Construction process with reinforced concrete. Photo by the authors.

Mix design of durable concrete with the additions of silica fume or fly ash

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Abstract: The aim of the research is the laboratory study of a durable concrete, according to UNI-EN 206-1 and 11104, comparing four types of concrete by varying the type of binder to highlight some aspects of durability. For each type of concrete, to graph the correlations between: W/C ratio - resistance; cement dosage - strength; days of ripening-resistance; three mixes were packaged by varying the W/C ratio and the cement dosage. Three durable concretes were then designed, by way of example, with resistance class C30/37, exposure class XS1, workability class S5, maximum diameter 20 mm, by varying the type of binder to enhance some aspects of durability:

- Type 1) With Portland II-A-LL 32.5 R cement
- Type 2) With Portland II-A-LL 32.5 R cement + 11% silica fume
- Type 3) With Portland II-A-LL 32.5 R cement + 22% fly ash.

A cost analysis was then conducted for the concretes type 1), 2), 3), to highlight the incidence of additions in the concrete, and the benefits in terms of mechanical resistance to compression..

Keywords: concrete, durability, silica fume, fly ash.

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1. Ancient concrete

From an etymological point of view, the term concrete derives from the Latin calcis-structi, i.e., lime-based structure. The term used by Vitruvius to define a conglomerate, a pier like the concrete we use today, was opus caementicium, made up of stone or brick scraps mixed with lime, sand and water. For hydraulic works, or works exposed to the action of rainwater, the sand was partly replaced by pozzolana (pulvis puteolana) or earthenware. The scrap stone used to make the concrete was "no bigger than a hand" and was called caementum, from the Latin caedo "to cut pieces". The choice of materials, the composition and methods of implementation of the concrete used at the time of the Roman Empire are reported in detail by Vitruvius in his 10 books of "De Architectura".

Beyond the etymological aspects, the main difference between ancient and modern concrete lies in the type of binder: the Romans used lime and pozzolana or lime and silica or alumina impurities which gave the mixture hydraulic properties, while in modern concrete the binder is the cement.

Before the advent of concrete, the construction of large buildings could last for centuries due to the difficulty and slowness in moving the large stones that were used. To get the order of magnitude of construction times, just remember that five centuries took place in saxum quadratum for the construction of the Temple of Apollo in Didima (from 332 BC to about 130 AD), while the Pantheon was built in opus caementicium only seven years (118 AD to 125 AD).

The technique was simple: two wall facings were built which served as formworks and the concrete was poured inside. However, the reduced execution times of the opus caementicium depended above all on the use of pozzolana which, mixed with lime, gave the conglomerate an accelerated hardening. The discovery of pozzolana marked progress in ancient concrete constructions due to the ability of the lime-pozzolana mixture to harden, not only in the absence of CO_2, but also with a speed greater than that required by the lime carbonation process. The hydraulic qualities of the pozzolana were well known to Vitruvius who, in the fifth book in chapter XII of De Architectura, with regard to the construction of ports writes:

> The structure of the pier intended to remain underwater must be manufactured with pozzolan powder imported from that region which extends from Cuma to the promontory of Minerva, mixed with lime in the ratio of two to one. Therefore it will be necessary to lower it into the water, in the area pre-established, bottomless caissons which will be firmly tightened with oak poles and anchored by means of chains, then we will proceed to level and clean up the part of the seabed between them, making sure to make a casting of mortar and concrete as is as mentioned above, until the wall structure has completely filled the void of the caissons.

On the merits of the sand, Vitruvius in the second book to chapter IV of his treatise writes:

> In concrete constructions, first you need to find the right sand, not mixed with the ground, to mix the mortar. The varieties of quarry sand are black, white, red and dark red. Excellent is the one that when rubbed between the fingers produces a slight crackle. The one mixed with the ground, on the other hand, has no roughness characteristics. Equally good in quality is that which, thrown on a white sheet, will not leave traces of earth or dirt after being shaken off.

The workers, called "lime cookers", to produce the lime they chose limestone stones with a high content of CaO, to obtain a very fat lime. To leave no doubts about the basic materials to be used, Vitruvius provided, in the seventh book of De Architectura in chapter II, specific indications on the quality of the lime:

> Once the maceration is complete and after having scrupulously prepared everything for implementation, take a trowel and in the same way as you cut wood with an axe, cut it with that of lime. If lumps are found, it means that the lime is not ready; if the trowel comes out dry and clean it means that the lime is weak and arid, while to be greasy and well macerated it must remain stuck like glue to the iron of the trowel.

In conclusion, mixtures of sand-based aggregates (0-5 mm) and stone or brick scraps (30-50 mm) were used in ancient concrete, resulting in practically no intermediate fractions. For the good result of the work, they relied on beating, or compaction, both for the plaster mortars and for the concretes and Vitruvius' warnings in this regard were also confirmed by Pliny who, for the concretes used for the construction of the cisterns, recommended that the foundations and sides be well hammered with iron hammers.

Table 1 summarizes the differences in performance and composition of ancient concrete and modern concrete.

Table 1 | Comparison of performance and composition between ancient and modern concrete.

	Antique concrete	Modern concrete
Binder	lime; lime + pozzolan; hydraulic lime;	Portland cement; pozzolan cement; blast furnace cement;
Concrete aggregate	sand and coarse scrap of natural stone or brick;	sand and gravel or crushed stone with continuous particle size distribution;
Additive for concrete	natural products (sugar, etc.) with an undefined function;	chemical products: plasticizers, superplasticizers, air entrainers, accelerators, retarders, etc;
Composition	suggested relationships between sands, lime, pozzolan and stone debris;	importance of the water/cement ratio;
Mixing	manual	by mechanical means (concrete mixers);
Transport	only a short distance away;	even long distances with truck mixers and pumps;
Formwork	in wood or with brick or stone facings;	metal, wood, plastic;
Compaction	rudimentary with iron clubs;	very effective, with mechanical means (needle or wall vibrators)
Seasining	not specified;	jet protection with sheets, water nebulizers, anti-evaporation films;
Hardening	fair (up to 10-15 MPa);	excellent well over 30 MPa

2. The experimentation

The experimentation was conducted with the aim of defining the mix design of a durable concrete, according to UNI-EN 206-1 and 11104, comparing four types of concrete, characterized by different binders and additions:

a) Portland concrete CEM: II-A-LL 32.5 R

b) Pozzolanic Cement CEM: IV-B-P 32.5 R

c) CEM Portland cement: II-A-LL 32.5 R + 11% silica fume

d) CEM Portland cement: II-A-LL 32.5 R + 22% fly ash.

In order to then graph the correlations between the W/C – strength ratio, cement dosage C – strength and maturation days - strength, three mixes were made by varying the W/C ratio and the cement dosage:

- Mix 1) W/C = 0.6; C =270.00 kg/m^3
- Mix 2) W/C = 0.52; C =315 kg/m^3
- Mix 3) W/C = 0.45; C =361 kg/m^3
- Once the correlation graphs were determined, obtained from the breaking strengths of the cubes for each packaged mix, it was possible to design the mix design of a durable concrete.
- The experimentation was conducted using three types of aggregates:
- Sand 0/4 coming from pit "Irpinia Calcestruzzi" of Avellino;
- 4/8 crushed stone from the "Beton Cave" of Cava dè Tirreni;
- 8/20 crushed stone from the "Beton Cave" of Cava dè Tirreni;

Using the Bolomey granulometric curve, the optimal granulometric curve and the percentages of use of the available aggregates were determined (Fig. 1 and Table 2).

Table 2 | Granulometric range.

Sand 0/4	42%
crushed stone 4/8	68% - 42% = 26%
crushed stone 8/20	100% - 68% = 32%

In the doughs have been added:

- Superplasticizer additive: Creative LGX produced by Axim Italia
- Silica fume produced by Axim Italia
- Fly ash produced by Italcementi S.p.A.

For each type of concrete, five cubes were made which were then "broken" to:

1) 3 days of seasoning;

2) 7 days of seasoning;

3) 14 days of seasoning;

4) 28 days of seasoning;

5) 56 days of seasoning.

Each cube has been characterized with the initials type: cube n. a)1-1 where "a" indicates the type of concrete, "1" the W/C ratio and dosage, "-1" the seasoning time.

To analyze each mix in detail, an Excel spreadsheet was created where the volume of the aggregate and the kg/m^3 in s.d.s. (saturated to dry surface) are automatically calculated as the cement and additive vary.; the mixtures

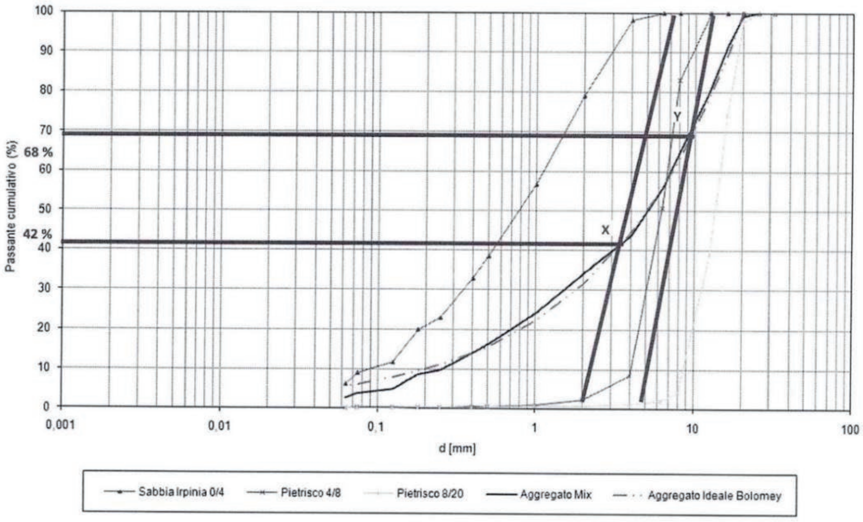

Figure 1 | Logarithmic particle size distribution of aggregates. Abscissa axis d[mm]; Ordinate axis Passerby [%].

of each mix were proportioned by volume to 30 lt. compared to 1000 lt.

In the preparation phase of each mix, the humidity value of the aggregates was measured, finding that the sand was always in a dry condition, therefore it was necessary to add water to saturate the pores and bring it to (s.d.s.), while the crushed stone 4/8 and 8/20 were always in the condition (s.d.s.). Tests were carried out on the fresh concrete for each type of mixture, namely: slump test, measurement of spreading on the shake table, measurement of the density in the fresh state, measurement of the entrained air, measurement of the external temperature and humidity, measurement of the fresh temperature and pH.

By way of example, Tables 3, 4 and 5 show the mixes for the type of mix d) 1, d) 2 and d) 3.

Using a press, compliant with UNI-EN 12390-3, the tensile strength at the pre-established deadlines in MPa was determined for each specimen.

It was thus possible to determine the following correlations for each concrete: W/C - Strength; dosage C - Resistance; seasoning days - Resistance.

By way of example, Figures 2 and 3 show the Correlation of W/C and dosage C with strength (MPa) at 28 days of maturation.

By studying the correlation graphs it was possible to deduce the following.

The use of IV-B-P 32.5 R pozzolanic cement, with the same C dosage and W/C ratio, has very low compressive strength, compared to II-A-LL 32.5 R Portland cement, of the order of:

- 54.1÷55.2% less after 3 days of maturity;
- 50÷51.9% in 7 days;
- 36.5÷40.0% in 14 days;
- 30.9÷35.9% in 28 days;
- and finally to 56 days by 25.6÷32.47%.

The use of silica fume in addition to II-A-LL 32.5 R cement produces:

- after 3 days a higher strength, of the order of 1.34÷2.79%, of the same mix without addition;
- in 7 days an increase of 2.1÷5.93%;
- 6.34÷18.12% in 14 days;
- 15.7÷26.02% in 28 days;
- and finally at 56 days of 19.94÷29.03%.

The use of fly ash in addition to II-A-LL 32.5 R cement produced:

- after 3 days of maturation, a compressive strength equal to that of the same mix without additions;
- in 7 days, a slight initial increase of 1.47÷2.81%;
- in 14 days an increase of 5.38÷5.54%;
- in 28 days an increase of 6.42÷9.50%;
- and finally in 56 days an increase of 9.62÷10.30%.

From the previous observations it is legitimate to deduce the following.

Table 3 | Mix d) 1.

Components	%	kg/m^3	M. Vol	Volumes	Ass %	Humidity	H_2O	kg/m^3 effective	Mix kg/prova
Sand	38,4	753,38	2,69	280,07	1,20	0,50	-5,2	748,17	22,445
Crushed stone 4/8	26	515,06	2,71	189,68	0,41	0,41	0,00	515,06	15,452
Crushed stone 8/20	32	633,85	2,71	233,65	0,11	0,11	0,00	633,85	19,015
Fly ash	3,65	59,97	2,25	26,65	0,00	0,00	0,00	59,98	1,799
CEM II A-LL 32,5		271,60	3,15	86,22					8,148
Superplasticizer	0,95	2,73	1,06	2,57					0,082
Project water	163,0	160,91	1	160,91				166,12	4,984
Air trapped	2	20,00							
M. Volum. theoretical		2397		1000				2397,51	71,925
W/C 0,60									

Table 4 | Mix d) 2.

Components	%	kg/m^3	M. Vol	Volumes	Ass %	Humidity	H_2O	kg/m^3 effective	Impasto kg/prova
Sand	37,6	725,78	2,69	296,81	1,200	0,50	-5,02	7230,76	21,623
Crushed stone 4/8	26	505,55	2,713	186,37	0,412	0,41	0,00	505,55	15,166
Crushed stone 8/20	32	622,14	2,712	229,38	0,1	0,11	0,00	622,14	18,664
Cenere volante	4,36	70,24	2,25	31,22	0,00	0,00	0,00	70,24	2,107
CEM II A-LL 32,5	-	313,26	3,15	99,47				313,26	9,398
Superplasticizer	1,36	4,508	1,06	4,25				4,51	0,135
Project water	162,9	159,49	1	159,49				164,51	4,935
Air trapped	2	20,00	1	20,00				20,00	
M. Volum. theoretical	-	2401	-	999,96				2401	72,029
W/C 0,52									

Table 5 | Mix d)3.

Components	%	kg/m^3	M. Vol	Volumes	Ass %	Humidity	H_2O	kg/m^3 effective	Mix kg/prova
Sand	36,9	695,93	2,69	258,71	1,200	0,500	-4,81	691,12	20,734
Crushed stone 4/8	26	494,35	2,71	182,24	0,412	0,412	0,00	494,35	14,830
Crushed stone 8/20	32	608,36	2,71	224,30	0,107	0,107	0,00	608,36	18,251
Cenere volante	5,09	80,27	2,25	35,68	0,000	0,00	0,00	80,28	2,408
CEM II A-LL 32,5	-	362,08	3,15	114,95				362,08	10,862
Superplasticizer		6,34	1,06	5,98				6,340	0,190
Project water		158,15	1	158,15				162,97	4,889
Air trapped		20,00	1	20,00				20,00	
M. Volum. theoretical		2405	-	1000				2405	72,164
W/C 0,45									

The use of a limestone Portland cement (II-A-LL 32.5R) certainly produces good resistance characteristics but offers poor resistance to aggressive agents. To improve the durability of this cement, an inert (type II addition envisaged by UNI-EN 206-1) of a pozzolanic nature (silica fume or fly ash) must be added to the concrete, capable of making the cement matrix more compact and resistant to attacks by external agents.

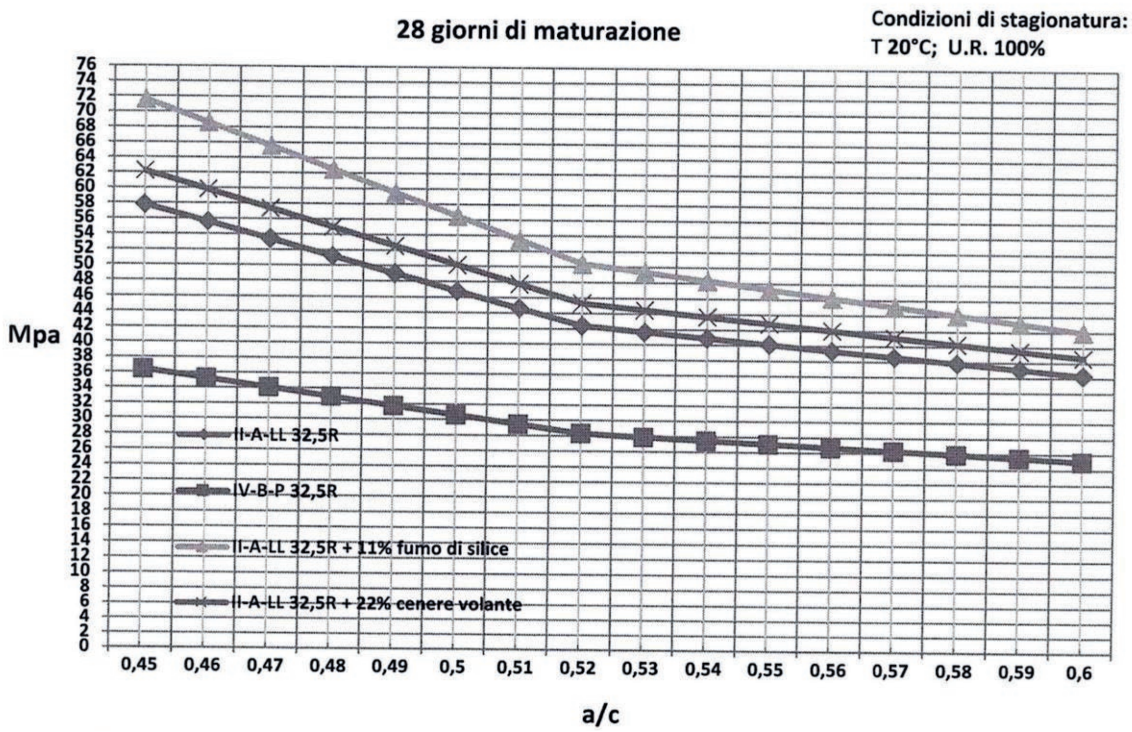

Figure 2 | Correlation W/C – Strength (MPa) at 28 days of maturation; seasining conditions: T=20°C, U.R. 100%; Abscissa axis W/C.

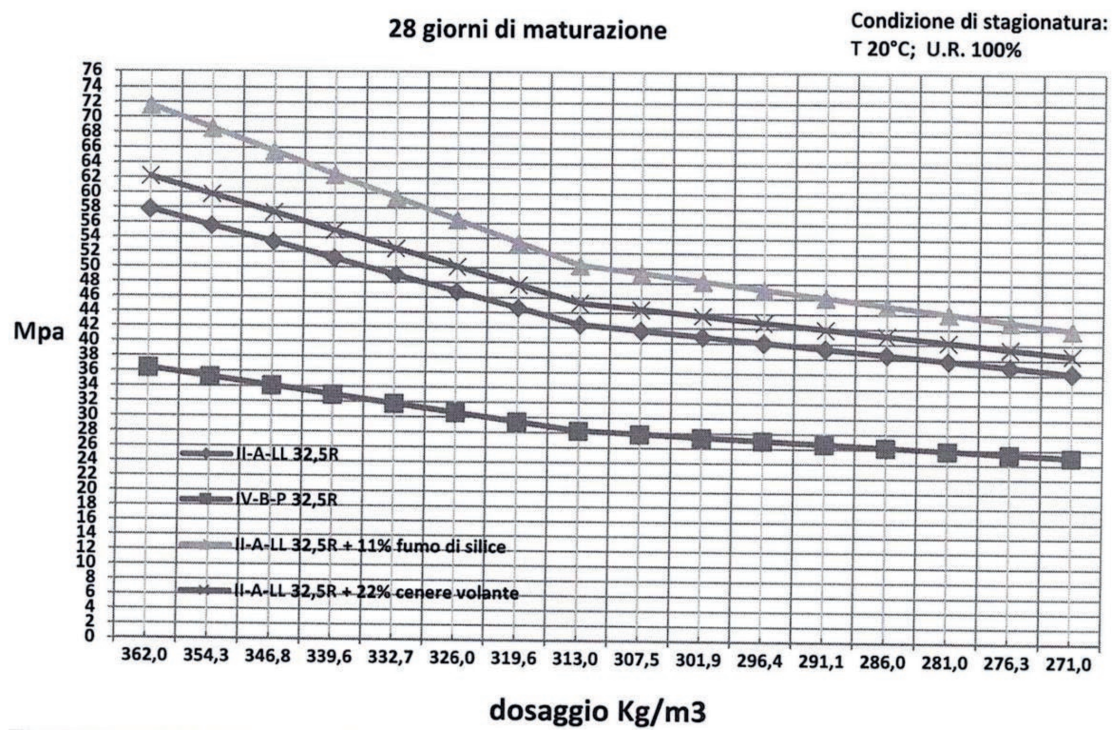

Figure 3 | Correlation Assay C - Strength (MPa) at 28 days of maturation; seasining conditions: T=20°C, U.R. 100%; abscissa axis C [kg/m^3].

A concrete prepared with pozzolanic cement (IV-B-P 32.5R) produces poor compressive strength but offers good durability due to the pozzolanic effect. In fact, the pozzolana reacts with the calcium hydroxide, producing a fibrous and compact cementitious matrix. The use of this cement for high strength classes would require a lot of cement, creating workability problems, greater shrinkage, cracking, etc. In conclusion, this concrete responds well to the problem of durability but not to that of compressive strength.

The use of silica fume in addition to the concrete determines a pozzolanic reaction producing two advantages:

- a notable increase in resistance already in the first days of maturation;
- the formation of a much more compact cement matrix that is not easily penetrated by aggressive agents, generating good durability characteristics.

This concrete with the addition of silica fume can exploit both the greater compressive strength (it is used for high strength HPC or HSC concretes), and the best durability even for very aggressive environments.

The use of fly ash produces advantages both in terms of resistance and durability; but in this case on a very small scale because the pozzolanic effect of the ash is less than that produced by fly ash.

This concrete, therefore, takes advantage of the slight increase in resistance to long curing but is used for durable concretes in non-aggressive environments.

3. Mix design of a durable concrete

Using the results of the experiment illustrated above, we proceeded with the study of the mix design of a durable concrete, with resistance class C30/37, exposure class XS1 (intended in a marine environment exposed to wind dragging of water), workability class S5 and with a maximum diameter dmax of 20 mm.

In these hypotheses, three types of concrete were designed, varying the type of binder to enhance the aspects of durability:

- Type 1) Portland cement II-A-LL 32.5 R
- Type 2) Portland cement II-A-LL 32.5 R + 11% silica fume
- Type 3) Portland cement II-A-LL 32.5 R + 22% fly ash.

3.1. Mix design Type 1

To have a Rck 37 N/mm^2 on site, it is necessary to assume a compressive strength at 28 days equal to:

$$R_{cm28} = R_{ck} + 1,48 \times S$$

Where:

- Rck represents the cubic compressive strength (MPa);
- 1.48 is a multiplier coefficient established by the NTC 2008 standard;
- S is the standard deviation of the concrete mixing plant which can be deduced from the statistical control of production, equal on average to 4 MPa;

and therefore the cubic compressive strength at 28 days will be:

$$R_{cm28} = 37 + 1,48 \times 4 = 42,92 \text{ MPa}$$

For R_{cm28} = 42.92 MPa, from Figure 2 we obtain (W/C)1= 0.518, while from Figure 3 we obtain the cement dosage C1 = 316 kg/m^3.

For a durable concrete with exposure class XS1, UNI-EN 206-1 provides:

(W/C) ≤ 0.50; Rck ≥ 37 MPa and Cmin ≥ 300 (kg/m^3).

To have a W/C ratio = 0.50, a compressive strength R_{cm28} = 46.42 MPa is required.

Therefore, to satisfy both structural requirements (Rck = 37 MPa) and durability (XS1 exposure class in accordance with UNI-EN 206-1) it is necessary to adopt the more restrictive value of (W/C) = 0.50.

Having identified the compressive strength value equal to R_{cm28} = 46.42 MPa necessary to manufacture a Rck 37 in exposure class XS1, Figure 3 shows that the quantity of cement to be used is equal to 326.00 kg/m^3 which is greater than that prescribed by the law (300 kg/m^3).

At this point we can calculate the quantity of water, necessary to satisfy the required workability, using the relationship:

$$W = C \times (W/C) = 326,0 \times 0,50 = 163 \text{ lt}$$

In the tests carried out, the quantity of water was assumed to be almost constant and equal to 163 liters for the three mixtures 1), 2) and 3), and for each type of concrete a), b), c), d), for to prevent the addition or reduction of water from compromising the compressive strength comparison between the various packaged mixes.

Figure 4 shows that the percentage of additive will be 1.35%; and, for C = 326 kg/m^3, we will have 4.40 kg/m^3 of additive necessary to satisfy the project workability S5.

At this point, to define the composition of the concrete in terms of kg/m^3, once the water (W), additive (add) and cement (C) are known, we proceed to calculate the volume of the aggregate (Vi) which is determined with a simple volume balance by subtracting the volume of water (Vw), cement (Vc), additive (Vadd) and air (Va) from one cubic meter of concrete:

Vi = Vcls - Vc - Vw - Vadd - Va

which in the specific case becomes:

Vi = 1000 - 326/(3.15) - 163 - (4.40)/(1.06) - 20 = 709.36 lt

To calculate the quantities of sand 0/4, crushed stone 4/8 and crushed stone 8/20, in kg/m^3, which constitute the total quantity of inert material (i), proceed with the optimal proportioning based on the Bolomey granulometric curve.

Therefore, it results that the percentages of use of the aggregates, per m^3 of concrete, are equal to:

42% Sand 0/4; 26% crushed stone 4/8; 32 % crushed stone 8/20, and therefore:

Vi × 42 % = 297.93 l/m^3 × 2.69 = 801.43 kg/m^3 of Sand 0/4

Vi × 26 % = 184.43 l/m^3 × 2.713 = 500.29 kg/m^3 of crushed stone 4/8

Vi × 32 % = 227.00 l/m^3 × 2.712 = 615.62 kg/m^3 of crushed stone 8/20.

Table 6 summarizes the masses, in the s.s.a. condition, to prepare a cubic meter of concrete with compressive strength class C30/37, exposure class XS1 and workability class S5.

Table 7 shows the chloride content in mix design 1 calculated on the basis of what is declared by the producers of the concrete components (aggregates, cement, water, additives, additions).

Proceeding in the same way, the mix designs of durable concretes no. 2 and 3. Tables 8 and 9 show the respective compositions.

For the three compositions the chloride content results less that the value of 0,2%.

Abscissa axis C [kg/m^3]; Ordinate axis Percentage of additive [%]

4. Conclusion

Mix design study completed 1), 2), 3), for durable concretes with compressive strength class C30/37, exposure class XS1, workability class S5 and, respectively, Portland

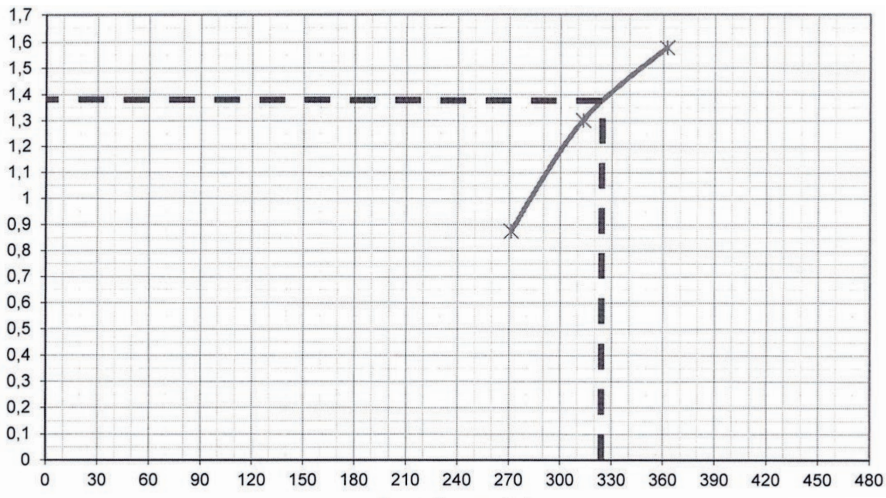

Figure 4 | Percentage additive for consistency S5 of Mix with concrete 32,5 R II-A-LL and W=163lt.

Table 6 | Mix design n. 1 of a durable concrete with compressive strength class C30/37, exposure class XS1 and workability class S5 and with Portland cement II-A-LL 32.5 R.

Components	%	kg/m³	M. Vol	Volumes	Ass %	Humidity	H_2O	kg/m³ effective	Mix kg/prova
Sand	42	801.43	2.69	297.93	1.200	1.200	0.00	801.432	24.043
Crushed stone 4/8	26	500.29	2.71	184.43	0.412	0.412	0.00	500.292	15.009
Crushed stone 8/20	32	615.68	2.71	226.99	0.107	1.107	0.00	615.673	18.470
CEM II A-LL 32,5	-	326.00	3.15	103.49				326.00	9.780
Superplasticizer	1.35	4.40	1.06	4.15				4.40	0.132
Project water	163	163.00	1	163.00				163.00	4.890
Air trapped	2	20.00	1	20.00				20.00	
M. Volum. theoretical		2411		1000				2411	72.324
W/C 0,50									

Table 7 | Chloride content in mix design n. 1 of a durable concrete.

Components	dosage for 1 m³	U.M.	CL⁻	CL⁻		grams CL⁻	grams CL⁻
			by law	declared		by law	declared
Sand	801.43	kg/m³	0.01	0.01	%	80.14	80.14
Crushed stone 4/8	500.29	kg/m³	0.01	0.01	%	50.03	50.03
Crushed stone 8/20	615.68	kg/m³	0.01	0.01	%	61.57	61.57
CEM II A-LL 32,5	326.00	kg/m³	0.01	0.04	%	326.00	130.40
Project water	163.00	l/m³	92	92	mg/l	14.99	14.996
Superplasticizer	4.151	l/m³	0.1	0.1	mg/l	4.15	4.151
Total grams of chloride m³						536.89	341.29
Total % chloride content with respect to cemen						0.165 %	0.105 %
Maximum permissible content						0.2 %	0.2%

Table 8 | Mix design n. 2 of a durable concrete with compressive strength class C30/37, exposure class XS1 and workability class S5 and with Portland cement II-A-LL 32.5 R + 11% silica fume.

Components	%	kg/m³	M. Vol	Volumes	Ass %	Humidity	H_2O	kg/m³ effective	Mix kg/prova
Sand	39,8	758,15	2,69	281,84	1,200	1,200	0,00	758,15	22,745
Crushed stone 4/8	26	500,07	2,71	184,40	0,412	0,412	0,00	500,06	15,002
Crushed stone 8/20	32	615,40	2,71	226,89	0,107	0,107	0,00	615,40	18,462
Silica fune	2,25	35,89	2,25	15,95	0,000	0,000	0,00	35,89	1,077
CEM II A-LL 32,5	-	326,00	3,15	103,49				326,00	9,780
Superplasticizer	1,46	4,74	1,06	4,47				4,74	0,142
Project water	163	163,00	1	163,00				163,00	4,890
Air trapped	2	20,00	1	20,00				20,00	
M. Volum. theoretical		2403		1000				2403	72,098
W/C 0,50									

Table 9 | Mix design n. 3 of a durable concrete with compressive strength class C30/37, exposure class XS1 and workability class S5 and with Portland cement II-A-LL 32.5 R + 22% fly ash

Components	%	kg/m³	M. Vol	Volumes	Ass %	Humidity	H_2O	kg/m³ effective	Mix kg/prova
Sand	37,5	714,80	2,69	265,73	1,200	1,200	0,00	714,80	21,444
Crushed stone 4/8	26	500,16	2,71	184,38	0,412	0,412	0,00	500,16	15,005
Crushed stone 8/20	32	615,51	2,71	226,93	0,107	0,107	0,00	615,51	18,465
Fly ash	4,53	72,31	2,25	32,14	0,000	0,000	0,00	72,31	2,169
CEM II A-LL 32,5	-	326,00	3,15	103,49				326,00	9,780
Superplasticizer	1,41	4,60	1,06	4,34				4,60	0,138
Project water	163	163,00	1	163,00				163,00	4,890
Air trapped	2	20,00	1	20,00				20,00	
M. Volum. theoretical		2396		1000,00				2396	71,892
W/C 0,50									

cement II-A-LL 32.5 R, Portland cement II-A-LL 32.5 R + 11% silica fume, Portland cement II-A-LL 32.5 R + 22% fly ash, an analysis was conducted both of the costs to highlight the incidence of additions in the concrete, and of the benefits in terms of compressive strength.

4.1. Costs

The market cost of the three concretes is equal to:

- for type 1) approximately €74.00/m^3;
- for type 2) approximately €103.00/m^3 (74.00+29.00);
- for type 3) approximately €85.00/m^3 (74.00+11.00).

From this we derive that the cost of concrete with the addition of type 2) silica fume is approximately 39.18% higher than the type1) without addition; the high cost of silica fume and therefore of concrete is due both to its limited availability on the market but also to the very high pozzolanic characteristics it offers; for this reason silica fume is used in batching plants only in exceptional cases for the production of special concretes when a high impermeability is required or when mixtures with high and very high mechanical compressive strength are to be produced.

Instead for concrete type 3), its cost is 14.86% more than type 1) without addition; due to the large commercialization of fly ash, the cost of this concrete is more acceptable than silica fume. Type 3) concrete therefore finds widespread use in batching plants both to improve those lean concretes poor in very fine content and to exploit the pozzolanic effect of the ash.

4.2. Benefits

Types 1), 2) and 3) concretes are all durable, as they comply with the requirements of UNI-EN 206-1 (in terms of W/C ratio, cement dosage, strength class, chloride content), but they differ in the compressive strength and the ratio (W/C)equiv.

In particular, it results:

- for type 1): Rcm28 = 46.42 MPa; (W/C) = 0.50
- for type 2): Rcm28 = 56.50 MPa;

  (W/C)equiv = 0.456
- for type 3): Rcm28 = 50.10 MPa;

  (W/C)equiv = 0.485

From the above values we note:

- for type 2), compared to type 1), the Rcm28 increases by 21.70% and the W/C ratio decreases by 8.80%;
- for type 3), compared to type 1), the Rcm28 increases by 7.92% and the W/C ratio decreases by 3.00%.

The aforementioned variations are to be attributed to the presence of the type II addition (silica fume or ash) which generates a pozzolanic reaction capable of providing the concrete, not only with an increase in compressive strength but also with a much more fibrous and compact cement matrix.. For the purpose of contributing to the final strength, the densifying or filling effect is important; in fact, the microsilica particles, thanks to their small size, can be inserted into the voids existing between the cement particles and the product of the “amorphous silica - calcium hydroxide” reaction can make the cementitious matrix very compact and therefore mechanically more resistant concrete.

In conclusion, the choice of placing type 1), 2), or 3) concrete essentially depends on the degree of environmental aggression to which the structure will be exposed.

The designer of the structure will have to choose which type of concrete to adopt (with or without the addition of ash or silica fume) in relation to external environmental attacks.

From the results obtained from the experimentation carried out, it is possible to state that with the addition type II (flying ash or silica fume), the durability of the concrete against aggressive environmental stresses improves:

- both due to the pozzolanic reaction which produces a more fibrous and more resistant cementitious matrix to environmental attacks
- both for the lower content of calcium hydroxide in the cement matrix which is involved in the pozzolanic reaction with both the fly ash and the silica fume.

The higher cost of durable concrete, with or without type II additions, is amply justified by the savings obtained in the maintenance costs of a reinforced concrete structure. or zip code

In fact, even if the use of type II additions increases the cost of concrete by 10-40% compared to one that is not durable and without additions (with an increase in the cost of the entire work of no more than 0.6 – 2.4 %), on the other hand, the restoration costs for a non-durable concrete work can reach up to 125 times the original cost of the work when the deterioration is so advanced as to make it unusable for its original functions.

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Attributions

This work was written by the authors in close collaboration and with unity of purpose. However Chapters 1 and 4 are to be attributed to Renato Iovino, chapters 2 and 3 to Emanuele La Mantia

The conclusions were conducted by the authors jointly.

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UNI-EN 12390-4 Prova su calcestruzzo indurito. Resistenza alla compressione. Specifiche per macchina di prova.

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