel.
RKW Architektur	*Motel One*	2014	GFRC. Spray applied.
Rogers Partners	*Henderson-Hopkins Elementary School*	c.2015	Integrated color pigment
Rudy Ricciotti Architecte	*MuCEM*	2013	UHPC. Cast in closed, vertical mold.
Rudy Ricciotti Architecte	*Pavilion 52*	2018	UHPC
Rural Urban Framework	*Angdong Hospital Project*	2011	Rubber molds
SHoP Architects	*290 Mulberry Street*	2013	Concrete and brick composite panel. Rubber mold cast against CNC-milled master mold. Master mold dammed to create rubber mold varieties.
Silvio d'Ascia Architecture	*Kenitra Train Station*	2019	UHPC
SOM	*Chhatrapati Shivaji International Airport Terminal 2*	2014	GFRC. Spray applied.
Spridd	*Weave*	2018	
SR Arquitectos	*Alqueria Gourmet Market*	2019	Polymer-based concrete
studio kimiis	*Concord Park Pavilion & Trellis*	2019	UHPC
TF International	*Chinese Cultural Center of Belgrade*	2020	UHPC
THE_SYSTEM LAB	*Hannam-Dong HANDS Corporation Headquarters*	2014	Steel molds.
Thomas Phifer and Partners	*Glenstone Museum*	2018	Plywood molds.
Touzet Studio	*Nike Miami*	2017	UHPC
University of Southern California School of Architecture	*Carapace Pavilion*	2022	UHPC. Cast in closed mold. Upper mold half made from bent plywood. Lower mold half made from CNC-milled foam with GFRP outer layer. Mold was dammed and plugs for apertures were removed as needed to increase panel variety.
Urbanus	*Shum Yip UpperHills Loft*	2018	UHPC
Willmotte & Associes	*Le Verone*	2021	UHPC
WORK Architecture Company	*Kew Gardens Hills Library*	2017	GFRC with integrated color. Spray applied.
Zaha Hadid Architects	*One Thousand Museum Tower*	2019	GFRC. Spray applied.

3.0 AVAILABLE BOOK LITERATURE

Most of the books on precast concrete focus on structural precast and are good resources for civil and structural engineers; books include *Novel Precast Concrete Structural Systems* by Gang Wu et al., *PCI Design Handbook* by

PCI, and *Precast Concrete Structures* by Hubert Bachmann and Alfred Steinle. For this paper, we provide a narrative-style literature review of books that architects would use to learn about the possibilities of designing with architectural precast. Books are listed as they would appear in a bibliography.

3.1 *Architectural Precast Concrete*. 3rd ed. Chicago, IL: Precast/ Prestressed Concrete Institute, 2007.

This book is written by the PCI Architectural Precast Concrete Committee. PCI is the "technical institute and trade association for the precast, prestress concrete structures industry" in the United States (PCI, 2024). This book communicates what the industry would like architects to know about architectural precast concrete. The book covers an overview of architectural precast; design concepts related to use and economics; surface aesthetics that include mix design, design parameters, postproduction finishing, and weathering; structural design; construction documents and specification language; sustainability issues such as life-cycle analysis and building rating systems; and performance metrics such as thermal and blast resistances and acoustics. It does include basic design parameters based on the precast mold. This book does not include exemplary architectural projects, nor does it include the latest innovations regarding mold fabrication technologies (e.g. CNC equipment), mold configuration techniques (e.g. tessellated patterns), or closed vertical molds. Also, it does not include information about UHPC, FRC, or polymer concrete.

3.2 Bennett, David. *The Art of Precast Concrete: Colour Texture Expression*. Basel: Birkhäuser, 2005.

This book uses built case studies to provide information on architectural precast. The beginning gives an overview of architectural precast in northern Europe, including economics of use, manufacturing culture, and alternative precast mix designs (e.g. UHPC, GFRC). Each case study includes text, written by the architecture firm, about the project's architectural statement, and text by the project's precaster. The case studies include architectural drawings (e.g. plans, sections, and elevations); photographs of the completed building, precast elements, and details; and for most projects there are photographs of the precast's manufacturing and installation. The focus of the book appears to be on the case studies' mix design and post-production finishing. Most of the book's case studies use simple molds to form flat panels, with only a few that have highly articulated surfaces afforded by CNC equipment.

3.3 Cohen, Jean Louis and G. Martin Moeller, Jr., Ed. *Liquid Stone: New Architecture in Concrete*. New York: Princeton Architectural Press, 2006.

This book is the result of a 2004-2006 exhibition by the same name, presented at the National Building Museum in Washington, DC. The book begins with individual author-contributed architectural essays on concrete that position the material relative to architectural historic and theoretic frameworks. The remaining five-sixths of the book are dedicated to architectural examples of projects that celebrate concrete, curated around particular themes. The book refers to technical aspects of concrete only when necessary and presents technical details for only some of the projects. Most of the examples are of site-cast concrete, with only two being of precast concrete. Although the curated projects are compelling there is little technical information presented in this book that helps advance our understanding of the architectural implications of concrete.

3.4 Levitt, Maurice. *Precast Concrete: Materials, Manufacturing, Properties and Usage*. 2nd ed. London: Taylor & Francis, 2008.

This book is a good introductory resource for beginning civil and industrial engineers that will either work with precast concrete or in the precast concrete industry. Topics include in-depth information on ingredients, reinforcing and prestressing steel, hardware, molds, production control, manufacturing processes, curing, performance, quality control and quality assurance, and finishing. The chapter on molds focuses on the reusability and longevity of different molds, while secondarily discussing the mold material's impact on the precast surface. Like *Architectural Precast Concrete*, this book does not discuss mold innovations. There is limited information on fiber reinforced concrete and no information on UHPC or polymer concrete.

3.5 Peck, Martin and Christina McKenna ed. *Modern Concrete Construction Manual: Structural Design Material Properties, Sustainability.* Munich: Institute für Internationale Architektur-Dokumentation, 2014.

Part of a series published by *Detail*, the first two-thirds of this book provides an overview of concrete, design consideration criteria, CAD/ CAM fabrication methods, and performance metrics. The book distinguishes between site cast and precast concrete and discusses the benefits and differences of each. The last third of the book includes nineteen examples of completed buildings with short project statements, photographs of the completed project, and often architectural drawings (e.g. plans, sections), section and plan details, and construction and fabrication photographs. Although many of the examples are of precast concrete, most examples have flat panels with little articulation or innovation in manufacturing methods.

3.6 Phillips, David and Megumi Yamashita. *Detail in Contemporary Concrete Architecture*. London: Laurence King Publishing, 2017.

Part of a series published by Laurence King, this book presents contemporary case studies of buildings that make notable architectural use of concrete and includes both site and pre-cast casting methods. Organized by building type, each case study includes photographs of the completed building, architectural drawings (e.g. plans, sections), and technical details. Each case study includes the building title, location, client, architecture design team, structural engineer, and contractor, as well as a brief project overview. The book includes a CD of the book's vector files in .dwg format. The book makes little distinction of different concrete mixes, their properties, and casting methods.

CONCLUSION

CAD/CAM has allowed for the design and fabrication of custom components with geometric complexity and the architectural precast concrete industry has responded by developing techniques to produce panel variety while balancing the need to reuse molds. This paper presented typical precast variables that designers need to consider when working with architectural precast, a list of exemplary projects with notable architectural precast elements, and a narrative-style literature review of current book publications.

Our literature review focused on books that would appeal to architects and designers. In our review, some books provided inspiring examples and technical information about precast but included it with site-cast concrete as if the two materials are similar. We would argue that although both site-cast and precast concrete generally use the same raw materials, the variables associated with precast make it distinct from site-cast concrete. Some books were dedicated to precast concrete; however, those books do not include exemplary architectural projects or innovations in mold-making techniques. The current books on precast would not inspire architects and designers to consider architectural precast in their designs or push precasters to explore new manufacturing techniques. Our future goal of this research is to propose creating a guide for architects that demonstrates what is possible when designing with architectural precast.

ACKNOWLEDGEMENTS

Some of the case study information is a result of our PCI Foundation-supported studios.

REFERENCES

Bachmann, Hubert and Alfred Steinle. 2011. *Precast Concrete Structures*. Berlin: Ernst & Son.

Bennett, David. 2005. *The Art of Precast Concrete: Colour Texture Expression*. Basel: Birkhäuser.

Cohen, Jean Louis and G. Martin Moeller, Jr., eds. 2006. *Liquid Stone: New Architecture in Concrete*. New York: Princeton Architectural Press.

Cutrer, Jonathan. 2017. *Perot Museum of Nature and Science in Dallas, Texas.* Flickr.https://www.flickr.com/photos/joncutrer/ n.d.

Harald. 2020. *MuCEM*. Flickr. https://www.flickr.com/photos/haarald/ n.d.

Lawing, Brittany and Meredith Layman. 2020. "MuCEM: Museum of Civilizations of Europe and the Mediterranean." In *Creations in Concrete*. North Carolina State University ARC 503 Advanced Architecture Design Studio.

Levitt, Maurice. 2008. *Precast Concrete: Materials, Manufacturing, Properties and Usage*. 2nd ed. London: Taylor & Francis.

Phillips, David and Megumi Yamashita. 2017. *Detail in Contemporary Concrete Architecture*. London: Laurence King Publishing.

Precast/Prestressed Concrete Institute. 2007. *Architectural Precast Concrete.* Chigago, IL: Precast/Prestressed Concrete Institute.

Precast/Prestressed Concrete Institute. 2021. *PCI Design Handbook: Precast Prestressed Concrete.* Chigago, IL: Precast/Prestressed Concrete Institute.

Precast/Prestressed Concrete Institute. 2024. "About". https://www.pci.org/PCI/About n.d.

Winterstetter, Thomas, Mustafa Alkan, Radu Berger, Maiko Watanabe, Agatha Toth, and Werner Sobek. 2015. "Engineering Complex Geometries - the Heydar Aliyev Centre in Baku." *Steel Construction: Design and Research* 8 (1): 65-71

Wu, Gang et al. *Novel Precast Concrete Structure Systems*. 2023. Singapore: Springer Nature Singapore.

ENDNOTES

[1] We have chosen not to include architectural projects that rely heavily or fully on single use-molds. An example is Zaha Hadid's Heydar Aliyev Center, which uses single use plywood molds for each of its GFRC panels (Winterstetter, 2015).