

# SELF-COMPACTING CONCRETE IN THE TEMPLE OF SAGRADA FAMILIA

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## Abstract

The Temple of Sagrada Familia presents singularities both in terms of the original design of the architect Antoni Gaudí and of the duration of the construction, which started more than 120 years ago. In fact, its design was conceived before the development of reinforced concrete. Therefore, the construction materials and processes have evolved in order to adapt to the new technologies without compromising the vision of Gaudí. This willing to maintain the original designs has obliged the technicians to solve details that were not defined in the project, among them is the issue of how to cast elements at great heights and with high amount of reinforcement. In this context, the possibility of using self-compacting concrete (SCC) emerged. The present study describes the different experiences in the Temple of Sagrada Familia with SCC, from requirements that led to use this material, to the design of the mixes and the casting of the elements in situ.

**Keywords:** self-compacting concrete, Sagrada Familia, Gaudí

## INTRODUCTION

The Temple of Sagrada Familia is one of the most internationally recognised works of the Catalan architect Antoni Gaudí and it generates great interest in architecture and engineering since it is a major construction laboratory that differs from traditional construction and that applies singular methods and materials. Such interest is reflected in the extensive studies and research conducted on the architecture of the Temple (Puig Boada 1929, Bonet 1997, Faulí 2006), the symbology of Gaudí (Puig 2010, Fargas and Vivas 2009) or the evolution of the concrete used (Grima 2004, Grima et al. 2007 and 2013, Espel et al. 2009).

The construction of the Temple started in 1882 and it is still unfinished due to the great number of details in the structure and the complexity to execute them. However, the past 25 years have been intense in terms of construction since in that period the volume constructed is greater than in the first 100 years of construction (Grima et al. 2007). The fact that the Temple is visited by more than 3 million people per year has contributed significantly to that boost in the construction as a result of the funding obtained with the visitors.

46 In more than 130 years of construction, the materials and the construction techniques and  
47 procedures used have evolved drastically. Hence, Sagrada Familia is a unique site that  
48 combines old structures made of stone and early reinforced concrete (RC) with new elements  
49 made of special concretes such as high-strength or sprayed concrete (HSC and SC,  
50 respectively). In this regard, even though the main building material in the early years of  
51 construction was stone, Gaudí had already planned the use of RC. In fact, he was one of the  
52 first architects to use RC in Spain since Eusebi Güell, who was patron of Gaudí, was the  
53 owner of one of the first Portland cement factories in the country (Espel et al. 2009). Despite  
54 the traditional construction procedures employed at that time, Gaudí managed to take  
55 advantage of the available resources to face the complexity of building the Temple, such as  
56 installing railways to transport the material in wagons or building cranes to handle big  
57 weights.

58

59 After the death of Gaudí, his disciples and subsequent architects have followed the original  
60 ideas of Gaudí for the construction of the Temple. Their willing of keeping the dimensions  
61 and slenderness of the original design represents a great challenge considering that the current  
62 standards and design codes are more demanding in terms of strength and durability of the  
63 structures. Therefore, new materials and construction procedures have been introduced in  
64 order to meet the requirements of the codes without compromising the original design.

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66 Recently, self-compacting concrete (SCC) has also been used for certain elements of the  
67 Temple which are difficult to cast due to their geometry or dense reinforcement, given the  
68 ability of SCC to flow and to reach any location of the framework without the need of  
69 compaction. The use of this material in the Temple of Sagrada Familia reflects the evolution  
70 of the construction materials employed in this particular project and how techniques and  
71 construction procedures have adapted to the always changing conditions of such a unique  
72 project, which started more than a century ago.

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74 Considering the above, this study aims at presenting the experiences conducted at Sagrada  
75 Familia with SCC, from the design of the mixes to the casting of the elements in situ,  
76 describing the strict structural and construction requirements to comply with in order to  
77 maintain the vision of Gaudí.

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## 79 **EVOLUTION OF THE BUILDING MATERIALS USED IN SAGRADA FAMILIA**

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81 The construction of the Temple of Sagrada Familia may be divided into three periods  
82 according to the architect involved in the project: the early period (1882-1926) corresponds to  
83 the time when Gaudí was the architect responsible for the construction, the beginning of the  
84 second period (1926-1985) is defined by the death of Gaudí and the takeover by his disciples  
85 and the third period starts in 1985 when an architect that did not have a direct relationship  
86 with Gaudí is appointed for the first time. Table 1 presents a summary of the main materials  
87 used in the construction of the Temple grouped according to different periods. This  
88 information was obtained from the investigation carried out by Grima (2011).

89

90 *Table 1. Summary of the building materials used in Sagrada Familia over the years.*

91 The first period (1882-1926) of construction of the Temple of Sagrada Familia is  
92 characterised by the use of stone as the only building material and by the use of traditional  
93 building techniques. Reinforced concrete was introduced in Spain in the end of the 19<sup>th</sup>  
94 century by French architects (Ignacio et al. 2016). Therefore, at the end of this first period,  
95 RC was used sporadically in some of the works of Gaudí. However, it was not until 1954 that  
96 RC was used for the first time in Sagrada Familia alongside with cyclopean concrete.  
97 Cyclopean concrete was used for filling cavities of walls, whereas RC was used in columns,  
98 foundations slabs, arches and spires. The use of concrete, either cyclopean or reinforced,  
99 spread during the second period (1926-1985) and became one of the most often used  
100 materials. Figure 1 shows the construction of the crypt of the Passion façade where cyclopean  
101 concrete was used in the lower levels and the reinforced concrete columns of the same façade  
102 (the images were obtained from the Archive of the Expiatory Temple of Sagrada Familia,  
103 hereinafter ATESF).

104  
105 *Figure 1. Construction of the crypt and the columns of the Passion façade (©Expiatory Temple of the*  
106 *Sagrada Familia)<sup>1</sup>*  
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109 In the third period (1985-present), the manufacture of concrete was mechanized and a general  
110 modernization of the construction processes occurred, introducing new technologies and  
111 materials, due to the increase in the funding through donations (Gómez Serrano et al. 1996).  
112 A reflection of the modernization and the availability of resources is the use of different types  
113 of concrete, such as precast concrete, sprayed concrete and high-strength concrete. In  
114 addition, the tradition of building with stone returned for decorative purposes given the  
115 advances in stonecutting techniques.

116  
117 The use of special concretes in the third period responds to the specific demands of the  
118 Sagrada Familia such as high flowability (obtained through superplastizers) in order to cast  
119 elements with high amount of reinforcement or high strength in order to bear the stresses  
120 generated by the weight of the towers designed by Gaudí without increasing the dimensions  
121 of the columns.

## 122 123 **INTRODUCTION OF SCC IN SAGRADA FAMILIA**

124  
125 The use of SCC in the Temple of Sagrada Familia responds also to the need of meeting  
126 certain requirements demanded to the material. The construction of the naves, the transept and  
127 the apses of the Temple of Sagrada Familia required the use of a concrete that was compatible  
128 with the high amount of reinforcement and allowed avoiding the compaction of the material  
129 due to the long distances and complex geometries of some of the structural elements. Figure 2  
130 shows the dense reinforcement of several elements of the tower of Jesus Christ and the

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131 elevation of the concrete skip from the ground floor where the concrete plant is located up to  
132 the height where the elements to be cast are placed. In this regard, Figure 2b reveals how due  
133 to space restrictions, the performance or efficiency in the casting is not high. Such conditions  
134 justify the need to use a SCC in the Sagrada Familia.

135

136 *Figure 2. a) Reinforcement in elements of the apse and b) elevation of a concrete skip.*

137

138 In this context, in 2009 the use of SCC is considered as a feasible alternative to deal with  
139 demands described. Besides flowability, the use of SCC had additional advantages such as  
140 extending the service life of the frameworks (by avoiding vibration), improving the labour  
141 working conditions both in terms of safety and health or reducing construction times.

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## 143 **EXPERIENCES WITH SCC**

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### 145 **Conditioning factors**

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147 The main conditioning factor to take into account in the definition of the mixes is the location  
148 of the concrete plant. Notice that the concrete used in the Temple of Sagrada Familia is  
149 produced in the same work-site, where there is a small concrete plant with limited space for  
150 storing materials. Therefore, the SCC mix cannot be defined with any materials, only with  
151 those available in the concrete plant of the work-site of Sagrada Familia, which are the  
152 materials used for other types of concretes applied in the construction of the Temple.

153

154 *Figure 3. a) Location of the concrete plant at the work-site of Sagrada Familia (©Expiatory Temple of  
155 the Sagrada Familia) and b) top view of the concrete plant (García 2010).*

156

### 157 **Materials**

158

159 Two types of cement (grey and white) are available in the concrete plant in order to obtain  
160 different shades. The grey cement is usually applied for conventional concrete, whereas the  
161 white cement was introduced with the HSC. Table 2 presents the main properties of the two  
162 cements which comply with the standards UNE 80305:2001 (AENOR 2001) and EN 197-  
163 1:2000 (CEN 2000).

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166

*Table 2. Properties of the cements used.*

167 Three types of aggregate (fine aggregate, medium aggregate and coarse aggregate) and a filler  
168 are used in the concrete plant at Sagrada Familia in order to obtain a continuous grading.  
169 Table 3 includes the properties the aggregates and the filler and Figure 4a shows the grading  
170 curve of the coarse, medium and fine aggregates as well as the filler. Notice that the grading  
171 of the filler used in the SCC mixes in Sagrada Familia is such that 100% passes the sieve of 2  
172 mm, 60% the sieve of 0.125 mm and 36% the sieve of 0.063 mm. Furthermore, Figure 4b  
173 includes de combined curves for the aggregates for the concrete mixes presented in  
174 subsequent sections.

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*Table 3. Properties of the aggregate.*

*Figure 4. a) Grading curves of the aggregates and the filler and b) combined curves of the aggregates for the different concrete mixes.*

The admixtures available at Sagrada Familia concrete plant and that were used in some of the mixes are silica fume, a superplasticizer (based on polycarboxylates) and a polyfunctional admixture (based on lignosulfate). The silica fume is mainly composed of SiO<sub>2</sub> and has a specific weight of 2.3 g/cm<sup>3</sup>. Notice that even though two colours are available (grey and white), only the white silica fume is used in order to avoid coloring the concrete when white cement is used. The superplasticizer is used in SCC to improve the flowability of the mix and a polyfunctional admixture is also added to increase the superplasticizing effect of the former. The specific weight of both admixtures are 1.04 and 1.18 g/cm<sup>3</sup>, respectively.

### **Characterization tests**

The fresh-state properties assessed in the study are flowability, viscosity and cohesion. The evaluation of these properties requires performing tests that are different from the previously conducted at the work-site of Sagrada Familia: the slump flow test performed according to the standard EN 12350-8:2010 (CEN 2010), the J-ring test (a normalized ring with reinforcement bars) which is used to evaluate the capacity to pass through the reinforcement bars EN 12350-12:2011 (CEN 2011). Figures 5a present the test setup of the slump flow test. An additional test was conducted with some of the first mixes to evaluate flowability, segregation as well as how the concrete flow advances through the reinforcement and fills all the spaces (see Figure 5b). The so-called maze test consists in pouring a certain volume of concrete in a wooden formwork with the shape of a maze and with reinforcement, allowing the concrete to flow free until the formwork is filled. If the tests showed that the mixes do not meet the requirement of self-compactability the mixes were modified until the fresh-state properties correspond to those of a SCC.

*Figure 5. a) Slump flow test and b) additional test to evaluate the flow through reinforcement.*

The hardened-state properties were only assessed in terms of the compressive strength at 28 days. For that, cylindrical specimens with a diameter of 15 cm and a height of 30 cm were tested according to EN 12390-3:2009 (CEN 2009). The specimens were cast in disposable formworks and demoulded at 24 hours. Then, they were stored in water with lime until the date of the test.

### **Self-compacting concrete mixes**

Several mixes were defined to meet the requirements of the different structures where the mixes were applied. Table 4 presents the SCC mixes proposed, divided in three stages that correspond to the different requirements established. Stage 1 and stage 2 correspond to SCC

219 mixes with compressive strengths of 60 MPa and 40 MPa. Stage 3 corresponds again to a  
220 SCC of 60 MPa with a certain color shade and embossment in the surface, which needs to be  
221 considered in the definition of the mix. The combined grading curves of the aggregates used  
222 in each mix is presented in Figure 4b.

223

224 *Table 4. SCC mixes proposed for each stage (kg/m<sup>3</sup>) and properties.*

225

### 226 *Stage 1*

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228 The initial strategy consisted in taking the HSC mixes previously used in the construction of  
229 the Temple of Sagrada Familia as a reference (see Table 4) and reverse the granular skeleton.  
230 This strategy responds to the convenience of using mixes that were known by the labour in  
231 charge of manufacturing the concrete and the fact that the compressive strength obtained with  
232 these mixes was between 60 and 80 MPa depending on the type of cement used, which is a  
233 range of strengths that meet the requirements set for the SCC mix at stage 1.

234

235 The mix SCC1 was defined reversing the granular skeleton in order to increase the fine  
236 aggregate and reduce the coarse aggregate. In addition, medium aggregate was added to the  
237 mix. Furthermore, a polyfunctional admixture was also added to the mix to increase the  
238 flowability for the same w/c ratio. Despite reaching the required compressive strength, the  
239 mix SCC1 did not comply with the flowability expected. Therefore, mix SCC2 was proposed.  
240 This new mix included filler and higher content of water in order to improve the flowability.  
241 The properties of SCC2 were suitable to be applied in the walls of the abse between 45.0 m  
242 and 60.0 m above ground level, as shown in Figure 6.

243

244 *Figure 6. Casting of the walls of the apse: a) plan view of location, b) profile of location, c)*  
245 *reinforcement at the base and d) reinforcement of the walls (©Expiatory Temple of the Sagrada*  
246 *Familia).*

247

248 Subsequently, another modification was included in the mix for stage 1 to avoid using silica  
249 fume and filler (see SCC3). The approach followed in the definition of SCC1 and SCC2 was  
250 based on a triangular granular skeleton. This means that the content of fine aggregate was  
251 higher than that of the medium aggregate and in turn the content of the latter was higher also  
252 than that of the coarse aggregate (see Table 4). The new mix for stage 1 (SCC3) sought a  
253 diabolo shape for the granular skeleton. The higher content of coarse aggregate (with a  
254 maximum size of 12.5 mm) provides higher strength. The properties of this mix were suitable,  
255 thus confirming that the silica fume and the filler are not required.

256

### 257 *Stage 2*

258

259 Given that the required compressive strength was 40 MPa, the cement content was reduced  
260 and the content of fine aggregate was increased in order to compensate for that reduction (see  
261 SCC4 in Table 4). In this case the approach followed for the granular skeleton is more similar

262 to a diabolo shape with higher content of fine aggregates. The compression tests confirmed  
263 that this mix led to values of strength that fulfilled the requirements for casting. This mix was  
264 used in the central hyperboloid at the top of the apse as shown in Figure 7.

265

266 *Figure 7. Casting of the central hyperboloid: a) plan view of location, b) profile of location and c)*  
267 *construction of the apse (©Expiatory Temple of the Sagrada Familia).*

268

269 At this point it is important to highlight that the use of SCC leads to significant pressure in the  
270 formwork, higher than in the case of conventional concrete. This phenomenon should be  
271 considered in the design and selection of the formworks for SCC. Specifically, these  
272 formworks should be anchored or fixed tight in order to avoid their opening due to the  
273 pressure. In the case of Sagrada Familia, due to the always changing building materials and  
274 construction processes, the type of formworks used in the work-site of Sagrada Familia have  
275 adapted to the new requirements throughout the years (Gómez-Serrano et al. 2009).

276

277 *Stage 3*

278

279 The compressive strength required at this stage for the SCC5 was 60 MPa. Additionally, a  
280 certain color shade and embossment of the surface is sought for its application in the crossing  
281 of the Temple. In order to obtain the shade, both cements (grey and white) were used at this  
282 stage. Notice that the crossing hall will be accessible for visitors, therefore the visual aspect of  
283 the concrete takes special relevance.

284

285 The concrete mix defined for this application presented a granular skeleton with a diabolo  
286 shape. In addition, filler and silica fume were included. The results of the slump flow test are  
287 satisfactory since the concrete reached a diameter of 76 cm. Furthermore, the J-ring test  
288 performed 30 minutes after the production of the concrete also provided suitable results.  
289 Regarding the compressive strength, the results show that the desired strength was reached at  
290 only 4 days after casting.

291

292 *Figure 8. Casting of the crossing: a) plan view of location and b) profile of location (©Expiatory*  
293 *Temple of the Sagrada Familia).*

294

## 295 **CONCLUSIONS**

296

297 The Temple of Sagrada Familia is a singular project that combines the challenges of building  
298 according to the original designs of Antoni Gaudí and finding the materials and construction  
299 processes that allow remaining true to those designs. The introduction of self-compacting  
300 concrete in the project responds to the need to overcome these challenges by using the new  
301 construction materials and technologies. The study described the evolution of the building  
302 materials until present time, when self-compacting concrete has proved to be material that  
303 complies with the structural and aesthetic requirements of the project.

304

305 In this regard, different SCC mixes were proposed according to the requirements established  
306 in each case, with compressive strengths ranging from 40 MPa to 60 MPa and, in some cases,  
307 demanding a certain flowability not only after the mixing but over time to confront the  
308 production and casting conditions at the work-site, which have influenced significantly the  
309 definition of the mixes. Nevertheless, the successful application of the mixes to elements with  
310 different shapes and with different loading demands indicates that this type of material is  
311 adaptable to a wide range of structures.

312

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314

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321

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