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MyConcrete:
The Bulletin of the American Concrete Institute – Malaysia Chapter

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CONTENT

Page	Contents of Bulletin

NOTE FROM MEDIA HEAD

Greetings concrete enthusiast! We are proud to present you the latest issue of MyConcrete bulletin. On behalf of American Concrete Institute – Malaysia Chapter, we would like to thank all the support from our fellow members. On top of that, as the head of Media group, I would also like to personally highlight how much I appreciate the effort from the editorial team to provide us this monthly bulletin with such informative articles and event updates. Nonetheless, our bulletin will not be able to be shared if it is not for the article contribution from this month's writers. First of all, we like to show our gratitude to Mr. Lee Chiew Fook for providing us an industrial article regarding; "Substrate Preparation Procedure" which explains the Do's and Don't during the preparation. Subsequently, we also like to thank Mr. Abir Mahmood and Dr. Amrul Kaish for the technical report on "Cementitious Composites for Structural Strengthening". That broadens our horizon in what composite is available in the market that are able to be used in concrete. Furthermore, with the permission of America Concrete Institute International, we have also posted a case study article regarding "Structure of Biblical Proportions". In this article, the topic of high strength concrete is touched on for the world's tallest cathedral, Sagrada Familia. Apart from showing our gratitude to the writers, we must also thank our fellow sponsors for this month's successful sharing. Our premium sponsor of the month is STRUCTURAL REPAIRS (M) SDN.BHD. They have been contributing to Malaysia's concrete industry for over 35 years by repairing, and strengthening buildings in Malaysia. We understand is never an easy job for repair works but they have done it for such long period of time which has proven their contribution to Malaysia concrete society. Furthermore, our loyal sponsor this month is FOONG LET ENGINEERING SDN. BHD. They are concrete machine provider with mainly supplying to concrete flooring industry. Without such sponsorship, we will not have been able to launch and share another successful bulletin. To all members, we are continuously seeking for your sharing and contribution. Do contact our admin shall there be any enquiry. Once again, we like to sincerely thank all our contributors and also the media team together with the editorial team for another month of successful sharing. The pandemic is yet to be endemic. We also like to urge everyone to stay safe, follow the required S.O.P and bring our nation back on the right track. Together, we can.

Oscar Teng
Head of Media Committee

INTRODUCTION TO ACI MALAYSIA CHAPTER

American Concrete Institute - Malaysia Chapter (ACI-Malaysia) is a non-profit technical and educational society representing ACI Global in Malaysia, which is one of the world's leading authorities on concrete technology. Our members are not confined to just engineers; in fact, our invitation is extended to educators, architects, consultants, corporate, contractors, suppliers, and leading experts in concrete related field. The purpose of this Chapter is to further the chartered objectives for which the ACI was organized; to further education and technical practice, scientific investigation, and research by organizing the efforts of its members for a non-profit, public service in gathering, correlating, and disseminating information for the improvement of the design, construction, manufacture, use and maintenance of concrete products and structures. This Chapter is accordingly organized and shall be operated exclusively for educational and scientific purposes.

Objectives of ACI-Malaysia are:

- ACI is a non-profitable technical and educational society formed with the primary intention of providing more in-depth knowledge and information pertaining to the best possible usage of concrete.
- To be a leader and to be recognized as one of Malaysia's top societies specializing in the field of concrete technology by maintaining a high standard of professional and technical ability supported by committee members comprising of educators, professionals and experts.
- Willingness of each individual member/organization to continually share, train and impart his or her experience and knowledge acquired to the benefit of the public at large.

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NOTICE

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Important Notes:

i) ACI Malaysia is only a platform for our members to advertise for interns.

ii) All application to be made direct to companies and would be subject to their terms and conditions.

UP COMING EVENTS

Free Webinar - The Tech-Talk Hour

Speaker: Mr. Louis Tay / Ir Edward Han
Topic: BIM Application
Date: 28th October 2021
Time: 8:00pm - 9:00pm

Speaker: Mr. Martin David
Topic: Flatness Control To Concrete Floors Slabs
- With Reference To ACI-117-10
Date: 18th November 2021
Time: 8:00pm - 9:00pm

Speaker: Mr. Lim Kean Meng
Topic: Defects & Failures in Polymers Floors
Date: 9th December 2021
Time: 8:00pm - 9:00pm

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PRECEDING EVENTS

ARTICLE

Written by: Lee Chiew Fook
MAPEI Malaysia Sdn Bhd

SUBSTRATE PREPARATION PROCEDURES: WHAT AND WHY

Proper substrate preparation is the all-important first step for a durable installation, be it of adhered waterproofing, concrete repair works, industrial flooring, etc.

Different types of overlay materials may require different substrate preparation procedures. Installers are well-advised to read the manufacturer's datasheet to learn what is important for each application.

We are all familiar with the need for a clean substrate that is free from contaminants such as dirt, oil, and grease which affect adhesion. However, other, more specific actions may be necessary before the actual application can begin. This article looks at three of them and explains why they are important: (I) substrate pre-wetting, (II) treatment of corners, and (III) treatment of cracks.

I. Pre-wetting of substrates

Manufacturers typically recommend pre-wetting of cementitious substrates (e.g. concrete slabs, screeds, plasters) before applying cementitious material over-lays (e.g. repair mortars, waterproofing slurries, etc). There is a good reason for this.

Cementitious substrates are absorbent to varying degrees due to the presence of capillary pores in the matrix. This can be demonstrated by dropping water on a bare concrete surface. The droplets will shortly disappear, sometimes in a matter of seconds.

Cementitious overlay mortars are prepared for use by mixing powder formulations with water. The resulting hydration reaction creates the binder which (a) keeps the mass together and gives it body and mechanical strength, and (b) develops adhesion bond to the substrate.

However, porous surfaces are "thirsty"; they absorb water from the freshly-mixed mortar at the interface, leading to under-hydration of the cement where the bonding is expected to occur. This causes weak adhesion. The problem is prevented by pre-wetting the substrate to "saturated, surface-dry" (SSD) condition, which means all the capillary pores are filled and will no longer draw water from the applied material but the surface must be free from standing water.

Rightly, SSD conditions can only be assured by soaking the substrate and mopping up or sweeping away all excess water afterwards. If soaking is not practical, at the very least, hosing-down liberally is recommended. You can perform a simple test to check that pre-wetting is properly done by placing the palm of your hand on the substrate; it should feel damp without wetting your hand. Apply the overlay mortar immediately.

II. Treatment of corners

Stresses arising from movements in the supporting substrate are evenly distributed over an adhered waterproofing membrane which stretches across a plain, flat, and unbroken surface. However, discontinuities or changes in the surface profile - such as cracks, holes, and corners –lead to localised increases in the intensity of the stress. If the heightened stress exceeds the material's cohesive or tensile strength, the material fractures. On the other hand, if the bond strength (to the substrate) is low relative to its tensile strength, loss of adhesion happens.

Therefore, ways must be found to either (a) minimize these stress build-ups, or (b) reinforce the waterproofing membrane where there are discontinuities or changes in the substrate profile. For corners, this is done by:

a) Providing 25 mm x 25 mm fillets at internal corners to eliminate sharp bends and reduce the effect of stress concentrations. This is commonly done using a latex-admixed, cement/sand mortar which must be allowed to cure before the waterproofing membrane is applied.
b) Reinforcing the corner with an alkali-resistant, elastic, and waterproof band which has the required physical properties for handling the increased stresses and is designed to provide the waterproofing function.

External corners are ground smooth to a radius of at least 20 mm prior to installation of waterproofing membranes.

III. Treatment of cracks

(Note: The treatments described below refer to remedial actions for the purpose of making the substrate suitable for overlaying coating and finishing materials and not for restoring the integrity of concrete slabs which have suffered from structural cracks.)

Cracks are discontinuities in the substrate which result in localised peaks in the stresses imposed on fully-adhered membranes. Over time, they lead to accelerated fatigue and shortened service life of the membranes. Therefore, substrate preparation actions must be aimed at either removing these discontinuities or mitigating their effects.

With regard to cracks, waterproofing materials with elastic behaviour - measured in terms of dynamic crack-bridging capability (tested to recognised standards) – obviously perform better than non-elastics.

Nevertheless, good practice dictates that substrate preparations for installation of liquid-applied coatings and membranes must include crack treatments. Since cracks are common, especially in large roof slabs, the question may be asked: must all cracks be sealed?

As there are no standard guidelines on this, installers may follow the rule of sealing all visible, open-surface cracks. These are typically 0.2 mm or wider and the locations are easily identifiable by wetting the substrate. Small cracks can be sealed simply by brushing over with an epoxy resin of fluid consistency. Bonding of the membrane to surplus epoxy resin on the surface is improved by sprinkling sand on it while it is still fresh.

Wider, static cracks need to be opened up into V-grooves and then patched flush with the surface using an epoxy adhesive of pasty consistency.

If the crack is known or suspected to be "live" (i.e. still moving), sealing it using the methods described above is futile if the sealing material is rigid. Alternative treatment methods for live cracks are:

a) Strengthening the membrane over the length and beyond the ends of the crack with a suitable reinforcement fabric, or,
b) Applying a de-bonding tape over the length of the crack. This means that the overlay membrane is isolated from the substrate over the de-bonding tape and the added free-play allows it to accommodate the crack movements.

We can see, therefore, that there are good reasons why substrate preparation procedures are recommended and why they are necessary for the successful installation, performance and durability of overlay applications.

(Reference must be made to the manufacturer's technical data sheet for instructions on use of particular products.)

TECHNICAL REPORT

Cementitious Composites for Structural Strengthening

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Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

Abstract— Due to demands on higher loads, structural degradation, re-configuration etc. there is a constant need for repair or strengthening of existing concrete structures. Various methods and materials are available to strengthen concrete structures, among them most commonly used materials are Fibre Reinforced cementitious matrix (FRCM), Ferrocement, Fibre Reinforced Polymer (FRP), Engineered cementitious composite (ECC) and Ultrahigh-performance concrete (UHPC). Each composites have its own advantages and disadvantages. Each method is very efficient and has achieved worldwide attention at time. This article provides a brief overview of different cement-based systems, all with very promising results for structural upgrading. Studied parameters are structural retrofit for bending, shear and confinement. It is concluded with encouragement of further investigation towards creating versatile industry standards.

I. INTRODUCTION

Reinforced concrete (RC) structures show excellent performance in terms of structural behaviour and durability except for the zones that are exposed to severe environmental influences and high mechanical loading. Large parts of the infrastructure are in need of repair or strengthening due to ageing, rehabilitation, or obsolete design [1]. They experience aging and function degradation, resulting in insufficient serviceability, sustainability, and durability due to external environment change and high mechanical loading [2]. Rehabilitation of deteriorated concrete structures is a heavy burden from the socio-economic viewpoint since it leads to significant user costs. Every moderate to high seismic shaking causes damage ranging from cracks to partial or total collapse with a high death toll and economic loss. This work is very significant since many civil structures are no longer considered safe which can be due to increased load specifications in the design codes, overloading, under-design of existing structures or to the lack of quality control [3]. In order to maintain efficient serviceability, older structures must be repaired or strengthened so that they can meet the same requirements demanded of structures built today and in the future [4]. It is also becoming both environmentally and economically preferable to repair or strengthen the structures rather than to replace them totally, particularly if rapid, effective and simple strengthening methods are available. As a consequence, novel concepts for the rehabilitation of concrete structures must be developed [5]. In the future, sustainable concrete structures will be those requiring just minimum intervention for preventive maintenance with no or little service disruptions. Several methods and materials had been reported to be viable for strengthening existing RC structures. The four major structural strengthening components are listed in Table 1.

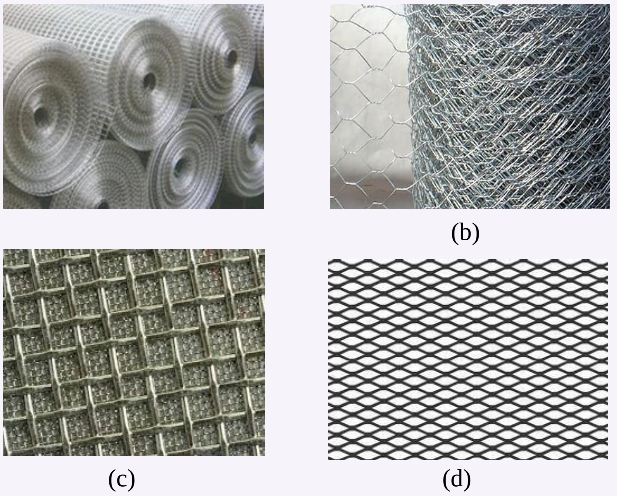
Table 1: Different types of cement composites

Cementitious Composite	Properties
Ferrocement	Cost-efficient, effortless, high in-plain shear and moment capacity, flowable.
Fibre-based composite (i.e FRCM/TRM/FRCC)	Corrosion resistance, a high strength-to-weight ratio, fire resistance, UV resistance, applicable in wet and cold surface.
Engineered cementitious composite (ECC)	Ultimate tensile strain, crack control capable, enhanced load capacity, stiffness, deformation capacity, and energy dissipation.
Ultrahigh-performance concrete (UHPC)	Extreme durability and ultrahigh compressive strength, strain hardening and early high strength.

This article is intended to summarize the properties, applications and advantages of each composite and briefly analyze the feasibility as current technology.

II. FERROCEMENT

Ferrocement is the oldest known kind of reinforced concrete, dating back two centuries and mainly utilized in the construction of boats in Italy and France, starting from 1848 by Frenchman Joseph Louis Lambot [6]. It's constructed of mortar and steel wire mesh, and it's generally cast in extremely thin layers to give it whatever shape required. In developing nations, ferrocement is a cost-effective technique since its raw ingredients are readily available. Furthermore, this material does not necessitate the use of highly trained labour. Ferrocement displays significantly higher in-plain shear strength capacity [7] and higher moment capacity [8]. The ductility of ferrocement-jacketed columns is high under axial compression [9]. Moreover, the shear strength capacity of ferrocement-confined RC columns that are subjected to cyclic loading is relatively high [10]. Depending on the application requirements, several types of meshes can be utilized to manufacture ferrocement sheets. In general, it can be claimed that the type and orientation of the reinforcement employed have a significant impact on the characteristics of the ferrocement. The main types of mesh used in ferrocement application are woven mesh, hexagonal mesh, expanded metal and welded mesh, as shown in Figure 1 [2].



(b)

(c) (d)

Figure 1: Different types of mesh (a) welded wire mesh; (b) hexagonal wire mesh; (c) woven wire mesh; (d) expanded metal [2].

It is a fascinating and adaptable material that has received little attention and provides a variety of new research and application opportunities. As long as a strong connection between the structural element and the ferrocement jacket is achieved, ferrocement improves the performance of reinforced components in all circumstances.

III. FRCM/TRM/FRCC

Fiber reinforced polymers (FRP) are part of a category of materials known as composites, which are made up of two or more component materials. FRP materials are made up of continuous high-strength fibres embedded in a polymer matrix (resin) [10]. The major reinforcing components are embedded fibres, while the polymer matrix functions as a binder, protecting fibres and allowing load transmission to and between them. Fiber-reinforced polymer (FRP) composites have slowly gained acceptance as feasible strengthening materials for reinforced concrete (RC) constructions since the early 1980s. FRP composites have a variety of properties that make them a potential alternative to conventional strengthening methods. Corrosion resistance, a high strength-to-weight ratio, and a wide range of applications are among these qualities. Fibers are placed in a polymer matrix, generally epoxy resin, to form FRPs. But the epoxy resin used in FRPs is incompatible with the concrete substrate, resulting in a critical bond surface/line [11]. They also function poorly at high temperatures and are incompatible with the substrate. Moisture-soaked surfaces and low temperatures make them difficult to apply effectively. Fabric-reinforced cementitious matrix (FRCM) systems, also referred to as textile-reinforced mortar (TRM), mineral-based composite (MBC) or textile-reinforced concrete (TRC) systems, have recently been introduced in the construction industry as an alternative to circumvent the problems associated with FRPs [12].

FRCM materials have revolutionize conventional design of modern reinforced concrete structures [8]. It comprised of fabric grids (made of fibers such as carbon, glass, etc.) and a cementitious agent (mortar) that serves as matrix and binder. When applying FRCM composites, a layer of mortar is typically placed before a layer of fabric grid is applied, followed by another mortar layer, as shown in Figure 2. Repetition of this technique occurs until the desired number of layers has been achieved. A mechanical interlock is produced when the mortar penetrates the grid gaps, forming the connection between the fabric and mortar. While the previous layer is still wet, each subsequent mortar layer must be placed. FRCMs are generally placed externally to the bottom surface of RC beams and slabs for flexural reinforcement.

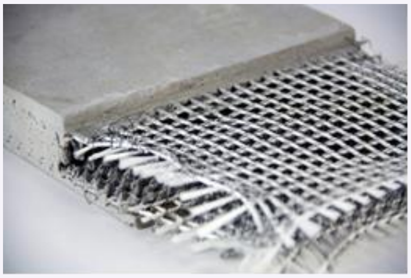


Figure 2: FRCM mesh

There are several advantages of FRCM which proves it to be an advanced composite material of FRPs. That includes high resistance to fire and high temperatures; resistance to UV radiation; ease of handling during the application because the inorganic binder is water-based; easy cleanup and reuse of tools; permeability compatibility with the concrete substrate and unvarying workability time (between 40° F and 105° F).

Referring to another attempt of alleviating the problems arising from the use of epoxies, researchers have introduced a novel composite material, namely textile-reinforced mortar (TRM), in which advanced fibres in the form of textiles are combined with inorganic matrix, such as cement-based mortars. TRM has been described in the literature as a highly promising alternative to the FRP retrofitting method during the previous decade. TRM has been employed in the seismic retrofitting of masonry-infilled RC frames as well as the strengthening of RC components, such as RC Column and RC beam shown in Figure 3.

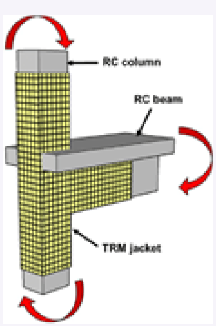


Figure 3: TRM reinforcement [11]

The replacement of organic matrices with inorganic ones, that is the use of textile reinforced mortar (TRM) instead of FRP, offers a viable solution to the shortcomings listed above, especially for heritage structures, where the limited invasiveness and compatibility aspects are extremely important [13]. Low-cost, fire-resistant, and compatible with concrete and masonry substrate materials. Parallel to the extensively utilised FRP, the use of TRM for reinforcing existing structures is becoming increasingly popular for all of these reasons. Since FRP is limited in its capabilities, the use of TRM systems to reinforce traditional or historical masonry structures is extremely promising [13].

IV. ECC

Engineered cementitious composite (ECC) is a kind of designed composite material reinforced with random short fibers with a volume fraction less than 2% to 3%, which features tensile strain hardening and multiple cracking properties [14]. The ultimate tensile strain can be more than 3%, even up to 8%, which is 300 to 800 times higher than that of normal or ordinary fiber reinforced concrete [15]. Cracking is one of the main reasons for the performance deterioration of material and then the structure; however, concrete is low in tension and is prone to cracking. Thus, researchers have been developing methods to reduce the width of cracks [15]. ECC is a material with a high crack-control capability. When ECC is applied in an RC beam, more tiny cracks spread over the tensile surface due to the bridging effect of fibers [14]. Also, compared to FRP and steel, ECC is advantageous in terms of the material compatibility between the concrete substrate and the strengthening layer because it is a cement-based matrix [16].

Figure 4: ECC reinforcement [16]

The bond strengths between ECC and concrete, including interfacial tensile strength and interfacial shear strength, are strong enough to transfer force from an original RC structure to the strengthening layer. The bond strength in the slant shear test is obviously higher than other tests. Also, the bond strength increases with the surface roughness. To reinforce RC constructions, ECC has been coupled with FRP fabrics or steel bars, as shown in Figure 4. Except for many bending strengthening beams, whose displacement was reduced, this strengthening approach may considerably enhance load capacity, stiffness, deformation capacity, and energy dissipation. These characters make it an attractive retrofitting material; thus many researchers have studied the strengthening effect of RC structures with ECC material.

V. UHPC

Ultrahigh-performance concrete (UHPC), a structural material also known as ultrahigh-performance fiber-reinforced concrete (UHPFRC), is an emerging field. UHPC is characterized by extreme durability and ultrahigh compressive strength due to the use of a low water-to-binder (w/b) ratio [17]. Cement, quartz powder, fly ash, silica fume, quartz sand, superplasticizers, and steel fibres were used as raw ingredients in UHPC [18]. It has far higher compressive and tensile strengths than fiber-reinforced strength concrete (up to 150 Mpa and 8 Mpa, respectively) [17]. Excellent physical performance like low permeability can withstand the invasion of harmful chemicals due to the high compactness and density of the UHPC matrix, resulting in improved durability [19]. The strain hardening behaviour of UHPC in tension due to the addition of steel fibres (1.5–3% by volume) is another appealing characteristic. Furthermore, UHPC's outstanding rheological characteristics make casting in the fresh state simple. The benefits of this approach include not only a considerable increase in the capacity and longevity of reinforced RC structures, but also the ability to build quickly through prefabrication and assembly, minimal changes in section size, and minimal traffic service disturbance. The roughening of the concrete substrate surface can improve the binding strength between the UHPC overlay and the concrete substrate, resulting in a greater improvement in ultimate strength. In addition, roughening the concrete substrate surface is recommended for future UHPC strengthening applications sincealternative approaches increase the time cost of substrate surface preparation.

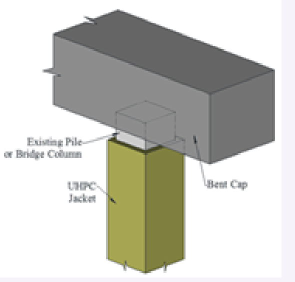


Figure 5: UHPC Jacket Design [19]

UHPC is promising in applications such as overlays and jackets for retrofitting and repairing decks, slabs, beams, columns, beam–column joints, and pavements to improve bond, axial, shear, and flexural performance while simplifying design and construction by eliminating steel rebar [20]. Overall, UHPC has shown excellent mechanical and physical performance. Because of these properties, using UHPC to strengthen or repair RC structures has proven to be an effective and promising technique compared to traditional techniques (such as steel plates and FRP) [21].

VI. CONCLUSION

Different types of cementitious composites provide different characteristics due to unequal properties of the materials. As a result, each of them is being used according to the needs. From ferrocement to fibre based cementitious composites, all have served well the needs of strengthening structural components on its own time. However, comparisons of the various cement-based strengthening methods are not fully fair. There are two main reasons for this. The first is that there is a design flaw in the experimental set-up. The design of the steel reinforcement in the concrete base is a key influencing factor. However, it is apparent that all of these reinforcing techniques contribute to the load-bearing capability of the structure, though with varying degrees of strength. In this respect, future research should be directed towards investigating a wide range of jackets reinforcing ratio for different strengthening configurations which will provide more versatility and contribute towards industry standards.

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CASE STUDY

Reprint from: CI Magazine

Structure of Biblical Proportions

High-strength concrete as a critical component in construction of the world's tallest cathedral—the Sagrada Família

When builders began construction of renowned Spanish architect Antoni Gaudí's Temple of the Sagrada Família in 1882, the primary construction material was sandstone. However, concrete has always been a component of the cathedral, which is in Barcelona, Spain. In fact, Gaudí first used what was then a novel material—reinforced concrete made from portland cement—in construction of the pinnacle of the first bell towers of the Nativity façade in 1924 and 1925 (Fig. 1).

Over the course of nearly a century and a half, construction of the Gothic and Art Nouveau basilica has been affected by wars, the influenza pandemic of 1918 and 1919, and variable funding levels. But thanks to an increase in tourism prompted by Barcelona hosting the Olympic Games in 1992 and the consecration of the basilica by Pope Benedict XVI in 2010, the cathedral has increased its construction funding stream through admission fees. A 2026 completion, in commemoration of the 100th anniversary of Gaudí's death, was scheduled.

Alas, the recent COVID-19 pandemic has pushed back the schedule yet again, and Junta Constructora del Temple Expiatori de la Sagrada Família architect Jordi Fauli says his team has yet to establish a new schedule. Fauli is the ninth chief architect to oversee Sagrada Família's design and construction and the only one who will likely live to see it finished.

Building per Gaudí's Plans

As construction continues on this cathedral, the tallest of the world's churches, materials have changed dramatically. Stone remains Sagrada Família's primary building component, but concrete—high-strength concrete in particular—has become a critical construction material for the cathedral in the last two decades and also helped accelerate the basilica's erection.

"Technical advances have made it possible to overcome the challenges of the past," says Fernando Villa, Director of

Fig. 1: The Nativity façade features two 107 m (351 ft) towers flanked by 98 m (321 ft) towers. This façade was nearly completed under the direction of *Gaudí (© Fundació Junta Constructora del Temple de la Sagrada Família)*

Fig. 2: The Passion façade features two 112 m (367 ft) bell towers flanked by two 102 m (334 ft) bell towers. Behind these, six more towers are under construction *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

Fig. 3: Close-up of two pinnacles of the Passion façade spires. The towers are decorated with mosaic tiles *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

Building and Technology for Sagrada Família. "Even though Gaudí built only a small part [of the cathedral in his lifetime], he left the path in his studies to be followed by his successors."

Sagrada Família features a Latin cross design with five longitudinal naves and three naves forming the transept (the arms of the cross). The Nativity façade is on the northeast end of the cross, and the Passion façade is on the southwest end of the cross.

The basilica's most prominent architectural features are its monumental spires. Gaudí's design included 18 spires, including 12 placed in the façades, representing Christ's apostles. Eight of the 12 spires representing the apostles are complete (Fig. 1 to 3). Four more will be constructed with the final façade—the Glory façade at the base of the cross—and six more spires are being constructed at the center of the transept (the crossing) and on top of the apse (the head of the cross). These spires are still partially concealed behind the spires on the Nativity and the Passion façades (Fig. 1 and 2), but they will soon become prominent. When completed, the four Evangelist towers will each be 135 m tall (443 ft); the Virgin Mary tower will be 138 m tall (452 ft); and the Jesus Christ tower will be 172.5 m tall (566 ft).

According to Villa, 25% of the basilica remains to be built, including finishing the central towers, the Glory façade and its spires, and a second sacristy.

Using Concrete to Surmount Architectural Hurdles

One of the most prominent design features of Gaudí's famous basilica is its lack of the conventional flying buttresses present in so many of Europe's Gothic cathedrals. Gaudí's design supports the structure's roof, towers, and soaring large windows via the columns of the central transept and apse. Those tree-like columns and their striking "branches" are all made with a structure of high-strength reinforced concrete encased in exterior "drums" made of stone or precast concrete.

"It was necessary to meet new building [code] requirements," says Villa. "In fact, [high-strength concrete] was the only alternative to meet new requirements for wind load while still maintaining the width of the walls and their unusual geometry. It was also the only way to withstand the compression load while maintaining the diameter of the columns defined by Gaudí."

According to Fauli, Gaudí formulated a system of slanted columns as trees with sloping branches supporting upper levels. "He wanted to design a church without flying buttresses and only with interior columns to support [the roof, towers, and windows]," says Fauli. The thrust of the roof and the weight of the central towers is resisted by those branching internal columns. All the columns have varying systems of proportions in diameters and in slenderness established by Gaudí. The columns of his original model of the main nave follow this system, as do the new columns of the transept and of the apse (Fig. 4).

Fig. 4: The interior of the cathedral is a celebration of light: (a) Tree-like columns and their "branches" line the main nave, seen here looking toward the apse. Four types of columns have been constructed: columns on each of the four corners of the crossing support the Jesus Christ tower and partially the weight of four Evangelist towers; columns that bear the main load of the four Evangelist towers; columns in the apse and naves; and columns that separate the side naves from the main nave; and (b) The longitudinal nave on the Nativity façade side of Sagrada Família features stained glass windows that gradually transition from yellow to green to deep blue *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

The architects who have taken up Gaudí's mantle in the nearly 100 years since his death have based construction on a 1:10 scale plaster model of the main nave the Catalan architect built while studying and perfecting his design. "He designed plaster models of everything," says Fauli. "When we built the main nave, we tried to reproduce [his plaster model]."

All of the columns have an exterior "drum," as Fauli calls it, shaped by a piece of stone or precast concrete. Inside the drum, workers placed high-strength concrete over reinforcing steel. Thus, the precast concrete or stone, depending on which one is used in the column's façade, was also used as a permanent form (Fig. 5 and 6).

The 56 columns rising from the ground floor that assume the place of flying buttresses are also unique in being grouped at different heights to provide the appearance of trees and tree branches (Fig. 4). The columns and branches transfer the weight of the vaulted structure and central towers above into the building's foundation. These columns were built from a variety of different stone classes, according to Fauli, with reinforced concrete on the inside as previously noted. The columns of the branches were built with precast concrete drum pieces for the exterior and reinforced concrete on the inside.

Fauli says his team built the columns with stone or precast concrete pieces on the exterior and reinforced concrete inside, using high-strength concrete in the more crucial columns as well as in most of the crossing and apse. "In the main nave, we managed to construct all the columns with normal reinforced concrete inside," Fauli says, "but in the

Fig. 5: Construction of the interior columns was completed inside the existing façades between 1991 and 2003 *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

Fig. 6: Stone or precast concrete exterior "drums" were used to form the trunks and branches with reinforced concrete cores *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

crossing, we needed to use the high-strength concrete."

To build the branches of the transept and apse columns, workers employed precast pieces of white concrete with different colors to construct the exterior surface of the columns ("drums") and to achieve the same look as the stone columns on the ground floor. The structural system of columns also allows openings in the vaults for the skylights that fill the interior of the cathedral with striking bands of natural light. Those skylights, designed by Gaudí in the 1920s, are in the unique shape of a hyperboloid—reportedly the first such use of this form in the history of architecture.

Concrete Placements at Soaring Heights

Sagrada Família's history of stops and starts in construction meant that by the time Fauli came on the job as Junior Architect in 1990, only three of the planned 56 interior columns had been built. High-strength concrete (characteristic strength of 80 MPa [11,600 psi]; 7-day compressive strength of 45 MPa [6500 psi]) was first employed in the cathedral's construction in 1998. High-strength white concrete has also been used to provide the base of the central dome (placed at a height of 80 m [262 ft]) as well as in construction of the central towers.

With the help of lightweight fiberglass molds coated with a wax-based form release agent, workers have been able to form many parts of the cathedral, like the lateral vaults and elements of the central dome, in-place, even at great heights. Other components have been prefabricated off-site.

Weight remains a perennial concern in construction of the basilica. The inclined columns or "tree trunks" that branch into innumerable smaller branches hold up the far heavier vaults and roofs and transfer the load to the foundation. The vaults will support the cathedral's central towers, all of them three times taller than the vaults on which they rest. This creates mass at a great distance from the ground and would make the structure vulnerable to earthquakes. "The use of reinforced concrete in the church since 1985 has been calculated to support seismic movements," Fauli explains. "In the central towers, for example, the big panels of stone tensioned by steel bars will resist earthquakes, and a standing structure of steel profiles and reinforced concrete placed in the corners joins the panels and ensures resistance to seismic forces."

In this respect, reinforced high-strength concrete has enabled simpler, lighter, and faster construction of Sagrada Família's complex geometries while still supporting a massive compression load without having to bulk up the diameters of the tree-like and ethereal branches and columns that grace the church's interior.

Since 2010, Germany-based Heidelberg Cement Group's subsidiary Hanson Hispania has been the structure's major concrete supplier when large volumes are needed, though the initial mixture for the white high-strength concrete was provided by Master Builders Solutions. Several other firms have supplied concrete as well, including PROMSA and Escofet. Normally, the concrete is fabricated in the on-site concrete production plant at the Sagrada Família.

Fig. 7: Construction of central towers using prestressed stone panels reinforced by stainless steel columns joined with high-strength concrete *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

According to Villa, the mixture proportions for the high-strength concrete components are:

- 475 kg/m3 (800 lb/yd3) of cement;
- 1030 kg/m3 (1736 lb/yd3) of gravel (5 to 12 mm [0.2 to 0.5 in.]);
- 800 kg/m3 (1348 lb/yd3) of sand (0 to 5 mm [0 to 0.2 in.]);
- 30 kg/m3 (51 lb/yd3) of microsilica (silica fume);
- 150 kg/m3 (252 lb/yd3) of water; and
- 12 L/m3 (2.4 gal./yd3) of high-range water-reducing admixture.

When white concrete is employed, suppliers must be careful to avoid changes in color and texture. Thus, the concrete trucks must be cleaned thoroughly before each new batch is loaded.

Building the Basilica's Final Pieces

The Glory façade, which will be at the base of the cathedral's Latin cross design, will be made up mostly of stone but with elements cast in gray high-strength concrete. Sixteen vast stone hyperboloids will be supported with slanted tree-like columns of stone (the same prestressed stone used for the central towers), with vaults and arches of high-strength reinforced concrete.

Workers began constructing the six central towers in 2014. The faces of the towers consist of prestressed stone with the bars placed inside, but the structural part used to join the different stone panels together is steel and high-strength concrete. The first stone panel of the towers was placed in 2016. The main structure of the Evangelist towers, the Virgin Mary tower, and the Jesus tower will be composed of this prestressed, post-tensioned (with ultra-high-strength stainless steel rods) polychrome stone from quarries at various locations in Europe, selected to mimic the look of the original Montjuïc sandstone Gaudí employed in the cathedral's construction during his lifetime. Nine hundred prestressed stone panels reinforced by stainless steel columns make up the six towers.

Following Gaudí's proposals for the future, architects based the design of the towers on the dome of the sacristy (it exists in an original Gaudí model), essentially stretching its design to the great heights of the towers. The dome of the sacristy and the towers are the intersection of paraboloids that contain triangular windows. The sacristy features five floors, but current technology has allowed for their elimination in the central towers, according to Fauli. The Virgin Mary and Jesus Christ tower structures will envelop a free space of 60 m (197 ft) with no floors.

Fauli explains that the panels made of stone and steel are produced and preassembled at a staging facility outside of Barcelona. Once the panels of stone and steel are placed on-site (Fig. 7), crews place the high-strength concrete mixture that joins the panels.

High-strength white concrete partially coated by blue ceramic pieces will make up the main part of the terminal or pinnacle of the Virgin Mary tower. Villa says the team selected white concrete both for its texture and high resistance to weather phenomena. Fauli confirms the Virgin Mary tower will be completed by the end of 2021.

The 14 corners of the stone panels are composed of high-strength concrete, and portions of the tower are composed of concrete as well. "The pinnacle is shaped in three parts," explains Fauli. "The first 6 meters [feature] a stone exterior with an internal structure of reinforced concrete, while the next 18 meters are composed of a pinnacle of reinforced concrete partially coated by ceramic." Lastly, at the top will be a 12-pointed star of steel and textured glass that will be prefabricated in a factory as well as on-site and then lifted into place using a crane.

The Evangelist towers will feature traditional biblical representations like the man, the lion, the bull, and the eagle, all winged, on the pinnacles. The wings of the eagle will have a span of 7 m (23 ft) and will be built with prefabricated, white high-strength concrete. The Jesus Christ tower will be the tallest and will be topped by a 17 m (56 ft) tall cross.

A Century and a Half in the Making

The Sagrada Família was designated a UNESCO World Heritage Site in 2005. It currently occupies about 9700 m2 (104,400 ft2). When fully completed, its footprint will consume an entire city block, and it will be the tallest cathedral in the world.

Fauli says the more than 140 years it has taken to build the Sagrada Família has been a blessing in disguise in many ways. "Gaudí would have had to use massive materials to build the cathedral," he explains. "We now have the opportunity to find the best technique for each element. We are building the central towers, for example, with prestressed stone. If we'd built them 20 years before, it would not have been possible."

But as Fauli points out, Gaudí was always trying to take advantage of new building materials. He built one of the spires of the Nativity façade in concrete coated with color ceramic pieces. "[The Sagrada Família] was a challenge for the future," Fauli says. "Gaudí was always thinking in the future and about new techniques that would assist construction."

Selected for reader interest by the editors.

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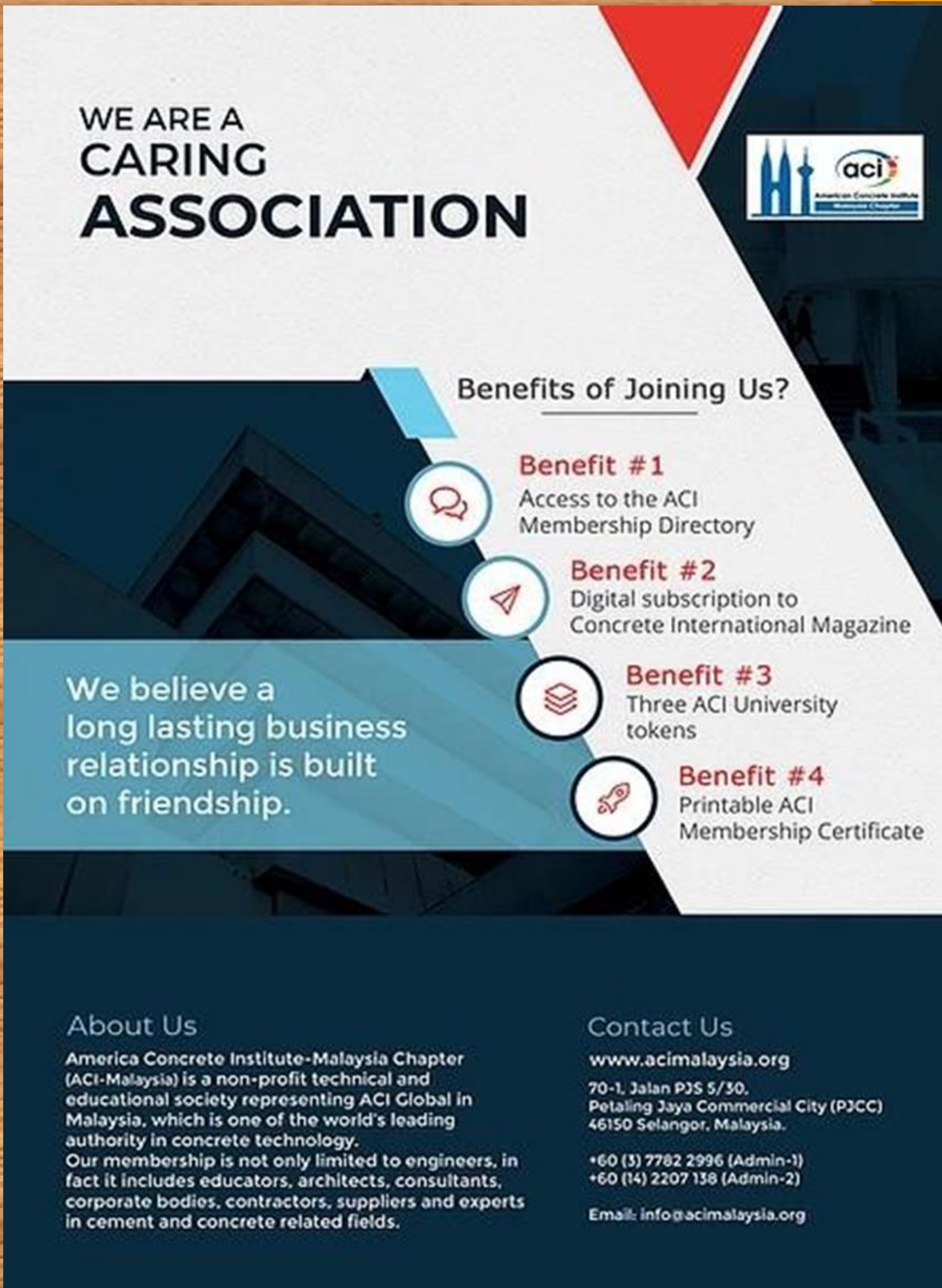
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