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What Can We Learn from over 1000 Tests on Fire-induced Spalling of Concrete? A Statistical Investigation of Critical Factors and Unexplored Research Space

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Abstract

This paper presents a comprehensive statistical investigation of the largest database on fire-induced spalling of concrete collected to date. In total, 1069 fire tests were collected and reviewed on specimens made from normal-strength concrete (NSC), high-strength concrete (HSC), and ultra-high-performance concrete (UHPC). This investigation examined 43 factors spanning material, mechanical, and geometrical properties, as well as environmental and casting conditions. Findings from this investigation report statistical trends on factors that are likely to increase the propensity of fire-induced spalling (i.e., substituting coarse aggregates with fillers, presence of edged shapes, higher moisture content, etc.). The same findings also identify critical gaps within the experimental scene as existing works seem to focus heavily on pre-identified mixtures and parameters within specific ranges – leaving valuable parameter space unexplored. Lastly, this work proposes future research directions to maximize the output of future fire testing campaigns and calls for establishing a more uniform and standardized spalling database.

Keywords: Spalling, Fire, Tests, Database, Statistical analysis.

1.0 Introduction

Concrete is one of the most widely used construction materials. Although concrete is naturally inert, it can spall (with chunks breaking or peeling off) once exposed to elevated temperatures [1,2] Fire-induced concrete spalling is a complex phenomenon associated with severe ramifications (e.g., loss of structural integrity, etc.) [2].

A number of theories were proposed to tackle the spalling phenomenon. For example, the *'moisture clog theory'* ties spalling to the concrete matrix's restrained and rising pore pressure. More specifically, the fire-induced temperature rise leads to moisture evaporation [3], which tends to migrate toward the cooler core. This creates a saturated region called the *'moisture-clogged region'*. Once the pore pressure at the clogged region exceeds the tensile strength of concrete, spalling occurs [4,5]. A second commonly accepted theory is the *'thermal stress theory'* [6] This theory stems from the different rates of contraction and expansion of the mixture raws that generate micro-cracks that weaken the matrix and eventually lead to spalling. Other theories also exist, such as *'BLEVE'* [7] and the *'hydraulic spalling theory'* [8], etc. Such theories and others can be found in recent reviews [9–11].

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Researchers and practitioners often propose using polypropylene (PP) or steel fibers to overcome spalling. While PP fibers melt at low temperatures (i.e., 160°C), creating additional pores that allow moisture to migrate and decrease the rising pore pressure, steel fibers inherently improve the tensile strength of concrete [12,13] One or a hybrid of these solutions are shown to limit the degree of fire-induced spalling.

A deep dive into this phenomenon acknowledges the large number of factors that are linked to spalling. Such factors fall under the material, mechanical, geometrical, and environmental features, and properties, to name a few. Understanding the relationship(s) between these factors could help researchers better understand spalling [14]. For instance, at the material front, cement, aggregates, water, and admixtures can have a direct or indirect influence on the mechanical properties (e.g., strength, permeability, etc.) of concrete as well as its propensity to spalling [15]. Additionally, geometric factors such as specimens' dimensions and shapes can also affect spalling [2,16]. Several environmental factors can influence spalling as well, such as heating rates and exposure temperature [2]. Recently, there has been a growing focus on the fire-induced spalling of concrete [17–20].

Traditionally, fire-induced spalling is often investigated via fire tests. For the most part, these tests champion small-sized concrete specimens that are cast and tested under fire conditions. Practically speaking, fire tests can be limited in scope and nature due to the complexity of fire testing, lack of accessibility to fire facilities, inadequate funding, etc.

To overcome such limitations, recent individual efforts were carried out to build spalling datasets. For example, Ali et al. [21] reported the results of fire-induced spalling as collected from 99 fire tests on concrete columns. Liu and Zhang [22–26] also collected more than 600 tests of various specimens and examined these tests in a series of papers. Evidently, the datasets collected by the above researchers have started an inertia toward updating the current state of knowledge from several building committees such as ACI 216.1 and RILEM 256-SPF.

From this lens, this paper aims to develop and analyze a more updated and comprehensive fire-induced spalling database. In this dataset, 1069 fire tests were collected and reviewed on specimens made from normal-strength concrete (NSC), high-strength concrete (HSC), and ultra-high-performance concrete (UHPC). In addition, 43 factors spanning material, mechanical, and geometrical properties, and environmental and casting conditions were reported and compared. Our goal is first to examine the collected dataset statistically and, secondly, to identify the most commonly tested ranges and conditions adopted in spalling fire tests.

2.0 Collection of the database

To compile this dataset, a comprehensive survey was carried out [8,13,27–66]. This survey started by identifying a number of keywords wherein related sources were collected from various scholarly platforms and peer-reviewed journals (see Fig. 1). The selected works were then

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analyzed individually to filter 43 commonly reported factors such as concrete types (i.e., NSC, HSC, and UHPC) and additives such as PP fibers and steel fibers, etc. (the list of collected factors will be presented shortly) [67]. This database was then independently examined on three occasions to ensure its correctness. Once the entries of the database were verified, a comprehensive statistical analysis took place to report on the selected factors and their influence on spalling.

Figure 1. Keywords visual representation

As mentioned above, we identified 43 factors for the collected specimens and the outcome of each fire-tested specimen (in terms of spalling / no spalling) – see Table 1. As expected, not all 43 factors were present for each specimen, as some sources did not report the full list of factors. Fortunately, 23 factors were collected for all 1069 specimens, as listed in Table 1. The same table lists general statistical insights, such as the minimum, maximum, median, skewness[1], mean, data distribution, and standard deviation of each factor. Finally, Fig. 2 presents a graphical distribution for each factor.

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[1] Skewness provides a measure of distribution symmetry. For example, having a skewness of 0 indicates normal distribution. A positive (and negative) skewness indicates a distribution that is shifted to the right (or left) and one that does not spread enough. Note that the base point at which we can consider the database to be highly skewed distribution is between a skewness value of larger than 1.0 or lesser than -1.0 [77,78].

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Table 1 Summary of statistical insights for the parameters of the dataset.

Parameter	Min	Max	Median	Skew	Std	Mean	Distribution	Count
Aggregate type	-	-	-	-	-	-	-	1069
Aggregate/binder ratio (%)	0.00	5.10	1.64	0.35	1.16	1.41	Normal	1069
Coarse aggregate (Kg/m^3)	0.00	1734.00	846.00	-0.37	495.78	680.67	Normal	1069
FA/binder ratio (%)	0.00	0.55	0.00	3.73	0.07	0.02	Lognormal	1069
GGBS/binder ratio (%)	0.00	0.48	0.00	2.93	0.12	0.04	Lognormal	1069
Shape	-	-	-	-	-	-	-	1069
Specimen height (mm)	40.00	1000.00	150.00	2.84	133.81	167.58	Lognormal	1069
Specimen length (mm)	0.00	3600.00	100.00	6.50	398.74	186.28	Lognormal	1069
Specimen width (mm)	0.00	3360.00	50.00	6.89	365.49	128.19	Lognormal	1069
Heating rate (°C/min)	0.10	200.00	10.00	1.94	35.62	25.96	Lognormal	1069
Maximum exposure temperature (°C)	75.00	1200.00	600.00	-0.05	226.90	577.23	Normal	1069
Moisture content (%)	0.00	0.09	0.03	0.04	0.02	0.04	Normal	1069
PP fiber diameter (µm)	0.00	150.00	0.00	3.50	21.13	10.84	Lognormal	1069
PP fiber length (mm)	0.00	30.00	0.00	1.88	5.73	3.35	Lognormal	1069
PP fiber quantity (Kg/m^3)	0.00	16.00	0.00	4.07	2.55	1.03	Lognormal	1069
Steel (S) fiber diameter (mm)	0.00	1.00	0.00	2.62	0.20	0.09	Lognormal	1069
S fiber length (mm)	0.00	60.00	0.00	3.04	10.72	5.00	Lognormal	1069
S fiber quantity (Kg/m^3)	0.00	180.00	0.00	2.33	37.59	18.79	Lognormal	1069
Max aggregate size (mm)	0.12	32.00	13.00	-0.02	7.86	10.53	Normal	1069
Sand/binder ratio (%)	0.45	3.41	1.20	1.38	0.51	1.36	Gumbel	1069
Silica fume/binder ratio (%)	0.00	0.23	0.00	0.83	0.08	0.06	Gumbel	1069
Water/binder ratio (%)	0.13	0.63	0.30	0.78	0.13	0.31	Lognormal	1069
Output (Spalling)	-	-	-	-	-	-	-	1069
Compressive strength (MPa)	20.00	214.00	84.10	0.53	40.44	91.05	Normal	1062
Silica fume (Kg/m^3)	0.00	240.00	0.00	1.53	63.57	39.90	Gumbel	982
Curing mechanism	-	-	-	-	-	-	-	951
Curing temperature (°C)	25.00	250.00	25.00	5.40	24.69	31.07	-	923

Cement (Kg/m^3)	234.00	1110.00	500.00	1.15	210.48	558.48	**Lognormal**	919
Fine aggregate (sand) (Kg/m^3)	200.00	1983.00	753.00	1.63	271.60	810.93	**Gumbel**	919
Water (Kg/m^3)	80.00	333.00	172.00	-0.01	41.96	173.20	**Normal**	919
Water/cement ratio (%)	0.16	0.83	0.32	0.99	0.13	0.34	**Lognormal**	919
Specimen age at fire test (Days)	28.00	730.00	90.00	2.95	109.58	117.34	**Lognormal**	704
Drying temperature (ºC)	18.00	250.00	80.00	1.07	51.20	66.77	-	601
Humidity (%)	20.00	100.00	60.00	0.00	16.81	64.33	-	522
Drying mechanism	-	-	-	-	-	-	-	499
Heating duration (min)	30.00	1440.00	120.00	4.10	172.20	155.47	**Lognormal**	494
Slump (mm)	3.30	200.00	150.00	-0.54	66.84	120.57	**Weibull**	397
Residual compressive strength (MPa)	0.00	207.50	57.47	1.18	43.19	67.08	**Normal**	374
Heating curve	-	-	-	-	-	-	-	177
Spalling weight (%)	0.00	71.70	9.31	1.30	18.41	16.80	**Gumbel**	140
Core temperature (ºC)	25.00	450.00	300.00	-0.68	114.24	255.17	**Normal**	129
Spalling depth (mm)	0.00	111.00	18.88	1.44	25.46	25.37	**Gumbel**	93
Spalling time (min)	1.00	125.00	5.00	6.07	17.10	9.17	**Normal**	88

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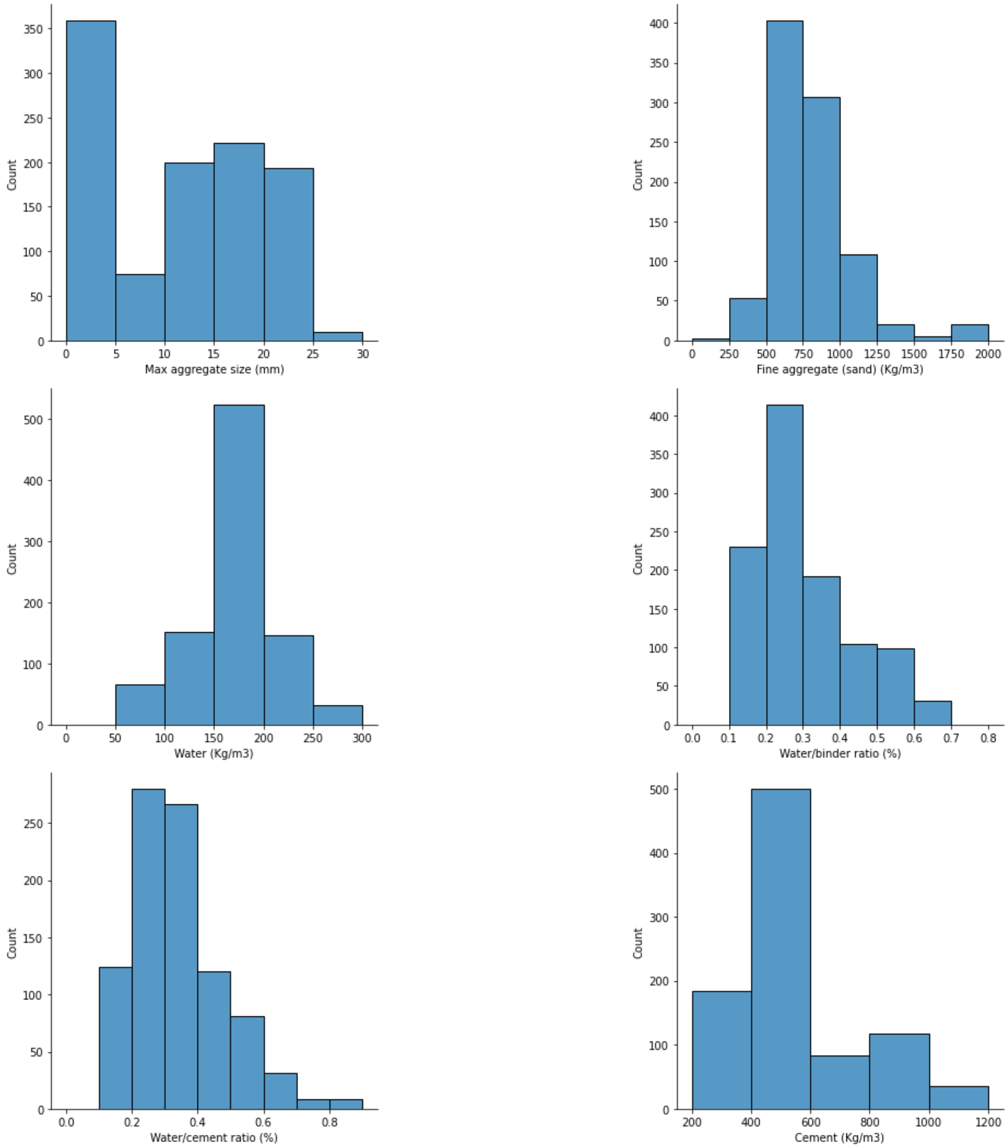
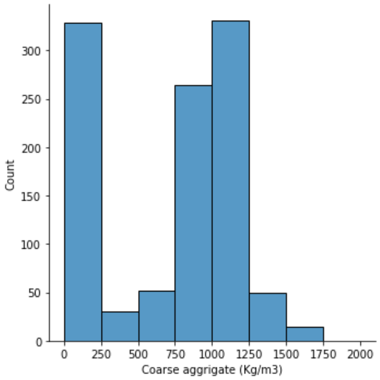
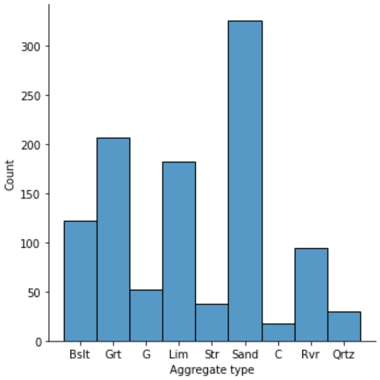
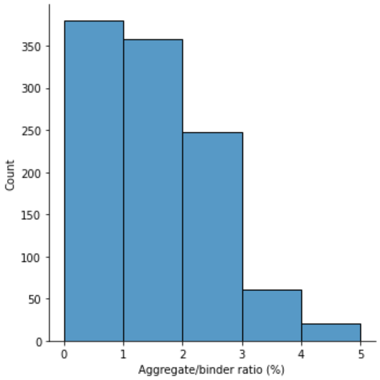
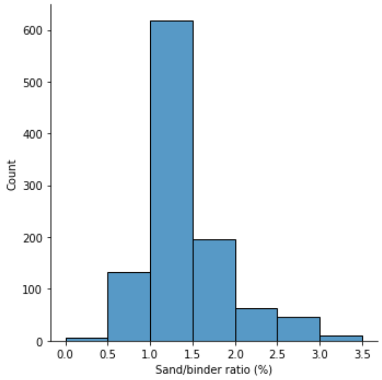


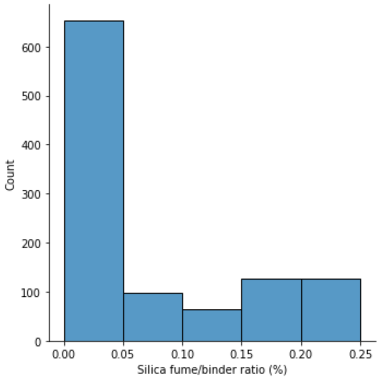

Count
0
50
100
150
200
250
300
0
250
500
750
1000
1250
1500
1750
2000
Coarse aggrigate (Kg/m3)

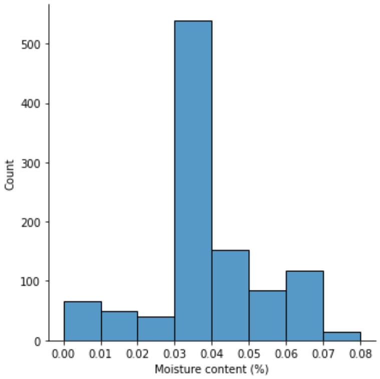

Count
0
50
100
150
200
250
300
Bslt
Grt
G
Lim
Str
Sand
C
Rvr
Qrtz
Aggregate type

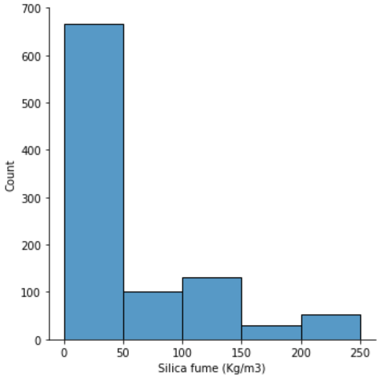

Count
0
50
100
150
200
250
300
350
0
1
2
3
4
5
Aggregate/binder ratio (%)

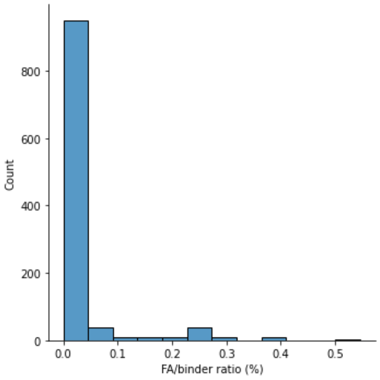

Count
0
100
200
300
400
500
600
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Sand/binder ratio (%)

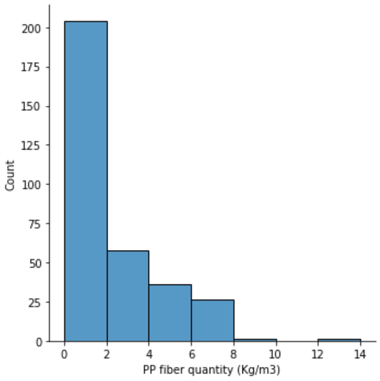
e

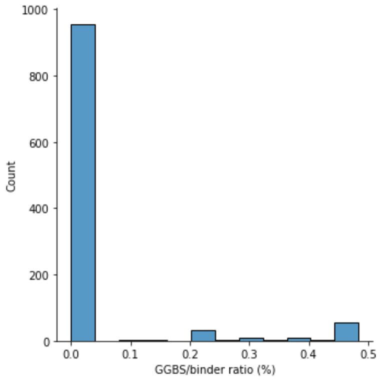

Count
0
100
200
300
400
500
600
0.00
0.05
0.10
0.15
0.20
0.25
Silica fume/binder ratio (%)

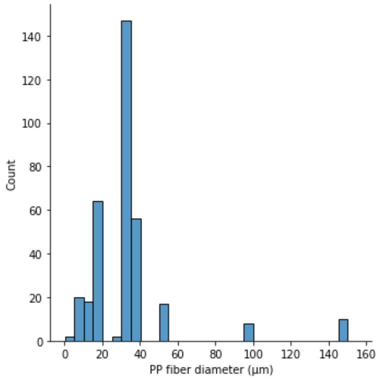

Count
0
100
200
300
400
500
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Moisture content (%)

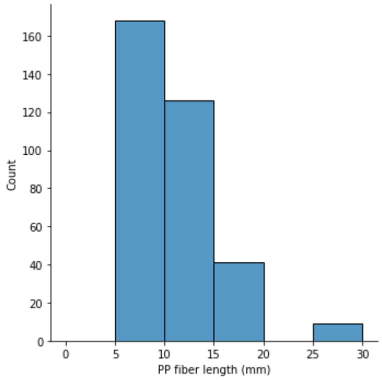

Count
0
100
200
300
400
500
600
700
0
50
100
150
200
250
Silica fume (Kg/m3)

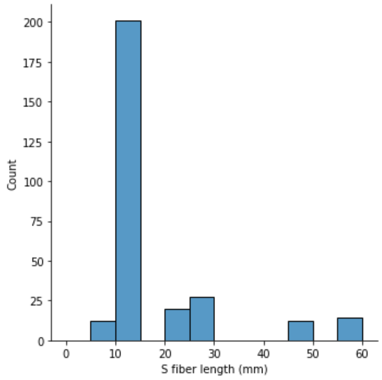

Count
0
200
400
600
800
0.0
0.1
0.2
0.3
0.4
0.5
FA/binder ratio (%)

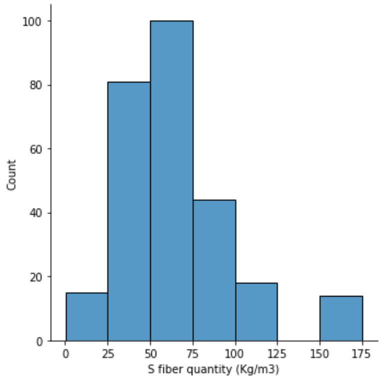

Count
0
25
50
75
100
125
150
175
200
0 2 4 6 8 10 12 14
PP fiber quantity (Kg/m3)

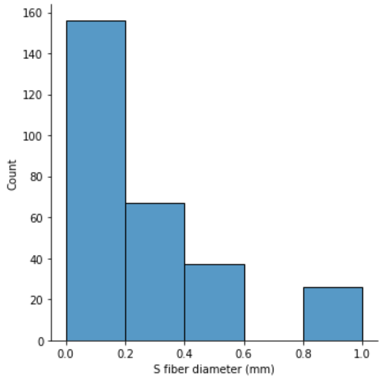

Count
0
200
400
600
800
1000
0.0 0.1 0.2 0.3 0.4 0.5
GGBS/binder ratio (%)

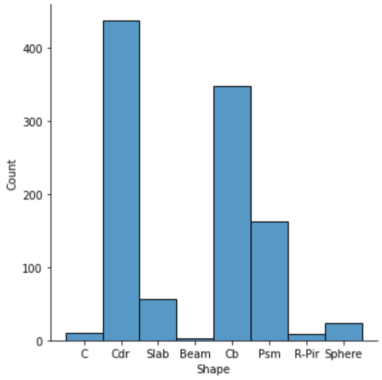

Count
0
20
40
60
80
100
120
140
0 20 40 60 80 100 120 140 160
PP fiber diameter (µm)

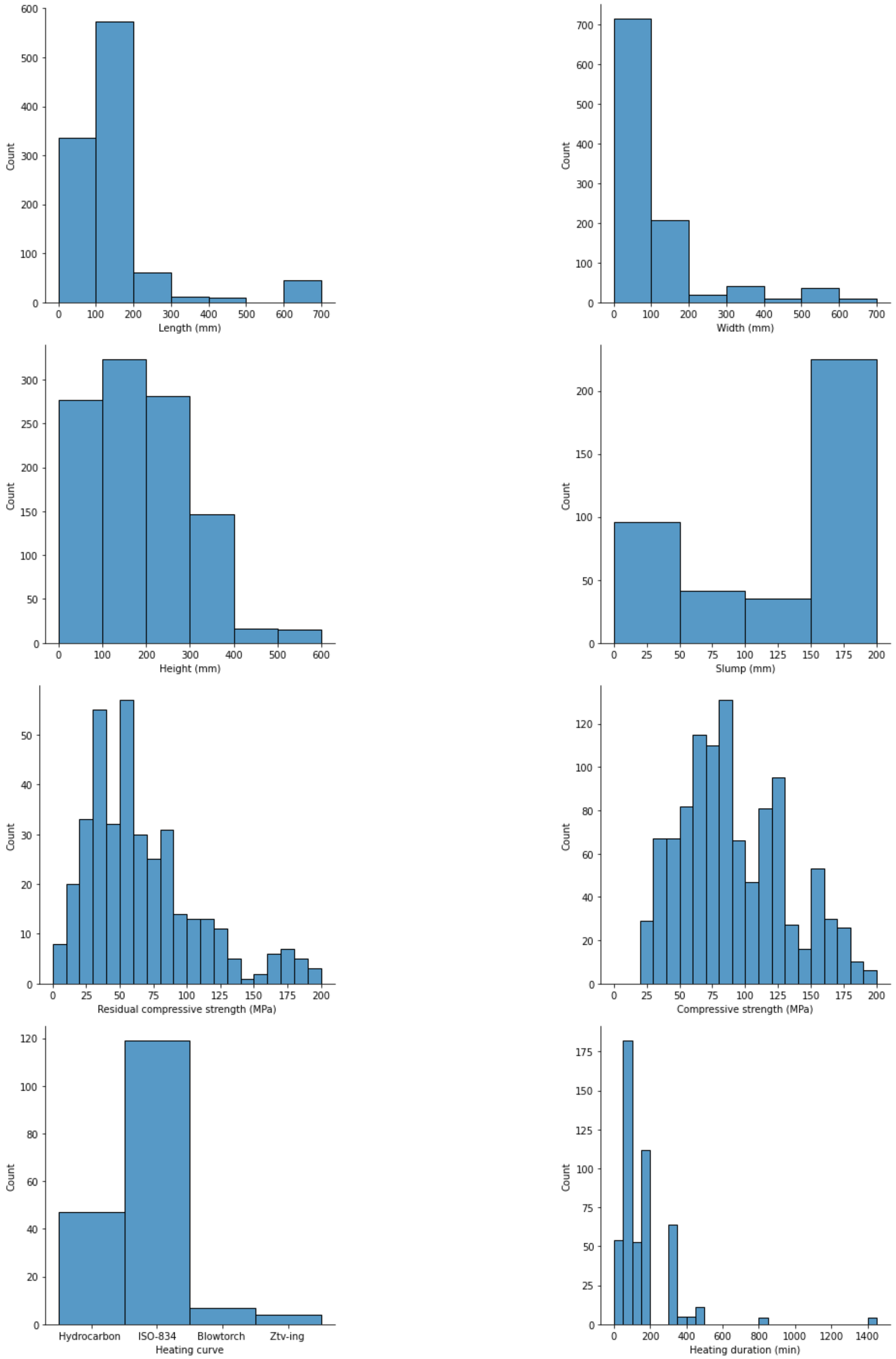

Count
0
20
40
60
80
100
120
140
160
0 5 10 15 20 25 30
PP fiber length (mm)

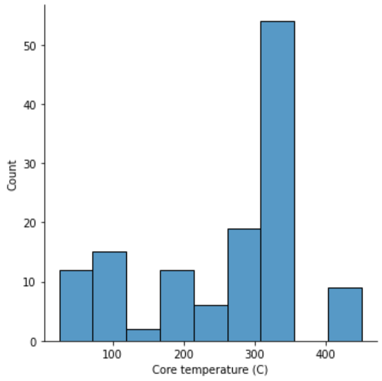

Count
0
25
50
75
100
125
150
175
200
0 10 20 30 40 50 60
S fiber length (mm)

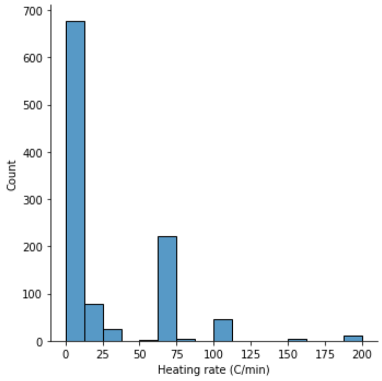

Count
0
20
40
60
80
100
0 25 50 75 100 125 150 175
S fiber quantity (Kg/m3)


Count
0
20
40
60
80
100
120
140
160
0.0 0.2 0.4 0.6 0.8 1.0
S fiber diameter (mm)


Count
0
100
200
300
400
C Cdr Slab Beam Cb Psm R-Pir Sphere
Shape


Count
0
100
200
300
400
500
600
0
100
200
300
400
500
600
700
Length (mm)
Count
0
100
200
300
400
500
600
700
0
100
200
300
400
500
600
700
Width (mm)
Count
0
50
100
150
200
250
300
0
100
200
300
400
500
600
Height (mm)
Count
0
50
100
150
200
0
25
50
75
100
125
150
175
200
Slump (mm)
Count
0
10
20
30
40
50
0
25
50
75
100
125
150
175
200
Residual compressive strength (MPa)
Count
0
20
40
60
80
100
120
0
25
50
75
100
125
150
175
200
Compressive strength (MPa)
Count
0
20
40
60
80
100
120
Hydrocarbon
ISO-834
Blowtorch
Ztv-ing
Heating curve
Count
0
25
50
75
100
125
150
175
0
200
400
600
800
1000
1200
1400
Heating duration (min)


Count
0
10
20
30
40
50
100
200
300
400
Core temperature (C)


Count
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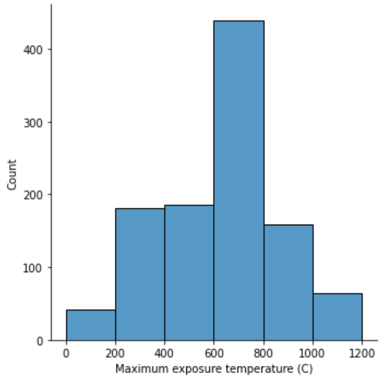
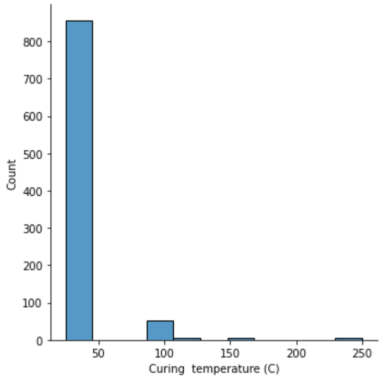
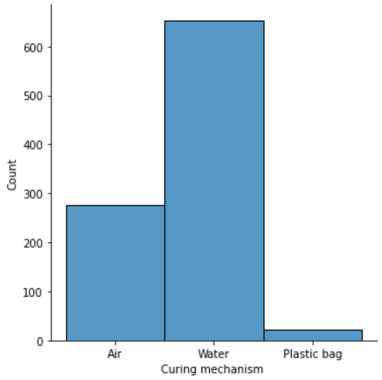
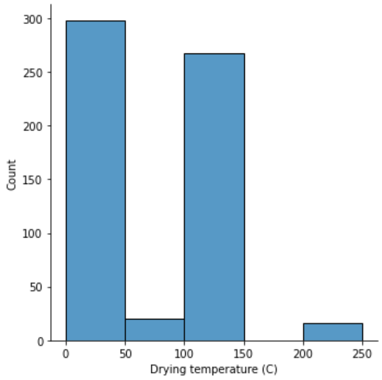
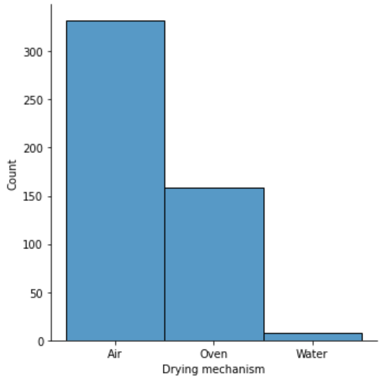
100
200
300
400
500
600
700
0
25
50
75
100
125
150
175
200
Heating rate (C/min)

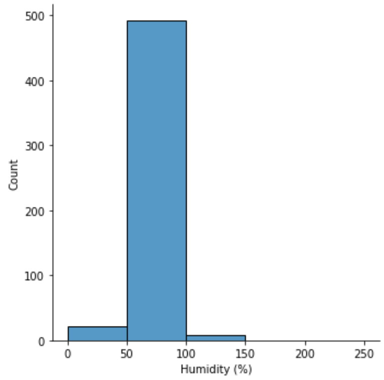

Count
0
100
200
300
400
0
200
400
600
800
1000
1200
Maximum exposure temperature (C)


Count
0
100
200
300
400
500
600
700
800
50
100
150
200
250
Curing temperature (C)


Count
0
100
200
300
400
500
600
Air
Water
Plastic bag
Curing mechanism


Count
0
50
100
150
200
250
300
0
50
100
150
200
250
Drying temperature (C)


Count
0
50
100
150
200
250
300
Air
Oven
Water
Drying mechanism


Count
0
100
200
300
400
500
0
50
100
150
200
250
Humidity (%)

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2023.133200.

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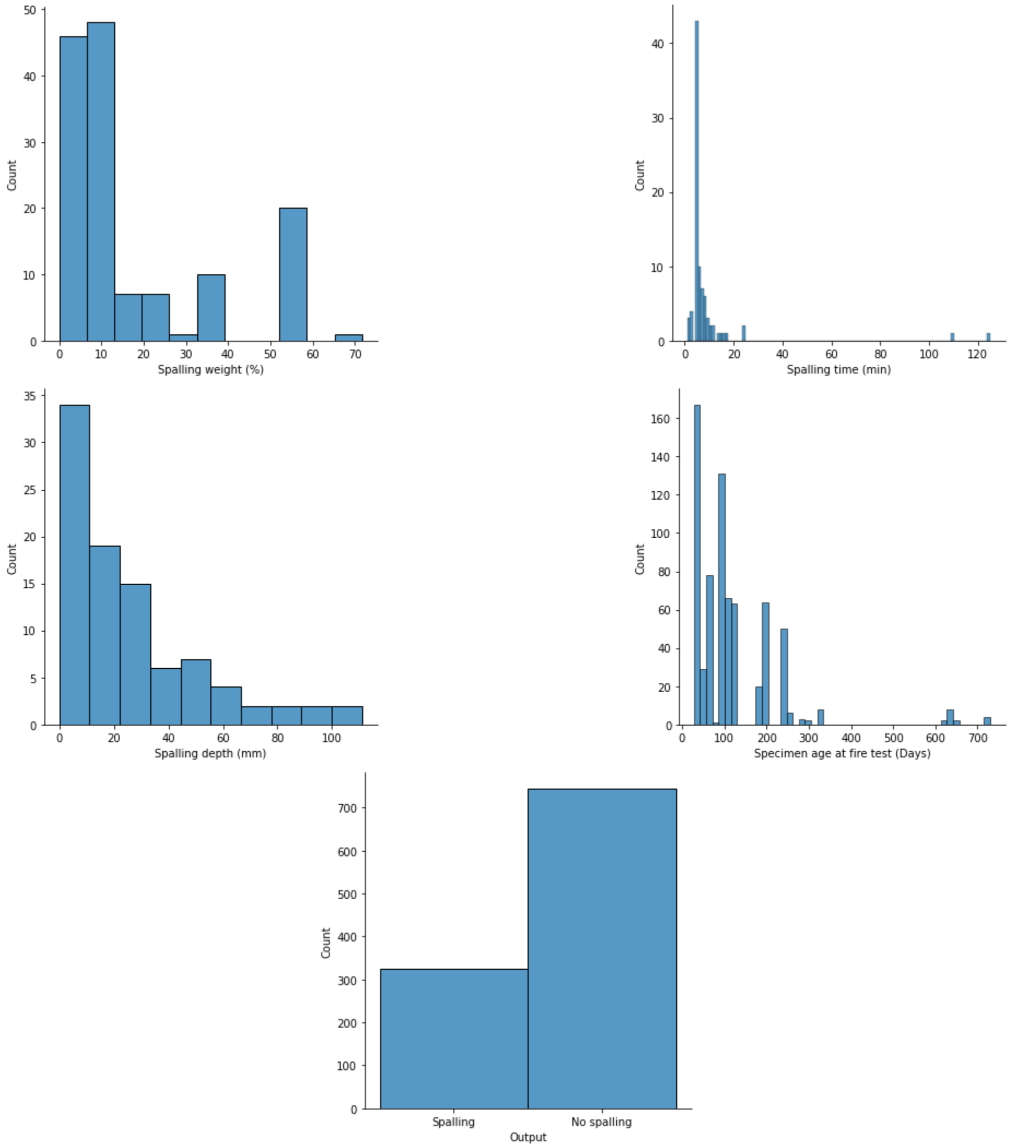

Figure 2 Summary of statistical analysis.

3.0 Database descriptive statistics

This section further describes the collected dataset in terms of factors belonging to material, mechanical, and geometrical properties and environmental and casting conditions.

3.1 Material properties

Fifteen factors fall under material properties, namely: aggregate type and size and the degree of moisture content, coarse aggregate, fine aggregate, water, cement, and silica fume, water/binder ratio, water/cement ratio, aggregate/binder ratio, sand/binder ratio, silica fume/binder ratio, FA/binder ratio, and GGBS/binder ratio, are considered herein. It is worth noting that binders are

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defined as the cumulative mixture of all the fine particles in the concrete mix, such as cement, FA (fly ash), GGBS (ground granulated blast furnace slag), and silica fume.

Ten of these 15 factors are fully reported in each collected specimen, and only eight are considered normally distributed (see Table 2). Further, the quantity of sand and silica fume, sand/binder ratio, GGBS/binder ratio, and FA/binder ratio have positive skewness (indicating a skew toward low values). In addition, this dataset contains nine types of aggregate [68]: 1) sand (no aggregate), 2) sa''tertorp, 3) river aggregates, 4) quartz, 5) limestone, 6) gravel, 7) granite, 8) carbonate, 9) basalt – see Fig. 3.

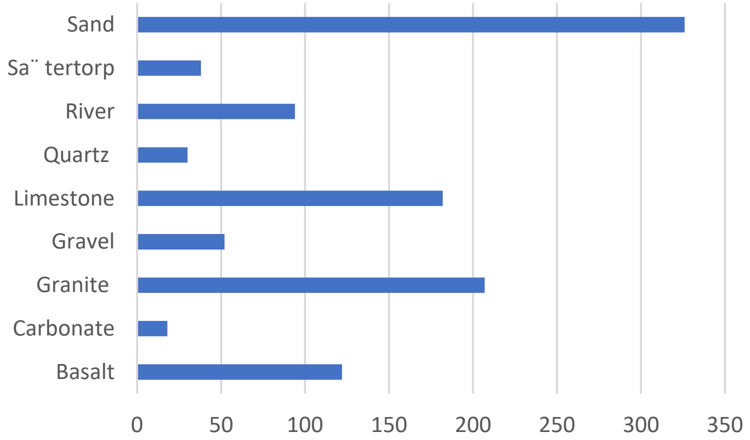

Figure 3 Summary of the aggregate types

3.2 Mechanical properties

In addition, the compressive strength of concrete was reported in most samples, and this factor is noted to be normally distributed. The number of samples accounting for the three types of concrete is as follows, NSC ranges from 0-50 MPa (164 samples), HSC ranges from 50-80 MPa (263 samples), and UHPC ranges above 80 MPa (638 samples). In addition, six factors, namely, PP fibers and steel fibers quantities, diameters, and lengths, were collected.

3.3 Geometric properties

While the majority of fire tests favored cylinders or cubes, some adopted other shapes, such as prisms, slabs, spheres, and pillars. Herein, four geometric-related factors were included, namely: specimen shape (i.e., cubes, prisms, and cylinders), height, width, and length of the specimen (see Fig. 4). As one can see, cylinders and cubes comprise more than 78.5% of all collected specimens.

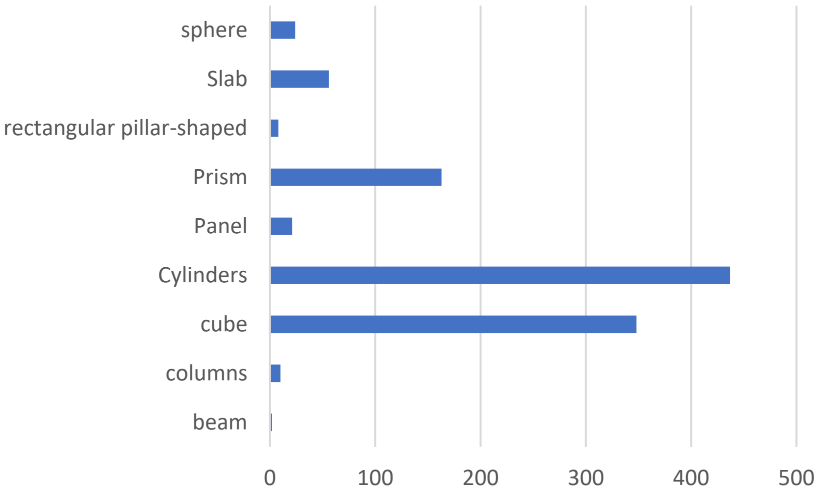

Figure 4 Summary of collected shapes.

3.4 Environmental conditions

The following factors are considered as part of the environmental properties: the heating rate, heating profile, fire duration, maximum exposure temperature, and specimen's core temperature. However, heating curves, core temperature, and the duration of fire exposure were not reported for all the reviewed tests[2]; hence, they were not selected for the filtered database.

On a more positive note, two heating curves dominated the database and accounted for 90% of the observations. These curves belong to the standard fire curve (ISO 834) and the more severe hydrocarbon fire curve. From a statistical point of view, the maximum exposure temperature is seen to be normally distributed in our dataset with a negative skewness of 0.13. Contrarily, 2.3 positive skewness was recorded for the heating rate parameter. We suspect that this significant skewness is based on the assumptions made to unify the heating curves in a procedure similar to that proposed by our colleagues [43,65], as follows:

- *If a specimen was tested under a standard fire curve, the maximum exposure temperature was taken after 10 minutes of exposing the specimen to fire. The linear heating rate from the start of the fire until reaching the maximum exposure temperature is considered the heating rate of that observation.*
- *If a multi-stage heating curve was used, the heating rate would be equal to the linear heating rate from the normal temperature (23°C) up to the maximum exposure temperature.*

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[2] Oftentimes, temperature rise was reported in only one or two specimens. A practice that is common in the reviewed works.

3.5 Concrete casting conditions

Research efforts in the open literature [69,70] note that spalling could be influenced by factors that belong to the fabrication and casting process of concrete. Thus, seven factors, namely, curing mechanism, curing temperature, curing cover, humidity, drying mechanism, and the drying temperature, in addition to specimen age at the point of testing, were collected. Statistically describing these factors shows that specimen age at fire test and curing temperature were highly skewed, indicating that we lack enough data that is distributed over the space. We would like to point out that these factors are accompanied by high skewness and thus may be difficult to interpret.

4.0 Statistical analysis

In order to carefully analyze the collected data, an effort was put to use a consistent methodology to visualize and plot the data via histograms. Table 2 lists some of the widely accepted methods to identify a proper number of bins. Upon closer inspection, we noted that these methods do not reflect the commonly adopted practical ranges reported by the surveyed papers nor the same we often see in structural fire engineering design and concrete design. For example, all methods returned a large number of bins that, in some instances, resulted in bin widths of a 0.25% point as opposed to the normally reported values of 1.0%. As such, we opt to maintain a similar number of bins that reflect commonly adopted practical ranges as reported by studies in this area, as we believe this will be more beneficial to the readers of this study.

Table 2 Summary of commonly used histogram binning methods [71–74].

Rule	Number of bins	Bin width
Sturges Rule	$Ceil(log2N)+1$	$\frac{Max-Min}{Ceil(log2N)+1}$
Rice rule	$2\times\sqrt[3]{N}$	$\frac{Max-Min}{2\times\sqrt[3]{N}}$
Scott Rule	$\frac{Max-Min}{3.5\times\frac{St.dev}{\sqrt[3]{N}}}$	$3.5\times\frac{St.dev}{\sqrt[3]{N}}$
Freedman-Diaconis rule	$\frac{Max-Min}{2\times\frac{IQR}{\sqrt[3]{N}}}$	$2\times\frac{IQR}{\sqrt[3]{N}}$

Where *N*: total number of observations, *IQR*: interquartile range, *Ceil*: rounding up to the nearest integer.

For completion, the following section presents the results of our statistical analysis. It should be noted that we refrained from drawing any inferences on bins having less than 30 samples [75] In addition, the present discussion only tackles factors having more than 300 observations in total.

4.1 Material properties

The factors that fall under this category include water, water/cement ratio, water/binder ratio, moisture content, cement, sand, sand/binder ratio, binders, and aggregates.

4.1.1 Water

Figure 6 shows that of all the collected data, almost 30%, which accounts for 272 fire tests, experienced spalling, while 646 (70%) did not spall. In total, there are 918 samples with a specified amount of water in the concrete mix, and the largest number of samples falls between 150-200kg/m^3. Unfortunately, 149 samples did not report the amount of water quantity.

As one can see, the largest number of fire tests used water content in the range of 150-200kg/m^3. In this range, the proportion of the spalled samples was 28.3%. One hundred forty-six fire tests were conducted with a water range between 200-250 kg/m^3, and the number of spalled samples were significantly high, as more than 40% of the samples exhibited spalling. Comparatively, these indicate that the higher the water content, the higher the chances of a specimen to spall. For larger bins (>250 kg/m^3), the collected data points contained an insufficient number of samples.

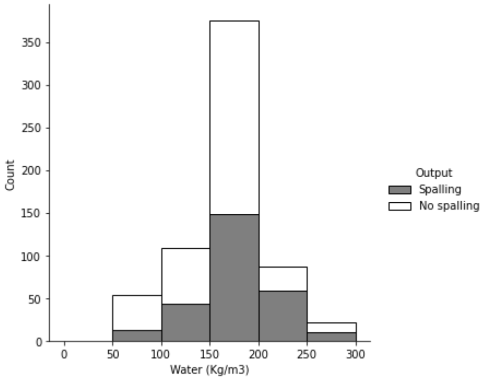


Figure 6 Water content

4.1.2 Water/cement ratio

Again, a total of 919 tests recorded the amount of water and cement quantities; 273 samples exhibited spalling, while 646 did not spall. Figure 7 shows that most reported mixtures had a low to moderate water/cement ratio. This chart reports that about 30% of the specimens within the range of 0.1-0.2% have spalled. A significant one-to-one likelihood of spalling is noted in the next range of 0.2-0.3%. The susceptibility for spalling declines between 0.3-0.4, 0.4-0.5, 0.5-0.6, and 0.6-0.7 to 21%, 26%, and 10% going forward.

In this chart, ratios ranging between 0.5%-0.9% did not satisfy the (< 30) sample limit, and thus, no inferences were made. It should be noted that a small number of specimens (~150 samples) did not include the exact quantities of water or cement, and these were substituted by using the average water-to-binder ratio (which is 0.31%).

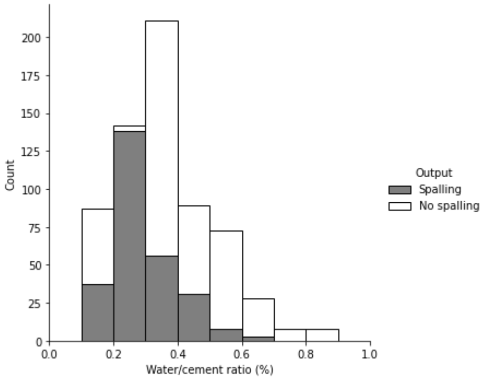


Figure 7 Water/cement ratio

4.1.3 Water/binder ratio

The water/binder ratio is included herein to cover many of the specimens that included other types of fillers. For example, a low water/binder ratio can produce higher-strength concrete reduce the permeability, and in turn, increases the vulnerability of the concrete to spalling.

Figure 8 shows that about 21.6% of the entire database accounts for samples that contain water/binder ratios ranging between 0.1 and 0.2%. In this bin, 30% of the samples spalled. This percentage increased to 38% in the next bin (i.e., 0.2-0.3%). The trend then fluctuated before declining steadily over the next ratios to 26%, 31%, 16%, and 10%, respectively. It should be noted that a higher water/binder ratio in a concrete mix is seen to lower the chances of spalling due to the fact that higher water content is tied to specimens of low compressive strength and higher permeability, thus, more spaces for moisture to migrate when exposed to fire.

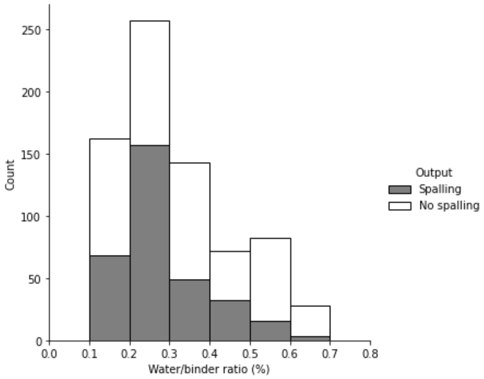


Figure 8 Water/cement ratio

4.1.4 Moisture content

A closer look into Fig. 9 shows that the likelihood of a concrete specimen to spall increases with the increase of moisture content. To illustrate the above, there were 157 with moisture content that is less than 3%, of which over 31% spalled. Furthermore, 22% and 47% of all specimens within the range of 3-4% and 4-5% have spalled. More than half of the samples contained a moisture content ranging between 5%-6%, and about 29% spalled between 6-7%.

Moisture content is one of the few factors that were explicitly listed in the Eurocode 2 to influence spalling. A limit of 3% is set as a critical limit, specifying that concrete with moisture content less than that threshold value is *unlikely* to spall under elevated temperature. As mentioned above, about one-in-three specimens is seen to spall with a moisture content of, or less than 3%.

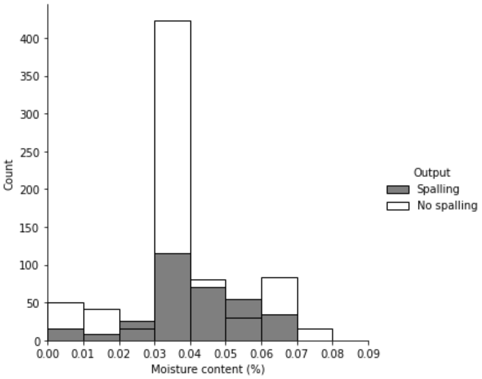


Figure 9 Moisture content

4.1.5 Cement

Most (919) specimens provide full details of the amount of cement used in their concrete mixtures. Figure 10 shows that about 11% of concrete mixtures with a cement quantity of 200-400 kg/m^3 spall in this bin range. The following bin (400-600 kg/m^3) range consists of the largest number of conducted tests of 500 samples and noted a spalling percentage of about 29%. Unlike the above, the next bin shows a one-to-one likelihood of spalling. The propensity for spalling increases beyond this range.

In one instance, the percentage of the spalled specimen boomed at the cement range of 1000-1200kg/m^3 when more than 77% of the samples exhibited spalling. However, it should be noted that all of these specimens were collected from one source and were made from UHPC.

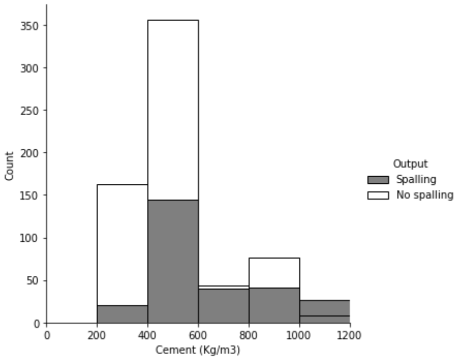


Figure 10 Cement

4.1.6 Sand

Sand is often used in concrete mixtures as a means to limit the amount of cement used and the shrinkage of concrete. The same material also helps to fill the voids created by the coarse aggregates. Looking at the collected data in Fig. 11 shows that there are 919 fire tests, of which 273 samples exhibited spalling while 646 samples did not spall (30:70). Overall, the higher the quantity of sand, the higher the propensity to spalling.

More specifically, the 250-500 kg/m^3 range shows the lowest proportion of spalled specimens, wherein only two specimens spalled. In the next bin, 22% of specimens spalled. The percentage of spalled specimens increased to 33% in the range of 750-1000kg/m^3. Lastly, the highest proportion was recorded at the sand range of 1000-1250 kg/m^3 when 108 tests were conducted; more than half (56%) of them exhibited spalling.

It is worth noting that bins between 0-250 kg/m^3, 1250-1500 kg/m3, 1500-1750 kg/m^3, and 1750-2000 kg/m^3 consisted of 3, 20, 5, and 20 samples, respectively, and hence do not satisfy the minimum required tests; thus, they were eliminated from making any conclusions.

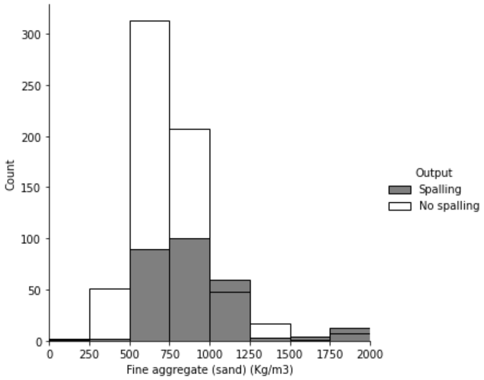


Figure 11 Sand

4.1.7 Sand/binder ratio

The database contained 1069 fire tests separated into 325 spalled samples and 744 samples that did not spall. Despite the last two bins shown in Fig. 12, we can infer that the higher the ratio of sand/binder, the lower the chances of spalling. The second bin (0.5-1%) shows that over 36% of specimens spalled with respect to the total number of tests in that bin. Similarly, the next bin shows that about 32% of specimens spalled. The percentage of spalled specimens drops to 18% in the sand-to-binder ratio of 1.5-2% and then increases beyond 3%. It should be noted that all the samples that fall in the range of 2.5-3% were exposed to a maximum exposure temperature of more than 600°C and a high heating rate of more than 65°C/min; also, almost all the spalled samples at this range had a moisture content of 5% or more. It is clear that the first and last bins can be discarded for not satisfying the 30 samples rule.

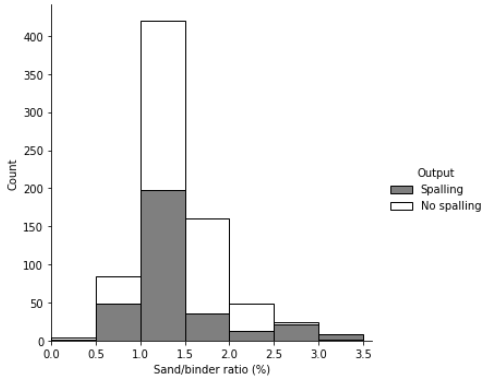


Figure 12 Sand/binder ratio

4.1.8 Binders

Binders are all the fine materials that were accounted for in the concrete mixture; in this section, the focus is on the GGBS, FA, and silica fume [48]. Note that GGBS reduces the thermal rise in the concrete and avoids early-stage cracking, and FA reduces the required water in the concrete mix and enhances the flowability of the mix. From a spalling perspective, both the GGBS and FA are under-studied, wherein more than 88% of the collected mixtures did not include GGBS or FA. In fact, only 120 samples contained FA in the concrete mix, while 113 used GGBS; hence, these two factors were not studied further.

On the contrary, silica fume is a fine binder that helps in blocking the pores within the fresh concrete matrix and reduces the bleeding of the mix. A closer look into Fig. 13 shows that increasing the silica fume/binder ratio increases the chances of concrete spalling. Most of the collected samples fall under the bin belonging to the 5% silica fume/binder ratio (about 23% of these samples spalled). Also, 98 samples used silica fume/binder ratios of a range between 5% and 10%, and almost half of these samples spalled. Checking the third and the fourth bins (ranging between 10%-15% and 15% - 20%) shows that 20% and 35% spalled specimens, respectively. Finally, larger amounts of silica fume/binder ratio of 20-25% result in a one-to-one spalling likelihood.

Similarly, it is interesting to investigate the effect of silica fume from an individual point of view. As one can see, the general trend shows that there is a direct relationship between silica fume and spalling propensity. Overall, 982 samples recorded the amount of silica fume that was included in the concrete mix; however, around 667 samples didn't use silica fume in the concrete mixture. Therefore, the chances of spalling were at its lowest proportion of 23%. A slight increase to the propensity of spalling has been observed by adding a small quantity (i.e., 50-100kg/m^3) when a quarter of the samples spalled. Along the same lines, the chances of spalling increase with adding more silica fume when all the fourth, fifth, and sixth bins show a 40-50% chance of spalling. It should be noted that the bin spaced between (150-200kg/m^3) is at the edge of satisfying the 30 samples rule that was put forward.

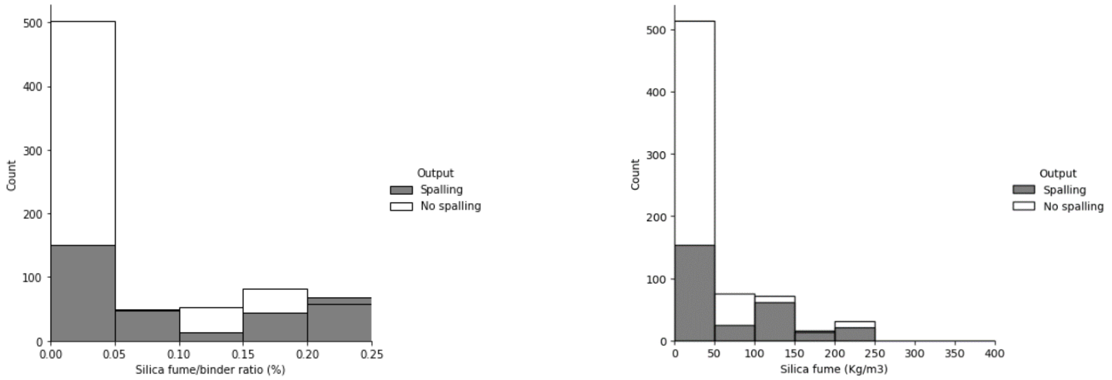


Figure 13 Silica/binder ratio (left), Silica fume (right)

4.1.9 Aggregate

Aggregates influence on spalling has been debatable over the years. Fortunately, it has been of great interest to the tests collected herein. This section is dedicated to this factor.

4.1.9.1 Coarse Aggregate

Figure 14 shows the quantities of aggregates in a concrete mix binned from 0-1750 kg/m^3. This figure reveals that there are 1069 fire tests, of which 30% of samples exhibited spalling. Overall, the trend of spalling fluctuates over different quantities of aggregates. Spalling increases at first and reaches 60% of spalling proportion before plummeting back to less than 6% with an aggregate quantity of more than 1250 kg/m^3.

Further, one can see that about one-third of the collected mixtures did not include coarse aggregates or included a small amount (0-250 kg/m^3), and about 40% of these specimens spalled. Then, in the range of 250-500 kg/m^3, 14 specimens spalled (47%) out of 30 fire tests, compared to the next bin of the 500-750 kg/m^3 range, when 30 specimens exhibited spalling (58%) out of 52 conducted tests. Above 750 kg/m^3, the spalling trend decreases to 6% at an aggregate quantity of 1250-1500 kg/m^3 when only three samples spalled out of 49 conducted fire tests.

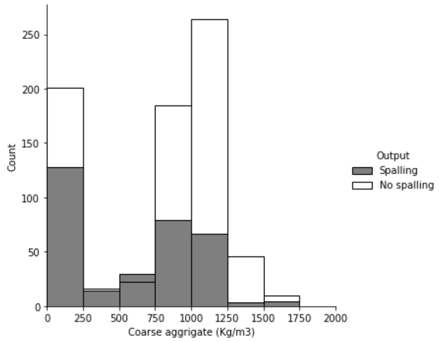


Figure 14 Coarse Aggregate

4.1.9.2 Aggregates/binder ratio

Here we analyze the aggregates/binder ratio and how this ratio impacts the propensity of spalling. Figure 15 shows that the number of spalled specimens steadily decreases with the rise in the aggregate/binder ratio. The conducted tests over the five presented bins show spalling in the proportions of 40%, 27%, 28%, and 8%. As mentioned above, the last bin was discarded due to the insufficient number of present tests.

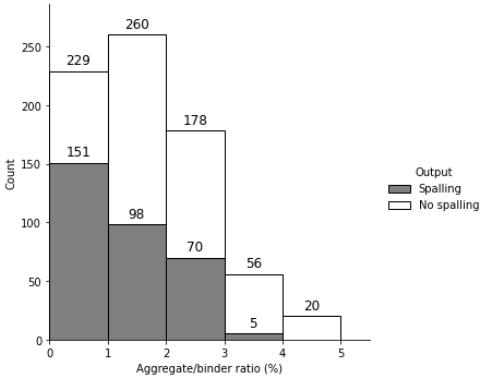


Figure 15 Aggregate/binder ratio

4.1.9.3 Aggregate type

Nine types of aggregate were found in the collected database. These include:

1. Sand fine aggregate, with a maximum size of up to 4 mm.
2. River (Rvr) aggregate, with a maximum aggregate size between 15 mm - 20 mm.
3. Granite (Grt) aggregates, with a maximum aggregate size between 7 mm - 32 mm.
4. Basalt (Bslt) aggregates, with a maximum aggregate size between 7 mm - 20 mm.
5. Carbonate (C) aggregates, with a maximum aggregate size spaced between 8 mm - 16mm.
6. Gravel (G) aggregates, with a maximum aggregate size between 10 mm - 16mm.
7. Limestone (Lim) aggregates, with a maximum aggregate size between 0.6 mm – 20 mm.
8. Sa¨tertorp (Str) aggregates, with a maximum aggregate size of 16 mm.
9. Quartz (Qrtz) aggregates with a maximum size of 0.5 mm.

In total, the type of aggregate was reported for all specimens. On the one hand, Fig. 16 shows that some of these types are more prone to spalling than others. For example, the largest percentage of spalled specimens (63%) is Sa¨tertorp aggregates, followed by quartz (47%). Sand aggregate showed a similar trend as 39% of these specimens spalled. 34% of basalt aggregates spalled, and 33% of gravel spalled as well. Overall, granite, limestone, and river aggregates showed a potential to minimize spalling, wherein only 27%, 14%, and 12% of these specimens exhibited spalling.

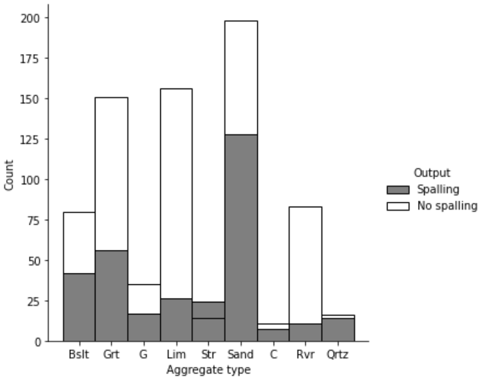


Figure 16 Aggregate type

4.1.9.4 Maximum aggregate size

This factor was found for all collected specimens. Figure 17 shows that spalling is less likely to occur for mixtures with relatively larger aggregate sizes (> 10 mm). The same figure also shows the absence of mixtures with aggregates larger than 25 mm. Evidently, 359 tests were performed without using a coarse aggregate and were substituted by fine aggregates of a maximum aggregate size of less than 5 mm (which may imply that these mixtures were of UHPC). The outcome of these tests did not improve the concrete performance under fire, as 40% of these specimens spalled. Similarly, 47% of specimens with aggregate size spaced between 5 and 10 mm spalled – see Fig. 17. Beyond this bin, the chances of spalling drop to about one-in-four to one-in-three.

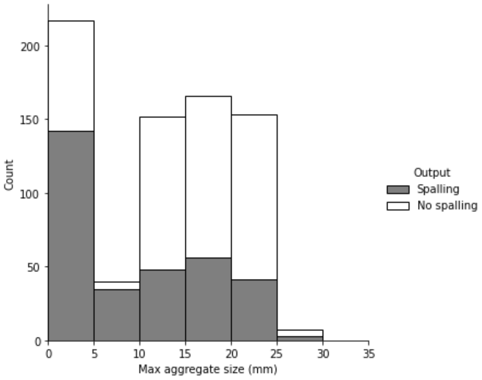


Figure 17 Maximum aggregate size

4.2 Geometric factors

In our database, different specimens' dimensions and shapes have been reported. Generally, the shapes of the tested specimens seem to influence spalling, wherein sharp-edged specimens are more prone to spalling, while round-edged shapes are less likely to spall. Also, larger surface areas (facing the fire) are more likely to spall than smaller surface areas.

Four shapes have been used, which are as follows: cubes, cylinders, prisms, and slabs. For each specimen, the length, width, and height were reported. The majority of the collected specimens were cylindrical and cubic shapes. For instance, 437 fire tests have been conducted by testing cylinders with different diameter ranges between 28 mm and 300 mm, wherein about 21% spalled. In addition, 29% of cubes and 33% of prims spalled. These percentages may indicate that there is a direct relationship between spalling and the exposed area to fire. Other shapes were also seen in the dataset; however, these do not satisfy the set limit of 30 samples.

Figure 18 also shows about 30% of samples with a height of less than 400 mm spall during testing. Most of the specimens had a width between 0-200 mm, and more the half of the database spans between the 0-100 mm range, with 23% of these specimens spalled. Also, the following bin shows that 29% of samples with a width between 100-200 mm spalled. This figure also shows that most of the samples' length range between 0-200 mm. For specimens with a length of 0-100 mm, 26% of these samples spalled. On a similar trend, 573 samples with a length of 100-200 mm, and 23% of them spalled.

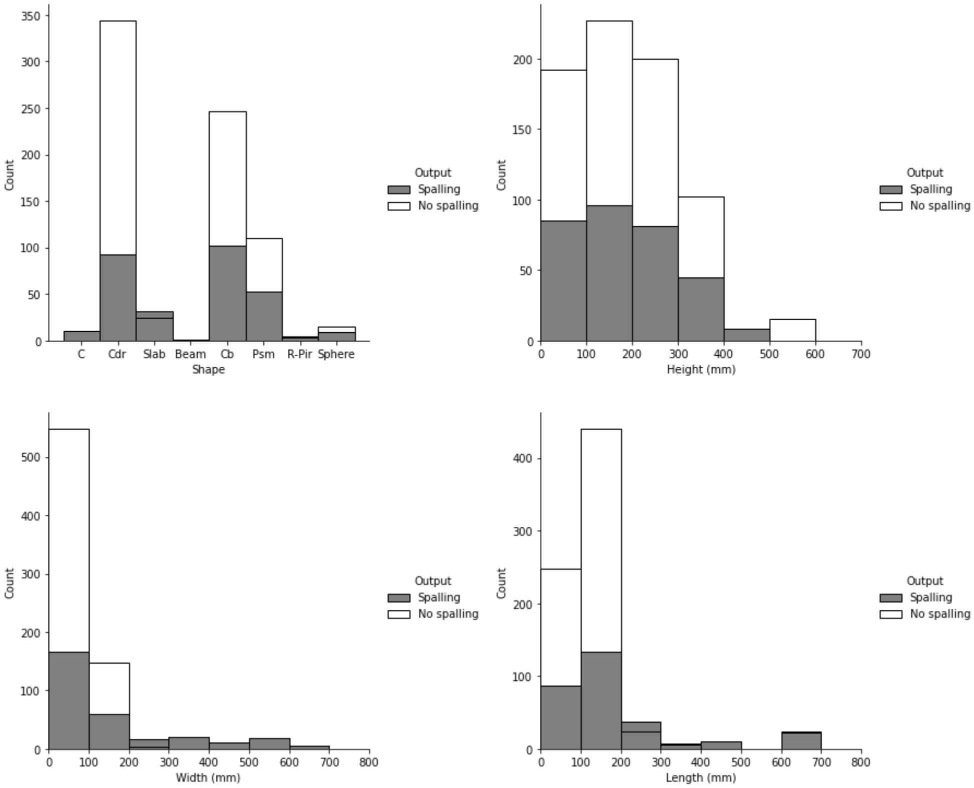


Figure 18 Geometric factors

4.3 Environmental conditions

It is well accepted that maximum exposure temperature and heating regimes are exogenous environmental factors that can influence spalling. Herein, we include data on maximum exposure temperatures, heating rates, and the duration of fire exposure. Figure 19 demonstrates these factors. This figure denotes that the higher the exposure temperature and heating rate, the higher the propensity for spalling. Further, the heating duration does not seem to show a meaningful trend or correlation to spalling.

4.3.1 Maximum exposure temperature

The lowest number of tests that exhibited spalling were recorded for the samples exposed to a relatively low temperature, below 400^{o}C (~ 6%). On the contrary, specimens exposed to relatively higher temperatures suffered from spalling. For example, 23% and 37% of specimens exposed to 400-600^{o}C and 600-800^{o}C were reported to spall. At much higher temperatures, 800-1000^{o}C and 1000-1200^{o}C, the spalling tendency increases to 35% and 80%, respectively.

4.3.2 Heating rate

Almost half of the database was subjected to low heating rates of less than 10^{o}C/min, while the other half sat in the high heating range of 10^{o}C/min and above. At a heating rate between 0-4^{o}C/min, 14% spalled. Between 4-6^{o}C/min, 22% of specimens spalled. At 6-8 ^{o}C/min and 8-10 ^{o}C/min, 7% and 31% of specimens spalled, respectively. On the high end of heating rates, 10-60 ^{o}C/min, 33% of the specimens spalled, while 58% of specimens spalled when exposed to heating rates between 60-110 ^{o}C/min.

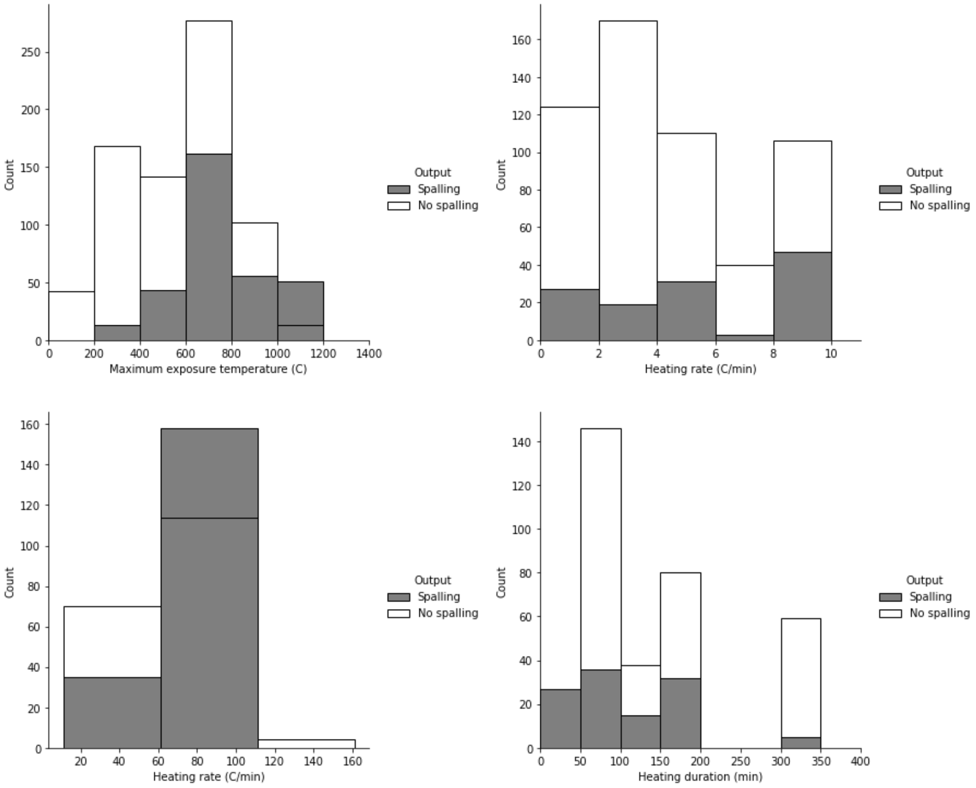
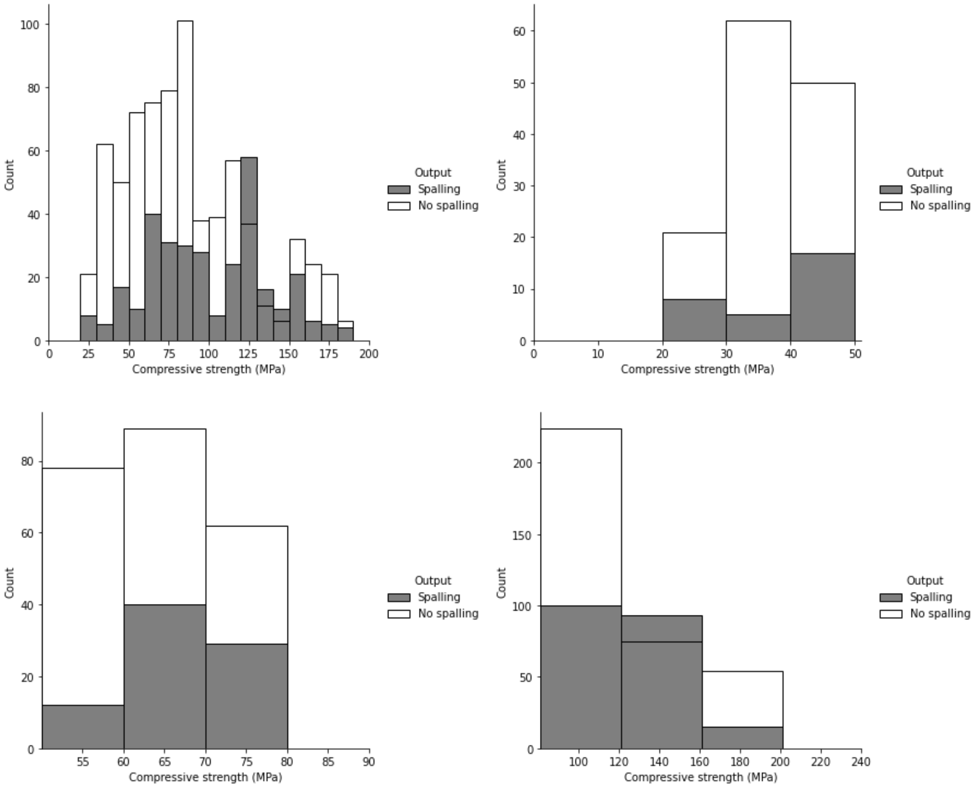


Figure 19 Heating rate

4.4 Mechanical properties

Concrete mechanical properties are the term that describes the parameters that govern the strength of the concrete. The compressive strength is one critical factor. Oftentimes, concrete is divided into three types: NSC (<50 MPa), HSC (50-80 MPa), and UHPC (>80 MPa). In this dataset, 16% of the collected fire tests were NSC type, around 29% were HSC, and the rest were UHPC. Under NSC, HSC, and UHPC, 20%, 25%, and 35% of the specimens spalled, respectively. Thus, one can see that the higher the strength, the larger the propensity to spall (see Fig. 20).

Another factor that falls under the mechanical properties is the result of the slump tests (used to evaluate the workability of fresh concrete). For concrete of low workability (slump = 0-50 mm) and high workability (150-200 mm), 15% and 32% of the specimens spalled. It seems that the higher the slump of a concrete mixture, the higher the propensity to spalling under elevated temperatures.



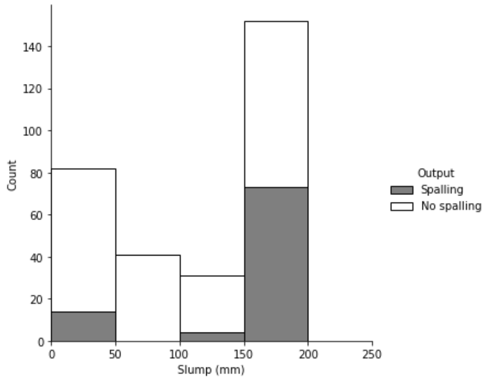


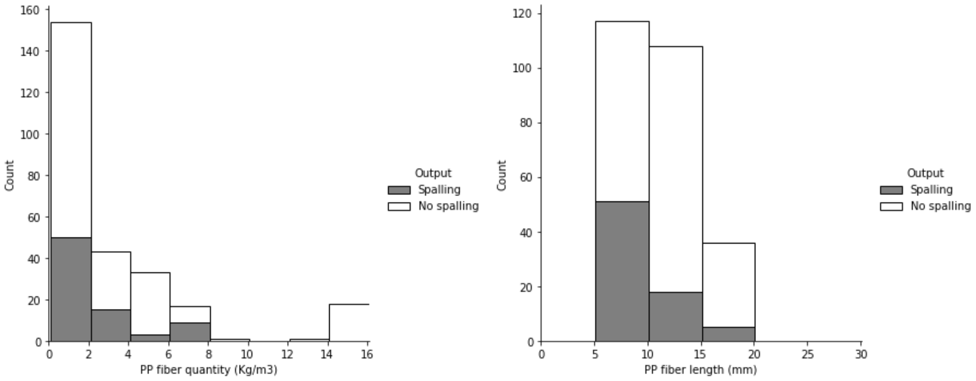
Figure 20 Mechanical properties

4.5 Fibers

A few solutions have been proposed recently to mitigate spalling, such as using PP and steel fibers [56,76]. This section goes over these fibers.

<u>4.5.1 PP fibers</u>

In this dataset, PP fibers were only used in about 32% of all the surveyed tests. The majority of these tests used PP fibers within the range of 2 kg/m^3 and the 2-4 kg/m^3 range (see Fig. 21). About 25% of the specimens in these ranges spalled. The geometric features in terms of the length and diameter of the PP fibers were collected. As one can see, there seems to be a positive association herein; as the length increases, the propensity of spalling decreases. For example, 30% of the specimens with PP fibers of a length between 5-10 mm spalled, and this percentage dropped to 14% for specimens with a length between 10-15 mm. We were not to identify a consistent trend for the PP diameter.



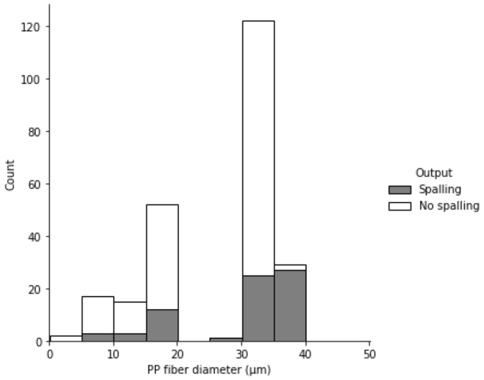


Figure 21 PP fibers

4.5.2 Steel fibers

There were 272 specimens with steel fibers in the database. In general, specimens with steel fibers did not spall as much (10-22%) for the most part, except for the ranges of 50-75 kg/m^3 and >100 kg/m^3. In the latter, the percentage of the spalled specimens significantly increased. Figure 22 shows that steel fibers of larger size have fewer specimens that spalled as opposed to specimens of smaller-sized fibers.

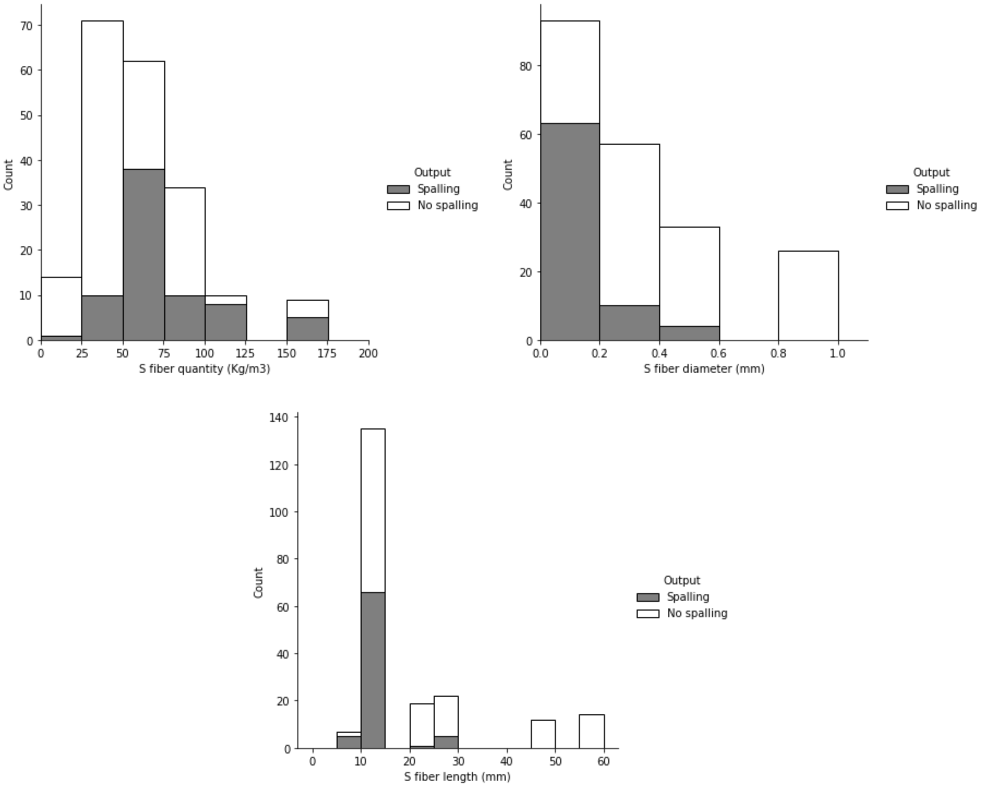


Figure 22 Steel fibers

4.6 Curing and drying (casting) conditions

The importance of curing and drying factors, from a spalling point of view, arises from the notion that such factors are tied to the strength of concrete and resulting moisture content. Six factors were considered: curing temperature, curing mechanism, humidity, drying temperature, drying mechanism, and specimen age. However, our discussion will only highlight the curing mechanism and the age of the specimens, as there was an insufficient number of specimens to cover the other factors.

4.6.1 Curing mechanism

There are 951 specimens with specified curing mechanisms – see Fig. 23. These mechanisms fall under; *air* (represents samples that were cured at ambient conditions), *lab* (represents samples that were cured while submerged under water), and lastly, covered (represents samples that were cured while covered by a plastic covering). The air mechanism consisted of 276 samples, which accounts for almost 29% of the database, while the water mechanism accounted for 653 (69%). The third mechanism did not contain enough fire tests to make solid inferences. Overall, samples cured via the air mechanism seem more prone to spalling than the water mechanism, as 46% and 26% of samples spalled when exposed to fire, respectively.

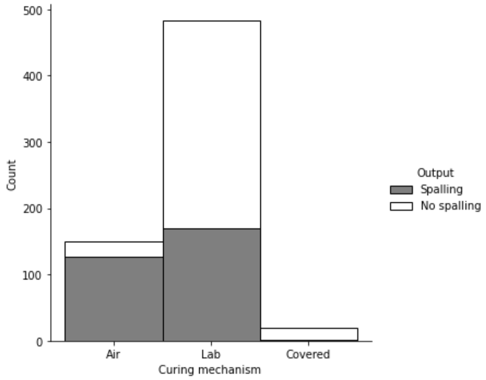


Figure 23 Curing mechanism

4.6.2. Specimens age

As we can see, the first three bins in Fig. 24 contain the majority of the collected samples. Only 20% of the first bin spalled during testing, while 37% and 46% of the specimens in the second and third bin spalled, respectively. In addition, 22% of specimens of older age (200-250 days) spalled.

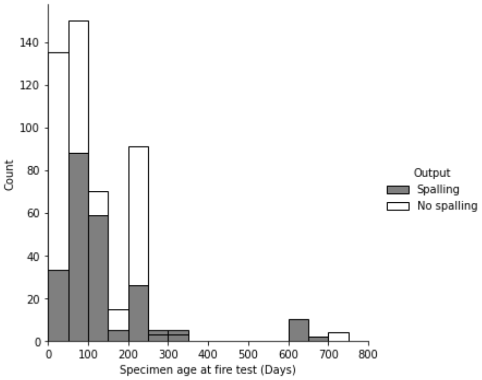


Figure 24 Specimen age

5.0 Summary

This section summarizes the above findings in a tabulated format. Table 3 shows further insights into all bins and data that were not explicitly mentioned in their respective discussions. This table also labels the ranges with a relatively small number of samples (>30) as taken throughout this paper. While we favor future research efforts to focus on such ranges (bins), additional research on all ranges of factors is welcome and of merit.

Table 3. showcases the overall database's outcomes

Bins									
Water (Kg/m^3)	0-50	50-100	100-150	150-200	200-250	250-300	300-350		
Number of spcms/Bin	0	66	151	523	146	27	6		
Number of spalled spcms/Bin	0	12	43	148	59	9	2		
Number of non spalled spcms/Bin	0	54	108	375	87	18	4		
% of spalled spcms	0	18	28	28	40	33	33		
Need future research	√	√	X	X	X	√	√		
Bins									
Water/binder ratio (%)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7		
Number of spcms/Bin	0	230	414	192	104	98	31		
Number of spalled spcms/Bin	0	68	157	49	32	16	3		
Number of non spalled spcms/Bin	0	162	257	143	72	82	28		
% of spalled spcms	0	30	38	26	31	16	10		
Need future research	√	X	X	X	X	√	X		
Bins									
Water/cement ratio (%)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9
Number of spcms/Bin	0	124	280	267	120	81	31	8	8
Number of spalled spcms/Bin	0	37	138	56	31	8	3	0	0
Number of non spalled spcms/Bin	0	87	142	211	89	73	28	8	8
% of spalled spcms	0	30	49	21	26	10	10	0	0
Need future research	√	X	X	X	X	X	X	√	√
Bins									
Cement (Kg/m^3)	0-200	200-400	400-600	600-800	800-1000	1000-1200	1200-1400		
Number of spcms/Bin	0	184	500	83	117	35	0		
Number of spalled spcms/Bin	0	21	144	40	41	27	0		
Number of non spalled spcms/Bin	0	163	356	43	76	8	0		
% of spalled spcms	0	11	29	48	35	77	0		
Need future research	√	X	X	X	X	X	√		
Bins									
Coarse aggrigate (Kg/m^3)	0-250	250-500	500-750	750-1000	1000-1250	1250-1500	1500-1750		
Number of spcms/Bin	329	30	52	264	331	49	14		
Number of spalled spcms/Bin	128	14	30	79	67	3	4		
Number of non spalled spcms/Bin	201	16	22	185	264	46	10		
% of spalled spcms	39	47	58	30	20	6	29		
Need future research	X	X	X	X	X	X	√		
Bins									
Aggregate/binder ratio (%)	0-1	1-2	2-3	3-4	4-5	5-6			
Number of spcms/Bin	380	358	248	61	20	2			
Number of spalled spcms/Bin	151	98	70	5	0	1			
Number of non spalled spcms/Bin	229	260	178	56	20	1			
% of spalled spcms	40	27	28	8	0	50			
Need future research	X	X	X	X	√	√			
Bins									
Fine aggregate (sand) (Kg/m^3)	0-250	250-500	500-750	750-1000	1000-1250	1250-1500	1500-1750	1750-2000	
Number of spcms/Bin	3	53	403	307	108	20	5	20	
Number of spalled spcms/Bin	2	2	90	100	60	3	4	13	
Number of non spalled spcms/Bin	1	51	313	207	48	17	1	7	
% of spalled spcms	67	4	22	33	56	15	80	65	
Need future research	√	X	X	X	X	√	√	√	
Bins									
Sand/binder ratio (%)	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5		
Number of spcms/Bin	5	133	618	196	62	45	10		
Number of spalled spcms/Bin	1	48	198	35	13	21	9		
Number of non spalled spcms/Bin	4	85	420	161	49	24	1		
% of spalled spcms	20	36	32	18	21	47	90		
Need future research	√	X	X	X	X	X	√		
Bins									
Moisture content (%)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9
Number of spcms/Bin	66	50	41	539	152	85	118	15	3
Number of spalled spcms/Bin	15	9	25	116	71	55	34	0	0
Number of non spalled spcms/Bin	51	41	16	423	81	30	84	15	3
% of spalled spcms	23	18	61	22	47	65	29	0	0
Need future research	X	X	X	X	X	X	X	√	√
Bins									
Silica fume/binder ratio (%)	0.0-0.05	0.050.1	0.1-0.15	0.15-0.2	0.2-0.25	0.25-0.3			
Number of spcms/Bin	653	98	65	127	126	0			
Number of spalled spcms/Bin	151	50	13	45	68	0			
Number of non spalled spcms/Bin	502	48	52	82	58	0			
% of spalled spcms	23	51	20	35	54	0			
Need future research	X	X	X	X	X	√			
Bins									
GGBS/binder ratio (%)	>0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6			
Number of spcms/Bin	1	2	42	10	58	0			
Number of spalled spcms/Bin	1	0	4	0	16	0			
Number of non spalled spcms/Bin	0	2	38	10	42	0			
% of spalled spcms	100	0	10	0	28	0			
Need future research	√	√	X	√	X	√			
Bins									
FA/binder ratio (%)	>0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6			
Number of spcms/Bin	38	27	46	8	0	1			
Number of spalled spcms/Bin	4	8	0	0	0	1			

Number of non spalled spcms/Bin	34	19	46	8	0	0			
% of spalled spcms	11	30	0	0	0	100			
Need future research	X	√	X	√	√	√			
Bins									
Max aggregate size (mm)	0-5	5-10	10-15	15-20	20-25	25-30	30-35		
Number of spcms/Bin	359	75	200	222	194	10	9		
Number of spalled spcms/Bin	142	35	48	56	41	3	0		
Number of non spalled spcms/Bin	217	40	152	166	153	7	9		
% of spalled spcms	40	47	24	25	21	30	0		
Need future research	X	X	X	X	X	√	√		
Bins									
Aggregate type	Basalt	Granite	Gravel	Limestone	Sa¨ tertorp	Sand	Carbonate	River	Quartz
Number of spcms/Bin	122	207	52	182	38	326	18	94	30
Number of spalled spcms/Bin	42	56	17	26	24	128	7	11	14
Number of non spalled spcms/Bin	80	151	35	156	14	198	11	83	16
% of spalled spcms	34	27	33	14	63	39	39	12	47
Need future research	X	X	X	√	X	X	√	X	X
Bins									
PP fiber quantity (Kg/m^3)	>0-2	2-4	4-6	6-8	8-10	10-12	12-14	14--16	
Number of spcms/Bin	204	58	36	26	1	0	1	18	
Number of spalled spcms/Bin	50	15	3	9	0	0	0	0	
Number of non spalled spcms/Bin	154	43	33	17	1	0	1	18	
% of spalled spcms	25	26	8	35	0	0	0	0	
Need future research	X	X	X	√	√	√	√	√	
Bins									
PP fiber diameter (μm)	<0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
Number of spcms/Bin	2	20	18	64	0	2	147	56	35
Number of spalled spcms/Bin	0	3	3	12	0	1	25	27	6
Number of non spalled spcms/Bin	2	17	15	52	0	1	122	29	29
% of spalled spcms	0	15	17	19	0	50	17	48	17
Need future research	√	√	√	X	√	√	X	X	X
Bins									
PP fiber length (mm)	<0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
Number of spcms/Bin	0	168	126	41	0	9	0	0	
Number of spalled spcms/Bin	0	51	18	5	0	3	0	0	
Number of non spalled spcms/Bin	0	117	108	36	0	6	0	0	
% of spalled spcms	0	30	14	12	0	33	0	0	
Need future research	√	X	X	√	√	√	√	√	
Bins									
S fiber quantity (Kg/m^3)	<0-25	25-50	50-75	75-100	100-125	125-150	150-175	175-200	
Number of spcms/Bin	15	81	100	44	18	0	14	14	
Number of spalled spcms/Bin	1	10	38	10	8	0	5	5	
Number of non spalled spcms/Bin	14	71	62	34	10	0	9	9	
% of spalled spcms	7	12	38	23	44	0	36	0	
Need future research	√	X	X	X	√	√	√	√	
Bins									
S fiber diameter (mm)	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1				
Number of spcms/Bin	156	67	37	0	26				
Number of spalled spcms/Bin	63	10	4	0	0				
Number of non spalled spcms/Bin	93	57	33	0	26				
% of spalled spcms	40	15	11	0	0				
Need future research	X	X	X	√	√				
Bins									
S fiber length (mm)	0-5	5--10	10--15	15--20	20-25	25-30	>30		
Number of spcms/Bin	0	12	201	0	20	27	26		
Number of spalled spcms/Bin	0	5	66	0	1	5	0		
Number of non spalled spcms/Bin	0	7	135	0	19	22	26		
% of spalled spcms	0	42	33	0	5	19	0		
Need future research	√	√	X	√	√	√	√		
Bins									
Shape	Column	Cilyinder	Slab	Beam	Cube	Prism	R-P-Column	Sphere	Panel
Number of spcms/Bin	10	437	56	2	348	163	8	24	21
Number of spalled spcms/Bin	10	93	31	1	102	53	5	9	21
Number of non spalled spcms/Bin	0	344	25	1	246	110	3	15	0
% of spalled spcms	100	21	55	50	29	33	63	38	100
Need future research	√	X	X	√	X	X	√	√	√
Bins									
Length (mm)	0-100	100-200	200-300	300-400	400-500	500-600	600-700	>700	
Number of spcms/Bin	335	573	61	12	10	0	45	33	
Number of spalled spcms/Bin	87	133	38	5	10	0	22	30	
Number of non spalled spcms/Bin	248	440	23	7	0	0	23	3	
% of spalled spcms	26	23	62	42	100	0	49	91	
Need future research	X	X	X	√	√	√	X	X	
Bins									
Width (mm)	0-100	100-200	200-300	300-400	400-500	500-600	600-700	>700	
Number of spcms/Bin	714	207	20	40	10	37	10	31	
Number of spalled spcms/Bin	166	60	17	20	10	19	5	29	
Number of non spalled spcms/Bin	548	147	3	20	0	18	5	2	
% of spalled spcms	23	29	85	50	100	51	50	94	
Need future research	X	X	√	X	√	X	√	X	
Bins									
Height (mm)	0-100	100-200	200-300	300-400	400-500	500-600	600-700	>700	
Number of spcms/Bin	277	323	281	147	16	15	0	10	

Number of spalled spcms/Bin	85	96	81	45	8	0	0	10	
Number of non spalled spcms/Bin	192	227	200	102	8	15	0	0	
% of spalled spcms	31	30	29	31	50	0	0	100	
Need future research	X	X	X	X	√	√	√	√	
Bins									
Heating rate (C/min)	0-2	2-4	4-6	6-8	8-10	10-60	60-110	110-160	160-200
Number of spcms/Bin	151	189	141	43	153	105	272	4	11
Number of spalled spcms/Bin	27	19	31	3	47	35	158	0	5
Number of non spalled spcms/Bin	124	170	110	40	106	70	114	4	6
% of spalled spcms	18	10	22	7	31	33	58	0	45
Need future research	X	X	X	X	X	X	X	√	√
Bins									
Maximum exposure temperature (C)	0-200	200-400	400-600	600-800	800-1000	1000-1200	1200-1400		
Number of spcms/Bin	42	181	185	439	158	64	0		
Number of spalled spcms/Bin	0	13	43	162	56	51	0		
Number of non spalled spcms/Bin	42	168	142	277	102	13	0		
% of spalled spcms	0	7	23	37	35	80	0		
Need future research	√	√	X	X	X	√	√		
Bins									
Specimen age at fire test (Days)	0-50	50-100	100-150	150-200	200-250	250-300	300-350	>350	
Number of spcms/Bin	168	238	129	20	117	8	8	16	
Number of spalled spcms/Bin	33	88	59	5	26	5	5	12	
Number of non spalled spcms/Bin	135	150	70	15	91	3	3	4	
% of spalled spcms	20	37	46	25	22	63	63	75	
Need future research	X	X	X	√	X	√	√	√	
Bins									
Curing mechanism	Air	Water	Plastic cover						
Number of spcms/Bin	276	653	22						
Number of spalled spcms/Bin	127	170	2						
Number of non spalled spcms/Bin	149	483	20						
% of spalled spcms	46	26	9						
Need future research	X	X	√						
Bins									
	NSC			HSC			UHPC		
Compressive strength (MPa)	20-30	30-40	40-50	50-60	60-70	70-80	80-120	120-160	160-200
Number of spcms/Bin	29	67	67	82	115	110	325	191	77
Number of spalled spcms/Bin	8	5	17	10	40	31	90	105	17
Number of non spalled spcms/Bin	21	62	50	72	75	79	235	86	60
% of spalled spcms	28	7	25	12	35	28	28	55	22
Need future research	√	X	X	X	X	X	X	X	X
Bins									
Slump (mm)	0-50	50-100	100-150	150-200	200-250	250-300			
Number of spcms/Bin	96	41	35	225	0	0			
Number of spalled spcms/Bin	14	0	4	73	0	0			
Number of non spalled spcms/Bin	82	41	31	152	0	0			
% of spalled spcms	15	0	11	32	0	0			
Need future research	X	X	X	X	√	√			

6.0 Challenges and limitations and future research direction

This section outlines some of the challenges and limitations faced during this work. As typical of a statistical investigation, we must be cognizant of the fact that the collected tests were compiled from different and diverse research groups. While the compilation of the presented database and this presented statistical analysis aim to shed more light on the spalling phenomenon, it is equally important to note that one of the factors that were not discussed pertains to the effect of testing set-up and equipment used in the fire tests. We hope that such a factor, as well as those that may fall under testing equipment and procedure, will be examined in future works. In addition, this database considers three types of concrete based on their compressive strength (NSC, HSC, and UHPC). Other types of concrete, such as lightweight, pre-cast, or self-compacted concrete, were not examined herein. In addition, some of the spalling related factors that seem to be of high interest in the domain (i.e., spalling temperature, spalling time, spalling depth) were not mentioned in many of the database sources. We invite interested researchers to examine such database via clustering or segmentation analysis. In addition, various correlation/association analyses can be carried out to examine new relationships between the complied factors. Machine learning could potentially be used as well to predict the spalling phenomena.

7.0 Conclusions

This study presents a statistical investigation of over 1000 fire tests with a focus on fire-induced concrete spalling. In this analysis, 43 factors spanning material, mechanical, and geometrical properties, as well as environmental and casting conditions concerning the spalling phenomenon, were explicitly analyzed and discussed. The following inferences further summarize the findings of this investigation:

- This statistical investigation has shed light on some critical gaps that need to be considered and filled in order to pave the way to better understand spalling. Future works may consider conducting tests on these critical zones, which will, ultimately, help us understand how concrete behaves in these specific parameters' spaces.
- Increased water content typically raises the chance of spalling because of the micro cracks that could potentially form due to the evaporation process during the fire. Similarly, a greater water-to-binder ratio in concrete appears to reduce spalling probability.
- As the aggregate-to-binder ratio rises, the potential for concrete spalling diminishes as aggregates dilate at a different rate than cement shrinks, which forms stresses that can lead to spalling.
- Granite, limestone, and river aggregates were associated with a lower tendency for spalling as these aggregates can maintain their strength properties to a higher level than others (i.e., quartz).
- Concrete is less likely to spall when using larger aggregate sizes, significantly when we exceed an aggregate size of 10 mm, taking into consideration the types of aggregates used.

- Larger surface areas exposed to fire are more likely to spall in comparison with smaller surface areas.
- The higher the exposure temperature, the more the propensity of a specimen to spall, initially around 500^{o}C and extensively above 800^{o}C.
- The spalling tendency increases with the increase of compressive strength property.
- PP fibers were only used in about 32% of all the surveyed tests. More tests on PP fibers and steel fibers are needed to better quantify their role with respect to spalling.
- Overall, samples cured in open air seem more prone to spalling than those cured under water.
- There is limited data on heating rates in the range of 10^{o}C/min and above.

8.0 List of abbreviations

NSC: Normal-strength concrete

HSC: High-strength concrete

UHPC: ultra-high-performance concrete

GGBS: ground granulated blast furnace slag

FA: Fly ash

PP fibers: polypropylene fibers

ACI: Amereican concrete institute

RILEM: The International Union of Laboratories and Experts in Construction Materials, Systems and Structures

BLEVE: The Boiling Liquid Expanding Vapour Explosion

Rvr: River aggregate

Grt: Granite aggregates

Bslt: Basalt aggregates

C: Carbonate aggregates

G: Gravel aggregates

Lim: Limestone aggregates

Str: Sa¨tertorp aggregates

Qrtz: Quartz aggregates

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